The Role of Modeling and Scenario Planning in Energy Transitions

March 10th, 2025

Dr. Jeremy Hargreaves

Benjamin Preneta

CLMT5008G Climate Change Mitigation

Class Agenda

- Introductions
- Scenario planning and accounting
- What is energy modeling? Types, purposes, comparisons
- Planning and modeling challenges with clean energy and emissions targets
- Evolved’s modeling approach
- Why model? Applications and case study
- Spatial analysis and modeling co-benefits

Introductions

EVOLVED
ENERGY
RESEARCH

Evolved Energy Research (EER) is a research consulting firm focused on providing long-term planning and strategies for energy decarbonization using optimization, capacity expansion, and production cost models.

Jeremy focuses on economy-wide decarbonization and least-cost electricity system planning, supporting decision making for state governments, nonprofit organizations, utilities, and investors. He has authored, managed, and provided stakeholdering in several state-driven decarbonization strategies, most recently supporting policymaking in Oregon, Maine, Washington, and New Jersey, as well as helping his private clients navigate the changing energy landscape. He developed the formulation of Evolved's Regional Investment and Operations (RIO) model and holds a PhD in energy systems optimization from Johns Hopkins University.

Ben Preneta joined EER full time as a Senior Analyst following his graduation from the MA in Climate & Society program after completing a summer fellowship. Ben's work focuses on spatial components of modeling such as energy development land-use impacts, transmission routing, and renewables siting. Ben previously worked with CGEP, UN OSAA, and served in the US Army.

Evolved Energy Research Clients

Evolved addresses key policy, investment and strategy questions to enable the energy transition

Example Utility RTO Clients

SPP, CenterPoint Energy, SCE, Alliant, ConEd, NJR, DTE, PGE, Hydro Quebec, PG&E and others

State Energy Offices

Washington, California, Montana, Massachusetts, Maine, New Jersey, and Oregon

NGOs/Academic/Regulatory

NRDC, SDSN, GridLab, TNC, Sierra Club, CETI, OCT, UCS, EDF, CATF, BPC, Third Way, Princeton University, Breakthrough Energy, Inter-American Development Bank, DOE, NREL, RAP

EVOLVED
ENERGY
RESEARCH

Emissions targets, scenarios, and pathways

What’s the point of emissions targets?

EVOLVED
ENERGY
RESEARCH

- **Main Quest: Save the planet from the worst effects of global warming**
  - Emissions targets are usually tied with projected climate scenarios and their associated impacts
    - Ideally <1.5°C but will be higher
- **Side Quest(s): Conscious or unconscious priorities**
  - Create a blueprint for others to follow? Global problem doesn’t end with isolated local reductions
  - Drive down cost curves with early technology adoption? Make it easier for others to follow
  - Local policy priorities such as equity and inclusion, jobs growth and economic development, air quality improvements, budget controls etc.
- **In the US, target setting and planning for emissions reductions is democratic and heavily influenced by stakeholders with diverse interests**

What's the role of energy and emissions modeling in meeting emissions targets?

EVOLVED
ENERGY
RESEARCH

- **Everything is connected**
  - Economy-wide emissions target: Taking an action to reduce emissions in one part of the economy means doing less in another
- **We know something more about the future**
  - The future is still highly uncertain, but we often now know our goal and it puts us on a different planning time horizon
- **What is the most useful information we can provide decisionmakers and stakeholders to help achieve emissions/energy targets?**

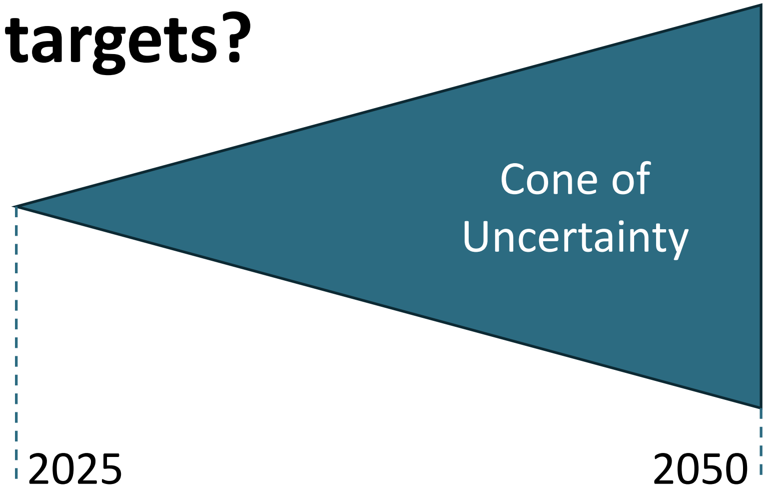
Illuminate the big picture

- **Often people know a lot about one part of a problem and less about another**
  - Transport people know transportation, electricity people know electricity etc.
- **Help them understand the tradeoffs**
  - Roadblocks are present everywhere in changing the energy economy
  - Understand cause & effect of finding solutions:
    - "If we don't electrify/decarbonize in sector x, sector y will have to take on more of the burden"
    - Is that easier/harder/less expensive/more expensive?
- **Understanding can help stakeholders buy into an energy/emissions plan**

Understand our limitations

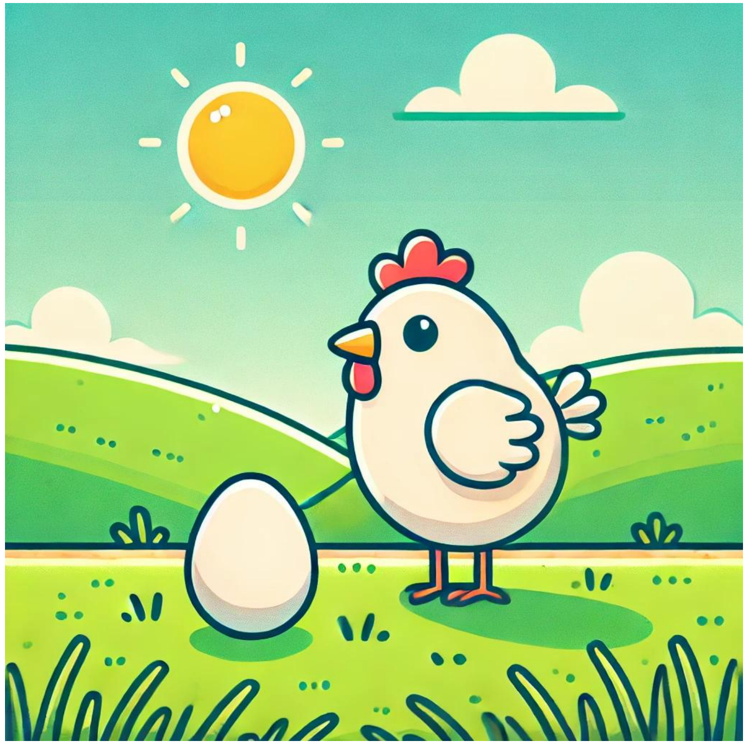
- **Models are a balance between available computation, mathematical representation, and realism**
  - Tailor models to suit the problem to best use available resources
  - Life is messy, what is most useful in a complex world of cooperation between groups with differing priorities?
- **The Cone of Uncertainty**
  - Today we know what the price of things is, how much energy we use, and our emissions (simplifying here for the sake of the Cone)
  - Tomorrow, 3 years from now, a decade, these things become more and more uncertain
  - Do the most with what we have today and recognize that plans must be updated with new information (we don't even know the technologies that will exist in 20 years)

What are the actions we can take in the next year or 3 years that minimize cost and risk but put us on the path to emissions targets?



Pathways to emissions targets

- **Proactive rather than reactive planning**
  - Long timescales with changing conditions (emissions caps, costs, etc.)
  - Investments, structural changes need sufficient time for development and sufficient value over their lifetimes
  - What portfolios of solutions work together to achieve targets while satisfying economic and policy priorities?
  - What needs to come first to make everything else possible?



- **How might future decisions be impacted by different policy priorities or uncertain outcomes?**
- **Test different scenarios on how the future will play out**
  - Near-term decision making in the context of long-term planning: What do different pathways teach us about what to do right now?

Why use scenario planning?

- **Scenarios explore different future worlds by making assumptions about how things play out, including:**
  - Controllable things: Policies such as emissions targets, clean energy targets, incentives, market structures, siting and permitting processes…
  - Uncontrollable things: How customers respond to policies, technological development and costs, climate impacts…
- **Whether something is controllable depends on:**
  - Timing: For example, market structures are set in the near-term, but become a lever to pull in the long-term
  - Planning authority: Who is doing the planning and what can they change?

- **Scenarios are often designed to span a range of uncertain outcomes and represent different policy priorities to provide information about costs and tradeoffs**

Scenario Example: Oregon State Energy Strategy
What If scenarios and assumptions

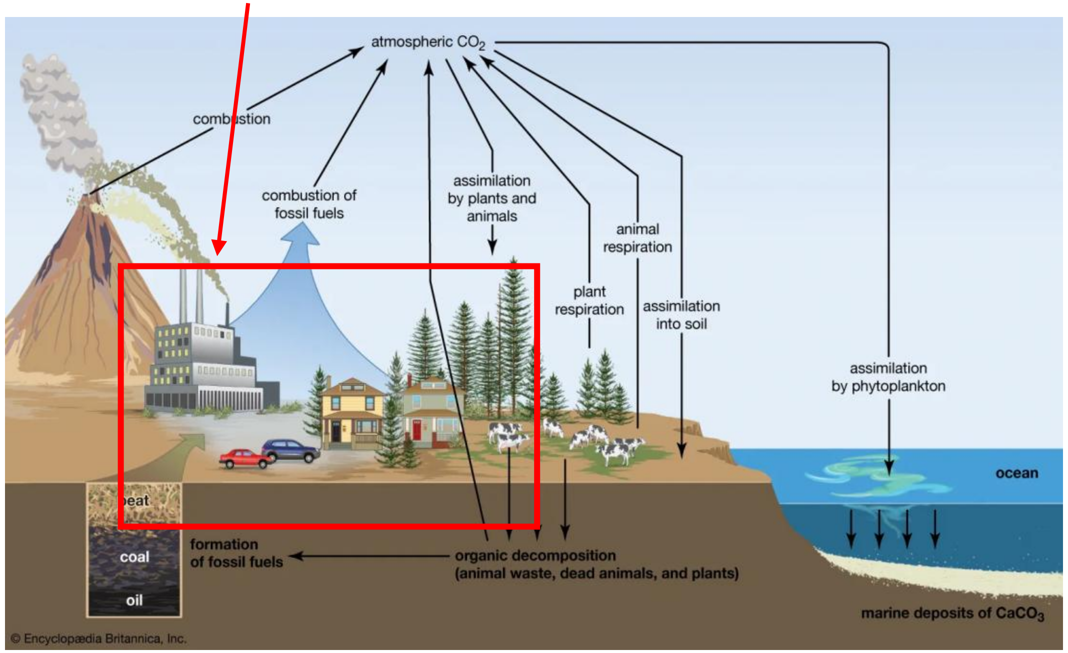
Reference. Least-cost way to achieve goals. All other scenarios build on the Reference by changing a key area:

1. What if energy efficiency and building electrification is delayed by 10 years?
2. What if full transportation electrification of medium- and heavy-duty vehicles is delayed 10 years, from 2040 to 2050?
3. What if there is limited demand response participation?
4. What if there is limited utility-scale electricity generation in Oregon?
5. What if there are higher levels of rooftop solar and behind-the-meter storage and transmission is limited to reconductoring only (no new build)?
6. What might an alternative portfolio of flexible resources for electricity reliability look like?

Challenges of emissions accounting & target setting

- **Local emissions contribute to global problem**
  - No direct link between local actions and local benefits of CO2 reductions (though PM2.5 and other pollutants reduced at the same time)
  - If it costs something, it is driven by recognition of its importance and trust in action taken elsewhere
- **Who is doing the planning, what can they change?**
  - Has a big impact on what targets are and how they are met
  - Larger planning areas more economically efficient

Only some of this exists in the jurisdiction of a given policymaker



© Encyclopædia Britannica, Inc.

- **Emissions accounting: What can be measured, and accounting philosophy impacts emissions reduction options**
  - Responsible for emissions reductions from sources within a geographical boundary or by consumption?
  - Anthropogenic emissions only, or including land sink?

Examples of challenges (1)

- **Emissions accounting within geographic boundaries versus consumption-based emissions**
  - Holes in accounting because imported emissions are not tracked
  - Distorting incentives to rely more on imports
- **Counting natural emissions land sink**
  - If counting land sink, states with large land sinks need take little action even though low hanging fruit exists, while states with little land sink must rely on higher cost measures
  - States often choose not to count land sink but sometimes count incremental land sink measures that can offset anthropogenic emissions
- **Unbundled renewable energy credits (RECs) in an uneven policy landscape**
  - If a state requires bundled RECs, resources local to that state are needed to meet policy targets. What if there are cheaper resources elsewhere?
  - But conversely, renewables are being built economically even in states without binding policy. Taking an unbundled REC from those resources is then an accounting trick that doesn't lower emissions
- **Leakage of fossil power emissions**
  - Example: Coal electricity previously delivered to a state with targets may find new markets elsewhere, displacing cleaner power sources

Examples of challenges (2)

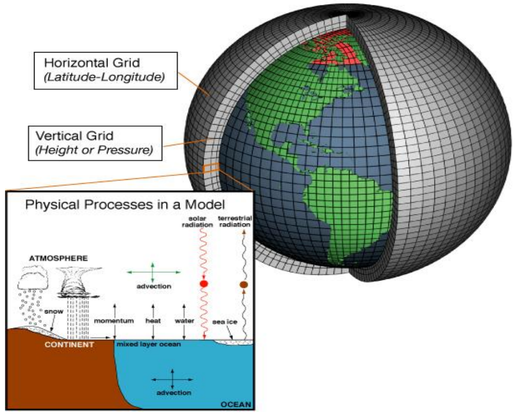
- **Emissions in the supply chains of products we use (scope 3 emissions)**
  - State accounting for scope 1 and 2 consumption-based emissions have a hole in their accounting
    - Potentially leads to distortions: Expensive investments in clean fuels, in-state industrial decarbonization etc., while still using products produced with coal
  - Without protections from competition with unregulated industry, how much can industrial emissions be controlled?
- **Unfairness, difference in local economies including difficulty of decarbonizing some sectors**
  - Example: States with large agricultural sectors
- **Bunkering credit**
  - Example: Newark Airport – international jet fuel use not on New Jersey ledger. Where is it controlled?

- **Overarching theme: Lack of control**
  - ***More expensive pathways to emissions reductions than larger regions that can see more low hanging fruit***
  - ***States are currently the centers of power for emissions reductions in the United States. What are the best solutions within this regulatory framework?***

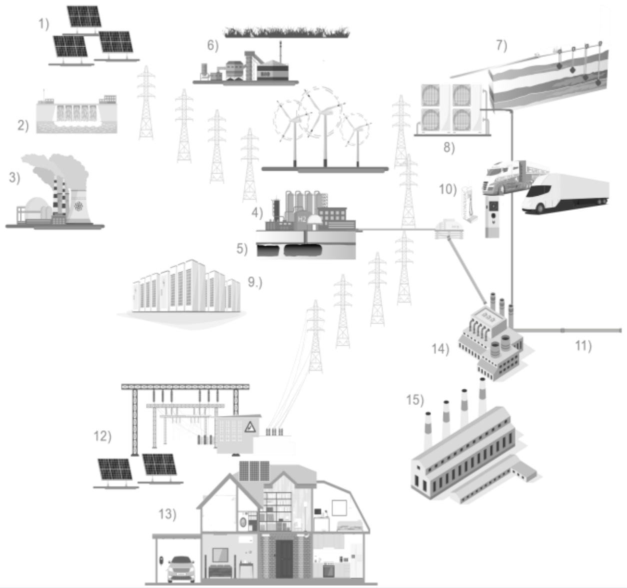
What is energy modeling?

Modeling basics

- Representation of a system, process or phenomenon
- Describes elements and relationships between elements
- Broad types:
  - Analytical: Cause and effect terms, inputs and outputs
  - Mathematical: Quantitative terms to illustrate concepts
- Simulates real environments with conceptual ones, allows for testing hypotheses

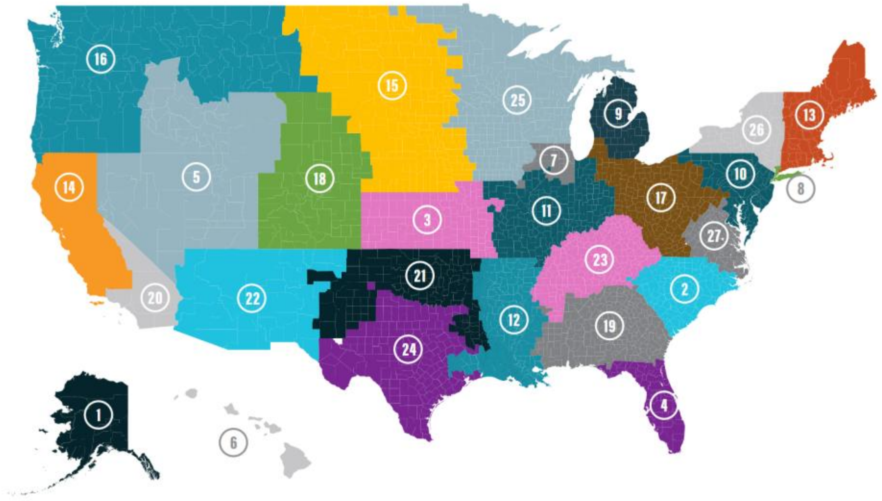


From: NOAA
https://www.climate.gov/maps-data/climate-data-primer/predicting-climate/climate-models

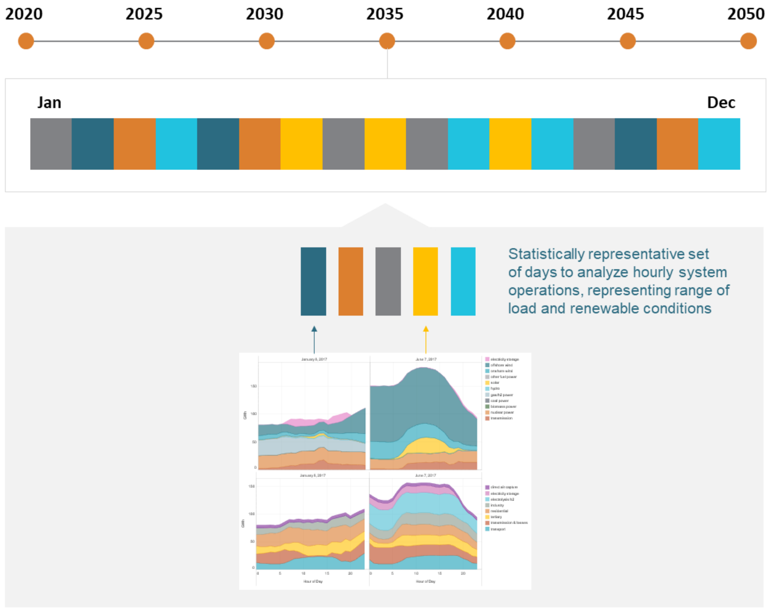


Model dimensions

- Geography
  - ○ Boundaries
  - ○ Granularity

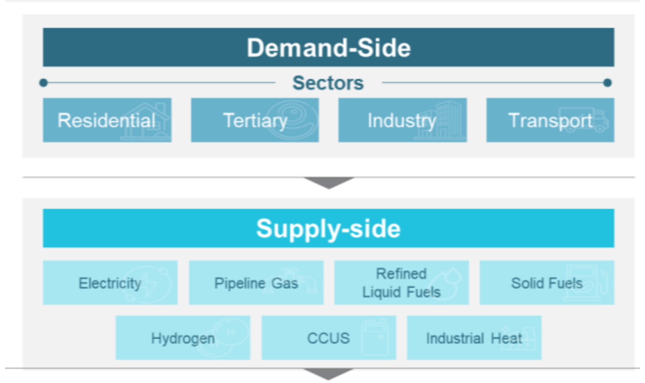


- Time
  - ○ Time period
  - ○ Granularity



Statistically representative set of days to analyze hourly system operations, representing range of load and renewable conditions

- Sector
  - ○ Single or multi-sector
  - ○ Sectoral granularity
  - ○ Technology detail



Demand-Side

Sectors

Residential | Tertiary | Industry | Transport

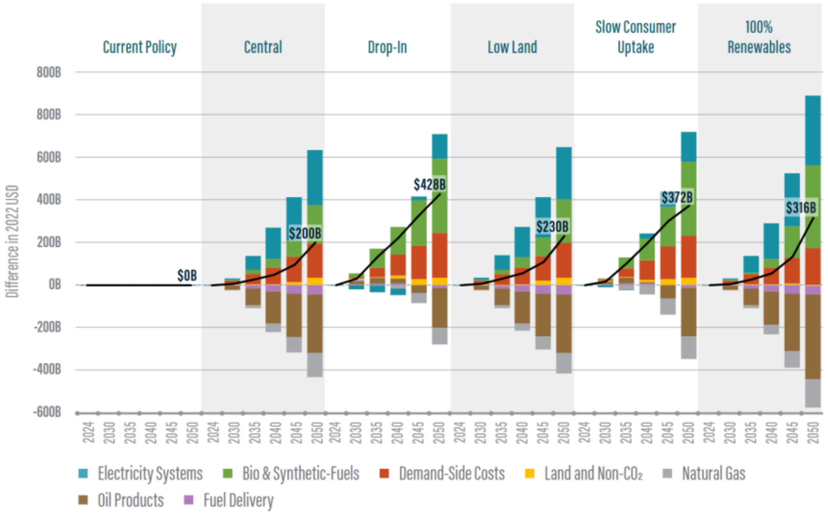
Supply-side

Electricity | Pipeline Gas | Refined Liquid Fuels | Solid Fuels

Hydrogen | CCUS | Industrial Heat

Model dimensions

- Cost
  - System-wide
  - Marginal
  - Unit of commodity (ex. $/kWh)
  - Cost to customer



- Additional Quantities
  - Money/item price (ex. cost of EV)
  - Emissions
  - Spatial or physical aspects

FIGURE 40. Downscaled wind and solar in 2050 for the 100% Renewables scenario

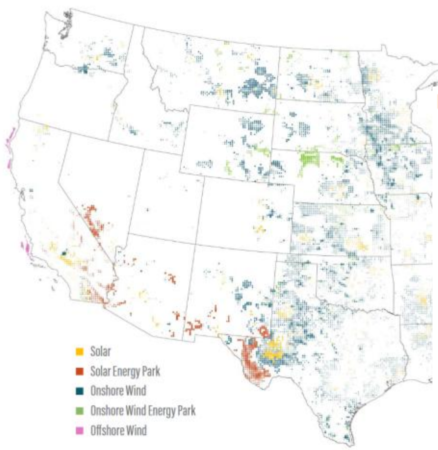
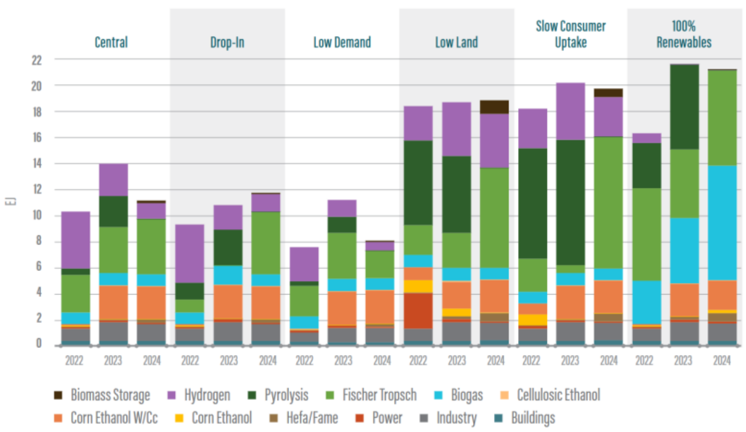


FIGURE 49. Biomass use by type in 2050 across scenarios in ADP 2022, ADP 2023, and ADP 2024

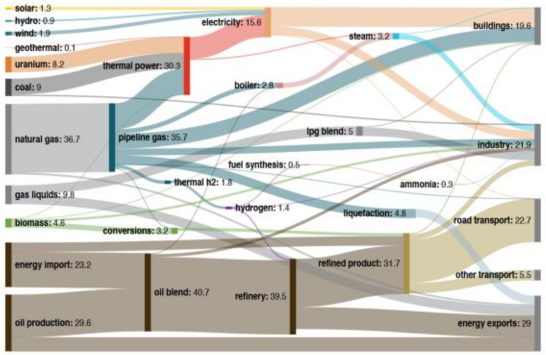


Model methods in energy analysis

- **Accounting:**
  - Energy balance
  - Emissions
  - Stock and flow of physical quantities (e.g. infrastructure, resources)
  - Net costs

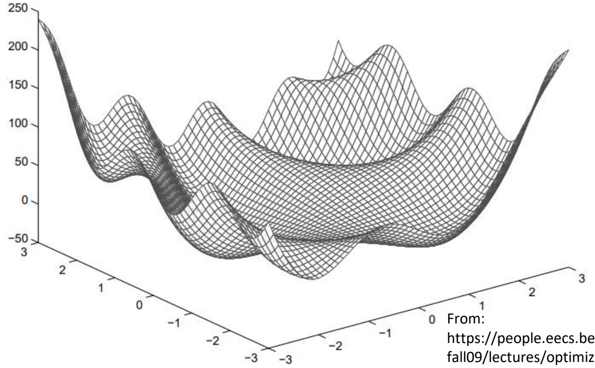
"What goes where in a given system and how do quantities interact"

FIGURE 20. Sankey Diagram for 2024 (Exajoules)



- **Optimization:**
  - Objective function (e.g. minimize cost)
  - Constraints (e.g. must meet emissions limit in each year)
  - Boundary conditions (e.g. constant or changing imports or exports)

"Given these constraints and this desired objective, which course is best"



From: https://people.eecs.berkeley.edu/~jordan/courses/294-fall09/lectures/optimization/slides.pdf

Energy related model types

Energy is parameter but not the focus

- **Environmental** [climate models, air quality, environmental site impacts]
- **Macroeconomic** [computable general equilibrium, input/output, econometric]
- **Integrated Assessment (IAM)** [combination of sub-models: earth, energy, climate, economic]

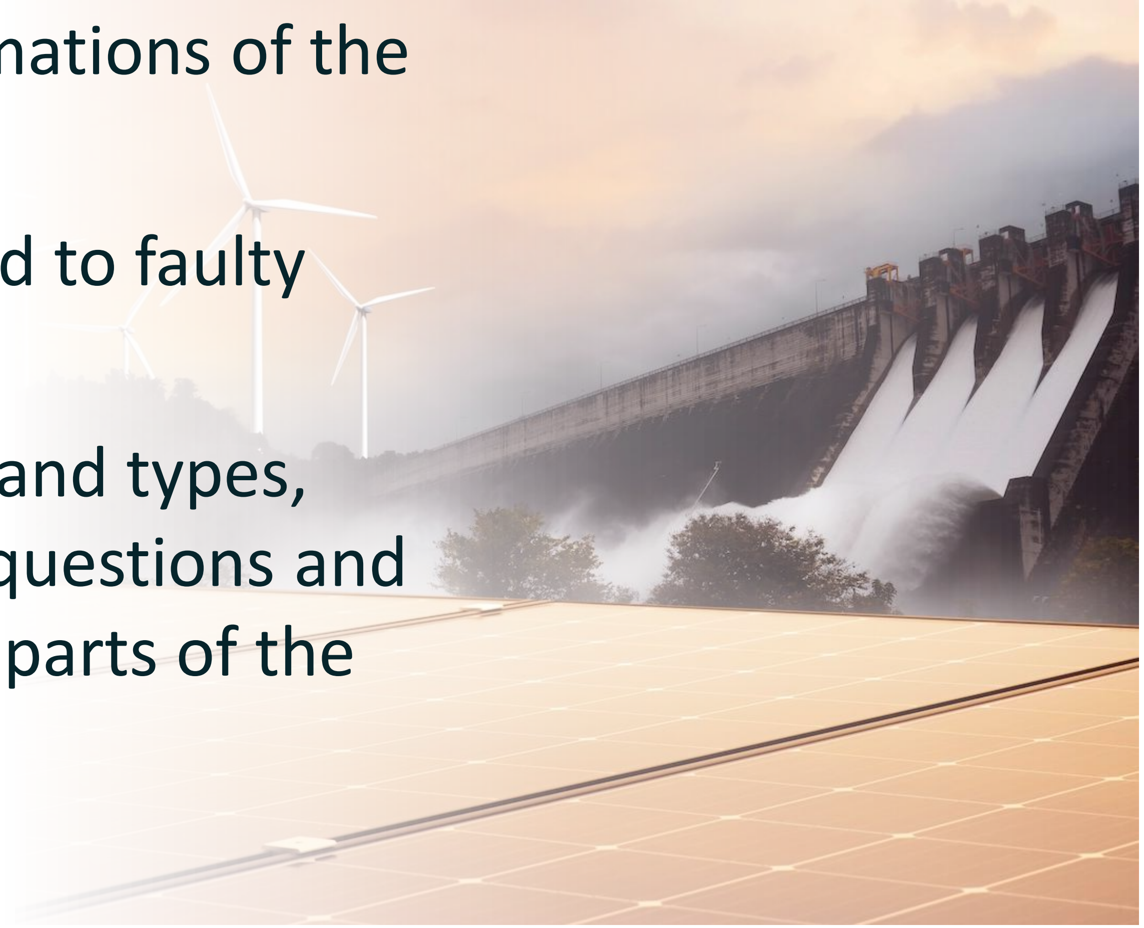
Energy is the focus

- **Energy System** [energy flows between coupled sectors]
- **Capacity Expansion** [optimal long-term generation and transmission investment]
- **Electricity System Reliability** [power flow and fault protection models]
- **Electricity System Cost – Operations** [production cost models and dispatching]

Engineering is the focus

- **Electricity System Cost – Planning** [load forecasting, utility investment decisions]
- **Scientific/Engineering Device Model** [physical performance models]
- **Engineering Control Model** [monitor and design for control equipment]

Nature of modeling



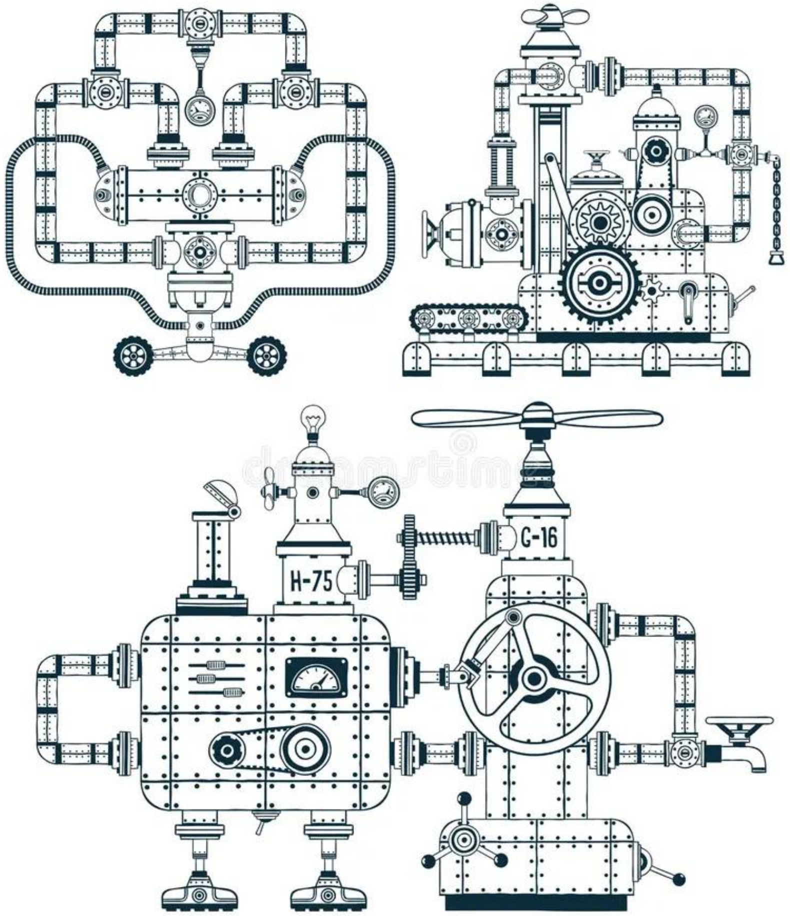
- Model representations are approximations of the real world, not replications
- Failure to acknowledge this may lead to faulty results or justified skepticism
- Energy modeling takes many forms and types, answering fundamentally different questions and having applications within different parts of the system.

EVOLVED
ENERGY
RESEARCH

Planning and modeling challenges with clean energy and emissions targets

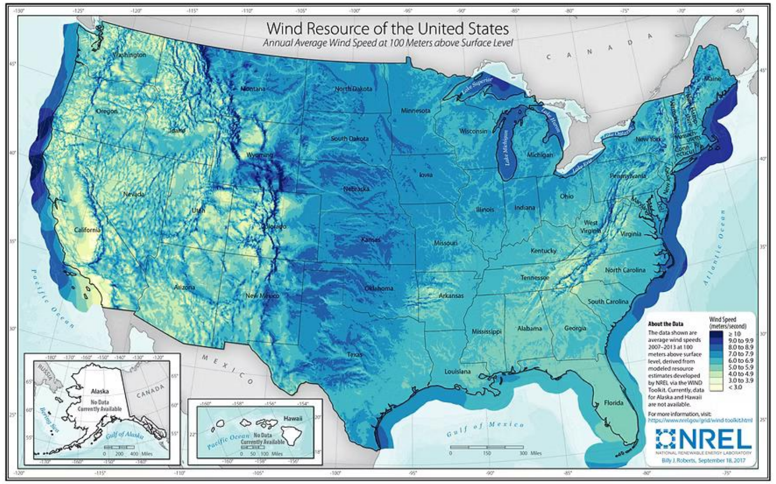
The energy system as a machine

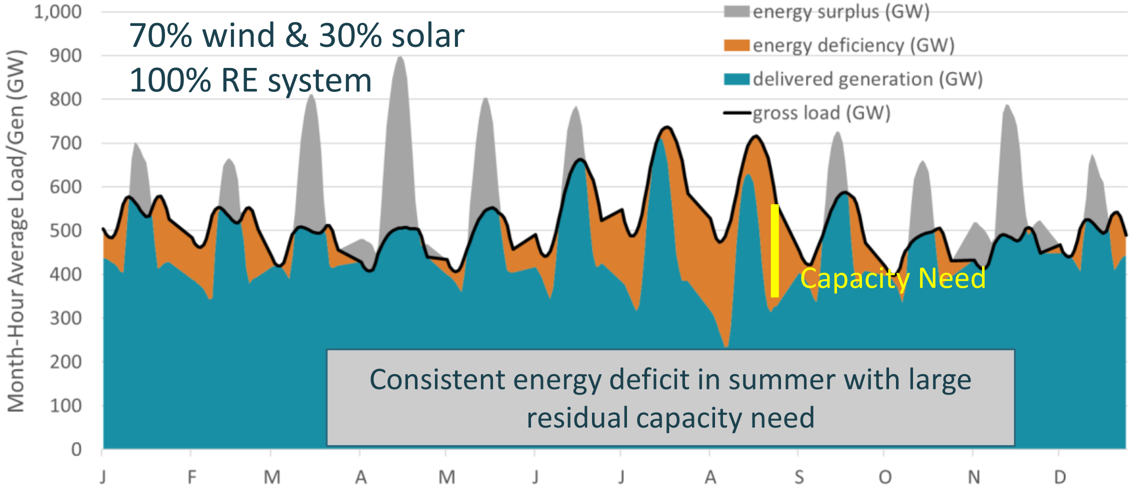
- Every change to one part of the system has knock on effects in other areas
- Changing a part requires planning for other parts as well
- Historically planning and analysis has been siloed to sectors or industries
    - Cross sectoral opportunities becoming more pronounced as solutions
- Both the supply and demand of energy are part of this ‘machine’
    - Load growth previously considered something that ‘happens to us’ as planners but potentially a controllable part of the solution in the future



Planning with renewables: challenges

- Renewables have certain characteristics that make them particularly difficult to manage in the context of today's electricity system
    - **Variability** – output is not controllable and can change rapidly
    - **Uncertainty** – future output can be difficult to predict
    - **New locations** – deployment in locations not anticipated when the grid was built
    - **Inverters vs. synchronous motors** – technical character of inverters are different



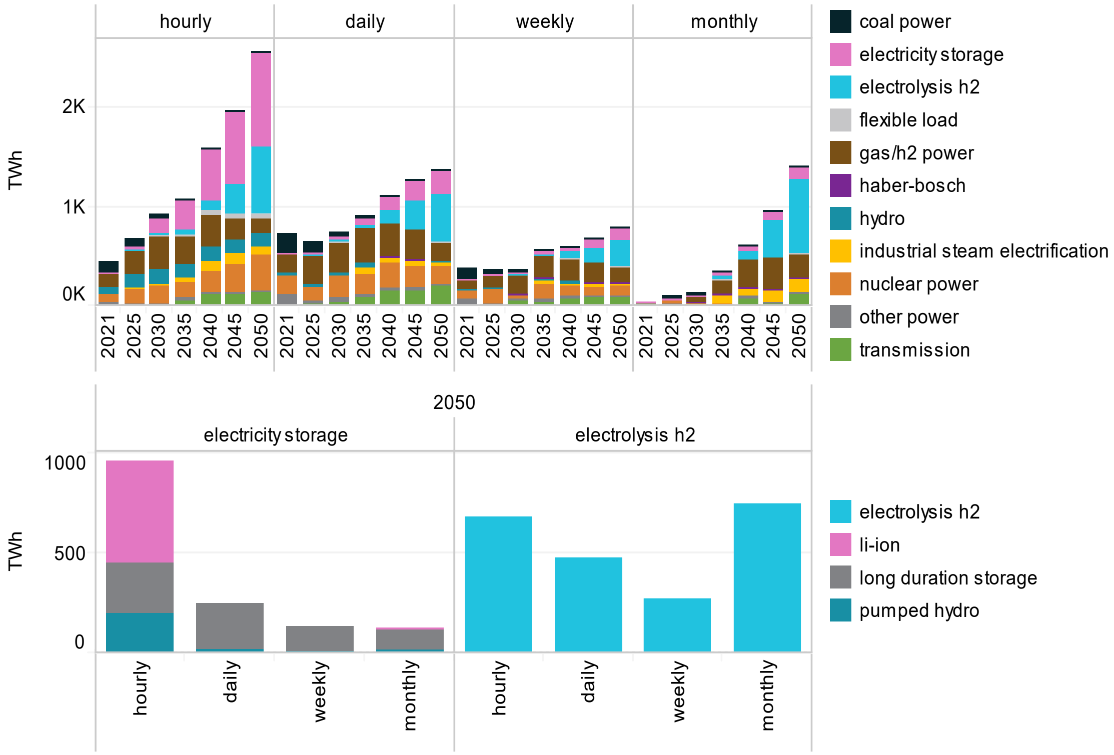


70% wind & 30% solar
100% RE system

Consistent energy deficit in summer with large residual capacity need

With renewable uncertainty and intermittency

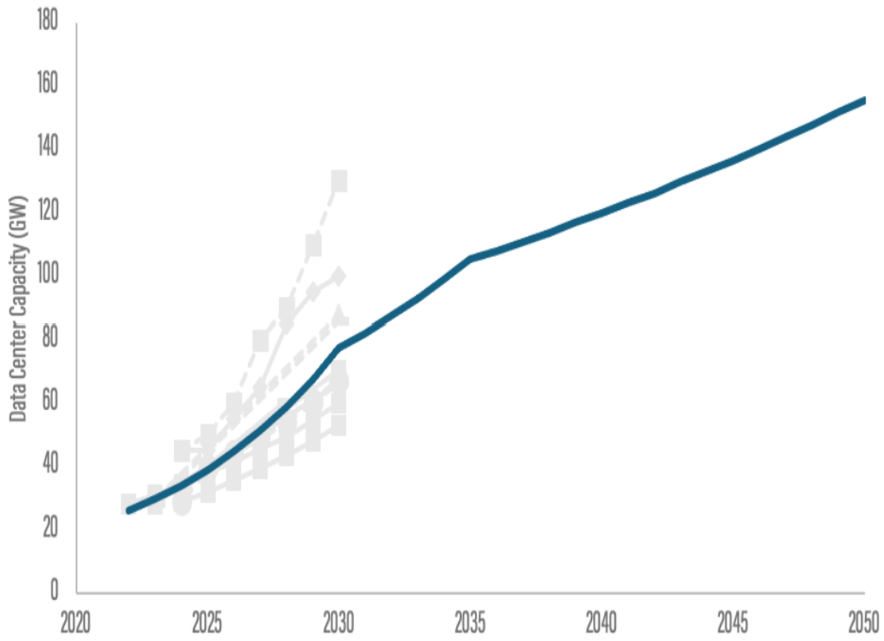
- Storage, transmission expansion, flexible load, and renewable curtailment are each best for solving certain types of balancing problems
  - Using storage alone is prohibitively expensive
  - Using transmission alone won't solve interconnection level problems
  - Using flexible load alone may degrade service
  - Some renewable curtailment is rational but using it alone is inefficient
- Portfolio approach to planning



Load growth and reliability

- Not only does supply contain uncertainty but often so does the demand in future pathways
- Electrification and exogenous growth like data center expansion require more energy infrastructure and supply
    - These loads often demand high reliability and have high *capacity factors* (facilities are running near constantly) but have less certainty on where they will be located.
    - There are fundamental planning differences between 500MW of demand from 75k EVs vs. 1 large data center
- State decarbonization goals may clash with economic growth programs if not managed properly, public purpose vs. private gain

National Data Center Capacity Projections.



Note. *The grey lines represent different estimates from literature; the blue line represents the median estimate compiled by EER and extrapolated through 2050.*

Solutions under uncertainty

- Scenario analysis:
  - **"When we pull certain levers how do the outcomes and impacts change? How do different changes affect our end goal?"**
- Forecasting:
  - **"What do we think is likely to happen and, given that, what should we do about it?"**
- Proactive planning:
  - **"What do we want to happen and, given that, what should we do about it?"**

Decarbonizing the economy

- Under an economy-wide emissions target, solutions can come from all sectors, gases, and supply chains
- What is cheapest?
- Pathways are a growing portfolio of different solutions
  - Path dependency
  - Increasing integration between traditionally siloed parts of the economy
- Need tools that can evaluate all these things together to give realistic guidance to decisionmakers/policymakers

Evolved’s modeling approach

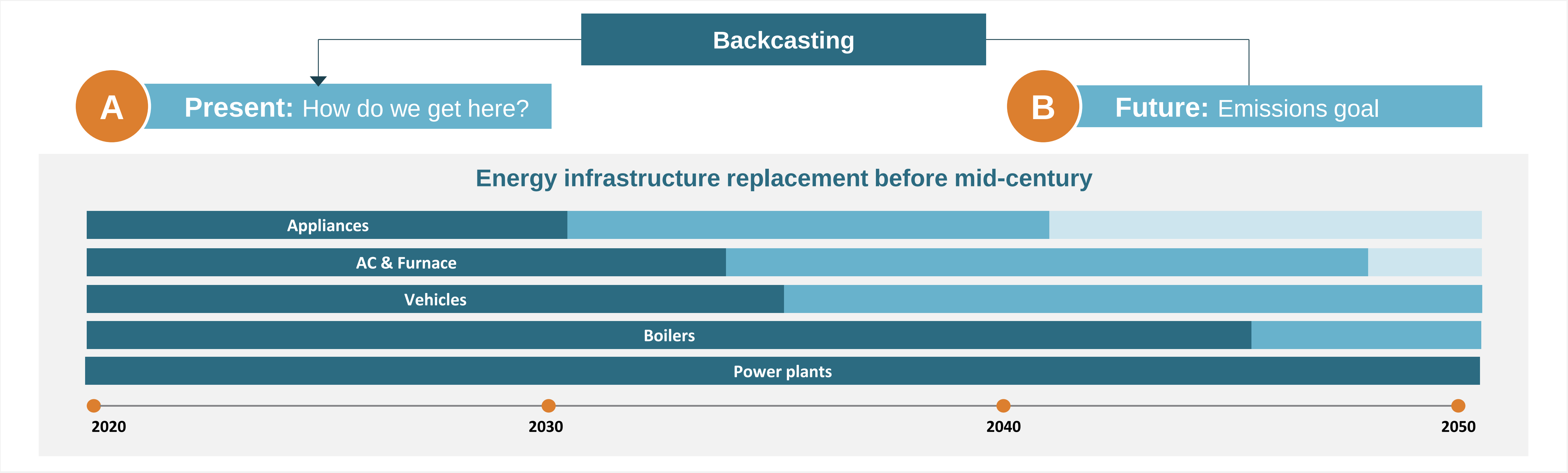
Energy systems modeling: Backcasting

Backcasting:
start with the end-goal and work backwards to understand implications

Shift to a low-carbon economy requires clarity on infrastructure needs

Large energy projects have long lead times and lifespans

Pathways demonstrate the long-term emissions and cost implications of energy infrastructure investments



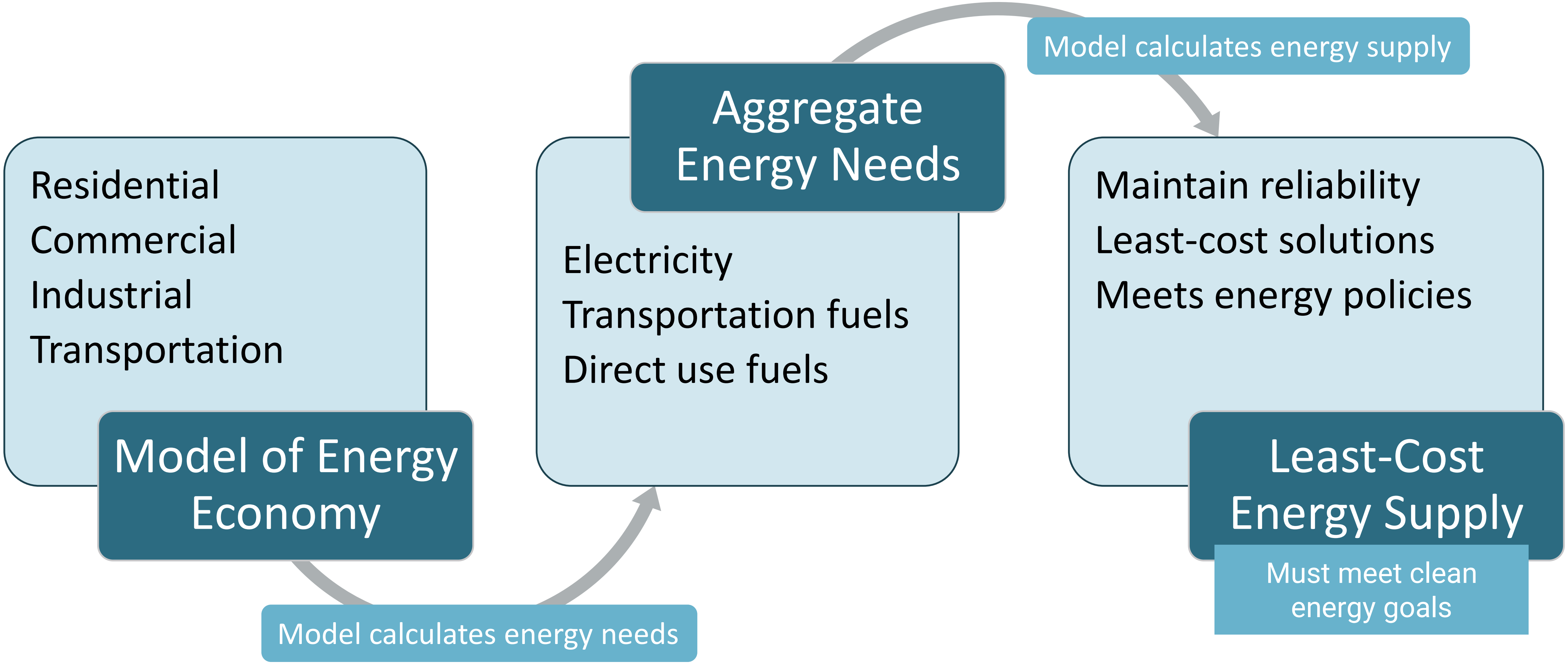
Backcasting

A **Present:** How do we get here?

B **Future:** Emissions goal

Energy infrastructure replacement before mid-century

Overview of Modeling Approach



Residential
Commercial
Industrial
Transportation

Model of Energy Economy

Model calculates energy needs

Aggregate Energy Needs

Electricity
Transportation fuels
Direct use fuels

Model calculates energy supply

Maintain reliability
Least-cost solutions
Meets energy policies

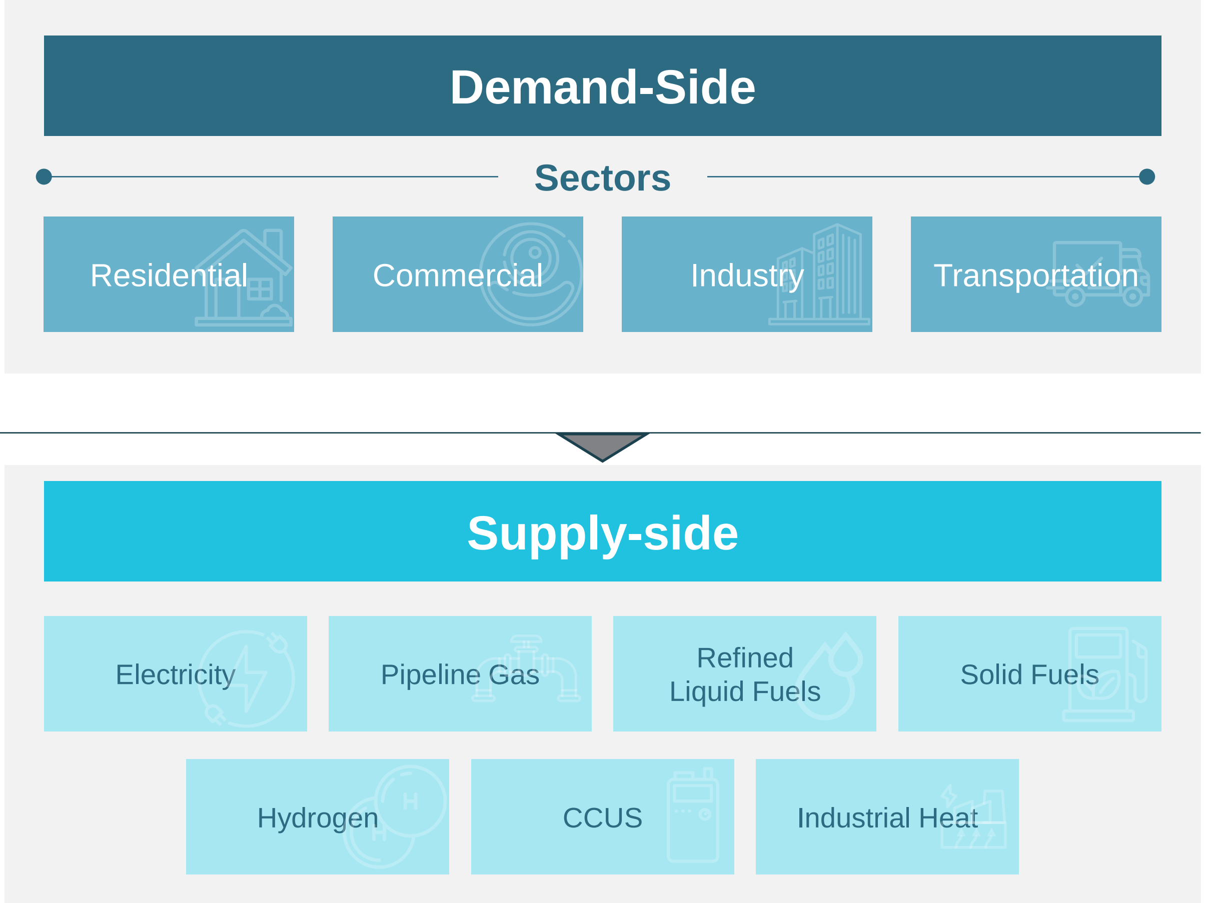
Least-Cost Energy Supply

Must meet clean energy goals

Energy systems modeling: high-level approach

EnergyPATHWAYS model used to develop demand-side cases

- Apply fuel switching and energy efficiency levers
- Strategies vary by end-use (residential space heating to heavy-duty trucks)



Demand-Side

Sectors

Residential | Commercial | Industry | Transportation

Supply-side

Electricity | Pipeline Gas | Refined Liquid Fuels | Solid Fuels

Hydrogen | CCUS | Industrial Heat

Regional Investment and Operations (RIO)

- Model provides cost-optimal energy supply combining a comprehensive supply-side capacity expansion framework with hourly system operations

Demand-side modeling

- Scenario-based, bottom-up energy model (not optimization-based)
- Simulates the change in total energy demand and load shape for every end-use
- Characterizes rollover of stock over time
- Illustration of model inputs and outputs for light-duty vehicles

ENERGY PATHWAYS

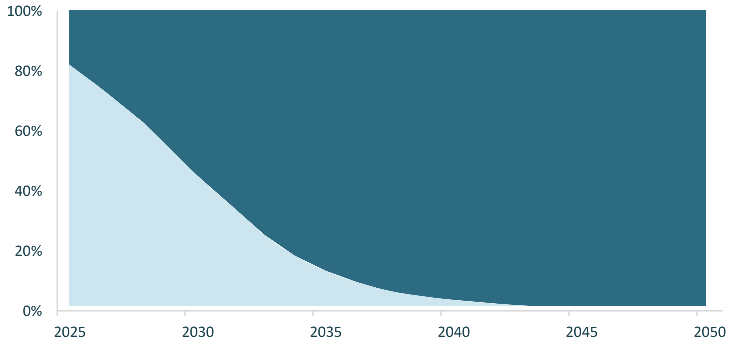
Input: Consumer Adoption
EV sales are 100% of consumer adoption by 2045 and thereafter

Output: Vehicle Stock
Stocks turn-over as vehicles age and retire

Output: Energy Demand
EV drive-train efficiency results in a drop in final-energy demand

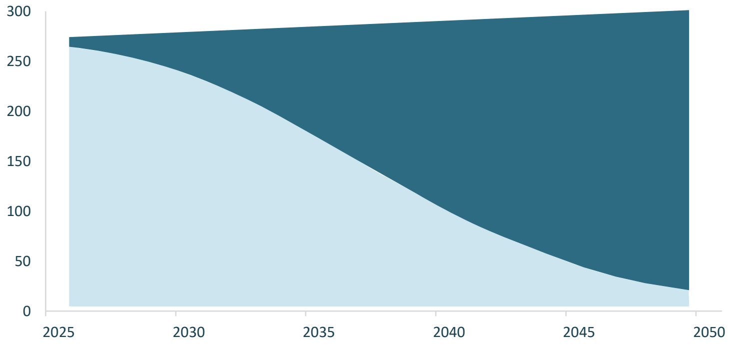
Sales Share

%



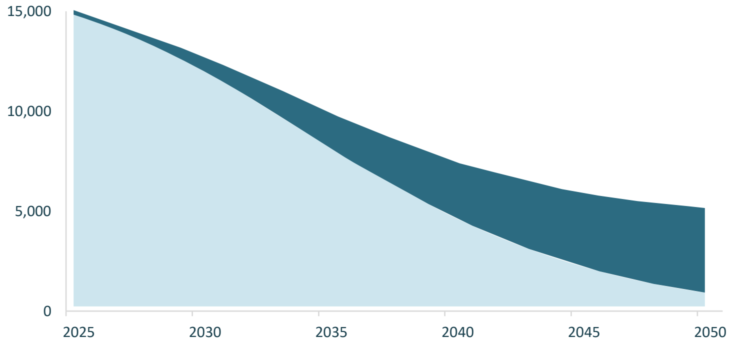
Stock

Vehicles on the road



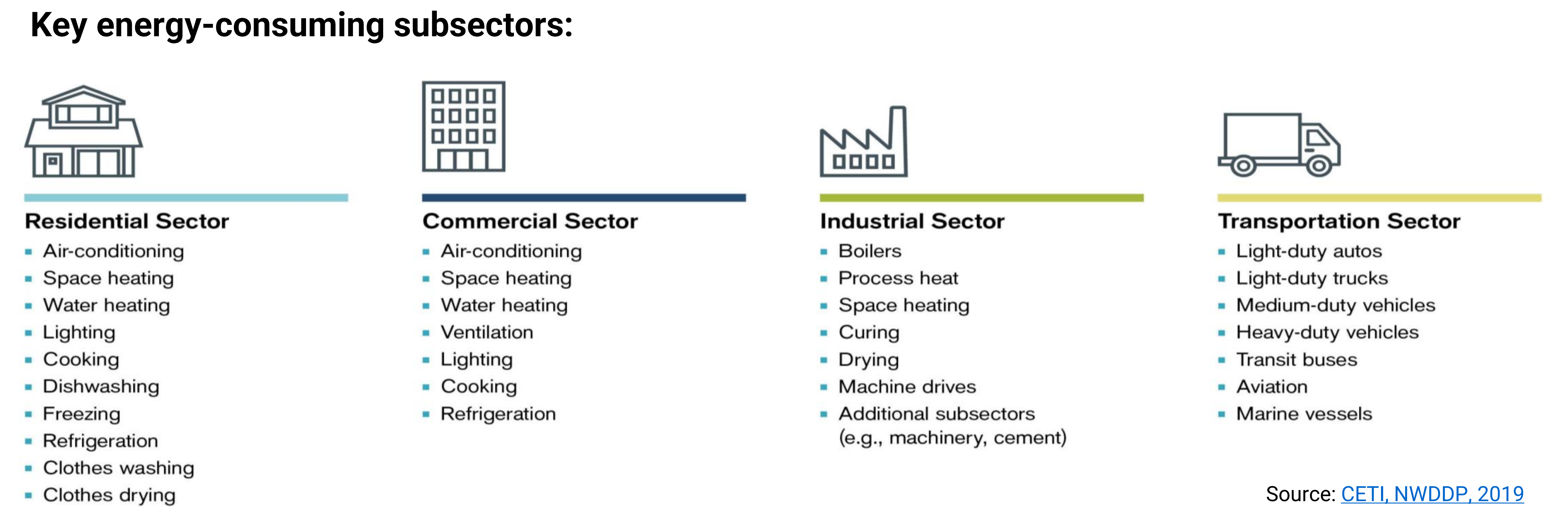
Energy Demand

TBtu



End-use sectors modeled

- Approximately 70 demand sub-sectors represented
- The major energy consuming sub-sectors are listed below:



Key energy-consuming subsectors:

Residential Sector
- Air-conditioning
- Space heating
- Water heating
- Lighting
- Cooking
- Dishwashing
- Freezing
- Refrigeration
- Clothes washing
- Clothes drying

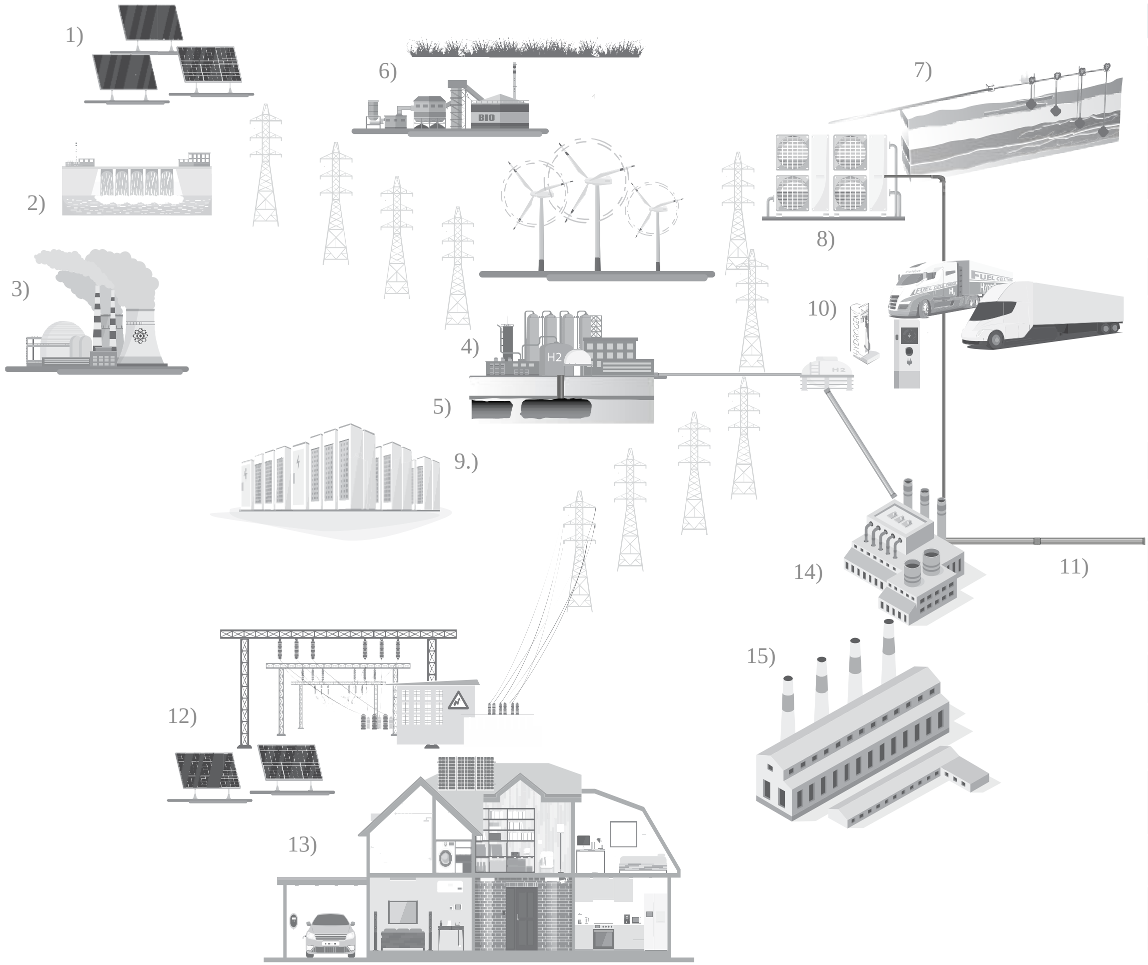
Commercial Sector
- Air-conditioning
- Space heating
- Water heating
- Ventilation
- Lighting
- Cooking
- Refrigeration

Industrial Sector
- Boilers
- Process heat
- Space heating
- Curing
- Drying
- Machine drives
- Additional subsectors (e.g., machinery, cement)

Transportation Sector
- Light-duty autos
- Light-duty trucks
- Medium-duty vehicles
- Heavy-duty vehicles
- Transit buses
- Aviation
- Marine vessels

Source: CETI, NWDDP, 2019

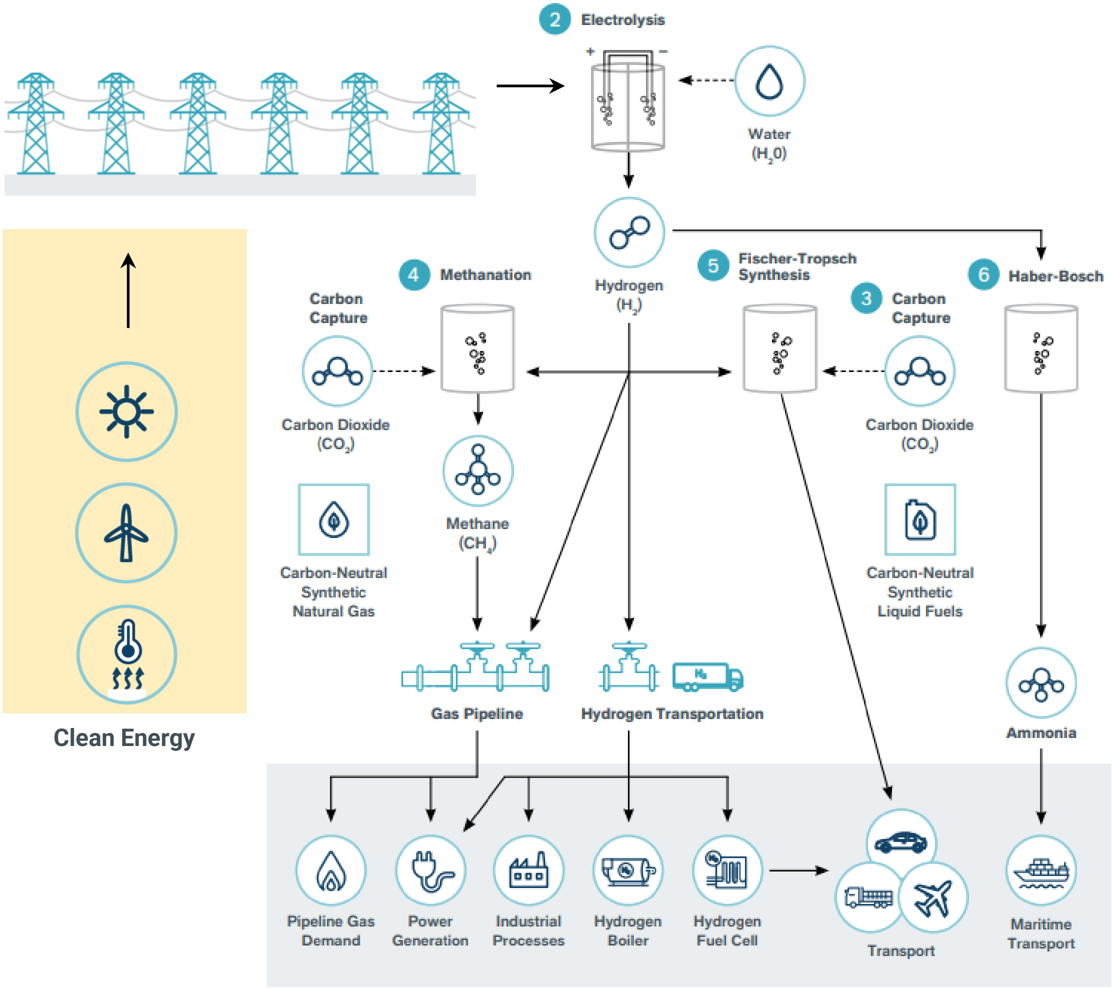
Economy-Wide Optimization Scope



	Resource Categories	Examples
1.	Utility-Scale Renewables	Solar PV, Onshore Wind, Offshore Wind, Geothermal
2.	Dispatchable Hydroelectric	Reservoir hydro, On-Stream Pumped Hydro
3.	Thermal Power Plants	Gas CT, Gas CCGT, Coal, Coal w/CC, Gas w/;CC, Gas w/CC (Allam), SMR, Gen IV nuclear, Biomass, Biomass w/CC, Biomass w/CC (Allam), Gas and Coal CC retrofits
4.	Hydrogen Production	Electrolysis, BECCS H2, SMR, SMR w/CC, High-Temp Electrolysis, ATR w/CC
5.	Hydrogen Storage	Aboveground tanks, underground pipes, salt cavern storage
6.	Biomass/Biomass Conversion	Biomass supply curves including existing woody and waste resources, new woody/herbaceous/waste resources, corn ethanol land displacement, anaerobic digestion feedstocks (LFG, water resource recovery facilities, food waste, animal manure). Conversion technologies including Fischer-Tropsch, pyrolysis, BECCS H2, cellulosic ethanol, corn ethanol, and biochar.
7.	Geologic Sequestration	EOR, onshore saline, offshore saline
8.	Direct Air Capture	DAC for synthetic hydrocarbon production (e-fuels), DAC for geologic sequestration
9.	Electricity Storage	Li-Ion, Flow batteries, long duration energy storage (LDES), pumped hydro, thermal storage
10.	Zero Emission Vehicles	Light-duty, medium-duty, heavy-duty, and bus vehicle types
11.	Pipelines	Ammonia, hydrogen, CO_2
12.	Electric T&D Infrastructure	Distribution upgrades, generator interties, existing corridor upgrades, new AC and DC corridors
13.	Distributed Energy Resources	Flexible end-use loads (EVS, water heating, space heating, air conditioning, appliance loads)
14.	Zero-Carbon Fuel Synthesis	Ammonia, synthetic hydrocarbons (refined and unrefined), methanol
15.	Industrial Decarbonization solutions	Industrial carbon capture, solar thermal heat, dual-fuel boilers, hydrogen

Integrated Supply Side: Electricity and Fuels

- What are the supply side investments that best meet energy demands?
- Conventional means of “balancing” the electricity grid may not be the most economic or meet clean energy goals
- New opportunities: Storage and flexible loads
- Fuels are another form of energy storage
- Large flexible loads from producing decarbonized fuels:
  - Electrolysis, synthetic fuels production



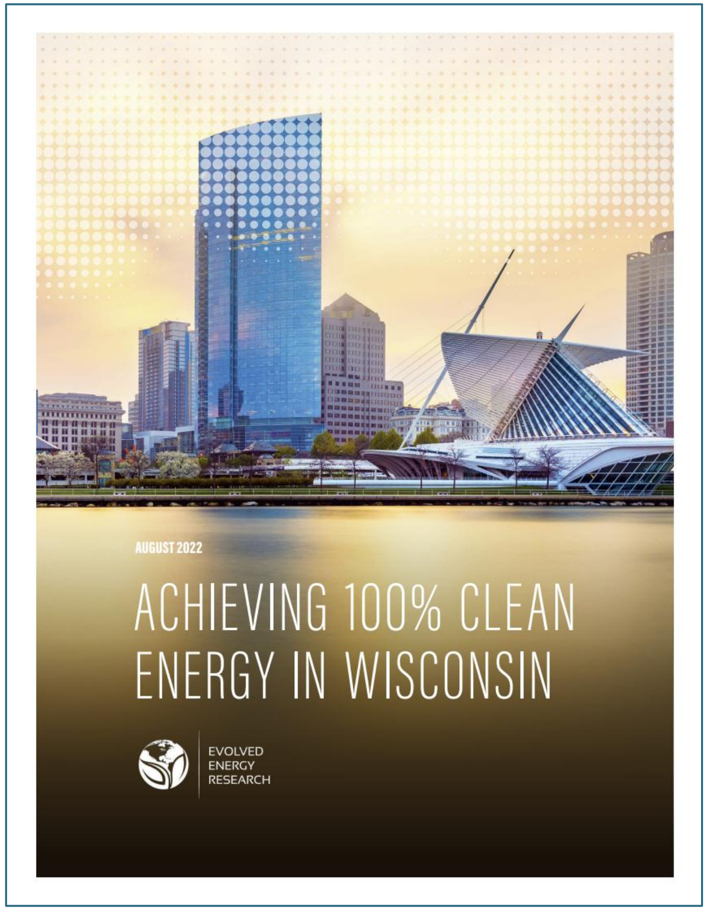
Source: CETI, NZNW, 2023

Why use modeling? Case study

Achieving 100% Clean Energy in Wisconsin

Wisconsin 100% clean energy

- Help RENEW Wisconsin, Clean Wisconsin, and GridLab find near, medium, and long-term pathways to zero carbon electricity
- Economy-wide context
  - Rate of electrification, fuels decarbonization
  - Electricity doesn't exist in a vacuum
- Nation-wide system modeling focused on establishing policy and investment strategy in Wisconsin to inform policymakers



AUGUST 2022

ACHIEVING 100% CLEAN ENERGY IN WISCONSIN

EVOLVED ENERGY RESEARCH

Approach

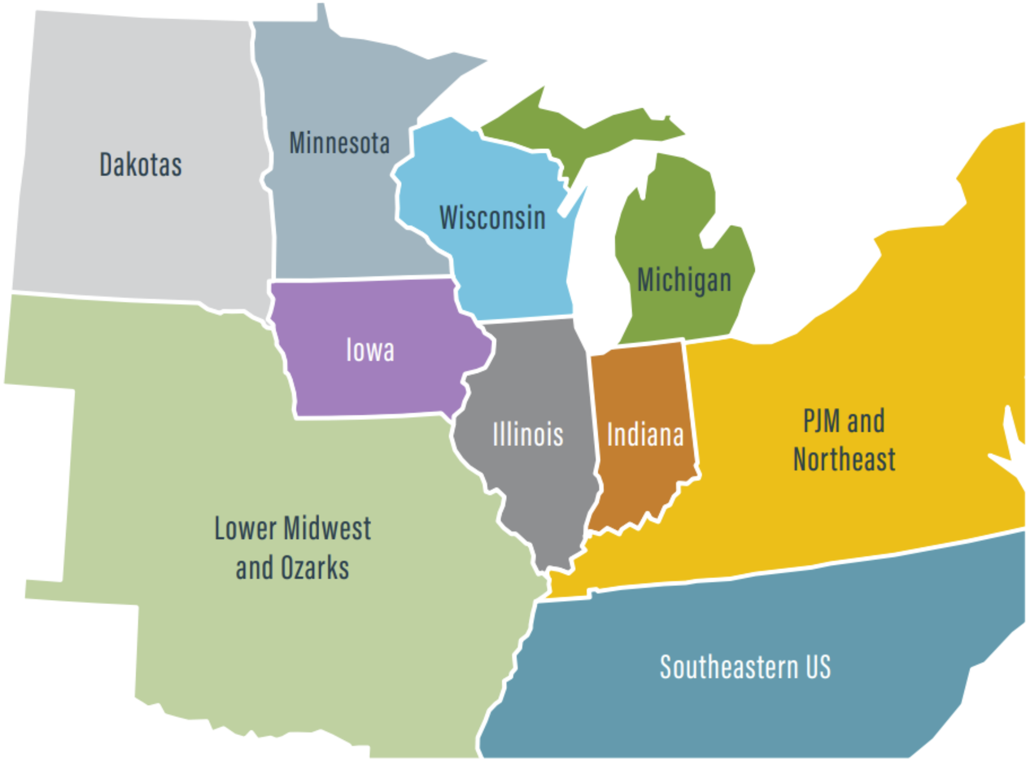
- Ask “what if” questions to investigate the impact of different policies or uncertainties when reaching clean energy goals, e.g.,
  - *What is the cost and feasibility of different policy options?*
  - *What is the impact of different policies/uncertainties on electricity sector investments?*
  - *What are the insights that will help future policy development?*

What Questions Did We Ask?

Scenario	Description	What are we investigating?
Baseline	No electricity or emissions policy, the way we consume energy remains similar to today	Setting a useful point of comparison to other scenarios
100% Clean Electricity	Reaching 100% clean electricity but no economy-wide emissions policy	What is the cost and impact on emissions of taking action only in electricity?
Net Zero Economy-Wide	100% clean electricity and economy-wide emissions policy. Aggressive electrification and efficiency of demand side energy consumption	With all resource options on the table, what is a least cost path to net zero in 2050 and what does the investment strategy look like?
No Tx Expansion	Transmission paths to other states cannot be expanded to access more out of state energy	How impactful is transmission expansion on overall costs and in state investments?
Accelerated Clean Electricity	Economy-wide emissions target and pushing to 100% clean electricity by 2040	How much more would it cost to push to 100% clean electricity faster?
Delayed Action	Delayed demand-side transformation, 15 years slower than Net Zero Economy-Wide	How important is pushing demand-side transformation on overall costs?
Limited Coal and Gas	No new gas, and coal retired by 2030	If near-term policy retired coal and prevented new gas investments what would be the impact?

Model geography: Wisconsin in the regional context

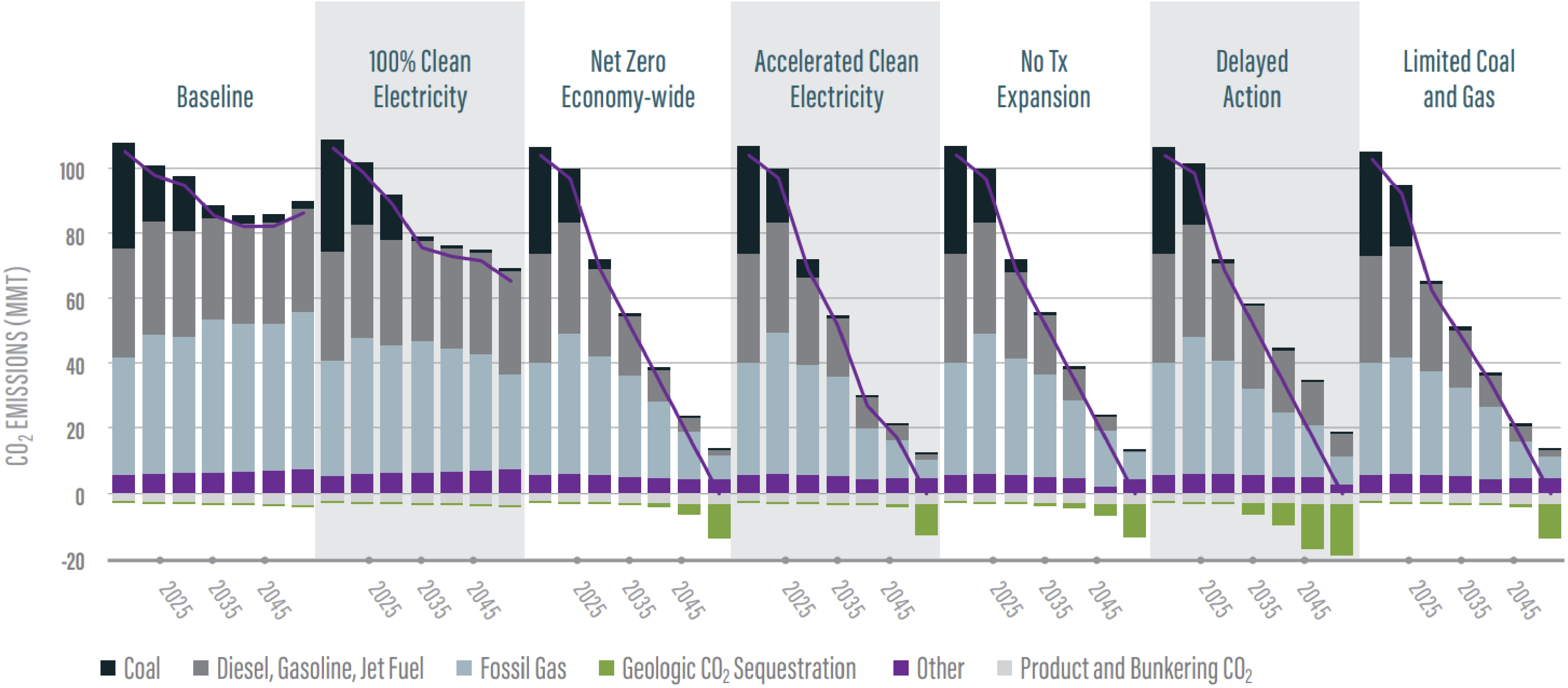
- Wisconsin modeled as part of larger energy system
- All states/regions modeled with their specific energy policies
  - Resource and load diversity
  - Resource competition for Wisconsin
- Transmission between zones modeled with existing transmission capability and the opportunity to expand with an associated cost
- Resource potentials based on screening land use



EVOLVED
ENERGY
RESEARCH

What could Wisconsin 2050 look like?

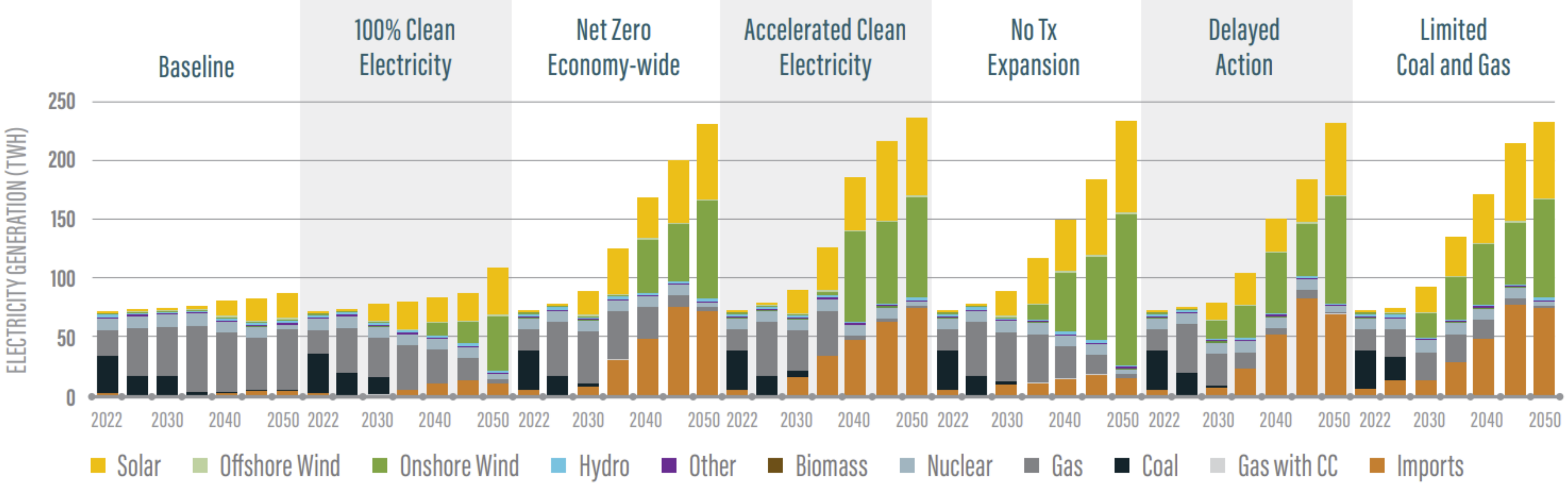
Net zero emissions come from electrification, clean electricity, and geologic sequestration



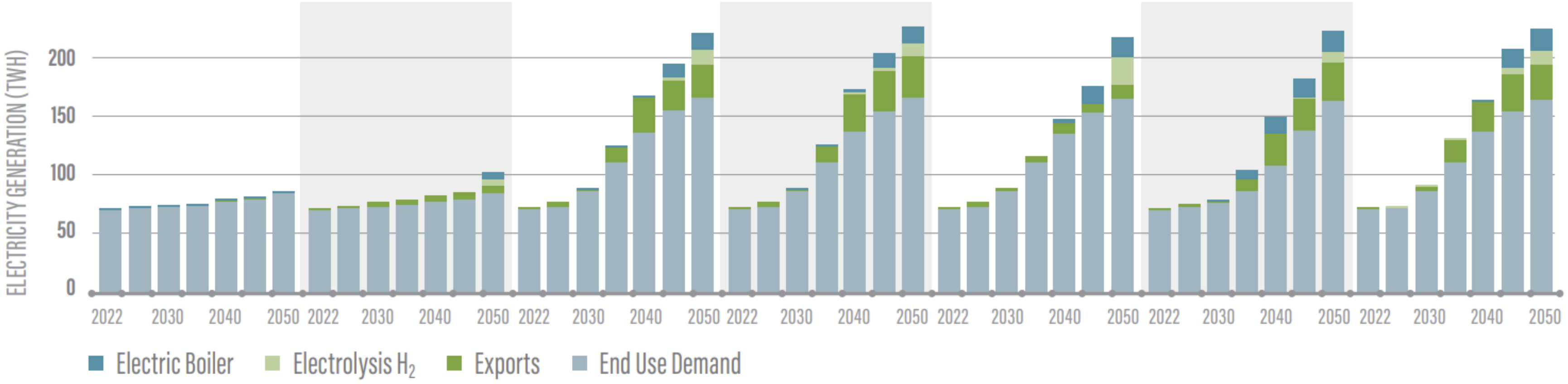
Electricity generation and demand up 160%

EVOLVED
ENERGY
RESEARCH

Electricity generation



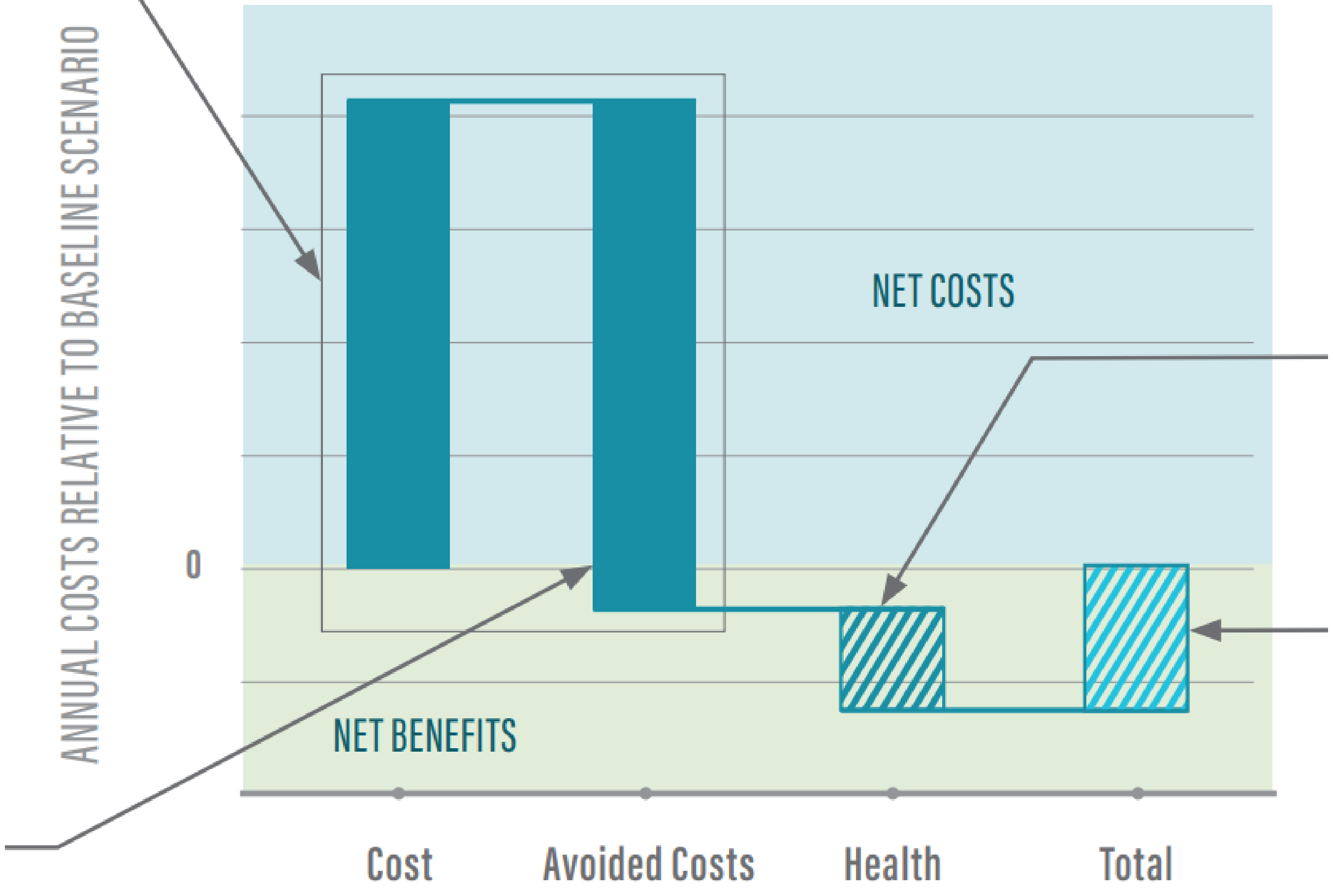
Electricity demand



Understanding the costs of decarbonization

Increased costs relative to Baseline Case:

- Demand side equipment
- Supply side equipment
- Operating costs



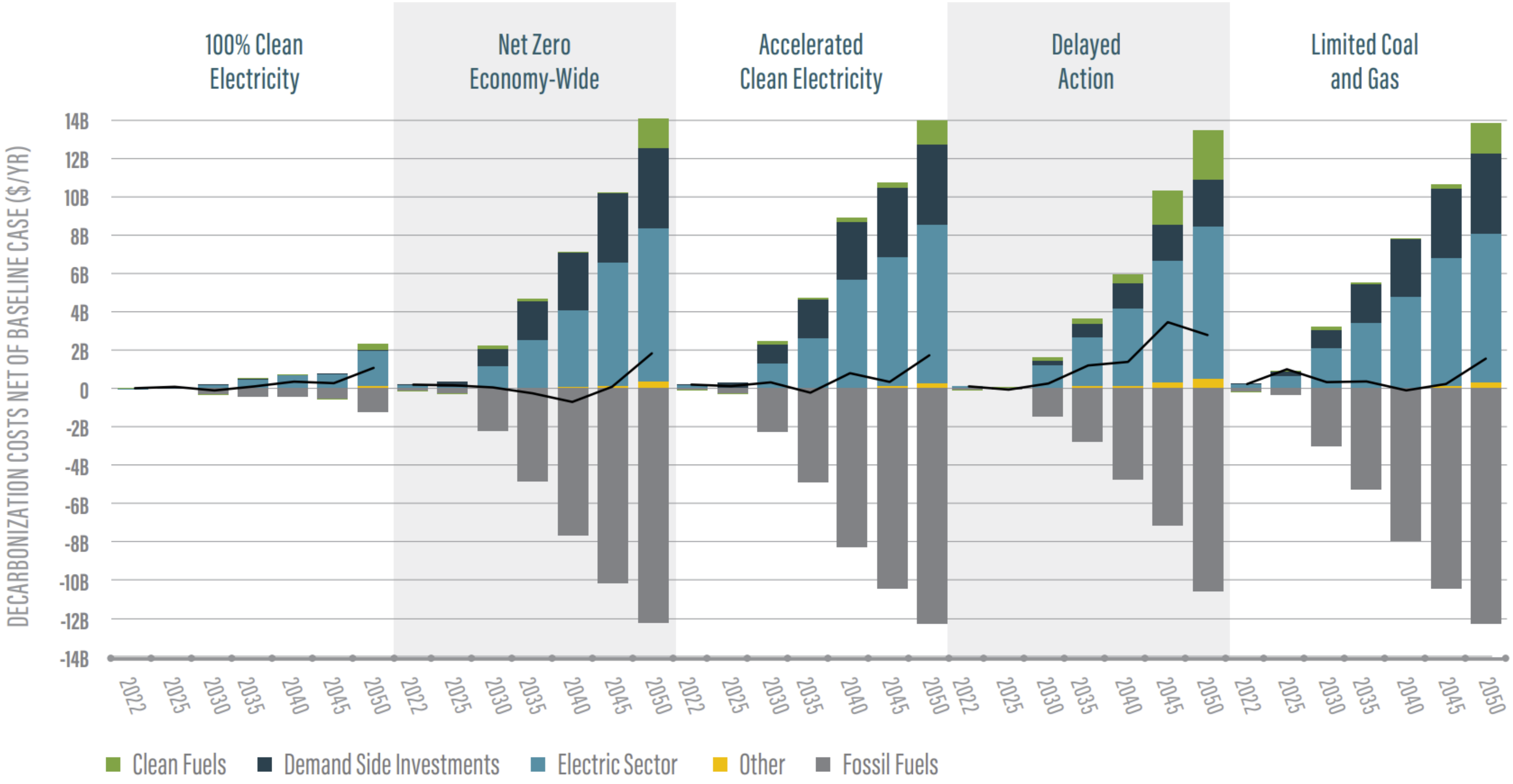
Health benefits from improved air quality

Net benefits* of decarbonization including health costs

Cost savings relative to Baseline Case:

Avoided equipment and operating costs (predominantly fuel purchases)

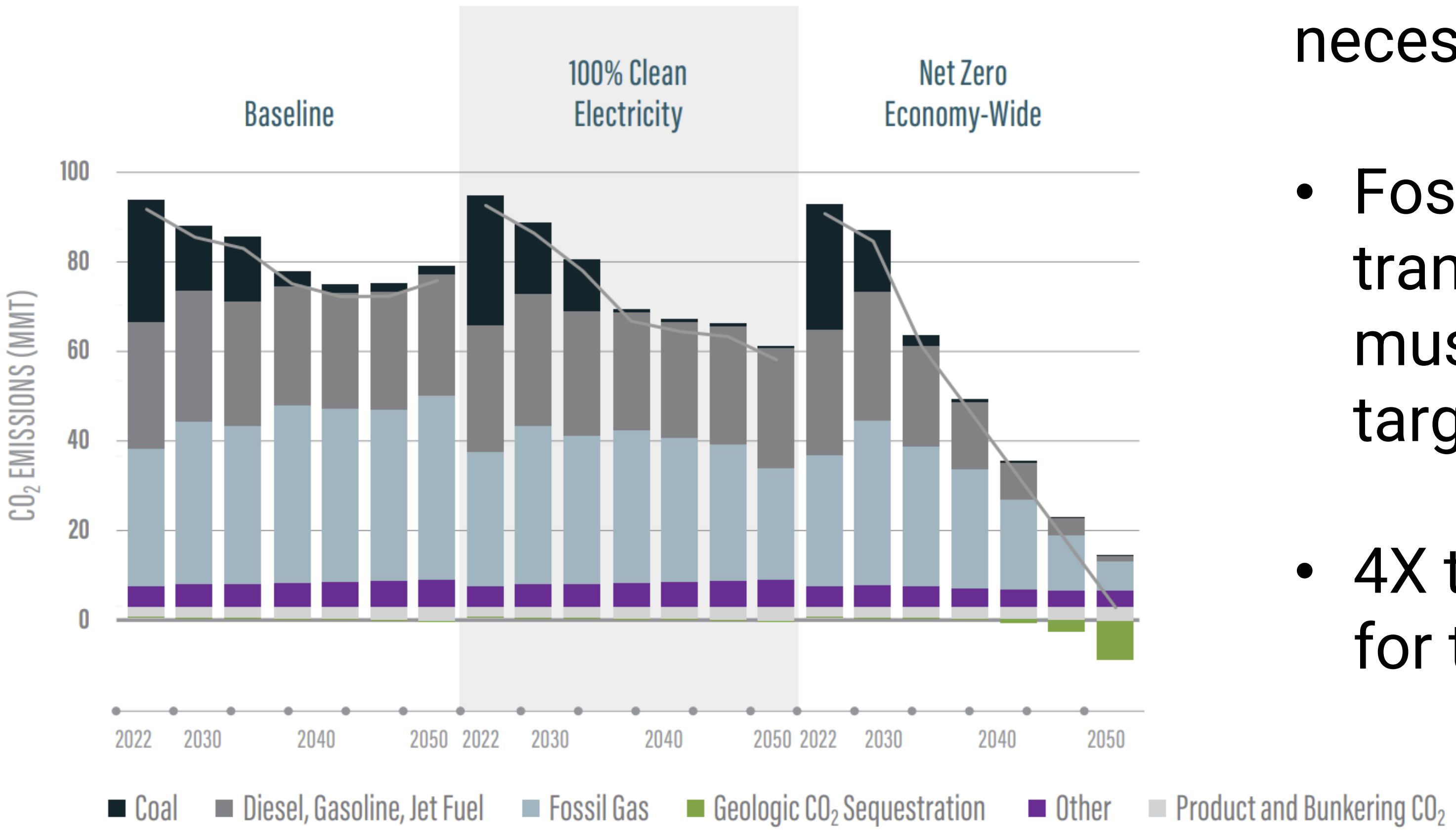
Net costs relative to baseline scenario



What key takeaways impact Wisconsin policymaking?

Clean electricity policy alone gets only 24% of the way to Net Zero

Wisconsin Energy and Industry Emissions by Clean Energy Policy Scenario

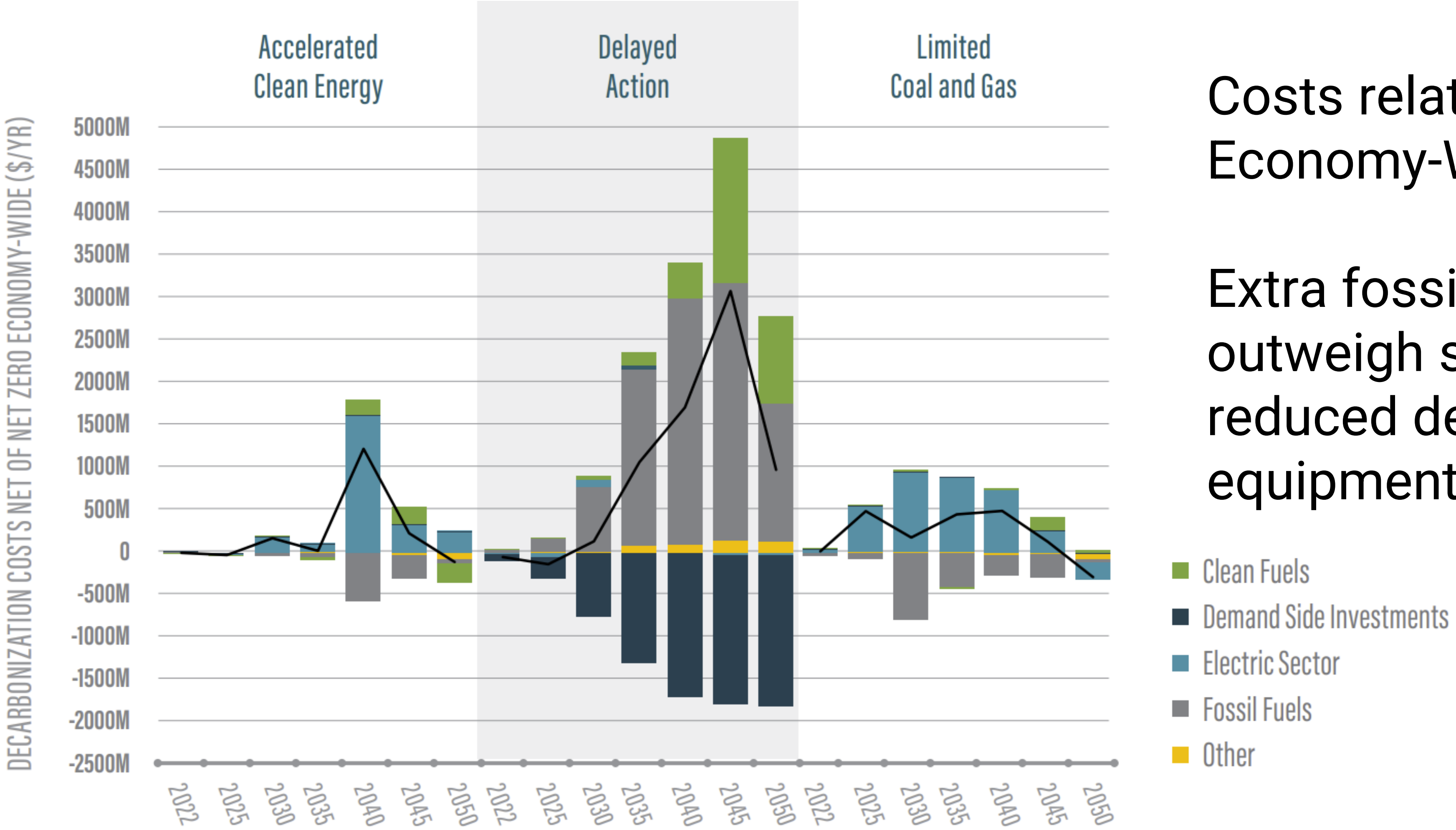


Economy-wide transformation necessary to reach net zero

- Fossil fuel use in buildings, transportation, and industry must drop to meet future targets
- 4X the emission reductions for the same cost

Delaying transformation of the demand side increases decarbonization costs

EVOLVED ENERGY RESEARCH



Costs relative to Net-Zero Economy-Wide scenario

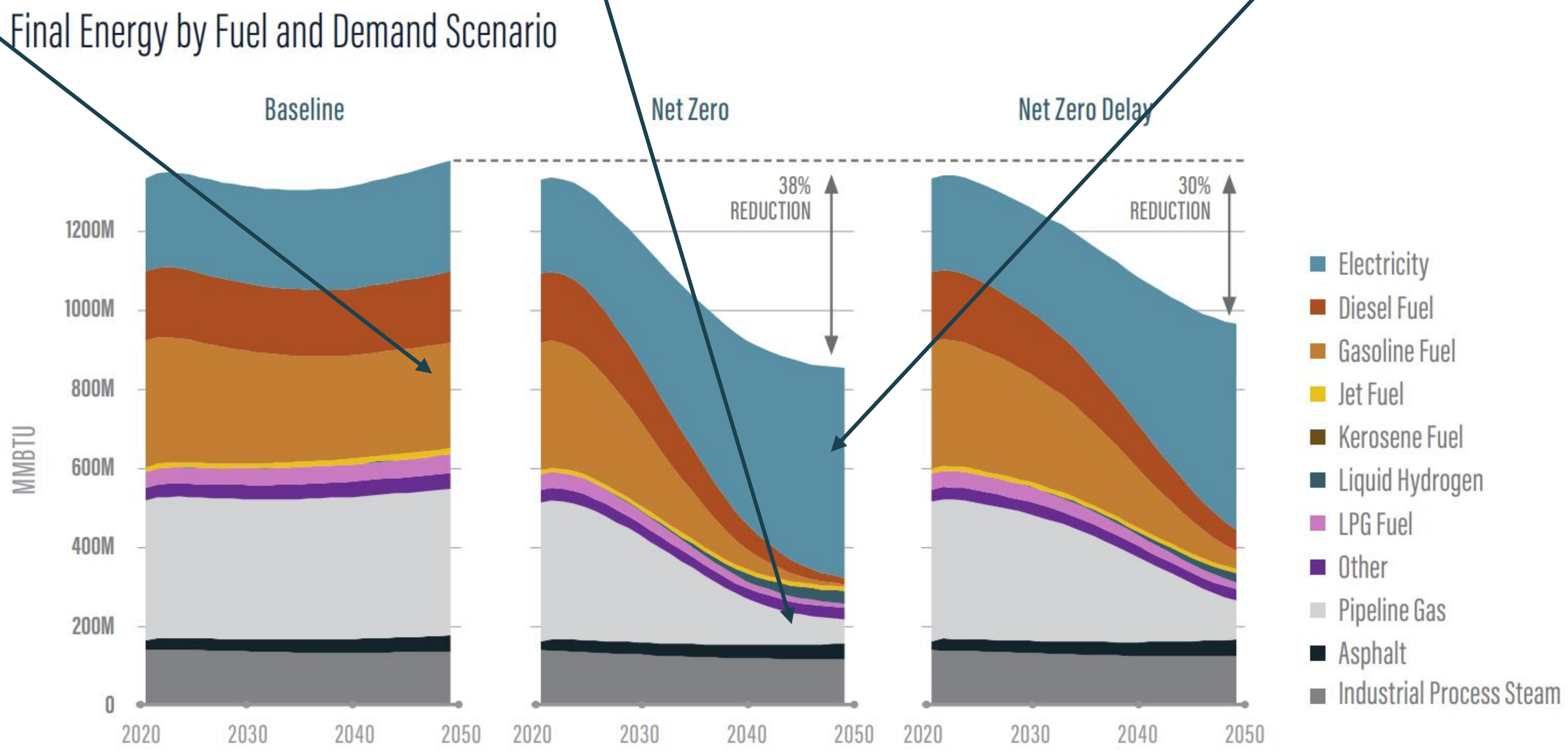
Extra fossil fuel costs outweigh savings in reduced demand side equipment costs

Reductions in economy-wide energy demand are key to cost effective decarbonization

Electrification of transportation drives major efficiency benefits

Transition of buildings to electrified and hybrid gas appliances

Cheaper to deliver clean electricity than clean fuels

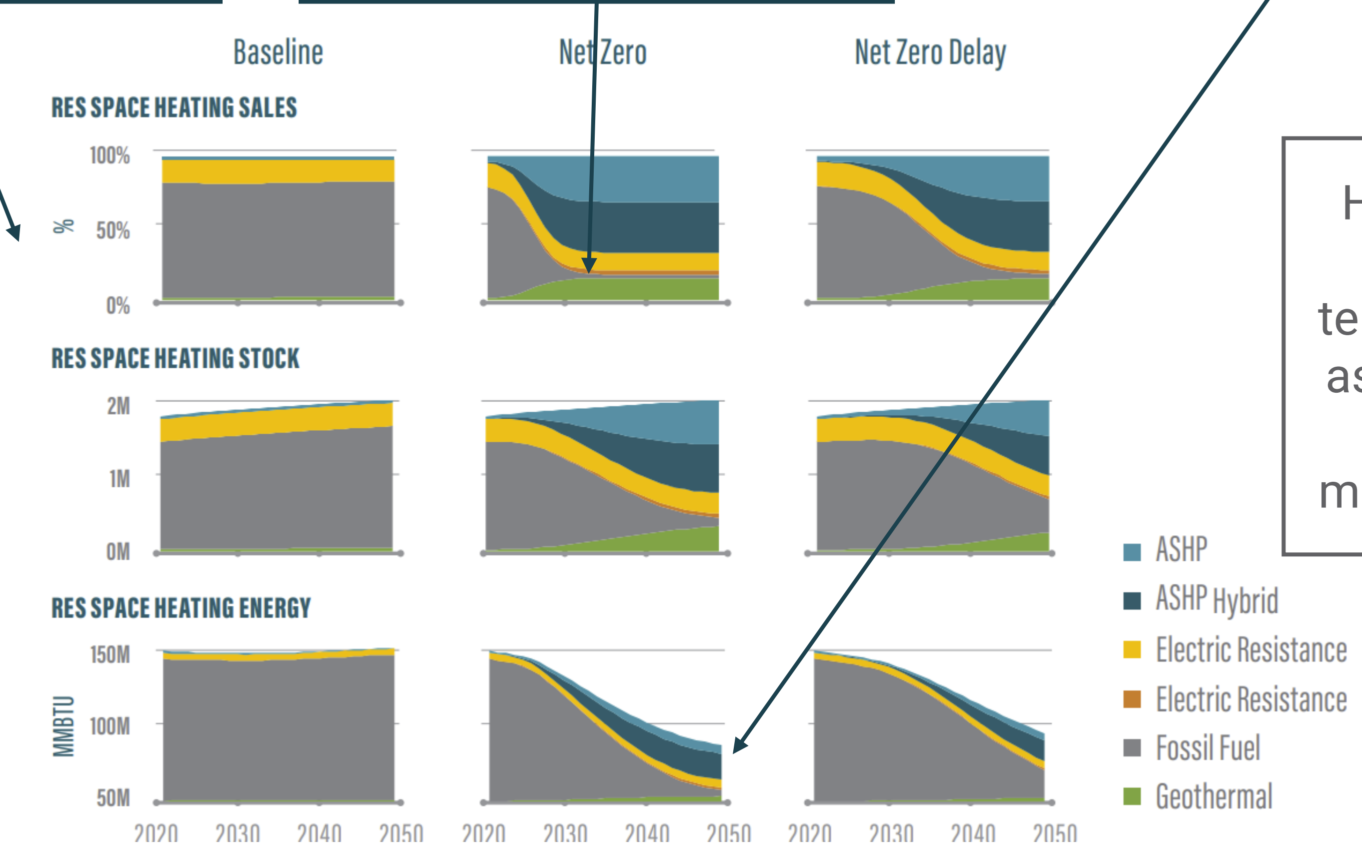


Requires early transition to sales of efficient technology

Example: Residential space heating sales, stocks, and energy

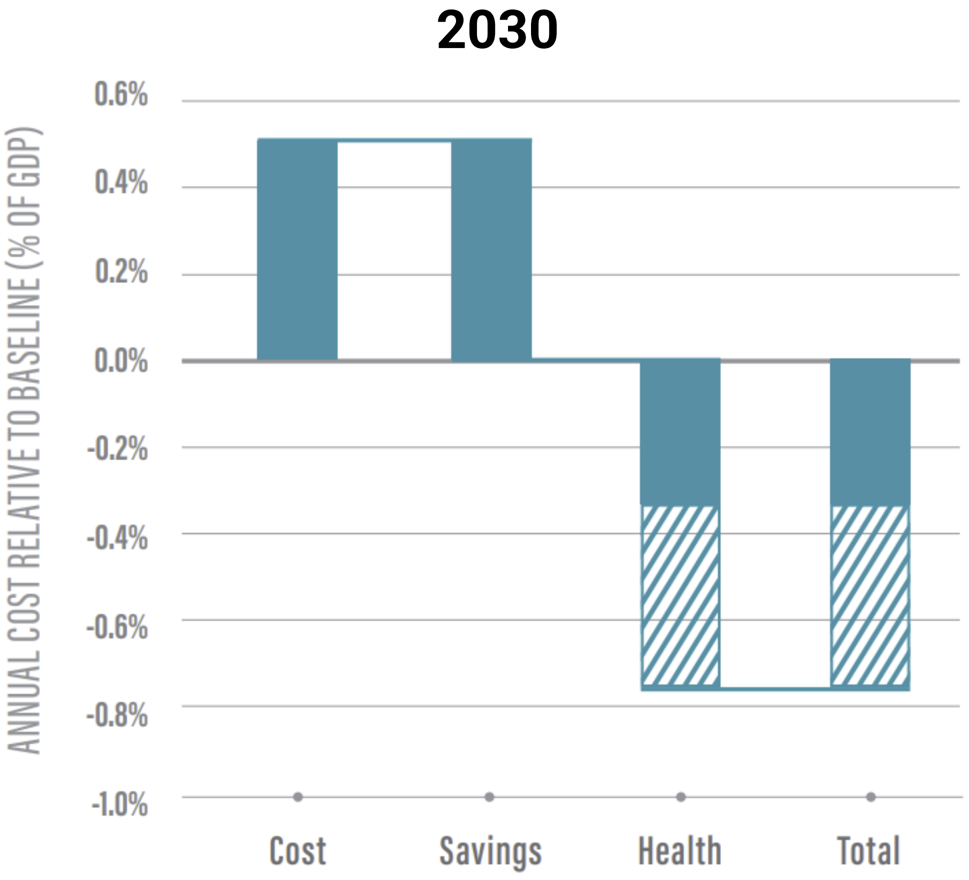
100% sales of electric, hybrid, and high efficiency appliances

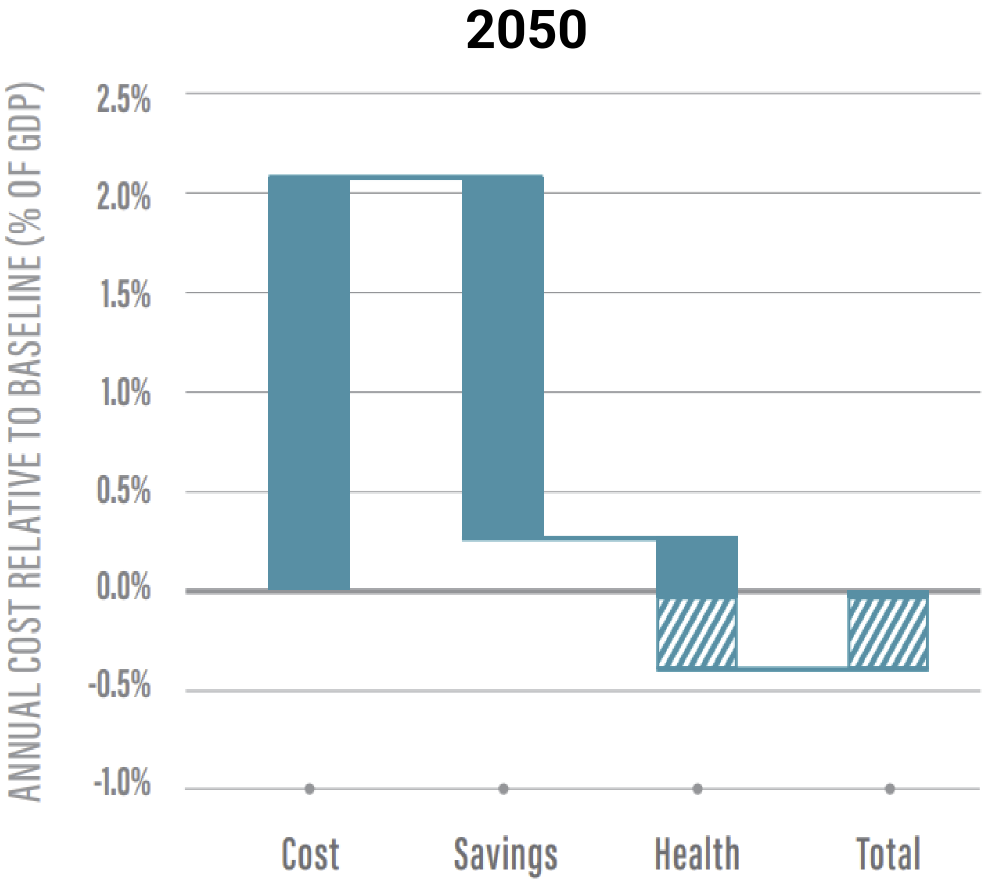
Efficiency improvements reduces demand for energy



Hybrid heating system sales in extreme low temperature climate. We assume heat pump only sales in regions with more moderate climates

Health benefits are substantial: net benefits of decarbonization in all years





Key actions by decade

Key actions in the 2020s

- **Retirement of coal** is Wisconsin's most impactful near-term path to significant emissions reductions
  - Wisconsin already on a path to retiring coal in the state. Modeled 2030 emissions target best achieved through even faster reduction in coal power generation
- **Investments in new electricity resources** to meet modeled policy targets and ensure reliability depends on the decarbonization pathway
  - Investments in solar and gas generation, or
  - Investments in solar, wind, and storage
- **Setting the groundwork for demand side transformation**
  - Early action required to achieve stock rollover of demand side technologies, delaying increases costs
  - Early development of policy initiatives to support electrification: how best to promote the shift to electrified end uses? How to minimize the adverse impacts of doing so?
- **Planning for load growth** is essential to meet new loads and support future electric vehicle charging
  - Rapid load growth will require investments in new T&D infrastructure to support electrification
  - Planning for long lead time transmission investments in the 2020s for construction in the 2030s

Key actions in the 2030s

- **Full retirement of coal** by the early 2030s
  - Coal generation in Net Zero Economy-Wide is 90% less than in Baseline in 2030 and fully retired by 2035
  - Coal is fully retired by 2030 in the Limited Coal and Gas scenario
- **Accelerated pace of investment in renewables** including solar and wind
  - Supported by significant investments in storage depending on the scenario
- **Transmission expansion** to facilitate imports of out of state clean electricity
  - The modeling finds large-scale development of additional intertie capacity to Iowa, Minnesota, and Illinois cost effective by 2040
- **Transitioning of gas in the power sector** from baseload to capacity resource
  - Drop in gas capacity factors as renewables displace gas as main form of power generation
- **100% electrification sales by 2035** across light duty transport and building appliances
  - Early electrification key to avoiding large decarbonization costs in the future

Key actions in the 2040s

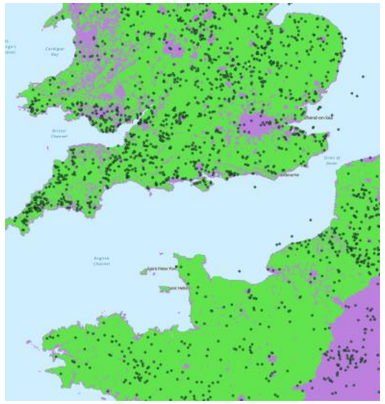
- **Continued rapid pace of renewable development**
  - Supported by large investments in storage
- **Increased imports of clean energy from out of state**
  - High utilization of new transmission capacity to support a third of Wisconsin's electricity needs
- **Complete transition of gas in power sector to reliability resource**
  - Gas capacity factors drop below 10% and gas in power becomes 100% clean by 2050
  - Retirement of unneeded gas capacity
- **Carbon capture and sequestration** used to offset remaining emissions in the economy
  - Carbon transportation networks required to reach sequestration potential out of state
- **Electrolysis** ramping up to support HDV fleet and provide balancing to the grid
- **Electrified and clean end uses** reach close to 100% penetration in many sectors of the economy

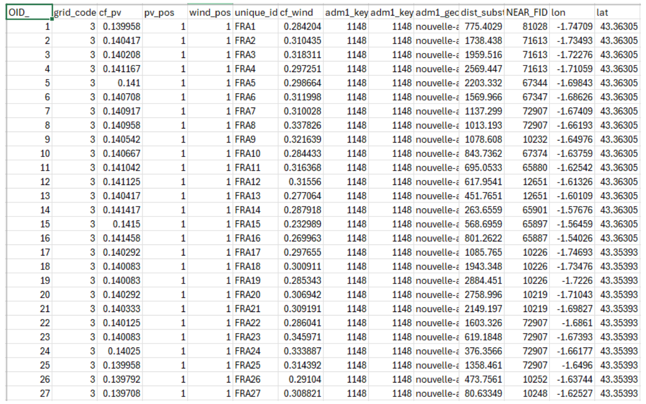
EVOLVED
ENERGY
RESEARCH

Modeling co-benefits and spatial analysis

Geography in energy system modeling

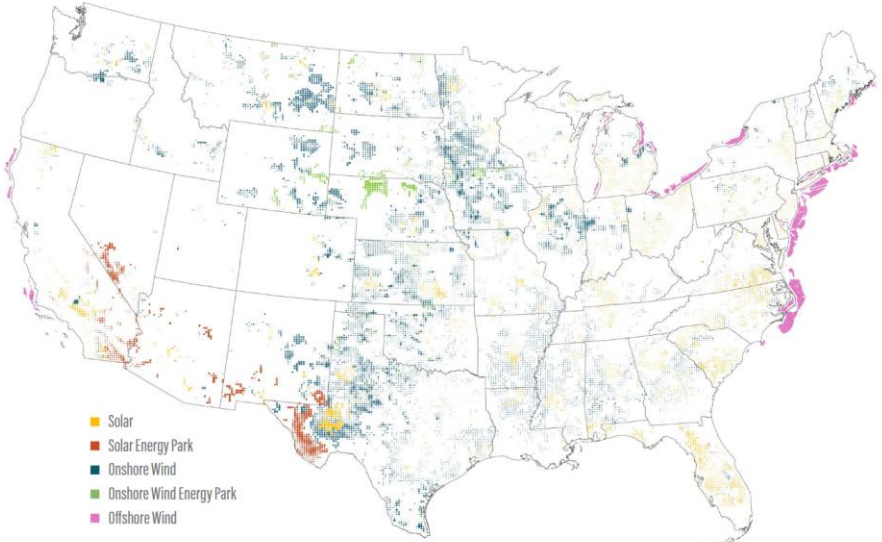
- Spatial analysis and geographic variables inherent to energy but even more so in renewable systems
- Internal to modeling (a parameter) or as an additional layer (downscaling and mapping/impacts analysis)





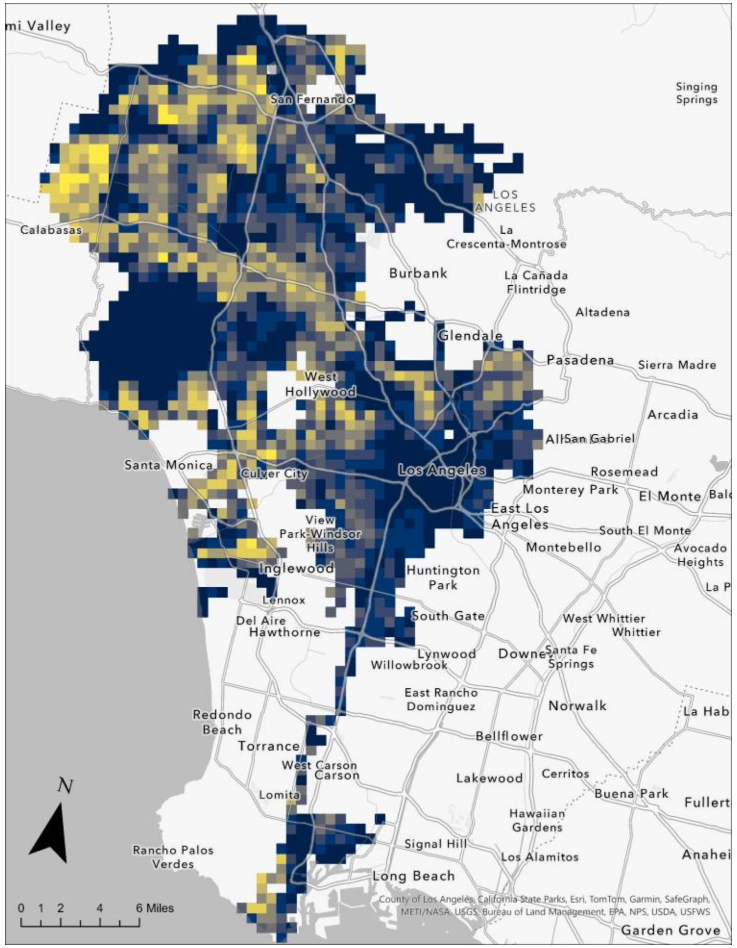
OID_	grid_code	cf_pv	pv_pos	wind_pos	unique_id	cf_wind	adm1_key	adm1_key	adm1_geo	dist_subst	NEAR_FID	lon	lat
1	3	0.139958	1	1	FRA1	0.284204	1148	1148	nouvelle-a	775.4029	81028	-1.74709	43.36305
2	3	0.140417	1	1	FRA2	0.310435	1148	1148	nouvelle-a	1738.438	71613	-1.73493	43.36305
3	3	0.140208	1	1	FRA3	0.318311	1148	1148	nouvelle-a	1959.516	71613	-1.72276	43.36305
4	3	0.141167	1	1	FRA4	0.297251	1148	1148	nouvelle-a	2569.447	71613	-1.71059	43.36305
5	3	0.141	1	1	FRA5	0.298664	1148	1148	nouvelle-a	2203.332	67344	-1.69843	43.36305
6	3	0.140708	1	1	FRA6	0.311998	1148	1148	nouvelle-a	1569.966	67347	-1.68626	43.36305
7	3	0.140917	1	1	FRA7	0.310028	1148	1148	nouvelle-a	1137.299	72907	-1.67409	43.36305
8	3	0.140958	1	1	FRA8	0.337826	1148	1148	nouvelle-a	1013.193	72907	-1.66193	43.36305
9	3	0.140542	1	1	FRA9	0.321639	1148	1148	nouvelle-a	1078.608	10232	-1.64976	43.36305
10	3	0.140667	1	1	FRA10	0.284433	1148	1148	nouvelle-a	843.7362	67374	-1.63759	43.36305
11	3	0.141042	1	1	FRA11	0.316368	1148	1148	nouvelle-a	695.0533	65880	-1.62542	43.36305
12	3	0.141125	1	1	FRA12	0.31556	1148	1148	nouvelle-a	617.9541	12651	-1.61326	43.36305
13	3	0.140417	1	1	FRA13	0.277064	1148	1148	nouvelle-a	451.7651	12651	-1.60109	43.36305
14	3	0.141417	1	1	FRA14	0.287918	1148	1148	nouvelle-a	263.6559	65901	-1.57676	43.36305
15	3	0.1415	1	1	FRA15	0.232989	1148	1148	nouvelle-a	568.6959	65897	-1.56459	43.36305
16	3	0.141458	1	1	FRA16	0.269963	1148	1148	nouvelle-a	801.2622	65887	-1.54026	43.36305
17	3	0.140292	1	1	FRA17	0.297655	1148	1148	nouvelle-a	1085.765	10226	-1.74693	43.35393
18	3	0.140083	1	1	FRA18	0.300911	1148	1148	nouvelle-a	1943.348	10226	-1.73476	43.35393
19	3	0.140083	1	1	FRA19	0.285343	1148	1148	nouvelle-a	2884.451	10226	-1.7226	43.35393
20	3	0.140292	1	1	FRA20	0.306942	1148	1148	nouvelle-a	2758.996	10219	-1.71043	43.35393
21	3	0.140333	1	1	FRA21	0.309191	1148	1148	nouvelle-a	2149.197	10219	-1.69827	43.35393
22	3	0.140125	1	1	FRA22	0.286041	1148	1148	nouvelle-a	1603.326	72907	-1.6861	43.35393
23	3	0.140083	1	1	FRA23	0.345971	1148	1148	nouvelle-a	619.1848	72907	-1.67393	43.35393
24	3	0.14025	1	1	FRA24	0.333887	1148	1148	nouvelle-a	376.3566	72907	-1.66177	43.35393
25	3	0.139958	1	1	FRA25	0.314392	1148	1148	nouvelle-a	1358.461	72907	-1.6496	43.35393
26	3	0.139792	1	1	FRA26	0.29104	1148	1148	nouvelle-a	473.7561	10252	-1.63744	43.35393
27	3	0.139708	1	1	FRA27	0.308821	1148	1148	nouvelle-a	80.63349	10248	-1.62527	43.35393

FIGURE 40. Downscaled wind and solar in 2050 for the 100% Renewables scenario



Downscaling

- A (usually) spatial process that seeks to increase the resolution or granularity of data
- How do we get from numerical data at state or regional level to examine impacts at county or below?
    - Statistical relationships
    - Dynamical relationships (meteorology/climate models)



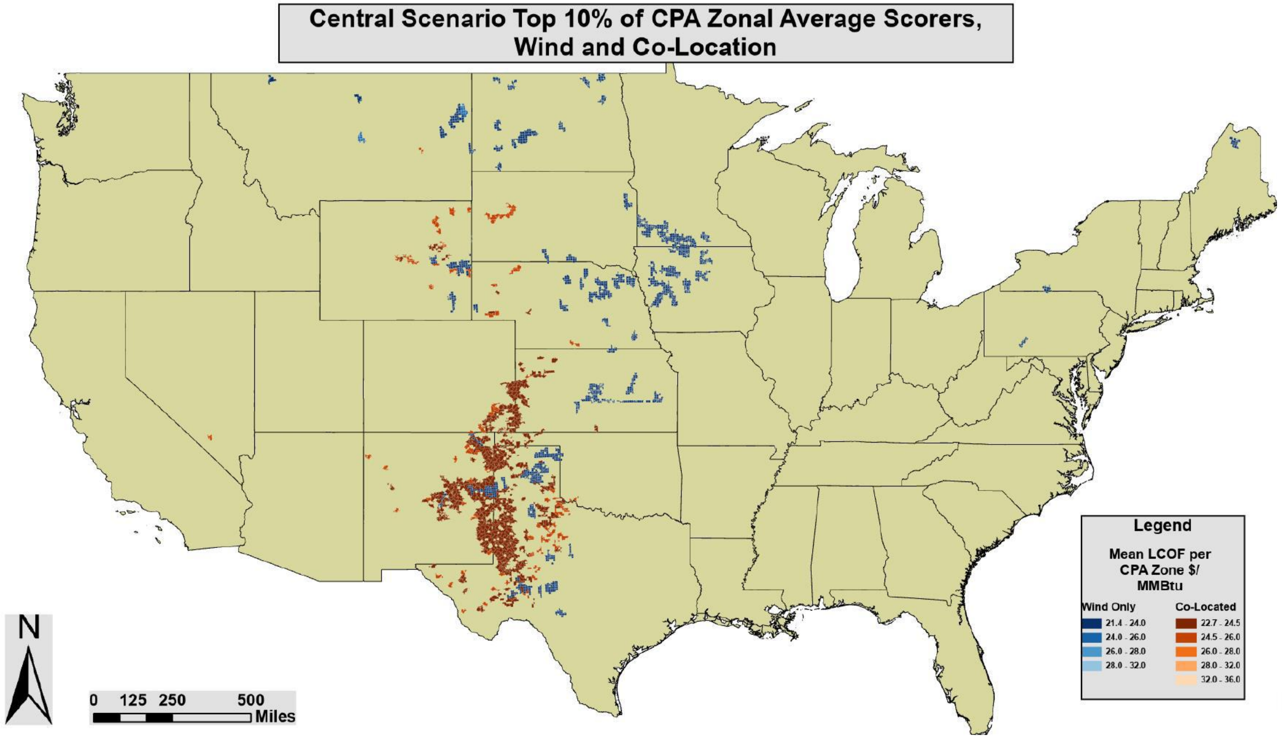
Example variables:

- Population
    - Density, occupation, rural/urban classification
- Economic
    - Income data, housing/property value or type, industry types
- Behavioral
    - Vehicle usage behavior, public transportation, political activity
- Environmental
    - Fire hazard, land use type, animal habitats

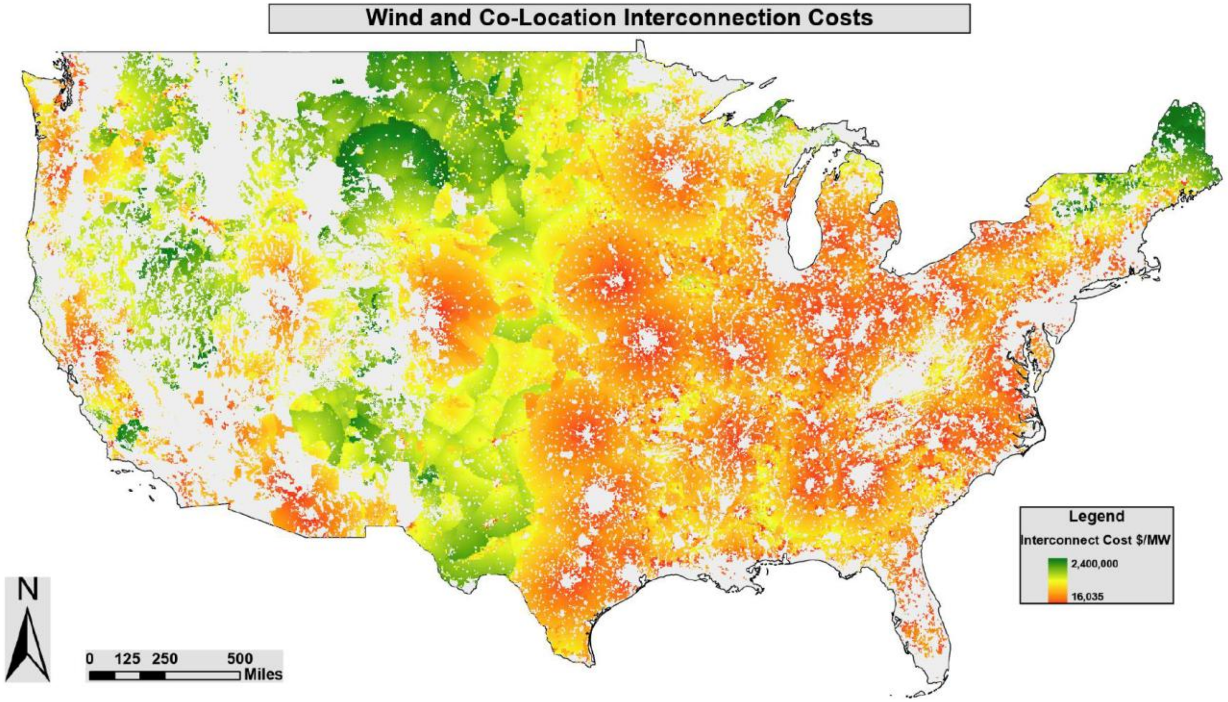
Impacts analysis

- Downscaling and impacts analysis often intersect, with impacts usually the final piece of the puzzle
    - Air quality, job creation, land-use, transmission routing
- Spatial challenges to energy (in the US in particular) remain some of the largest roadblocks
    - Transmission and infrastructure build-out
    - Optimized renewable siting
- In developing countries, limited resources make correctly targeted (in the right area and sector) action more imperative

Spatial analysis and interconnection

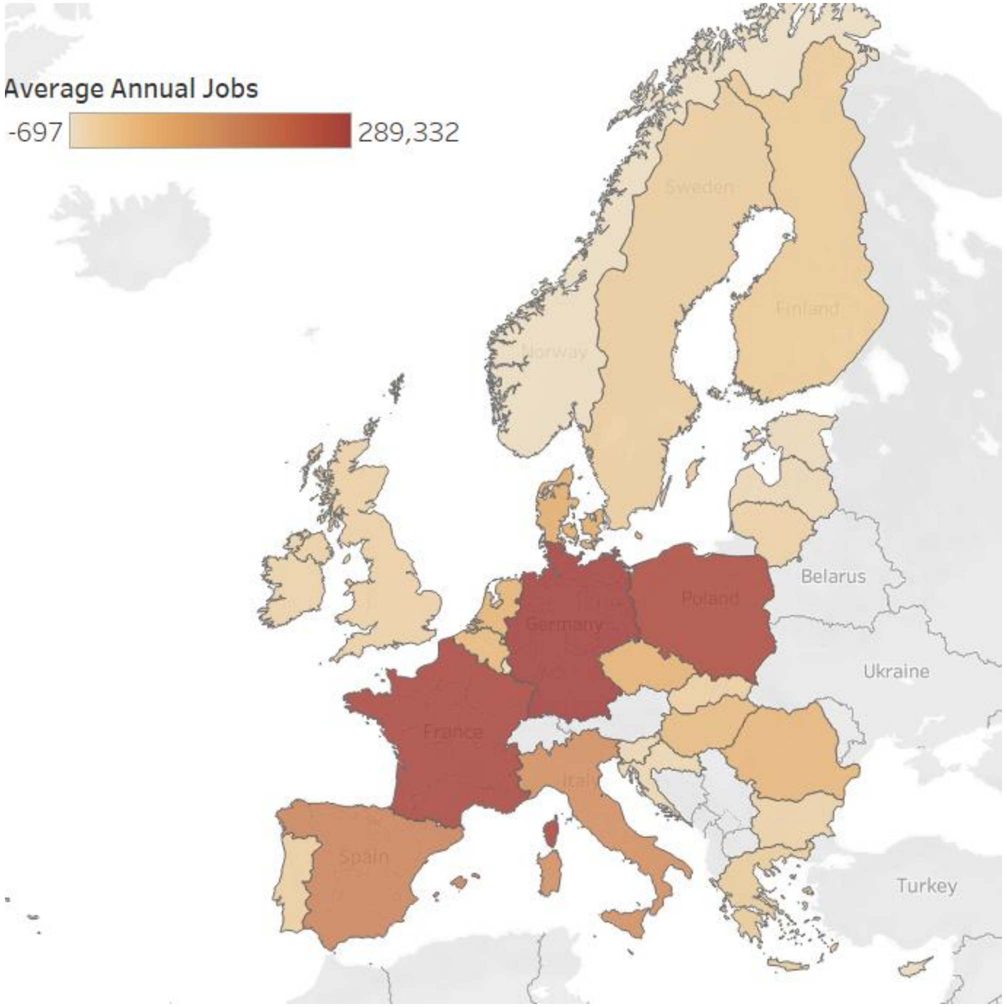


Central Scenario Top 10% of CPA Zonal Average Scorers, Wind and Co-Location

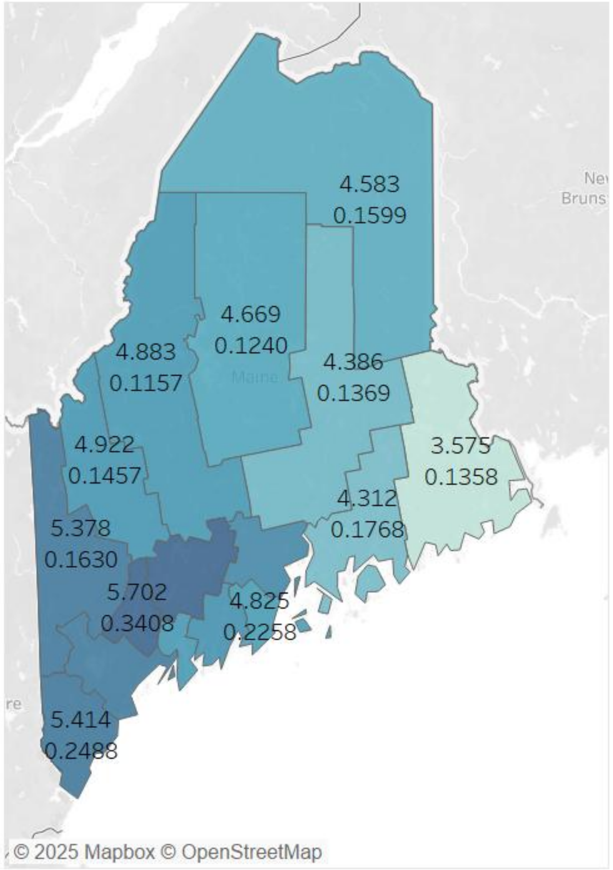


Wind and Co-Location Interconnection Costs

Air quality and jobs impacts

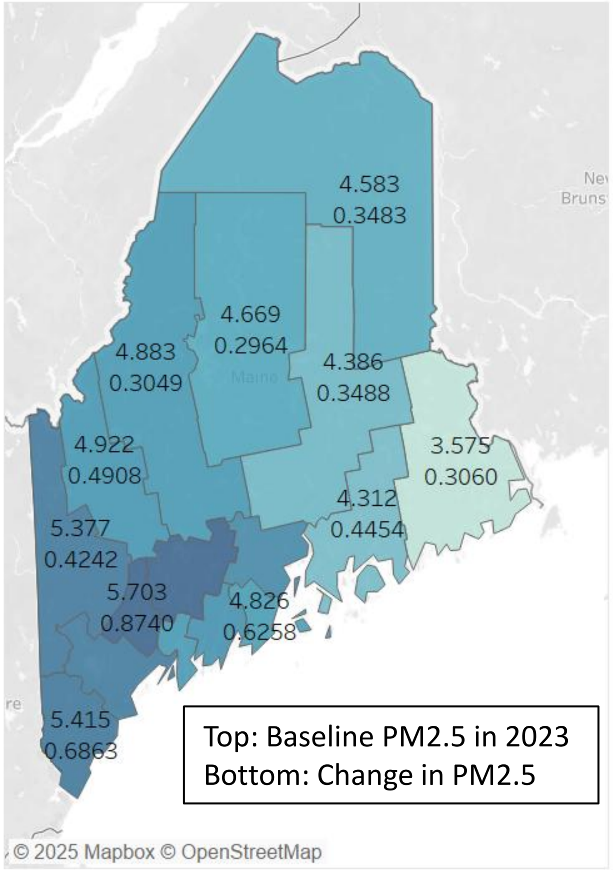


Particulate Matter Reduction (PM2.5) by 2030



© 2025 Mapbox © OpenStreetMap

Particulate Matter Reduction (PM2.5) by 2050



© 2025 Mapbox © OpenStreetMap

Top: Baseline PM2.5 in 2023
Bottom: Change in PM2.5

Using spatial outputs

- Model results can often be abstract, geographic impacts allow for direct study of effects on population
    - Energy wallet or electricity/energy savings and costs to households
    - Health outcomes and associated financial benefits
    - Job and economic opportunities, particularly in areas that are either historically disadvantaged or may be affected by energy transition
- Geographic modeling and downscaling have the same caveats as the energy system models that supply the raw data
    - Projections not predictions, this is not ‘siting’ or ‘development’
    - Offer insights on which levers and areas of focus have different results
- Understanding impacts at policy scale (municipal, state, regional etc.) is fundamental to making proactive choices

EVOLVED
ENERGY
RESEARCH

Takeaways

Takeaways (1)

- Models are mathematical or analytical representations that balance available computation, mathematical characterization, and realism
  - Goal: Useful guidance for decisionmakers and stakeholders to help achieve emissions/energy targets rather than crystal balls
- Models use scenarios to isolate and examine specific changes and the potential effects they may have under uncertain conditions
- Challenges such as future state uncertainty, hidden higher order impacts, renewable planning variability, data availability, and limited policy jurisdiction demand integrated modeling approaches

Takeaways (2)

- Energy systems and sources of emissions encompass every sector and economy-wide targets link them all together
  - Proactive planning involves modeling opportunities and challenges across the whole economy
- Asking and answering "what if" questions help policymakers understand both cause and effect and the consequences of different pathways—sadly, there are no free lunches!
- Energy system model outputs can be downscaled to better understand real physical and environmental impacts to populations, creating more calibrated policy outcomes

THANK YOU

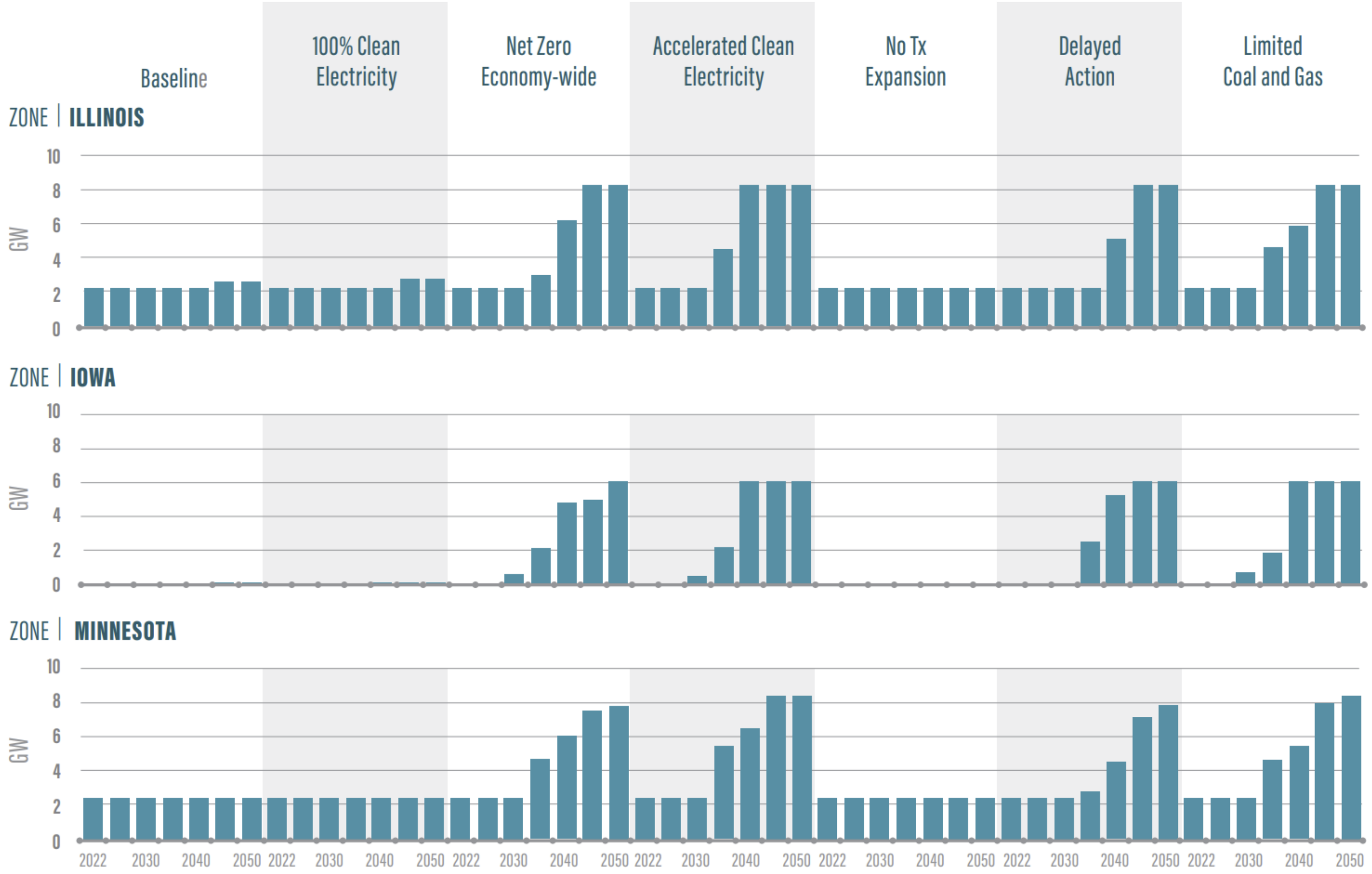
EVOLVED
ENERGY
RESEARCH

EVOLVED
ENERGY
RESEARCH

Appendix

Reliant on imports across expanded tx

EVOLVED
ENERGY
RESEARCH

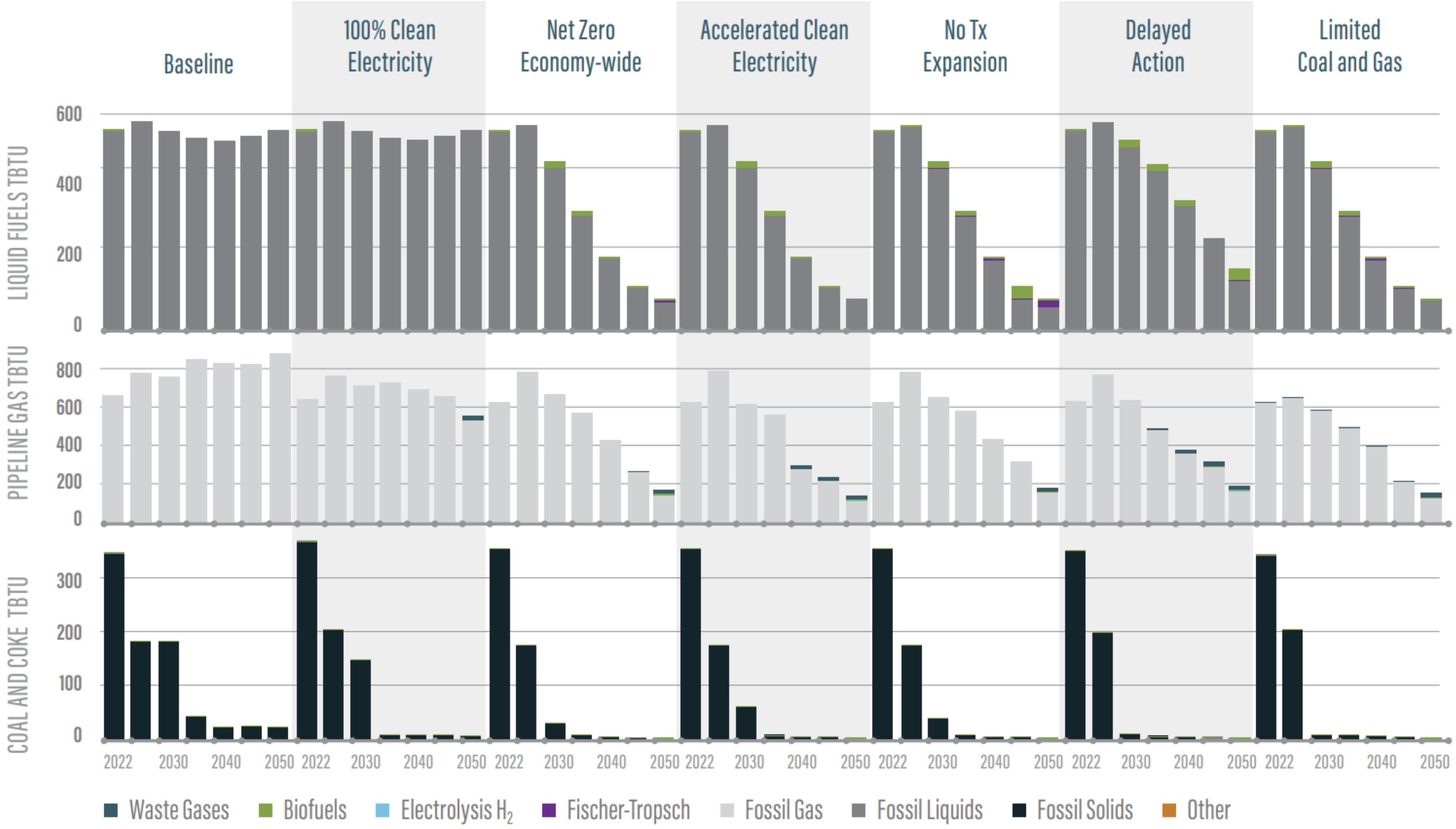


Fossil fuel use across the economy decreases

LIQUID FUELS

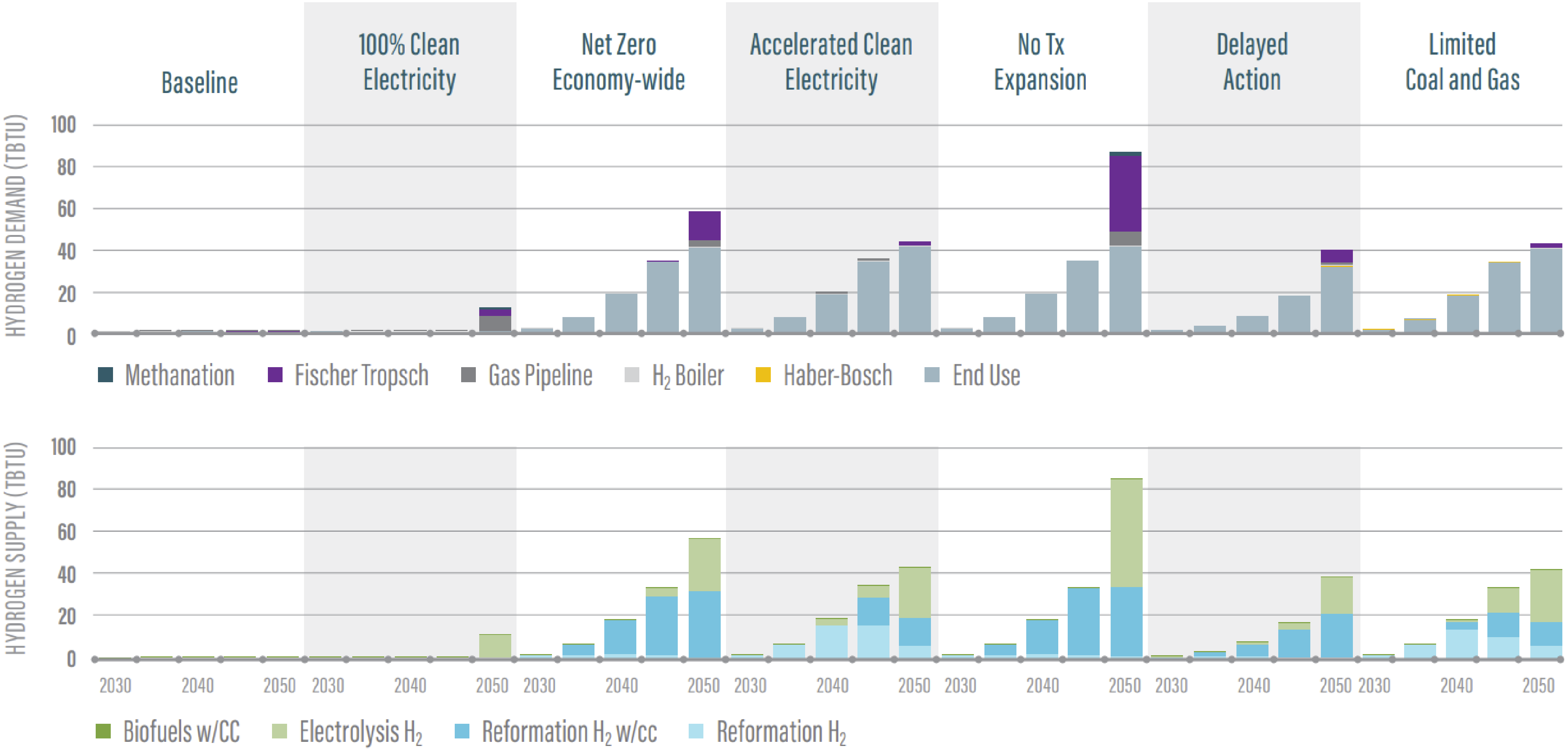
PIPELINE GAS

COAL AND COKE

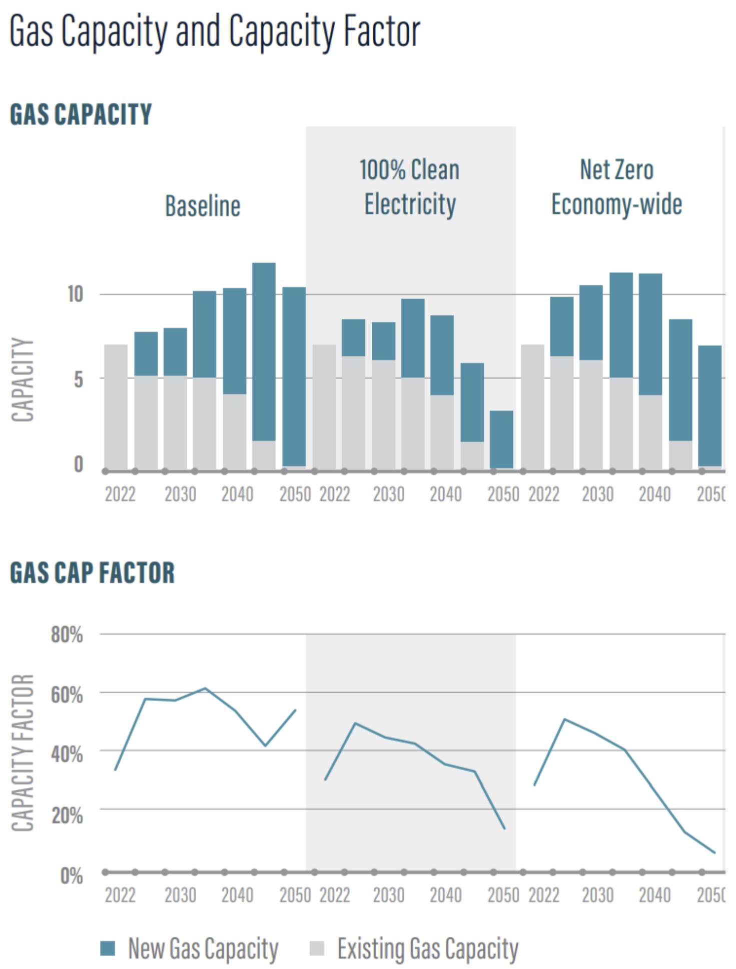


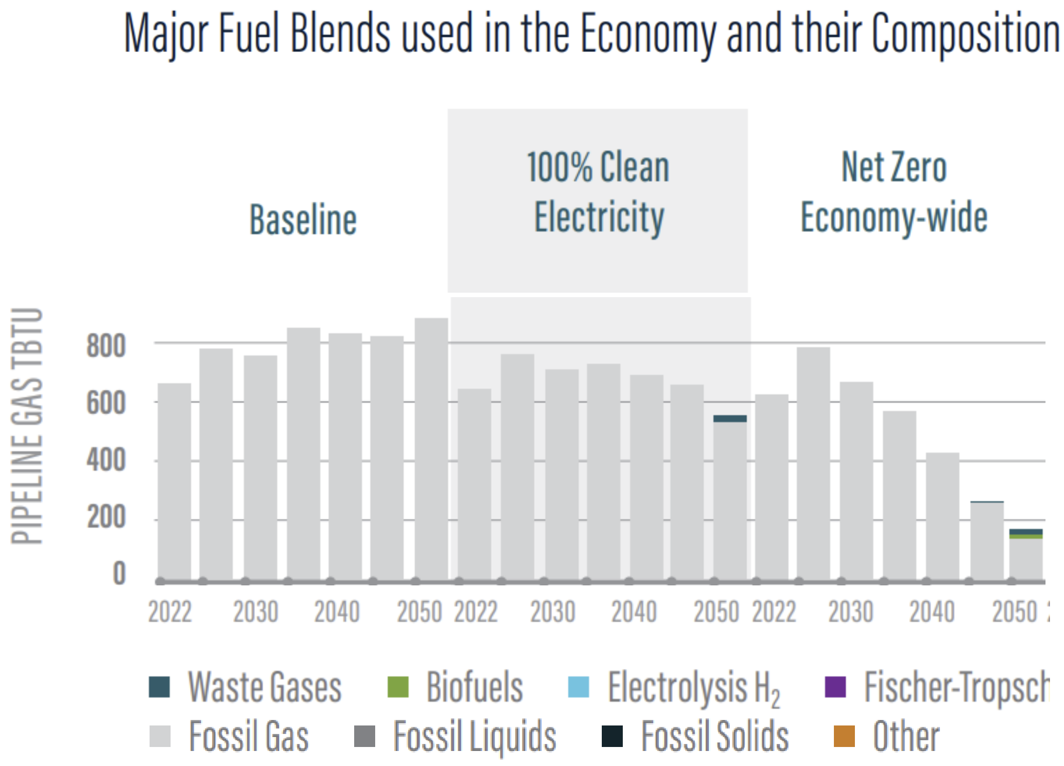
Relatively small hydrogen economy

EVOLVED
ENERGY
RESEARCH



Gas transitions from energy to reliability





High gas throughput = High cost
Get rid of gas entirely = High cost
Valuable for reliability in heat and electricity

Highest value of gas

EVOLVED
ENERGY
RESEARCH

- Reliability in heat and electricity
  - Buildings: Heating on the coldest days in cold climates, can avoid high peak electric loads and achieves better electric system utilization
  - Industry: Dual fuel boilers, provides greater system flexibility, integration with electric system
  - Electricity: Provides energy in low frequency energy deficit conditions
- Conditions where using gas avoids more expensive energy solutions
  - Gas usage starts to function as demand response
- Who pays? Challenges to implementation
- Cost uncertainty. Maintenance, decommissioning etc.

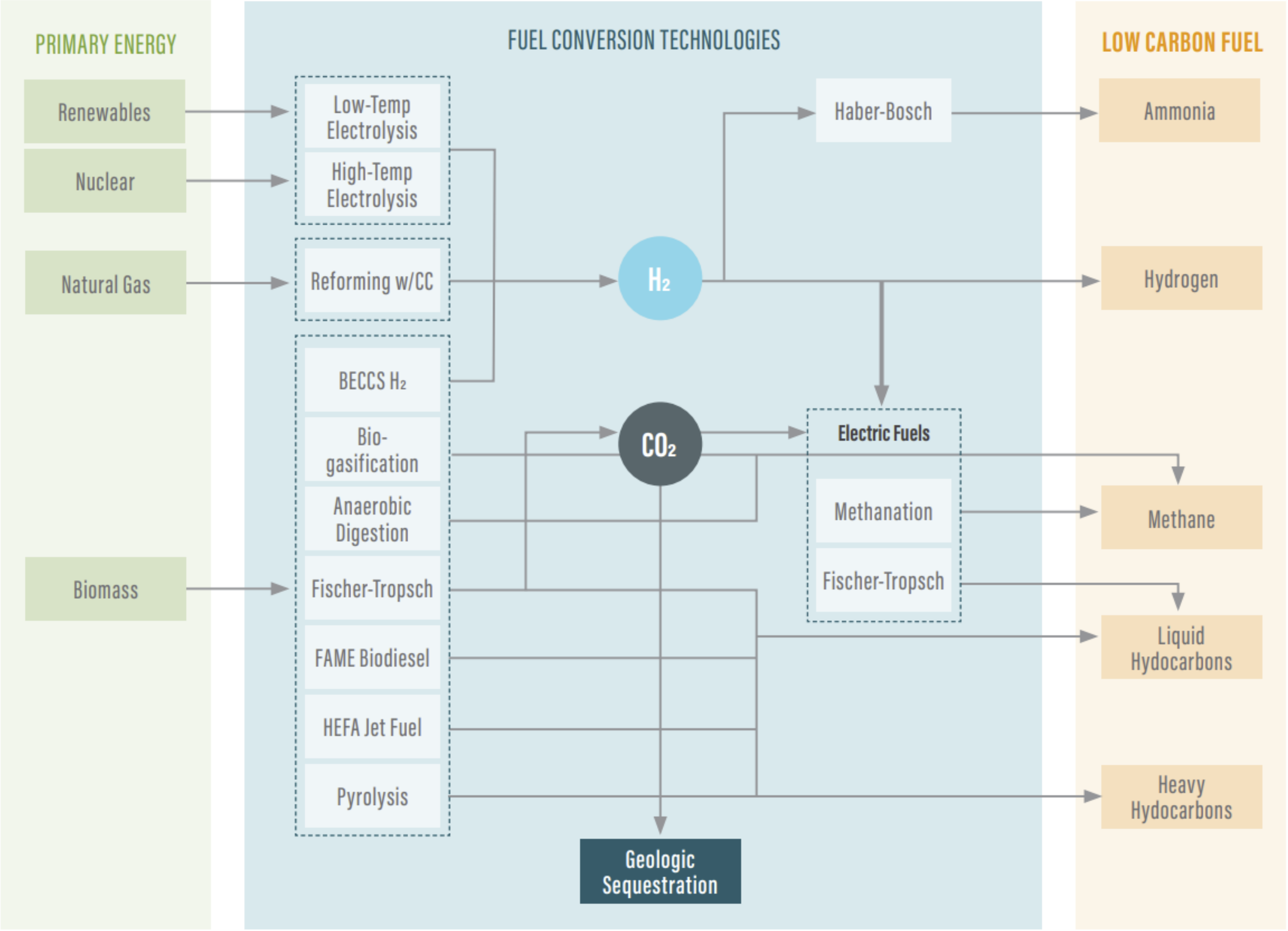
Modeling and data challenges

- Energy as a sector is unique:
  - Cross-sectoral: Academic and engineering applications, business implications, security aspects, justice and social impacts
- Data challenges:
  - Open-source models can be left behind advances or suffer from slower updates but open-source and public data foundational to all modeling exercises.
- Sectoral breadth
  - A model or expert in one area may not carry expertise into another: petroleum exploration modeling vs. renewable development siting

Clean Fuels Supply

EVOLVED
ENERGY
RESEARCH

- Optimize capital investments and operations across all elements of clean fuel supply chains
  - Renewables/biomass
  - Transportation and storage
  - Conversion processes
- Scenarios used to constrain opportunities for clean fuels supply chains and electric sector development



PRIMARY ENERGY

Renewables

Nuclear

Natural Gas

Biomass

FUEL CONVERSION TECHNOLOGIES

Low-Temp Electrolysis

High-Temp Electrolysis

Reforming w/CC

BECCS H_2

Bio-gasification

Anaerobic Digestion

Fischer-Tropsch

FAME Biodiesel

HEFA Jet Fuel

Pyrolysis

H_2

CO_2

Haber-Bosch

Electric Fuels

Methanation

Fischer-Tropsch

Geologic Sequestration

LOW CARBON FUEL

Ammonia

Hydrogen

Methane

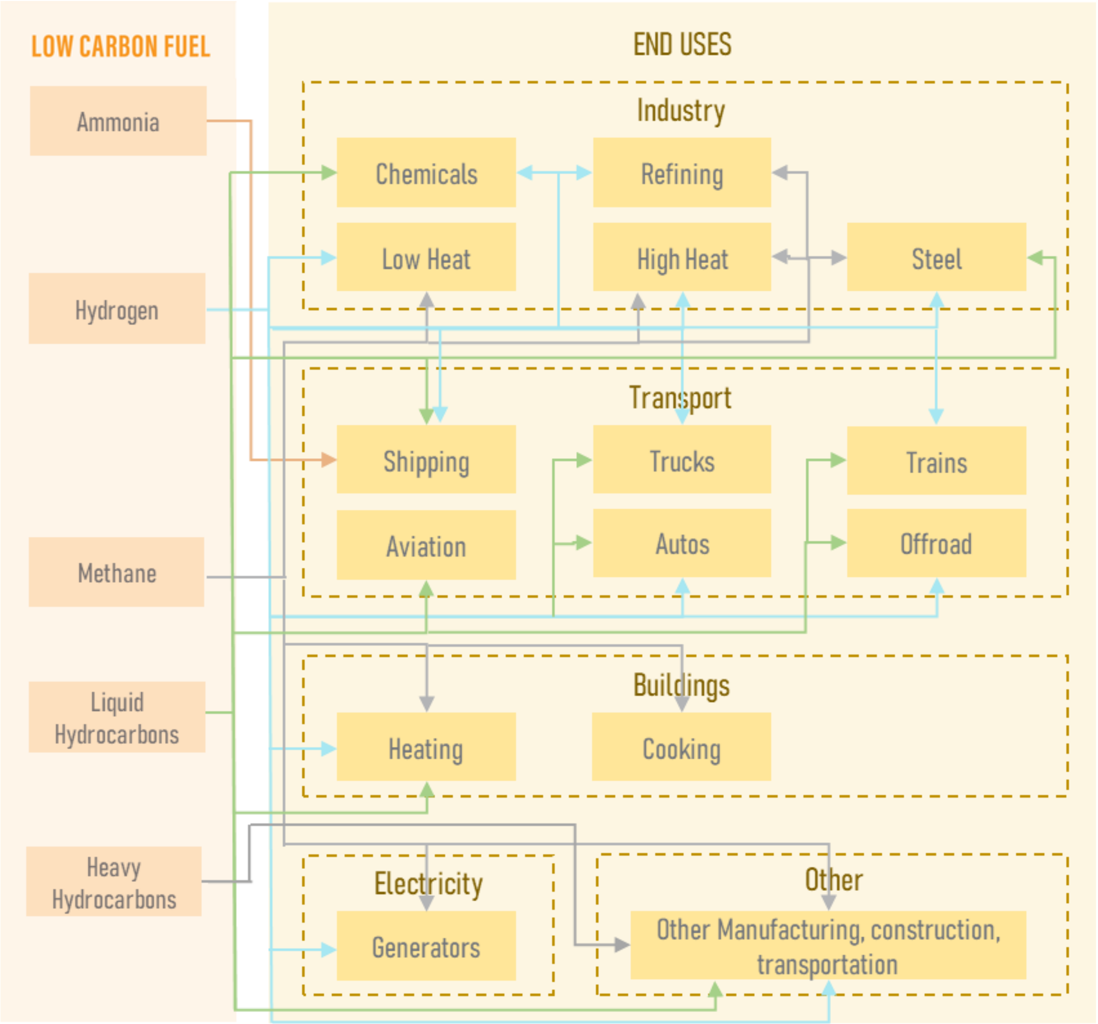
Liquid Hydocarbons

Heavy Hydocarbons

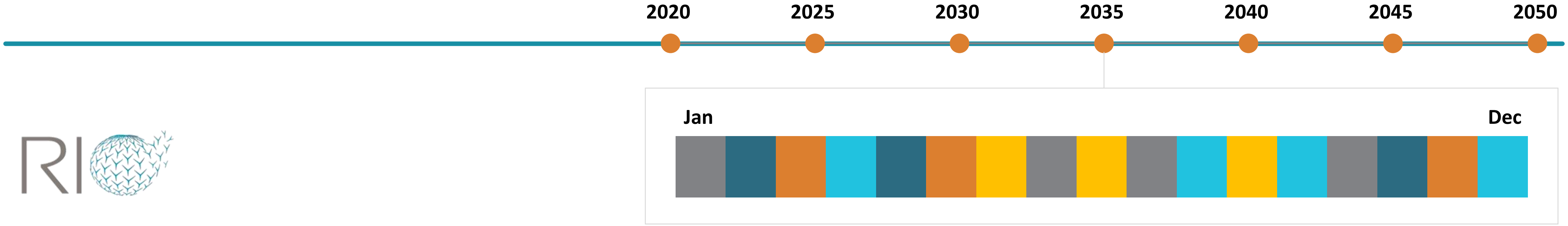
Clean Fuels Demand

EVOLVED ENERGY RESEARCH

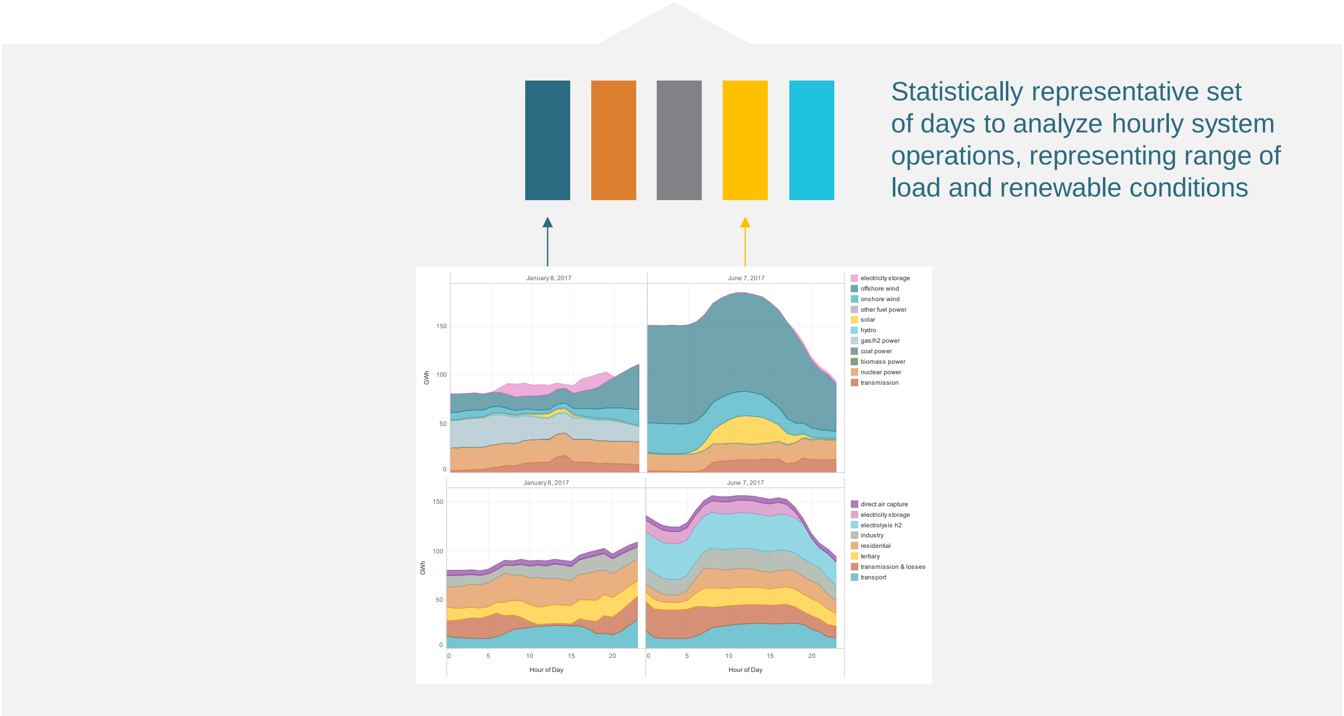
- Where are clean fuels used?
  - Replacing blue hydrogen with green
  - Drop in fuels: decarbonizing fuel blends
  - New markets for direct hydrogen use
  - New markets for ammonia
- Direct use of 100% hydrogen/ammonia blend in the economy defined with input assumptions
  - Fuel cells, 100% ammonia in maritime propulsion
- Share of clean fuels in fuel blends optimized by the model



Energy systems modeling: supply side



RIO is an energy system model designed from the ground-up to faithfully represent the economics of deeply decarbonized energy systems across all sectors. It extends the framework of a highly temporally resolved capacity expansion model past its traditional use in electricity planning to an economy-wide representation. This allows for integrated decision-making for electricity, gas, hydrogen, carbon management, and fuels as well as demand-side decisions.



Statistically representative set of days to analyze hourly system operations, representing range of load and renewable conditions

Present value of costs similar between electricity policy and net-zero policy