Modeling US Energy Futures Under Uncertainty

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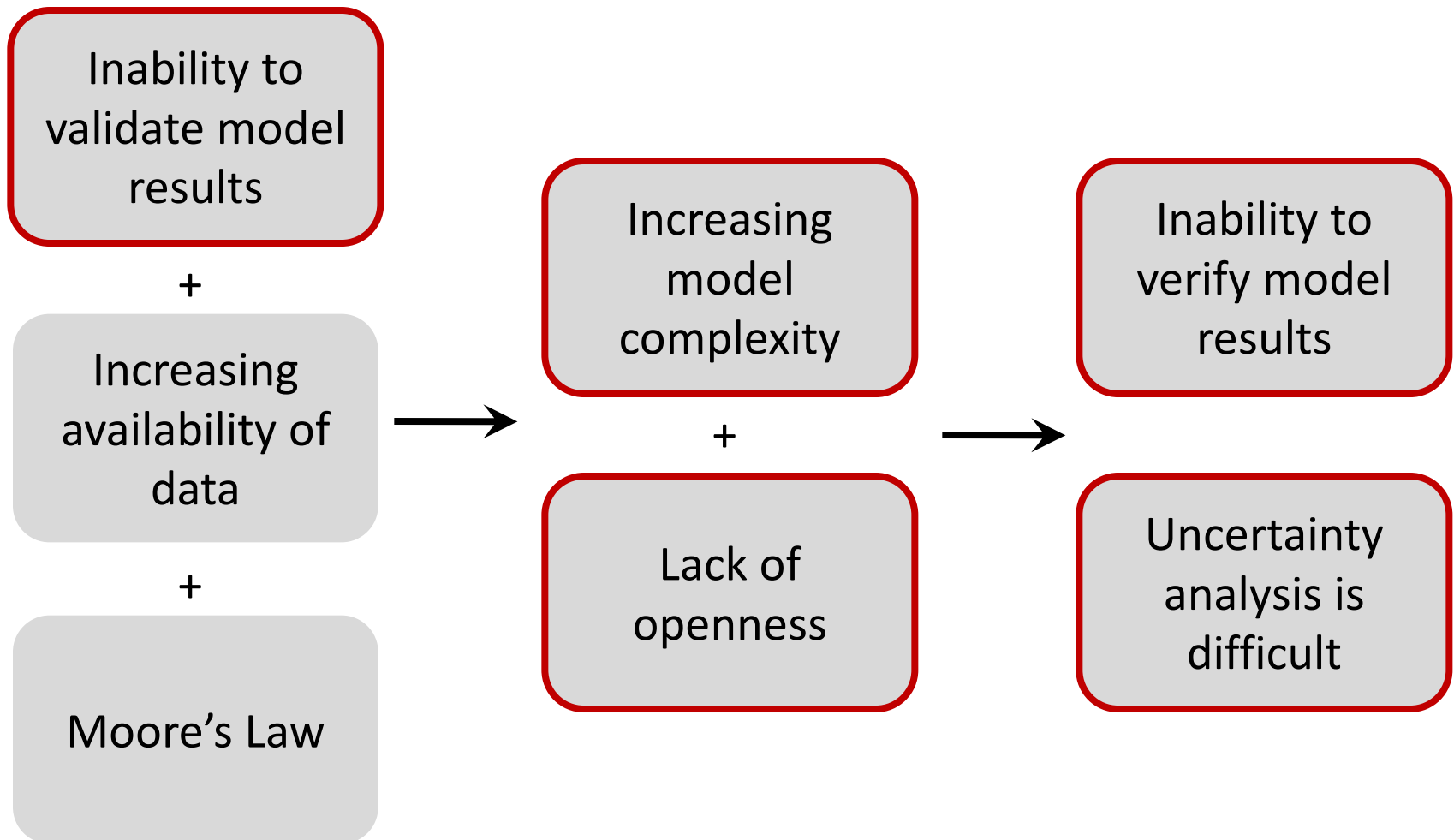
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Talk Outline

Provide very brief introduction to Tools for Energy Model Optimization and Analysis (Temoa), an open source energy system model.
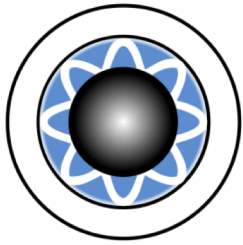
Describe recent modeling work that quantifies the range of US greenhouse gas emissions through 2040 in the absence of new federal climate or energy policy.

Present ideas to create a community modeling effort.

Brief Overview of Temoa

Problems with the status quo

Inability to validate model results

+

Increasing availability of data

+

Moore's Law

→

Increasing model complexity

+

Lack of openness

→

Inability to verify model results

Uncertainty analysis is difficult

Tools for Energy Model Optimization and Analysis (Temoa)

Temoa is a **bottom up, technology explicit model with perfect foresight**, similar to the MARKAL/TIMES model generators.
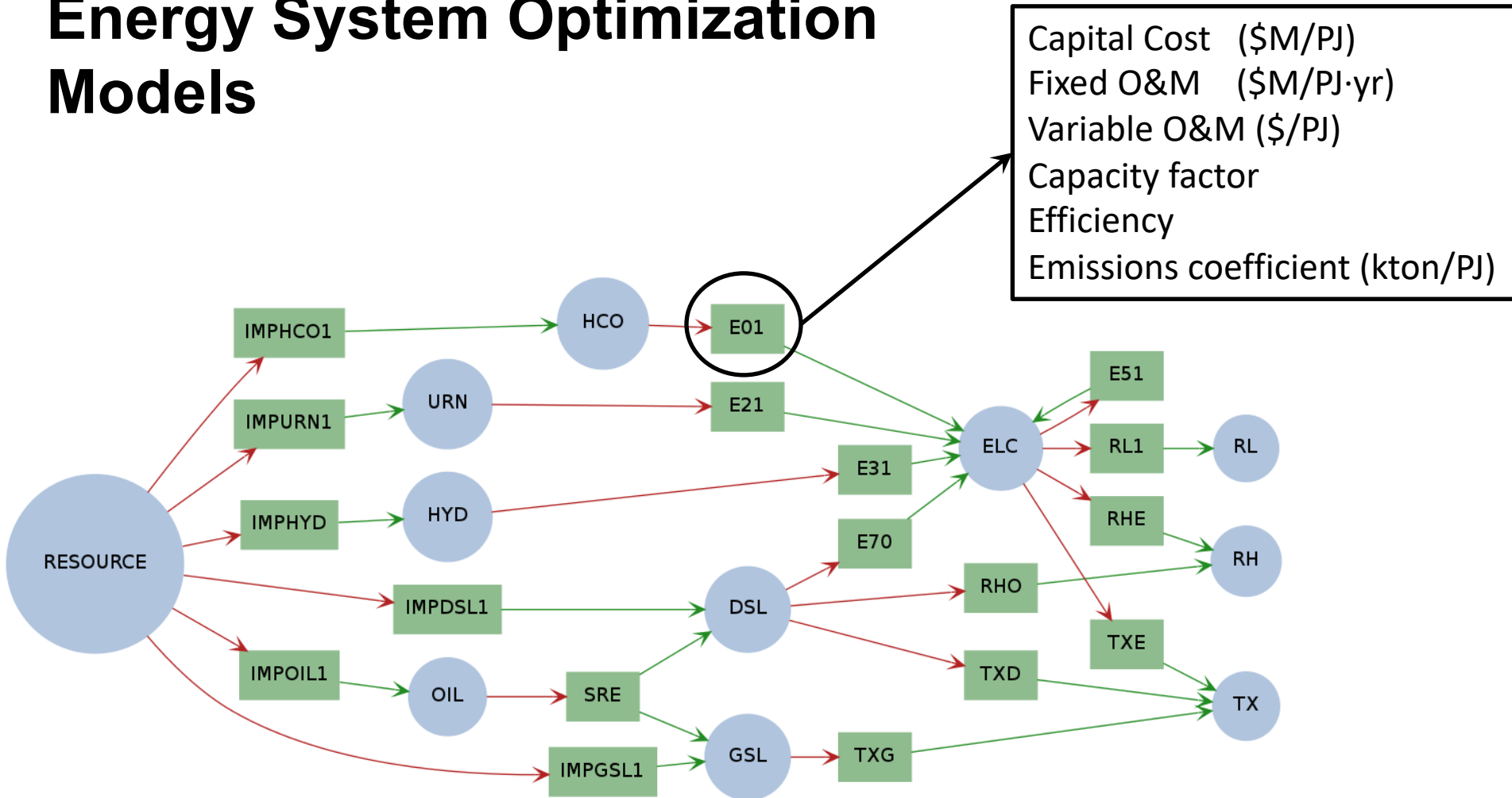
Goals

1. Repeatable analysis
- Data and code stored in a public web repository (github)
- Open source software stack

### 2. Rigorous treatment of uncertainty
- Designed to utilize high performance computing resources
- Several methods implemented to address an array of questions

Energy System Optimization Models

Capital Cost ($M/PJ)
Fixed O&M ($M/PJ·yr)
Variable O&M ($/PJ)
Capacity factor
Efficiency
Emissions coefficient (kton/PJ)

Objective function: minimize present cost of energy supply
Decision variables: activity (PJ) and capacity (PJ/yr) for each technology

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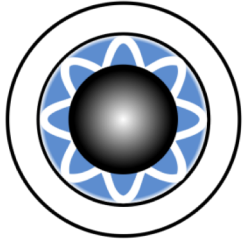
Temoa Capabilities

Current

- Visualization of energy system map
- Input/output data stored in a relational database
- Optional Excel output produced from database
- Online, cloud-based interface available for testing

Project website: http://www.temoaproject.org
Source code: https://github.com/TemoaProject
Cloud-based interface: http://model.temoacloud.com

Uncertainty Analysis

Useful model-based insight should account for uncertainty. The approach depends on the question at hand.

- Method of Morris (SALib)

  Perform a random walk in input parameter space; characterize impact of each parameter on output(s) of interest

- Monte Carlo simulation

  Select ranges or distributions for uncertain input parameters, make random draws, iterate the model, examine patterns in output

- Modeling-to-Generate Alternatives

  Modify the model structure to find feasible, near optimal solutions that are maximally different in decision space

- Stochastic Optimization (Pyomo)

  Devise a scenario tree that accounts for potential future outcomes, assign probabilities, and optimize over the whole tree; produces a near-term hedging strategy

US Energy-Related Greenhouse Gas Emissions in the Absence of Federal Climate Policy

climate policy

■ policy analysis

Evaluating the US Mid-Century Strategy for Deep Decarbonization amidst early century uncertainty

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The recent change in US presidential administrations has introduced significant uncertainty about both domestic and international policy support for continued reductions in GHG emissions. This brief analysis estimates the potential climate ramifications of changing US leadership, contrasting the Mid-Century Strategy for Deep Decarbonization (MCS) released under the Obama Administration, with campaign statements, early executive actions, and prevailing market conditions to estimate potential emission pathways under the Trump Administration. The analysis highlights areas where GHG reductions are less robust to changing policy conditions, and offers brief recommendations for addressing emissions in the interim. It specifically finds that continued reductions in the electricity sector are less vulnerable to changes in federal policy than those in the built environment and land use sectors. Given the long-lived nature of investments in these latter two sectors, however, opportunities for near-term climate action by willing cities, states, private landowners, and non-profit organizations warrant renewed attention in this time of climate uncertainty.

Key policy insights

■ The recent US presidential election has already impacted mitigation goals and practices, injecting considerable uncertainty into domestic and international efforts to address climate change.

■ A strategic assessment issued in the final days of the Obama Administration for how to reach long-term climate mitigation objectives provides a baseline from which to gauge potential changes under the Trump Administration.

■ Though market trends may continue to foster emission declines in the energy sector, emission reductions in the land use sector and the built environment are subject to considerable uncertainty.

■ Regardless of actions to scale back climate mitigation efforts, US emissions are likely to be flat in the coming years. Assuming that emissions remain constant under President Trump and that reductions resume afterwards to meet the Obama Administration mid-century targets in 2050, this near-term pause in reductions yields a difference in total emissions equivalent to 0.3−0.6 years of additional global greenhouse gas emissions, depending on the number of terms served by a Trump Administration.

What might US GHG emissions trajectories look like in the absence of new federal energy or climate policy?

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Objectives of our recent analysis

- Examine future US emissions pathways in the absence of new federal energy or climate policy

- Introspect our US Temoa model to identify the parameters that have a significant effect on national GHG emissions

- Explore parameter combinations that produce high or low emissions pathways, relative to our baseline

Input Database Description

- US as a single region

- Time horizon: 2015-2040, with 5 year time periods

- 12 time slices: 3 seasons, 4 times-of-day

- Key data sources: EPA 2016 MARKAL, EIA Annual Energy Outlook

- Assume exogenous fuel price trajectories from the Annual Energy Outlook

- Explicit technology representation in the electric, transport, residential, and commercial sectors; industrial sector represented with fuel share constraints
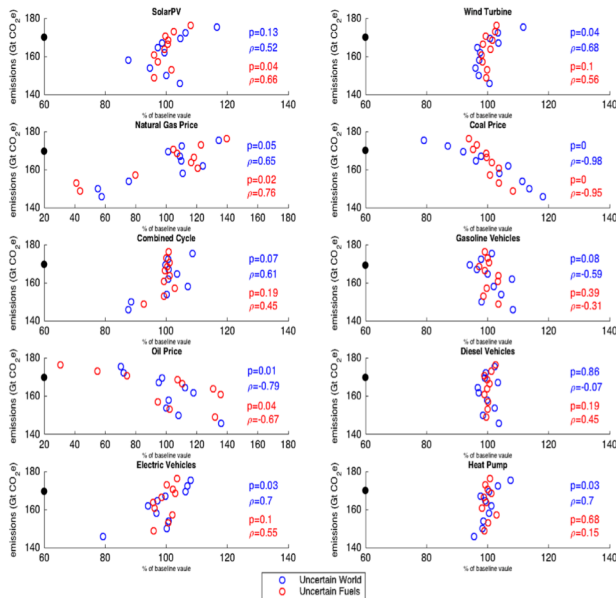
- Over 550 technologies represented

Analysis Framework

Temoa
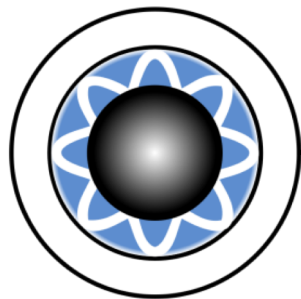
Method of Morris

Which parameters matter most?
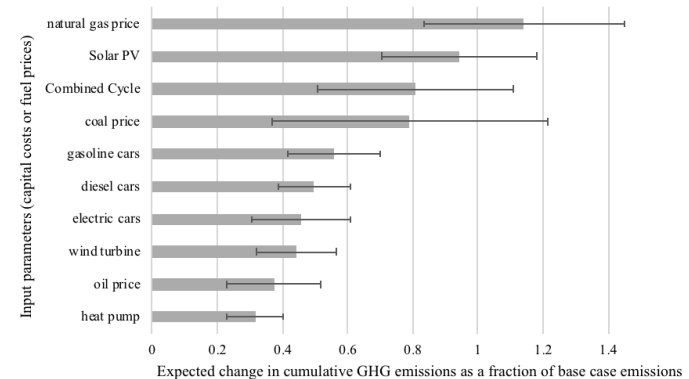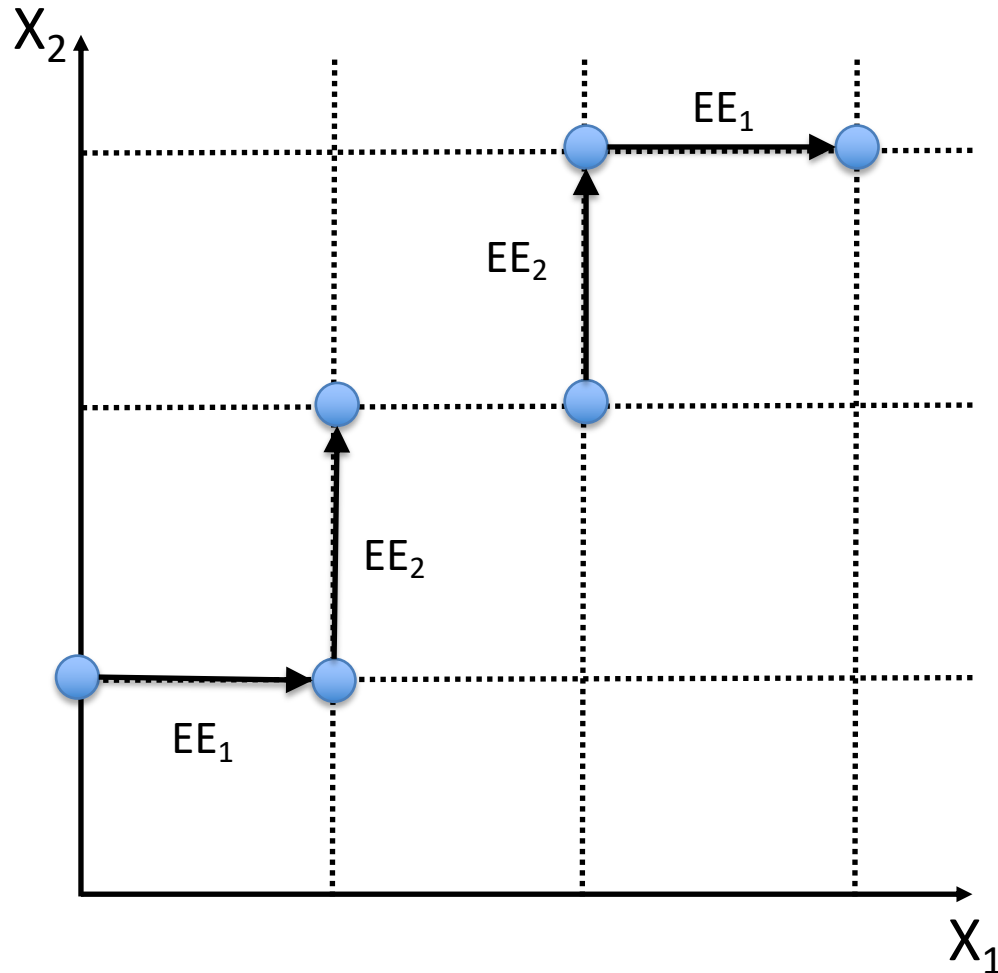

Which parameter combos produce low emissions?

k-Means Clustering

Monte Carlo Simulation

What is the resultant range in GHG emissions?

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Method of Morris

X_2

EE_1

EE_2

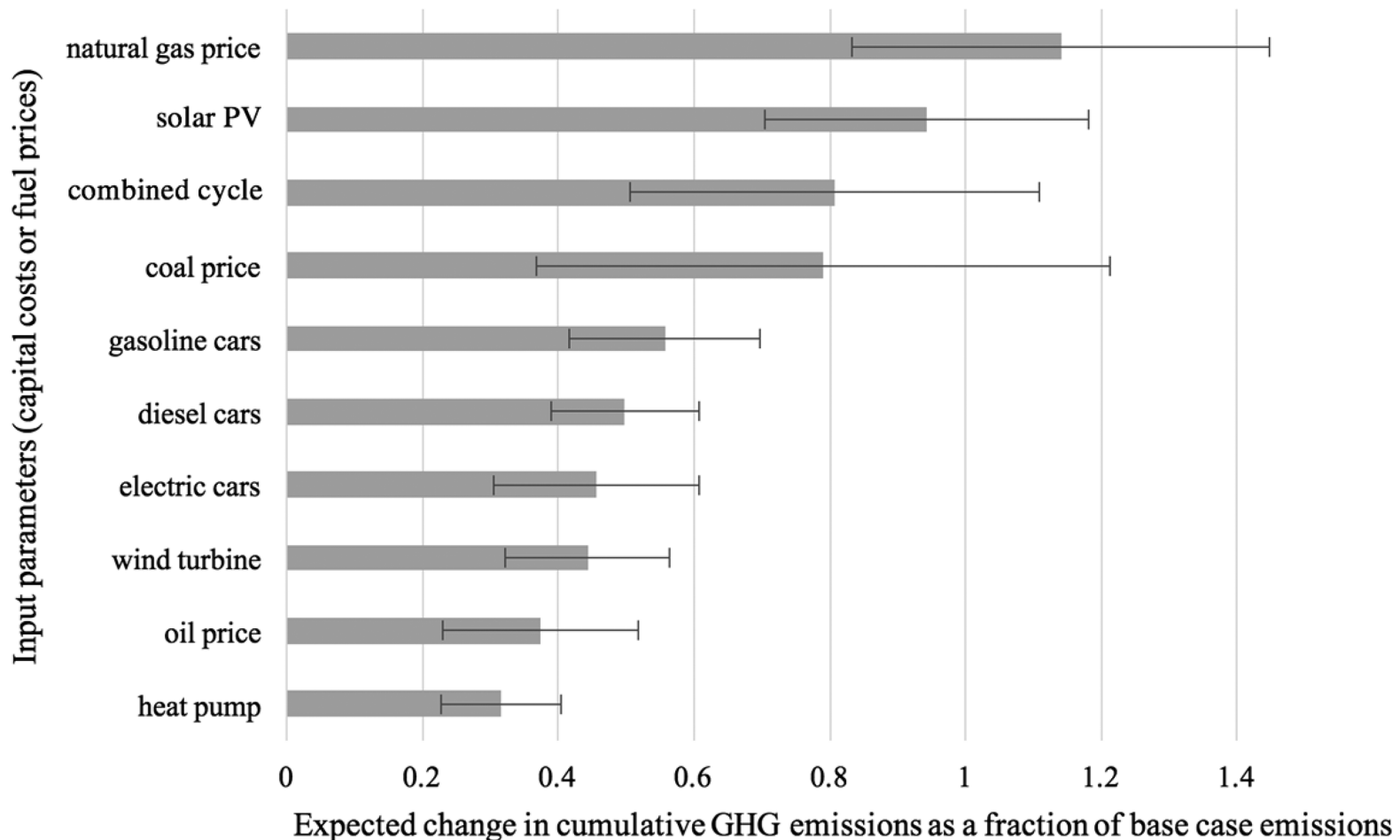EE_2

EE_1

X_1
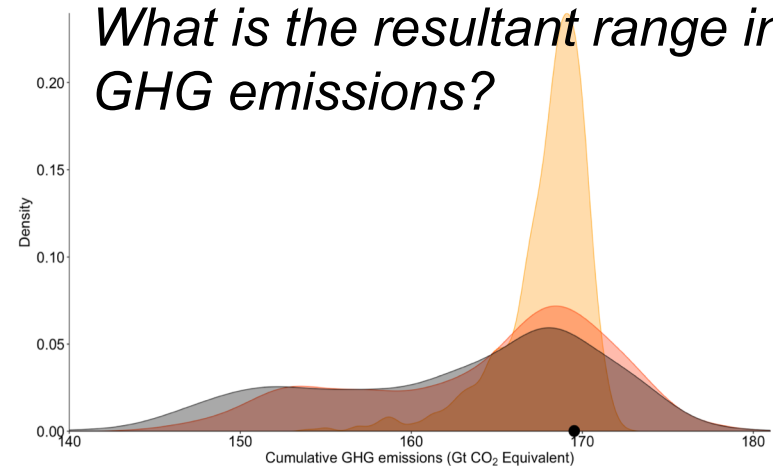
Uncertain Parameters:
- k=2 in this example
- k=41 in analysis

Number of Trajectories:
- T=2 in this example
- T=25 in analysis

$$EE_i = \frac{f(x_1, x_2, \ldots, x_i + \Delta, \ldots, x_k) - f(x_1, x_2, \ldots, x_i, \ldots, x_k)}{\Delta}$$

Method of Morris

- Sensitivity of 41 different input parameter groups, with ±**20%** range on each

- We test sensitivity of cumulative GHG emissions to each parameter

Monte Carlo Simulation

We look into three different future cases, each consisting of 1000 runs:

- **Stable World:** assumes all parameters change within $\pm20\%$ of their baseline values

- **Uncertain Fuels:** assumes all parameters change within $\pm20\%$ of their baseline values except for natural gas and oil prices which vary within $\pm80\%$ of their baseline values

- **Uncertain World:** assumes all parameters change within $\pm40\%$ of their baseline values, except for natural gas and oil prices, which vary within $\pm80\%$ of their baseline values
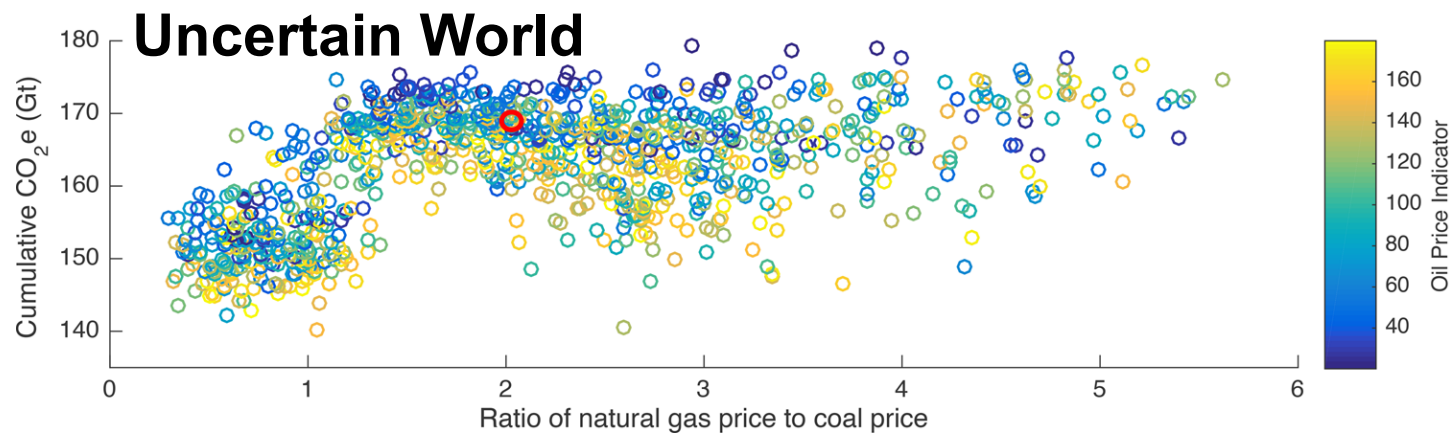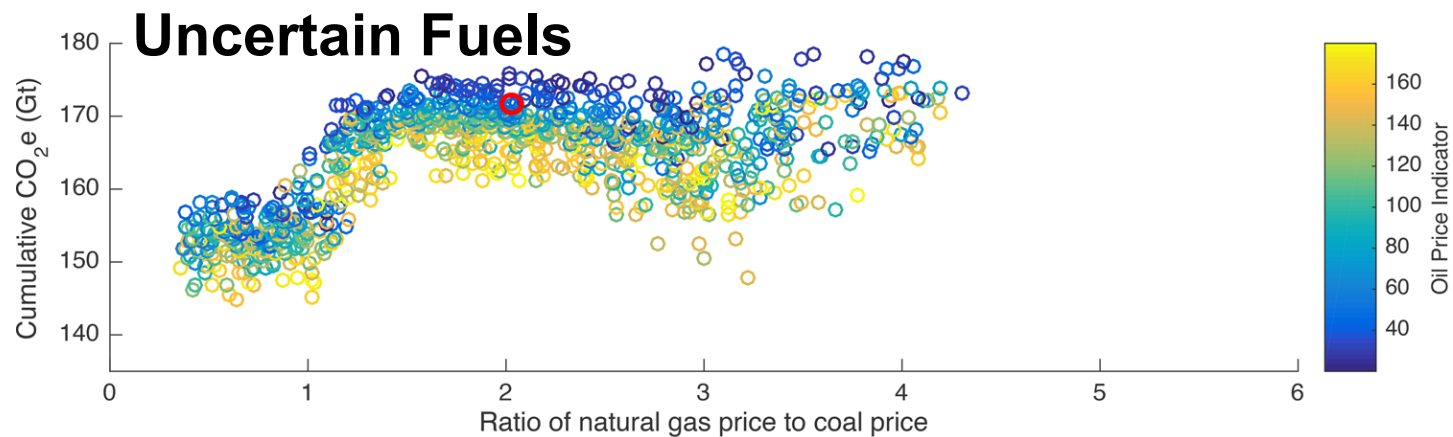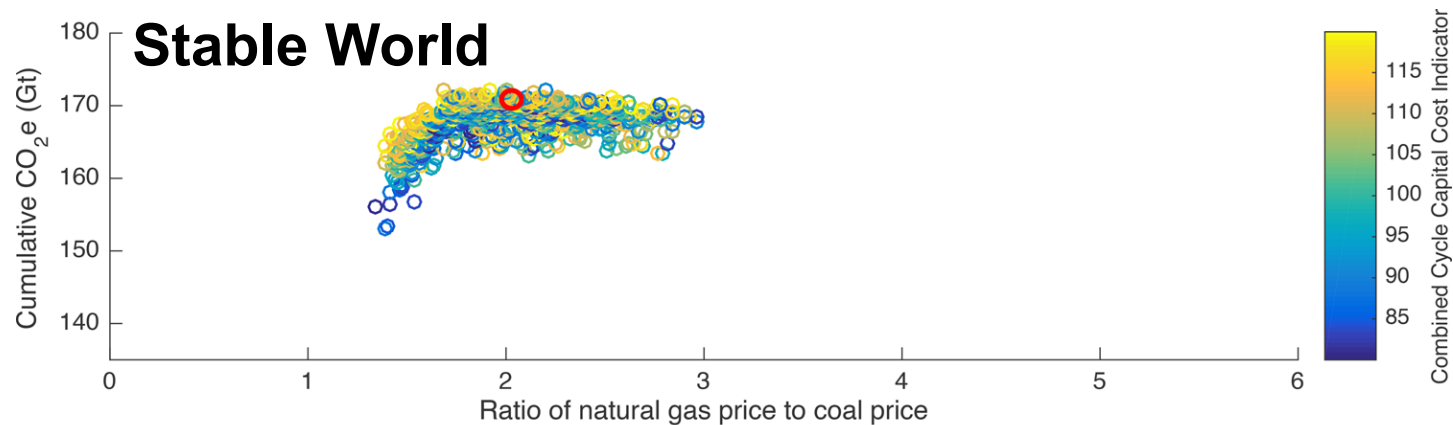
Key inputs follow uniform distribution. Outputs provide a sense of potential future outcomes, but should not be interpreted probabilistically

# Results: Cumulative GHG Emissions
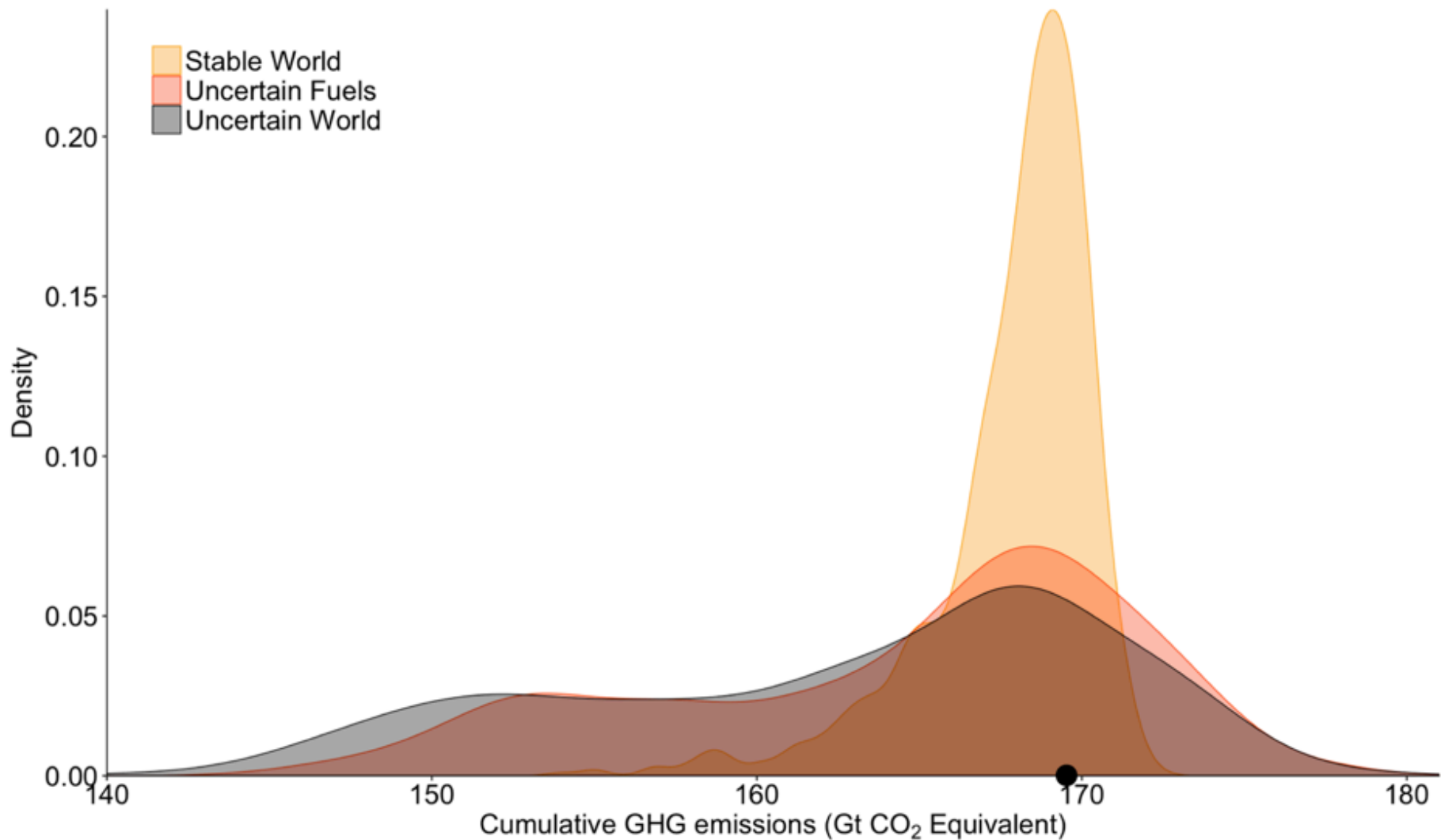
Results: CO$_2$ Pathways
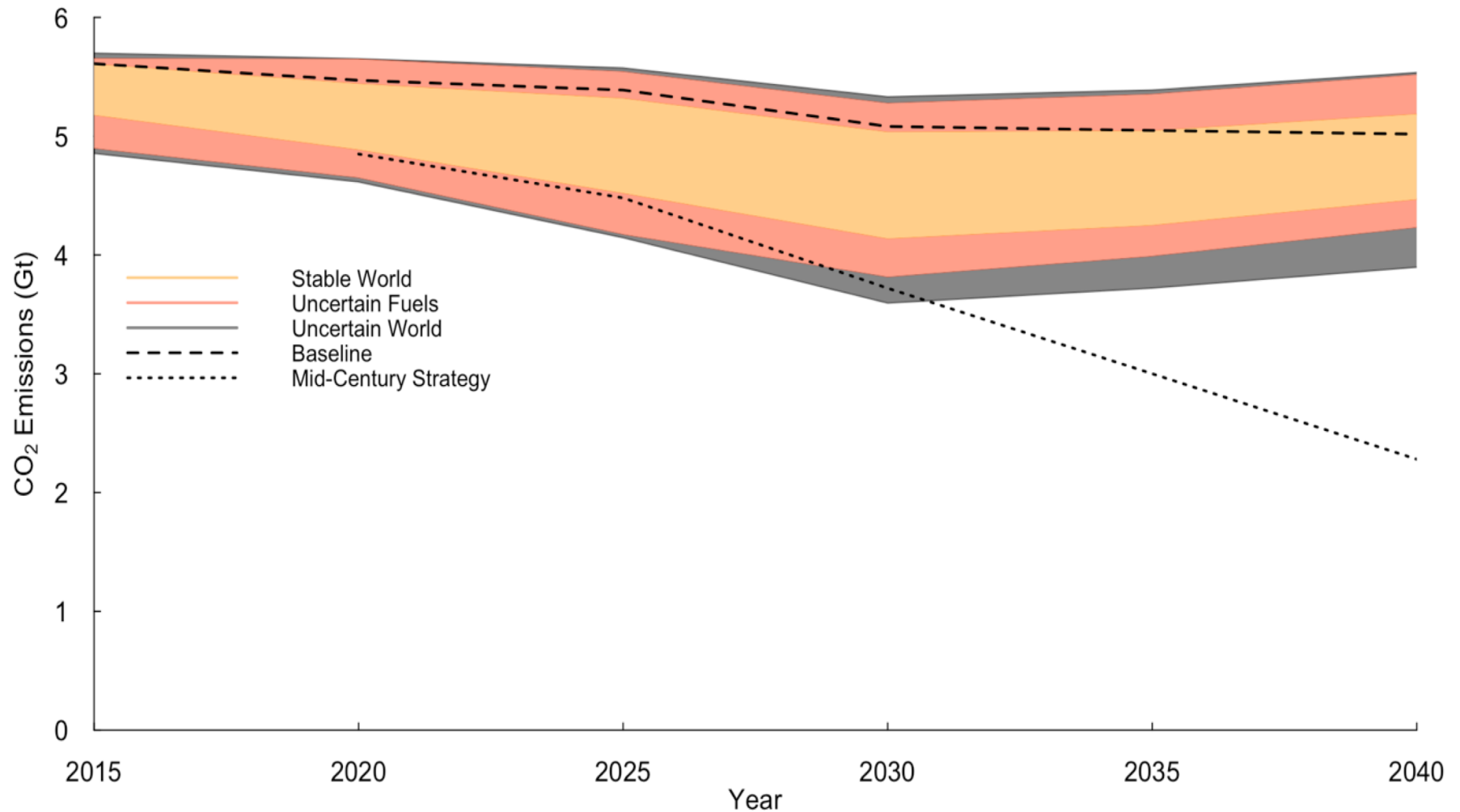
k-Means Clustering

- The *k*-means algorithm partitions the data set by creating groups or clusters with similar features.

- Each cluster consists of centroid values representing the 10 uncertain input parameters plus cumulative GHG emissions.

- The algorithm minimizes the Euclidean distance between the centroids of each cluster.

- We separate the data into ten clusters.

Results: K-means clustering

Highest and lowest emissions clusters
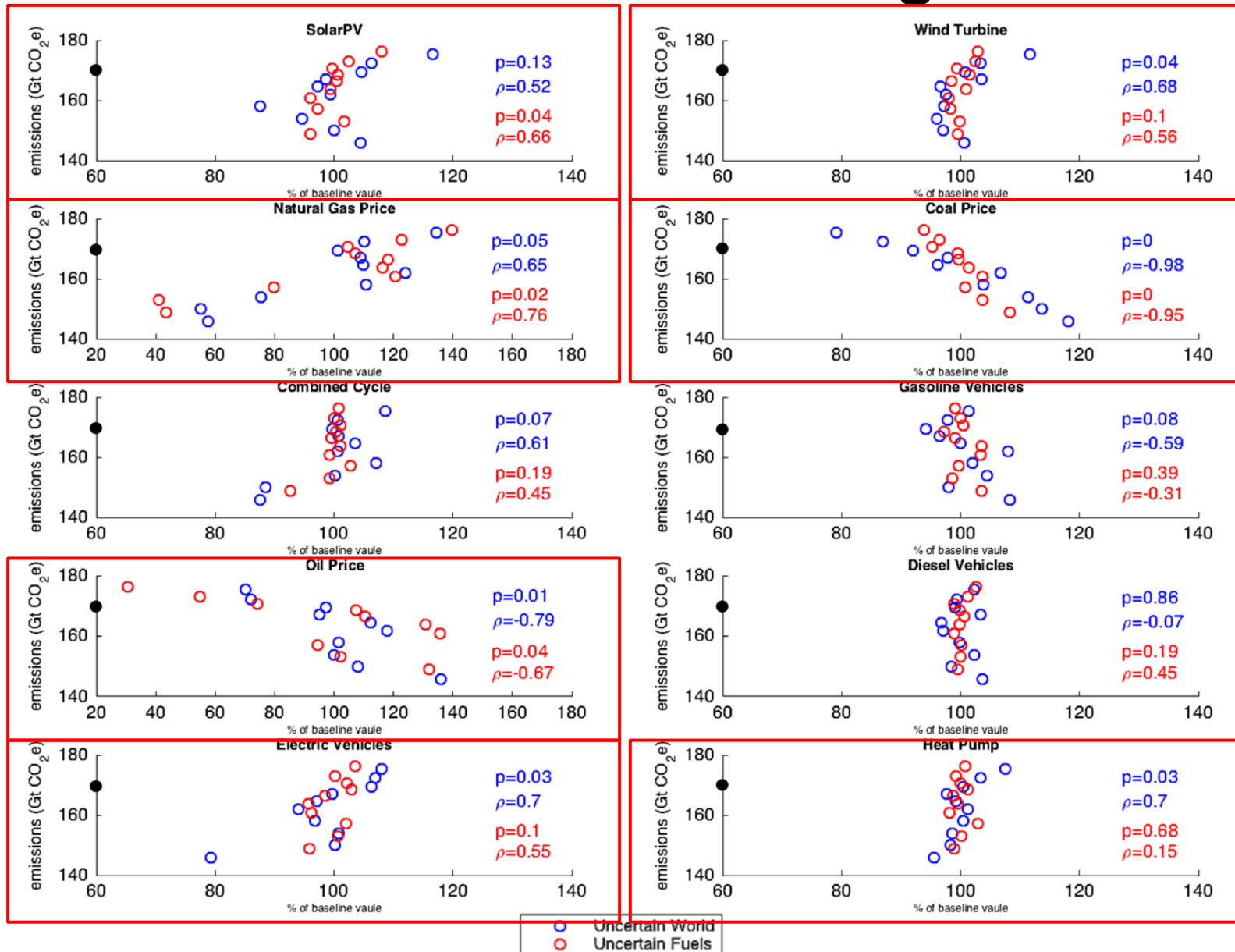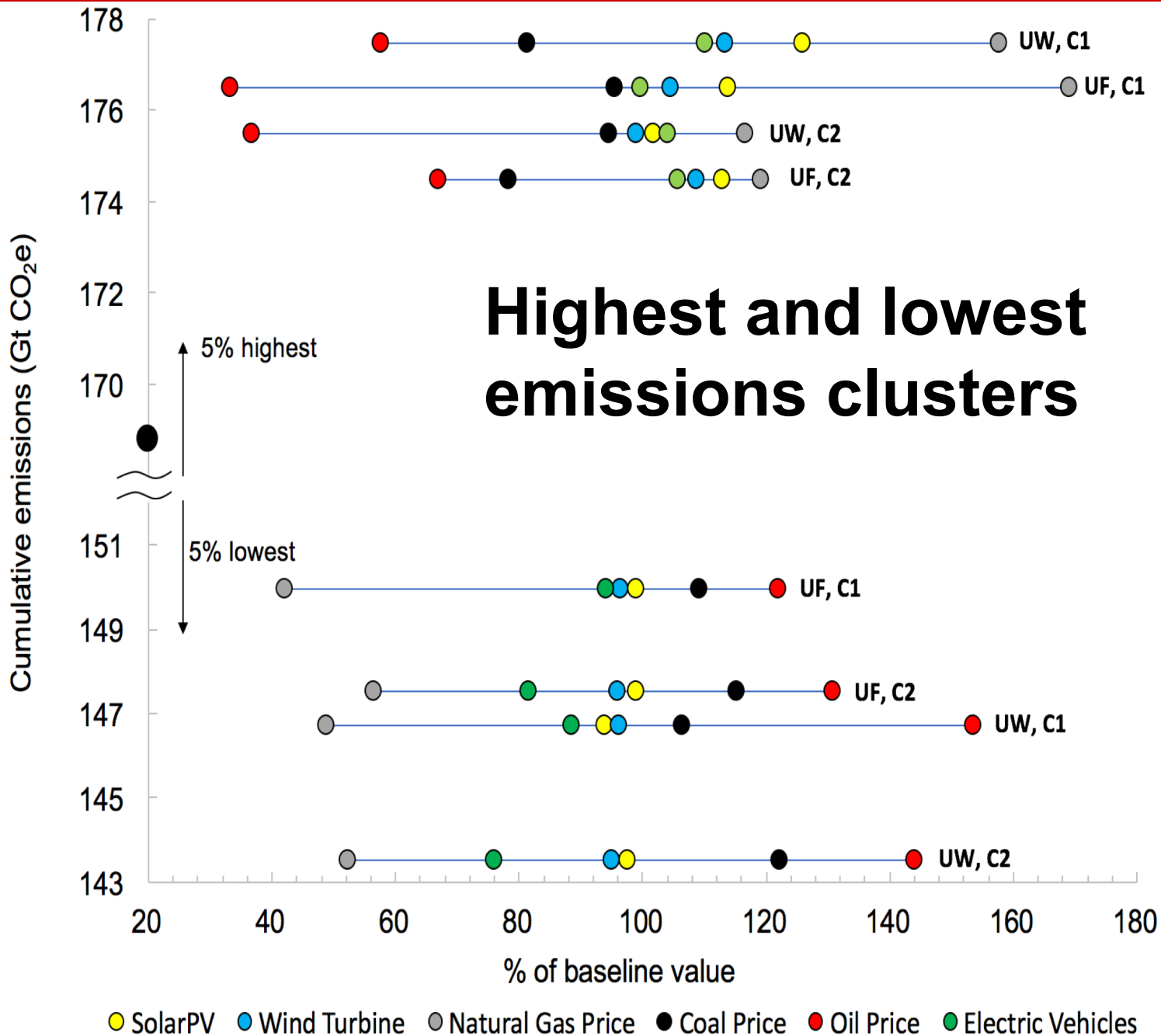
Clusters don't tell the whole story
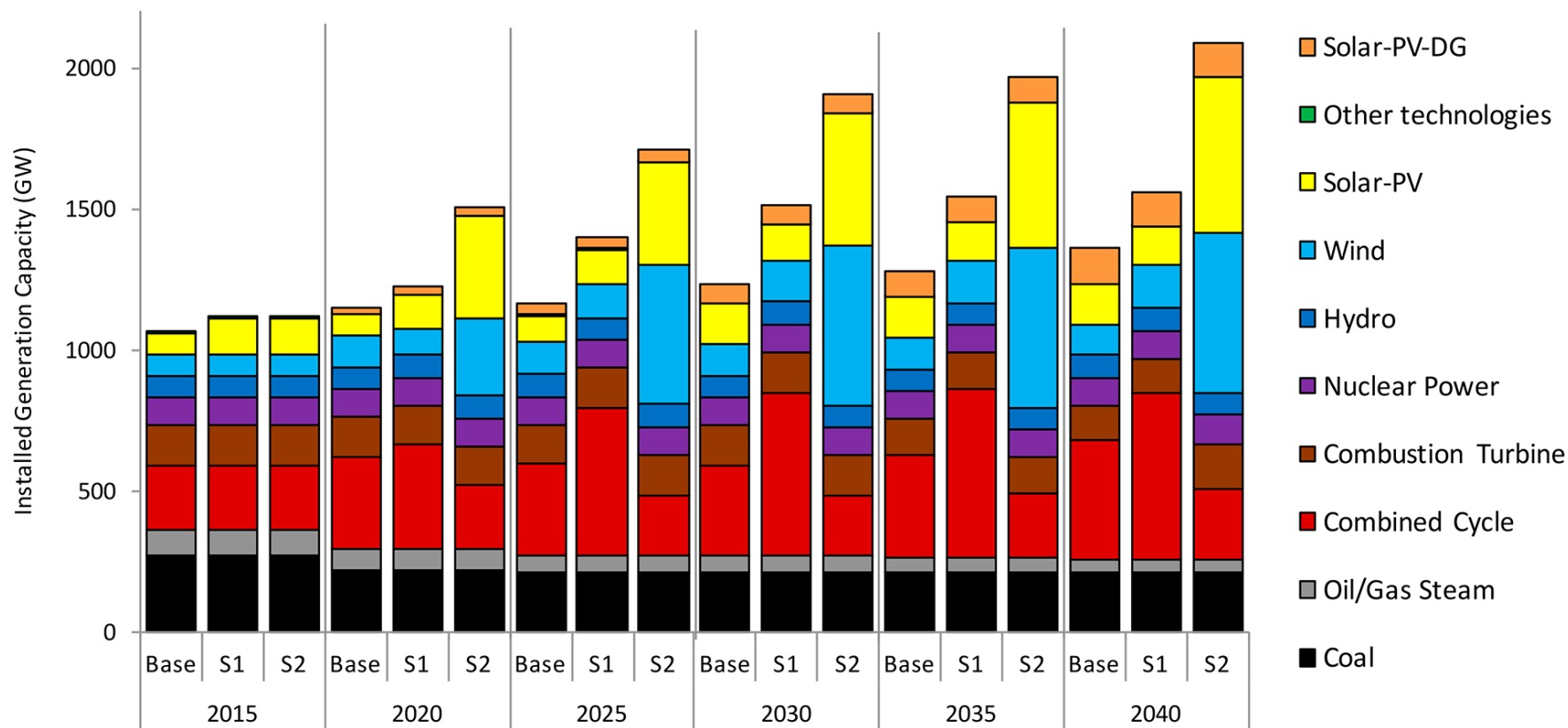
Conclusions

- With limited input variability, substitution between natural gas and coal in the electric sector represents a key tradeoff

- Uncertainty tends to skew the US energy system towards emissions below our baseline case. There are more ways to decrease emissions with renewables, natural gas, and electric vehicles than increase with coal.

- Projected GHG emissions in 2040 range from +10% to -23% of our baseline estimate.

- The cumulative CO_2e difference between the highest and lowest emissions scenario from 2020 to 2040 is nearly 6.6 times the 2015 emissions level.

- Parameter uncertainty can drive a significant emissions range, and much of this uncertainty is obscured by conventional scenario analysis with energy system models.

Acknowledgements

- Hadi Eshraghi, PhD student
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Past and Current Work with Temoa

Published

Hunter K, Sreepathi S, DeCarolis JF, 2013. Modeling for insight using tools for energy model optimization and analysis (Temoa). *Energy Economics*, *40*, pp.339-349.

DeCarolis JF, Babaee S, Li B, Kanungo S, 2016. Modelling to generate alternatives with an energy system optimization model. *Environmental Modelling & Software*, *79*, pp.300-310.

Eshraghi H, de Queiroz AR, DeCarolis JF, 2018. US Energy-Related Greenhouse Gas Emissions in the Absence of Federal Climate Policy. Environmental Science & Technology, 52(17): 9595–9604.

Current

- **North Carolina** electricity futures; includes careful examination of break-even investment costs and application of stochastic optimization
- Electricity planning under the risk of conflict in **South Sudan**; includes sensitivity analysis and stochastic optimization to examine potential hedging strategies
- Developing a regional US database for future analysis, including EMF34

Ideas for a Community Modeling Effort

Problems solved?

Maybe, but…

Who's going to read this work?

Who's going to replicate and extend this work?

How does this modeling work make a difference in the real world?

Inability to validate model results

+

Increasing availability of data

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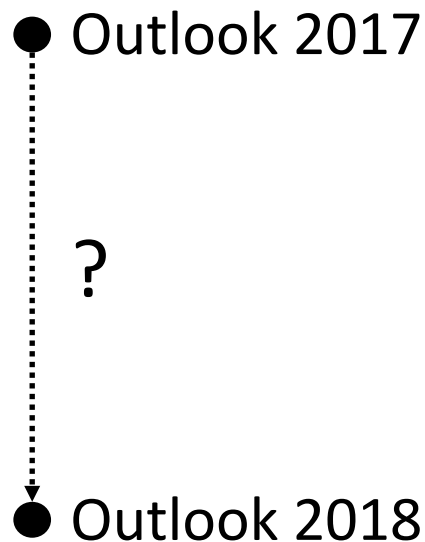
We Need a More Cohesive Community

- Much more focus on open source efforts, but we're still largely on our own islands

- Everyone creates a mental model based on experience with their own energy models.

- Hard to compare models given differences in model structure and data – so debates persist

- Jacobson versus Clack debate is a good example -- how do we move beyond critique?

What if we create a community platform where we can test hypotheses by starting from a familiar reference point?
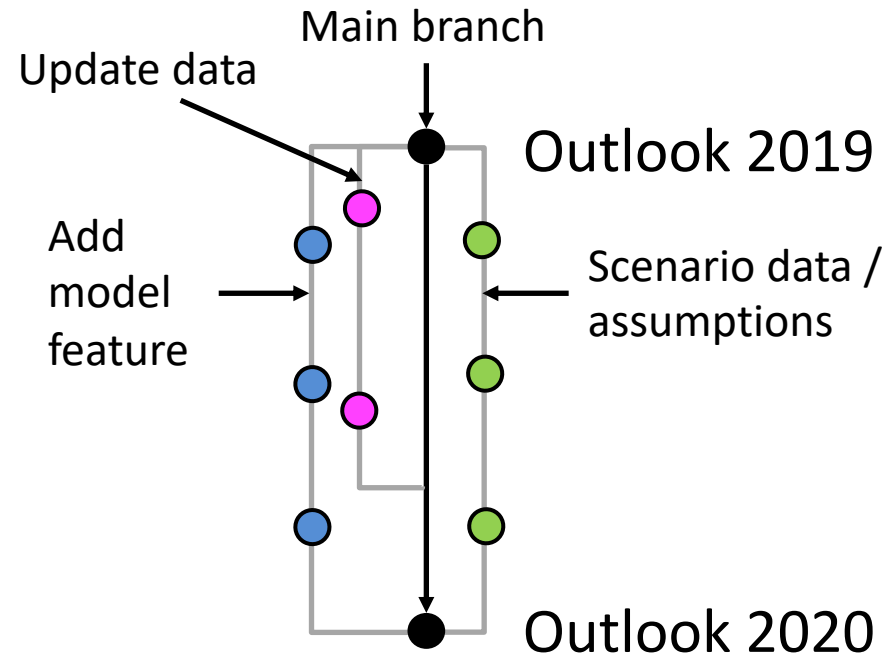
How about a community energy outlook for the US?

- Enlist folks to help us improve our regional US Temoa database

- Crowdsource ideas for future analysis

- Archive code and data in a common repository (e.g., GitHub)

- Create new branches to test formulations or data updates

- Use snapshots of code and data to produce new analysis

- Co-authorship based on contributions

Revised Approach

Revision Control System

Main branch

Update data

Outlook 2017

Add
model
feature

Outlook 2019

Scenario data /
assumptions

?

Outlook 2018

Outlook 2020

- Each "dot" represents a commit
- Provides data and code provenance
- Test hypotheses holding other factors constant

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Logistical challenges

- Funding required for web-based logistical support as well as graduate students or staff to perform the work
  - Funding sources not obvious; perhaps NSF Research Coordination Networks? Private Foundations? Environmental NGOs?
- For the broader community, what would make participation worthwhile?

Questions or Comments?