Computing and Systems in Support of Coordinated Energy-Environmental-Climate Planning

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Forward

- **Objectives of this presentation**

  Provide an overview of the linkages among energy, the environment and climate change

  Highlight recent and ongoing work to apply Computing and Systems to energy-environmental-climate research

  Share insights into how the modeling approaches, methods, and tools that I learned in my graduate program are being used in this research

- **Intended audience**

  Graduate students and faculty members within the Computers & Systems program of the N.C. State University Department of Civil, Construction and Environmental Engineering

Abbreviations

- CCS – carbon capture and sequestration
- CO – carbon monoxide
- CO_2 – carbon dioxide
- CSPV – centralized solar photovoltaics
- 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
- MARKAL – MARKet ALlocation energy system optimization model
- NOx – nitrogen oxides
- PV - photovoltaic
- RCP – representative concentration pathway (scenario)
- SLCP – short-lived climate pollutant
- SO_2 – sulfur dioxides

Outline

1. Context and motivation
2. Energy, environmental, and climate linkages
3. Computing and Systems applications
    - Technology assessment (sensitivity analysis)
    - Air Quality Futures (scenario analysis)
    - GLIMPSE (decision support system)
4. Reflections on the first half of my career and the role of Computing and Systems

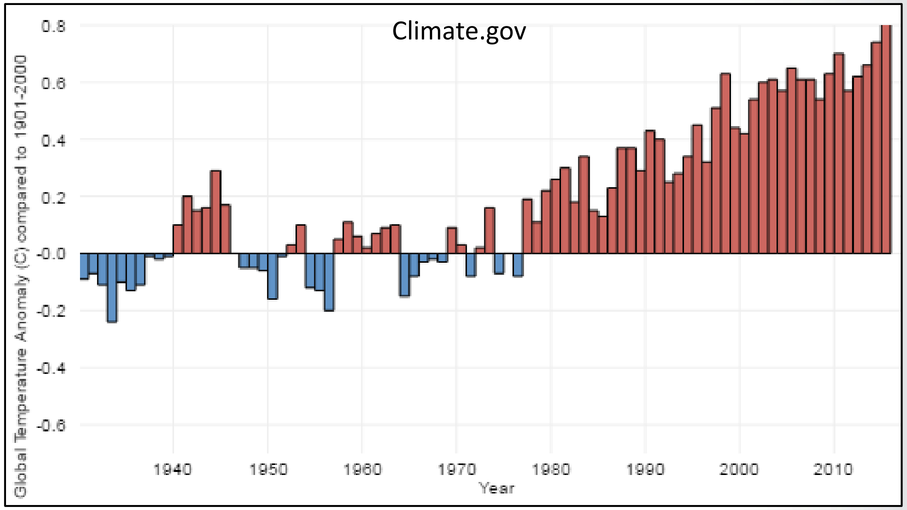
Part 1. Context and motivation

I. Context and motivation
Climate change is occurring

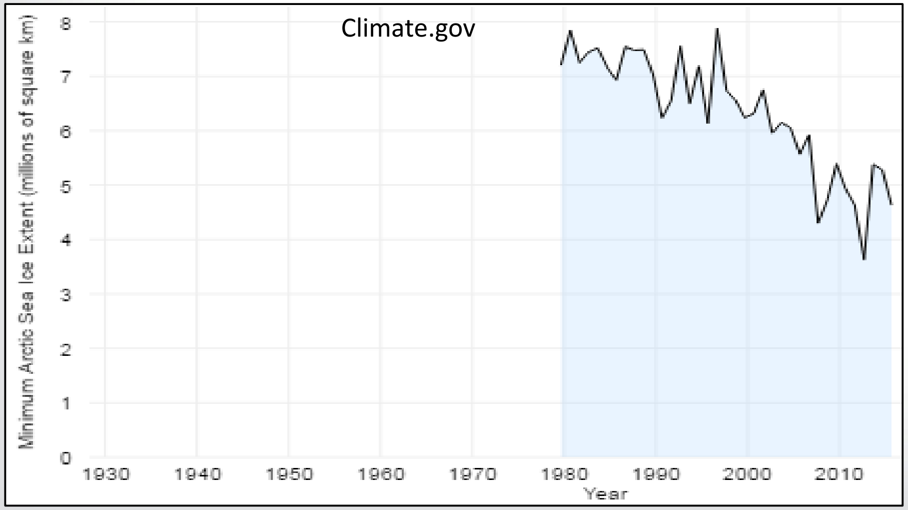
Key indicators are pointing to warming

Sources for more information:
U.S. Nat’l Oceanic and Atmospheric Administration (Climate.gov)
U.S. National Climatic Data Center (www.ncdc.noaa.gov)
U.S. Global Change Research Program (GlobalChange.gov)
U.S. Environmental Protection Agency (EPA.gov/ClimateChange)
European Environment Agency (EEA.Europa.eu/themes/climate)
Intergovernmental Panel on Climate Change (IPCC.ch)

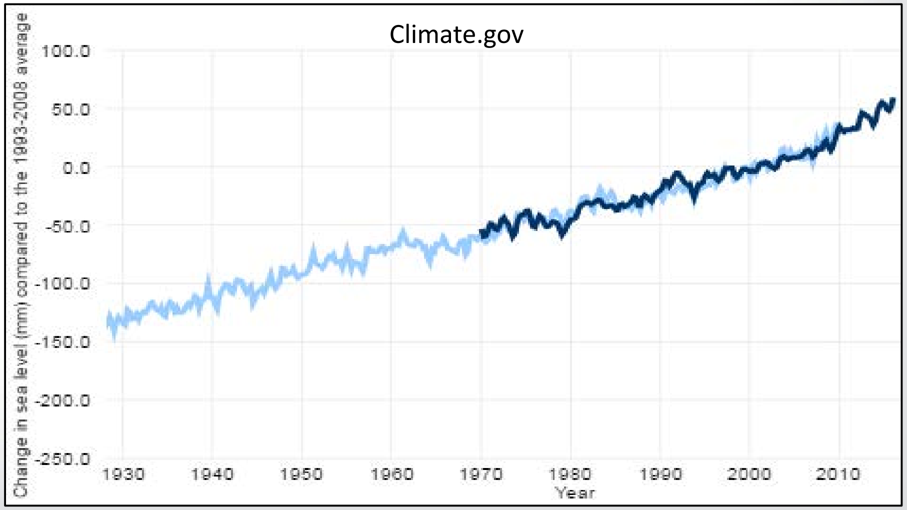
Δ Global mean temperature (°C)



Minimum arctic ice extent (million sq. km)



Δ Sea level (mm)

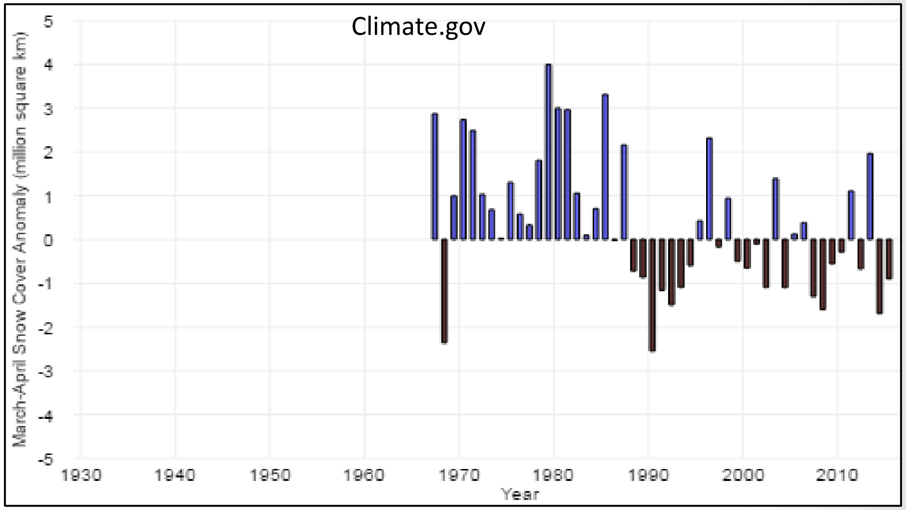


I. Context and motivation
Climate change is occurring, cont'd

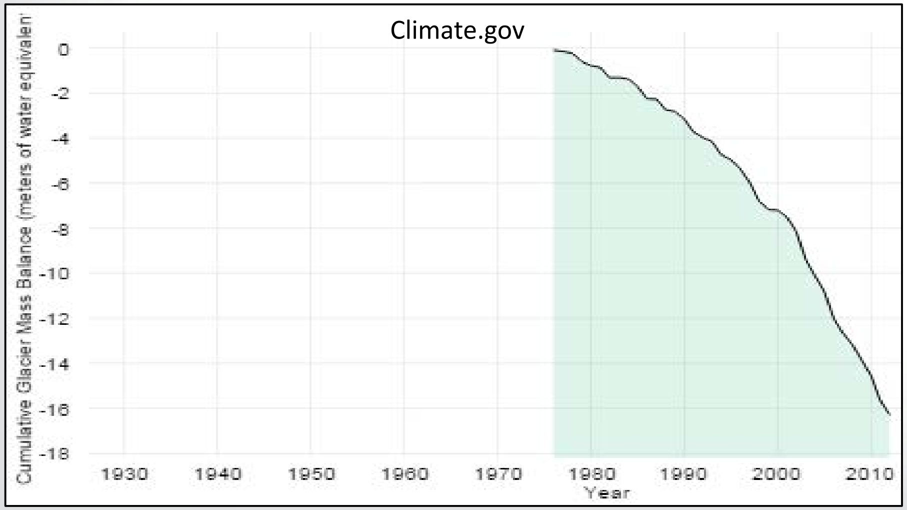
More key indicators

Sources for more information:
U.S. Nat'l Oceanic and Atmospheric Administration (Climate.gov)
U.S. National Climatic Data Center (www.ncdc.noaa.gov)
U.S. Global Change Research Program (GlobalChange.gov)
U.S. Environmental Protection Agency (EPA.gov/ClimateChange)
European Environment Agency (EEA.Europa.eu/themes/climate)
Intergovernmental Panel on Climate Change (IPCC.ch)

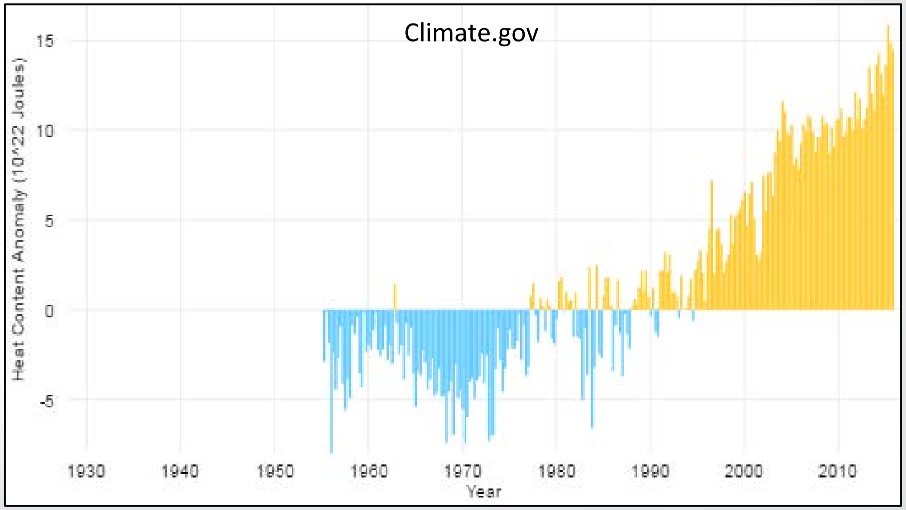
∆ N. Hem. Mar-Apr Snow cover (million sq. km)



∆ Glacial mass (m of water equivalent)



∆ Ocean heat content (joules)



I. Context and motivation
Climate impacts are occurring already

Warmest years on record (1880 – 2015)

Global mean, combined land and ocean

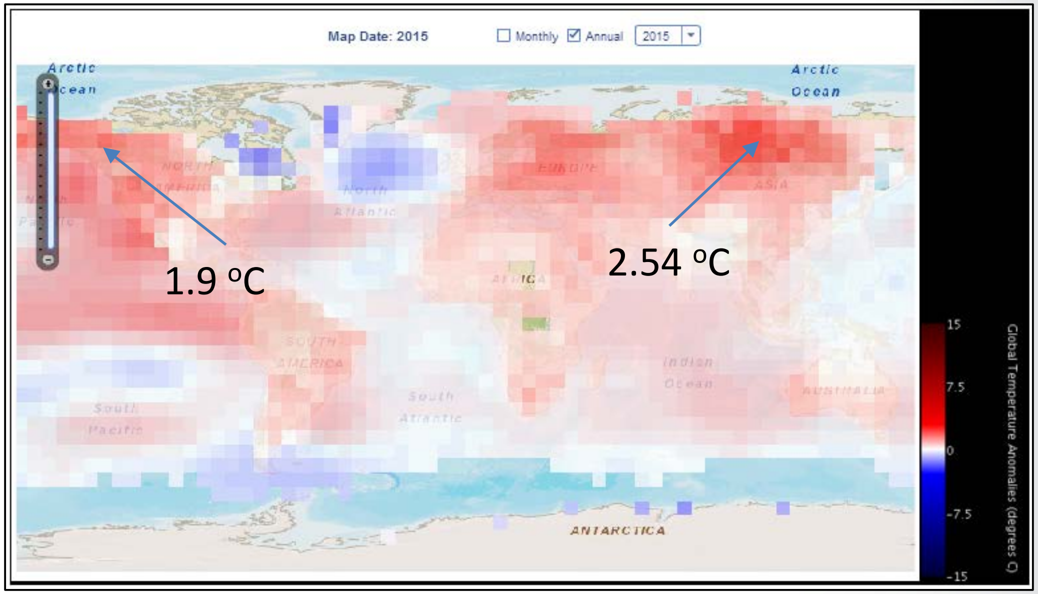
Rank	Year	Anomaly ºC	Anomaly ºF
1	2015	0.90	1.62
2	2014	0.74	1.33
3	2010	0.70	1.26
4	2013	0.66	1.19
5	2005	0.65	1.17
6	1998	0.63	1.13
6 (tie)	2009	0.63	1.13
8	2012	0.62	1.12
9	2003	0.61	1.10
9 (tie)	2006	0.61	1.10
9 (tie)	2007	0.61	1.10

https://www.ncdc.noaa.gov/sotc/global/201513

Impacts at specific locations can be very different from global averages

2015 Global surface temperature anomaly

relative to 1981-2010 mean



Map Date: 2015 ☐ Monthly ☑ Annual 2015

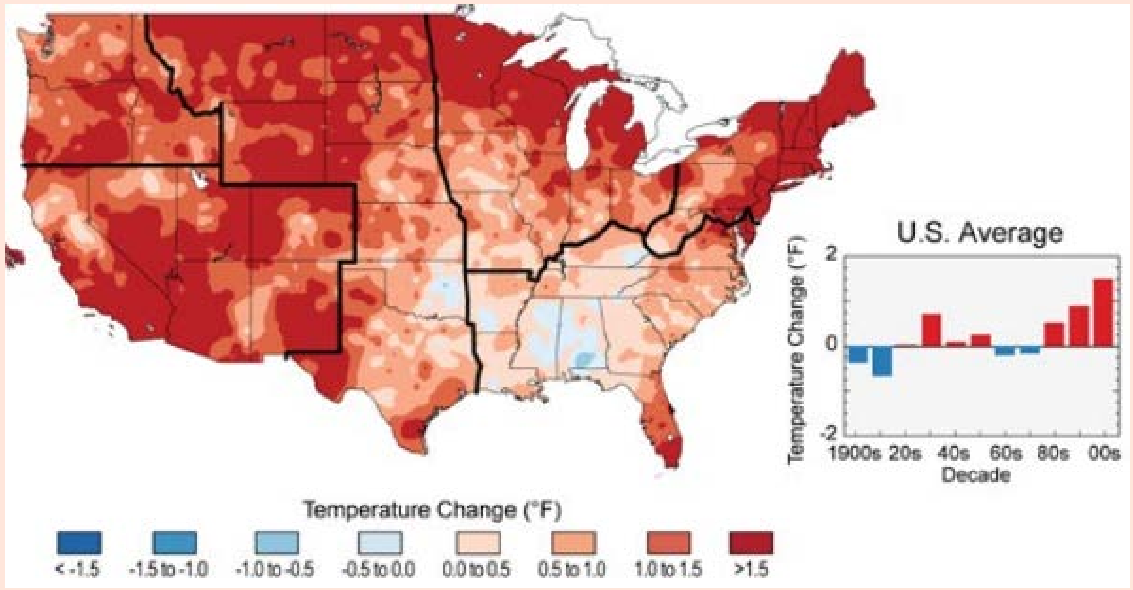
1.9 ºC

2.54 ºC

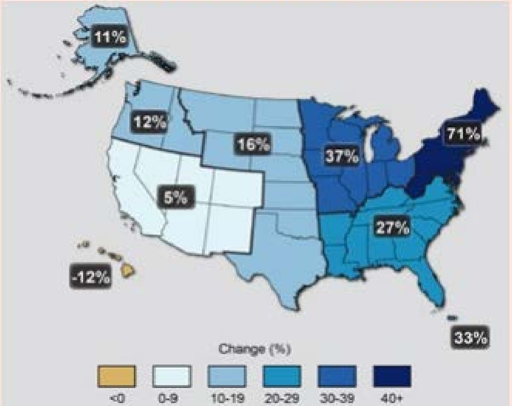
http://www.ncdc.noaa.gov/cag/mapping/global

I. Context and motivation
… including in the U.S.

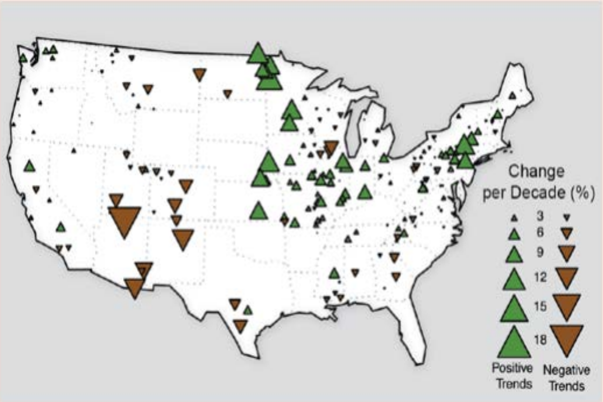
Change in mean annual temperature (°F), 1991-2012 vs. 1900-1960



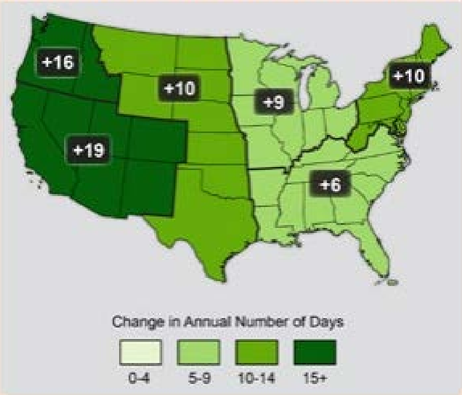
Observed Change in Very Heavy Precipitation



Trends in Flood Magnitude



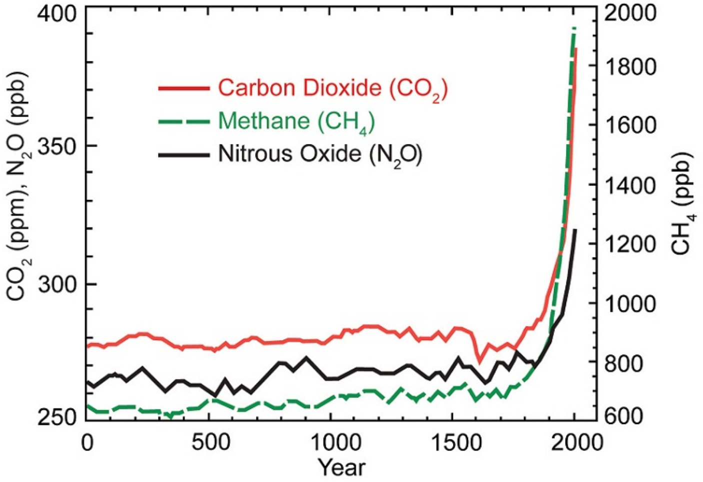
Observed Increase in Frost-Free Season Length



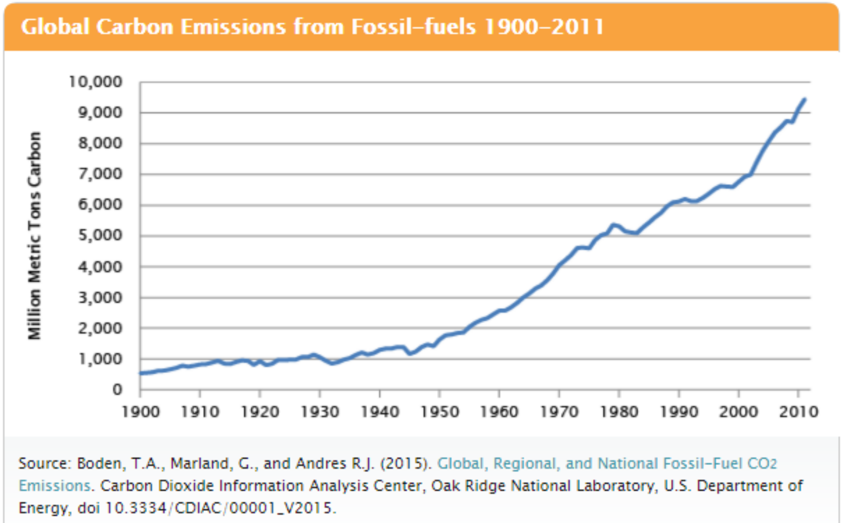
Examples of impacts described in the 3rd National Climate Assessment (http://nca2014.globalchange.gov/)

1. Context and motivation
Humans are driving recent changes

Greenhouse gas concentration trends



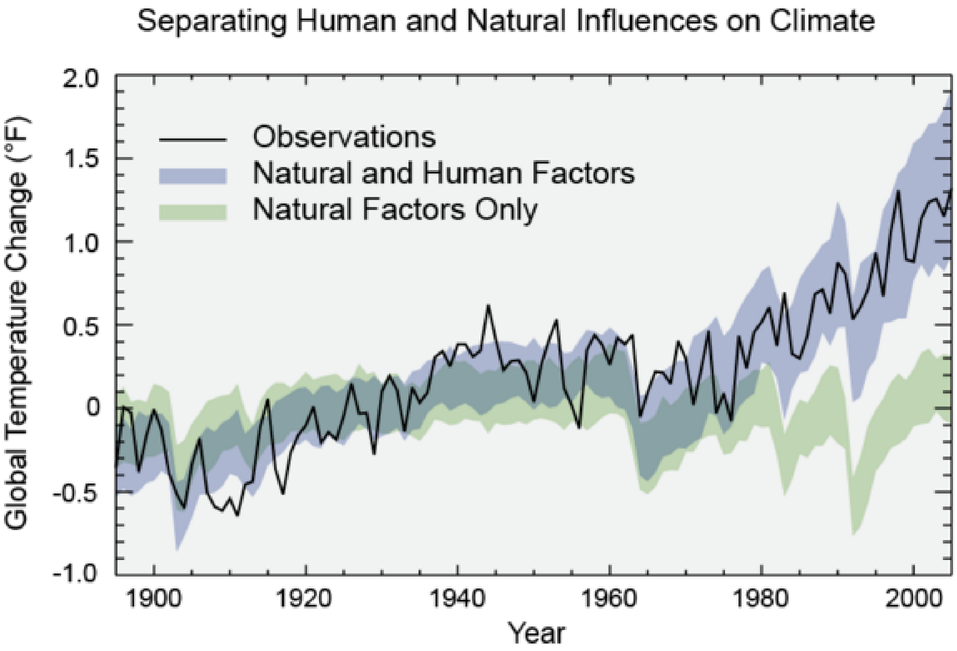
https://www3.epa.gov/climatechange/science/causes.html



Global Carbon Emissions from Fossil-fuels 1900–2011

Source: Boden, T.A., Marland, G., and Andres R.J. (2015). Global, Regional, and National Fossil-Fuel CO2 Emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, doi 10.3334/CDIAC/00001_V2015.

Modeling vs. Observations



Separating Human and Natural Influences on Climate

https://www3.epa.gov/climatechange/science/causes.html

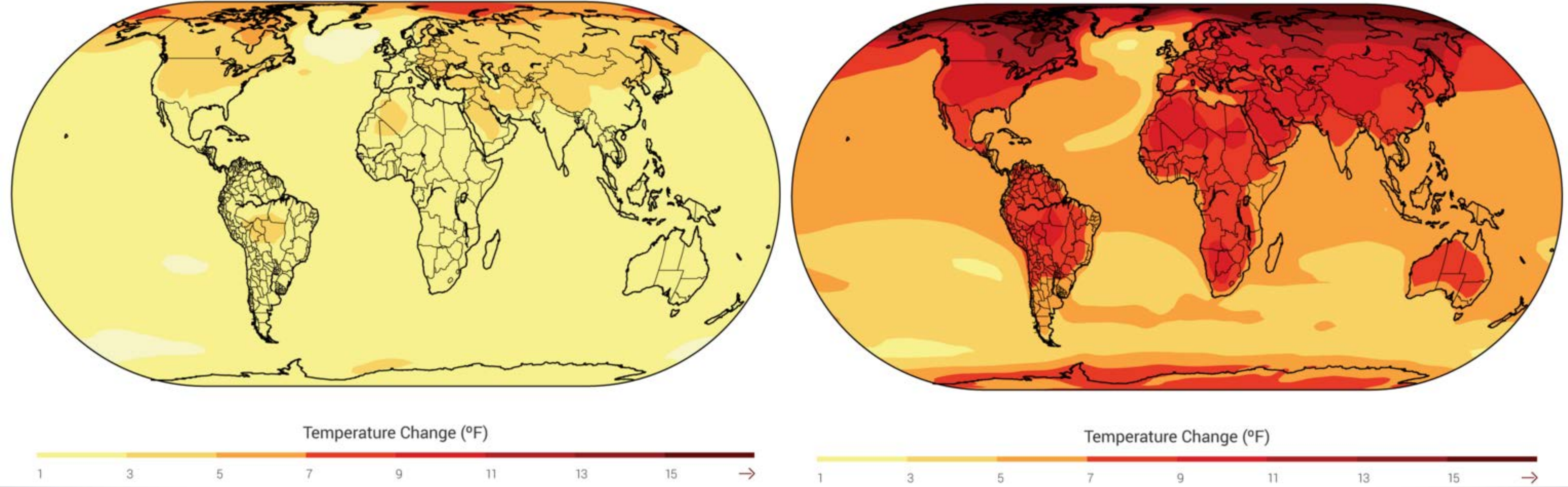
1. Context and motivation

Reducing GHGs can reduce future impacts

Modeling results for two emission scenarios

Rapid emission reductions (RCP 2.6)

Continued emission increases (RCP 8.5)

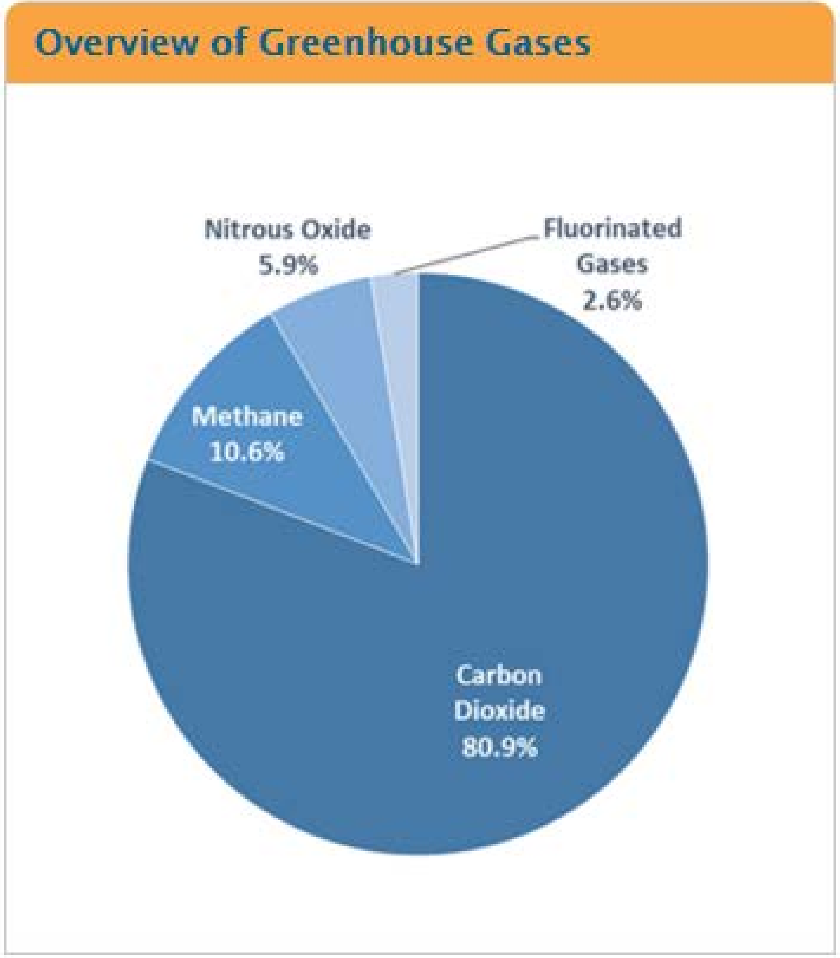


Projected change in average annual temperature over the period 2071-2099 (compared to 1970-1999)

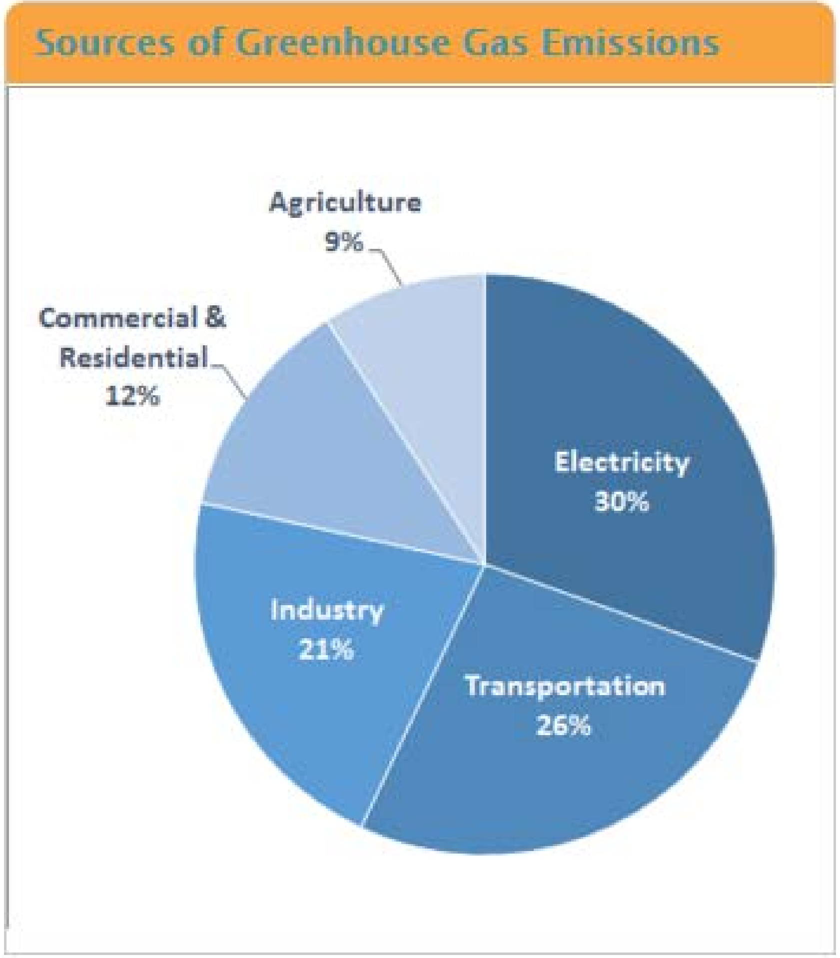
http://nca2014.globalchange.gov/report/our-changing-climate/future-climate-change

Part 2. Energy, environmental and climate linkages

2. Energy-environmental-climate links
Most U.S. GHGs are from fuel combustion



Overview of Greenhouse Gases

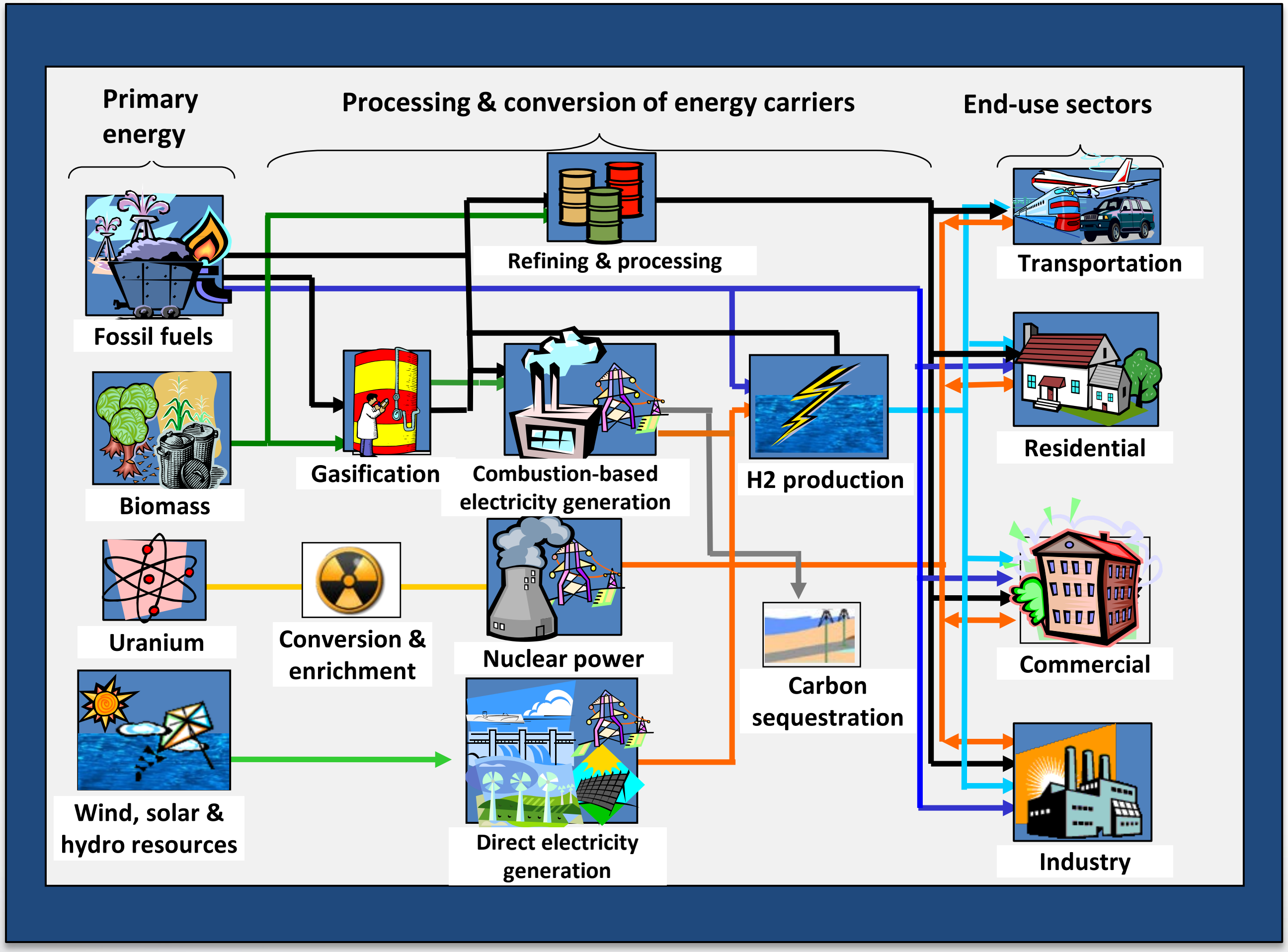


Sources of Greenhouse Gas Emissions

https://www3.epa.gov/climatechange/ghgemissions/sources.html

2. Energy-environmental-climate links
Energy also impacts air and water

The energy system consists of the fuels and technologies that extend from resource extraction through meeting end-use energy demands (e.g., lighting, space heating, travel)



Impacts

Contribution to U.S. anthropogenic emissions:

CO_2 ~ 94%
NOx ~ 95%
SO_2 ~ 89%
CO ~ 95%
Hg ~ 87%

air pollutants

Environmental concerns:

GHGs & SLCFs
Ozone
PM2.5
Acid deposition
Toxics, mercury
Water use & pollution
(51% of US water withdrawals)

2. Energy-environmental-climate links GHG mitigation options

- Examples of technological GHG mitigation options:
  - Electric sector
    - Fuel switching from coal to natural gas
    - Carbon capture and sequestration (CCS) retrofits to plants
    - New high-efficiency fossil plants with integrated CCS
    - Co-firing biomass in a coal plant
    - Gasifying biomass
    - Wind and solar power
    - Nuclear power
  - Transportation sector
    - Biofuels and other low carbon alternatives
    - Vehicle efficiency improvements through improved engines, lightweighting, etc.
    - Electrification
- Other options
  - Conservation and energy efficiency
  - Geo-engineering

2. Energy-environmental-climate links
There are tradeoffs among technologies

- Each of these has a different environmental signature
  - Air pollutant emissions (e.g., from combustion)
  - Water demands (e.g., thermoelectric cooling, biomass irrigation)
  - Water quality impacts (e.g., heat, effluent and deposition)
  - Waste material production (e.g., coal ash, wastewater)
  - Upstream impacts (e.g., from mining, construction, fertilizer)
- Some technologies may lead to increases in some impacts and decreases in others
- There are also cost and logistical considerations
  - Capital and operations and maintenance costs
  - Intermittency of generation and other grid integration issues
  - Reliance on rare and expensive materials
  - Resilience to drought
  - Physical footprint
  - Safety

2. Energy-environmental-climate links
Examples of research questions

- Technology assessment
  - How do these mitigation technologies compare if we consider energy, environmental, and climate implications from a systems perspective?
  - What performance targets are necessary for new technologies to be competitive within a mitigation strategy?
  - Can we predict any "gotchas," such as from fuel switching in other sectors?
- Pathway analysis
  - Are there energy system pathways that simultaneously meet energy, environmental and climate goals?
  - How do pathways options compare over a range of possible futures?
  - Are there attributes of pathways that make them more robust to uncertainty?
- Decision support
  - What regulatory levers are available for achieving energy, environmental, and climate goals?
  - What are the co-benefits of actions in any one of these areas?
  - What are the benefits of coordinated actions?

Part 3.

Addressing research questions with computing and systems

3. Computing and Systems applications
Available models, methods and tools

A sampling of models, methods and tools for addressing these questions:

- Modeling
  - Optimization (How do I …?)
  - Simulation (What will happen if ...?)
- 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

Technology assessment

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

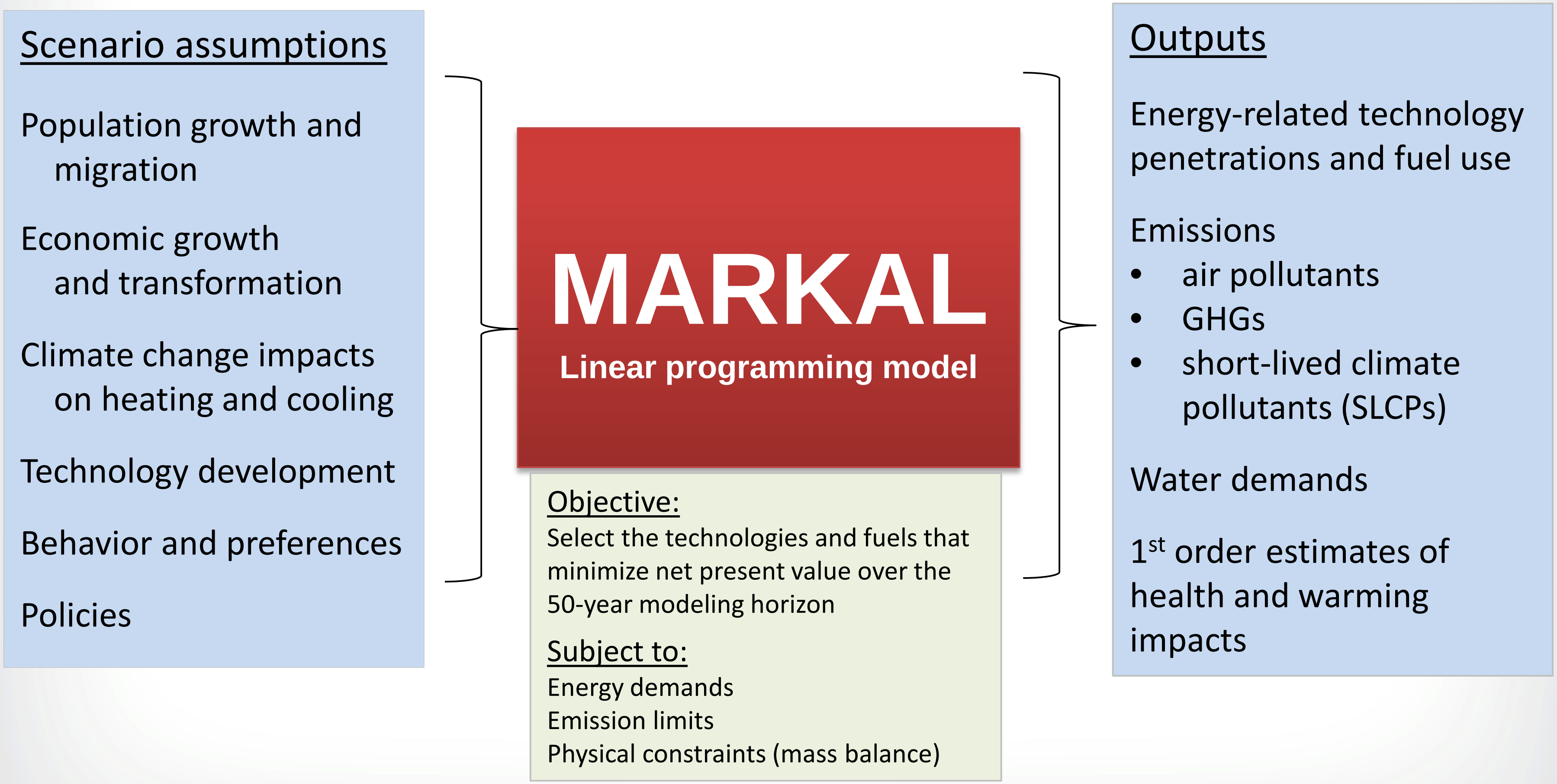
Tool: MARKAL energy system optimization model

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.

3. Computing and Systems applications
Technology assessment application

EPA MARket ALlocation (MARKAL) modeling framework



<u>Scenario assumptions</u>

Population growth and migration

Economic growth and transformation

Climate change impacts on heating and cooling

Technology development

Behavior and preferences

Policies

MARKAL

Linear programming model

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

<u>Subject to:</u>
Energy demands
Emission limits
Physical constraints (mass balance)

<u>Outputs</u>

Energy-related technology penetrations and fuel use

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

Water demands

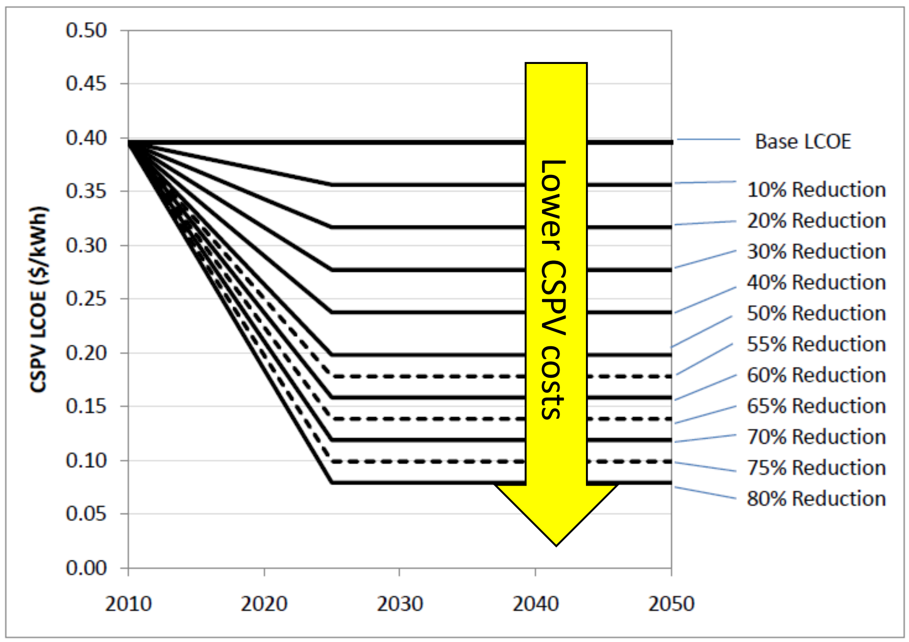
1st order estimates of health and warming impacts

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

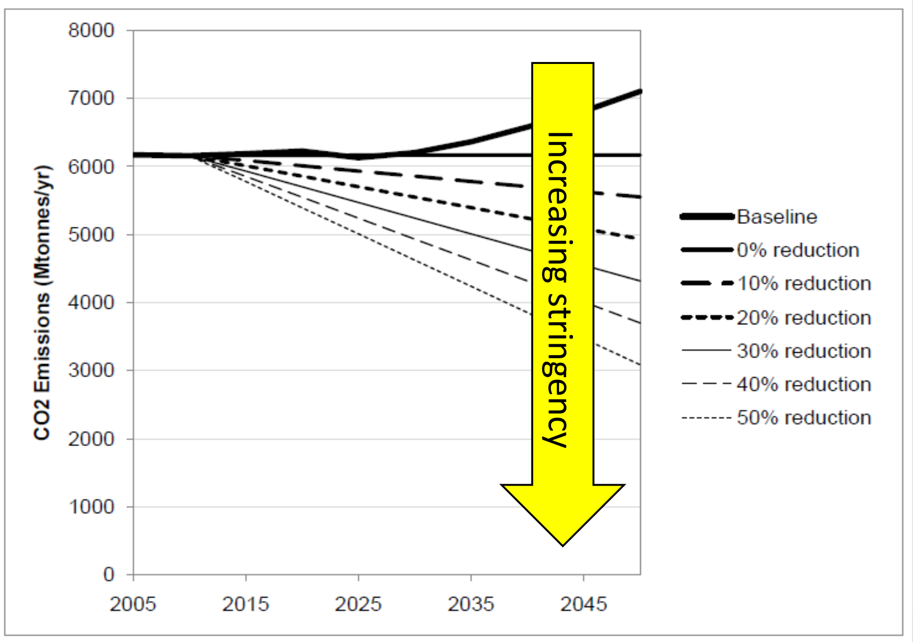
3. Computing and Systems applications
Technology assessment application

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

Alternative CSPV levelized cost trajectories



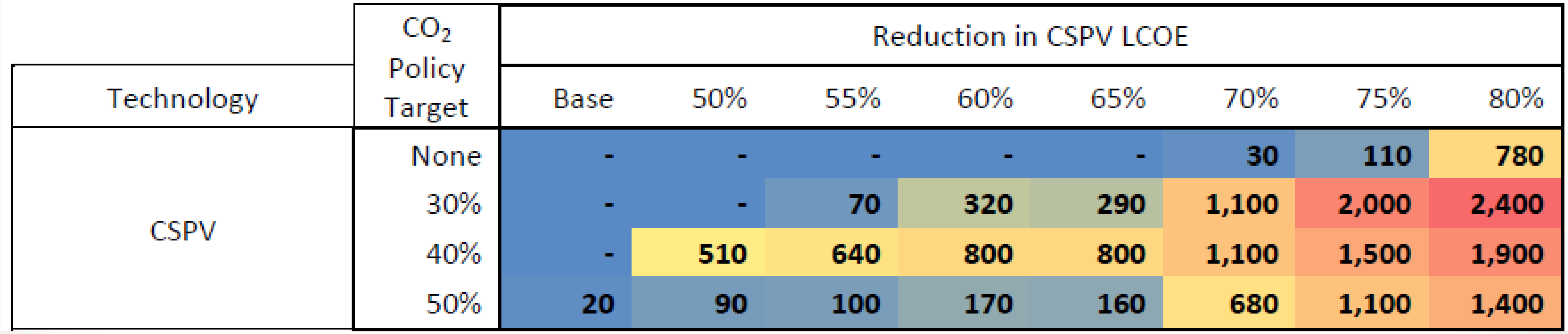
Alternative U.S. energy system CO_2 constraints



3. Computing and Systems applications 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

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.

3. Computing and Systems applications
Air Quality Futures

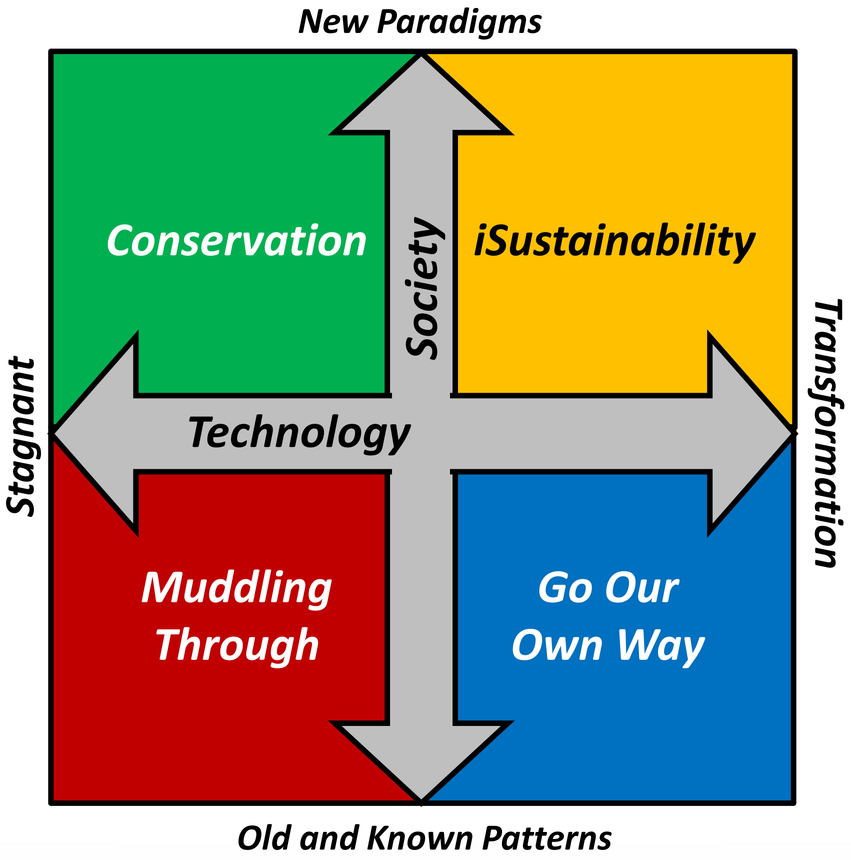
- We applied the Future Scenarios Method to develop a set of very different scenarios
- Future Scenarios Method steps:
  - Interview internal and external experts
  - Select the two most important uncertainties and develop a scenario matrix
  - Construct narratives describing the matrix's four scenarios
  - Implement the scenarios into a modeling framework and evaluate
- Levers for implementing the scenarios in MARKAL:
  - Technology-specific hurdle rates
  - Technology availability and cost
  - Shifts in energy demands

3. Computing and Systems applications
Air Quality Futures

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.



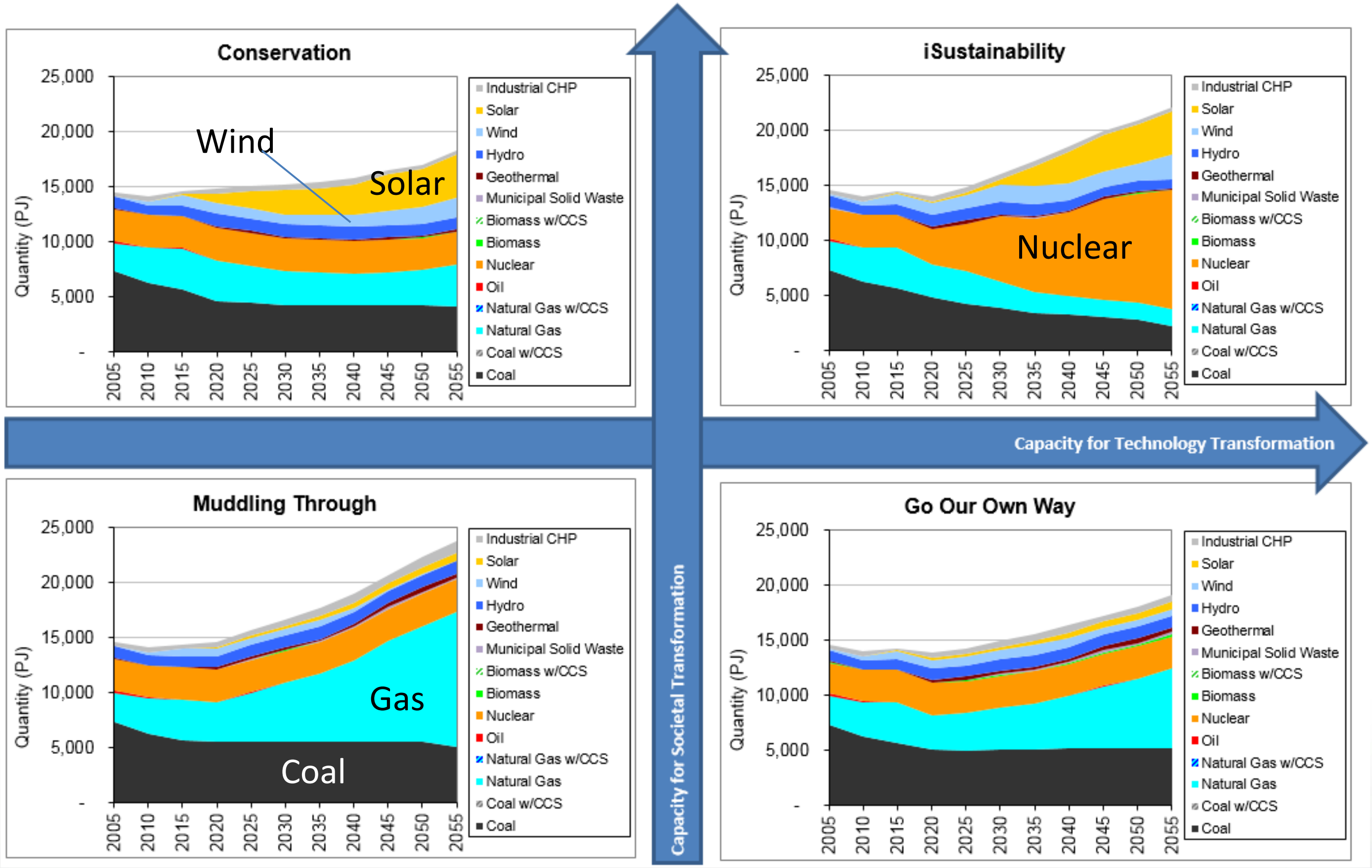
Muddling Through has limited technological advancements and stagnant behaviors, meaning electric vehicle use would be highly limited and trends such as urban sprawl and increasing per-capita home and vehicle size would continue.

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.

3. Computing and Systems applications
Air Quality Futures

Example of the differences from one scenario to another

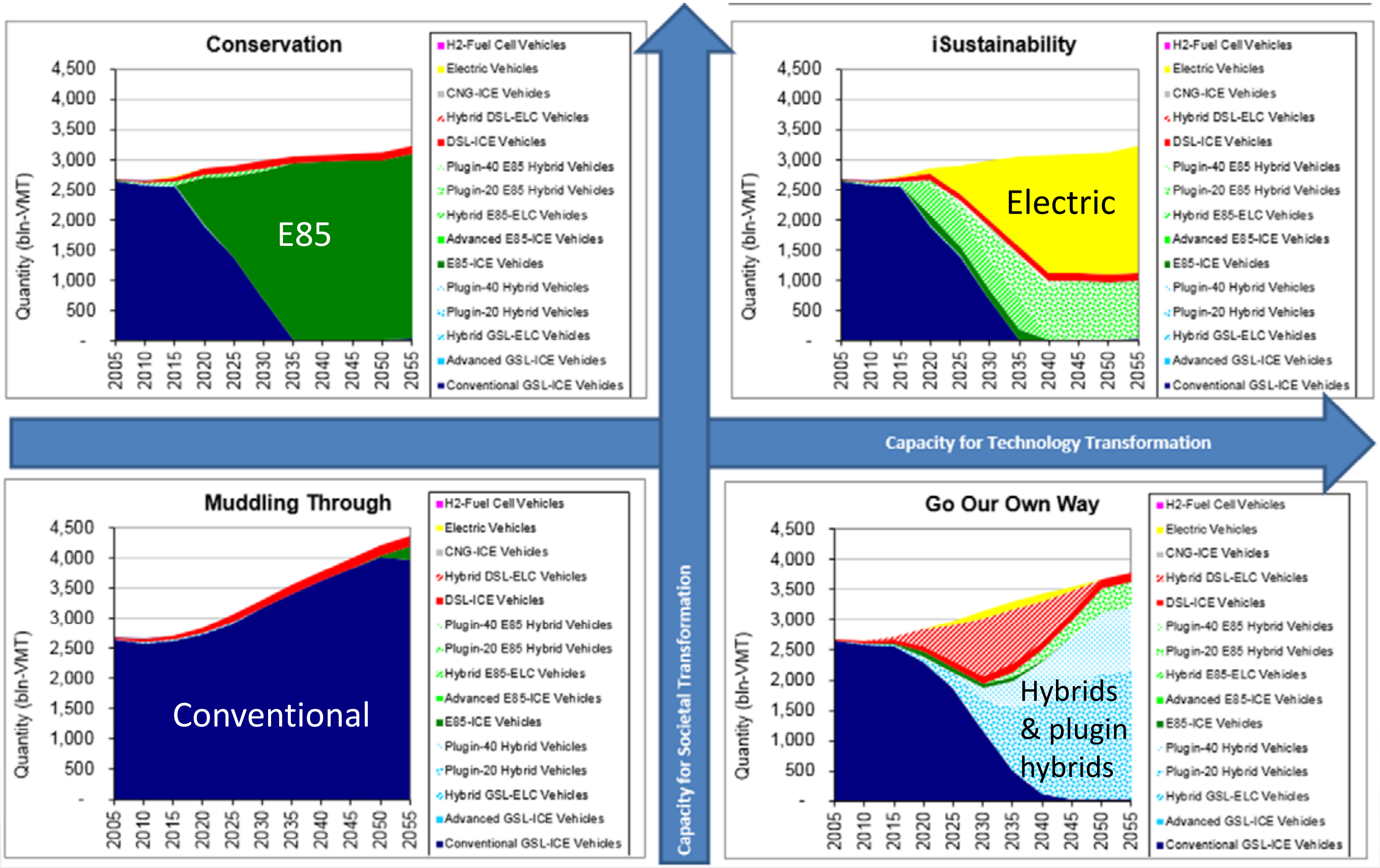
Electricity production by aggregated technologies



3. Computing and Systems applications
Air Quality Futures

Example of the differences from one scenario to another

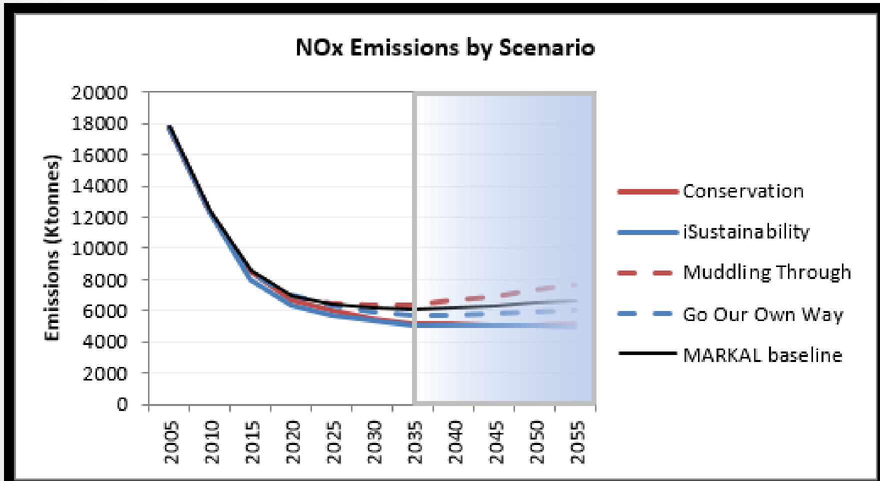
Light duty vehicle technologies

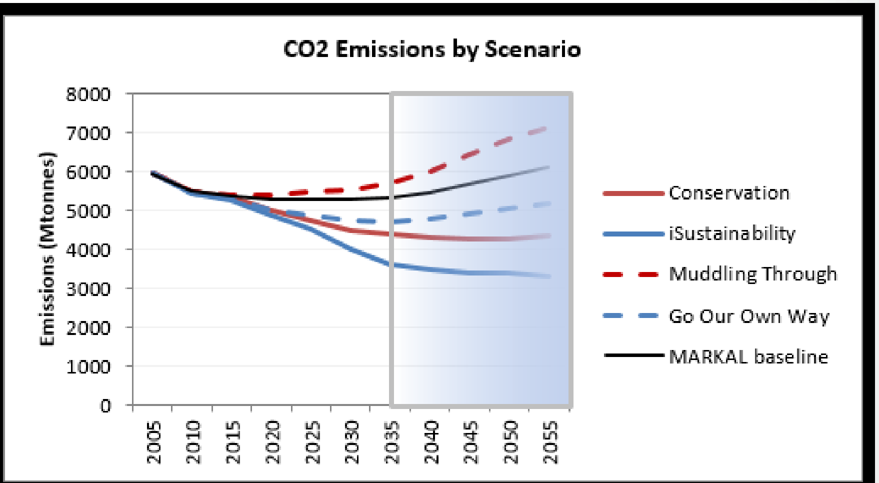


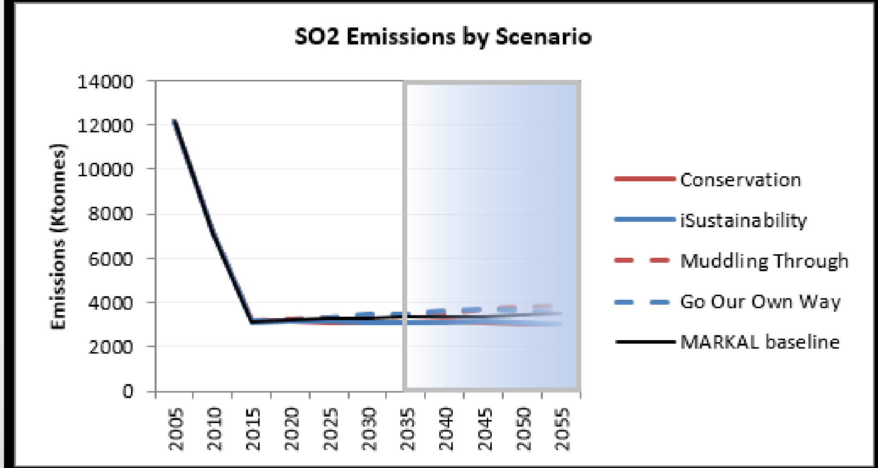
3. Computing and Systems application
Air Quality Futures

Emission projections across the alternative baselines

Emissions of nitrogen oxides (NOx), sulfur dioxide (SO_2), and CO_2.







Existing regulations are relatively robust in locking in expected reductions of criteria pollutants.

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

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

Decision support system

Project: GLIMPSE

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

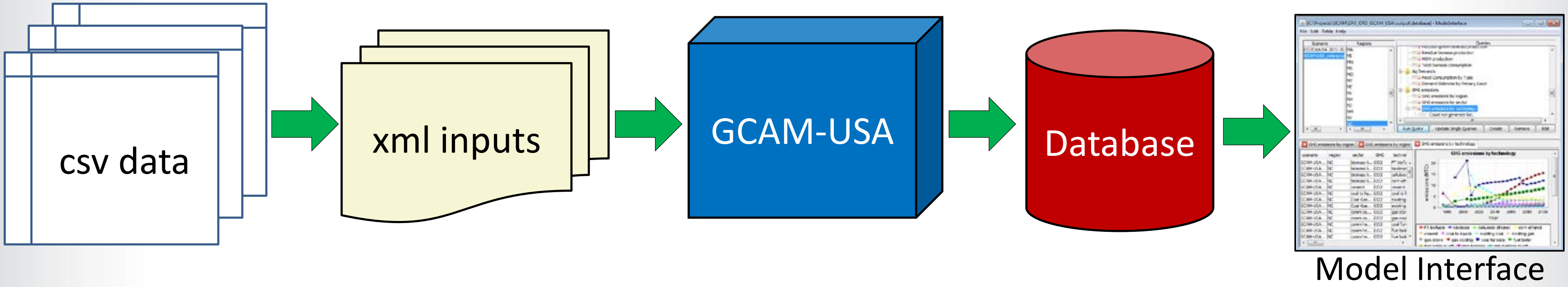
Requirements: Address decision-relevant sectors and time horizons, state-level resolution, easy to use, freely available

3. Computing and Systems application Decision support system

- Integrated Assessment Models (IAMs) are simulation models that link representations of human and earth systems
  - Components can include representations of:
    - Economy, energy, land use, agriculture, and climate systems
- IAMs have been used in global studies of climate change and GHG mitigation
- Recently, IAMs with a high spatial (state) and temporal (5 year) resolution have been developed
- Would such a model be of use to support state-, regional- or national-scale energy-environmental-climate planning?

3. Computing and Systems application Decision support system

GCAM-USA workflow:



csv data

xml inputs

GCAM-USA

Database

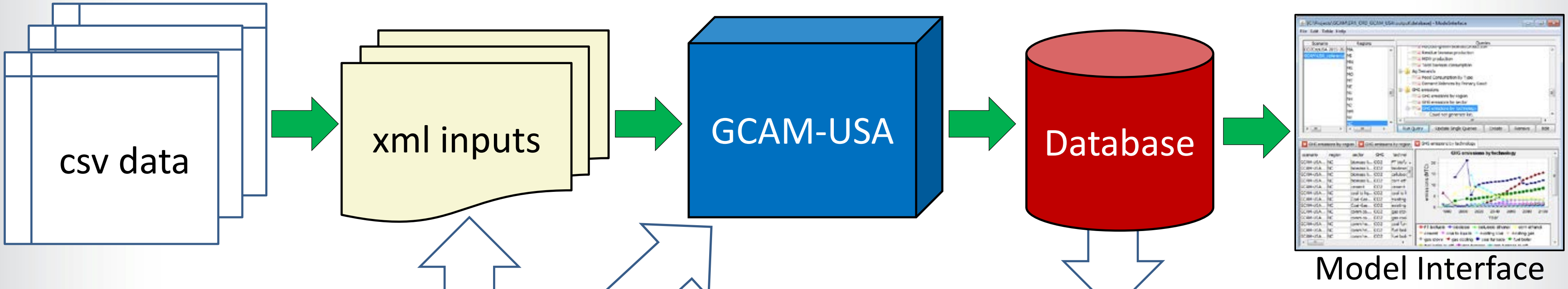
Model Interface

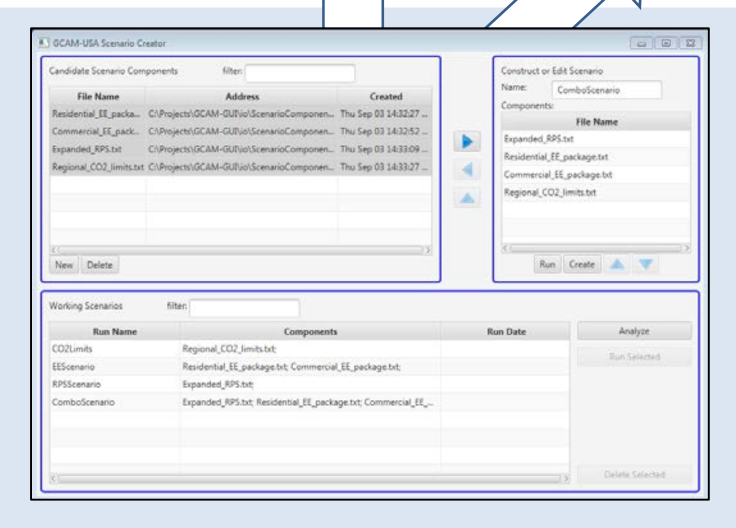
GCAM-USA is the state-level resolution version of the Global Change Assessment Model (GCAM).

We have modified GCAM-USA to incorporate US-specific emission factors, emission controls, and climate and air quality regulations.

3. Computing and Systems application
Decision support system

We are developing a Scenario Builder and analysis tools to facilitate its use for policy analyses





Candidate Scenario Components filter:

File Name	Address	Created
Residential_EE_packa...	C:\Projects\GCAM-GUI\io\ScenarioComponen...	Thu Sep 03 14:32:27 ...
Commercial_EE_pack...	C:\Projects\GCAM-GUI\io\ScenarioComponen...	Thu Sep 03 14:32:52 ...
Expanded_RPS.txt	C:\Projects\GCAM-GUI\io\ScenarioComponen...	Thu Sep 03 14:33:09 ...
Regional_CO2_limits.txt	C:\Projects\GCAM-GUI\io\ScenarioComponen...	Thu Sep 03 14:33:27 ...

Construct or Edit Scenario

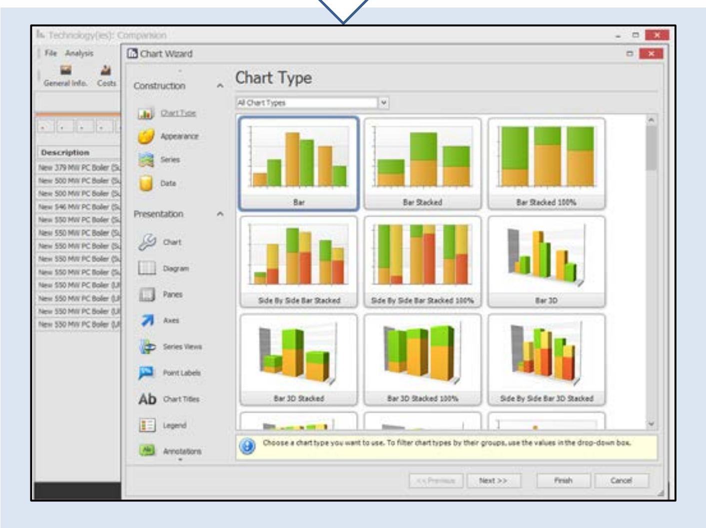
Name: ComboScenario

Components:

File Name
Expanded_RPS.txt
Residential_EE_package.txt
Commercial_EE_package.txt
Regional_CO2_limits.txt

Working Scenarios filter:

Run Name	Components	Run Date
CO2Limits	Regional_CO2_limits.txt;	
EEScenario	Residential_EE_package.txt; Commercial_EE_package.txt;	
RPSScenario	Expanded_RPS.txt;	
ComboScenario	Expanded_RPS.txt; Residential_EE_package.txt; Commercial_EE_...	



Description
New 379 MW PC Boiler (S...
New 500 MW PC Boiler (S...
New 500 MW PC Boiler (S...
New 546 MW PC Boiler (S...
New 550 MW PC Boiler (S...
New 550 MW PC Boiler (S...
New 550 MW PC Boiler (S...
New 550 MW PC Boiler (S...
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New 550 MW PC Boiler (U...

Choose a chart type you want to use. To filter chart types by their groups, use the values in the drop-down box.

Front end: Develop, manage and execute scenarios, set model options

Back end: View, analyze and compare scenario results

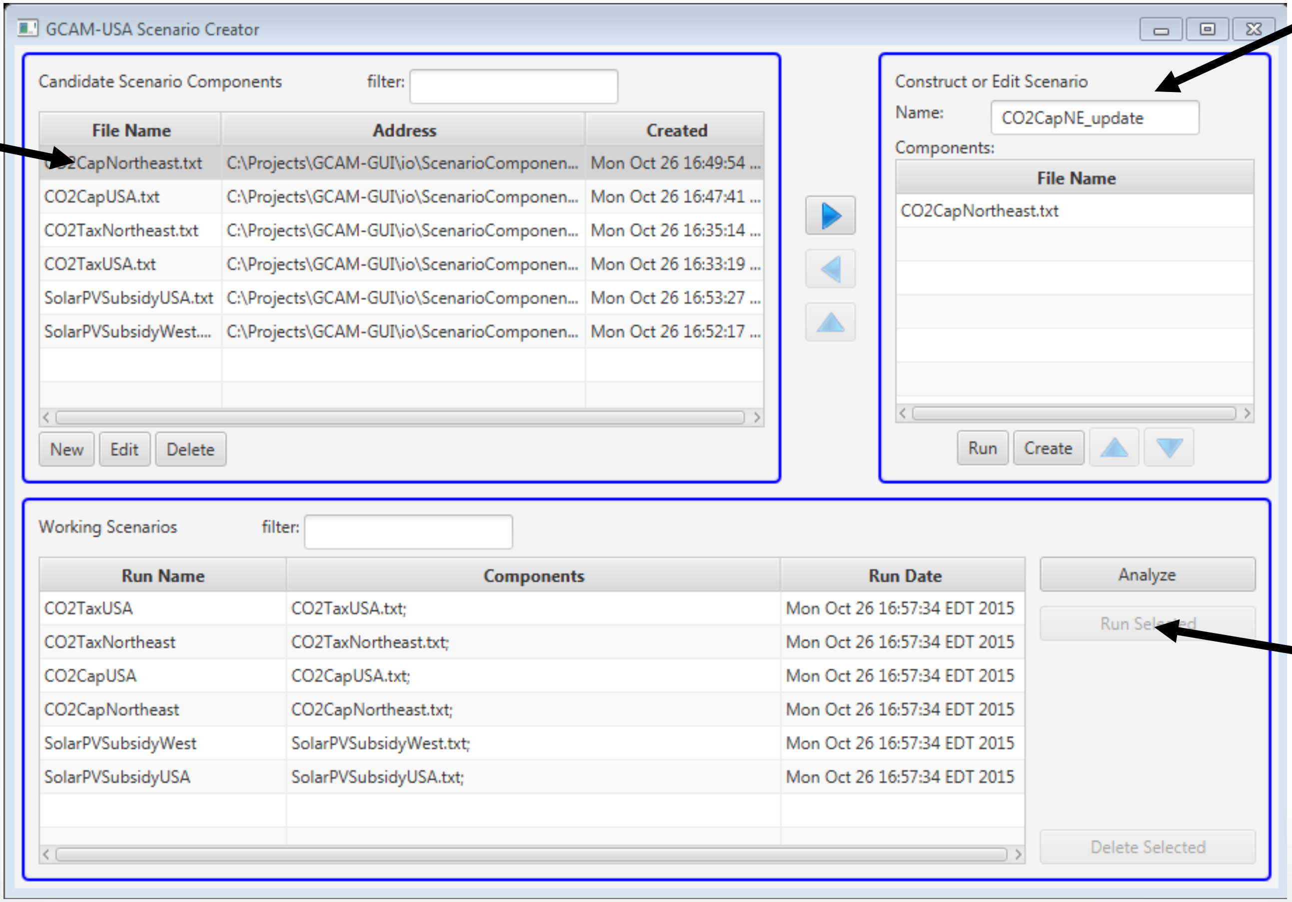
3. Computing and Systems application Decision support system

Scenario Builder: Managing scenarios

Library of scenario components

Creating a new scenario from existing components

Management and execution of scenarios



Candidate Scenario Components filter:

File Name	Address	Created
CO2CapNortheast.txt	C:\Projects\GCAM-GUI\io\ScenarioComponen...	Mon Oct 26 16:49:54 ...
CO2CapUSA.txt	C:\Projects\GCAM-GUI\io\ScenarioComponen...	Mon Oct 26 16:47:41 ...
CO2TaxNortheast.txt	C:\Projects\GCAM-GUI\io\ScenarioComponen...	Mon Oct 26 16:35:14 ...
CO2TaxUSA.txt	C:\Projects\GCAM-GUI\io\ScenarioComponen...	Mon Oct 26 16:33:19 ...
SolarPVSubsidyUSA.txt	C:\Projects\GCAM-GUI\io\ScenarioComponen...	Mon Oct 26 16:53:27 ...
SolarPVSubsidyWest....	C:\Projects\GCAM-GUI\io\ScenarioComponen...	Mon Oct 26 16:52:17 ...

Construct or Edit Scenario

Name: CO2CapNE_update

Components:

File Name
CO2CapNortheast.txt

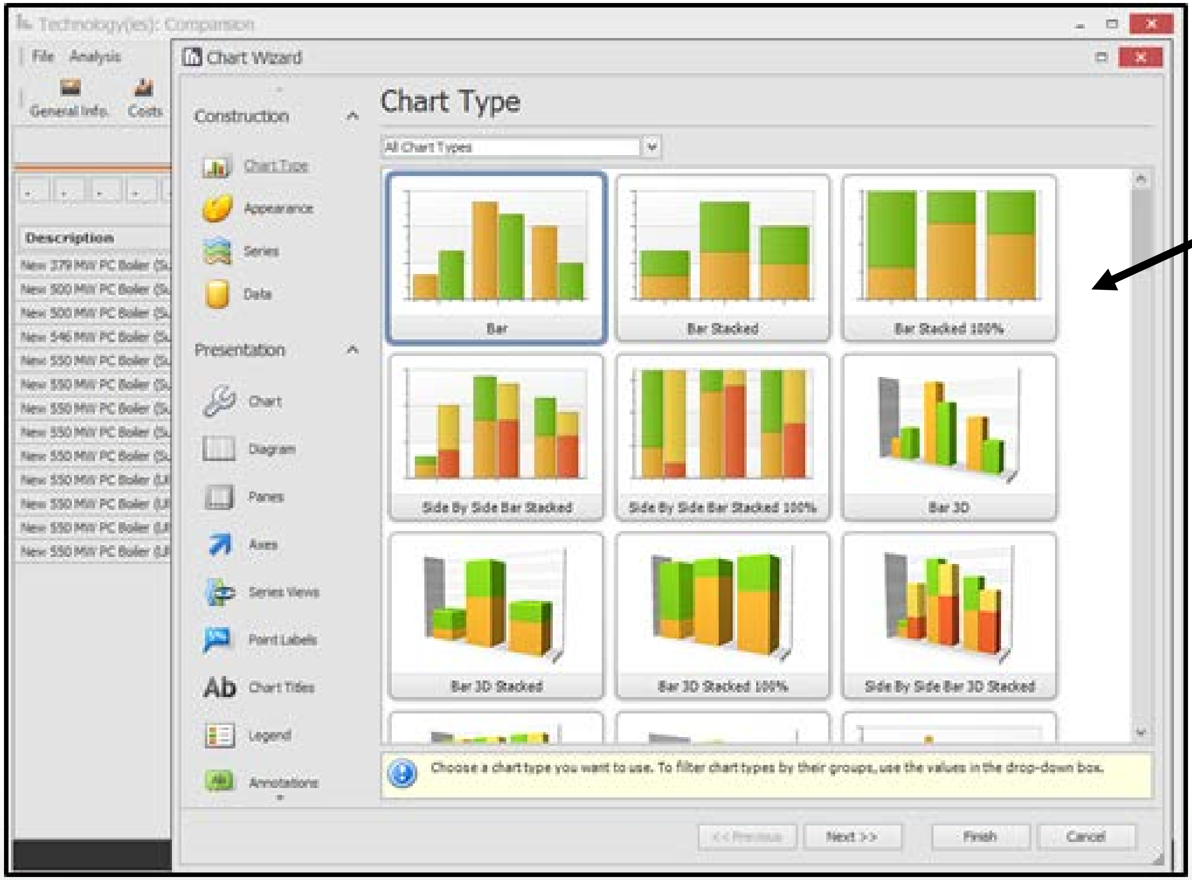
Working Scenarios filter:

Run Name	Components	Run Date
CO2TaxUSA	CO2TaxUSA.txt;	Mon Oct 26 16:57:34 EDT 2015
CO2TaxNortheast	CO2TaxNortheast.txt;	Mon Oct 26 16:57:34 EDT 2015
CO2CapUSA	CO2CapUSA.txt;	Mon Oct 26 16:57:34 EDT 2015
CO2CapNortheast	CO2CapNortheast.txt;	Mon Oct 26 16:57:34 EDT 2015
SolarPVSubsidyWest	SolarPVSubsidyWest.txt;	Mon Oct 26 16:57:34 EDT 2015
SolarPVSubsidyUSA	SolarPVSubsidyUSA.txt;	Mon Oct 26 16:57:34 EDT 2015

Initial development conducted by Farid Alborzi

3. Computing and Systems application Decision support system

Results visualizer: Exploratory data analysis



Choose a chart type you want to use. To filter chart types by their groups, use the values in the drop-down box.

Interactive nature facilitates exploratory data analysis

Development being conducted by Raj Bhander

3. Computing and Systems application Decision support system

- **Next steps**
  - GCAM-USA modifications to improve air pollutant emission projection capability
    - US-specific emission factors
    - On-the-books state-level climate and air quality policies
    - Control technologies
  - Adding impact factors
    - Health impacts of air pollutant emissions
    - Water demands
    - Nitrogen deposition
    - Life cycle factors
  - Completing Beta versions of Scenario Builder and Results Visualizer

Part 4.

Reflections on the first half of my career and the role of Computing and Systems

(Informal)

Questions?

Contact information:

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