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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

ABSTRACT: The energy system is the primary source of air pollution. Thus, evolution of the energy system into the future will affect society's ability to maintain air quality. Anticipating this evolution is difficult because of inherent uncertainty in predicting future energy demand, fuel use, and technology adoption. We apply scenario planning to address this uncertainty, developing four very different visions of the future. Stakeholder engagement suggested that technological progress and social attitudes toward the environment are critical and uncertain factors for determining future emissions. Combining transformative and static assumptions about these factors yields a matrix of four scenarios that encompass a wide range of outcomes. We implement these scenarios in the U.S. Environmental Protection Agency MARKet ALlocation (MARKAL) model. Results suggest that both shifting attitudes and technology transformation may lead to emission reductions relative to the present, even without additional policies. Emission caps, such as the Cross-State Air-Pollution Rule, are most effective at protecting against future emission increases. An important outcome of this work is the scenario-implementation approach, which uses technology-specific discount rates to encourage scenario-specific technology and fuel choices. End-use energy demands are modified to approximate societal changes. This implementation allows the model to respond to perturbations in manners consistent with each scenario.

1. INTRODUCTION

Scenarios are an important tool for supporting decision making[1,2] and helping planners identify, understand, and communicate uncertainties about key assumptions. Furthermore, by implementing scenarios within computational models, planners can anticipate future challenges and evaluate candidate policies over a wide range of possible conditions. The results may help clarify the strengths and weaknesses of the alternative policy options, provide information regarding potential pitfalls, and suggest characteristics that lead to robustness with respect to uncertainty.

The utility of scenarios has spawned the field of scenario planning, and the related literature now includes a wide array of methodological developments, syntheses, and applications.[3−7] Scenario planning has been integrated into many public and private sector decision-making processes,[8,9] including within a variety of environmental contexts.[10−12]

1.1. Uncertainty and Air-Quality Management. Despite the surge in interest in scenario planning, scenario applications in air-quality management have been limited. To date, most applications have used "scenario" to refer to one of several alternative management options.[13−15] Others refer to each run made in a parametric sensitivity analysis, which involves evaluating perturbations to a small number of model inputs (e.g., the price of oil, CO_2 mitigation targets, technology costs, or maximum growth rates of renewables).[16,17] Scenario applications also have sought to quantify a range of air pollutant trajectories associated with different realizations of the future.[18,19] While applications have historically focused on climate-change mitigation and its air pollutant emission co-benefits, air quality management specific applications have begun to emerge in the past several years.[20,21]

Air-quality management often involves the development of emission control strategies for achieving and maintaining the National Ambient Air Quality Standards.[22] These strategies can include control requirements, emission limits, and emission rate-based standards. Strategies to protect health

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can also incorporate incentives for behavioral changes, such as broadcast public health warnings and subsidies for mass transit during poor air quality episodes.

The performance of candidate management strategies is often evaluated using a series of computer models such as economic, energy, emissions, air quality, and health-benefit models.[23] The cost effectiveness or net benefits of a strategy is calculated by comparing its predicted cost and impacts with the cost and impacts of a baseline projection. Often, baseline future conditions are extrapolated from the past or are based upon the projections of groups such as the U.S. Census Bureau[24] and the U.S. Energy Information Administration.[25] In government analyses, baseline or business-as-usual scenarios usually include "on the books" regulations only.

Typically, cost−benefit analyses have examined air-quality management strategies no farther than 10 to 15 years into the future. This time horizon is reasonable for strategies that focus on end-of-pipe controls or episodic behavioral changes. Analysis timelines are being extended, however, as decision-makers begin to explore nontraditional measures such as switching to cleaner fuels and introducing renewable electricity and energy-efficiency targets.[26] Modeling out several decades into the future can more fully represent turnover from existing stock and capture additional impacts, such as climate co-benefits of policies directed at local emissions or air pollution co-benefits of programs to reduce carbon emissions.

The use of longer time horizons also yields a challenge: greater uncertainty in the baseline itself. Projections can change significantly, even in a decade.[27] The life cycle of fossil fuels, including extraction, processing, and use, is the primary source of most air pollutants and greenhouse gas emissions in the United States.[28] Thus, baseline emissions are dependent on assumptions about future energy demands as well as technologies and fuels that will be used to meet those demands. Factors influencing the evolution of the energy system include population growth and migration, economic growth and transformation, climate change, technology change, land use change, fuel price and availability, consumer choices, and policy drivers.[29] Multidecadal projections of each of these factors, even under baseline assumptions, involve considerable uncertainty.

1.2. Methods for Addressing Uncertainty.

A variety of methods are available for addressing uncertainty in air-quality management.[30] For example, uncertainty analysis methods propagate assumed distributions for uncertain inputs through a model, with the goal of estimating statistical distributions of model outputs. We do not have statistical distributions on inputs, and the Monte Carlo methods used to propagate uncertainty would be prohibitively computationally intensive for a model with up to a 2 h runtime.

Sensitivity analysis methods are another option.[31,32] In parametric sensitivity analysis, the values of the uncertain parameters are perturbed one at a time, with all other parameters held at their baseline values. The resulting changes in model outputs are recorded, and their responses to input changes are evaluated, compared, and often ranked. Limitations of this parametric approach include that it requires a baseline to be specified a priori and that it does not address sensitivities to simultaneous changes in large numbers of inputs.

Nested parametric sensitivity analysis addresses these limitations. The approach involves the discretization of multiple uncertain input parameters followed by an evaluation of some or all combinations of the discretized values. The baseline does not need to be specified a priori because perturbations can be examined from any combination. A limitation of nested sensitivity analysis is the "curse of dimensionality", which can yield a computationally intractable problem if there are more than a handful of uncertain parameters.[33] Alternatively, probabilistic methods such as a Monte Carlo simulation can be used to sample the uncertain input parameters much more efficiently than evaluating each option.[32]

Each of these approaches may require dozens to hundreds of model evaluations. While high-performance computing can reduce the clock time associated with iterative modeling, such resources and expertise are not always readily available to the governmental and nongovernmental organizations that conduct air-quality management.

Scenario planning methods can provide a tractable alternative.[34] These methods seek to integrate the domain knowledge of decision-makers in a structured manner, identifying a handful of scenarios that probe key known uncertainties.[35,36] In air-quality management, scenario planning methods have the potential to complement traditional control-versus-baseline policy analysis by producing a small set of very different alternative baselines. The scenarios provide distinct combinations of variables in the decision space that can be explored further with Monte Carlo analysis or other methods to propagate input parameter uncertainty. Policies and management strategies can then be evaluated across these baselines, providing a fuller picture of the management strategy performance under plausible realizations of the future. Relative to parametric and nested parametric sensitivity analysis, scenario planning has the downside of it being difficult to trace strategy performance to assumptions within the broader scenario.

A number of commonalities exist across formal scenario-planning methods that have emerged in the past decades:[1] Scenario planning begins with one or more focus questions, key uncertain factors affecting how the future will unfold are identified; the potential realizations of these key uncertain factors are combined to create scenarios of interest, and the resulting scenarios are applied in support of decision-making analysis.

In many instances, scenarios can be implemented within a modeling framework and used to assess management strategy performance quantitatively. Application is an iterative process: as the scenarios are applied, knowledge is gained that can be used to refine earlier steps. For this process to provide useful insights, the scenarios must be sufficiently distinct to represent a wide range of possible futures while at the same time being plausible, internally consistent, comprehensible, traceable, and transparent.[1]

We have applied one such scenario-planning method, the scenario matrix approach,[37,38] to demonstrate the utility of scenarios in air-quality management. In this paper, the scenario development and implementation processes are summarized, and we demonstrate the application of the resulting scenarios. We illustrate how scenarios yield very different evolutions of the energy system and explore the emission implications.

1.3. Emissions Implications of Energy Scenarios.

Energy use is a substantial contributor to emissions of a variety of pollutants. Energy models have been used to evaluate how emissions might change under a variety of future conditions. Previous investigations on the impact of future

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energy systems include analyses of how introduction or increased use of specific technologies such as coal and biomass to liquids,[16] natural gas combined cycle with carbon capture,[39] solar photovoltaics,[17] and electric vehicles[40] might interact within the larger energy system and alter emissions projections. Models have also been used to investigate how regional and national policies targeting emissions or fuels might alter the energy system and what impact that might have on emissions.[15,41−45] Additional research has used models to investigate how changes in the price of fuels or technologies might change the larger energy system.[46−48] Energy models that represent associated emissions are useful tools for investigations of the interplay between air quality and energy.[49]

2. METHODS AND MODELS

2.1. Scenario Matrix Approach to Air-Quality Management. In 2010, a facilitated scenario planning workshop was attended by the United States Environmental Protection Agency (U.S. EPA) air-quality managers, analysts, and research staff.[21,50] The focus question for the workshop was relatively broad: "What are the uncertain factors that will influence future air quality management in the coming decades?" From the discussion, the following two factors were identified: "capacity for technological change" and "capacity for societal change in response to environmental considerations." These two factors formed the basis for the resulting scenario matrix, which is shown in the abstract graphic.

A subset of the workshop attendees then met to expand upon the scenarios, and detailed scenario narratives involving dozens of assumptions were developed. Next, these narratives were implemented within the EPA MARKet ALlocation (MARKAL) energy system modeling framework. An overview of development of the scenarios is available in Gamas et al.[21] As the underlying MARKAL modeling framework and data have been updated, the scenario implementations have evolved as well. This evolution and the current implementation are described in section 3. These specific scenarios were chosen in response to the criteria identified in the workshop, the desire to have scenarios that are significantly differentiated as to be useful, and the desire to see how the social and technological factors interact with each other.

The Conservation scenario exemplifies new societal paradigms with stagnant technology. In this scenario, society is compelled to prioritize environmental protection. There are limited funds available to invest in research and development of new technologies. Although the technologies that are used are primarily those in existence today, markets are transformed to focus on goods with low life-cycle impact. Energy sources shift from fossil fuels to renewable energy and consumption patterns tend toward conservation, energy efficiency, and sustainable production practices.

The iSustainability scenario embraces new societal paradigms and transformative technology. The "i" in the name is indicative of technology "innovation." This scenario moves toward a new social paradigm from the bottom up, armed with cutting-edge technologies. Cheaper renewable energy and new efficiency measures help power economic growth. Highly networked individuals, initiatives, and technological innovations drive society toward local and distributed solutions to our needs for food, housing, and transportation. Support for science and technology are strong. However, there is also an emerging consensus that technological change needs to be coupled with societal change and transformation to provide a higher quality of life while minimizing environmental impacts.

The Muddling Through scenario is defined by old social paradigms and stagnant technological advancement. In this future, society is divided about priorities and technological development mirrors societal gridlock. Funds are diverted from the research and development of new energy technologies to concerns outside the energy sphere, and technological development is stagnant. Consumers prefer to purchase inexpensive and familiar technologies and spend any additional money on increased travel, larger houses, and more goods produced in the industrial sector.

The Go Our Own Way scenario features old societal paradigms paired with transformative technology. As domestic energy extraction expands, strengthening domestic energy security becomes a possibility. The push for domestic energy leads to increased investment in research and development. Energy technologies are improved, but the environment is not a priority in these developments. The improved technologies grow the economy, leading to increased investment in new technologies, with a significant efficiency benefit.

2.2. U.S. EPA MARKAL Energy-Modeling Framework. The EPA MARKAL framework is composed of the MARKAL energy system model[51,52] and the U.S. EPA nine-region database (EPAUS9r).[53] The database is publicly available and documentation can be found online.[53] MARKAL is a linear programming-based mathematical model that simulates evolution of an energy system. This simulation is accomplished by minimizing the present value of the cost of energy-related technology and fuel choices over a modeled time horizon, subject to constraints on energy supplies, energy demands, and efficiency and emissions limits. The EPAUS9r database allows MARKAL to be applied to the U.S. energy system, which includes the electricity production, refining, manufacturing, residential, commercial, industrial, transportation, and resource supply sectors. The database supports a spatial resolution of the U.S. Census Division, a modeling horizon of 2005 through 2055, and a 5 year temporal resolution.

A unique attribute of the EPA MARKAL framework compared with many energy modeling frameworks is its inclusion of not only greenhouse gases but also criteria air pollutant (CAP) emissions and air pollution controls. As a result, EPA MARKAL can approximate the energy system impacts of U.S. federal regulations, including the Cross-State Air Pollution Rule (CSAPR),[23] state-level Renewable Portfolio Standards (RPS) aggregated to the regional level,[54] the Corporate Average Fuel Economy (CAFE) standards,[55] the Tier 3 mobile vehicle emission standards,[56] and various New Source Performance Standards (NSPSs).[57,58]

The primary source of energy-related data for the EPAUS9r database is the U.S. Energy Information Administration's 2016 Annual Energy Outlook.[59] Emission factors are derived from several sources, including the EPA's WebFire database,[60] Inventory of Greenhouse Gas Sources and Sinks,[61] MObile Vehicle Emission Simulator (MOVES),[62] Integrated Planning Model,[63] the National Emissions Inventory (NEI),[64] the Facility Level Information on Greenhouse gases Tool (FLIGHT),[65] and various regulatory impact analyses.

3. IMPLEMENTATION

Implementation of the scenarios within MARKAL has been an iterative, learning process. In the initial published implementation,[21] MARKAL was constrained to adhere to the specific

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Table 1. Scenario- and Technology-Explicit Hurdle Rates in the Electric Sector[a]

Technology	Conservation	iSustainability	Go Our Own Way	Muddling Through
Biomass gasification	0.17	0.06	0.21	0.55
Biomass gasification with CCS	0.17	0.06	0.21	0.55
Coal gasification	0.34	0.11	0.15	0.38
Coal gasification with CCS	0.25	0.08	0.21	0.55
New pulverized coal	0.21	0.20	0.28	0.16
Existing pulverized coal	0.21	0.40	0.43	0.16
Advanced gas combined-cycle	0.24	0.08	0.15	0.38
Gas combined-cycle with CCS	0.25	0.08	0.21	0.55
Advanced gas turbines	0.21	0.15	0.21	0.23
Conventional gas combined-cycle	0.14	0.15	0.28	0.16
Conventional gas turbines	0.21	0.15	0.21	0.23
Solar PV (utility)	0.08	0.06	0.21	0.23
Solar thermal	0.08	0.06	0.21	0.23
Offshore wind	0.13	0.04	0.21	0.55
Onshore wind	0.08	0.06	0.21	0.23
New nuclear plant	0.15	0.15	0.28	0.16
Existing nuclear plant	0.15	0.29	0.43	0.16
Waste-to-energy	0.14	0.11	0.29	0.33

*CCS = Carbon capture and Storage, PV = solar photovoltaic

[a]The shading denotes relative values within each scenario, where dark-red shaded technologies have a very high hurdle rate and are less likely to be used while green cells, have a low hurdle rate, indicating that the technology is more likely to be used in that scenario. CCS: carbon capture and storage. PV: solar photovoltaic.

details of each narrative. This implementation provides valuable insights, particularly by testing the plausibility of narratives' assumptions from an energy-system standpoint. In several instances, the narratives were revised in response to infeasibilities identified in modeling. Ultimately, the scenarios successfully produced a set of alternative pollutant-, region-, and sector-specific emission projections through 2055.

A limitation of this approach became apparent as we explored application of the scenarios to policy analyses. By constraining technology and fuel choices to reflect the narratives, little room was left for the optimization routine to respond to additional perturbations. For example, with pre-specified passenger vehicle market shares, the scenarios could not respond to an increase in oil prices or to the imposition of more-stringent fuel efficiency standards. The large number of constraints required to implement the scenario narratives also made documentation and updating of the scenarios more difficult and less transparent. A more-flexible scenario implementation was needed.

This current analysis represents a new and functional implementation of the scenarios, which allows greater flexibility, transparency, and reproducibility. The approach is applicable not only to the MARKAL model and EPAUS9r database but also to other energy system modeling platforms. Instead of implementing detailed narratives via constraints to individual technology and fuel, we shifted our focus to a higher level representation of the axes of the scenario matrix. Only two modeling levers are used for this purpose: technology-specific hurdle rates and shifts in end-use energy demands. The implementation approach, which is summarized below, is described in more detail in sections S2 and S3 of the Supporting Information.

3.1. Technology-Specific Hurdle Rates. Technology-specific discount rates, called "hurdle rates", allow the societal preferences of each scenario for one technology or another to be reflected in the MARKAL optimization routine. Hurdle rates impact how capital investments are discounted over the time period in determining the present value of the cost of each technology. Section S2 in the Supporting Information provides additional information about hurdle rates, and their use in energy economic modeling is discussed in Garcia-Gusano et al.[66] Because MARKAL minimizes the present value of the energy system, hurdle rates are a good tool for this model. Hurdle rates are being used as a proxy for many possible changes such as technology subsidies or willingness to pay differences but do not necessarily represent a literal changing of discount rates for investments. While this simplified approach prevents a deeper understanding of the underlying mechanisms that bring about the scenarios, it allows the scenarios to be utilized for future analyses without being overburdened by constraints.

A higher hurdle rate leads to the technology being perceived as more expensive by the model. The hurdle rate could be increased to represent range anxiety leading consumers to hesitate to purchase electric vehicles. In a scenario in which consumers care more about the environment, they might be willing to pay slightly more for an environmentally friendly option, and hurdle rates allow us to adjust the present value of the technology accordingly. We use hurdle rates to remain impartial to particular mechanisms by which the futures might be driven.

Technology-specific hurdle rates were developed for each scenario. A system of hurdle rate multipliers is used to represent scenario-specific preferences regarding the attributes of each technology: conventional, advanced, renewable, beneficial to local environments, beneficial for the global environment, energy efficient, whether it requires lifetime extensions of older technology, whether it requires infra-structure or behavioral changes, or whether it has a high capital cost. These calculations are conducted in a spreadsheet in which each technology is scored for each of the above attributes and scenario-specific preferences for these attributes

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can be adjusted. For each attribute (i), we consider whether it would make the technology more or less favorable in a particular scenario or will not influence use in that scenario. We also weight each attribute based on its importance to the scenario narrative. The priority and alignment scores for each attribute are used to determine hurdle rates for each technology in each scenario. The values used in the calculation and their corresponding meanings are available in section S3 of the Supporting Information. Scoring is based on narratives developed in prior work[21] and summarized in section 2.1 and the need for divergence among results. These weights are used to calculate the hurdle rate according to eq 1:

$$\text{hurdle rate} = A \times \prod_{i=1}^{9} 1 + \left(\frac{1}{\text{alignment}_i} - 1\right) \times \text{priority}_i \tag{1}$$

where $A = 0.15$ is the base hurdle rate, a value often used in MARKAL modeling to reflect factors such as borrowing costs and risk aversion; i is attributes 1−9; alignment is a value expressing how the attribute (i) aligns with the narrative for this scenario; and priority is a value expressing how this attribute is weighted for this scenario.

Table 1 provides an example of the resulting technology- and scenario-specific hurdle rates in the electric sector. Section S3 in the Supporting Information gives relevant values for other sectors, technologies, and scenarios, and the spreadsheet in the Supporting Information includes all hurdle rates used across the full database. Reading down the columns allows a comparison of the preference for one technology or another in each scenario. Technologies with lower hurdle rates are more likely to be used.

While the use of hurdle rates allows the scenarios to be more flexible for use with additional policies or technologies, hurdle rates change relative preferences for technologies in calibration years. Therefore, we also added constraints on the model for years 2005, 2010, and 2015 to calibrate results to historical energy system characterization.

Hurdle rates function in the model by altering the present value of the technology. The objective of MARKAL is to minimize the present value of the entire system. The amortized annual capital cost, A_c, of a technology is calculated using the technology-specific hurdle rate, h:

$$A_c = C \times [h \times (1 + h)^n]/[(1 + h)^n - 1] \tag{2}$$

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 during optimization is then calculated by bringing A_c and other annual costs, A, back to the present using the system-wide discount rate, d:

$$V = (A_c + A) \times [(1 + d)^n - 1]/[d \times (1 + d)^n] \times 1/(1 + d)^t \tag{3}$$

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 in MARKAL 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 \$5000; 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, reflecting a preference for the technology, the present value becomes \$83 000.

Using the example of offshore wind, we show how the attribute scoring and weighting leads to the values shown in Table 1. In all scenarios, offshore wind is considered advanced, renewable, environmentally friendly on both the local and the global levels, and requiring infrastructure change. These attributes are scored differently in each scenario, leading to different hurdle rates. In iSustainability, each of the first four attributes aligns with the preferences ($\text{alignment}_i = 1.25$) in that scenario and infrastructure change is considered neutral ($\text{alignment}_i = 1$). Each of the aligned attributes is weighted as either high ($\text{priority}_i = 1.375$) or, for renewable, very-high ($\text{priority}_i = 1.5$) priority. Infrastructure change has a priority_i weight of 1 because it is neutral to the scenario. This calculation is shown in eq 4, based on eq 1:

$$\begin{aligned} \text{offWnd}_{\text{isus}} &= 0.15 \times \left[\left(\frac{1}{1.25} - 1\right) \times 1.375 + 1\right]^3 \\ &\times \left[\left(\frac{1}{1.25} - 1\right) \times 1.5 + 1\right] \times \left[\left(\frac{1}{1} - 1\right) \times 1 + 1\right] \\ &= 0.15 \times 0.73^3 \times 0.7 \times 1 = 0.04 \end{aligned} \tag{4}$$

In Muddling Through, the same attributes are valued differently. Advanced technologies and the need for infrastructure change are viewed negatively ($\text{alignment}_i = 0.75$), and the others are neutral. The priority of avoiding advanced technologies is extreme ($\text{priority}_i = 2$), while that for avoiding infrastructure change is high. In addition, all hurdle rates are higher due to a multiplier of 1.5 in Muddling Through to represent a desire to avoid high capital costs. This calculation is shown in eq 5:

$$\begin{aligned} \text{offWnd}_{\text{mudl}} &= 0.15 \times \left[\left(\frac{1}{0.75} - 1\right) \times 2 + 1\right] \\ &\times \left[\left(\frac{1}{1} - 1\right) \times 1 + 1\right]^3 \times \left[\left(\frac{1}{0.75} - 1\right) \times 1.375 + 1\right] \\ &\times 1.5 = 0.15 \times 1.67 \times 1^3 \times 1.46 \times 1.5 = 0.55 \end{aligned} \tag{5}$$

3.2. Energy Service Demand Adjustments. Energy service demands (such as space heating in buildings, industrial process heat, and vehicle miles traveled) are also modified to reflect assumed societal preferences for each scenario. Changes do not refer to differences in demand for electricity or fuel but are applied to services such as vehicle miles traveled. Various energy demands are assumed to increase or decrease by 15% in 2050 relative to their 2050 baseline projections. A 15% change in demand is not chosen on the basis of specific conservation measures but rather as the level of change that will allow the scenarios to diverge from one another. However, previous studies[67,68] report low- or no-cost measures to achieve similar reductions. These changes, which are implemented incrementally from 2025, are intended to reflect a general desire for energy conservation in the Conservation scenario, increasing energy intensity in the Muddling Through scenario, and a shift toward telework and mass transit in the iSustainability scenario. The Go Our Own Way scenario follows business-as-usual end-use energy-demand trajectories, which were derived from the AEO 2016 and extrapolated past 2040. Specific demand changes are detailed in Table 2. The version

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Table 2. Modifications to End-Use Demands in Each Scenario[a]

scenario	end-use demand	demand change in 2050	rationale
Conservation	all	−15%	conservation measures adopted across sectors, such as adjusting thermostats, turning off appliances, and carpooling
i-Sustainability	all commercial	−15%	online shopping and telework
	residential other electricity	+15%	home offices and gadgets
	commercial trucking	+15%	deliveries for online shopping
	busing	+15%	increased use of mass transit
	passenger vehicle travel	−15%	online shopping, telework, and a transition to mass transit
Go Our Own Way	none	0%	end-use energy demands equivalent to Annual Energy Outlook projections
Muddling Through	all	+15%	trends of increasing per capita travel demand, increasing house size, etc., continuing into the future

[a]Changes are implemented linearly, starting in 2025. Demand changes specifically represent a change in use, such as changing the thermostat, and not a change in electricity, which could be additionally impacted by device efficiency or fuel choice.

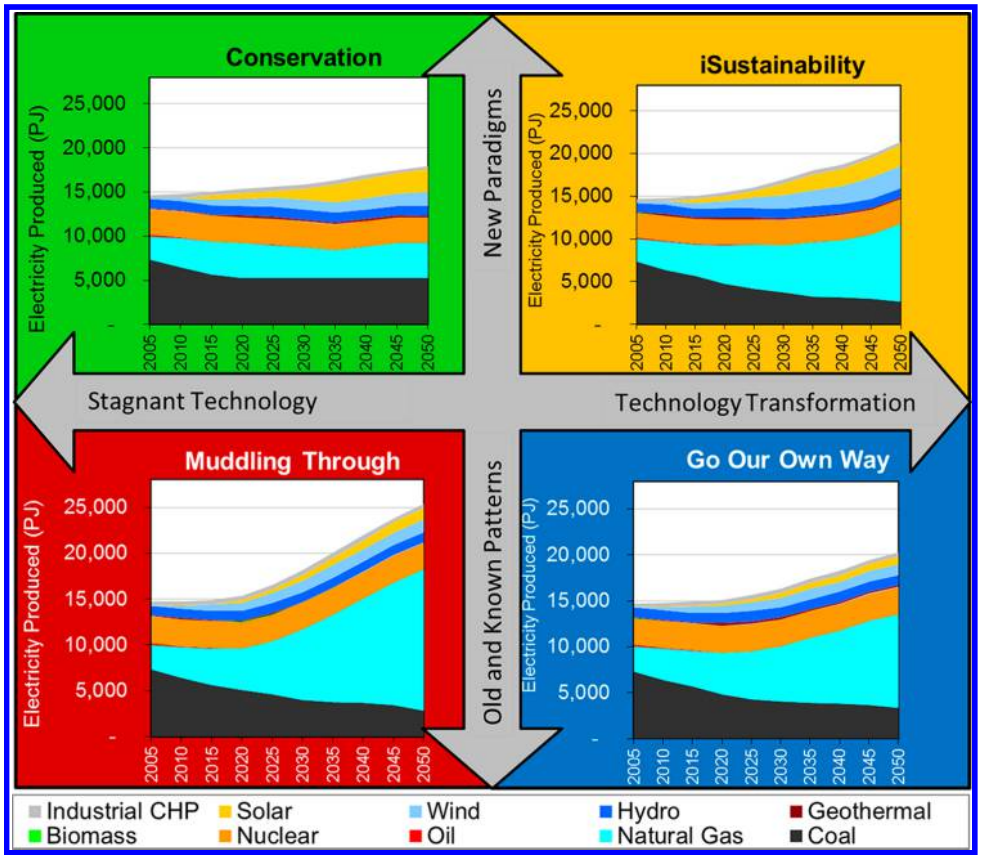

Figure 1. Electricity generation by energy sources in four alternative-future scenarios. CHP means combined heat and power.

of MARKAL used here does not include elastic demand, which would make the interpretation of results more difficult and less transparent and could reduce the distinction between the scenarios. The system can still react to fuel or electricity prices by switching fuels or purchasing more-efficient devices, but consumers' choices about end-use demand are based on values and societal norms more than on energy prices in this analysis. Subsequent policy analyses could be run with the elastic version of MARKAL, in which demand in each of the four baselines can change as prices change.

4. RESULTS

The future scenario implementations are each evaluated in MARKAL. Graphics showing electricity grid mix and light-duty vehicle technology mix illustrate differences among the scenarios. National emission trends are then compared across scenarios to examine the environmental impact of the possible pathways. Additional changes are described in section S4 of the Supporting Information.

4.1. Electricity Generation. Both the total amount of electricity generated and the grid fuel and technology mix vary across scenarios. Nuclear power is constrained to 2900 PJ per year in all scenarios. Residual capacity and no modeled new dam construction means that all scenarios have 1100 PJ per year of hydropower. The electricity mix in each scenario and time step is presented in Figure 1.

Conservation has the lowest total electricity generation due to decreased end-use demands associated with this scenario.

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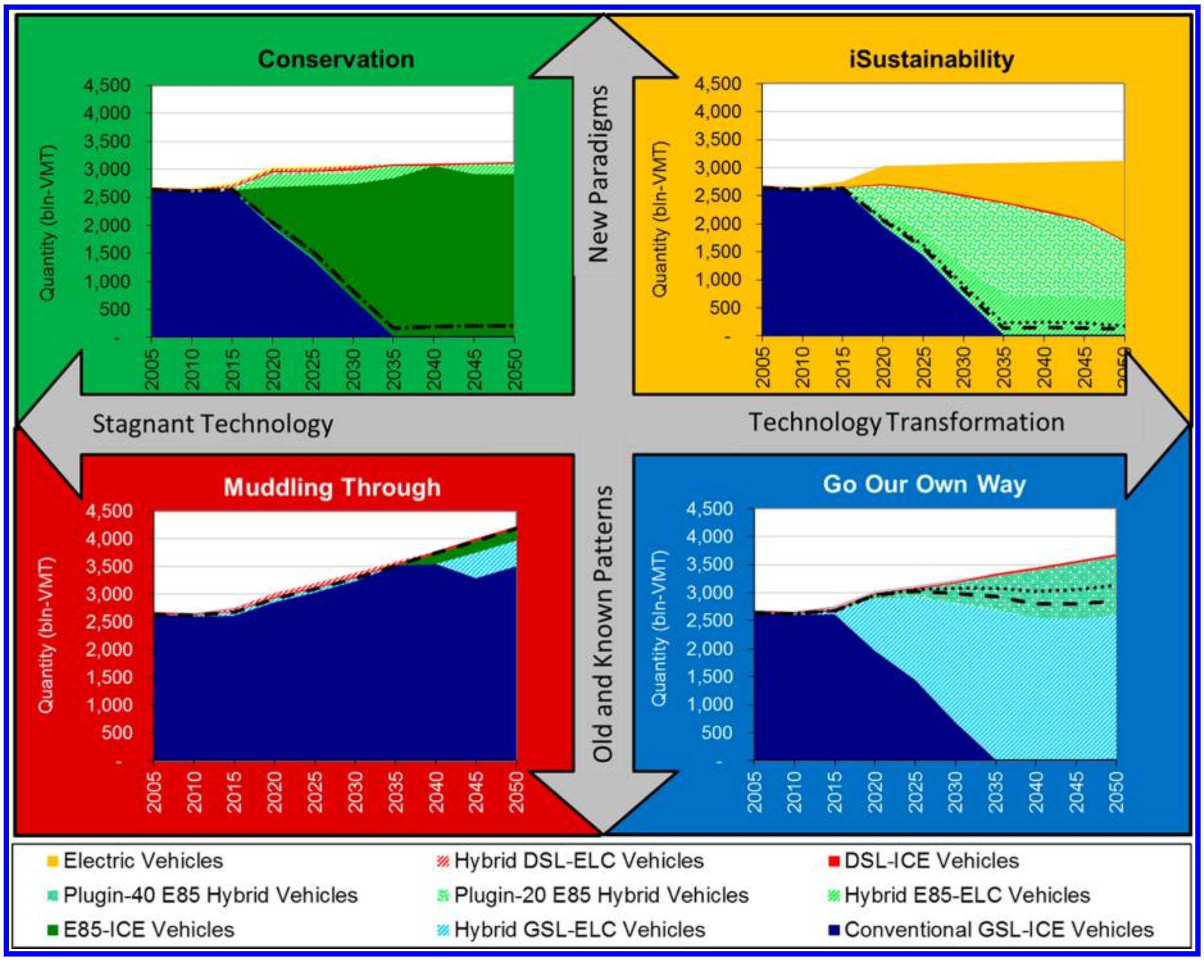

Figure 2. Light-duty vehicle technologies in four alternative future scenarios. DSL denotes diesel fuel use, ELC denotes partially electric vehicles, ICE denotes internal combustion engine (non-electric), E85 represents vehicles that can use ethanol−gasoline blends up to 85% ethanol, and the value after plug-in indicates the range in miles that the vehicle can travel on electricity only. GSL refers to gasoline, which is an E10 blend in 2015 and onward in all scenarios. All green areas include any E85 flex-fuel vehicle (FFVs), including FFVs that are also hybrids or plug-in hybrids. Fuel use in FFVs and hybrid vehicles is represented by dashed and dotted lines. The fraction of the green area below the dashed line represents operation using E85, the fraction from the dashed line to the dotted line represents the portion of flex-fuel energy supplied by electricity, and the remainder of the operation occurs using E10. The dotted line is omitted in the "muddling through" scenario because there are no plug-in hybrid vehicles.

Conservation also has the most coal because all coal-fired power plants in use in 2020 continue to be used throughout the modeled time horizon due to their low operating cost. At the same time, this scenario has significant market penetration by solar power, with 14% of generation from solar photovoltaic (PV) in 2050. The 2050 wind generation accounts for 9% of total U.S. electricity generation. These changes occur because PV and wind technologies already have competitive prices in many locations, and they are even more competitive with low hurdle rates in Conservation. Electricity production from natural gas combustion is lowest in this projection, accounting for only 22% of generation in 2050.

Muddling Through produces significantly more electricity than any other scenario, producing 25 400 PJ in 2050, which is 40% and 19% higher than the Conservation and iSustainability scenarios due to an increase in energy service demand and high hurdle rates on technologies that improve efficiency. In Muddling Through, natural gas is the dominant energy source, with 60% of total U.S. electricity being produced at natural gas power plants in 2050. An unanticipated result in this scenario is that electricity generation from coal decreases substantially, dropping from 5080 PJ in 2020 to 2860 PJ of electricity in 2050 due to increased generation and the need to comply with emissions constraints from existing regulations such as CSAPR. Some solar and wind power is built as well, producing approximately 10% of electricity in 2050.

iSustainability results in the second-highest electricity generation of all scenarios and includes many low-emission technologies. Coal-fired generation again decreases with time, reaching 2620 PJ in 2050. Natural gas generation increases in this scenario but is less dominant than in Muddling Through, contributing only 43% of generation in 2050. There is more renewable generation than in Conservation, with solar and wind contributing 24% of generation in 2050. The larger contribution of wind power in this scenario includes 224 PJ of offshore wind, which is not used in other scenarios. Technological advancement and social preference combine to make this and other renewable technologies more affordable through lower hurdle rates. Technological advancement in the iSustainability scenario thus allows more fossil generation to be displaced.

As might be expected with the two-axis structure, electricity generation in the Go Our Own Way scenario is similar in some ways to both the iSustainability and Muddling Through

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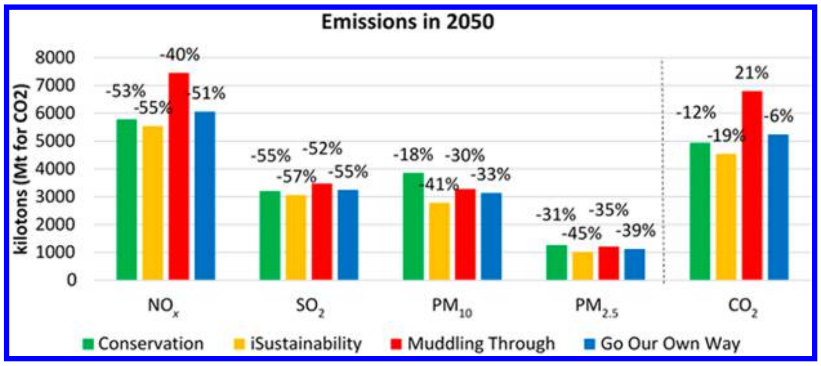

Figure 3. Emissions of pollutants of concern from each future scenario in 2050. Values above each bar reflect the percent reduction in emissions compared to 2010.

scenarios. Total generation is lower than in either as the demand for energy services is lower, producing 20 250 PJ in 2050. Coal generation is higher than in any scenario besides Conservation but still decreases to 3335 PJ in 2050, while natural gas generation is again substantial, contributing 50% in 2050. Generation from renewables is much smaller in this scenario, with wind and solar contributing only 10% in 2050.

There are shifts in demand for electricity in addition to the changes in production between scenarios. Section S4 in the Supporting Information elaborates on changes in electricity use. Electricity is primarily used in residential and commercial applications such as lighting, but a variety of technologies with different efficiencies exist to satisfy those demands. This means that the 15% change in end-use demands in a scenario may lead to a larger or smaller percentage change in electricity. More-efficient end-use devices are used in the iSustainability and Go Our Own Way scenarios because advanced technologies include efficient end-use devices in addition to new generation technologies.

4.2. Light-Duty Vehicles. The technology differentiation between scenarios is most striking in the light-duty vehicle sector, in which the dominant transportation choice shifts significantly for different technological and social changes. While electricity generation still relies on a mix of technologies into the future, one or two energy sources tends to dominate the landscape of passenger vehicles. Figure 2 represents technology mixes in the light-duty transportation sector for each scenario.

In the Conservation scenario, the dominant vehicles are flex-fuel vehicles (FFVs), which can be fueled with any blend of ethanol and gasoline up to E-85, where 85% of the fuel is ethanol, as opposed to the 10% ethanol that is standard at most pumps today and can be used in conventional vehicles. However, high-ethanol blends are not necessarily used, so while the vehicle technology appears different, the fuel use remains largely gasoline with small amounts of ethanol. This shift represents a consumer preference to purchase an alternative vehicle, although the lack of cost-competitive alternative fuel options minimizes the impact of this purchasing decision. In the Muddling Through scenario, conventional gasoline vehicles dominate. Hybrid gasoline electric vehicles are used in response to increasing gasoline prices from the high demand, but these account for only 10% of total vehicle miles traveled (VMT) in 2050. Some FFVs are also used for the same reason, accounting for an even-smaller 5% of total VMT in 2050. In the iSustainability scenario, significant electrification of the fleet occurs. By 2050, 45% of VMT is satisfied with fully electric vehicles, which have low hurdle rates in this scenario. Almost all other demand is satisfied by vehicles that use electricity and ethanol blend fuel up to E85. These vehicles are split between hybrid and plug-in hybrid vehicles and, as in the Conservation scenario, the gasoline content is much higher in actual use. In the Go Our Own Way scenario, technology improves and almost all vehicles are hybrids. Hybrids have a lower hurdle rate than conventional vehicles in this scenario, which balances the slightly higher investment cost. Most of the vehicles are gasoline hybrids, but 29% of the vehicles are plug-in flex fuel hybrids in 2050. Section S4 of the Supporting Information includes additional results and discussion regarding vehicle fuel use.

According to these scenarios, electrification of the vehicle fleet, either through hybridization or fully electric vehicles, is driven by advances in technology. These vehicles currently have higher investment costs, but as technology improves, the cost is expected to decrease, and efficiency gains can compensate for any additional cost. The purchase of FFVs without a change in E85 supply provides an example of how consumer action may not be enough to instigate emission reductions. Consumer choice can only drive change if progressive options are available. Progressive options include highly efficient vehicles and significantly different energy sources, which is exemplified here by electric vehicles but could also include options such as fuel cell vehicles or compressed natural gas. Additionally, change may require multiple action points. In this case, the initial vehicle purchase has minimal impact unless alternative fuels are available, and consumers choose to use them. Technological advancement, either in the fuel stream or vehicle options, is required for the energy system to depart significantly from the current paradigm.

4.3. Emissions. The scenario-planning method leads to differences in energy use and, therefore, emission levels among the different futures. Emissions of CO_2, NO_x, SO_2, and coarse and fine particulate matter (PM) are analyzed. The iSustainability scenario has the lowest emissions of each pollutant by 2025. The Muddling Through scenario has the highest emissions of NO_x, SO_2, and CO_2 starting in 2020. Conservation has the highest emissions of PM, which is due in part to continued use of coal. Emissions for each scenario in 2050 are presented in Figure 3. The potential health impact of these different emissions profiles is discussed in section 4.4.

4.4. Cost and Damages. The total, undiscounted cost of the energy system is different for the divergent futures. The cost of the energy system includes the cost of fuel, operation

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and maintenance costs, and the cost of investing in new technologies either to meet demand or to displace existing technologies. The Muddling Through scenario has, by far, the highest total system cost due to the 15% increase in demand across all sectors. Conservation has the lowest cost, but the other two scenarios are within 9% of that cost, while the Muddling Through scenario is nearly 40% more expensive. Note that we do not consider the cost of achieving technology innovations in these calculations. There are costs associated with emissions as well. While the energy system costs represent a transfer of wealth within the economy, the emissions costs represent an economic loss. We use marginal damage costs, which represent the cost of increased mortality occurring due to an additional ton of emissions, to monetize emissions of NO_x, SO_2, and $PM_{2.5}$. Fann et al.[69] modeled the change in $PM_{2.5}$ concentrations in the United States due to emissions from various sectors and calculated health impacts of an additional ton of $PM_{2.5}$, NO_x, and SO_2. They report a dollar value associated with reduction in risk of premature mortality due to the reduction of a ton of emission from each sector. The marginal damage value is an average across the entire United States, which obscures possible additional benefits associated with the location of emission increases or decreases across the scenarios. These values were calculated for 2016 and are here applied to years from 2005 to 2055, years in which the marginal damages may be different than those calculated. We multiply this marginal damage cost by the emissions in each of the MARKAL sectors to calculate a single damage value associated with the emissions in each scenario. This allows us to compare multiple emissions across scenarios. The undiscounted damage costs summed over the entire time period are lowest for the iSustainability scenario. The Go Our Own Way scenario is 3% higher than the iSustainability one, while the Muddling Through and Conservation scenarios are 7% and 8% higher, respectively. This calculation shows the benefit of technological advancement because damages are lowest for the futures with improved technologies. Undiscounted costs remove possible distortion from non-monetary hurdle rates, but these cumulative costs do not account for benefits associated with reducing emissions earlier or delaying new capital expenditures.

Monetized emissions can also be compared to the total energy used in each scenario. Figure S6 presents this information graphically. Low overall emissions are certainly beneficial, but if they are achieved through reduction in energy services, there could be consumer satisfaction or economic consequences. The iSustainability scenario has the lowest ratio of damages per unit of useful energy produced in 2050 because this scenario has low emissions with moderate-to-high demands. Meanwhile, the Conservation scenario has the highest damages per unit of useful energy. Although the Conservation scenario has relatively low emissions and, therefore, low damages, those low emissions are achieved more through reducing demand than by improving efficiency, leading to this scenario having the highest emissions intensity of energy. The Conservation and Go Our Own Way scenarios frequently have similar emission levels, but consumers in the Go Our Own Way scenario get more energy services per unit of damages. The Muddling Through scenario has a similar ratio to that of iSustainability because although the emissions are relatively high, energy use is high as well. This comparison is particularly useful in comparing scenarios with similar emissions because the health benefits of emission reductions do not change based on the energy supplied.

5. DISCUSSION

The results of these scenarios emphasize the importance of continued technological development into the future. In futures in which technology advances significantly (i.e., the Go Our Own Way and iSustainability scenarios), emissions are lower than scenarios without technological progress (i.e., the Muddling Through and Conservation scenarios). Even if society does not prioritize low emissions, improved technology will increase efficiency of the energy system, which eventually leads to lower emissions. This result is an indicator that continued funding of technological development can lead to a future in which air quality is improved and regulatory targets might be easier to meet. However, such technological improvement could be coupled with increased demand for energy services, which would tend to counter some of the emission reductions.[70] Although different demands were used in each scenario, this “rebound effect” was not included in the model.

Social preference is also an important force in determining the future of our environment and energy system. If people are motivated to take steps to reduce the impact of their energy use, emissions reductions can occur without technological development. Even with stagnation in technology development for several decades, emissions in the Conservation scenario continue to decline. Further research could continue to evaluate incentives and education programs that support consumers making more-informed decisions that benefit themselves and society.

Different sectors respond to the scenarios differently as well. Electricity continues to be generated by a wide variety of sources in all futures, while light-duty vehicles tend to be more uniform. Technological advancement is particularly important for the transportation sector. The scenarios with advanced technology use significantly different vehicles, while without technological change, most vehicle miles are still primarily powered by gasoline.

These scenarios can be used to complement analysis of emissions policies by adding additional plausible baselines and exploring the range of emissions reduction under each future scenario. Analyses similar to those done previously using MARKAL[15,42,47,48] can be layered on the four scenarios instead of relying on a single baseline. Because the runtime of the model is typically under an hour, it is feasible to test changes under all four possible futures and analyze a range of future results. For example, a group of states may decide to implement a CO_2 regulation, as the Regional Greenhouse Gas Initiative (RGGI)[71] has done. The four-scenario MARKAL approach would allow the region to evaluate how their proposed policy might change the energy system for the United States and their region under very different futures. Results could provide information about which technologies might be used, how co-emitted pollutants might be impacted, and whether their proposed policy would be feasible under all possible futures or if social acceptance or technological development might be key components to achieving their goals. This type of analysis would also help foresee unexpected consequences of future actions. While a policy might cause the intended impact in a business as usual case, it might lead to an unintended increase in some pollutant in a future with a

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different baseline. Whether an alternative is an improvement depends on what would have happened without it.

These modeling scenarios are not intended to be predictive. They represent several diverse and plausible pathways that the U.S. energy system might take over the next several decades. Running a variety of scenarios is helpful for evaluating the drivers behind technological choices and how those choices impact emissions. Using only four model runs, scenario planning provides significantly different futures in which the cause of the differences is explained by a combination of the major scenario drivers. By providing four scenarios, researchers can analyze how different assumptions might change the impact of the new technology, policy, or other stimulus. The differences might lead to a variety of impacts or at least a range of magnitudes. These scenarios can also provide bounds to cost benefit analyses because the change in emissions, technology shifts, and other drivers will be different within different scenarios. The estimated costs of regulations diverge from those calculated after implementation,[72,73] so considering a range of costs may better-characterize expected outcomes.

The benefit of the flexible implementation of the scenarios means that the modeling can evolve in the future. As technologies develop, the relative ranking of attributes might need to be adjusted, particularly the determination of which technologies are considered advanced. Re-examination of the attributes is also possible. The method of defining the scenarios allows for the periodic re-examination of the narratives as well as how technologies fit within them. Regular re-evaluation of narratives is important. For instance, compared with the initial storylines,[50] the importance of domestic energy sources in the Go Our Own Way scenario decreased because oil and gas production within the country has increased.

These scenarios are a starting point, not the end point of an analysis. These results are informative for investigating relationships between energy use, emissions, technological progress, and societal preferences. By using this scenario approach, we can further explore more relationships between various technologies than is possible otherwise. While these scenarios in MARKAL provide a tool to evaluate future possibilities, care should be taken in using and interpreting the results. There are limitations in the model and scenarios. In our analysis, the elastic demand feature of the MARKAL framework is not utilized. In addition, MARKAL is a bottom-up optimization model and not a general equilibrium model. We modeled the two dimensions that were deemed most critical and uncertain based on a structured scenario planning methodology. However, additional dimensions could be explored.

These scenarios were intentionally designed to facilitate decision making analysis. Additional forcing can be layered with these scenarios to evaluate how alternative future paths might impact the effect. These scenarios are useful to help us foresee unexpected consequences or benefits within an uncertain future landscape. While an analysis based on a business as usual case will provide some insight, the impact might be larger, smaller, or even in a different direction in another future.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.8b00575.

Additional details, tables, and figures on the process flowchart, hurdle rate description and calculation, and additional results. (PDF)

A table showing damages associated with NO_x, SO_2, and $PM_{2.5}$ for each energy sector in each case for each year and a table with the hurdle rate for each technology and scenario. (XLSX)

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