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ENERGY AND OUR ENVIRONMENT: A SYSTEMS AND LIFE CYCLE PERSPECTIVE

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Forward

- Objectives of this presentation
  - Provide an overview of system and life cycle approaches to modeling medium to long-term changes in drivers of changes in emissions sources
- Intended audience
  - Participants of 2017 NC BREATHE Conference
- 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.

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The storyline

- **Understanding our connected sources**
  - Why do we need an energy systems perspective to think about air quality?
  - Energy systems: NC and across the U.S.
  - Energy systems modeling 101
  - Trade -offs, co-benefits and unintended consequences
  - Example: biomass-based fuels
- **Gaining foresight**
  - What can we learn from scenarios?
  - Example: 4 air quality futures
  - Example: Vehicle automation
- **Tracking impacts along the full life cycle**
  - Broadening the range of impacts
  - Example: Just add water
  - Example: Lightweighting cars (time permitting)
- **From research to outreach**
  - How to convey the complexity and trade-offs to a broader audience (time permitting)

Understanding our connected emissions sources

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Why a systems perspective?

- *The production and use of energy touches on multiple aspects of our economy and our lives, has a highly diverse and complex set of impacts on the environment, and has deep uncertainty regarding how our energy system will unfold over time.*
- A long-range energy systems approach can address:
  - interactions among sectors
  - impacts across media
  - trade-offs and co-benefits
  - deep uncertainty
  - technology breakthroughs

Energy-related impacts

Criteria air pollutants*

NO_X – 93%
CO – 61%
SO_2 – 81%
$PM_{2.5}$ – 63% (excl. misc.)

Greenhouse gases:

CO_2 – 97%
Methane – 42%
Nitrous oxide – 12%

Water use

51% of total surface freshwater used for electric power

*includes fuel combustion (elec., ind. & other), petroleum & related industries, highway & off-highway from 2016 Air Pollutant Emissions Trends Data

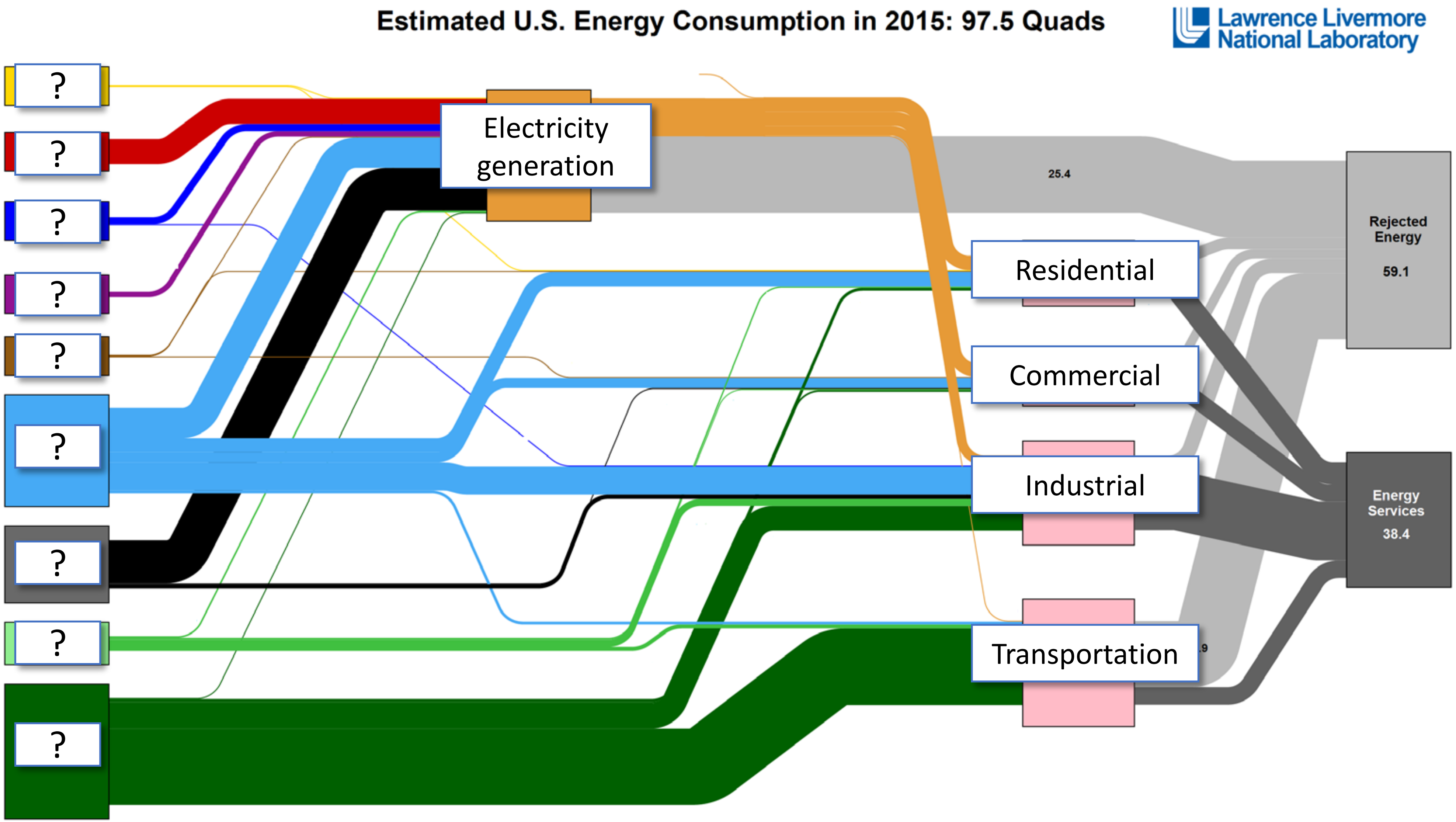
Energy: from extraction to use

- **Primary energy resources**
  - Fossil: coal, natural gas, petroleum
  - Other: uranium
  - Renewable: wind, solar, hydro, geothermal, biomass

- **Technologies to convert primary resources to useable energy like electricity, gasoline, …**
  - Refineries
  - Electric Power Generation

- **End-use sectors**
  - Residential
  - Commercial
  - Industrial
  - Transportation

- **Energy services --** What people actually demand: vehicle miles traveled, lumens of lighting, finished products and services. Energy is a "derived demand"



Coal
Natural Gas
Petroleum (Crude Oil)
Solar
Wind
Hydropower
Biomass
Geothermal
Nuclear

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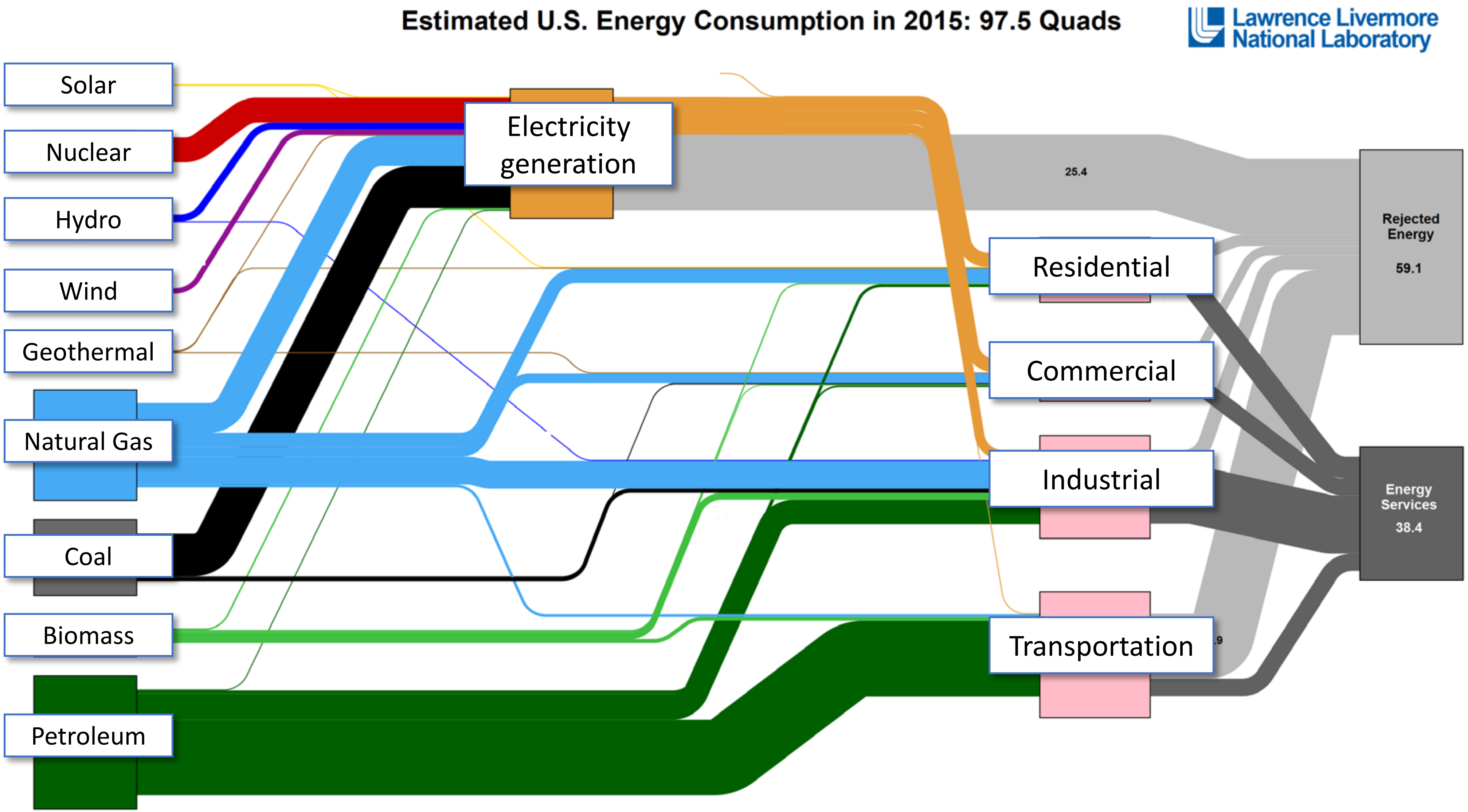
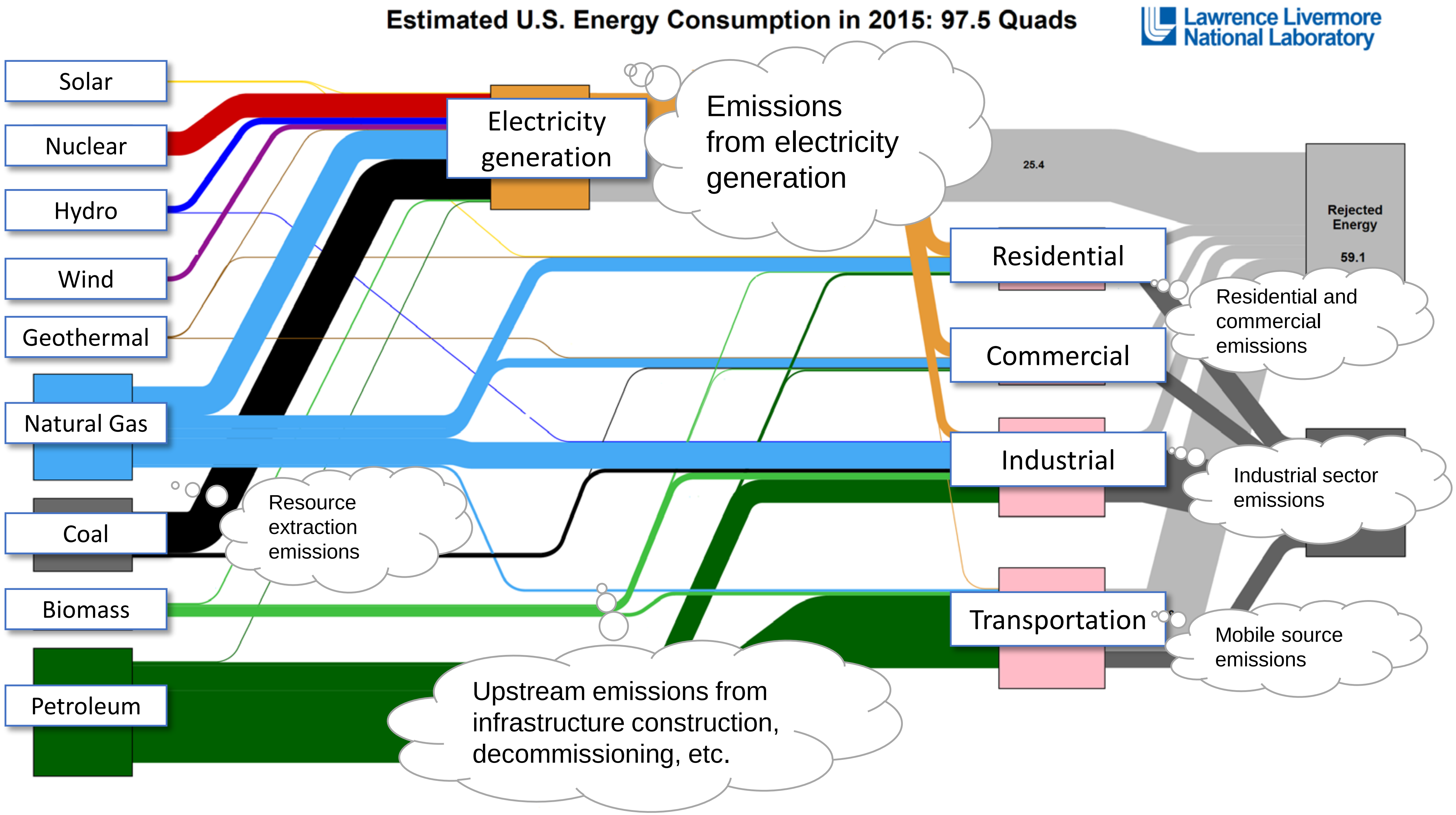


Coal	Solar	Biomass
Natural Gas	Wind	Geothermal
Petroleum (Crude Oil)	Hydropower	Nuclear



Sources are connected through our energy system

From the national level to state

- Energy profiles can be vastly different from one state to another
- The differences emerge from a range of technological, economic, social and political factors

North Carolina

Source: Energy Information Administration.
https://www.eia.gov/state/?sid=NC

North Carolina

Source: Energy Information Administration. https://www.eia.gov/state/?sid=NC

Coal

- Coal provides 21.0% of North Carolina's electricity generation (2016)

North Carolina

Source: Energy Information Administration. https://www.eia.gov/state/?sid=NC

Coal
Natural Gas

- Natural gas provides 33.5% of North Carolina's electricity generation (2015)

North Carolina

Source: Energy Information Administration.
https://www.eia.gov/state/?sid=NC

Coal
Natural Gas
Nuclear

- Three nuclear power plants
- 5th in the nation in net generation from nuclear power in 2015

North Carolina

Source: Energy Information Administration. https://www.eia.gov/state/?sid=NC

Coal
Natural Gas
Nuclear
Biomass

- Biomass includes landfill gas, wood and wood waste, etc.
- Often utilized as combined heat and power (CHP), including in industrial processes

North Carolina

Source: Energy Information Administration. https://www.eia.gov/state/?sid=NC

Coal
Natural Gas
Nuclear
Biomass
Hydropower

- Hydroelectric power prominent in the western part of the state

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North Carolina

Source: Energy Information Administration. https://www.eia.gov/state/?sid=NC

Coal
Natural Gas
Nuclear
Biomass
Hydropower
Petroleum

- Petroleum power plants provide 0.1% of net electricity generation

North Carolina

Source: Energy Information Administration.
https://www.eia.gov/state/?sid=NC

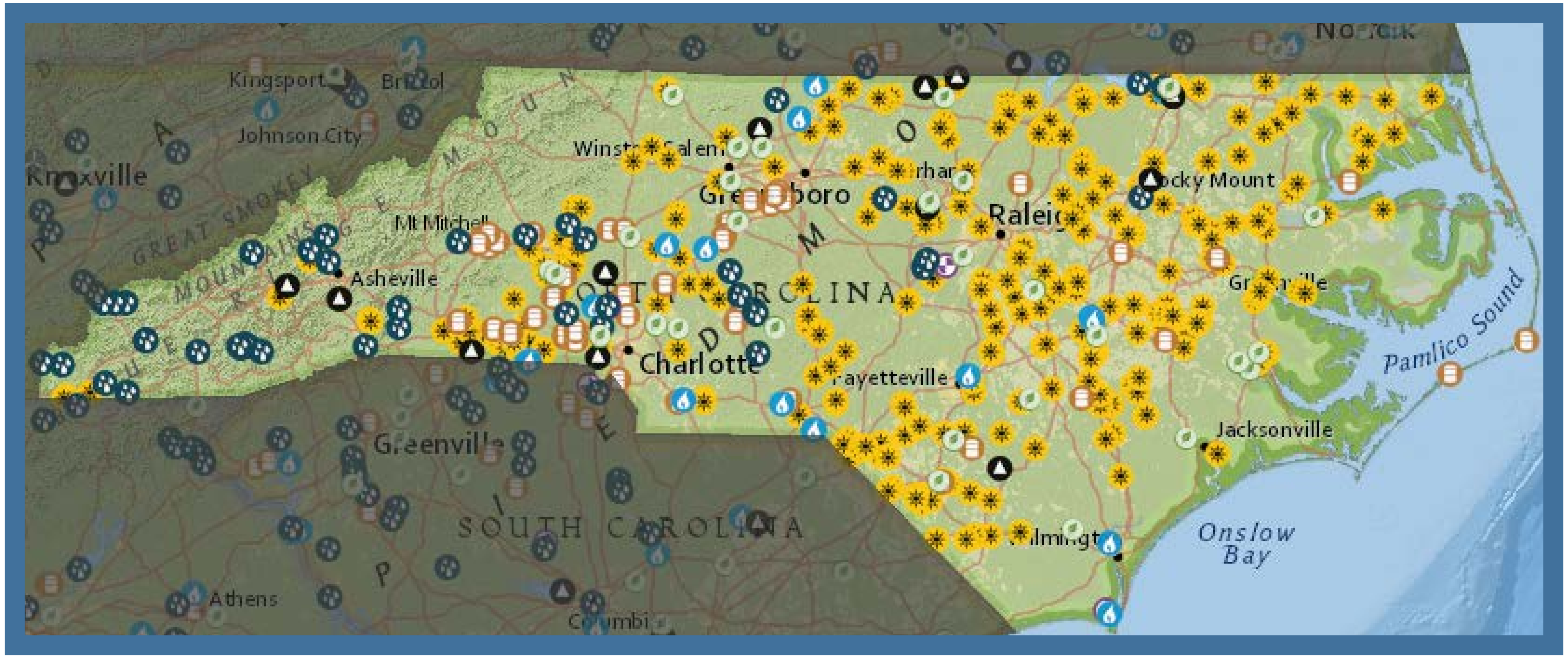
Coal
Natural Gas
Nuclear
Biomass
Hydropower
Petroleum
Wind

- Currently no utility-scale on-shore or off-shore wind

North Carolina

Source: Energy Information Administration. https://www.eia.gov/state/?sid=NC

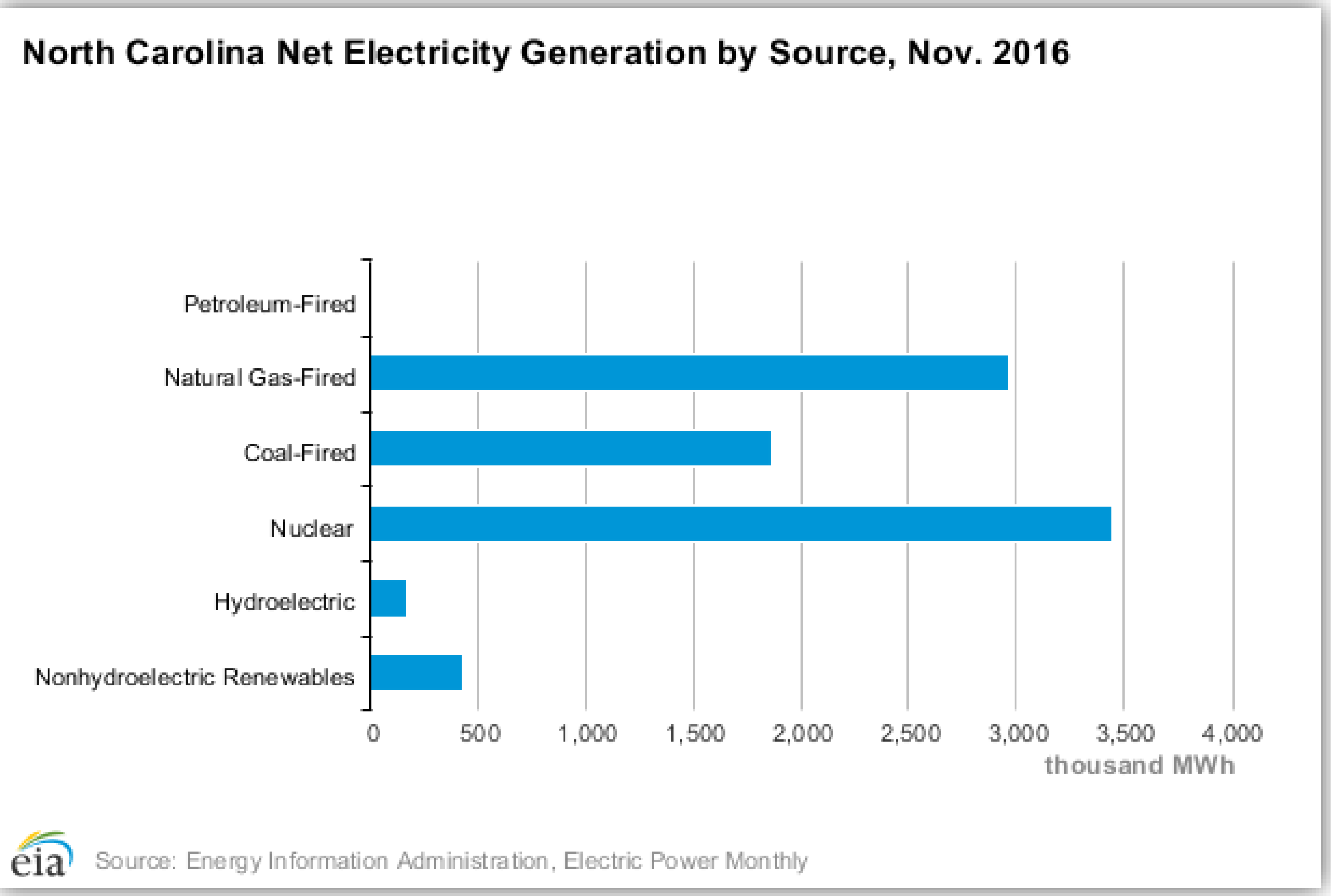
Coal
Natural Gas
Nuclear
Biomass
Hydropower
Petroleum
Wind
Solar



- Utility-scale solar PV spread throughout the state, does not include most distributed rooftop solar
- In 2015, North Carolina was the fourth-largest producer of electricity generated from solar PV in the U.S.

North Carolina’s electricity profile

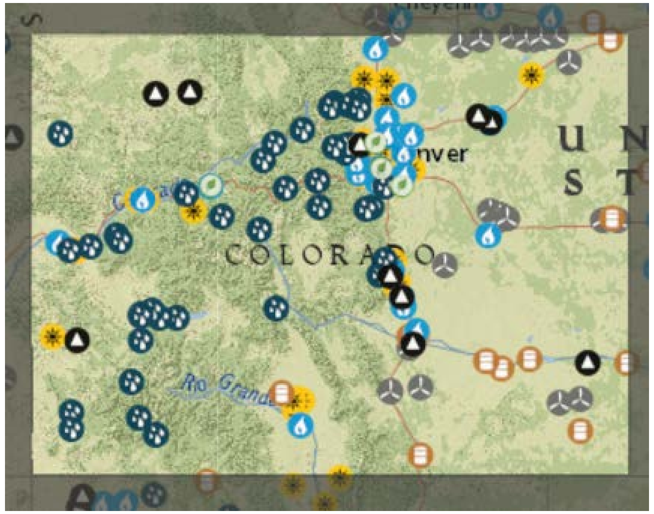
- Large nuclear power share provided by three plants
- Natural gas share growing
- Solar and biomass surpassing hydroelectric – total of 7.1% renewable generation in state



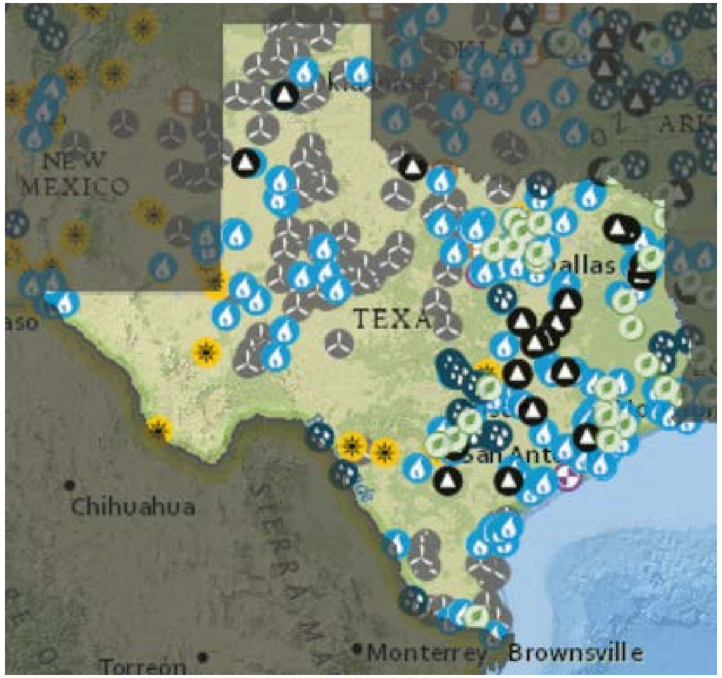
Other state electricity profiles

Washington

Colorado

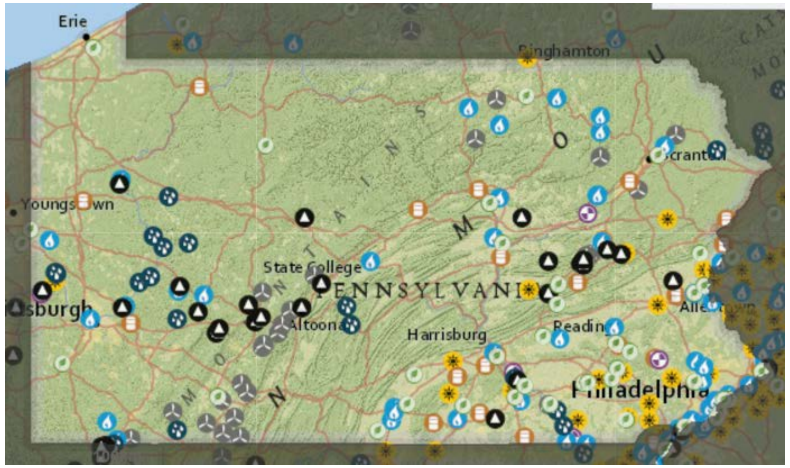


Texas



Coal
Natural Gas
Nuclear
Biomass
Hydropower
Petroleum
Wind
Solar

Pennsylvania



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Different choices with very different impacts

What material resources does it use to build out the infrastructure?

What are the GHG emissions?
How resilient is it to climate change?

What are the land use requirements?

How much does it cost?

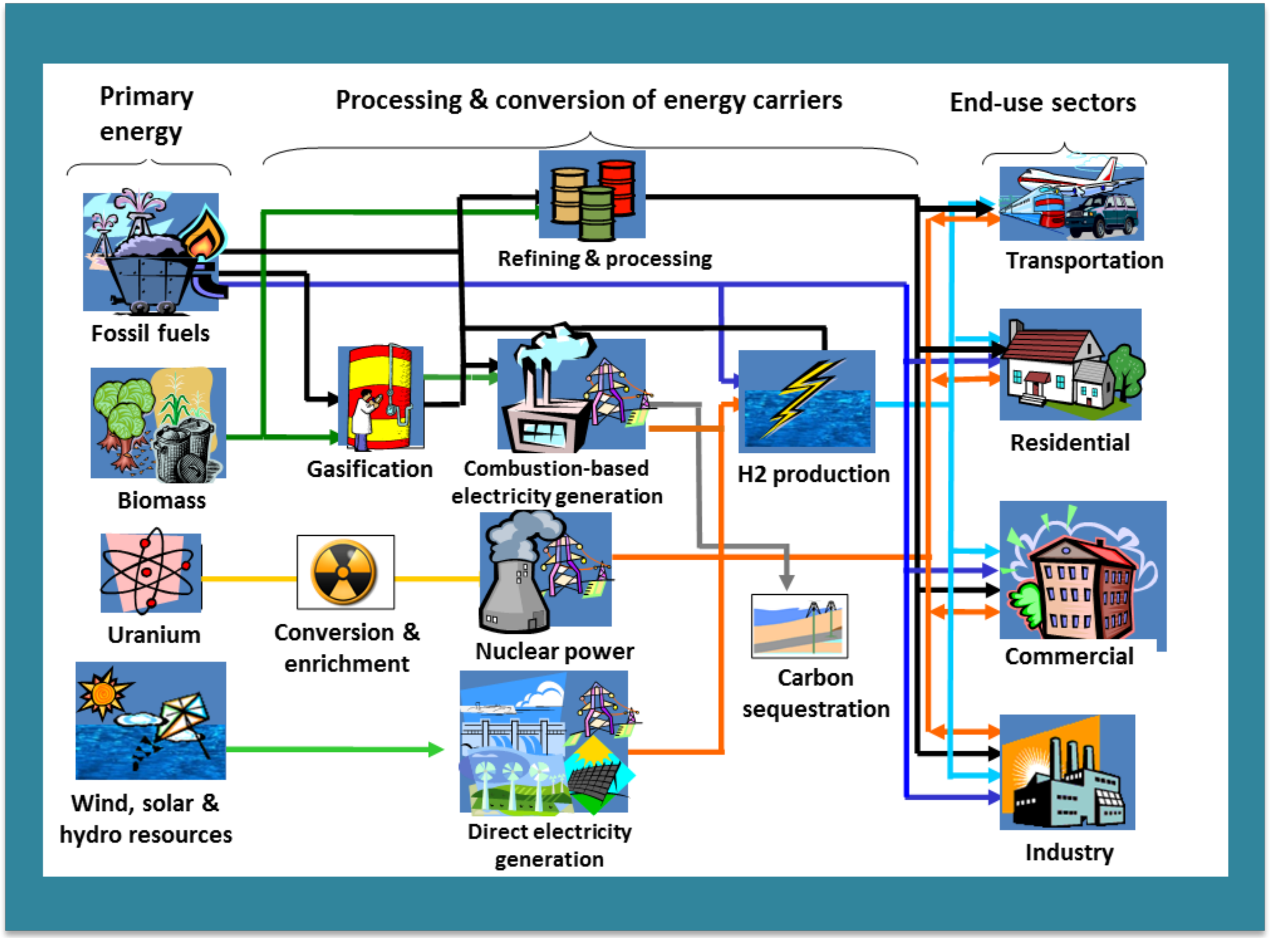
What are the air emissions?

What are the other environmental impacts?

How much water does it require?

Energy systems modeling (using MARKAL)

- Bottom-up technology-rich optimization energy system model
  - Captures the full system from energy resource supply/extraction to end-use in all sectors
  - Energy technologies (existing and future techs) are characterized by cost, efficiency, fuel inputs, emissions
  - Technologies are connected by energy flows
- Technology rich: looks at technologies across the energy system at a relatively fine level of detail



U.S. EPA's Office of Research and Development develops/maintains a database for the MARKet ALlocation (MARKAL) energy system model.

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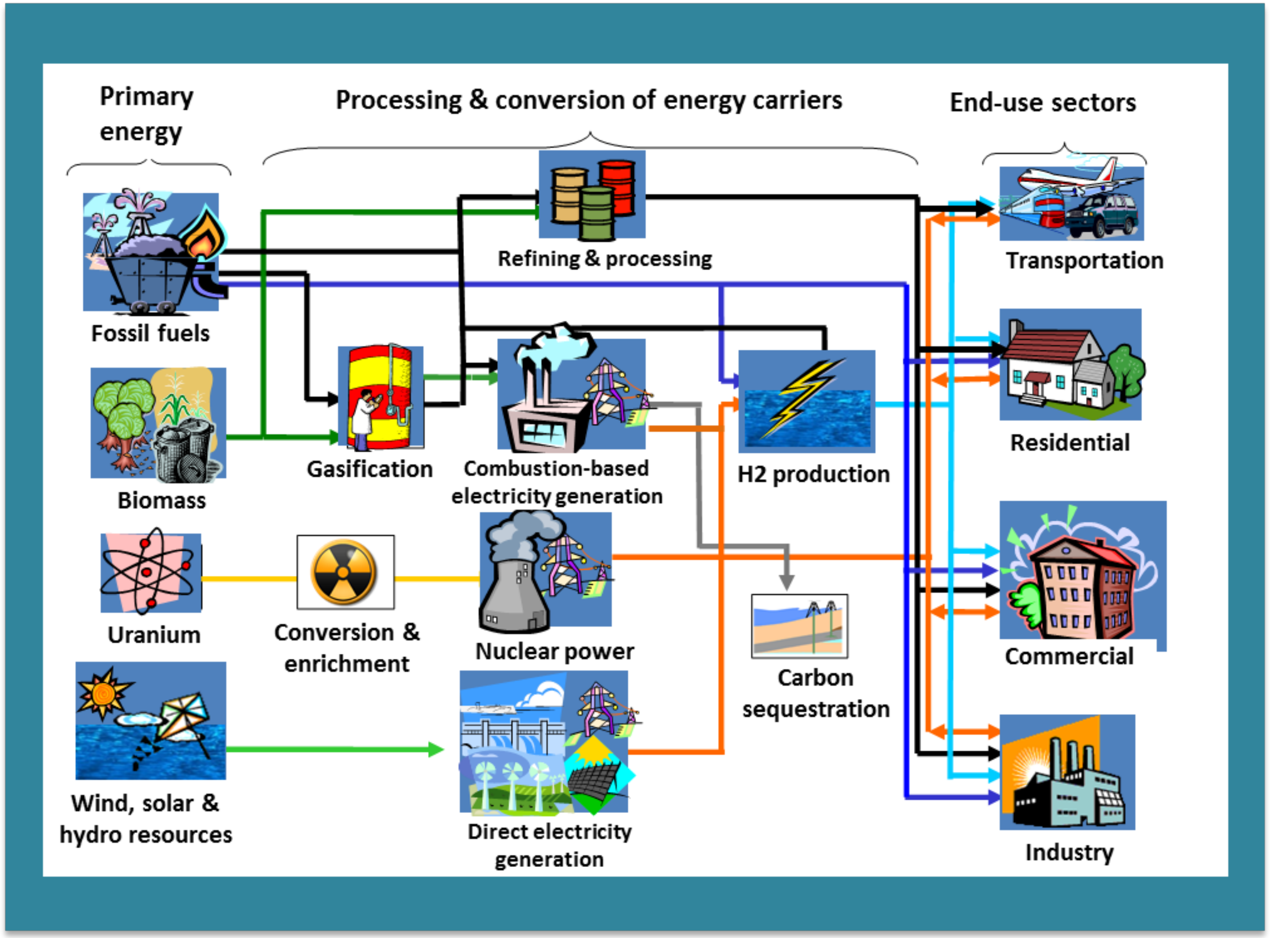
Energy systems modeling (using MARKAL)

- Optimization
  - The model picks the "best" way (lowest system-wide cost) to
    - Meet end-use energy demands
    - Choosing from the full "menu" of energy resources and technologies
  - The model makes these choices from 2010 to 2055, five year snapshots 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



Expanding energy analysis capabilities

Energy system modeling

Characterizes fuels, energy technologies, and air/GHG emissions

Supports a growing user base (50+) for ORD energy modeling tools

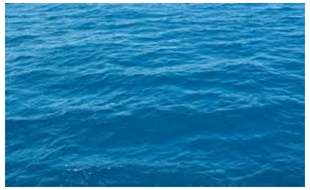
Biomass and biofuels

Inclusion of biomass resources and related land and water impacts

Feeds into multiple ORD and outside EPA analyses of biomass and environmental impacts

Water-energy nexus

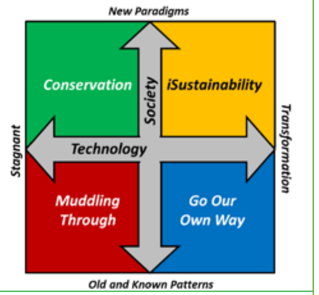
Assessing water demands of energy system scenarios



Consistent modeling of air, climate and water informs mitigation and resiliency

Future scenario analysis

Scenarios for air quality



Enhances foresight regarding long-range energy trends

+ Life Cycle Assessment

Expanded range of impacts

Upstream fuel cycle + energy infrastructure

Ongoing work…

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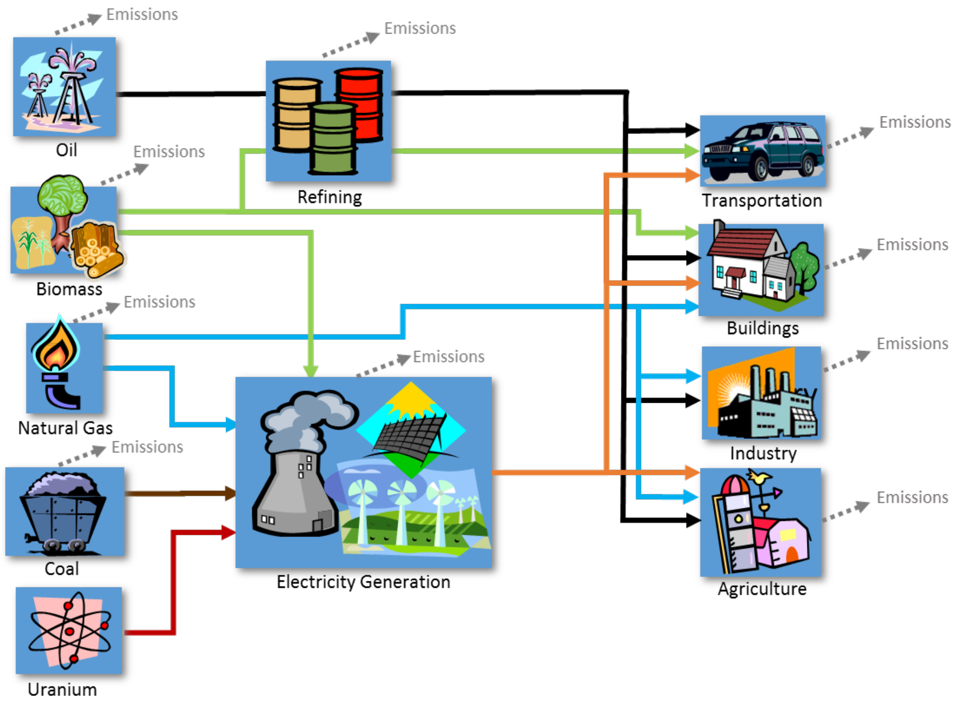
Trade-offs and unintended consequences

If A and B are impacts:

- **Trade-offs**
  - e.g., when A is positive, B is negative
- **Co-benefits**
  - e.g., when A is positive, B is positive
- **Unintended or unanticipated consequences**
  - e.g., when A is positive, C is negative…. and nobody (or few) saw it coming



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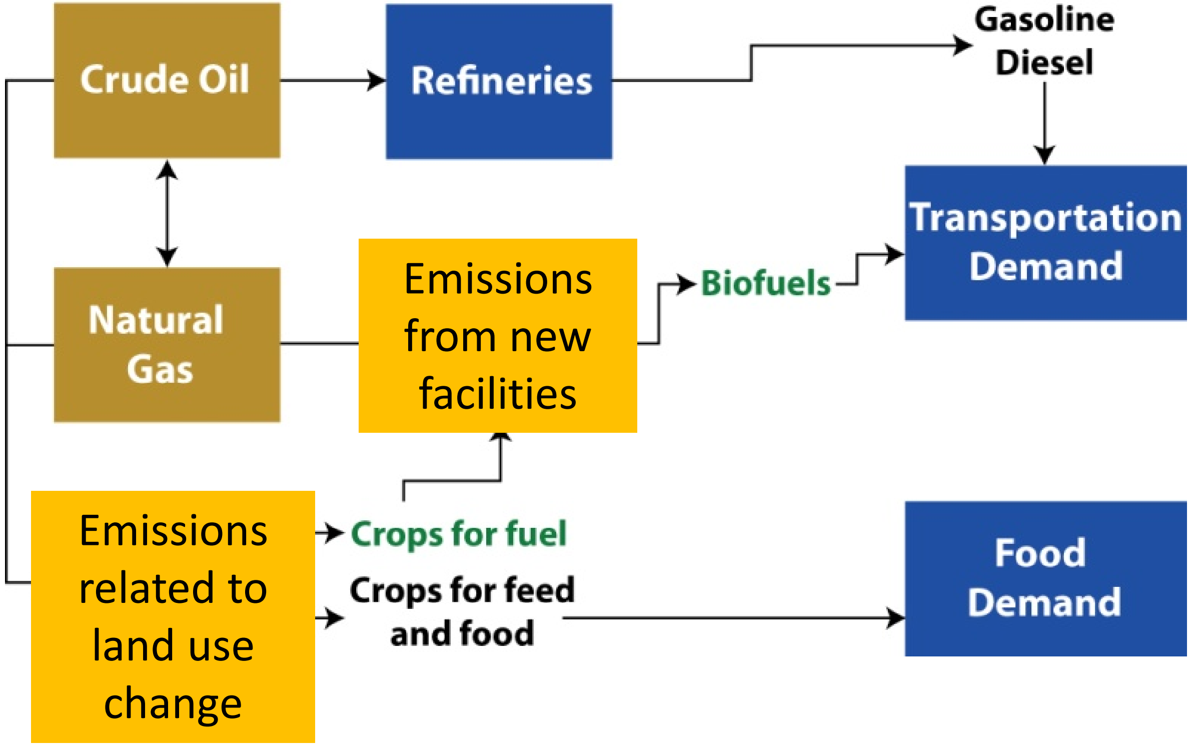
Example: biofuels linking agricultural and energy markets

Understanding the market dynamics…

- Energy (e.g., oil) and agriculture (e.g., corn) interact through markets for transportation fuels and inputs to agricultural production

… then translating results into environmental impacts

- Scenarios of biofuel production and associated land use and land management change
- Provide changes in air emissions (trade-offs, co-benefits)?



Elobeid, A., et al. 2013. Integration of agricultural and energy system models for biofuel assessment. *Env. Model. & Software*

Dodder, R.S., et al. 2015. Impact of energy prices and cellulosic biomass supply on agriculture, energy and environment. *Energy Econ*.

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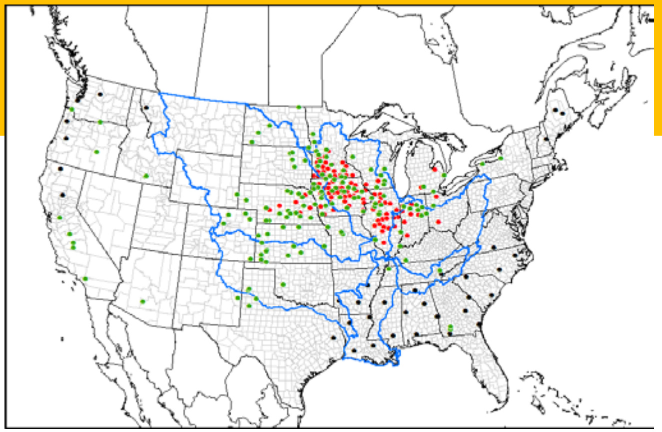
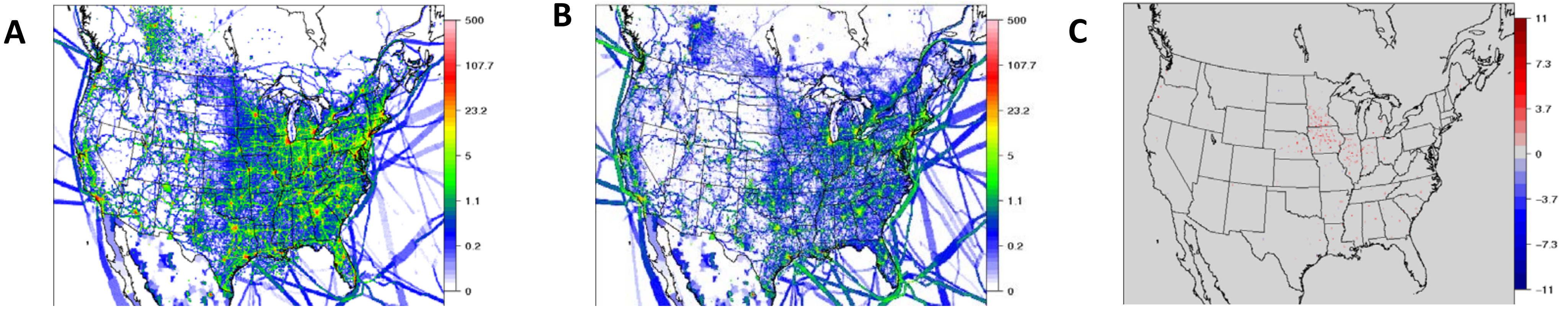
Example: biofuel facilities

- How do changes in biofuel production levels affect changes in NOx emissions for a 2022 scenario?



2022_{CROP} scenario: biofuel facilities



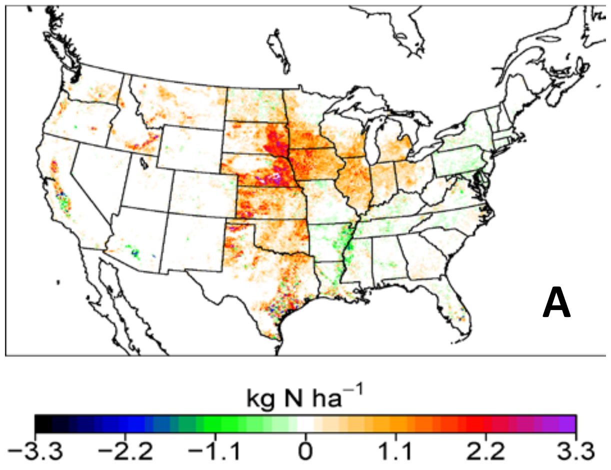
NO_X emissions (kg N ha^{-1}) for the A) 2002 scenario, B) 2022_{BASE} scenario, and C) difference between 2022_{CROP} NO_X and 2022_{BASE} NO_X emissions.

Cooter, Dodder, Bash, et al. (In review) Loose coupling of economic and physical process models supporting integrated multimedia research in the United States Mississippi River Basin.

Example: regional land management change

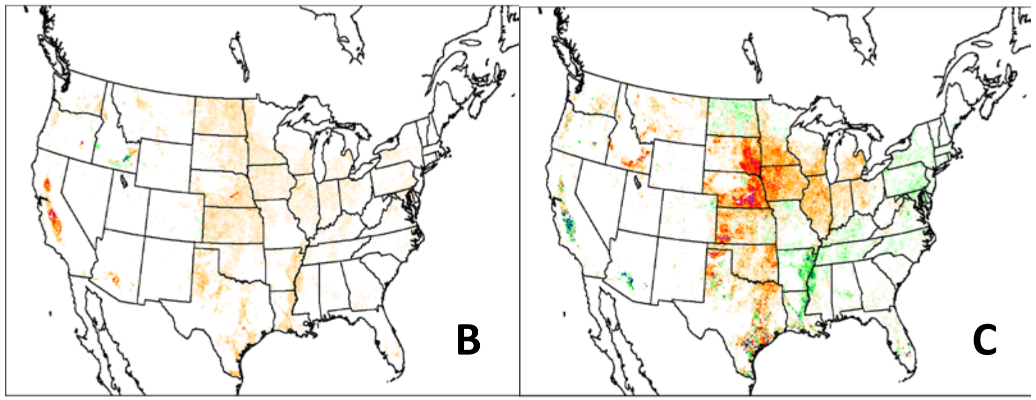
- How do resulting agricultural changes, including land use and land management practices, affect emissions? e.g., soil ammonia

Total soil NH_3 Emission Response



CO_2 and Yield Trends

Stover and Crop Shift



Soil ammonia emissions 2002-2022 A) total response, B) response to increasing CO_2 and yield trends, and C) response to stover removal, and cropland shifts.

Cooter, Ran, Dodder, et al. 2015. Integrated Multimedia Modeling System Response to Regional Land Management Change. *AGU Fall Meeting*.

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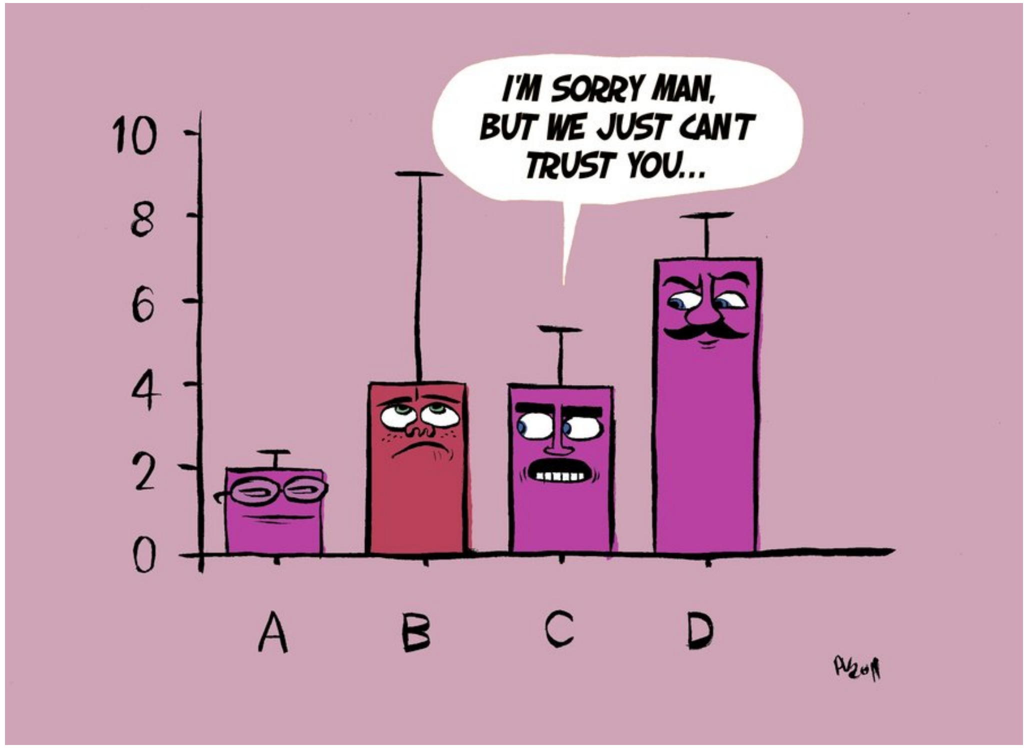
Gaining foresight

How to gain foresight in uncertain times?

Uncertainty



https://www.facebook.com/pedromics

Deep Uncertainty

https://www.flickr.com/photos/robinj/14635540659/
https://creativecommons.org/licenses/by-nc-nd/2.0/

Also appears on the RAND Corp. website
http://www.rand.org/capabilities/methods-centers/decision-making-under-uncertainty.html

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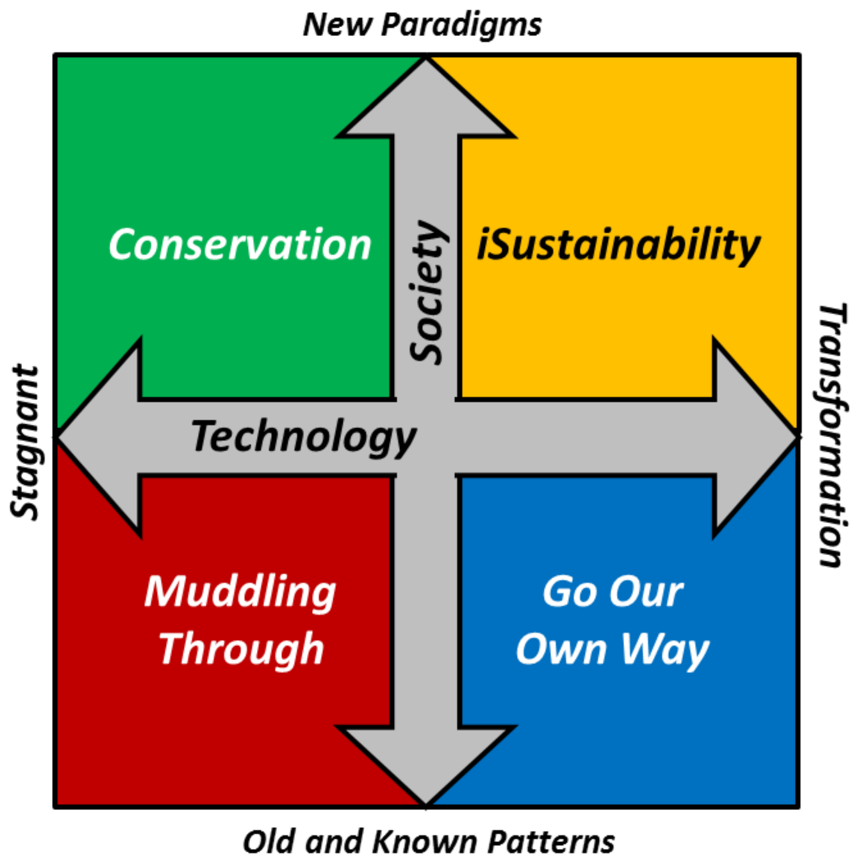
Future scenarios for air quality

Followed a scenario planning approach to explore a wider range of plausible futures

- Utilized internal and external expert interviews and workshops
- Identified key uncertainties and developed a scenario matrix
- Constructed narratives describing all four scenarios
- Implemented the scenarios into an energy systems modeling framework and evaluated air quality impacts

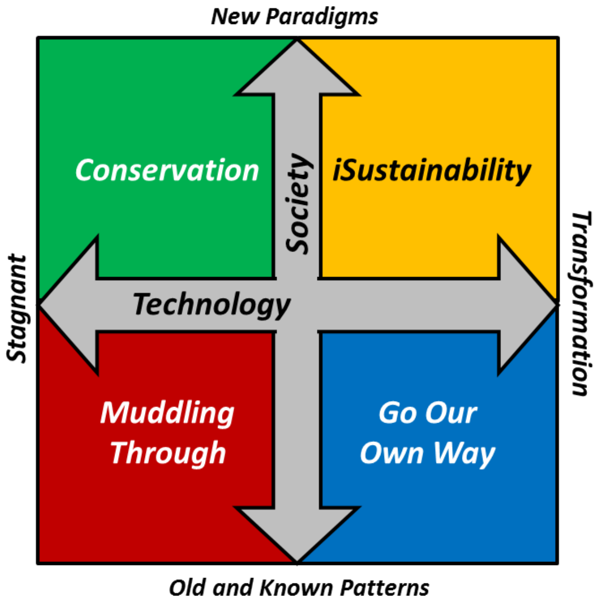


Gamas, J., Dodder, R., Loughlin, D., Gage, C. (2015). "Role of future scenarios in understanding deep uncertainty in long-term air quality management." *Journal of the A&WMA*

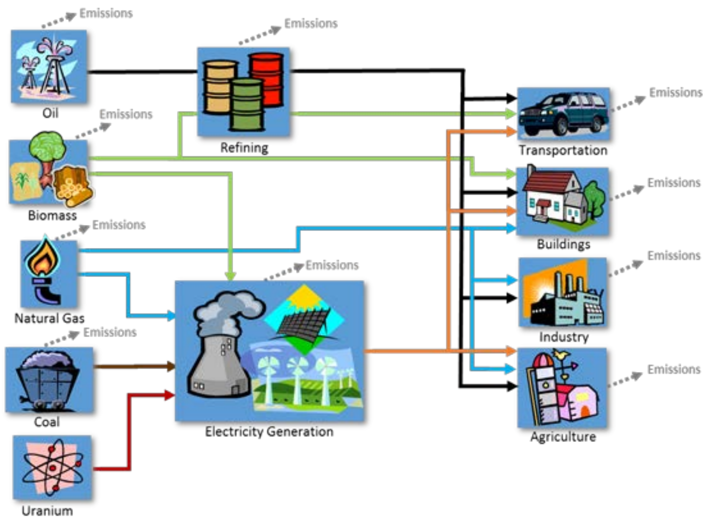
Future scenarios for air quality

- Different "futures" lead to small variations in emissions trends for some pollutants versus larger spreads for other pollutants
- **Robust strategies for air quality management should perform well across a range of possible futures**

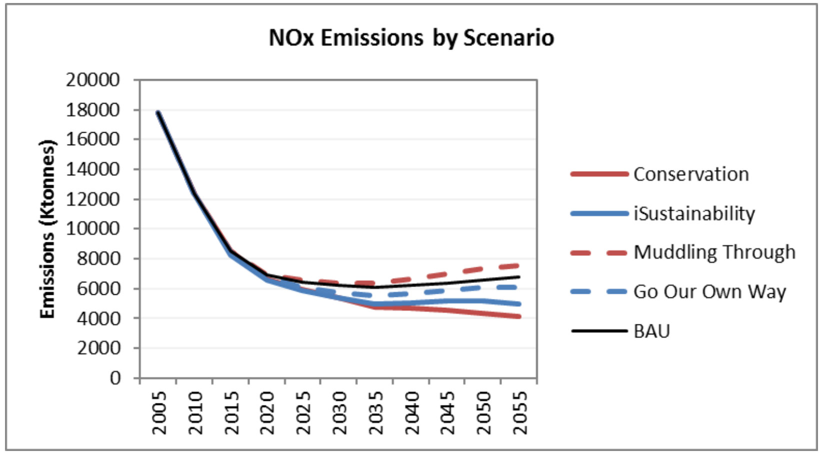
Scenarios



Energy modeling



Emissions trends



Illustrative results: Courtesy of Dan Loughlin, EPA ORD

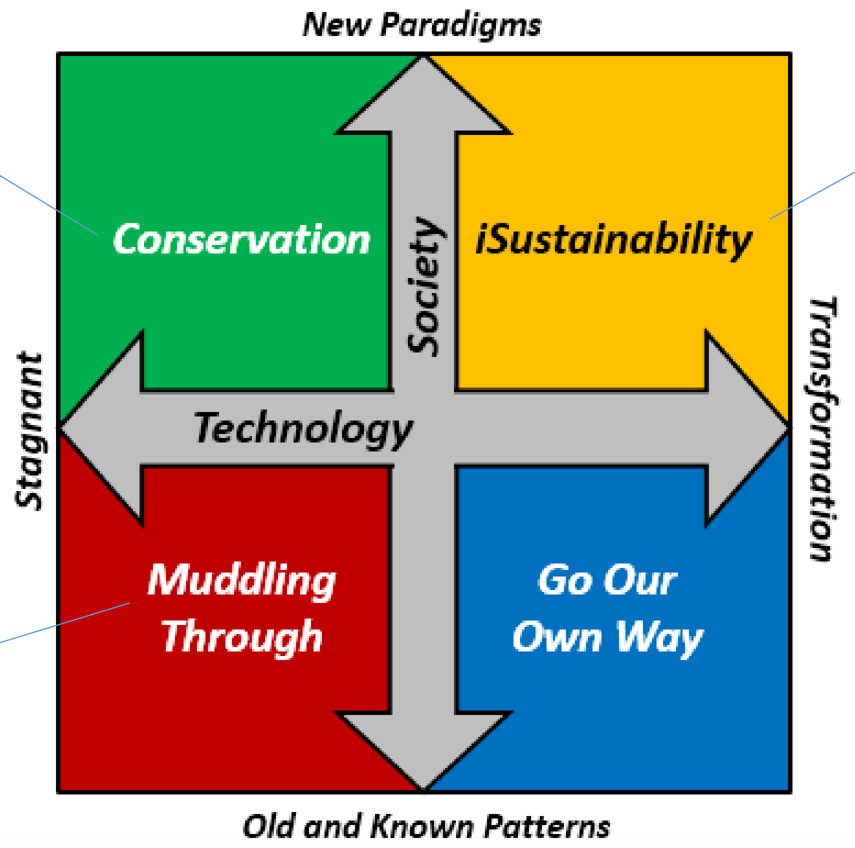
Scenario implementation

- Axis: Technological transformation or stagnation
    - *Lever: technological availability and cost*

No electric vehicles
No IGCC

Only considered technologies that are competitive today without subsidies

No electric vehicles
No IGCC

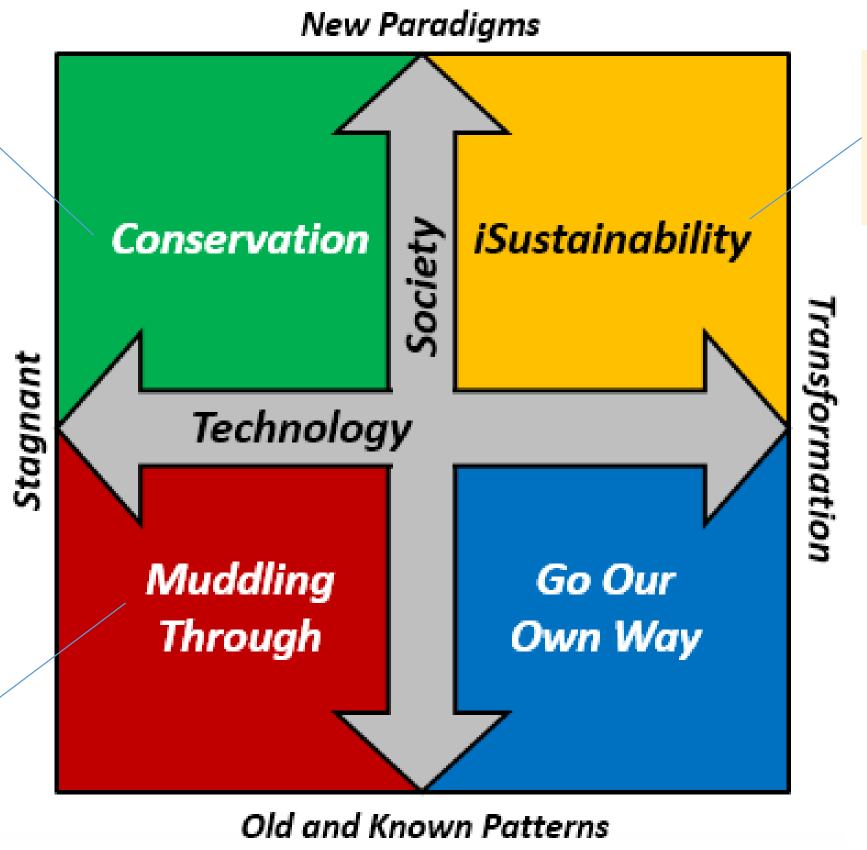


Electric vehicles achieve cost parity with conventional
Solar costs are reduced (obtained from IPM v5.15)

Scenario implementation

- 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

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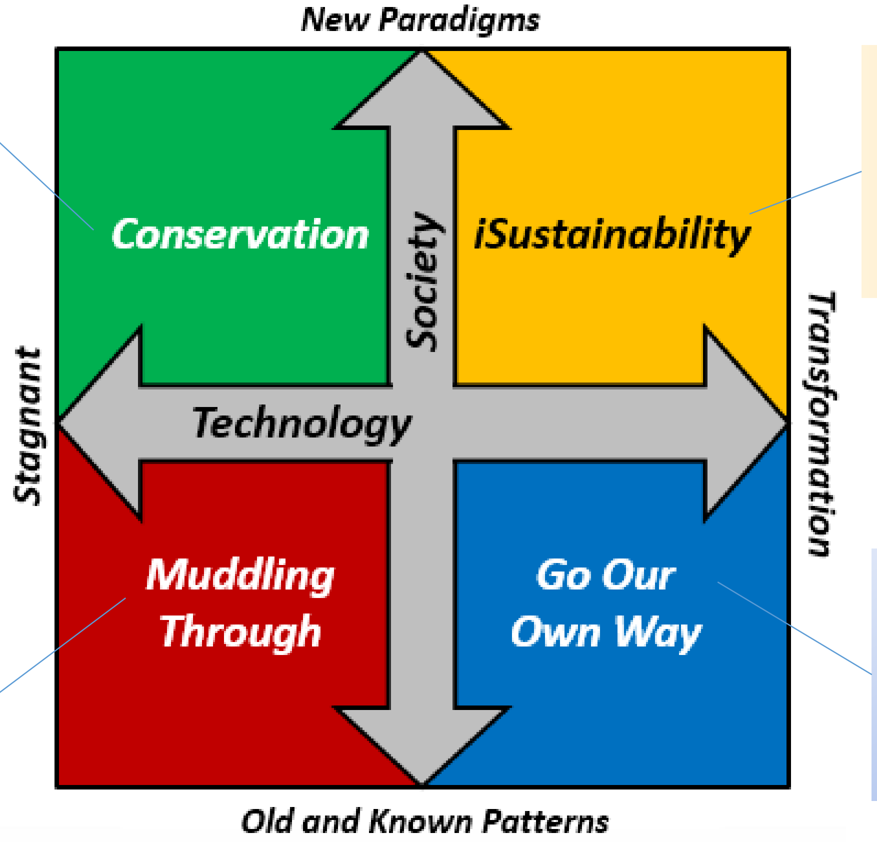
Scenario implementation

- Axis: Social transformation and behavioral change
  - *Lever: hurdle rates to reflect scenario-specific preferences*

Prefer:
Renewable
Environmental- and climate-friendly
Local
Energy efficient

Prefer:
Renewable
Environmental- and climate-friendly
Energy efficient
Advanced technologies



Prefer:
Conventional technologies
Avoid:
Advanced technologies
Infrastructure changes req'd
Environmental- and climate-friendly
High capital cost

Prefer:
Advanced technologies
Energy efficient
Avoid:
Infrastructure changes req'd
High capital cost

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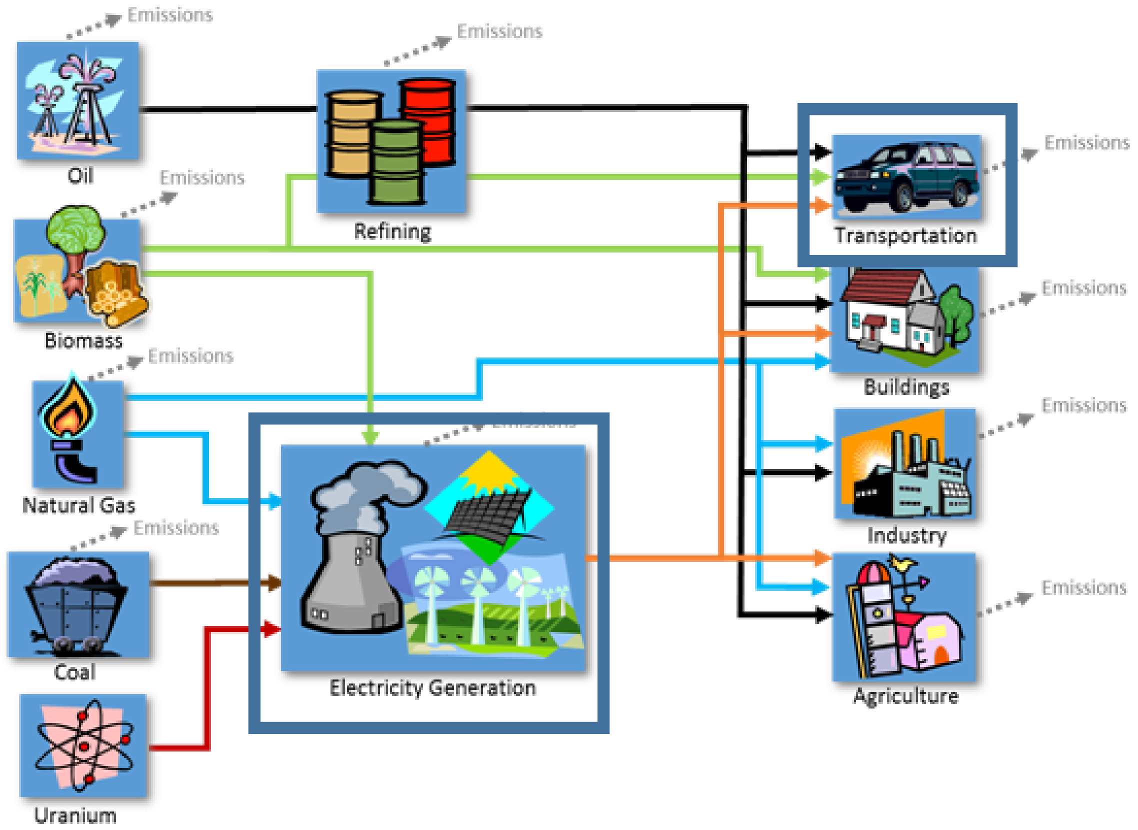
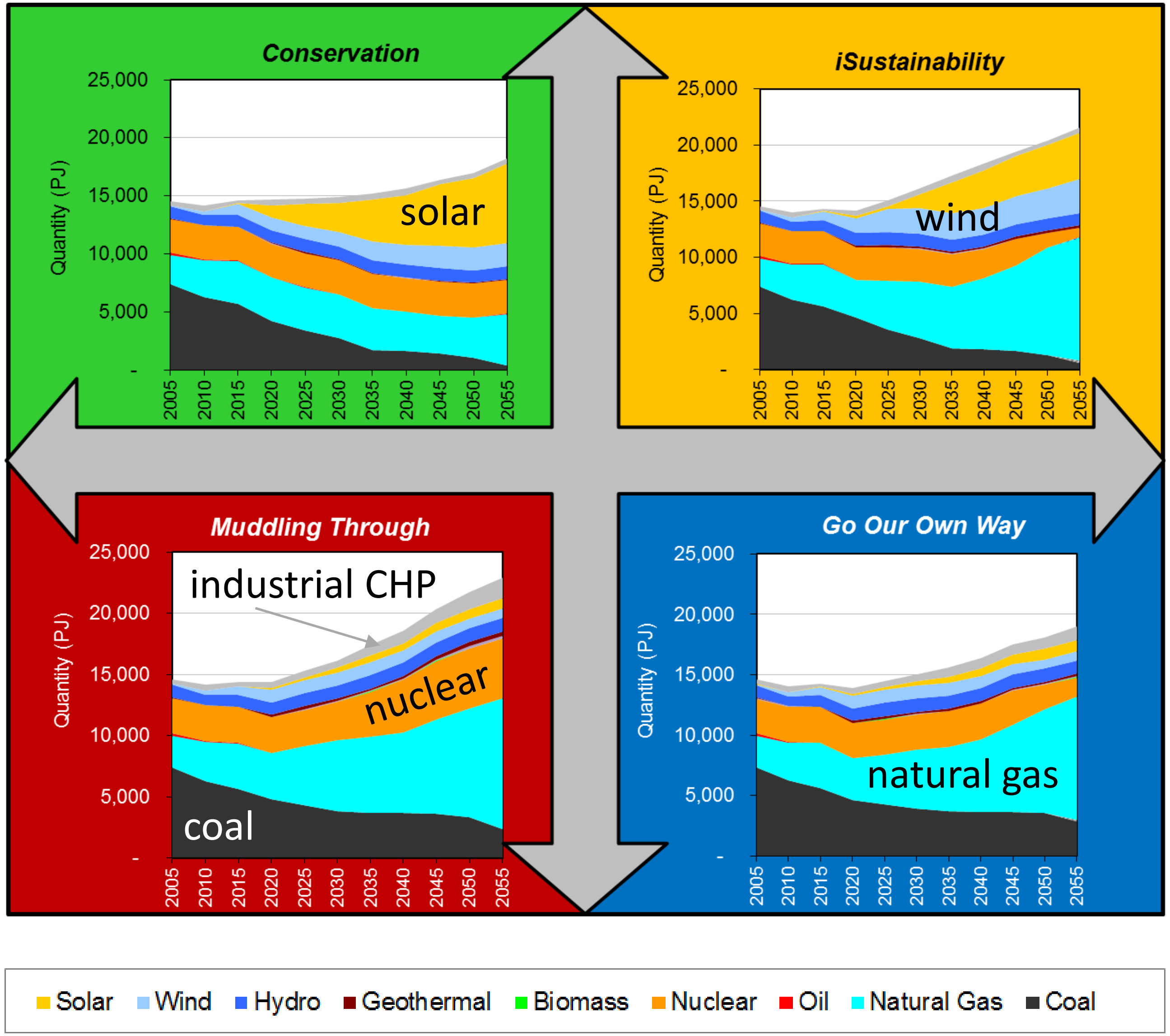
Plausible, divergent, and internally-consistent futures

- Running the scenarios through an energy system model
  - Provides **plausibility** in meeting energy balances
  - Shows how all sectors vary across scenarios in fuel/technology mix
  - Captures cross-sector impacts important for **internal consistency**
  - Allows development of emissions trends for each future scenario
  - Illustrates how **divergent** the results are across the four futures



Illustrative results

- Aggregated electricity production out to 2055
- Scenarios capture a range of outcomes
  - Different levels of demands, some driven by changes in end-use sectors
  - Range of generation mixes of fossil, nuclear and renewable power generation



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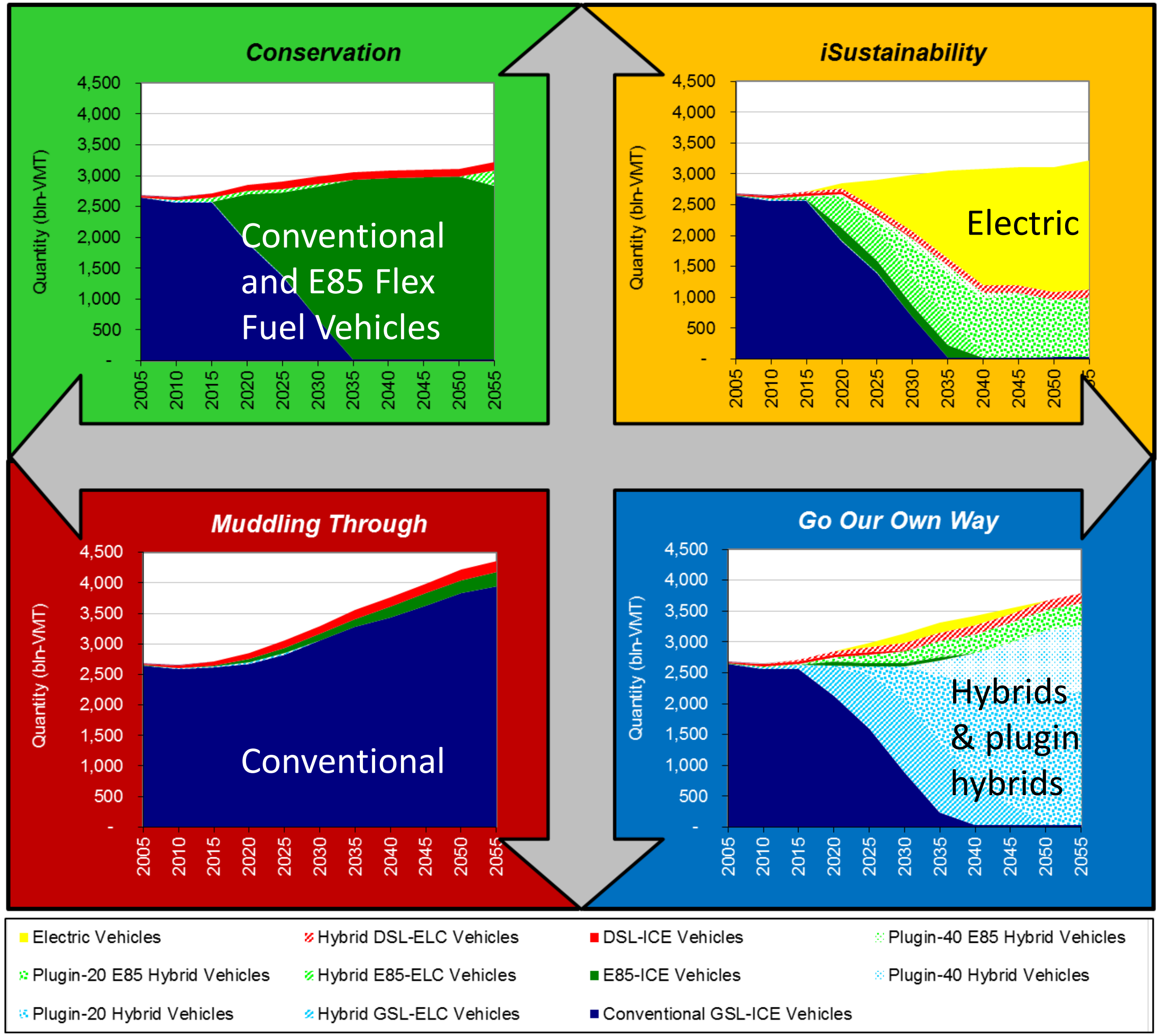
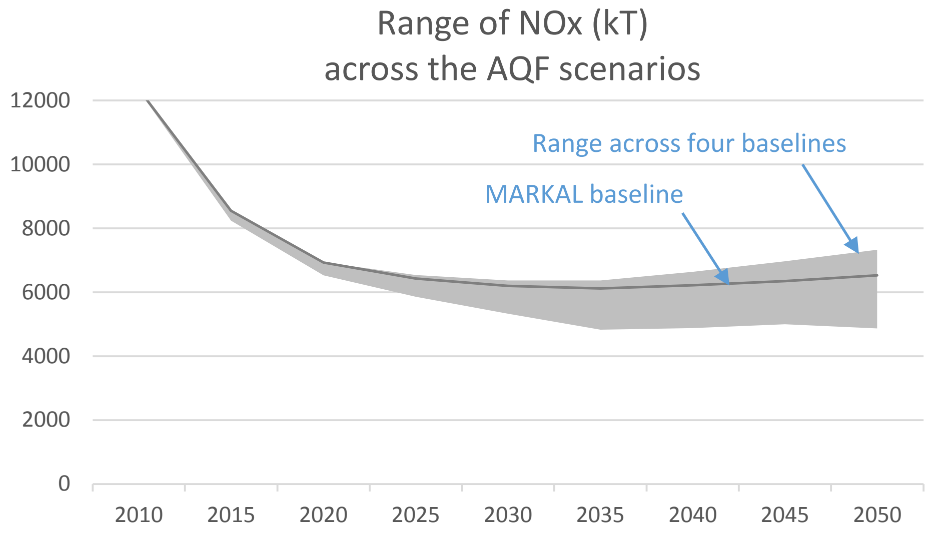
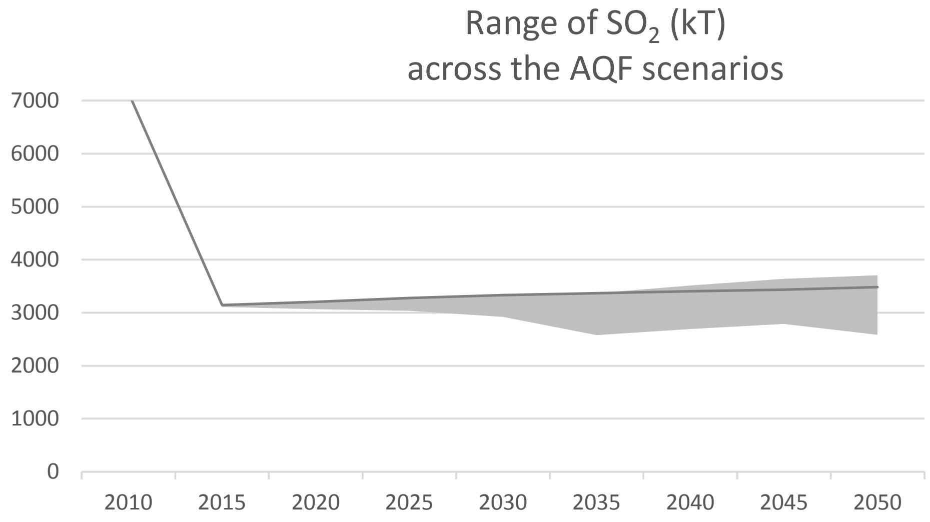
Illustrative results

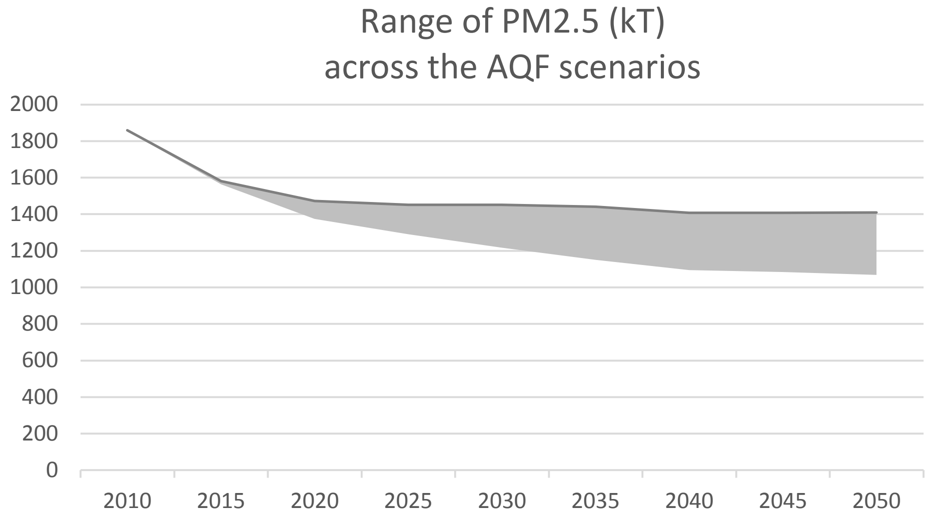
- Aggregated light duty vehicles results
- Scenarios capture a range of outcomes
  - Demand for travel as billion vehicle-miles traveled (VMT) per year
  - Different fleet mixes in terms of vehicle type and fuel
  - Fuel mix has implications for upstream fuel and electricity demands

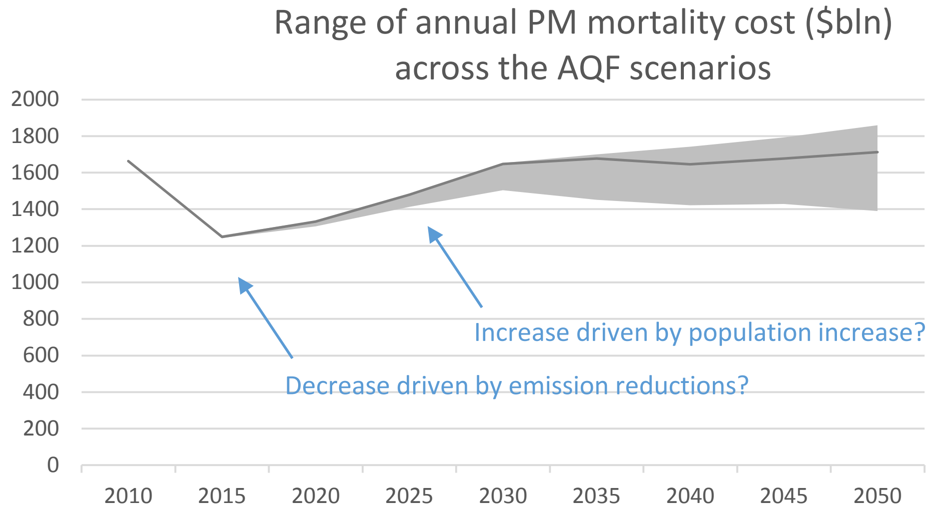


Range of outcomes across futures









Illustrative results: Courtesy of Dan Loughlin, EPA ORD

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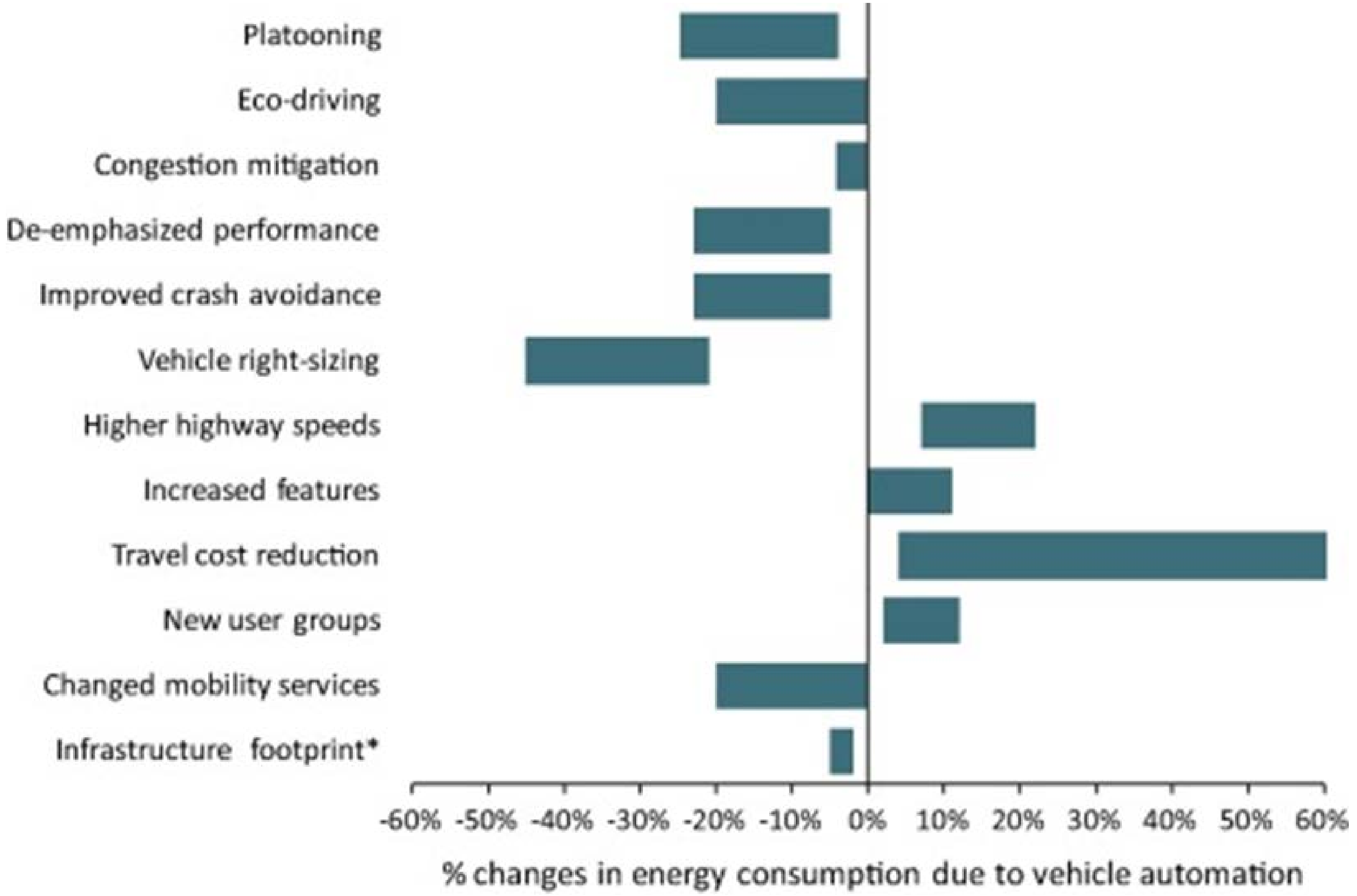
Further outside the box

The Three Revolutions in Transportation:

- **Connected and automated vehicles (CAVs)**
- Vehicle electrification
- Sharing economy

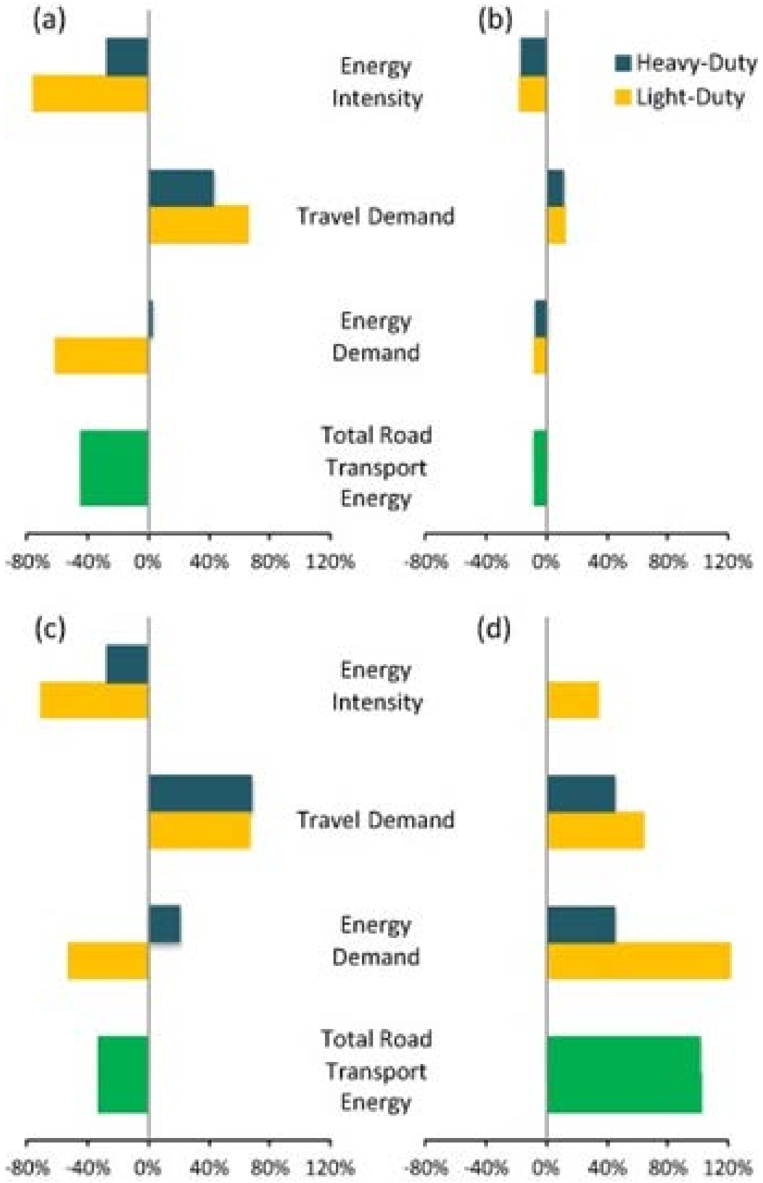
- This is a time of major convergence of innovations in the transportation… and major uncertainty.
- How will these factors play out with respect to changes in energy use and emissions of concern?



Wadud, MacKenzie, Leiby. (2016) Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. Transportation Research Part A.

Scenarios of automation

- Depending on the scenarios, the net effects could significantly reduce or increase total road transport energy and carbon emissions



Changes in energy intensity per kilometer, travel demand, and total road transport energy consumption for light-duty (LDV) and heavy-duty vehicles (HDV) under varying automation scenarios:
(a) "Have our cake and eat it too"
(b) "Stuck in the middle at Level 2"
(c) "Strong responses"
(d) "Dystopian nightmare."

Wadud, MacKenzie, Leiby. (2016) Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. Transportation Research Part A.

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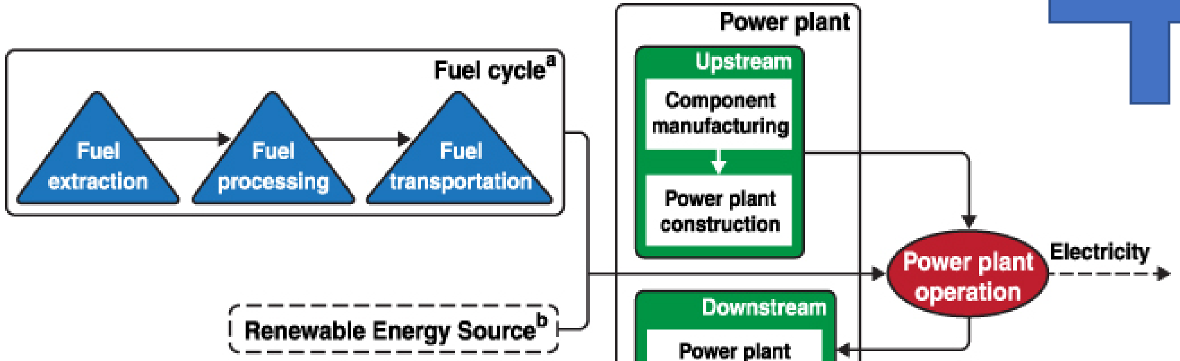
Tracking impacts along the life cycle

Life cycle assessment (LCA) and energy

Why look at LCA in addition to energy systems modeling?

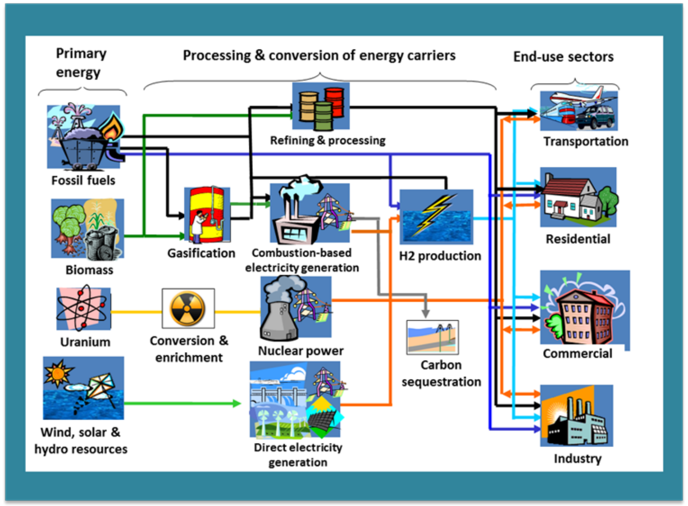
- Energy system modeling primarily focuses on energy flows, and associated air and GHG emissions
- Life cycle assessment looks at fuels and technologies from "cradle-to-grave"
  - LCA includes material flows of changing energy infrastructure
  - LCA expands the range of impacts assessed

Life cycle assessment



[a]Fuel cycle pertains to coal, natural gas, and nuclear only.
[b]Solar, wind, or geothermal energy; No water is required in the creation of renewable energy resources.

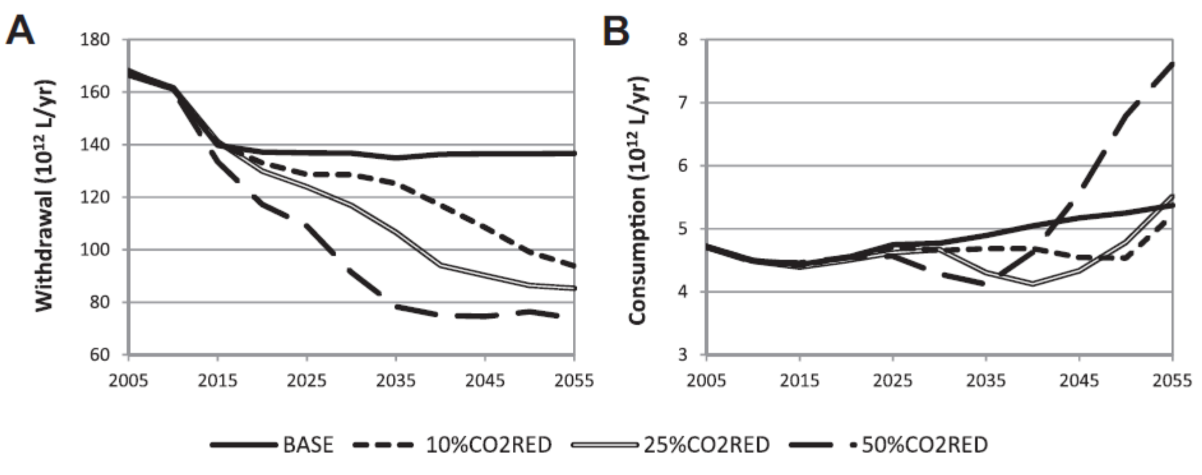
Energy modeling



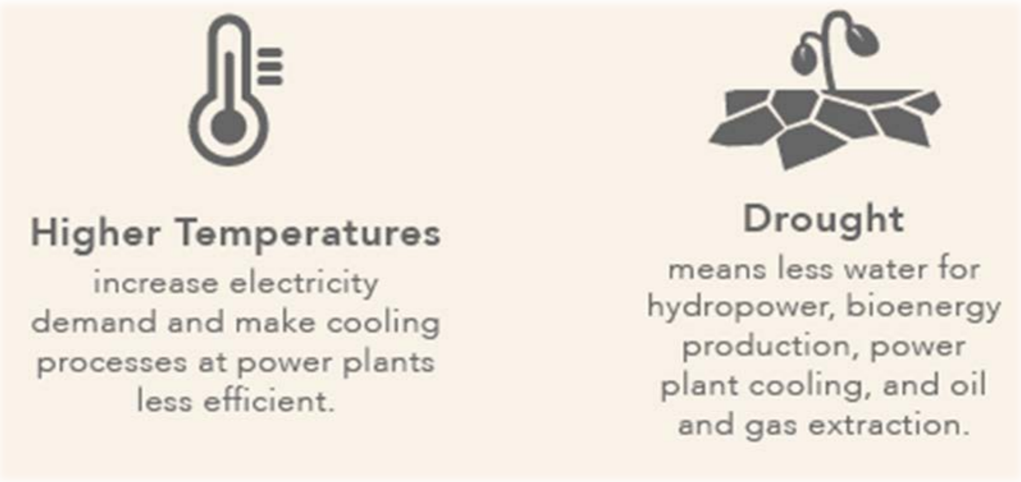
Water-energy nexus

As the energy system changes, so will the water demands

- 51% of U.S. fresh **surface water** withdrawals are for thermoelectric power
- There will be trade-offs in **(A) withdrawals** (water returned to the water body) and **(B) consumption** (evaporated/lost water)



Cameron, Yelverton, Dodder, West, 2014. Strategic responses to CO_2 emission reduction targets drive shift in U.S. electric sector water use. *Energy Strategy Reviews*



Water and energy systems are interdependent, and both are changing

- Changes in water temperature and availability affects electric power production

https://energy.gov/articles/ensuring-resiliency-our-future-water-and-energy-systems

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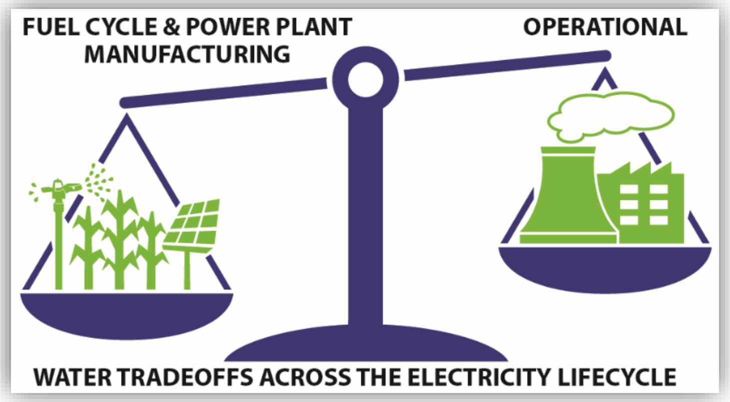
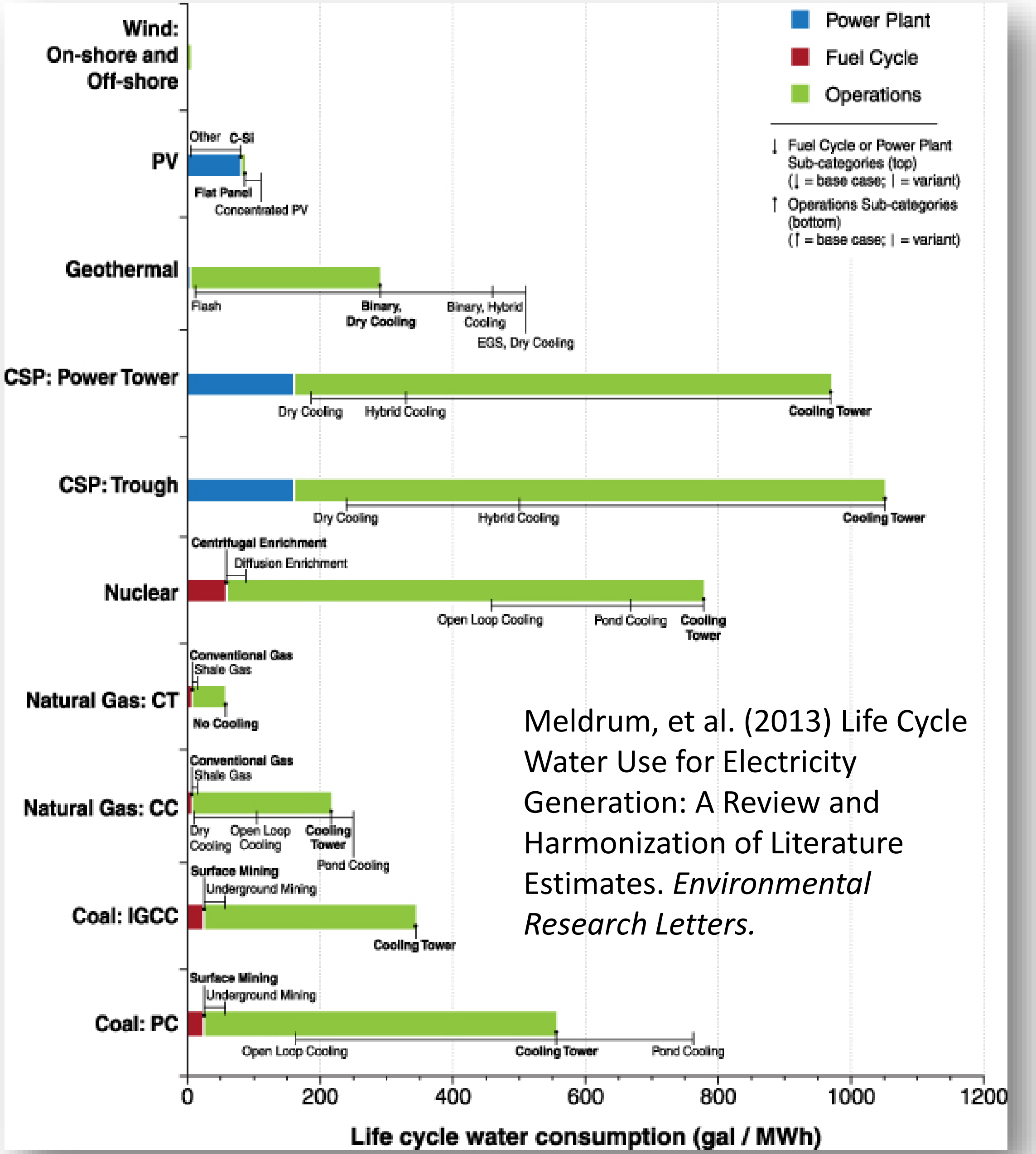
LCA and water-energy

Operational water use for thermoelectric cooling is not the only water use of interest

- “Upstream” life cycle water use for manufacturing new electric power capacity (e.g., PV)
- Fuel cycle water use (e.g., biomass irrigation) may also be significant



Dodder, R., et al. (2016). Scenarios for low carbon and low water electric power plant operations: implications for upstream water use. *ES&T*



Meldrum, et al. (2013) Life Cycle Water Use for Electricity Generation: A Review and Harmonization of Literature Estimates. *Environmental Research Letters.*

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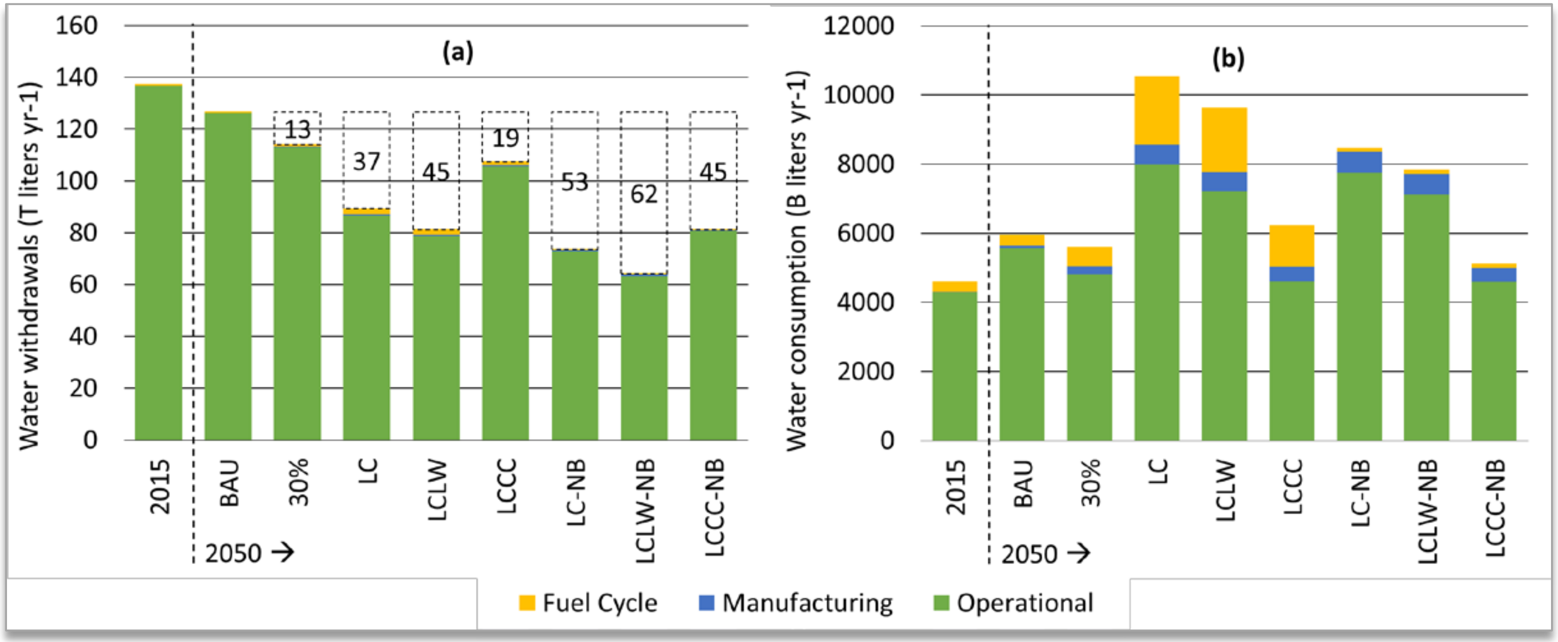
Synergies or trade-offs in water use?

Are there synergies or trade-offs between mitigation (lower CO_2) and adaptation (lower freshwater requirements) across the life cycle?

- Withdrawals generally fall with reductions in CO_2
- Consumption is more complex



<u>Scenario combinations:</u>
low carbon, electric only (30%)
lower carbon, system-wide (LC)
low withdrawals (LW)
constant consumption (CC)
no biomass (NB)

(a) National water **withdrawals** (T liters yr-1) by life cycle stage in 2015 and 2050 for the BAU and seven scenarios. The dashed boxes show the 2050 water withdrawal reductions relative to the BAU. (b) National water **consumption** (B liters yr-1) by life cycle stage in 2015 and 2050 for the BAU and seven scenarios.

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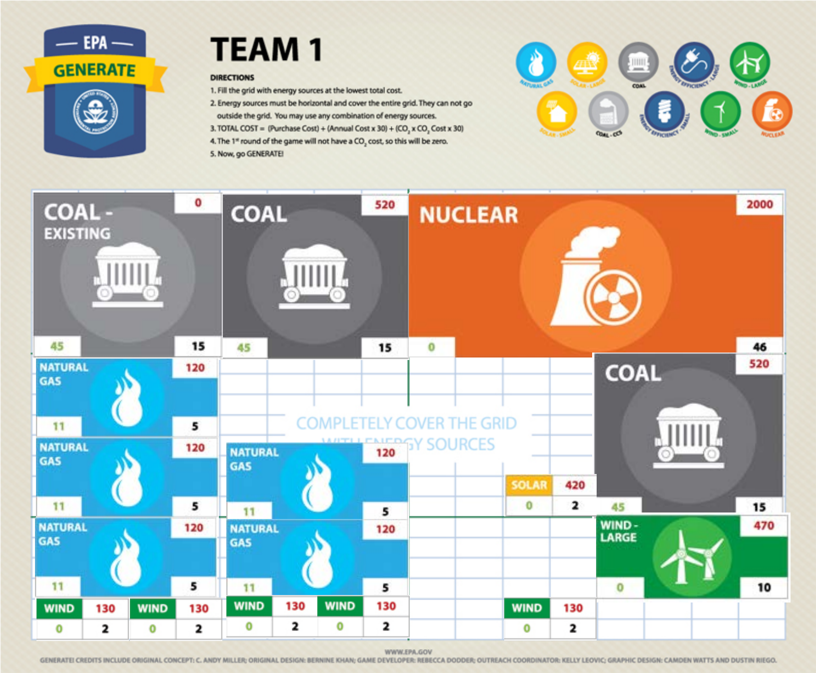
From research to outreach

It’s all fun and games…

Scientific models are approximations of the objects, systems or phenomena that they represent

…. in a basic way, games do the same thing.

- How to translate what we are learning from the research into something tangible for students and educators
- Different modes of outreach
  - Working with students
  - Working with educators
  - Development of classroom activities
  - Webinars or other modes of dissemination



“This is the best science board game EVER!”

“It was cool, funny and angering at times!”

https://www.epa.gov/air-research/hands-activities-and-other-resources-air-quality-and-climate-change-teachers

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Connecting to Community

Engaging directly with students, parents, teachers, educators, community groups, etc.

- Working with students through Citizen Schools
- 8 semesters of “apprenticeships” (~15 students per semester) with a strong environmental and STEM focus (*Power Play* and *Making Sense of Air Quality*)
- 10 weeks of project-based learning followed by a WOW! capstone events for the school, parents and community
- Teachers workshops and trainings

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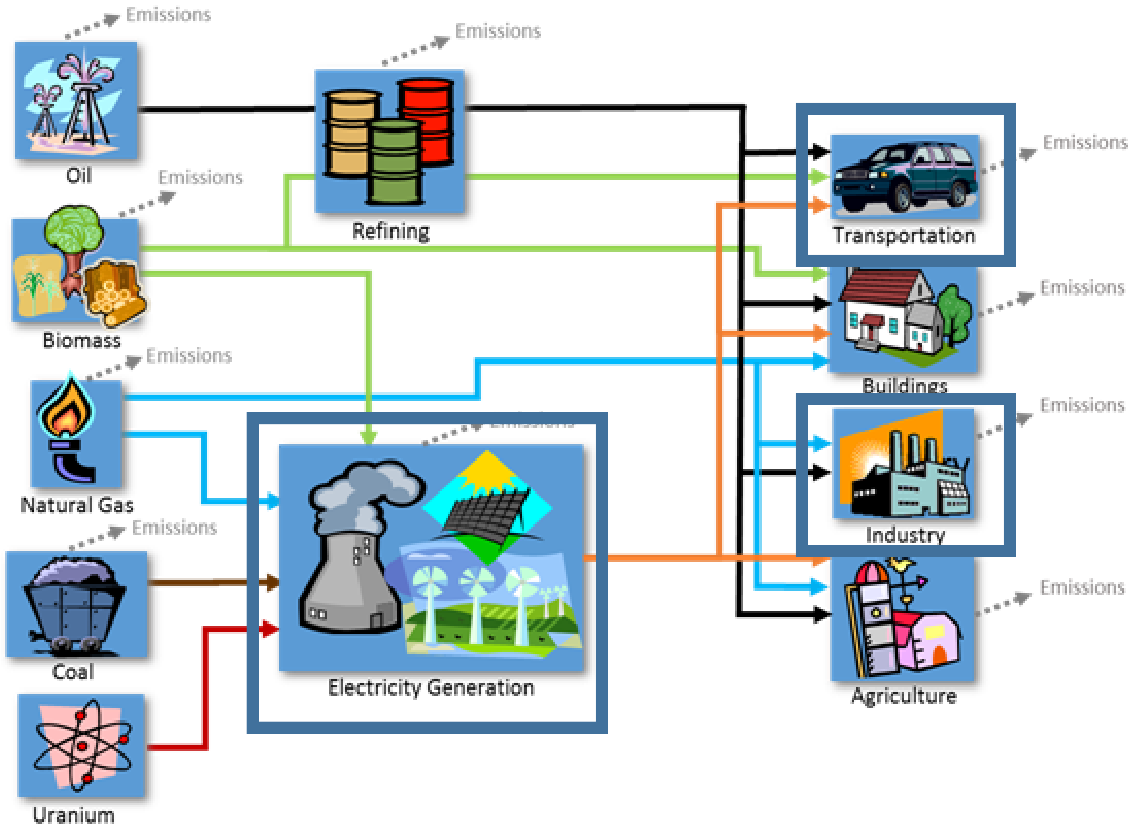
Thank you!
Questions?

Scenario implementation

- Implementation of the scenarios in an energy system model 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 were hard-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

Life cycle impacts through material flows

- Vehicle mass reduction (VMR) is one strategy manufacturers can use to improve fuel economy in light duty vehicles
- When changes affect multiple sectors, an LCA approach can track impacts
- Life cycle assessment (LCA) is a tool to understand impacts of changing vehicle materials and designs



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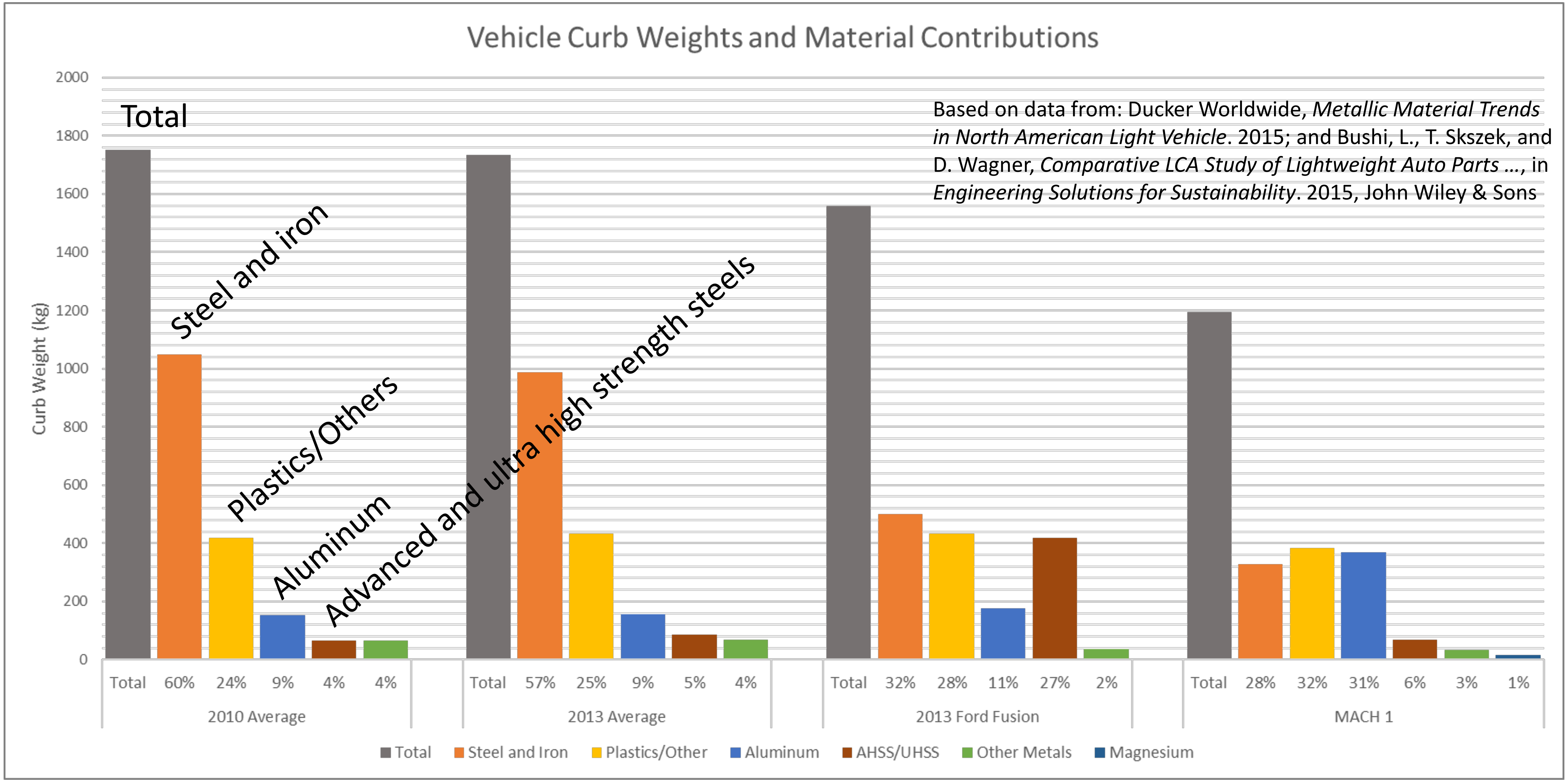
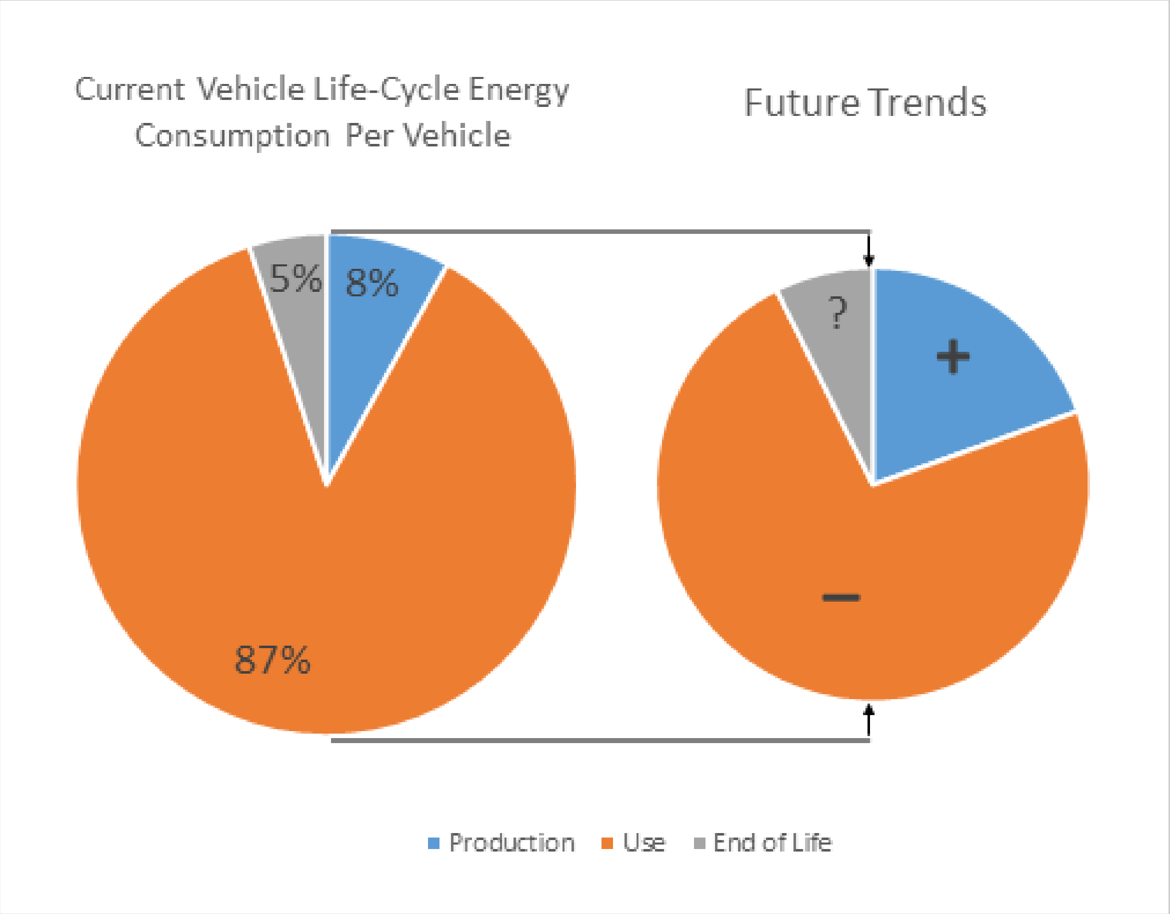
End-use efficiency changes material flows



Life cycle impacts through material flows

Reducing total life-cycle energy consumption per vehicle

- VMR is meant to improve **use phase** impacts
- High-tech nascent technologies may have increased **production phase** impacts
- The **EOL-phase** is largely dependent upon the recyclability of a material



Based on data from: Keoleian, G.A. and J.L. Sullivan, *Materials challenges and opportunities for enhancing the sustainability of automobiles.* MRS Bulletin, 2012. **37**(04): p. 365-373.

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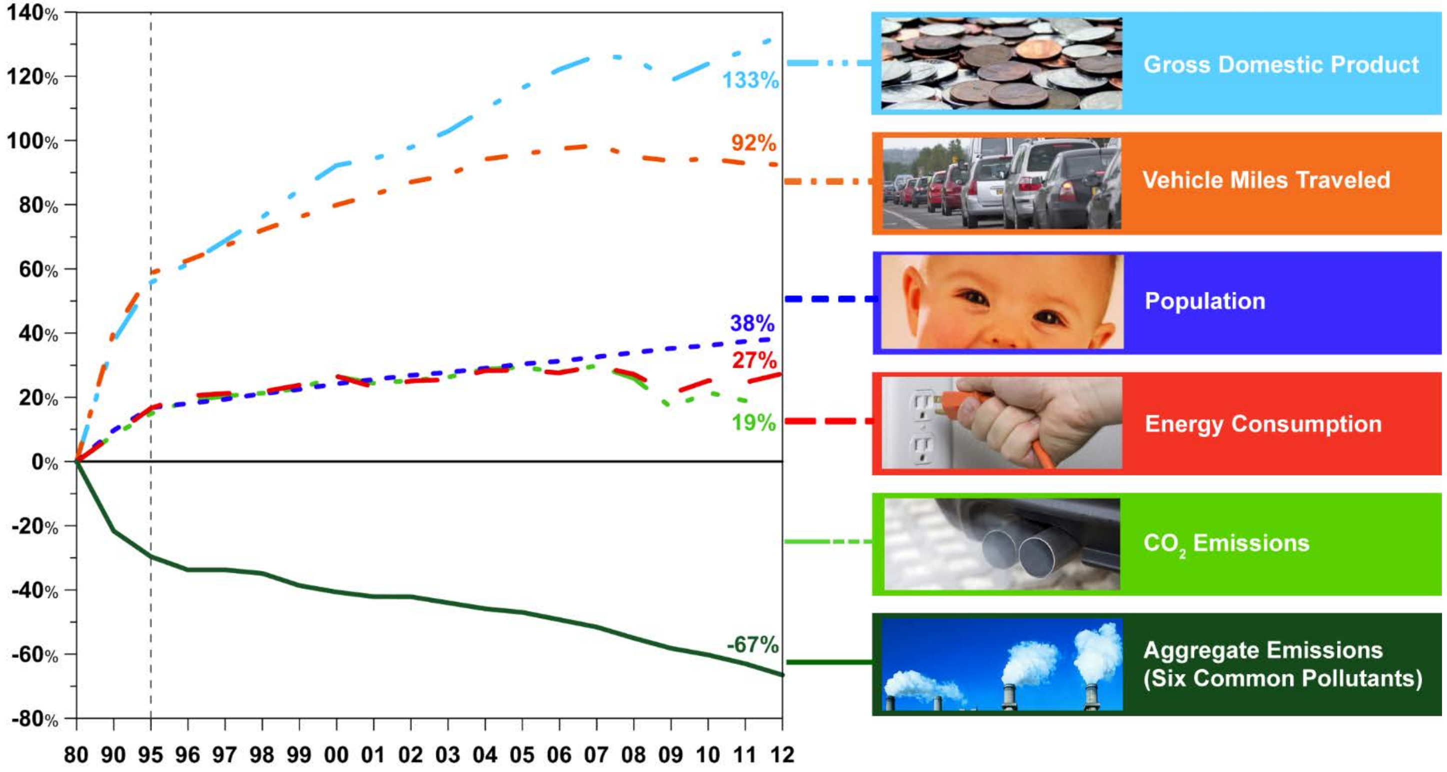
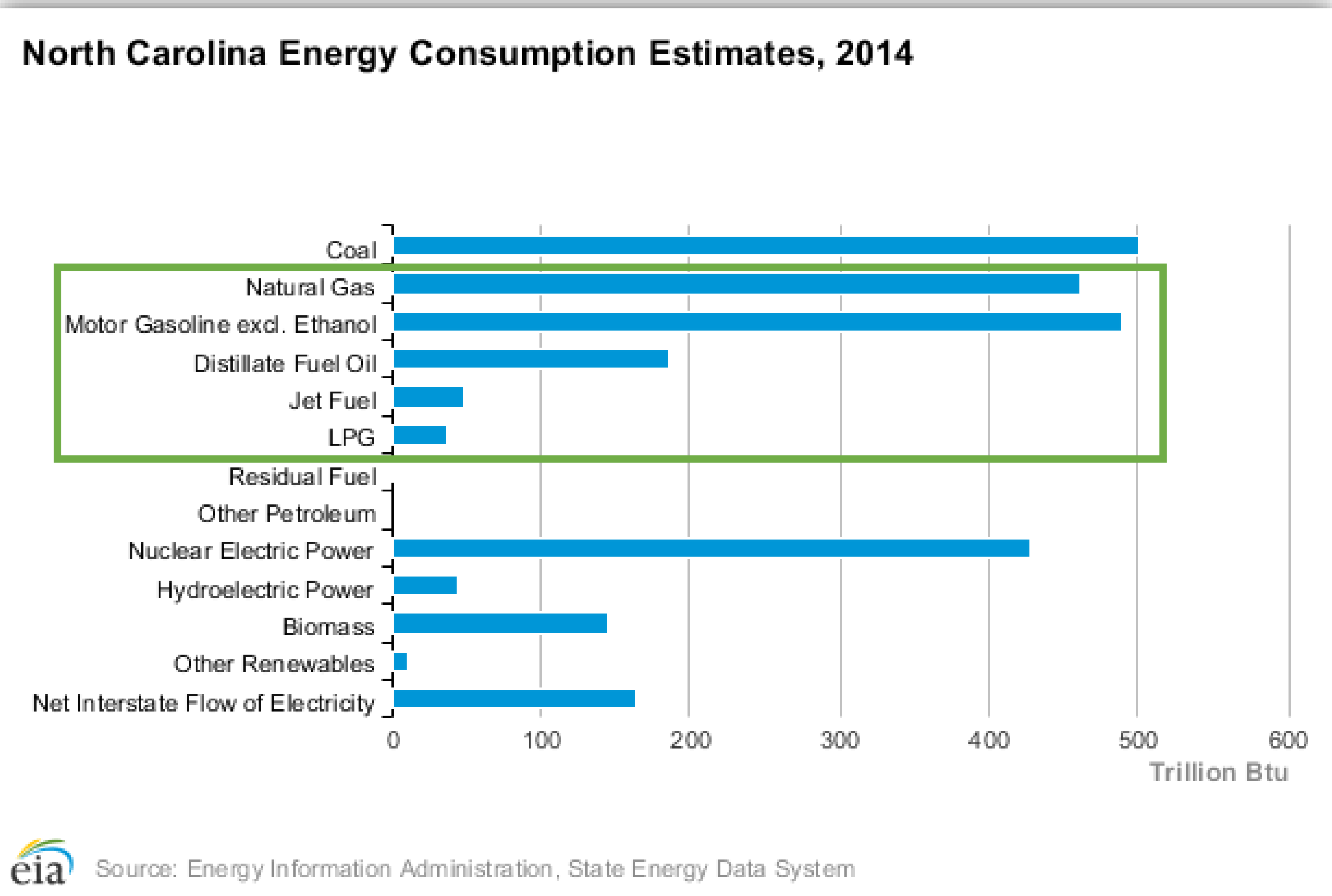
Growth measures and air emissions



http://www.epa.gov/airtrends/aqtrends.html#comparison

North Carolina's energy profile



Natural gas also meeting non-electric power energy demands in end-use sectors

Transportation sector another key energy demand (gasoline and diesel)

Travel demand: 108 billion VMT in 2014 (7^{th} in U.S.)

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