Analytic innovations for air quality modeling

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Forward

- **Objectives of this presentation**
  - Provide an example of air quality modeling at the EPA
  - Discuss analytical innovations being explored by ORD to inform Agency's future modeling activities
    - Air Quality Futures scenarios and GLIMPSE
- **Intended audience**
  - Graduate students interested in computational tools and methods for supporting environmental decision making
- **Acknowledgments**
  - Key contributors to the work presented here include Rebecca Dodder, Julia Gamas, Ozge Kaplan, Carol Lenox, Chris Nolte, Wenjing Shi, Yang Ou, Limei Ran, Steve Smith, Catherine Ledna, although many others have contributed.
- **Disclaimers**
  - The views expressed in this presentation are those of the author and do not necessarily represent the views or policies of the U.S. Environmental Protection Agency.
  - All results are provided for illustrative purposes only.

EPA air quality modeling example:

Analysis of the Ozone National Ambient Air Quality Standard

EPA air quality management

- **The Clean Air Act (1963) and its 1970, 1977 and 1990 Amendments**
  - **Provide authority to regulate air emissions**
    - Criteria pollutants (particulate matter, ground-level ozone, carbon monoxide, sulfur dioxide, nitrogen oxides, and lead)
    - Hazardous air pollutants (mercury and various toxics)
  - **Key issues addressed**
    - Acid rain, urban smog, regional haze, stratospheric ozone
    - Interstate and international transport of pollutants
  - **Examples of mechanisms**
    - New Source Performance Standards (NSPS)
    - New Source Review (NSR)
    - Maximum Achievable Control Technology (MACT) requirements
    - National Ambient Air Quality Standards (NAAQS)

Example: Ozone NAAQS

Every 5 years, the NAAQS for a pollutant is reviewed. The Administrator sets a limit that provides "an adequate margin of safety" "requisite to protect the public health."

2015 Revision of the Ozone NAAQS:

In 2015, based on EPA's review of the air quality criteria for ozone (O_3) and related photochemical oxidants and for O_3, EPA revised the levels of both standards. EPA revised the primary and secondary ozone standard levels to 0.070 parts per million (ppm), and retained their indicators (O_3), forms (fourth-highest daily maximum, averaged across three consecutive years) and averaging times (eight hours).

Basic Information

Legal Authority:

- 42 U.S.C. §7401

Federal Register Citations:

- 80 FR 65291
- 79 FR 75233

Code of Federal Regulations Citations

- 40 CFR Part 50
- 40 CFR Part 58

Docket Number

- EPA-HQ-OAR-2008-0699

Effective Date

- 12/28/2015

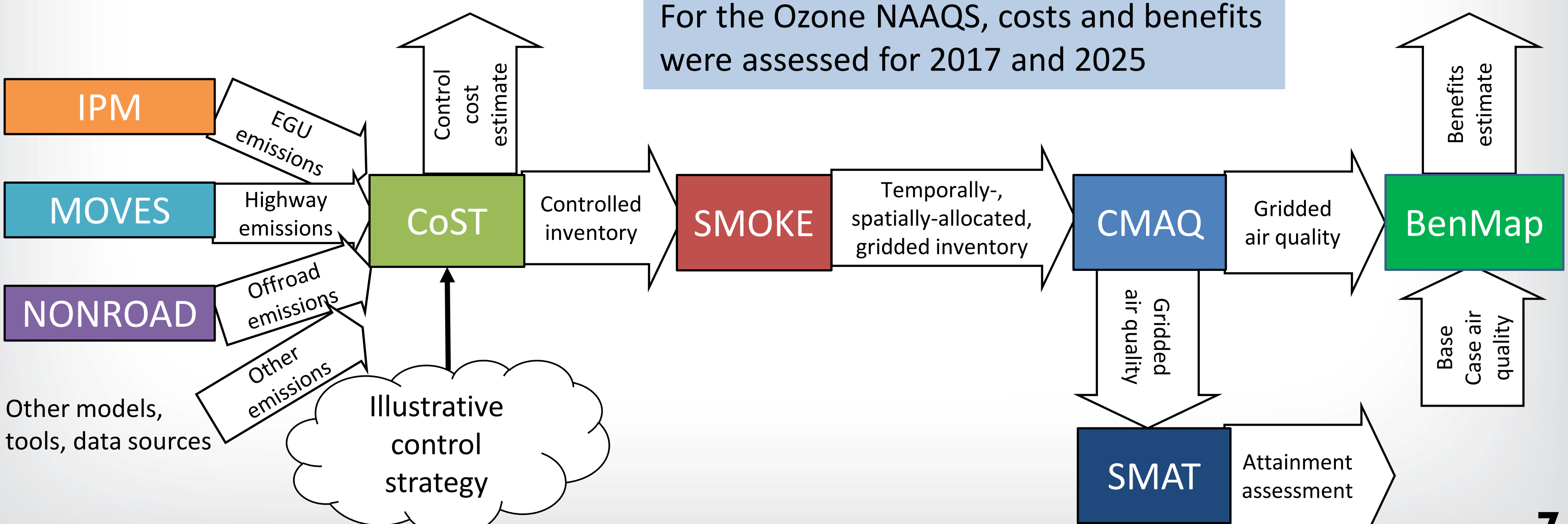
Ozone NAAQS review process

1. **Planning**
   - Gather input from scientific community and public, identifying relevant issues, questions
   - Develop schedule and outline process
2. **Integrated Science Assessment (ISA)**
   - Review, synthesis, and evaluation of policy-relevant science
3. **Risk/Exposure Assessment (REA)**
   - Estimates of exposures and risks, baseline versus possible standards
   - Characterization of uncertainty
4. **Policy Assessment (PA)**
   - Staff analysis of alternative policy options
   - Focus on basic elements: indicator, averaging time, form, level
5. **Regulatory Impact Analysis (RIA)**
   - Illustrative controls strategies inform implementation
6. **Rulemaking**
   - Proposal, comment period, and development of finalrule

RIA method and models

- **Method**
  - Assess costs and benefits in a future year by comparing:
    - Base Case – All "on the books" rules included
    - Control Case – Base Case plus illustrative control strategy for new rule
- **Models**

For the Ozone NAAQS, costs and benefits were assessed for 2017 and 2025



See appendix for definition of acronyms.

Analytical innovations regarding air quality modeling

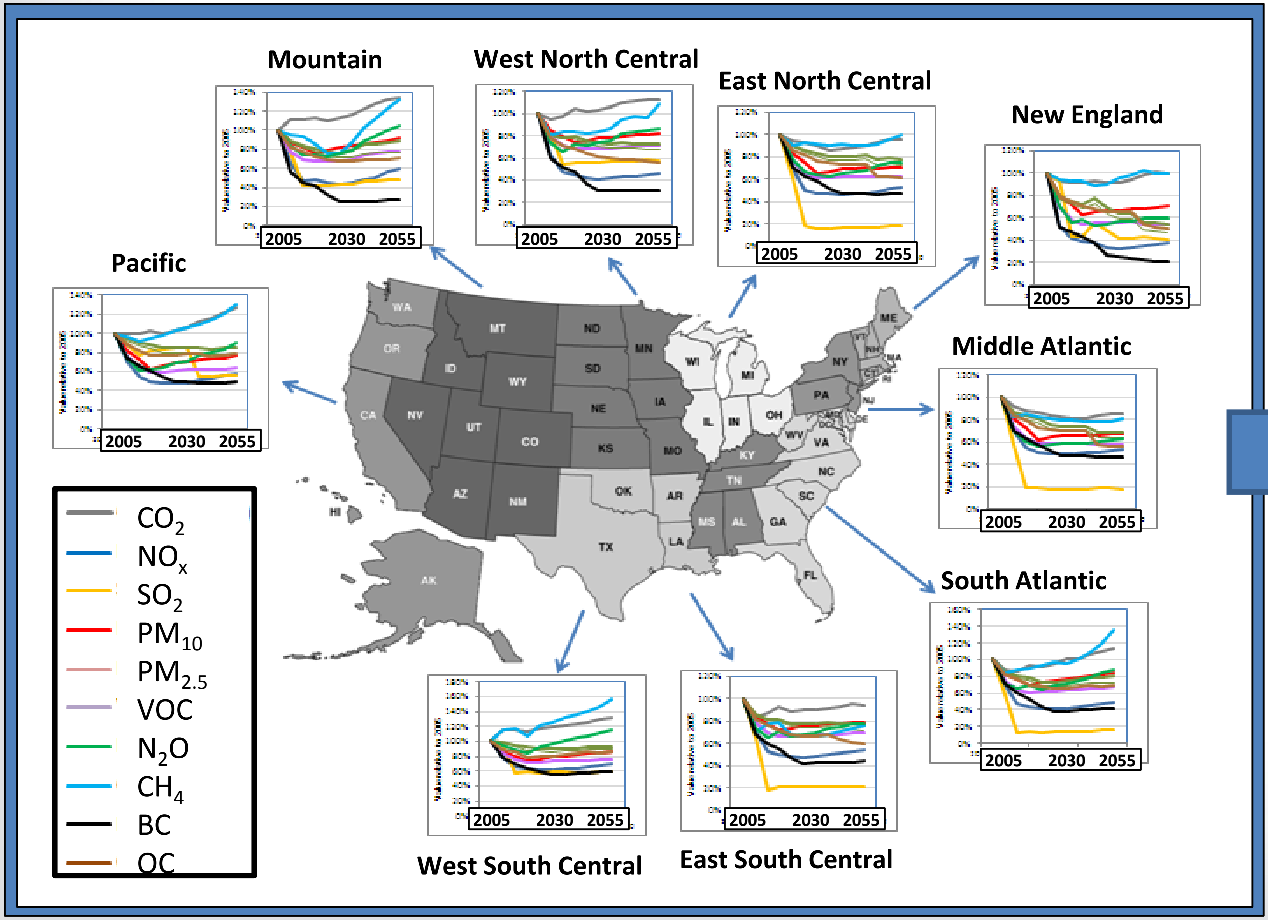
Enhancing modeling methods

- **Consideration of climate change and greenhouse gas emissions mitigation introduces the need for multi-decadal modeling**
- **Questions to be addressed may include:**
  - How do we project emissions several decades into the future, accounting for expectations regarding population, economic growth, climate change, land use change, behavior and policy?
  - How can we account for uncertainty in these factors?
  - How do we predict and then take into account spatial and temporal changes in emission profiles?
  - How do we identify important cross-sector and/or cross-media interactions?
  - How can we meet multi-pollutant objectives efficiently and robustly?

Emission projection methods

Loughlin, D.H., Benjey, W.G., and C. Nolte, C. (2011). ESP v2.0: Methodology for exploring emission impacts Of future scenarios in the United States. *Geoscientific Model Development*, 4, 287-297.

Energy system models can be used to develop emission projections



Future-year growth and control factors for SMOKE

Sector	NO_x	SO_2	PM_{10}
Electric	0.56	0.19	0.88
Industrial	1.69	0.93	1.05
Commercial	1.25	0.79	1.19
Residential	0.89	0.39	0.91
Light duty	0.12	0.21	0.41
Heavy duty	0.21	0.06	0.19
Aircraft	1.29	0.97	0.67
Marine	0.81	0.05	0.86
Nonroad	0.35	0.05	0.33
Railroads	0.48	0.02	0.21

Illustrative results

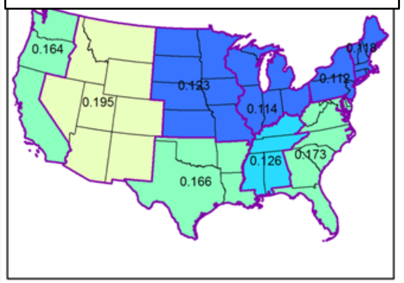
Spatial emission distribution

Ran, L., Loughlin, D.H., Yang, D., Adelman, Z., Baek, B.H., Nolte, C., and W.G. Benjey (2015). ESP2.0: Revised Methodology for exploring emission impacts of future scenarios in the United States – Addressing spatial Allocation. *Geoscientific Model Development*, 8, 1775-1787.

Land use models can be used to spatially allocate future emissions

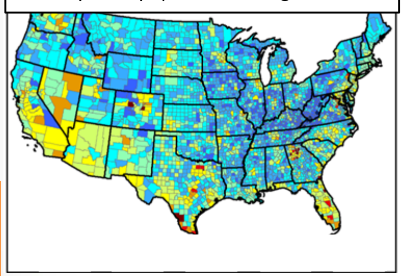
Energy model

Regional emission growth factors

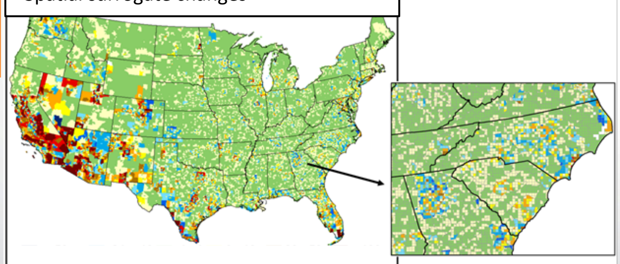


Land use model

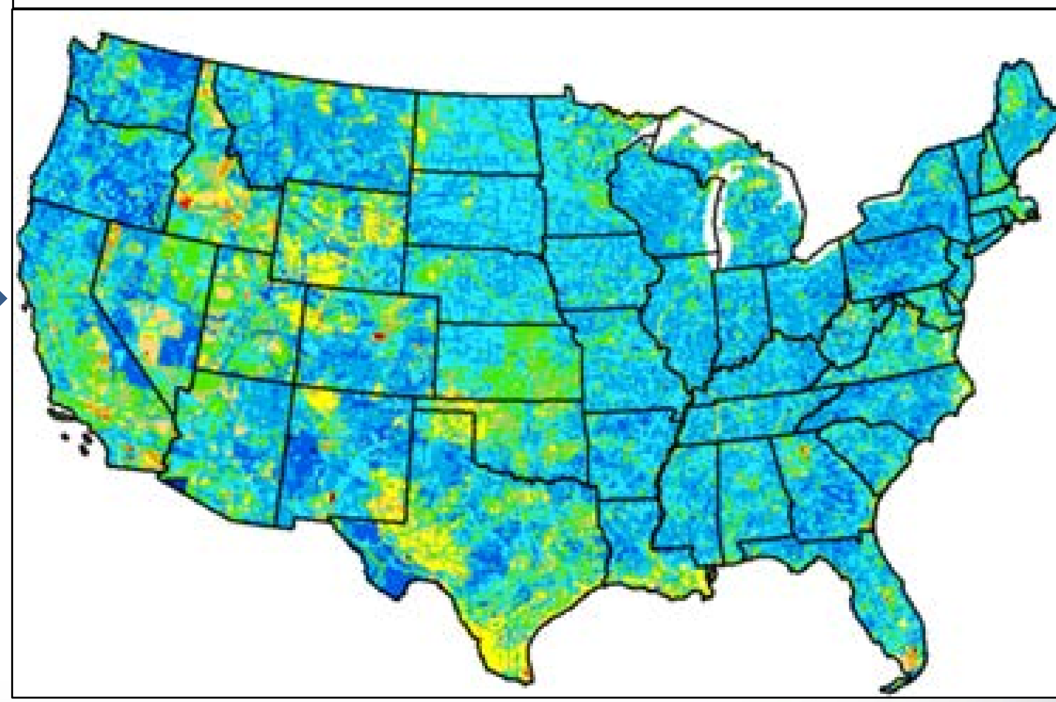
County-level population changes



Spatial surrogate changes



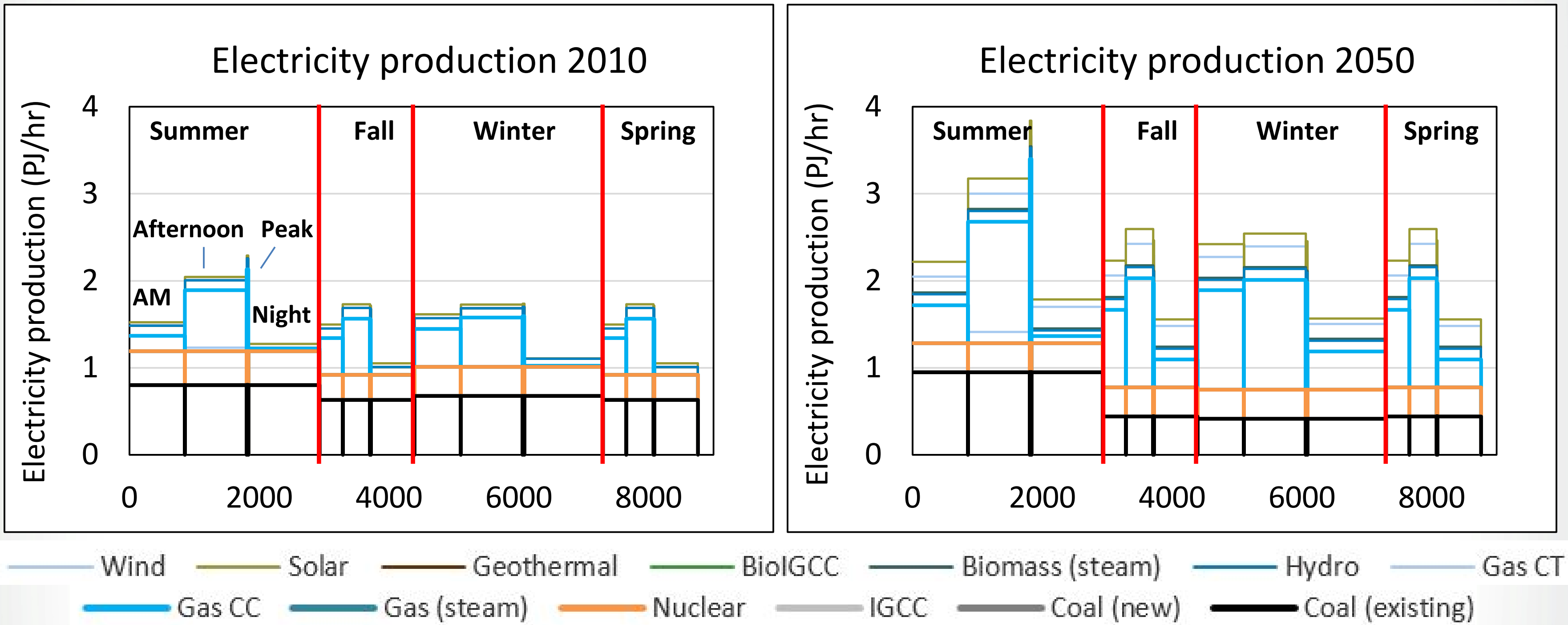
Future-year, spatially re-distributed inventory



Illustrative results

Temporal emission distribution

Energy model projections of technology and fuel use can inform temporal profiles



Winter natural gas emissions by time of day (%)

Winter	2010	2050
Morning	10%	10%
Afternoon	15%	16%
Peak	0.5%	0.4%
Night	2%	6%

As natural gas takes on more of a baseload role, its night-time emissions share increases.

Illustrative results

Available models, methods and tools

- **Modeling**
  - Optimization (How do I …?) e.g., NEMS (foresight mode), IPM, MARKAL
  - Simulation (What will happen if ...?) e.g., NEMS (myopic mode), GCAM-USA
- **Techniques**
  - Sensitivity analysis (response to incremental changes)
  - Scenario analysis (performance over very different conditions)
  - Modeling to Generate Alternatives (identification of very different pathways)
- **Tools**
  - Visualization
  - Statistics and data mining
  - Exploratory data analysis
  - Distributed computing
  - Software development and decision support systems
  - Integrated modeling frameworks

Air Quality Futures

Objective: Explore air quality management opportunities and challenges in the U.S. over a range of possible futures.

Tool: MARKAL energy system optimization model

Method: Future Scenarios Method

Reference: Gamas, J., Dodder, R., Loughlin, D., and C. Gage (2015). “Role of future scenarios in understanding deep uncertainty in long-term air quality management.” *Journal of the Air & Waste Management Assoc*. doi 10.1080/10962247.2015.1084783.

Motivation

- **Drivers of future pollutant emissions (and thus air quality) include:**
  - Population growth and migration
  - Economic growth and transformation
  - Technology development and adoption
  - Climate change
  - Consumer behavior and preferences, and
  - Policies (energy, environmental, climate, …)
- **As these drivers are uncertain, are there steps that we can take to:**
  - understand a range of future conditions that may occur,
  - anticipate conditions that may limit the efficacy of air quality management strategies, and,
  - develop management strategies that are robust over a wide range of future conditions?

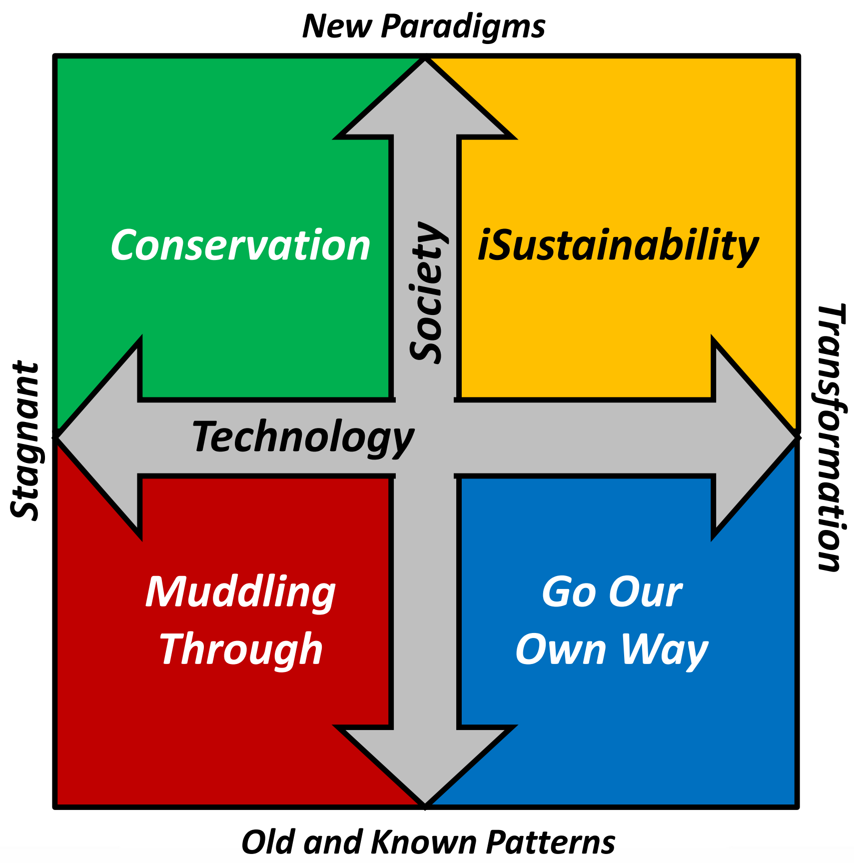
Future Scenario Method

- **We applied the <u>Future Scenarios Method</u> to develop scenarios that inform air quality management decisions**
- **Future Scenarios Method steps:**
  - Interview internal and external experts
  - Select the two most important uncertainties and develop a scenario matrix
  - Construct narratives describing the matrix's four scenarios
  - Implement the scenarios into a model (MARKAL) and refine as necessary
  - Apply the scenarios to inform decision-making

Note: In this application, we developed a 2x2 scenario matrix. The method is adaptable, however, and could be used to develop more or fewer scenarios.

Future Scenario Method, cont'd

This is the resulting Scenario Matrix:



Conservation is motivated by environmental considerations. Assumptions include decreased travel, greater utilization of existing renewable energy resources, energy efficiency and conservation measures adopted in buildings, and reduced home size for new construction.

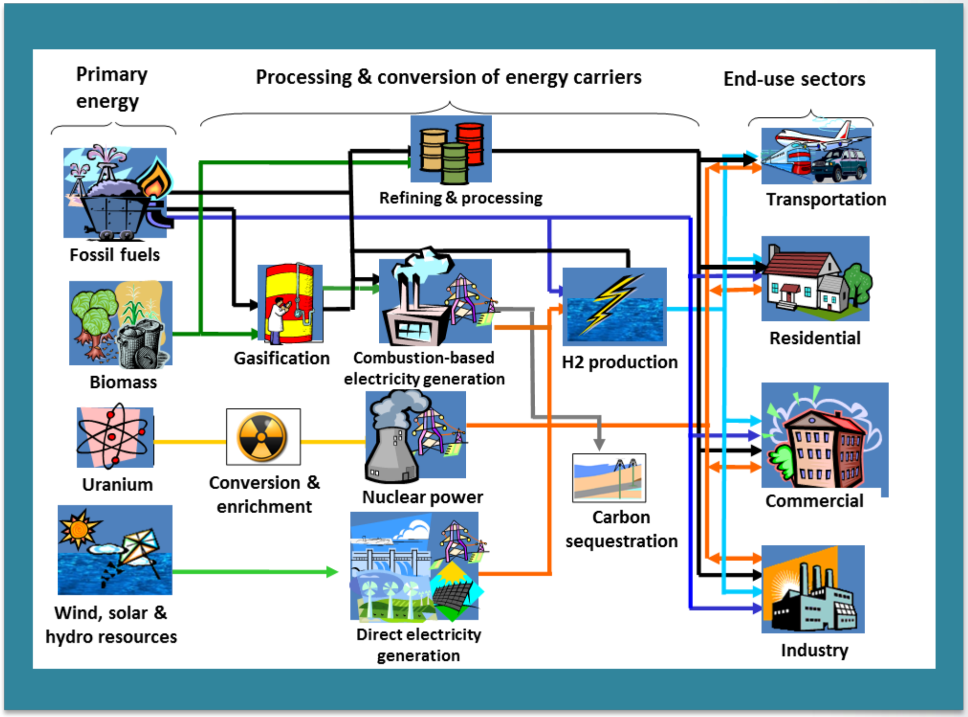
iSustainability is powered by technology advancements, and assumes aggressive adoption of solar power, battery storage, and electric vehicles, accompanied by decreased travel as a result of greater telework opportunities.

Muddling Through has limited technological advancements and stagnant behaviors, meaning electric vehicle use would be highly limited and trends such as urban sprawl and increasing per-capita home and vehicle size would continue.

Go Our Own Way includes assumptions motivated by energy security concerns. These assumptions include increased use of domestic fuels, particularly coal and gas for electricity production and biofuels, coal-to-liquids, and compressed natural gas in vehicles.

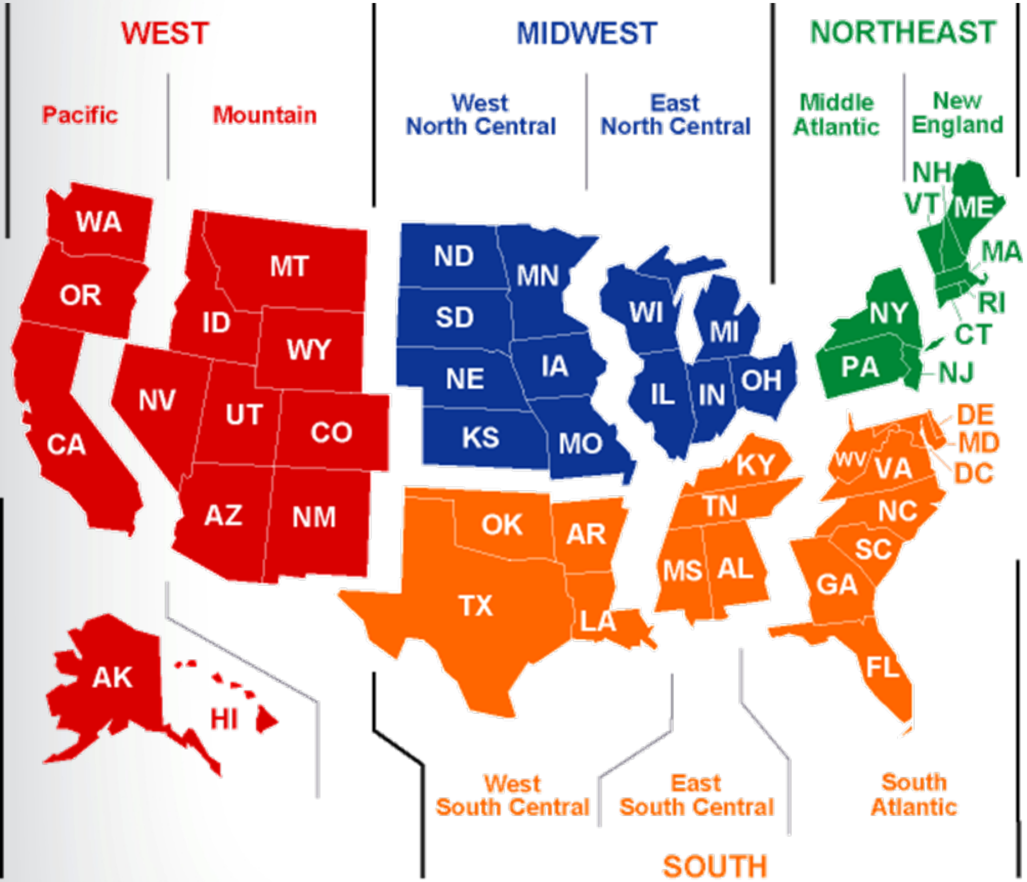
Energy system model: MARKAL

- **Bottom-up** and **technology-rich**
  - Captures the full **system** from energy resource supply/extraction technologies to end-use technologies in all sectors
  - **Energy technologies** (existing and future techs) are characterized by cost, efficiency, fuel inputs, emissions
  - Technologies are connected by **energy flows**
- **Optimization**
  - The model picks the "best" way (lowest system-wide cost) to meet energy demands choosing from the full "menu" of energy resources and technologies
  - The model makes these choices from 2005 to 2055, giving us a snapshot of possible future energy mixes



- **Emissions and impacts**
  - All technologies and fuels have air and GHG emissions characterized
  - Standards and regulations are included in the baseline, and additional policies can be modeled

U.S. EPA MARKAL regional database: EPAUS9r



- **Coverage**: U.S. energy system
- **Spatial resolution**: Nine Census divisions
- **Modeling horizon**: 2005 to 2055 in five year increments
- **Sectors**: Electricity production, transportation, industrial, residential, commercial, biomass
- **Main data source:** Annual Energy Outlook (2014)
- **Pollutants**: NO_x, SO_2, PM_{10}, $PM_{2.5}$, CO, VOC, CO_2, CH_4, N_2O, BC, OC, water use for electricity generation
- **Maintenance:** Updated and calibrated to Annual Energy Outlook every two years; housed at EPA/ORD; publicly available

Scenario implementation

- Implementation of the scenarios was a learning process
- Early approach:
  - Developed highly detailed narratives
  - Constrained MARKAL to follow the detailed narratives
  - Advantage: The scenarios differed considerably with respect to projected technology penetrations and air pollution emissions.
  - Disadvantage: The scenario assumptions werehard-coded, leaving the model little freedom to respond to a policy or other "shocks".
- Current approach:
  - Step back from the detailed narratives and focus on underlying drivers
  - Let the model drive the narratives

Scenario implementation, cont'd

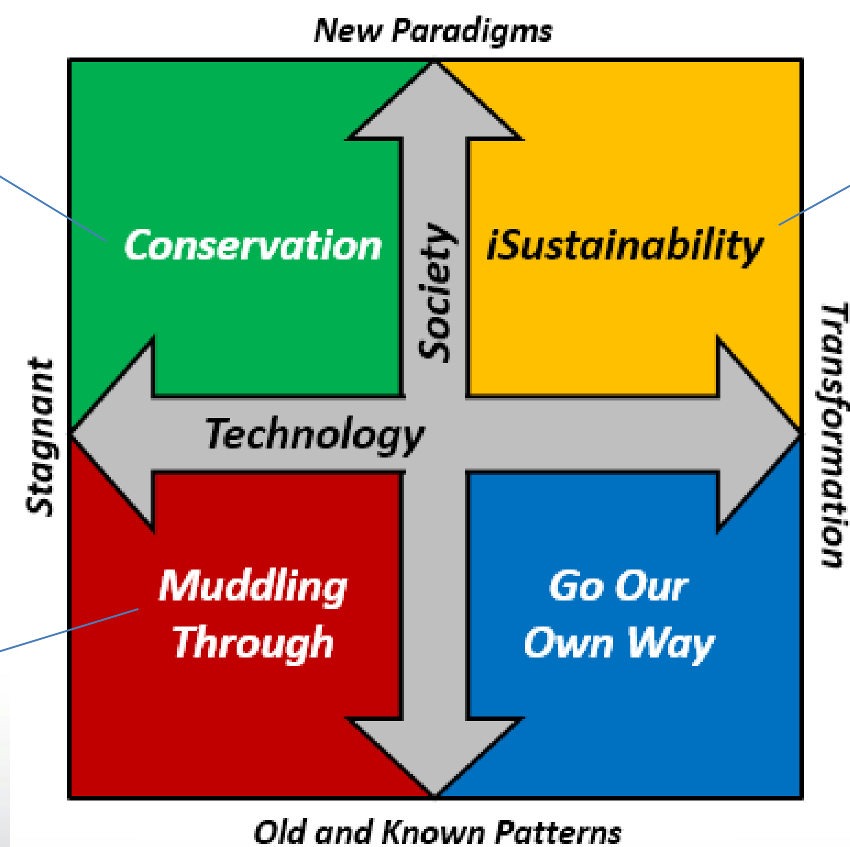
- **Current approach**
  - **Axis: Technological transformation or stagnation**

Lever: technological availability and cost

No electric vehicles
No IGCC

Electric vehicles achieve cost parity with conventional
Solar costs are reduced (obtained from IPM v5.15)

Only considered technologies that are competitive today without subsidies



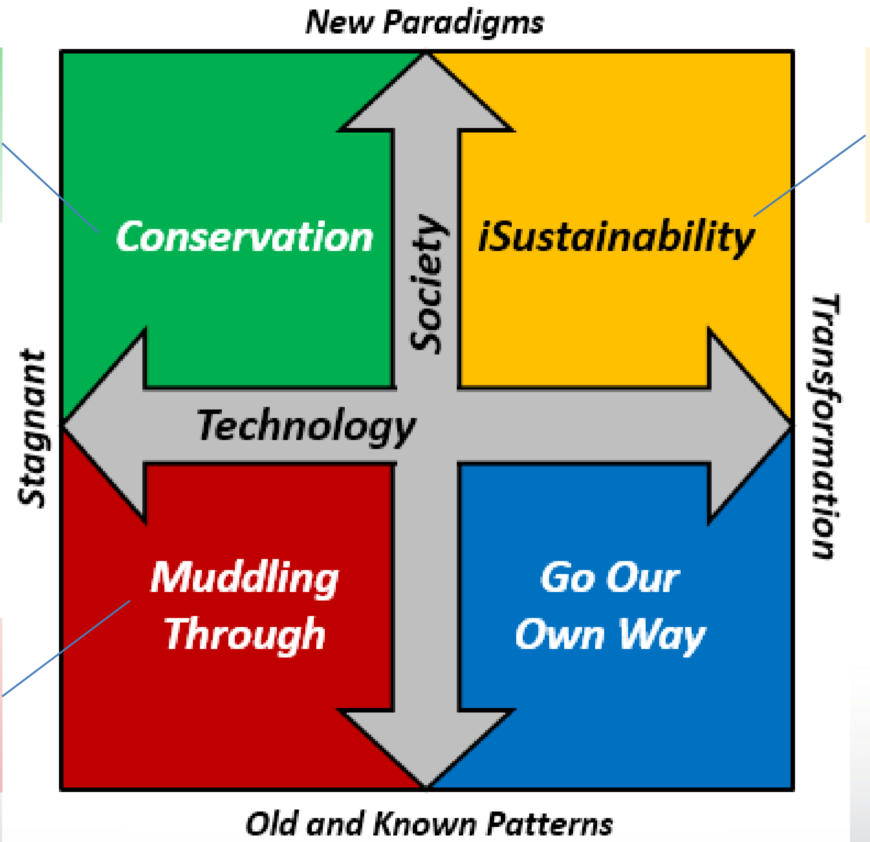
No electric vehicles
No IGCC

Scenario implementation, cont'd

- **Current approach**
  - **Axis: Social transformation and behavioral change**

Lever: end-use energy demands

Passenger vehicle demands reduced to reflect telework
New homes larger to accommodate home offices



Passenger vehicle demands reduced to reflect telework
New homes larger to accommodate home offices

Historic trends of increasing travel per person and increasing house sizes continue

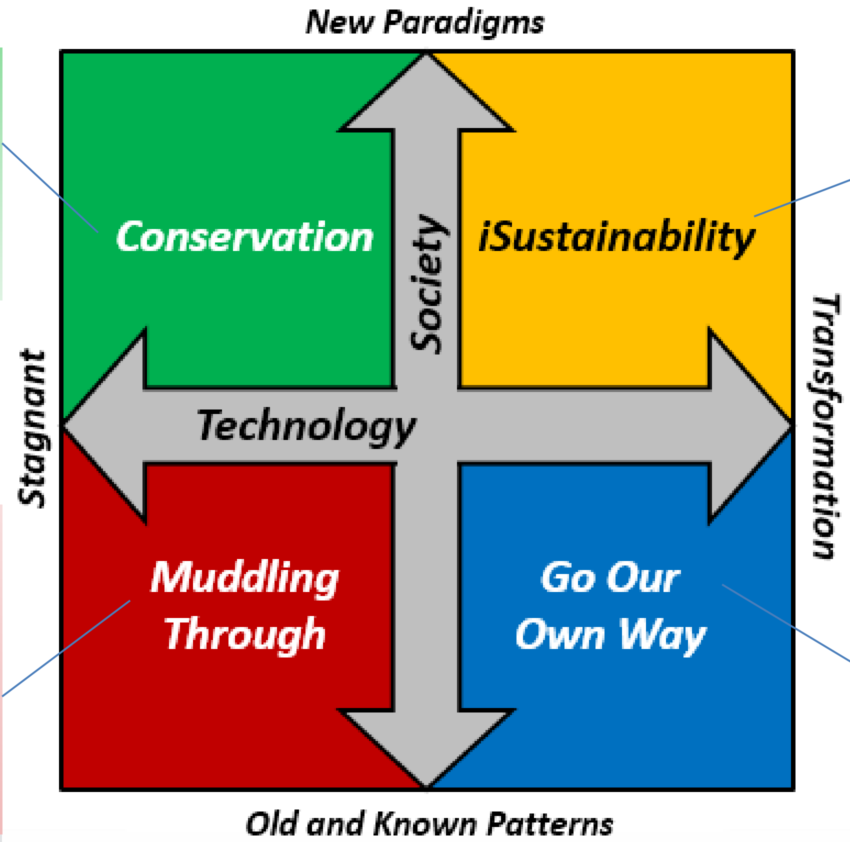
Scenario implementation, cont'd

- **Current approach**
  - **Axis: Social transformation and behavioral change**

Lever: hurdle rates to reflect scenario-specific preferences

<u>Prefer</u>:
- Renewable
- Environmental- and climate-friendly
- Local
- Energy efficient

<u>Prefer</u>:
- Renewable
- Environmental- and climate-friendly
- Energy efficient
- Advanced technologies



<u>Prefer</u>:
- Conventional technologies

<u>Avoid</u>:
- Advanced technologies
- Infrastructure changes req'd
- Environmental- and climate-friendly
- High capital cost

<u>Prefer</u>:
- Advanced technologies
- Energy efficient

<u>Avoid</u>:
- Infrastructure changes req'd
- High capital cost

Illustrative results

How different are the scenario results?

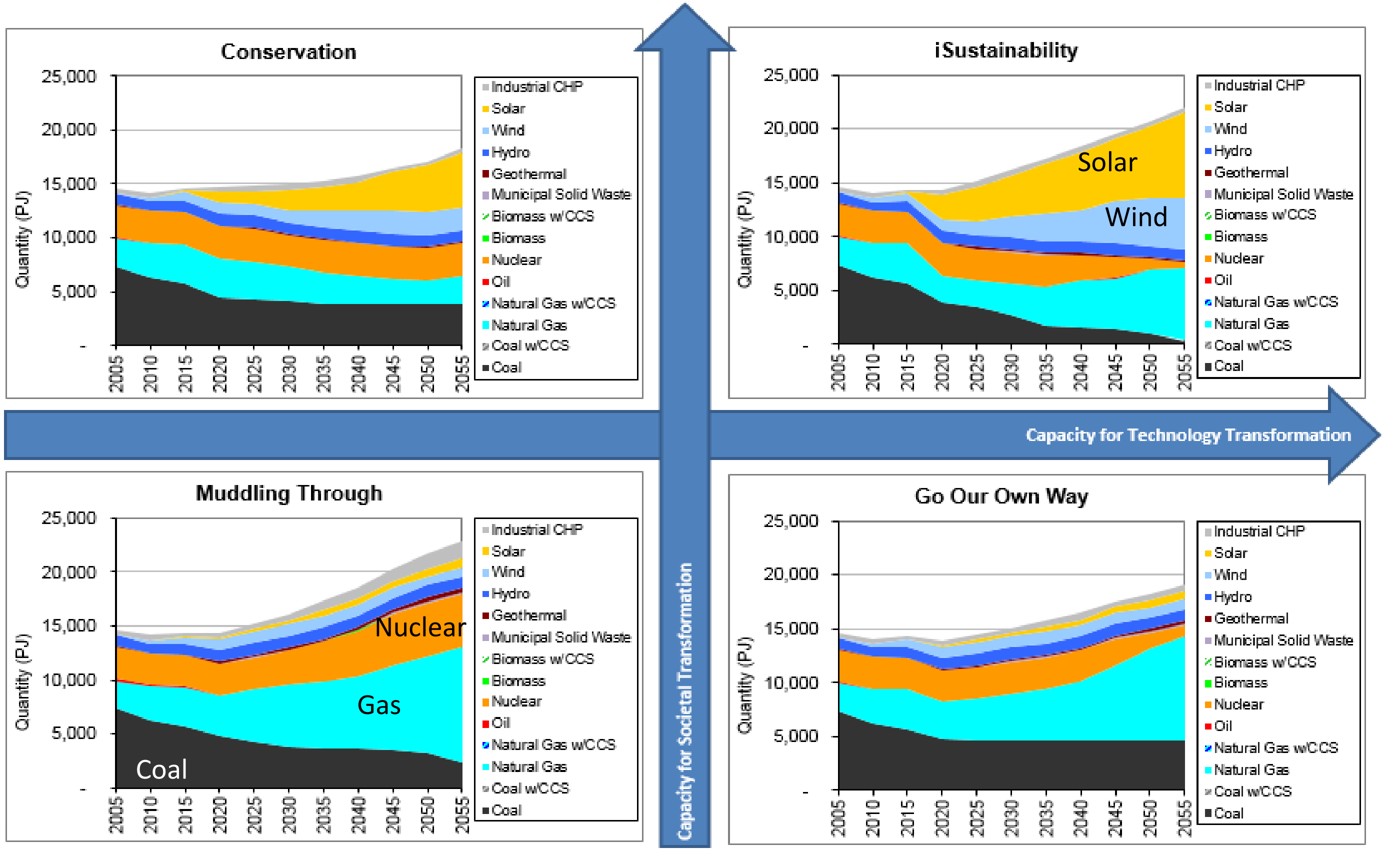
What are the long-term emission trends and how do they differ by region?

How effective are existing regulations at controlling emissions over wide-ranging scenarios of the future?

Illustrative results, cont'd

How different are the scenario results?

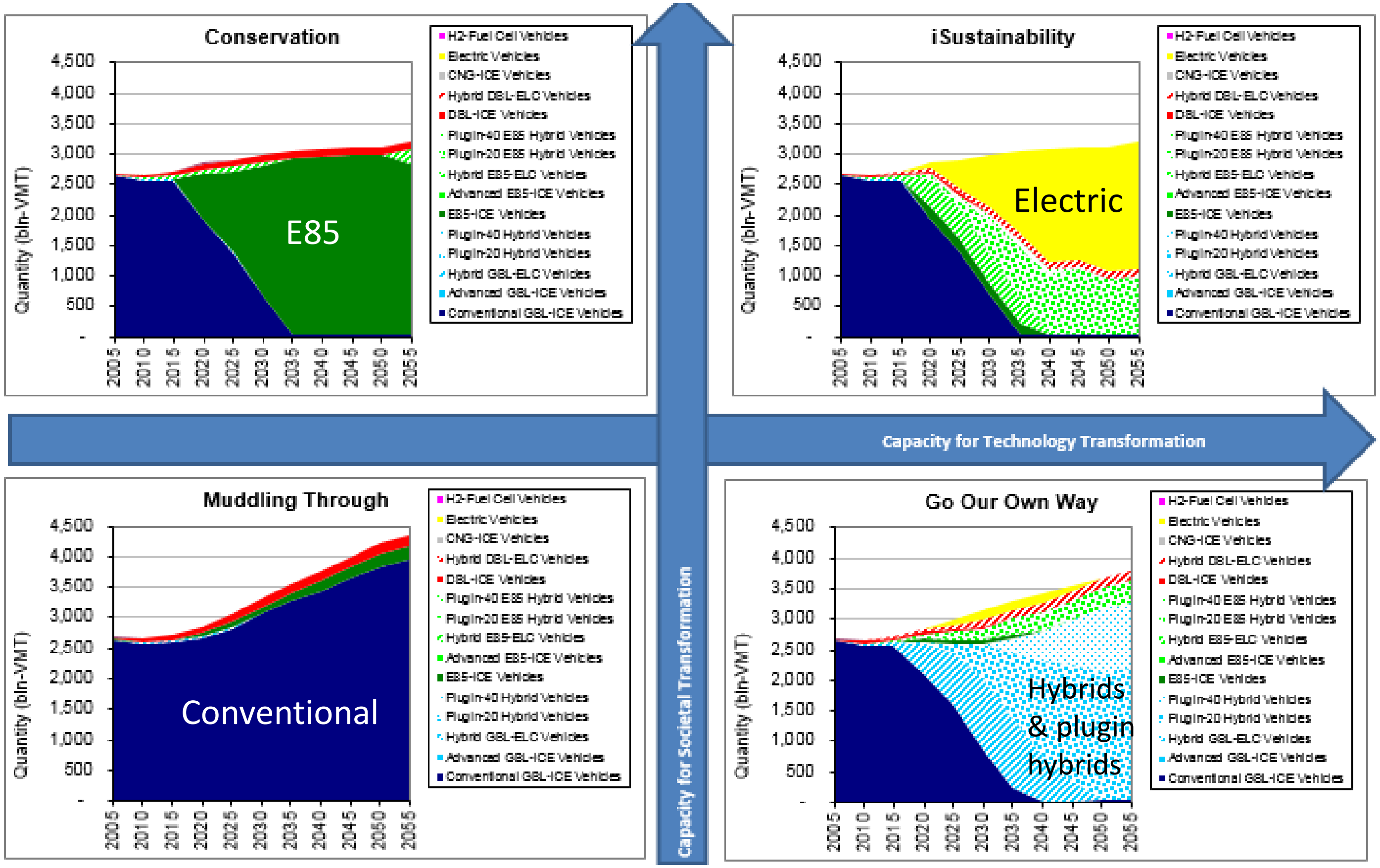
Electricity production by aggregated technologies



Illustrative results, cont'd

How different are the scenario results?

Light duty vehicle technologies



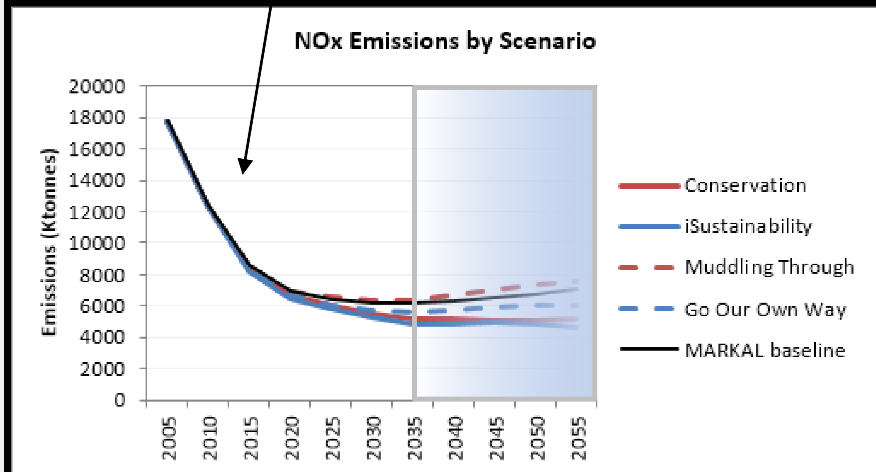
Illustrative results, cont'd

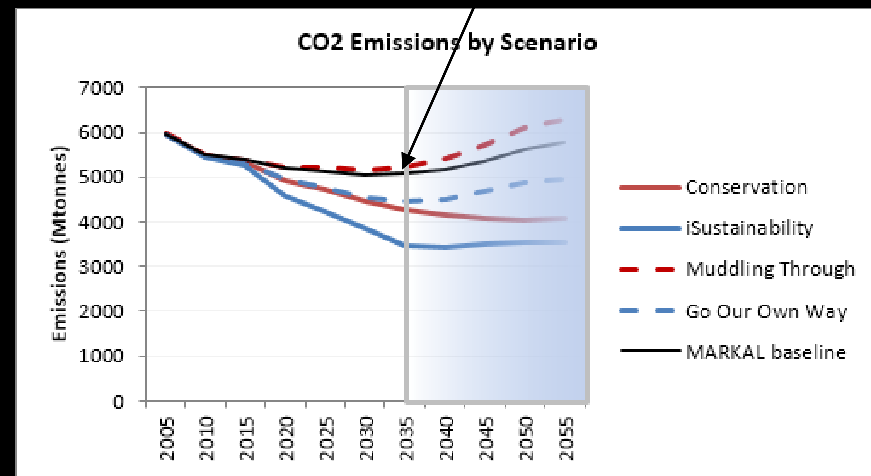
What are the long-term emission trends?

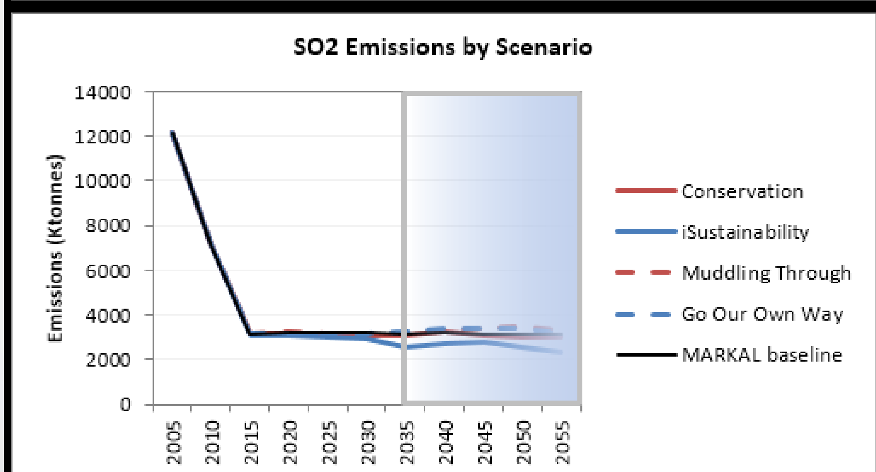
CAIR and Tier-3 drive NOx trend

Emissions

Greatest variability in CO_2







Historic SO_2 reductions are "locked in" but there is a small amount of variability.

Existing regulations are relatively robust in locking in downward trends for criteria pollutants.

The range of CO_2 emissions across the scenarios is considerably greater than that of the other pollutants.

Decision support system

Project: GLIMPSE

Objective: Provide decision support framework for evaluating state-level energy, environmental, and climate management levers

Requirements: Address decision-relevant sectors and time horizons, state-level resolution, easy to use, freely available

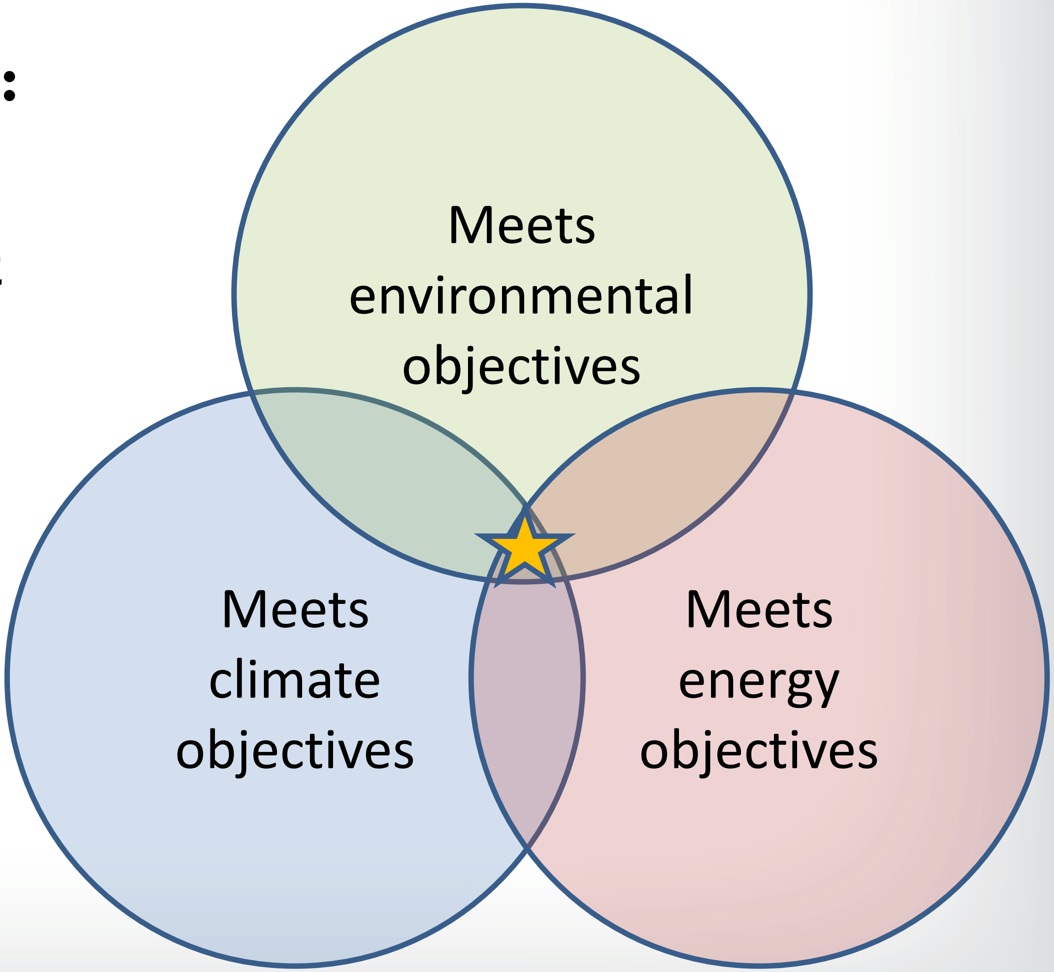
ORD's GLIMPSE project

Goal

Develop analytical tools for:

- Evaluating how candidate management strategies meet environmental, climate and energy objectives
- Characterizing tradeoffs among objectives
- Identifying strategies that efficiently meet all objectives

Management strategy space

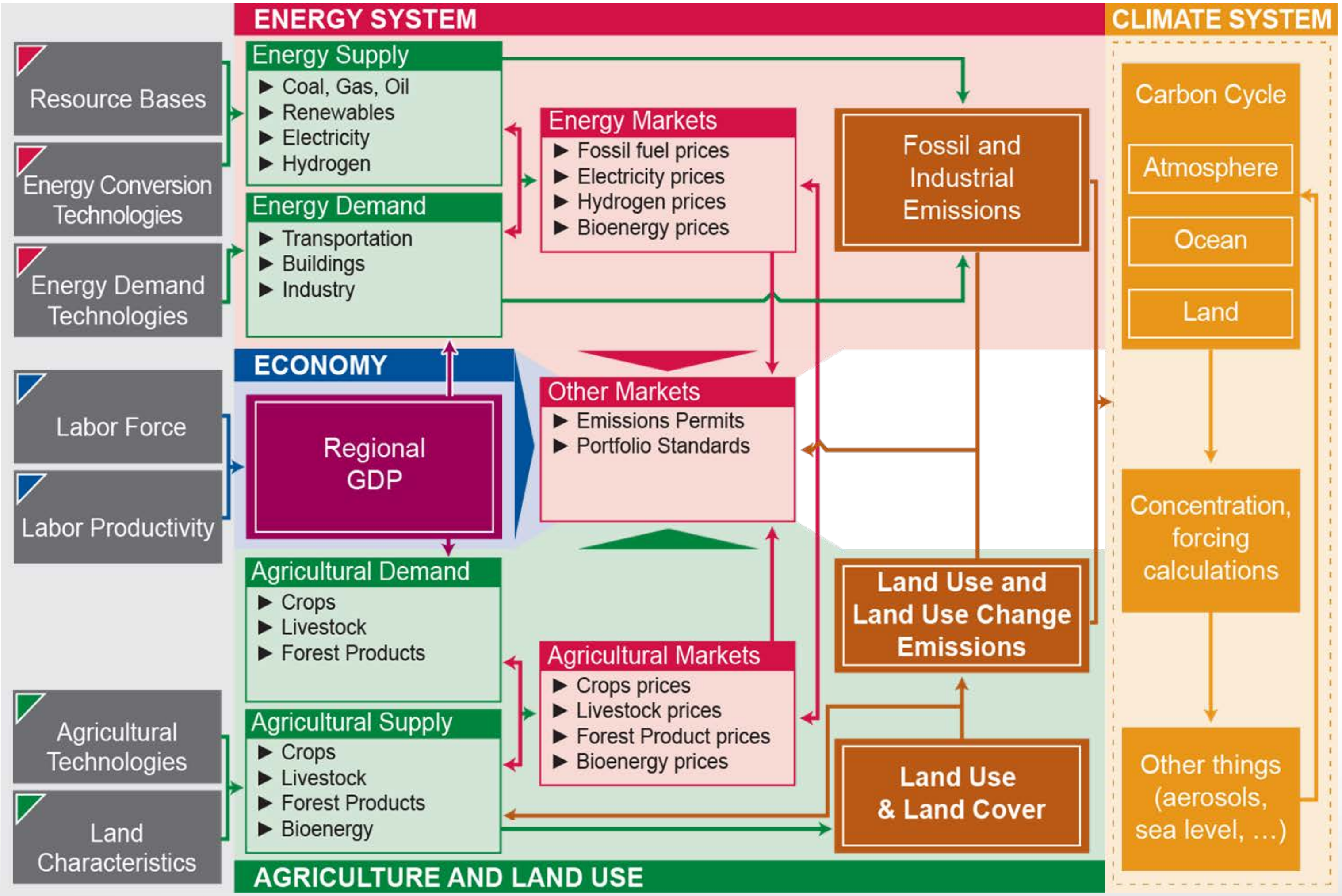


Why GCAM-USA?

- **GCAM track record**
  - USGCRP, IPCC, EMF …
- **Spatial coverage and resolution**
  - Global, covering U.S. at state-level
- **Time horizon and resolution**
  - 2005-2100 in 5-year time-steps
- **Sectoral coverage**
  - Energy, land use, agriculture, water, climate
- **Pollutant coverage**
  - GHGs and many criteria pollutants (e.g., NOx, SO_2, PM, NH_3, CO)
- **Technological representation**
  - Highly resolved compared to most Integrated Assessment Models
- **Other**
  - Free, open source, user community, no specialized software or equipment, structure is amenable to addition of graphical user interface

Why GCAM-USA?

GCAM Components



GCAM-USA modifications
FY16

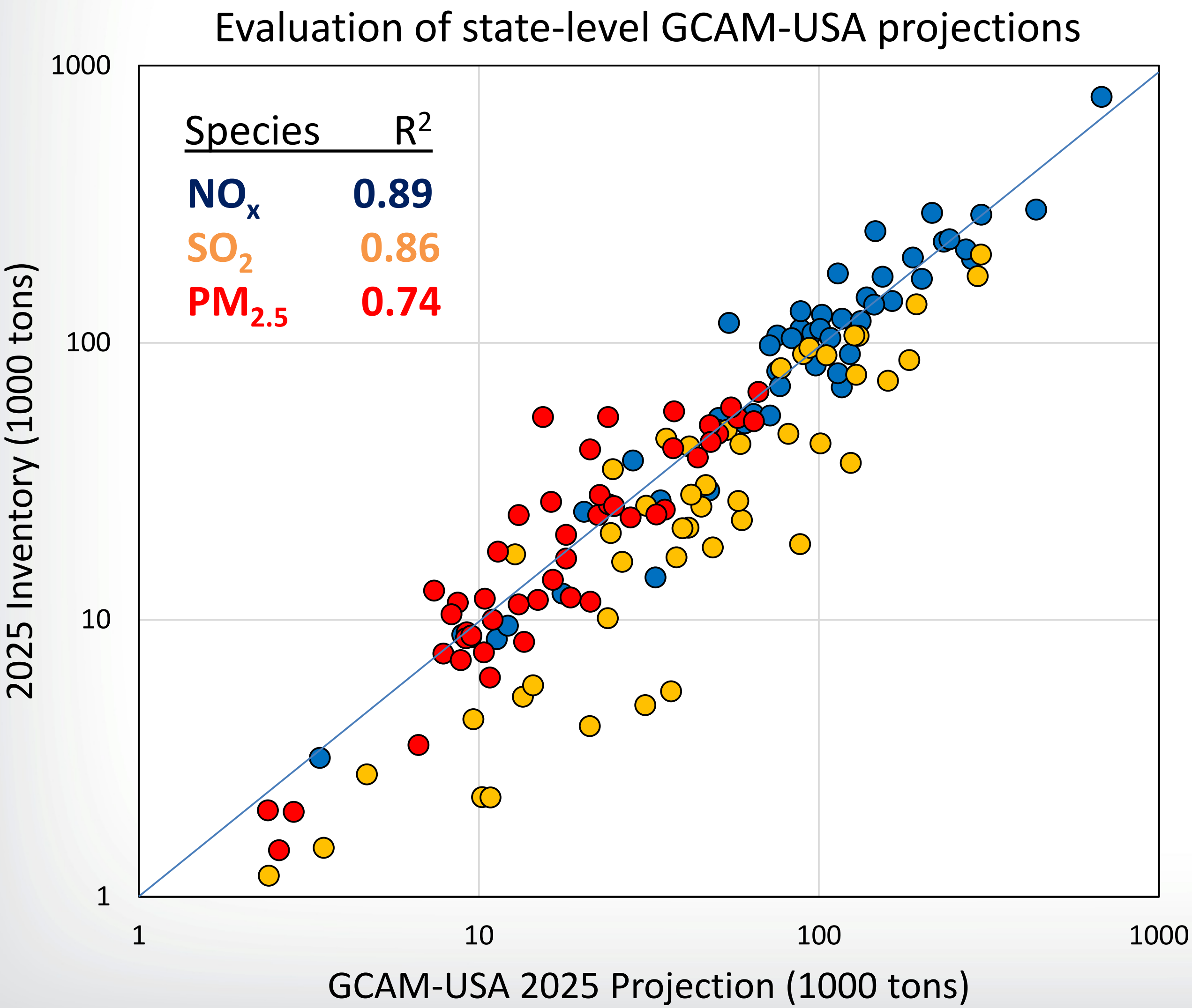
- **Emission factor updates**

Sector	Source
Electric	IPM version 5.14
Industrial	GREET, Regulatory Impact Analyses
Residential/commercial	Webfire database
Highway vehicles	MOVES 2014
Non-highway vehicles	NONROAD, various Regulatory Impact Analyses

- **Regulatory representations**

Regulation	Summary
Cross-State Air Pollution Rule	State-level, electric sector NO_x and SO_2 caps
Clean Power Plan	State-level, electric sector CO_2 caps
CAFE	National light duty vehicle efficiency requirements
Tier 3	Emission standards for highway vehicles

Evaluation of emissions



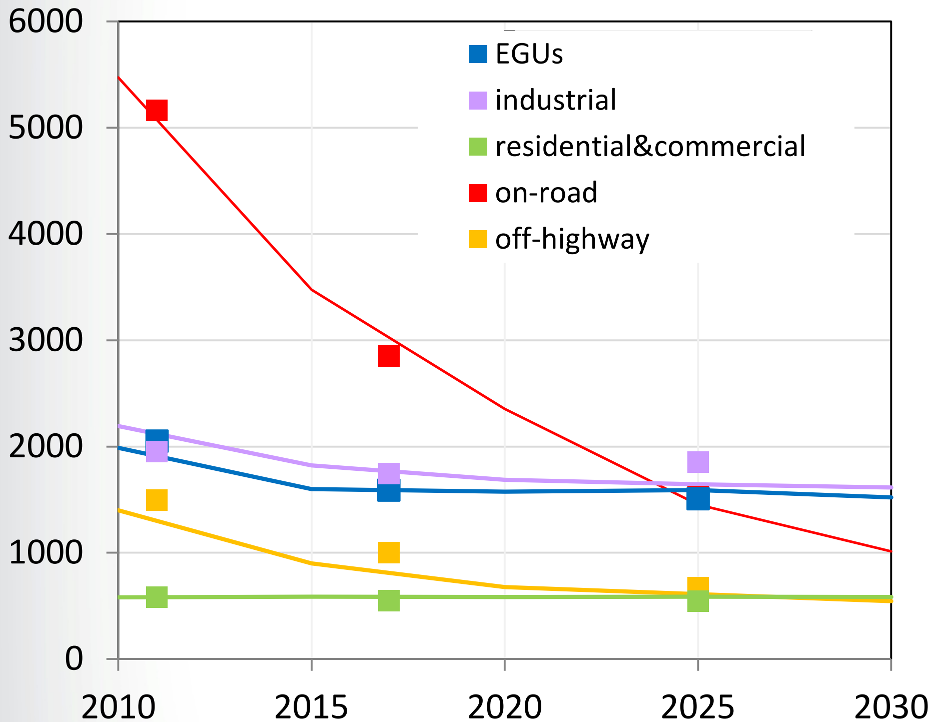
Observations:

Relatively good fit for NOx

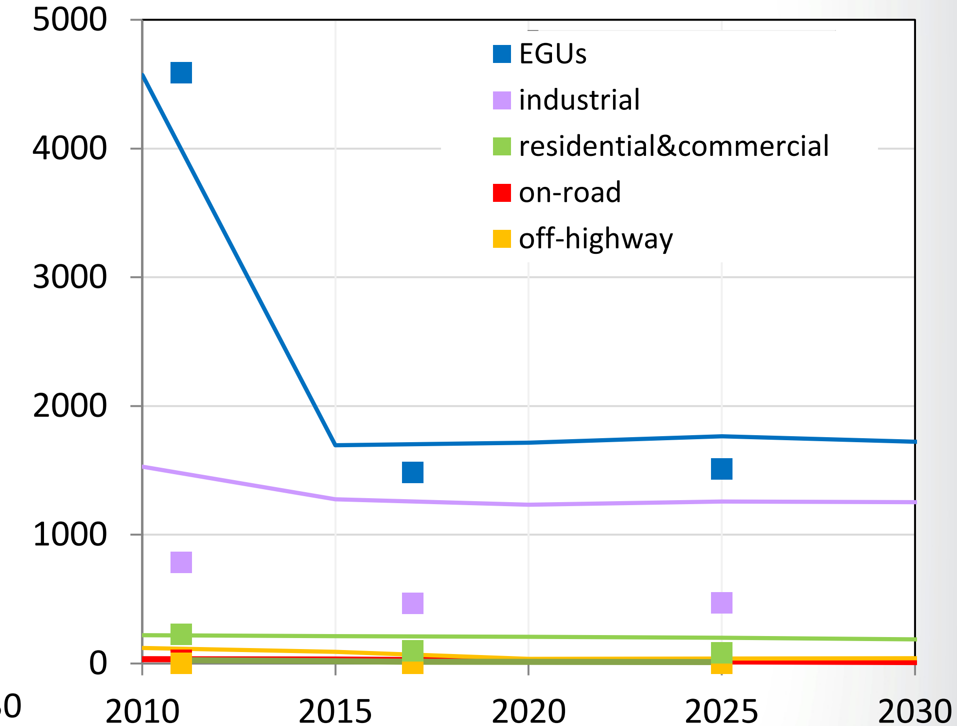
Tend to over-predict SO_2

Evaluation of emissions, cont'd

NOx emissions (tons x1000) compared to EPA 2011eh platform



SO2 emissions (tons x1000) compared to EPA 2011eh platform



- Off-highway NOx is low relative to the inventory, but this could be because of discrepancies in what is being compared
- Industrial sector SO2 from GCAM-USA are two times higher than the inventory. A hypothesis we are testing is that offroad mobile emissions included GCAM's industrial sector may not reflect mobile source fuel sulfur content limits. We also need to examine the assumed mix of industrial boilers, turbines, and engines in GCAM-USA.

Potential applications

Examples of policy levers that could be evaluated with GCAM-USA:

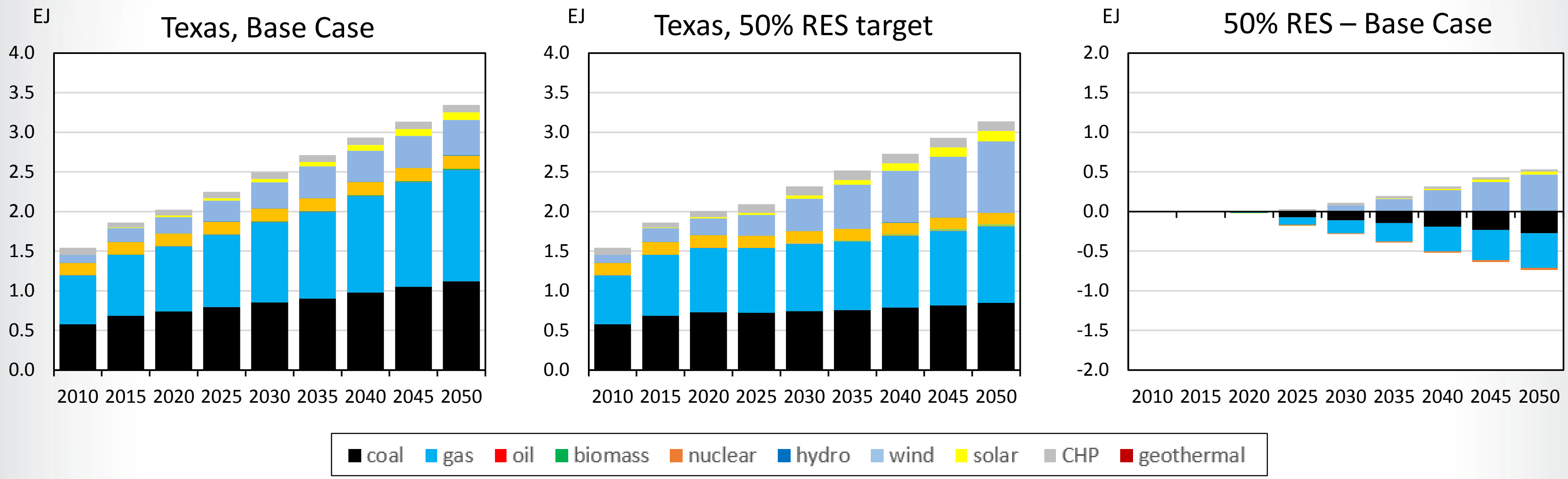
- **Types**
  - Air pollutant taxes or caps
  - GHG taxes or caps
  - Technology subsidies
  - Forced technology penetration
  - High-efficiency technology end-use requirements
  - CAFE standard
  - Renewable Electricity Standard
- **Geographic application**
  - Global, global region, or national
  - Group of states or individual state

Illustrative application:

– 50% Renewable Energy Standard introduced from 2025, applied to Texas
– Applies to annual electricity production from new builds in each state

RES application

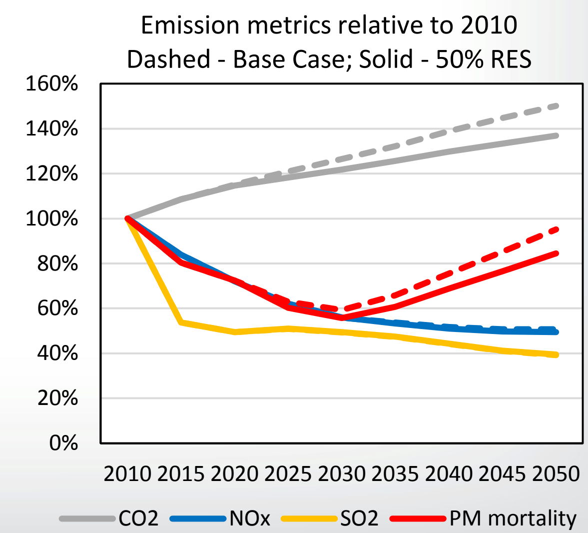
Electricity production by aggregated technology



Observations:

- A 50% RES (for new builds) in Texas reduces electricity production from coal and gas, which are displaced largely by wind
- This transition yields reductions of CO_2, NOx, SO_2, and PM mortality costs

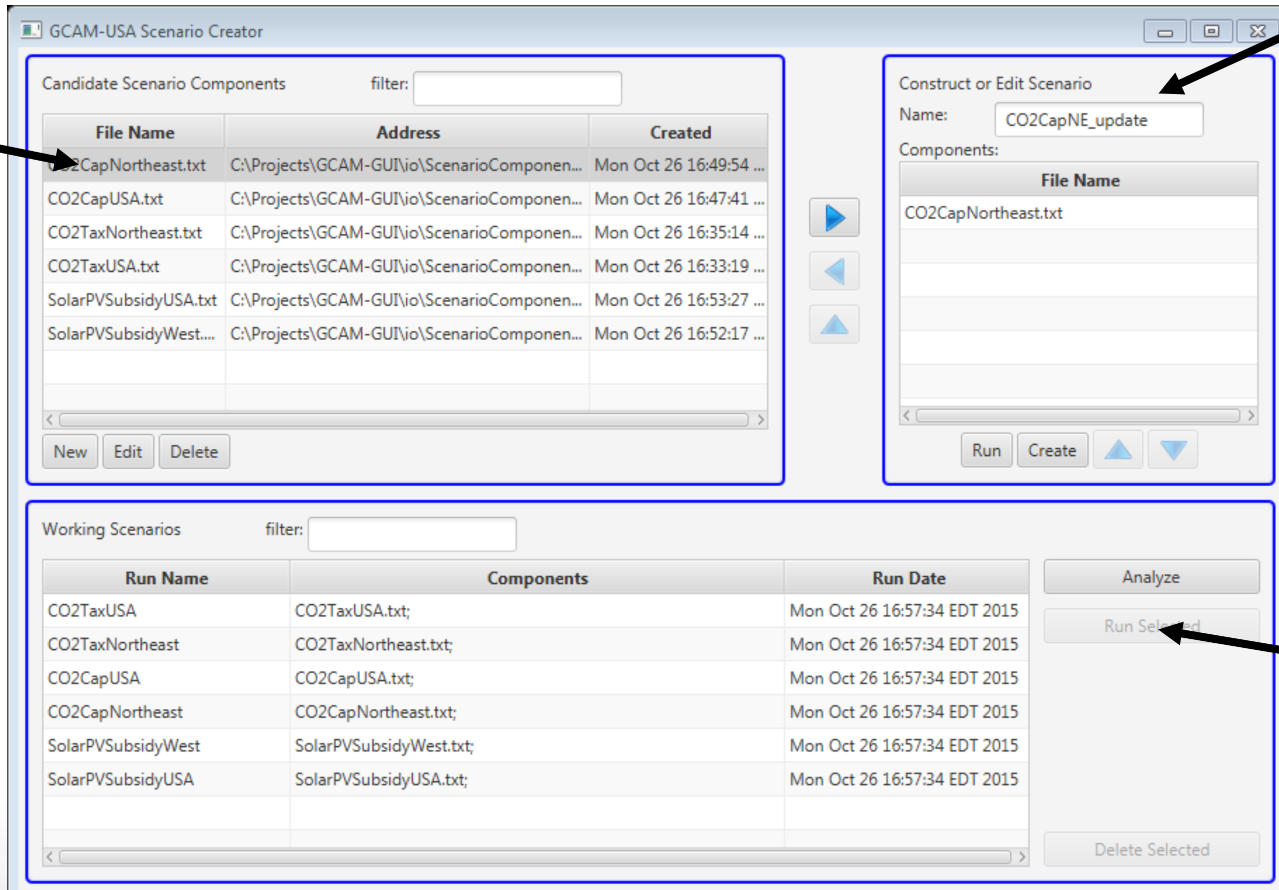
Note: The Clean Power Plan is not included in these results



Ongoing
Decision Support System integration

Scenario Builder: Managing scenarios

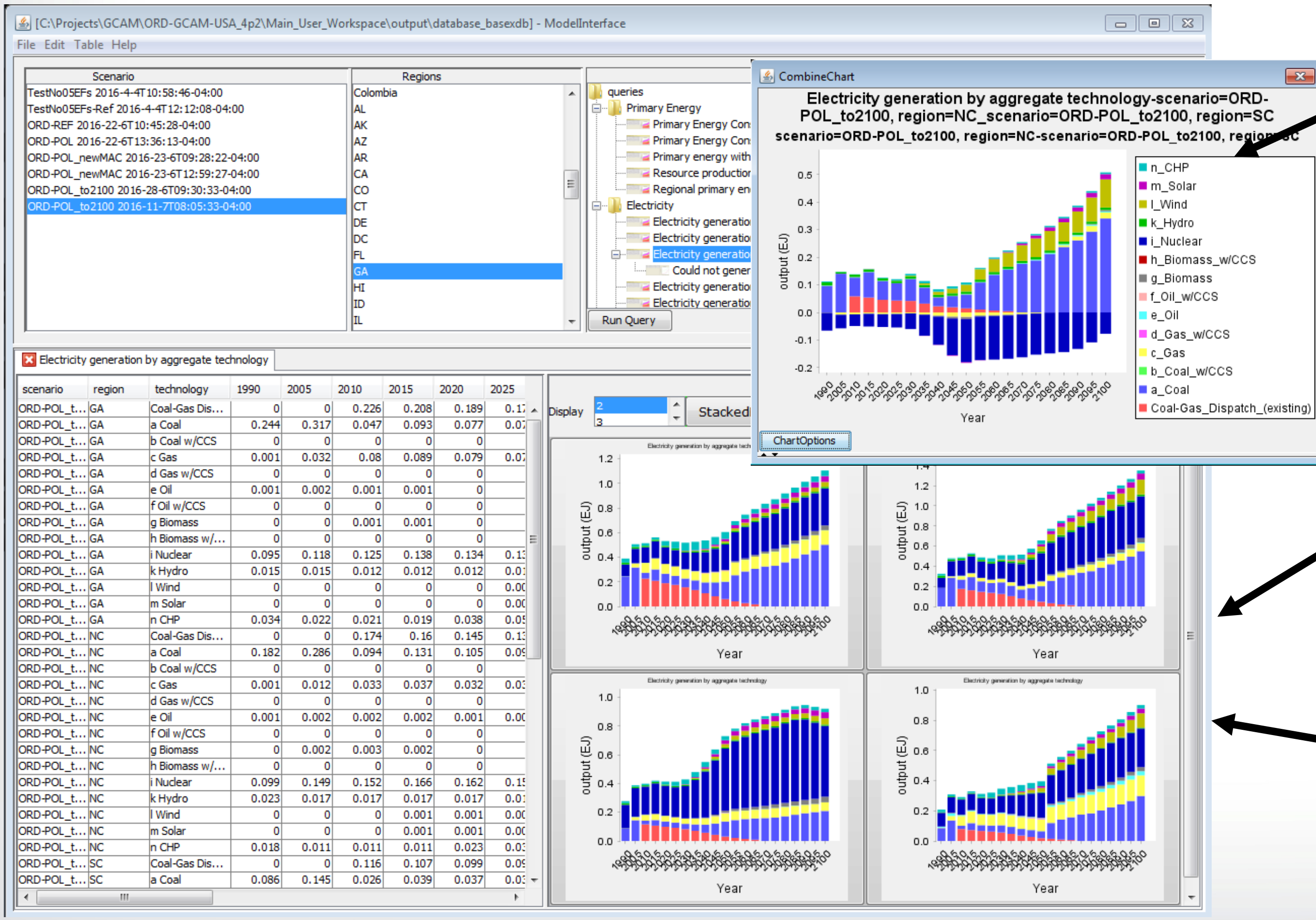
Library of scenario components



Creating a new scenario from existing components

Management and execution of scenarios

Enhancements to the Model Interface



Easily sum over regions and estimate differences across scenarios

Show results separate plots

Choose from line, bar, and pie charts

Concluding remarks

- This presentation touches on a handful of ways in which the U.S. EPA Office of Research and Development is working to explore how air quality management and greenhouse gas mitigation goals can be met more cost-effectively and robustly
- EPA has many internship and post-doctoral opportunities that may be of interest to current and graduating students
- There may be opportunities for collaboration with the ACE Centers, including the one in which JHU is participating

Questions?

Contact information:

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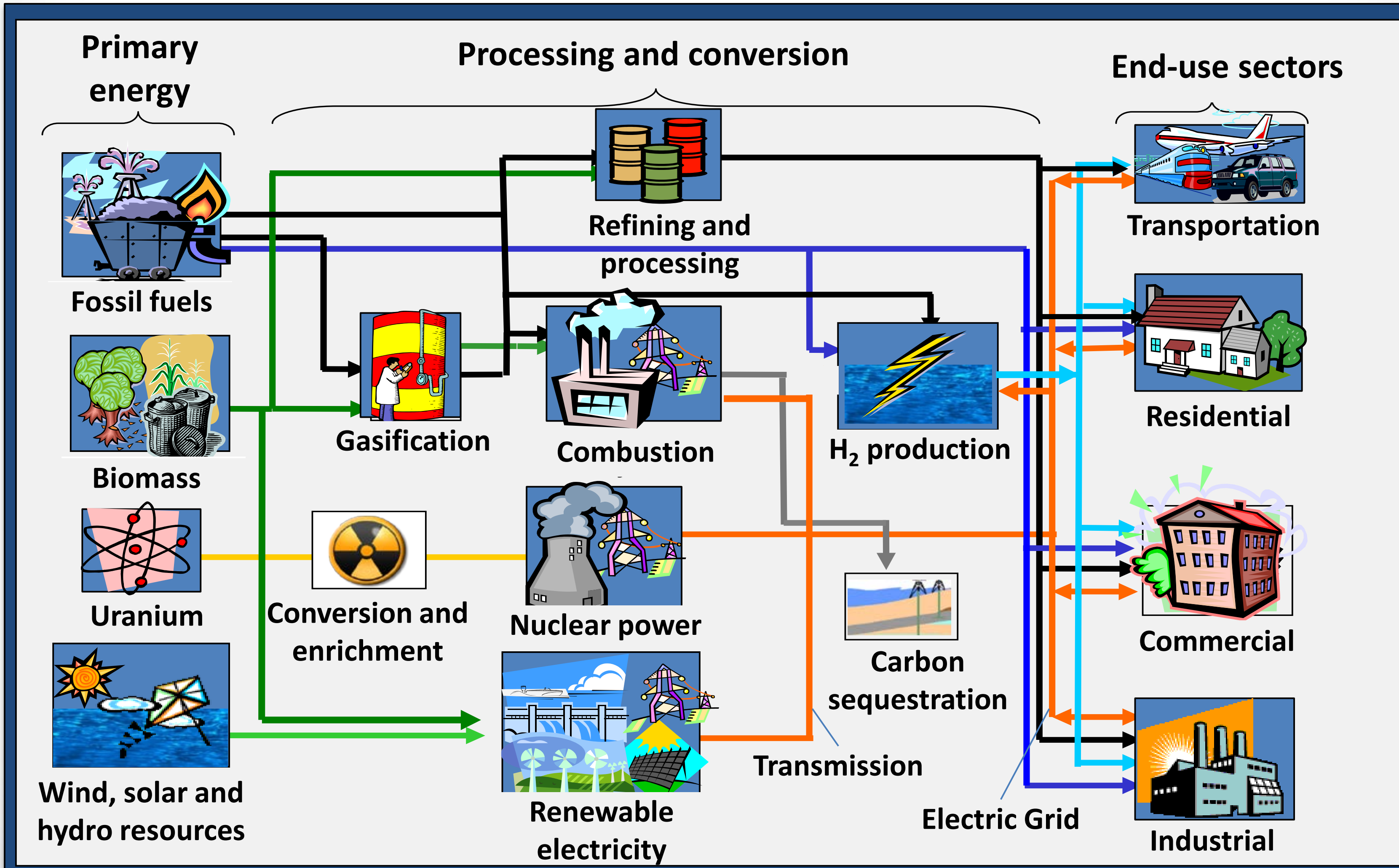
Extra slides

Abbreviations

- BenMAP – Benefits Mapping model
- BC – black carbon
- CCS – carbon capture and sequestration
- CO – carbon monoxide
- CO_2 – carbon dioxide
- CMAQ – Community Model for Air Quality
- CSPV – centralized solar photovoltaics
- EPA – Environmental Protection Agency
- EPAUS9r – EPA 9-region database for use with MARKAL
- GCAM – Global Change Assessment Model
- GCAM-USA - Global Change Assessment Model with state-level resolution for the U.S.
- GHG – greenhouse gas
- GLIMPSE - an energy-environmental-climate decision support tool. Acronym no longer applies.
- Hg - mercury
- IAM – Integrated Assessment Model
- ICLUS – Integrated Climate and Land Use model
- IPM – Integrated Planning Model
- MARKAL – MARKet ALlocation energy system optimization model
- MOVES – Mobile Vehicle Emissions Simulator
- NEMS – National Energy Modeling System
- NONROAD – Nonroad mobile source emissions model
- NOx – nitrogen oxides
- OC – organic carbon
- ORD – Office of Research and Development
- PM – particulate matter
- $PM_{2.5}$ – particulate matter with a diameter less than 2.5 microns
- PM10 – particulate matter with a diameter less than 10 microns
- PV - photovoltaic
- RCP – representative concentration pathway (scenario)
- RES – renewable electricity standard
- SLCP – short-lived climate pollutant
- SO_2 – sulfur dioxides
- SMAT – Speciated Modeled Attainment Test
- SMOKE – Sparse Matrix Operator Kernel Emission processor

Energy system focus

Components of the energy system



Why the energy system?

Energy system contributions to environmental concerns:

- **Air quality**[1]
  - Photochemical smog: 92% of nitrogen oxide (NOx) emissions*
  - Acid rain: 90% of sulfur dioxide (SO_2) emissions*
- **Climate change**[2]
  - Greenhouse gas emissions: 95% of carbon dioxide (CO_2) emissions*
  - Major source of short-lived climate pollutants (e.g., black carbon, methane)
- **Water**
  - Demands: electricity production accounts for 45% of U.S. water withdrawals[3]
  - Pollution:
    - wastewater from fuel extraction and processing, seepage from waste
    - eutrophication from N deposition, acidification from S and N deposition
- **Waste production**
  - Mine tailings, combustion residues, agricultural wastes

*Percentage of U.S. anthropogenic emissions from the energy system in 2014

[1] EPA trends report

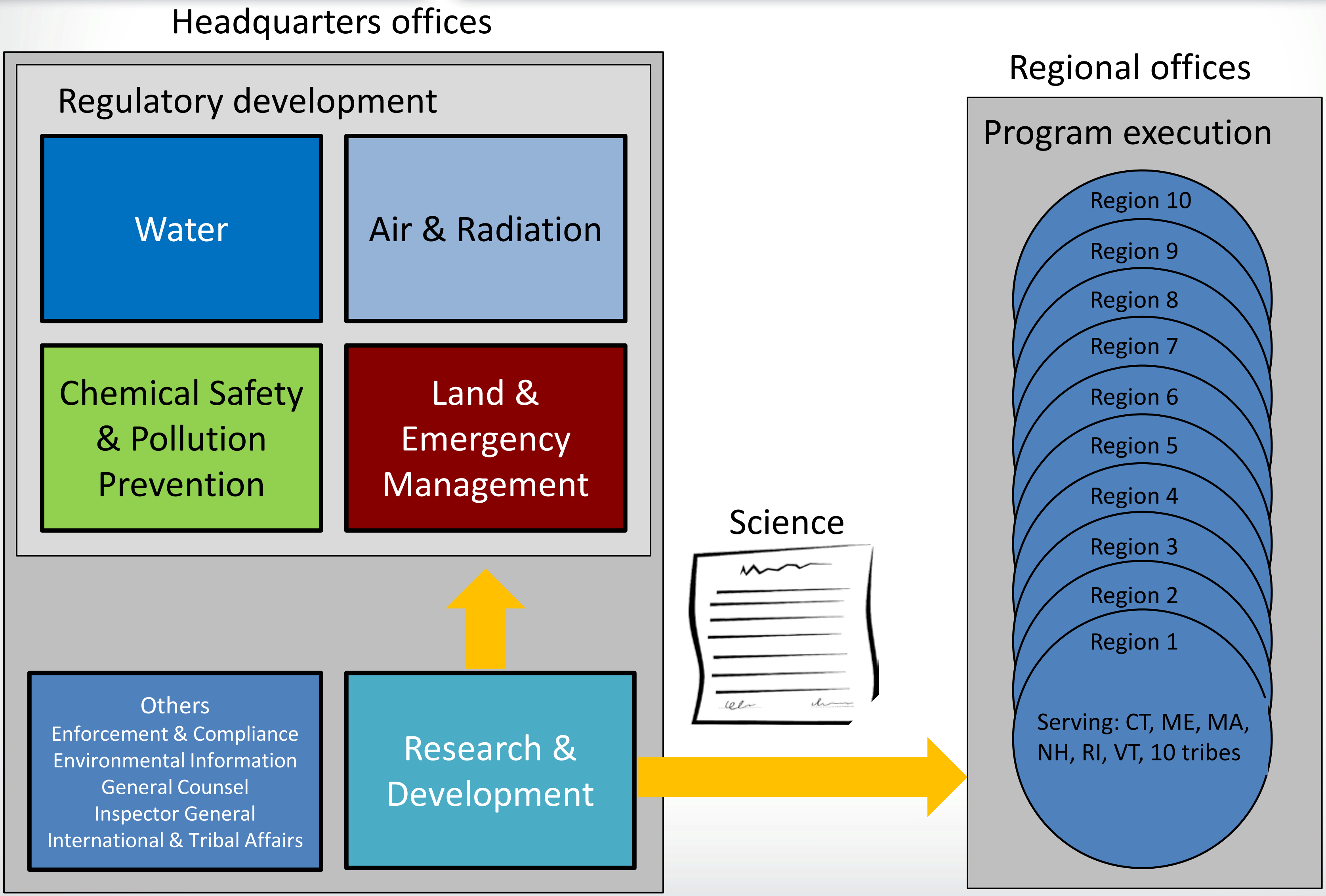
[2] EPA 2016 GHG Inventory

[3] Maupin et al., 2014 (USGS)

Models

Attribute	NEMS	IPM	EPA MARKAL	GCAM-USA
Type	Simulation or Optimization	Optimization	Optimization	Simulation
Formulation	Many modules, some of which are linear, nonlinear, mixed integer, etc	Linear or mixed-integer linear programming	Linear or mixed-integer linear programming	Dynamic, recursive nonlinear
Foresight	Myopic or Perfect (with computational penalty)	Perfect	Perfect	Myopic
Spatial	U.S. Census Division, NERC region	NERC region and state-level	U.S. Census Division	Global and state-level
Temporal	2015-2040 1-year time step	2016-2050 configurable time step	2005-2055 5-year time step	2010-2100 5-year time step
Sectoral	Energy system (Electricity, industry, residential, commercial, transportation)	Electricity production	Energy system (Electricity, industry, residential, commercial, transportation)	Energy, plus agriculture, land use, climate, and water
Technologies	Very high number	Medium number	High number	Medium number
Demand elasticity	Yes	Electricity demands are elastic to price	Optional, currently not used because of computational penalty	Yes
Runtime	Approximately half-day on computational server	Several hours on computational server	1 hour on typical desktop computer	1 hour on typical desktop computer
Availability	Special software required, economic model proprietary	Proprietary	Special software required, model is proprietary	Open source, no special software required

U.S. EPA Structure



Technology assessment

Objective: Explore the role that centralized solar photovoltaics (CSPV) can play in CO_2 mitigation

Tool: MARKAL energy system optimization model

Method: Nested sensitivity analysis

Reference: Loughlin, D., Yelverton, W., Dodder, R., and C. A. Miller (2012). "Examining potential technology breakthroughs for mitigating CO_2 using an energy system model." *Clean Technologies and Environmental Policy*. doi:10.1007/s10098-012-0478-1. Mar. 27, 2012.

Technology assessment application

EPA MARket ALlocation (MARKAL) modeling framework

Scenario assumptions

Population growth and migration

Economic growth and transformation

Climate change impacts on heating and cooling

Technology development

Behavior and preferences

Policies

MARKAL

energy system

linear programming model

Objective:
Select the technologies and fuels that minimize net present value over the 50-year modeling horizon

Subject to:
Energy demands
Emission limits
Physical constraints (mass balance)

Outputs

Energy-related technology penetrations and fuel use

Emissions
- air pollutants
- GHGs
- short-lived climate pollutants (SLCPs)

Water demands

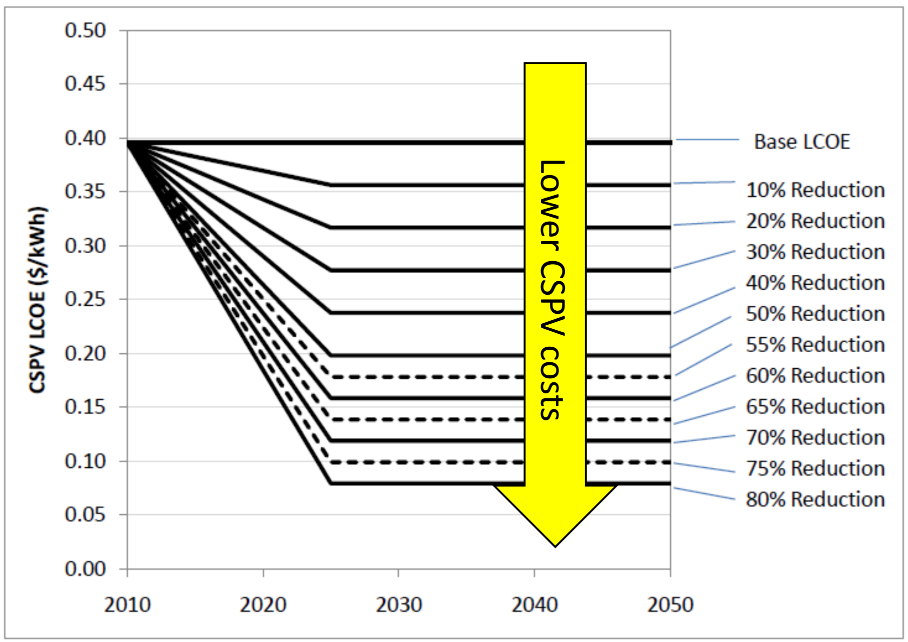
1st order estimates of health and warming impacts

Time horizon: 2005 – 2055; Temporal resolution: 5 years; Spatial coverage: U.S.; Spatial resolution: Census Division

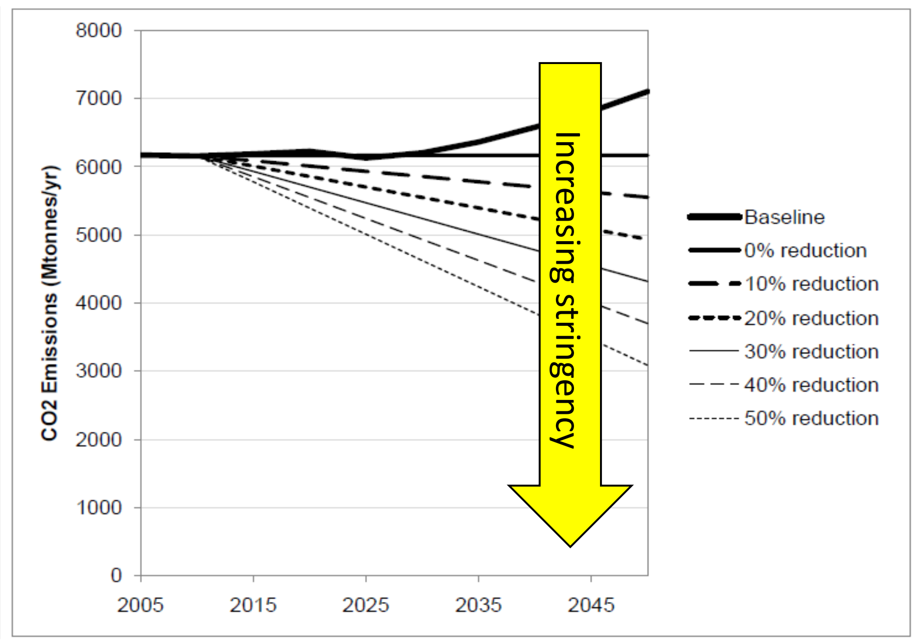
Technology assessment application

A nested sensitivity analysis was applied to evaluate CSPV penetration potential through 2050 over all combinations of the following:

Alternative CSPV levelized cost trajectories



Alternative U.S. energy system CO_2 constraints



Technology assessment application

Results:

Electricity output (billion kWh) from CSPV in 2050

Technology	CO_2 Policy Target	Reduction in CSPV LCOE							
		Base	50%	55%	60%	65%	70%	75%	80%
CSPV	None	-	-	-	-	-	30	110	780
	30%	-	-	70	320	290	1,100	2,000	2,400
	40%	-	510	640	800	800	1,100	1,500	1,900
	50%	20	90	100	170	160	680	1,100	1,400

Insights:

- For the 30% mitigation targets, CSPV penetration followed the expected trends
- Counter-intuitively, increasing the CO_2 reduction target to 40% or 50% reduced CSPV output
- Further analysis suggested:
  - the more stringent reduction targets led to electrification of end uses (e.g., vehicles and building heating systems)
  - these changes disproportionately led to more night-time electricity demands
  - other technologies respond better to nighttime demands (e.g., nuclear, wind, coal and gas with CCS)

Ongoing:

- Exploring vehicle time-of-charging assumptions, stationary storage, and regional considerations