Introduction to EPRI's Regional Economy, Greenhouse Gas, and Energy (REGEN) Model

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Overview

The U.S. Regional Economy, Greenhouse Gas, and Energy (US-REGEN) model is an energy-economy model developed and maintained by EPRI. The model links a detailed electric sector capacity planning and fuels supply model with representations of demand in buildings, transport, and industry. US-REGEN provides a customizable platform for policy analysis, technology assessment, and strategy that is informed by decades of EPRI research on energy modeling and technology analysis. This report provides a high-level introduction to the model and complements the detailed model documentation, peer-reviewed journal articles, and EPRI reports, which are available at https://esca.epri.com/.

Slides prepared by:
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CONTENTS

REGEN

Regional Economy, GHG, and Energy

EPRI

Electric Sector

- Investment and dispatch
- Transmission and interchange
- Integration of renewables
- Electrification
- Energy and capacity requirements
- Regional policies and constraints

Energy Use

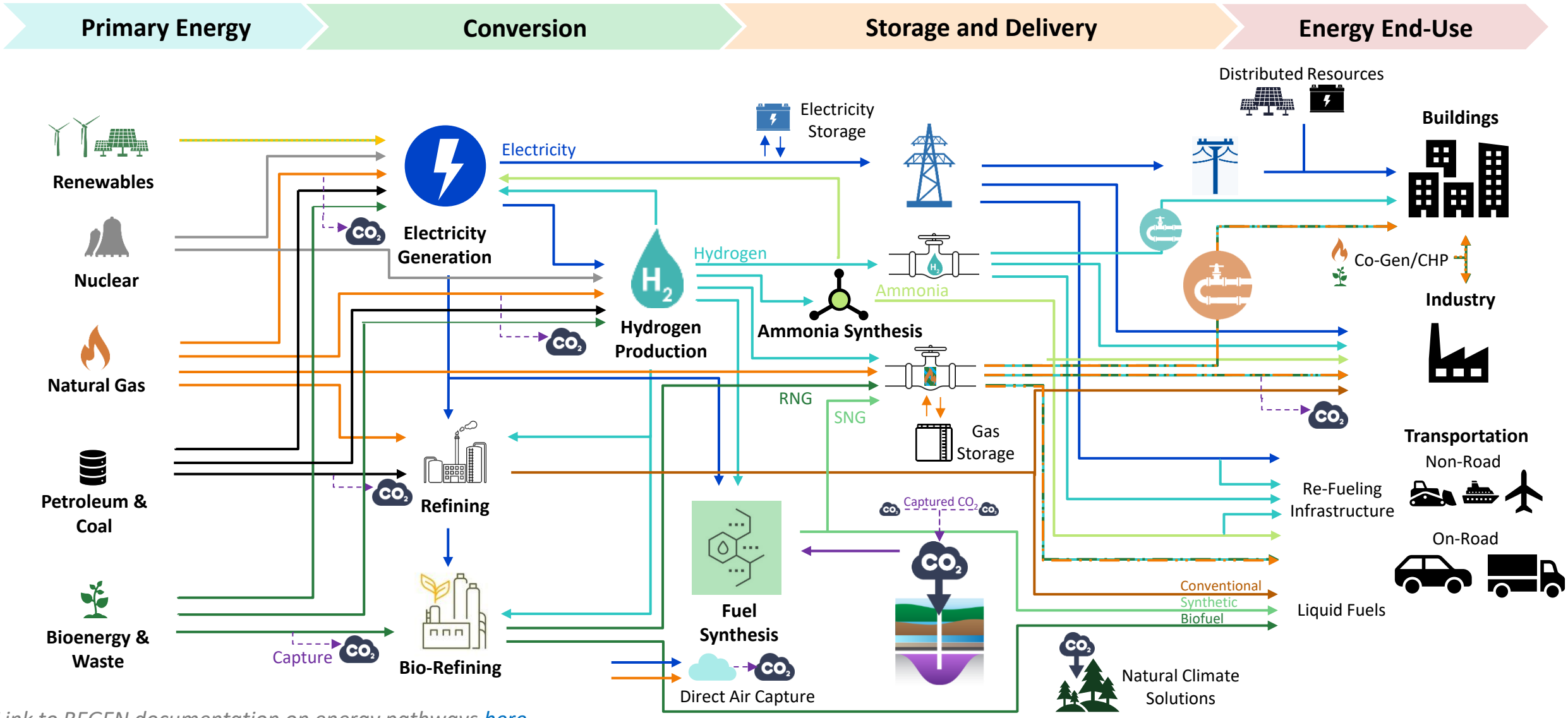
- Climate zones
- Building types
- Household characteristics
- Industrial mix
- End-use technology detail

Fuel Supply/Conversion

- Hydrogen, ammonia, biofuels, synthetic fuels production and conversion
- Pipeline investment and operation

Documentation, articles, and reports available at https://esca.epri.com

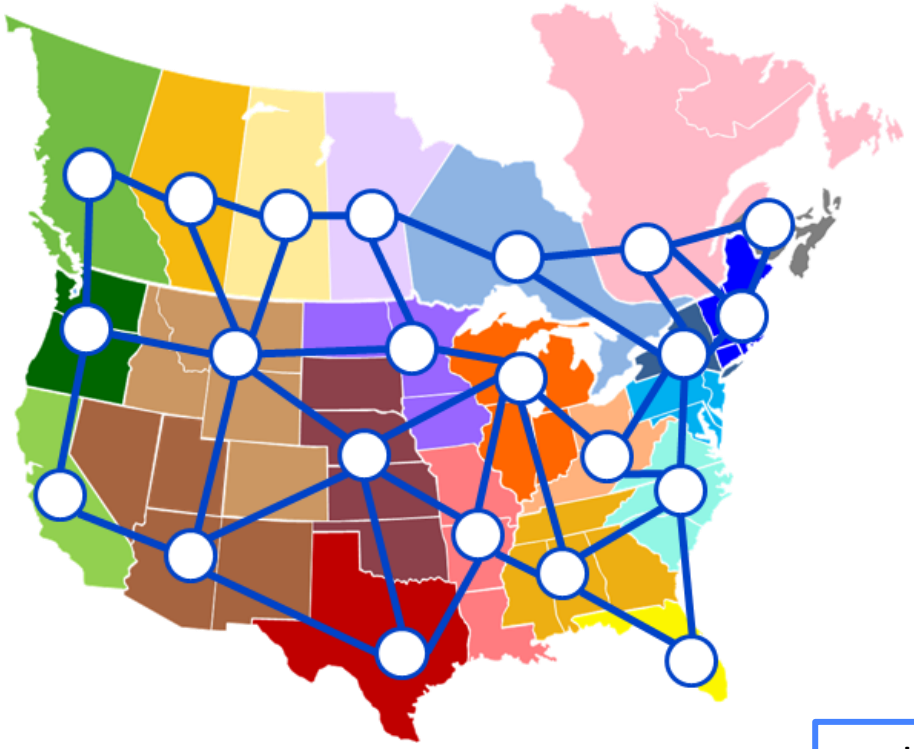
Economy-Wide Low-Carbon Energy Pathways



Link to REGEN documentation on energy pathways here

REGEN Combines National Coverage with Sub-National Detail

Example Regional Disaggregation from North American REGEN



Identify differences in regional resources (renewables, CO_2 storage, geothermal, etc.) and in projected energy demands

Understand existing ability to move energy between regions; co-optimize new inter-regional energy transfer capacity with energy production investments

Some REGEN versions offer ability to customize regions; zoom in on an area of interest while maintaining national coverage

Allows users to see and compare output data and insights by region

Link to North American REGEN documentation here

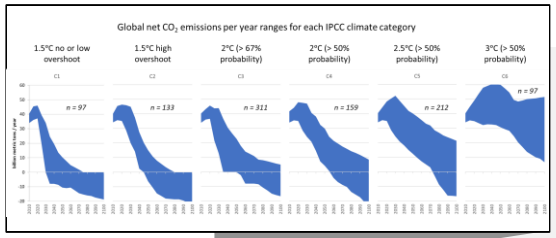
REGEN Designed to Assess Deep System Changes

Economy-Wide Technological Pathways to Deep Decarbonization

Understand technology pathways from the existing fleet to a future low-carbon fleet, while continuing to meet growing load in every hour.

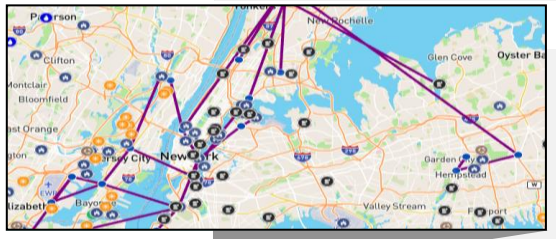
Climate and Energy Policies and Regulations

Analyze the impacts and unexpected outcomes of potential climate and energy policies and regulations, both electric sector and economy-wide.



Climate-Related Risk Assessment

Assist companies to evaluate climate-related risks from the transition to a low-carbon fleet to support their disclosure and target-setting strategies.



Scenario Design to Inform Resource Planning

Identify drivers of change beyond the boundaries of capacity expansion planning tools, including economy-wide policies and load changes, inter-regional trade, etc.

REGEN Representation of the Electric Sector

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REGEN Electric Sector Overview

Long Horizon Capacity Expansion Model with Regional Detail

Generation Capacity

Existing fleet and new investments to capture transition dynamics. Strong focus on low-carbon and emerging technologies not typically found in commercial planning models, with costs and performance based on EPRI expertise.

Energy Storage

Short-, medium-, and long-duration energy storage technologies included with hourly charging/discharging and option to track arbitrage, capacity, and ancillary services.

Inter-Regional Transmission

Endogenous representation of new inter-regional transmission capacity and hourly flows, all co-optimized with generation and energy storage investment and dispatch.

Regional and National Climate Policies

Large menu of climate policy and regulatory formulations, including policies that interact with other sectors, and coverage of existing policies and incentives, including state-based emissions policies, standards, and mandates.

Link to REGEN documentation on the electric sector model here

Electric Sector Investment Options in REGEN

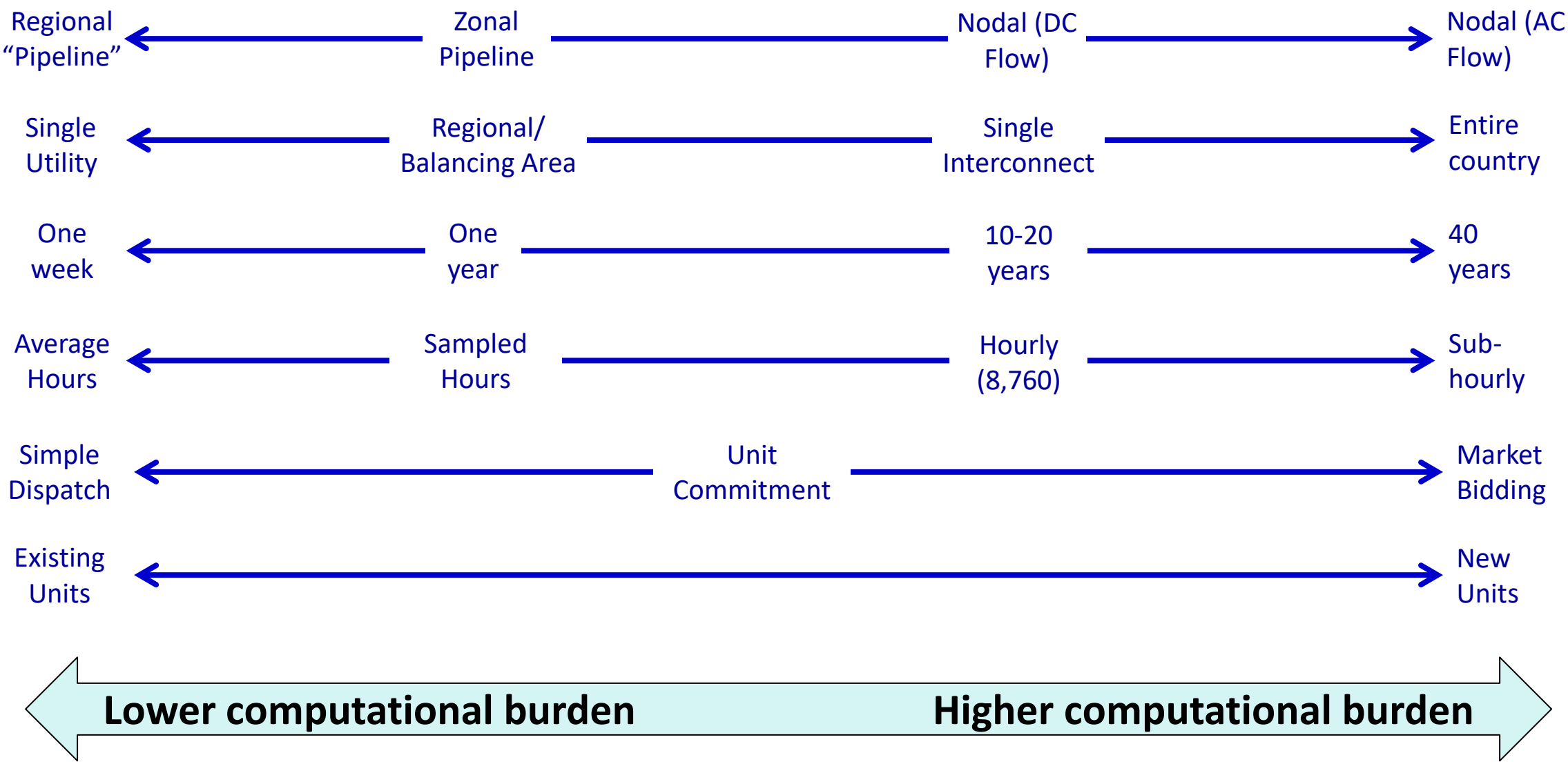
	Solar PV	**Variable Renewable Technologies**
	Onshore Wind	
	Offshore Wind	*Fixed Platform, Floating*
	Li Ion Battery	**Energy Storage Technologies**
	CAES/LAES	
	H_2/Electrolysis	
	Emerging Storage	*User Specified*
	Pumped Hydro	*Existing capacity endowment, no expansion*
	GT/RICE	**Dispatchable Generation Technologies**
	NGCC	
	NGCC+CCS	*90-98% capture; 90% retrofit option for existing units*
	Coal+CCS	*90-95% capture; 90% retrofit option for existing units*
	Bio+CCS	
	Nuclear	*Gen IV, SMR*
	Geothermal	*Enhanced geothermal forthcoming*
	Hydro	*Existing capacity endowment, no expansion*
		New Inter-Regional Transmission

Link to REGEN documentation on generation options here

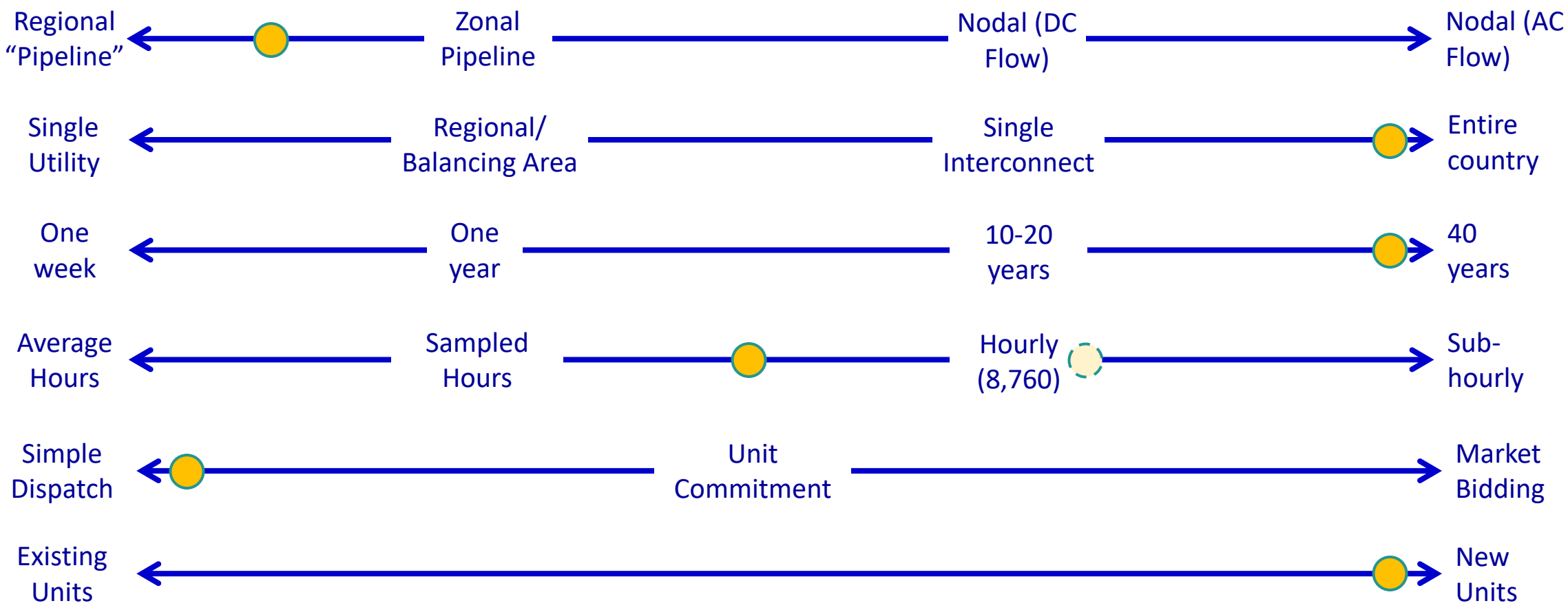
Other Technology Options Available in Selected Versions of REGEN

- Cofiring existing coal with biomass or ammonia
- Converting existing coal to NG or bio
- Cofiring existing NG units with H_2
- Biomass-fired (no CCS)
- Coal SCPC or IPCC (no CCS)
- Solar CSP with thermal storage
- Multi-fuel units

Key Computational Tradeoffs in Capacity Expansion Models

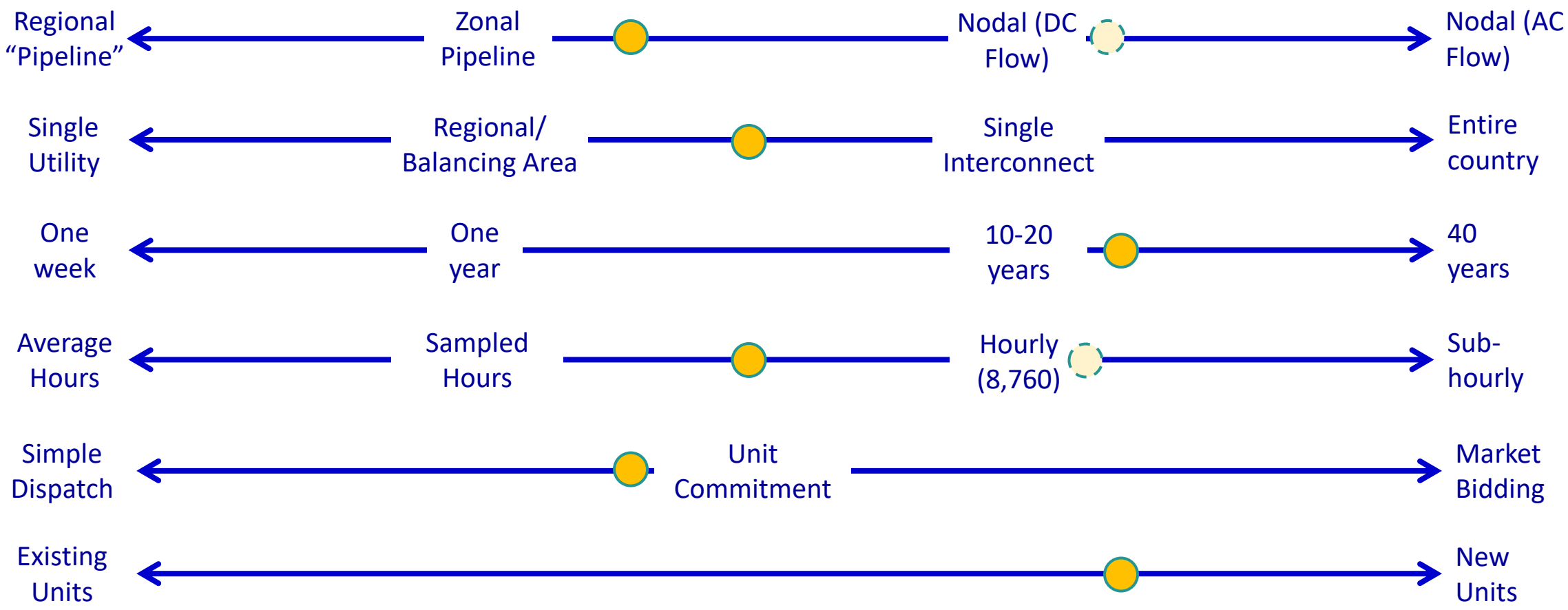


REGEN Electric Sector Capacity Expansion Model



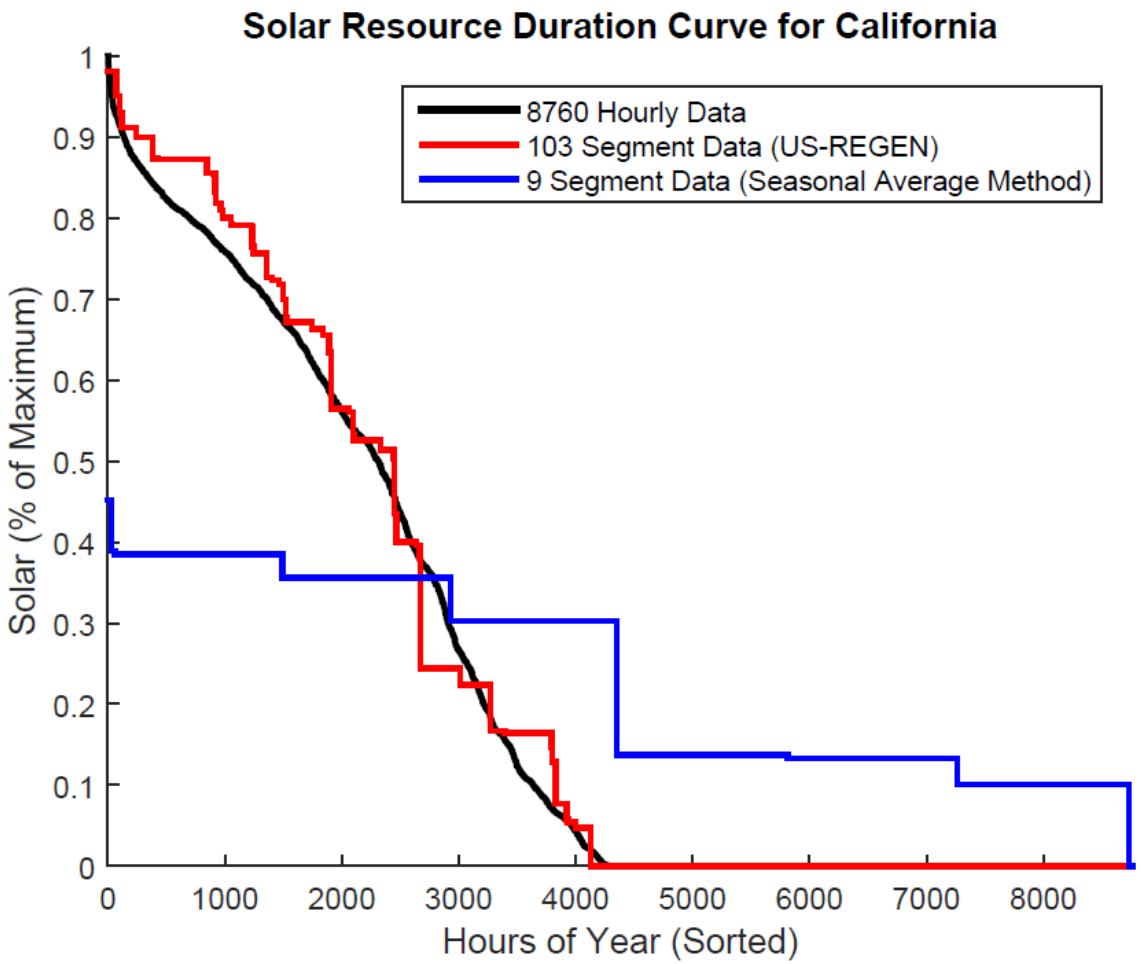
Best for exploring long-run system change

Typical Commercial Capacity Expansion Model



Best for evaluating investment needs for a given region assuming limited trade

REGEN Strength: Representation of Variable Renewables



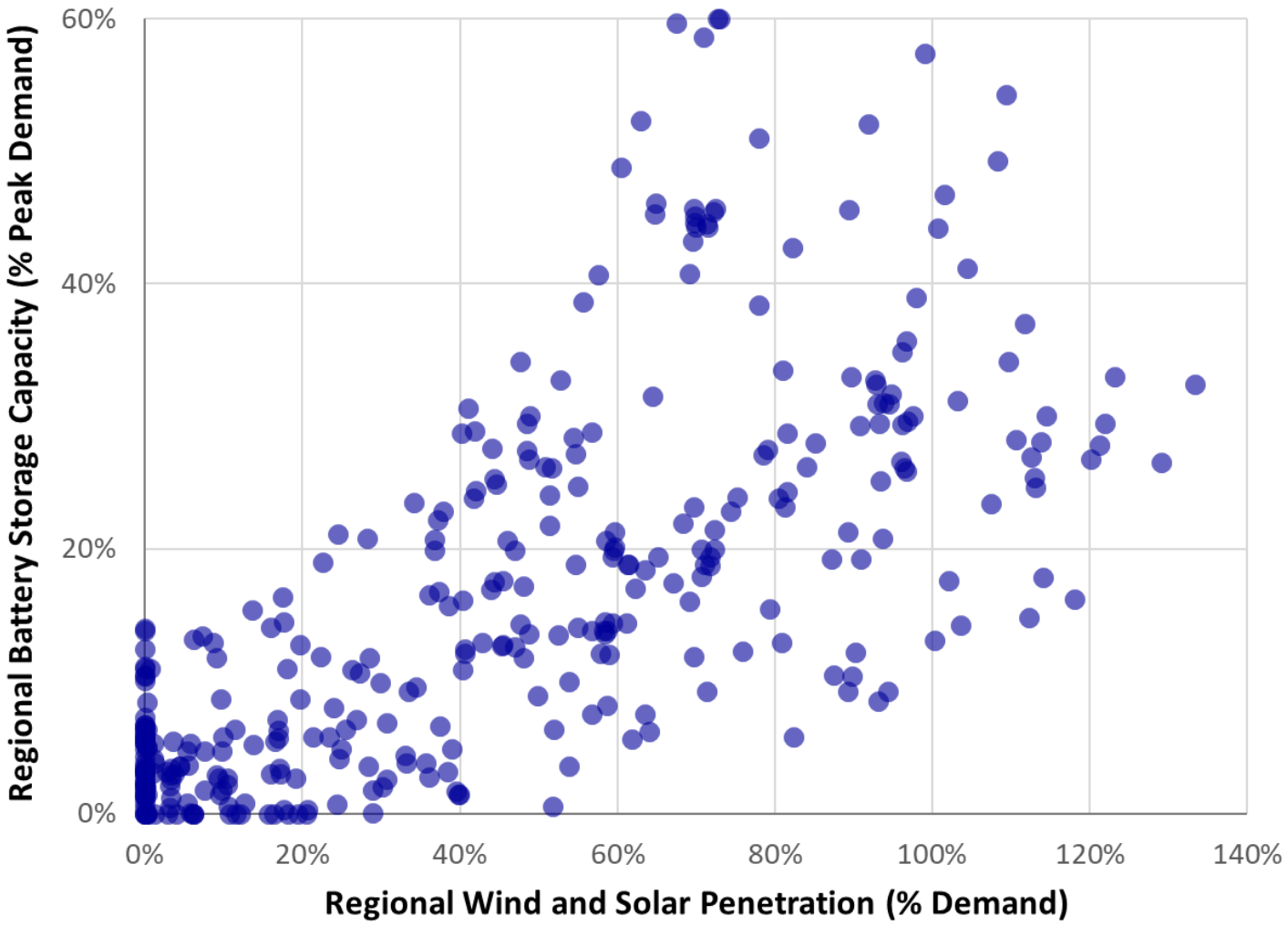
- US-REGEN employs an innovative "representative hour" selection algorithm to capture hourly wind, load, and solar shapes
- Captures hourly correlations in long time horizon models better than other approaches (e.g., Seasonal Average Method)

Source: Blanford, et al. (2018), "Simulating Annual Variation in Load, Wind, and Solar by Representative Hour Selection" (The Energy Journal)

Representing spatial and temporal variability are important for assessing system-dependent value

Link to REGEN documentation on hour selection approach here

REGEN Strength: Representation of Energy Storage



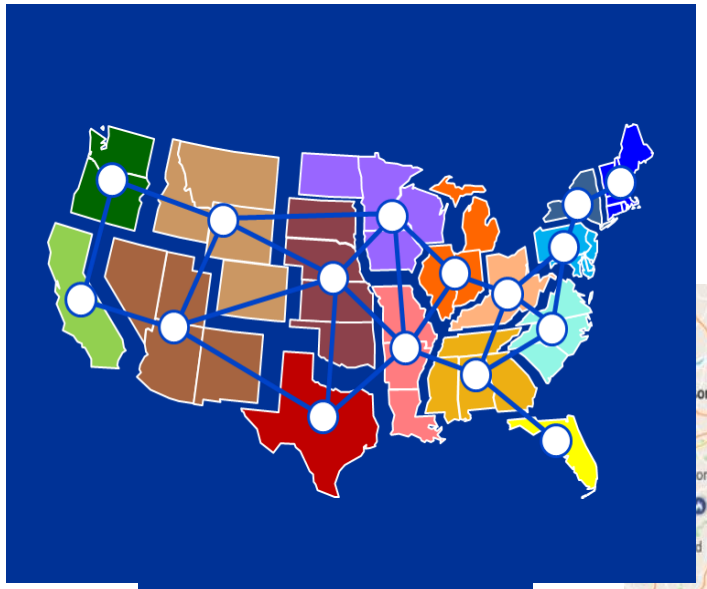
- Hourly resolution and chronology are important for capturing energy storage value
- Use 8,760 hours with single year investment and dispatch
- Storage valuation varies by region and assumptions about future technologies, markets, and policies (figure shows sensitivities on renewable costs, gas prices, CO_2 policy)

Source: Bistline and Young (2019), "Economic Drivers of Wind and Solar Penetration in the U.S." (Environmental Research Letters)

REGEN can accurately represent the economics of charging/discharging with hourly resolution

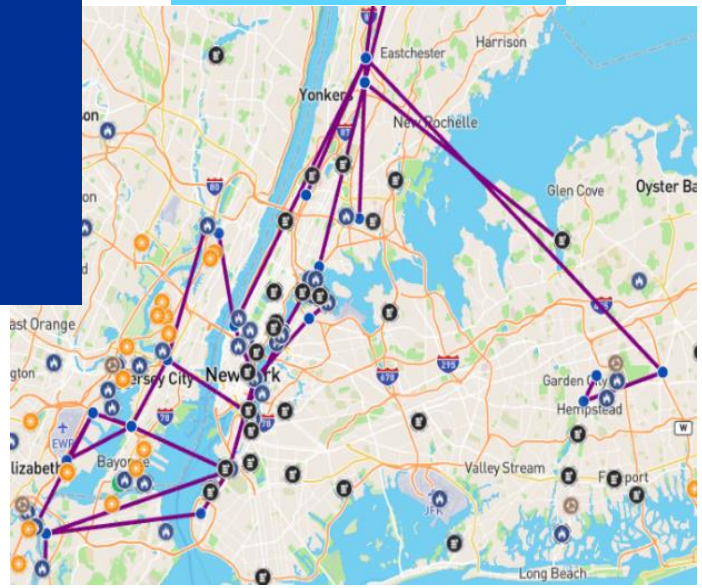
Link to REGEN documentation on energy storage here

REGEN Strength: Automated Link to PLEXOS



US-REGEN

PLEXOS
(ex. NYC System)



Source: de Mello, et al. (2023), "Linking Capacity Expansion, Resource Adequacy, and Production Cost Modeling Tools for Integrated Strategic System Planning" (EPRI, ID 3002028534)

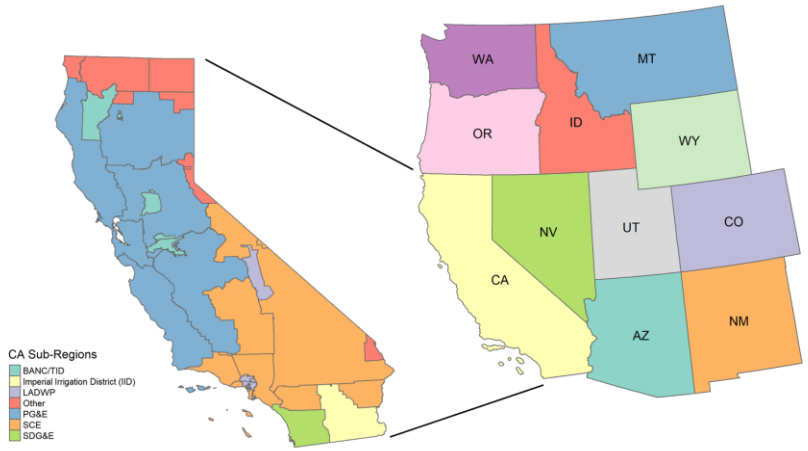
- EPRI's Integrated Strategic System Planning (ISSP) Initiative created the machinery to **automatically move input and output data from REGEN to PLEXOS**
- Allows for coordinated planning from long run scenario analysis (REGEN) through nodal, unit-level capacity expansion, resource adequacy, and production cost modeling, **using a consistent set of assumptions and data** across all tools
- REGEN provides a customized "starting point," informing optimal candidate generation resources, inter-regional transmission needs, and long-term load projections for the specific region of study

REGEN scenario analysis can support resource planning accounting for economy-wide interactions and risks

Use Case: Reliability of California SB100 Clean Electricity Rule

Scenario analysis of SB100 and decarbonization in California linked to reliability and resource adequacy analysis

CA-REGEN



- Integration of variable renewables
- Zonal transmission and interchange
- Regional policies and constraints
- Range of low and zero-carbon technologies
- Investment and dispatch

AUTOMATED LINK

Hourly Load, Renewables, Scenario Constraints, and Technology Characteristics

FEEDBACK LOOP

CA-PLEXOS Sub-State Level Expansion

PLEXOS BY ENERGY EXEMPLAR

- Individual electric generating units
- Localized load
- Nodal transmission and power flows
- Investment and dispatch
- Reliability assessments and mitigation opportunities

Modeling deployed for California Energy Commission report due Q4 2025

REGEN Representation of Energy Use

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REGEN Energy Use Modeling

Long Horizon 8,760 Hourly Customer Choice Model with Regional Detail

Buildings

Representation of existing building stock, current appliance use, and load-shapes. Representation of future temperature at an hourly basis, which drives heating/cooling demand, and emerging technologies (i.e., high efficiency heat pumps).

Transportation

Representation of light-, medium-, and heavy-duty vehicles, shipping, aircraft, rail. Representation of miles traveled, vehicle sub-classes, emerging technologies (e.g., hydrogen-fueled trucks).

Industry

Representation of industrial activities (e.g., process heat, machine drive) and off-road vehicles, excluding energy production and conversion processes captured by the fuels model. Some sub-sector detail for cement, iron, and steel as well as a detailed representation of steam demand by temperature requirements across all manufacturing.

Distributed Generation Model

Representation of residential and commercial rooftop solar adoption decisions based on retail electricity prices.

Link to REGEN documentation on buildings, industry, and transportation

REGEN Energy Use Level of Detail by Sector

On-Road Vehicles

- Personal Light-Duty
- Light Commercial Trucks
- Medium- and Heavy-Duty
- Buses

→ ICEV, PHEV, BEV, FCV, Mobility-as-Service (personal LDVs)

Non-Road Vehicles

- Passenger Rail
- Freight Rail
- Aviation
- Shipping
- Military

→ Liquid Fuels (ICE), CNG, Battery Electric, Hybrid Electric, Fuel Cell, Ammonia (shipping)

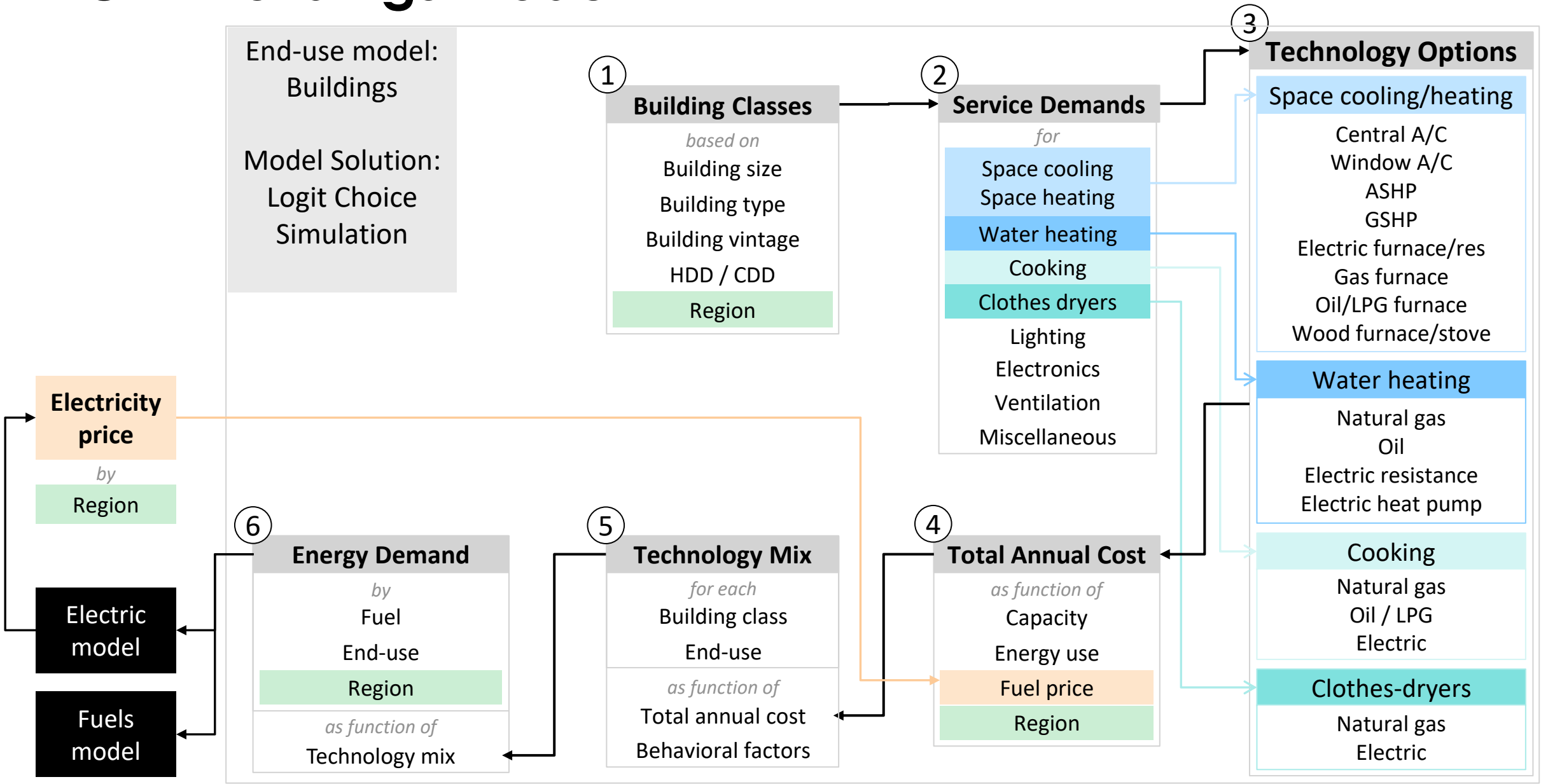
Residential and Commercial

- **Space Cooling** → Central A/C, Window A/C, Air-Source Heat Pump, Ground-Source Heat Pump, Electric Furnace/Resistance, Gas-Fired Furnace, Oil/Propane-Fired Furnace, Hydrogen-Fired Furnace, Wood-Fired Furnace/Stove
- **Space Heating**
- **Water Heating**
- **Clothes Dryers**
- **Cooking**
- Lighting
- Other Appliances
- Electronics
- Ventilation
- Other Building

- **Iron & Steel** → Blast Furnace (+ CCS), Electric Arc Furnace, DRI with NG or H_2
- **Cement** → Blast Furnace (+ CCS), Electric Arc Furnace, DRI with NG or H_2
- **Bulk Chemicals** → With CCS, Without CCS
- **Paper/Pulp/Wood** → With CCS, Without CCS
- **Food, etc.** → With CCS, Without CCS
- **Other Manufacturing** → With CCS, Without CCS
- **Agriculture** → Boilers: Co-gen Boilers, Process Heat, Machine Drive, Feedstocks, Facilities
- **Construction** → Boilers: Co-gen Boilers, Process Heat, Machine Drive, Feedstocks, Facilities
- **Mining (non-energy)** → Boilers: Co-gen Boilers, Process Heat, Machine Drive, Feedstocks, Facilities
- Non-Building Commercial → Boilers: Co-gen Boilers, Process Heat, Machine Drive, Feedstocks, Facilities
- Water Services → Boilers: Co-gen Boilers, Process Heat, Machine Drive, Feedstocks, Facilities
- Petroleum Refining → Boilers: Co-gen Boilers, Process Heat, Machine Drive, Feedstocks, Facilities
- Upstream Energy Extraction → Boilers: Co-gen Boilers, Process Heat, Machine Drive, Feedstocks, Facilities
- → **Non-Road Vehicles**

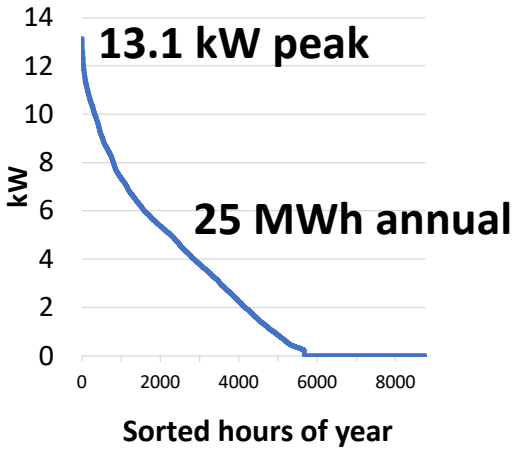
SECTORS / ACTIVITIES → **END-USES** → **TECHNOLOGIES**

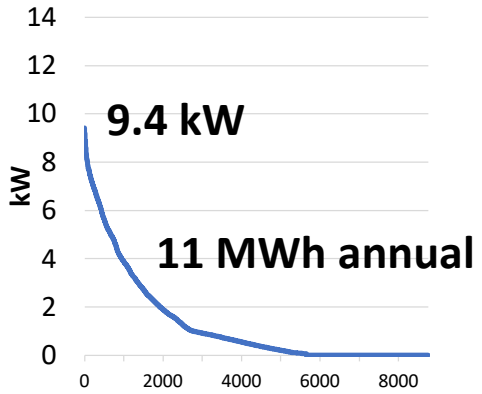
REGEN Buildings Model

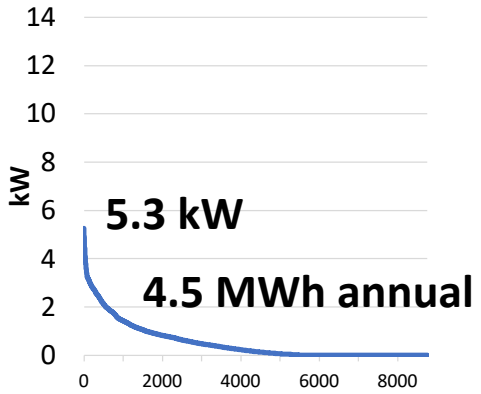


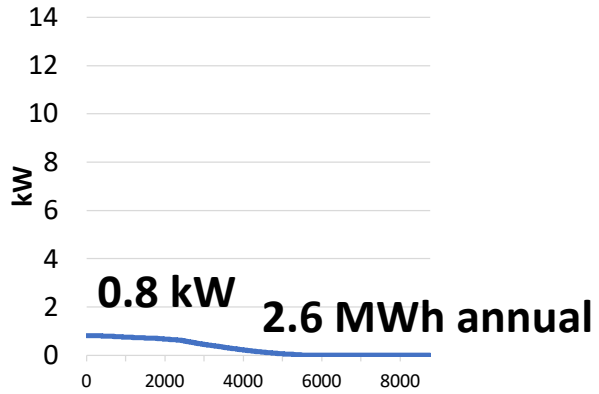
Space Heating Load Shape Examples

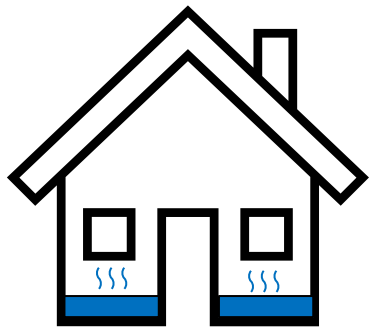
Sorted annual (diversified) load for representative house, a 3,000 sq. ft. single-family home in central Michigan



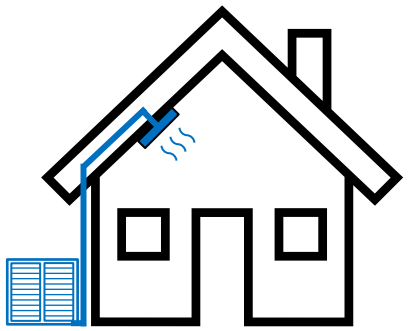




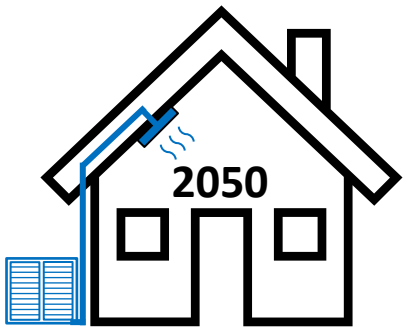




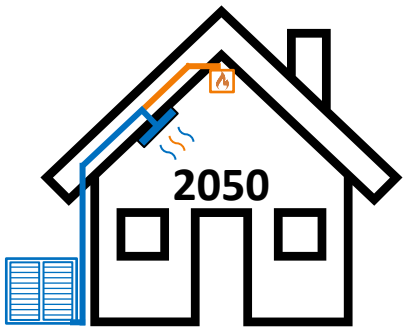
Older home with electric resistance heating



Current new home with current (single speed) air-source heat pump



Future new home with **future** variable speed air-source heat pump



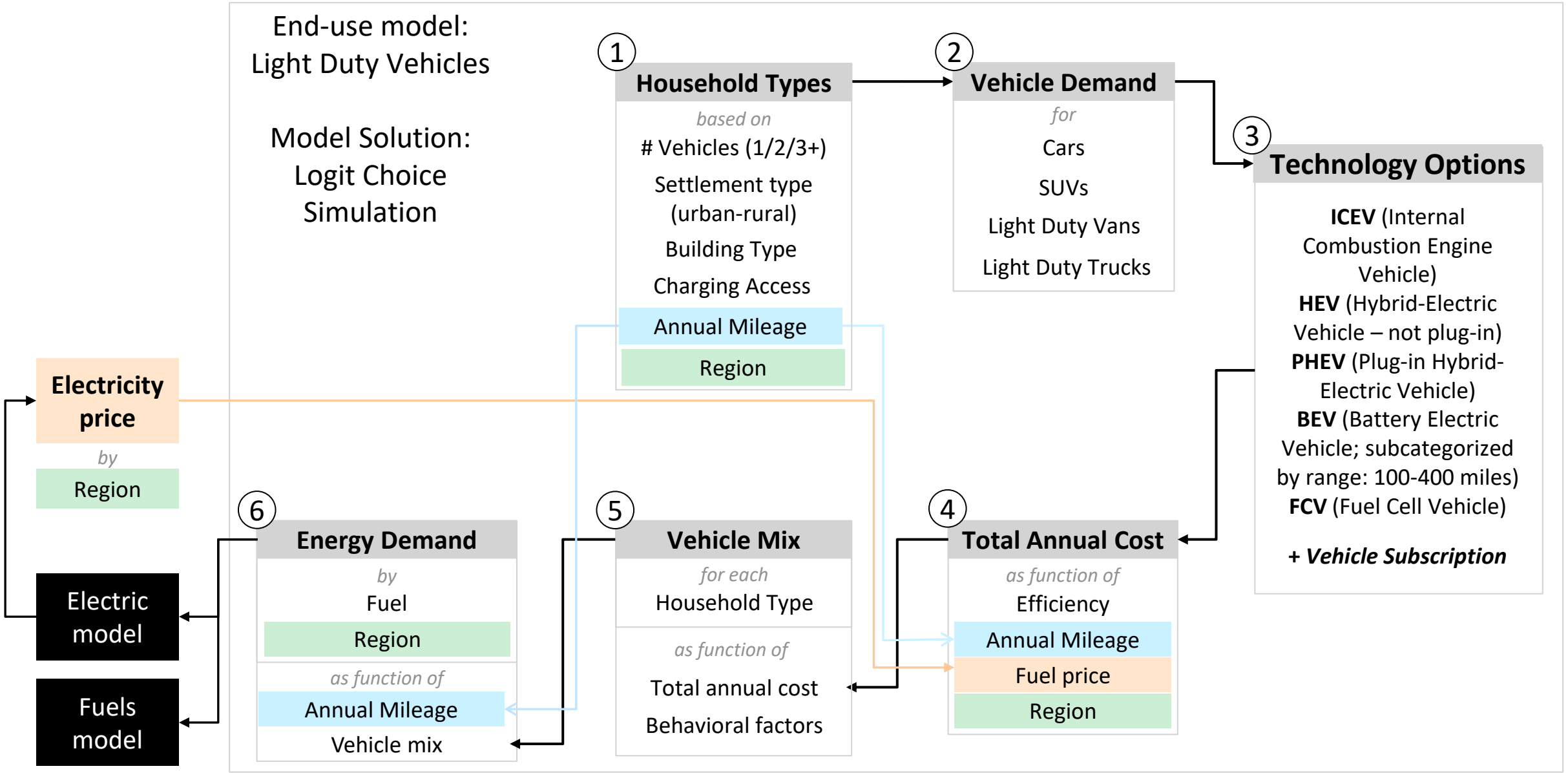
Future new home with **future** heat pump + hybrid gas back-up

Source: Molar-Cruz, et al. (2024), "Assessment of Buildings Sector Decarbonization Strategies in a Net-Zero Economy" (EPRI, ID 3002030650)

REGEN Light Duty Vehicles Model

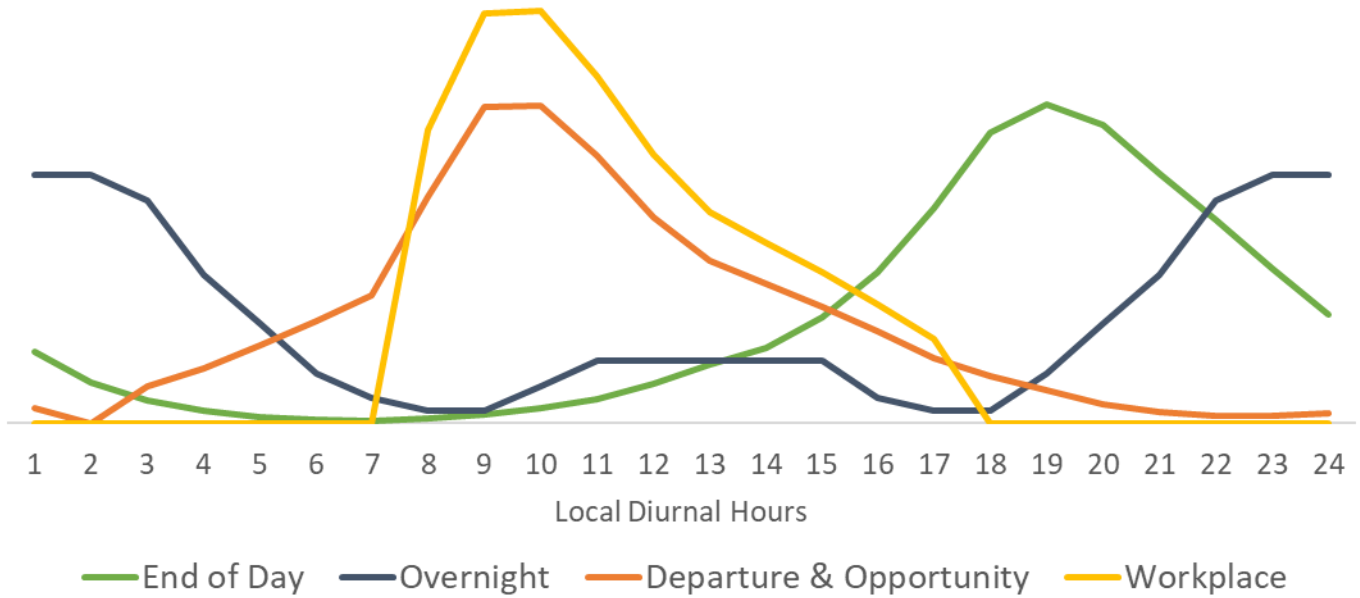
End-use model:
Light Duty Vehicles

Model Solution:
Logit Choice
Simulation

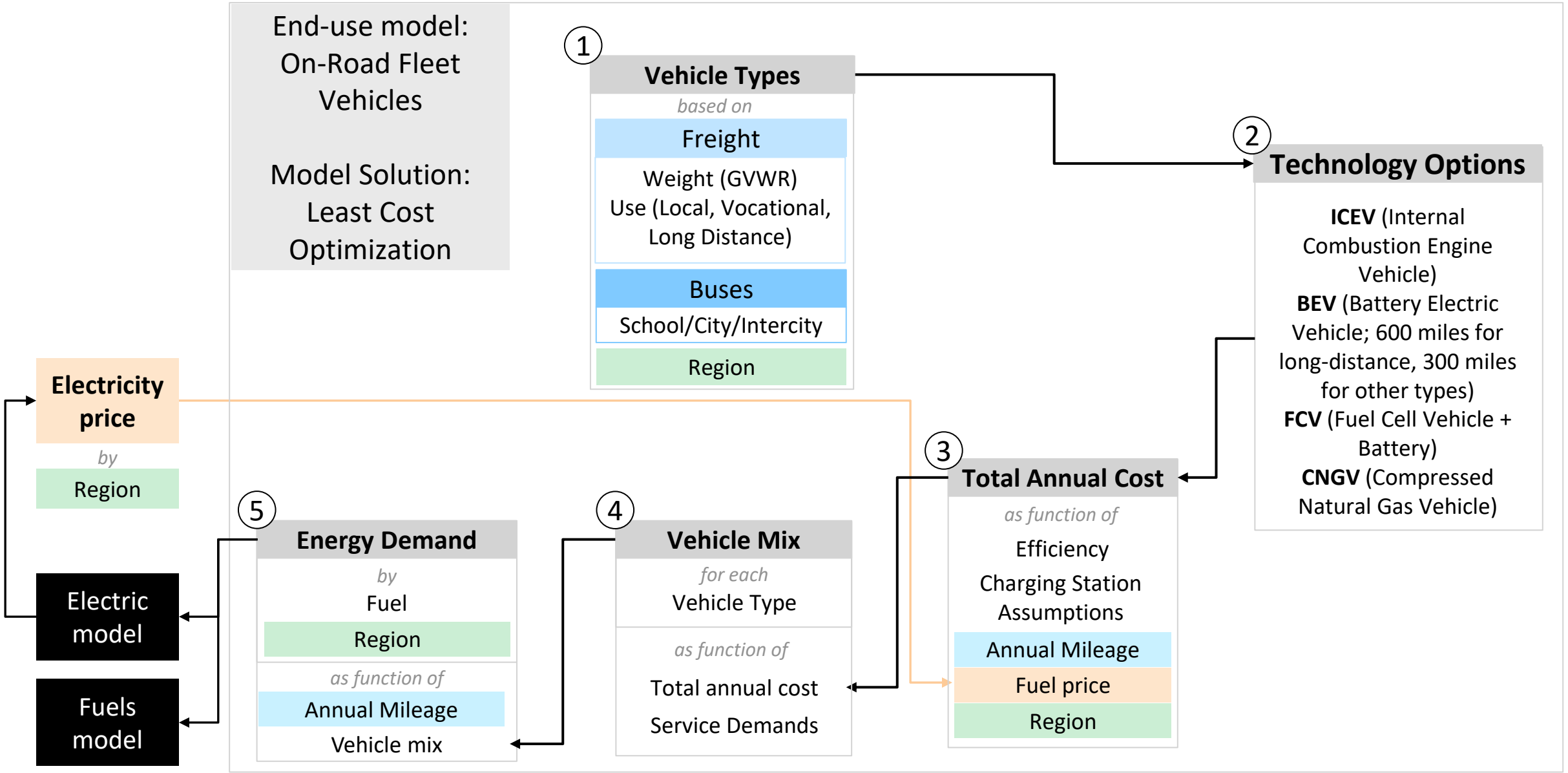


Default (Uncoordinated) Charging Profile for LDVs

- **Daily energy for charging** → Varies across structural classes, regions, and days based on annual vehicles miles traveled and temperature impact on charging efficiency
- **Allocation across exogenous diurnal profiles** →
  - End of Day
  - Overnight
  - Departure & Opportunity
  - Daytime



REGEN On-Road Fleet Vehicles Model



Charging Equipment Cost Assumptions

		Vehicles per Station	Charging Level / kW	Cost per station ($000)
Light-Duty	Single-Family Home with Home Charging	1 (2 for PHEV)	Level 2 / 6 kW	1 (1.5 for urban)
	Multi-Family with On-Site Public Charging	1-4 (depends on BEV range and access to workplace charging)	Level 2 / 6 kW	3 (6 for urban)
	Workplace Public Charging	1-4 (depends on BEV range and access to home charging)	Level 2 / 6 kW	3 (6 for urban)
	Destination Public Charging	1-2 if no home/work 10 if home or work 20 if home and work	Level 2 / 6 kW	3 (6 for urban)
	Highway Fast Charging	30	Level 3 DC / 60 kW	24
MD/HD	Class 3 Truck Fleet Charging	2	Level 3 DC / 60 kW	40
	Class 4-6 Truck Fleet Charging	2	Level 3 DC / 100 kW	60
	School Bus Fleet Charging	3	Level 3 DC / 135 kW	75
	Class 7-8 Truck / Bus Fleet Charging	3	Level 3 DC / 250 kW	150

REGEN Non-Road Vehicles Model

Non-Road Fleet Vehicles Model Solution: Least-Cost Optimization

1 Categories

Aviation
(Long/Short Distance)

International Shipping

Other Maritime
(Freight/Passenger/Rec.)

Rail
(Freight/Commuter/ Intercity/Transit)

Other Off-Road
(Ag./Const./Mining/Military)

2 Technology Options

Petroleum

Hydrogen

Ammonia

Electricity

Biofuels

Synthetic Fuels

3 Total Annual Cost

as function of

Efficiency

Charging Station Assumptions

Service Demand

Fuel price

Region

4 Technology Mix

For each

Category

as function of

Total Annual Cost

Service Demand

5 Energy Demand

by

Fuel

Region

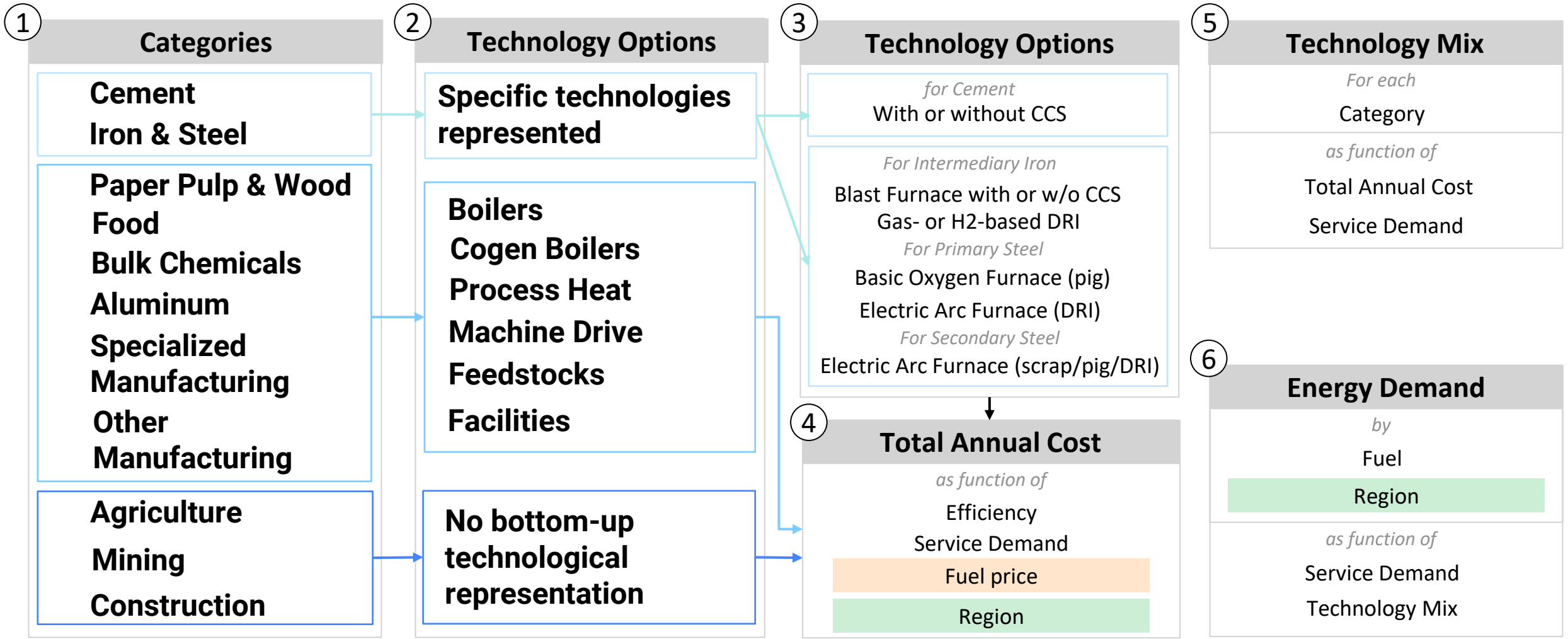
as function of

Service Demand

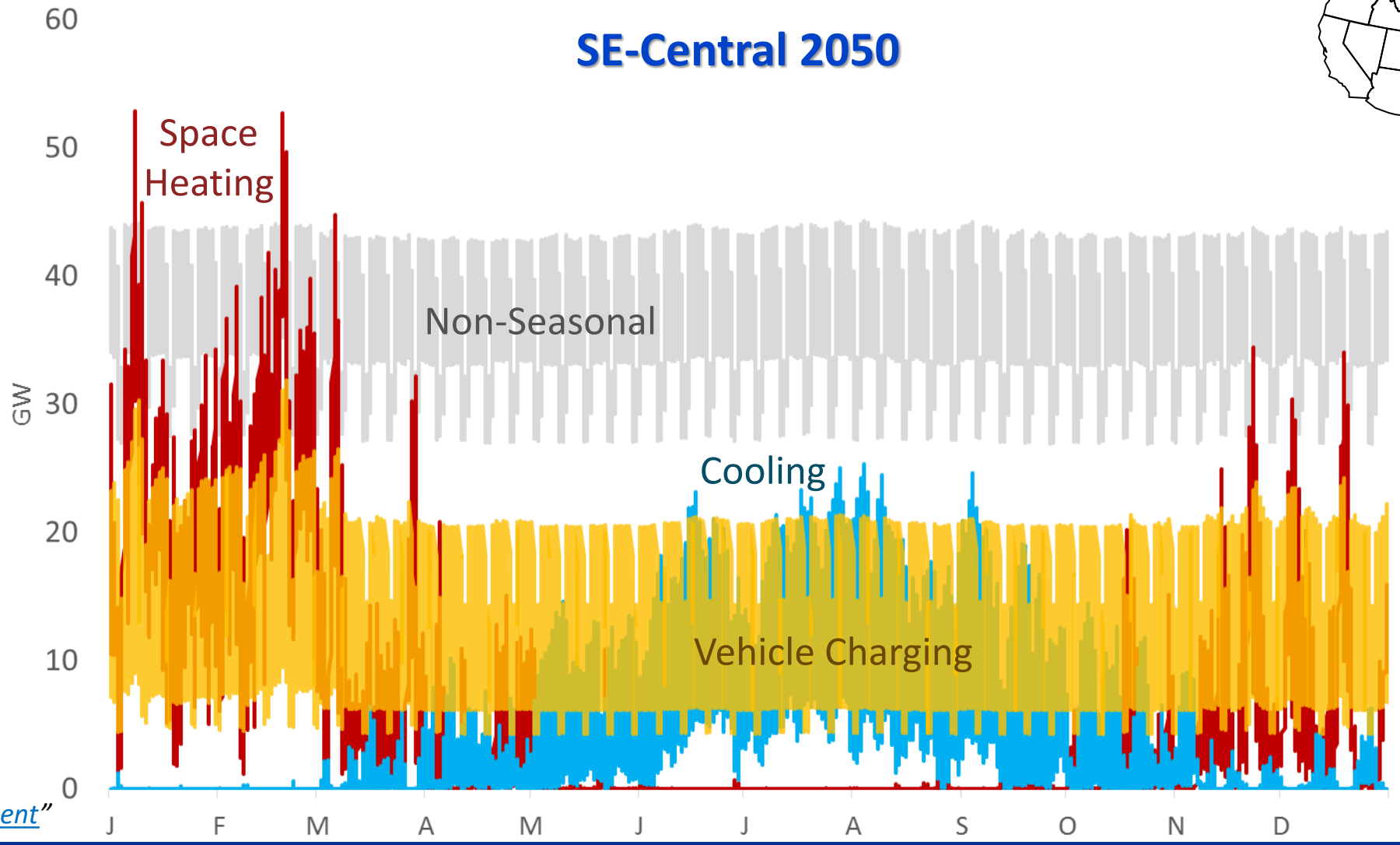
Technology Mix

REGEN Industry Model

Industry Model Solution: Least-Cost Optimization



REGEN Strength: Hourly Endogenous Load Projections

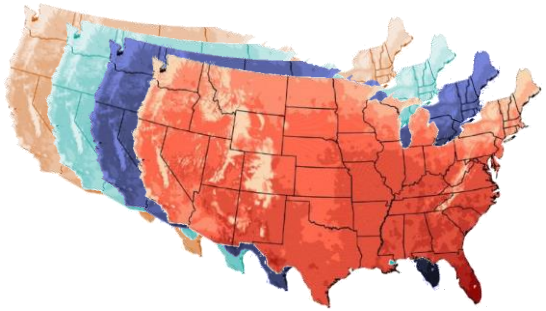


Source: EPRI (2018), "U.S. National Electrification Assessment"

REGEN projects how consumers invest and use energy hourly based on costs and fuel prices

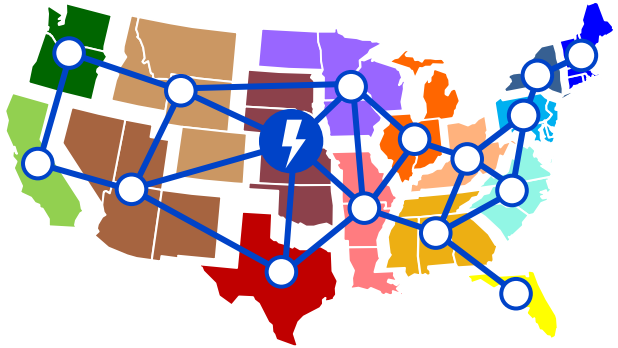
Link to detailed load shape analysis here

REGEN Strength: Future Climate Data and Impacts



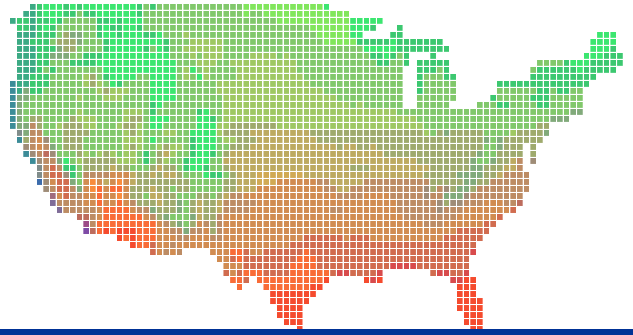
Multiple Weather Years + Warming Scenario

US-REGEN Electric Sector



- **Hourly wind and solar profiles**
- **Hourly air temperature**
  - **Solar PV efficiency loss**
  - **Thermal generator efficiency loss**
  - **Transmission line capacity loss**

US-REGEN Energy Use



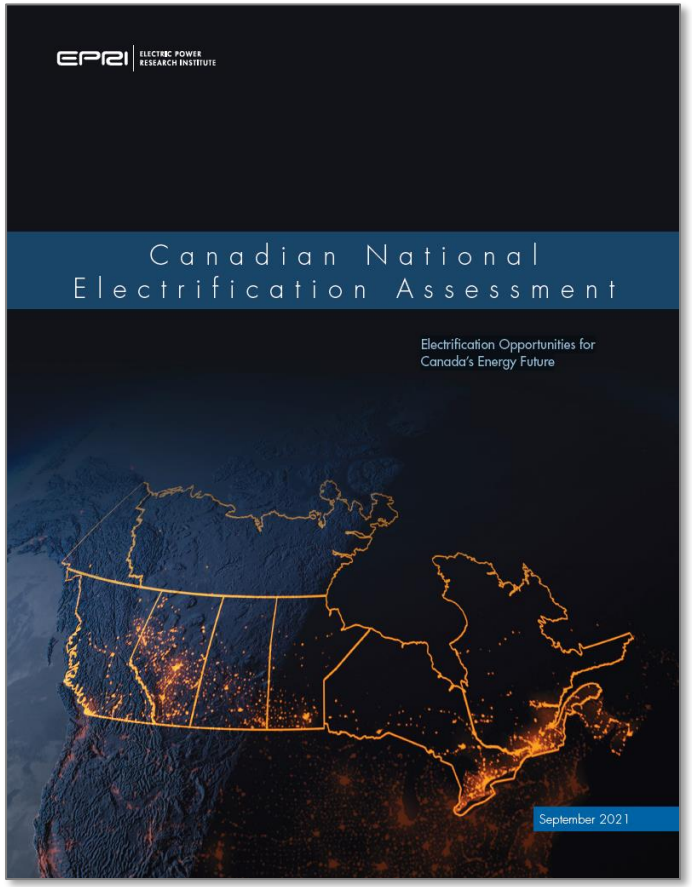
- **Hourly air temperature**
  - **Bottom-up estimates of building heating/cooling load**
  - **Electric vehicles charging load**

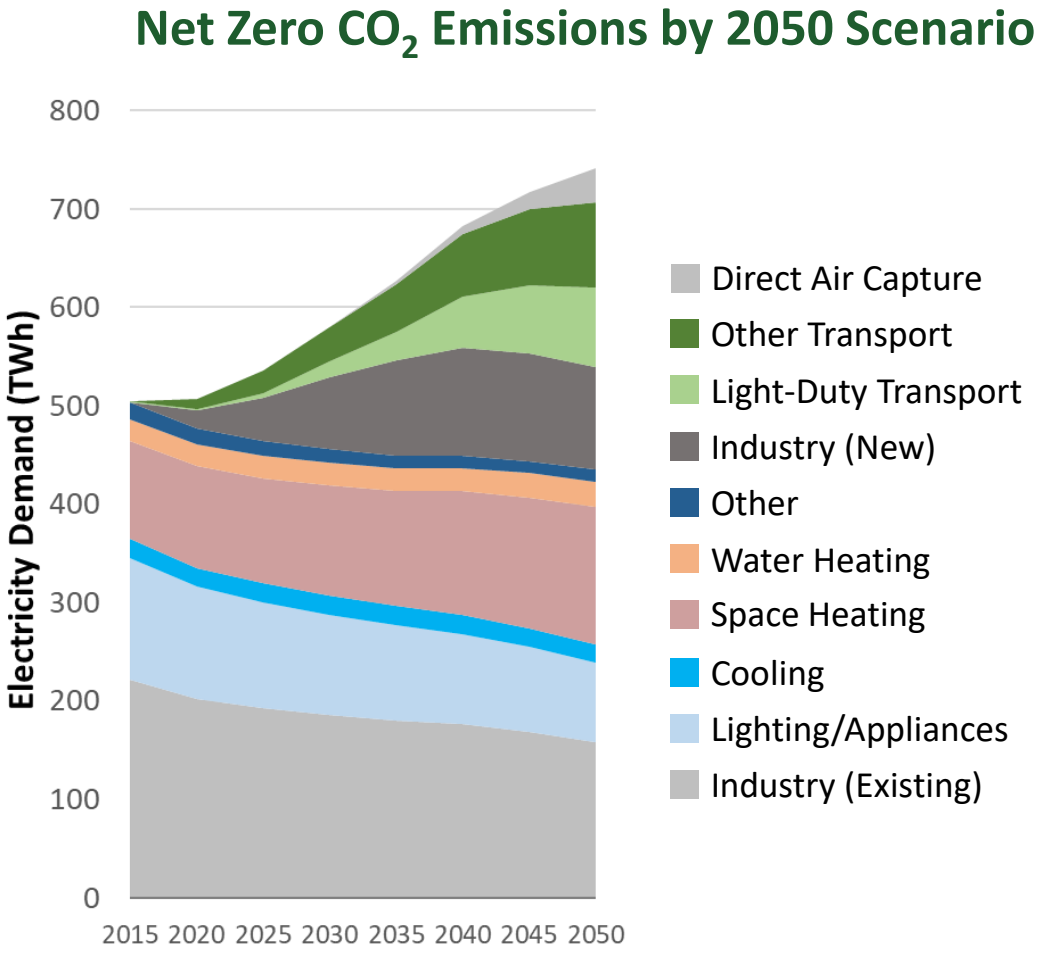
- REGEN builds in several climate impacts affecting supply and demand of electricity
- Scenario analysis can use different weather years and/or warming scenarios from the National Climate Assessment

REGEN leverages EPRI weather and climate expertise to incorporate future climate impacts in scenarios

Use Case: 2021 Canadian National Electrification Study

Scenario analysis of current and potential future Canadian climate policies and their impact on electrification





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https://www.epri.com/research/products/000000003002022642 (Français)

REGEN Representation of Fuels Supply

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REGEN Fuels Supply

Fuels Production, Conversion, and Transport Optimization Module with Regional Detail

Low-Carbon Fuels

Representation of low-carbon fuels, such as hydrogen, biofuels, ammonia, and synthetic fuels, many of which are not commercialized yet.

Integrated Fuel Supply and Conversion Pathways

Model co-optimizes over interdependent production and conversion technology pathways to find the least-cost fuel supply mix to meet end-use energy service demands.

Bioenergy Resource Curves

Bioenergy resource curves from FASOM land-use model inform cost and quantity of potential feedstock supply by region for biofuel pathways.

Fuel Delivery Infrastructure

Model accounts for infrastructure costs to move alternative fuels between production, conversion, storage, and delivery.

Link to REGEN documentation on the fuels supply model here

Fuel Conversion Investment Options in REGEN

Hydrogen Technologies

- Conventional SMR (using NG)
- Biomass Gasification
- Coal Gasification

With or without CCS

- Electrolysis — *PEM, Alkaline, High-temp steam*

Ammonia Technologies

- Conventional Haber-Bosch (using NG)
- Haber-Bosch with CCS
- Haber-Bosch with H_2 input (incremental synthesis)

Biofuel Technologies

- Conventional Ethanol
- Renewable NG from Waste Streams — *Limited Resource*
- Bio-based gasoline
- Bio-based diesel
- Bio-based jet fuel

Fischer-Tropsch

- Renewable NG from bio-gasification

From cellulosic bio-feedstocks, With or without CCS

Synfuel Technologies

- Synthetic NG from H_2 and CO_2 (e.g. methanation)
- Synthetic jet fuel from H_2 and CO_2

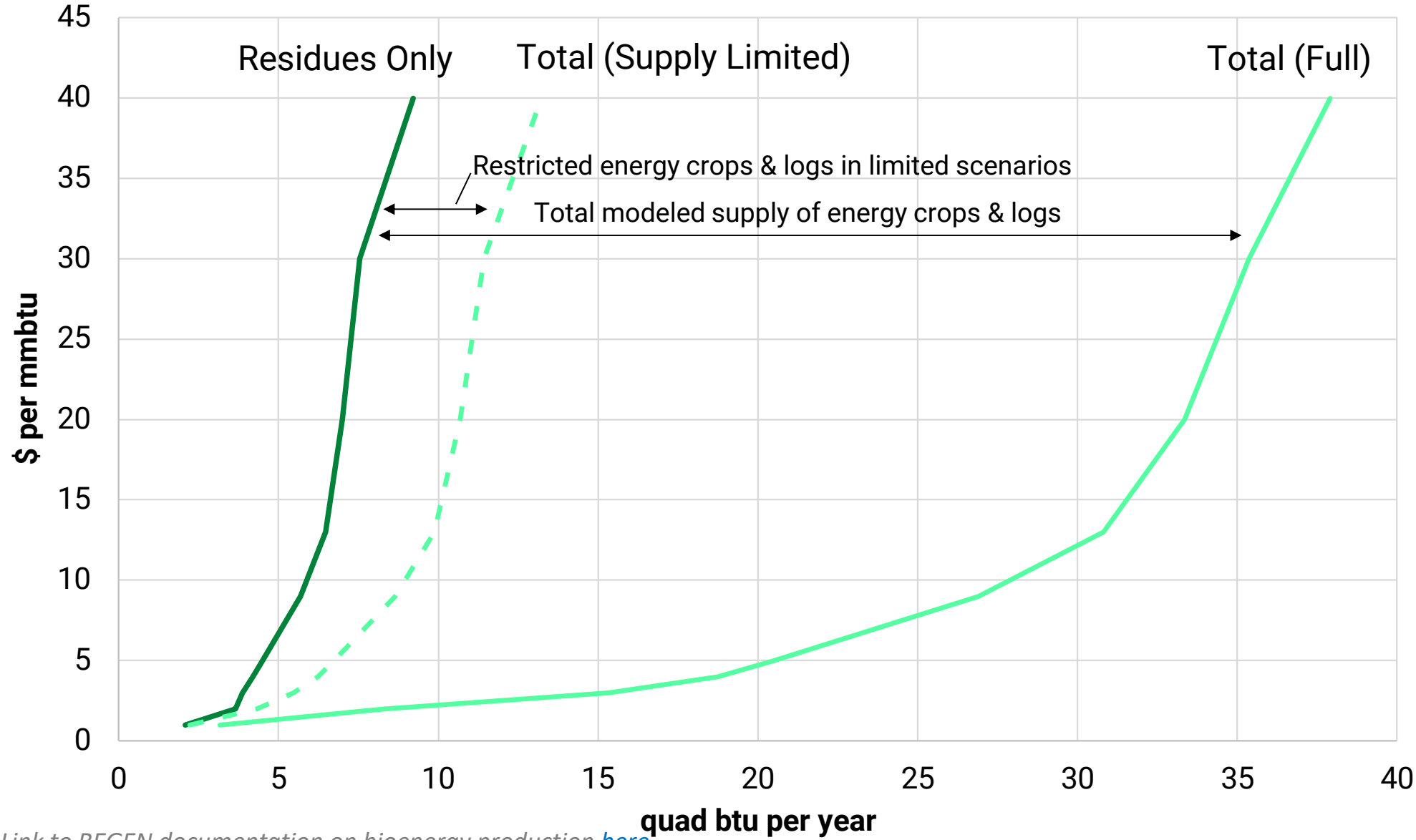
- Direct Air Capture

New Inter-Regional CO_2/H_2 Pipeline, CO_2/H_2 Storage Capacity

Other Technology Options Available in Selected Versions of REGEN

- Petroleum refining
- Coke ovens
- Solid biomass from feedstocks
- Retrofit ethanol with CCS
- Distributed hydrogen electrolysis
- Methanol production
- Ethylene production

Bioenergy Feedstock Supply Curves in 2050 (U.S. Total)

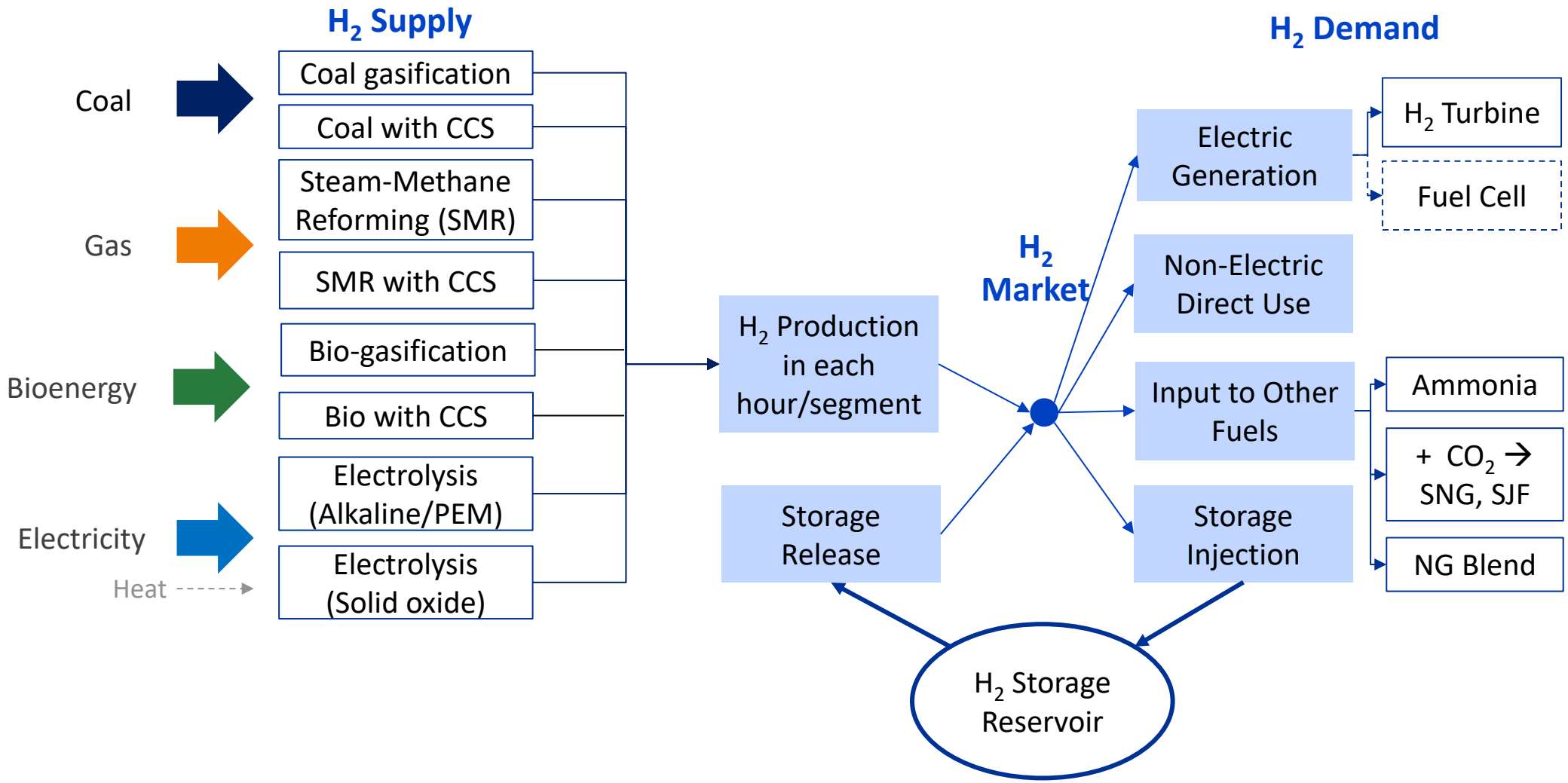


Crop Residues

Giant Miscanthus

Link to REGEN documentation on bioenergy production here

REGEN Strength: Hydrogen Production & Use

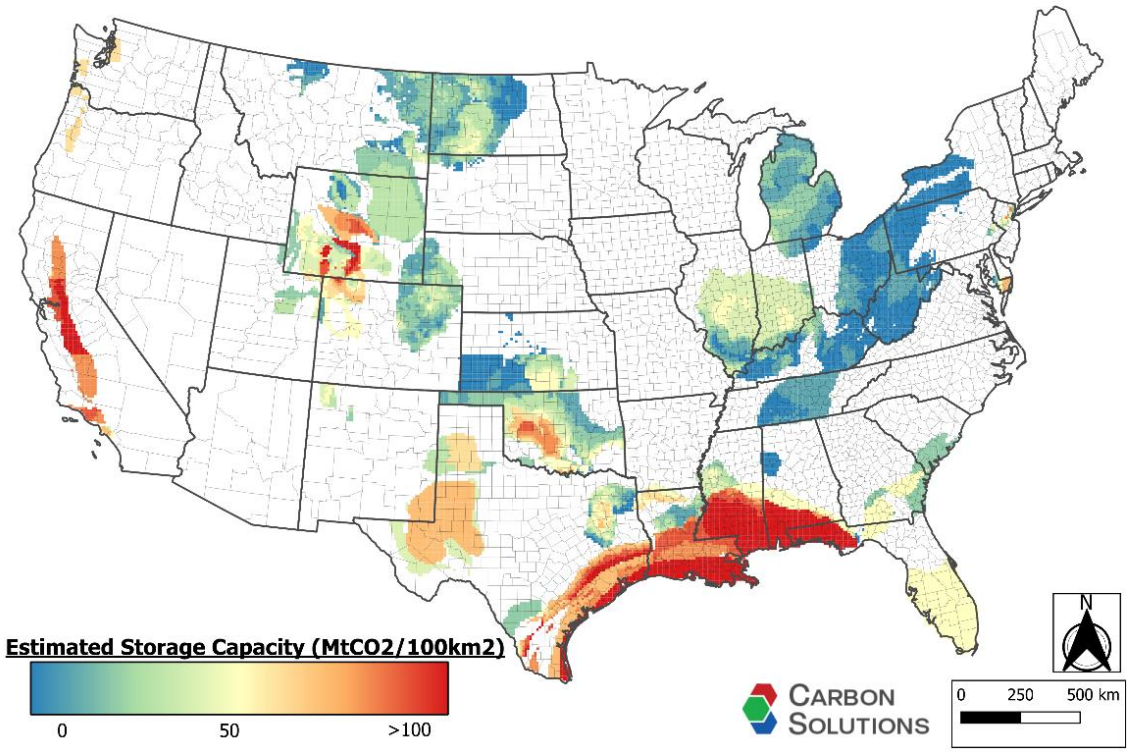


REGEN represents multiple hydrogen production and use pathways informed by EPRI LCRI research

Link to REGEN documentation on hydrogen production here

REGEN Strength: CO_2 Storage & Pipeline Modeling

CO_2 Storage Capacity: Reference Case



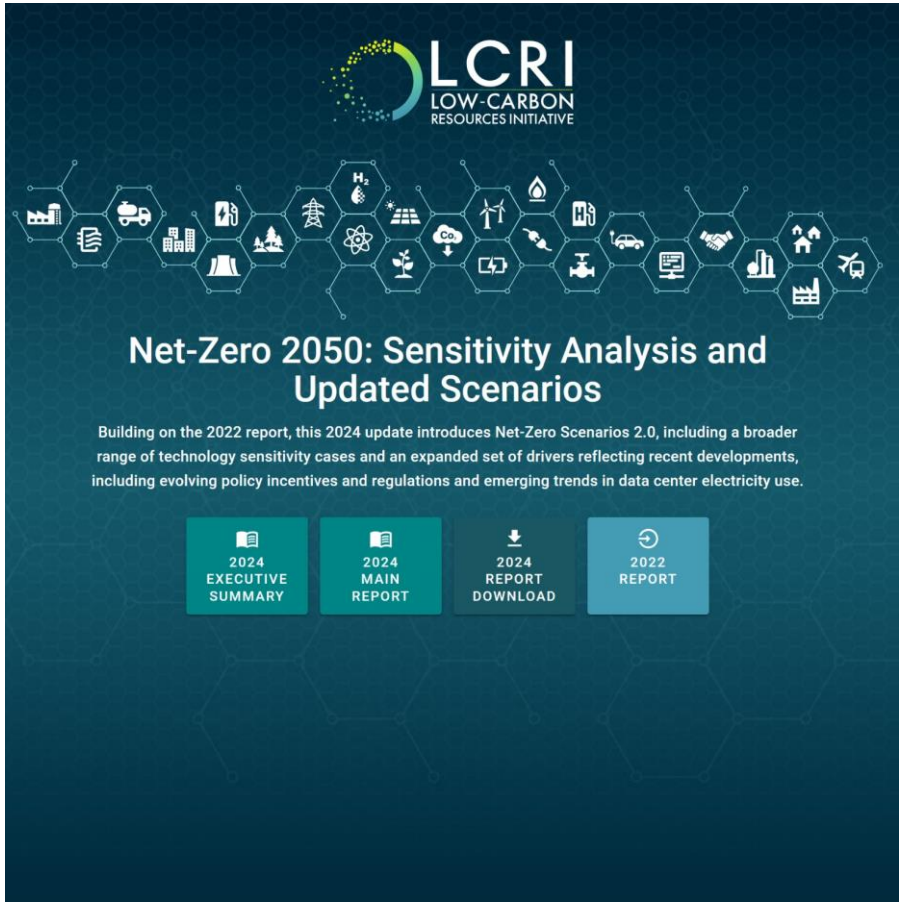
- REGEN can represent CO_2 storage and injection costs, and new CO_2 pipelines between model regions
- Costs and capacity based on a recent LCRI study with Carbon Solutions, with three scenarios to capture uncertainty related to formation thickness, porosity, and permeability
- Requires significant geological data and modeling

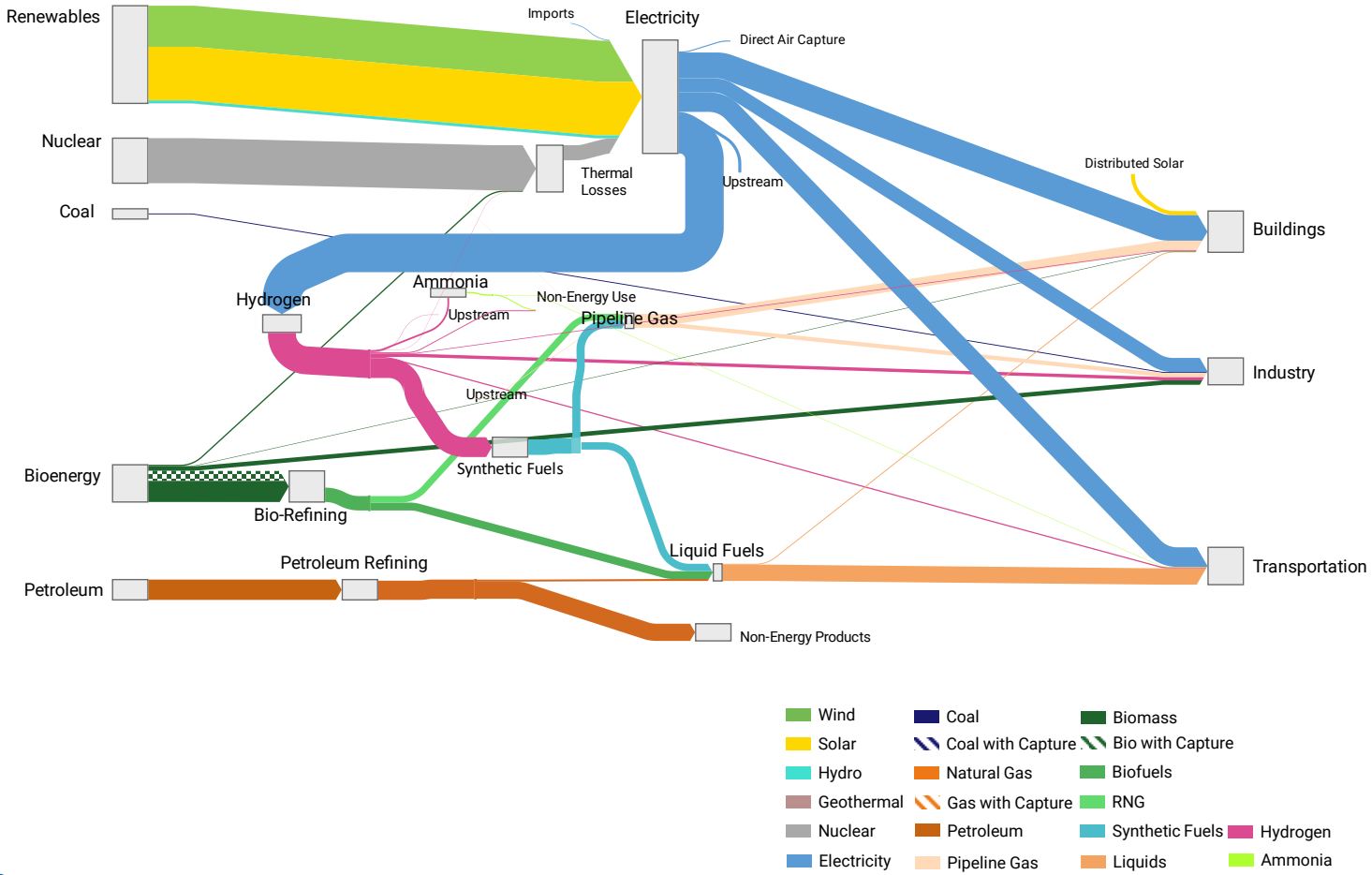
Leveraged recent EPRI LCRI research to understand cost and availability of CO_2 storage

Link to REGEN documentation on CO_2 storage here

Use Case: LCRI Net-Zero Report 2024

Scenario analysis of technological pathways to economy-wide net-zero emissions in the U.S, with sensitivities to nuclear costs, CCS costs, bioenergy supply, and natural gas prices





Source: Blanford, et al. (2024), "LCRI U.S. Economy-Wide Deep Decarbonization Scenario Analysis" (EPRI ID 3002031777)

International REGEN & Additional Resources

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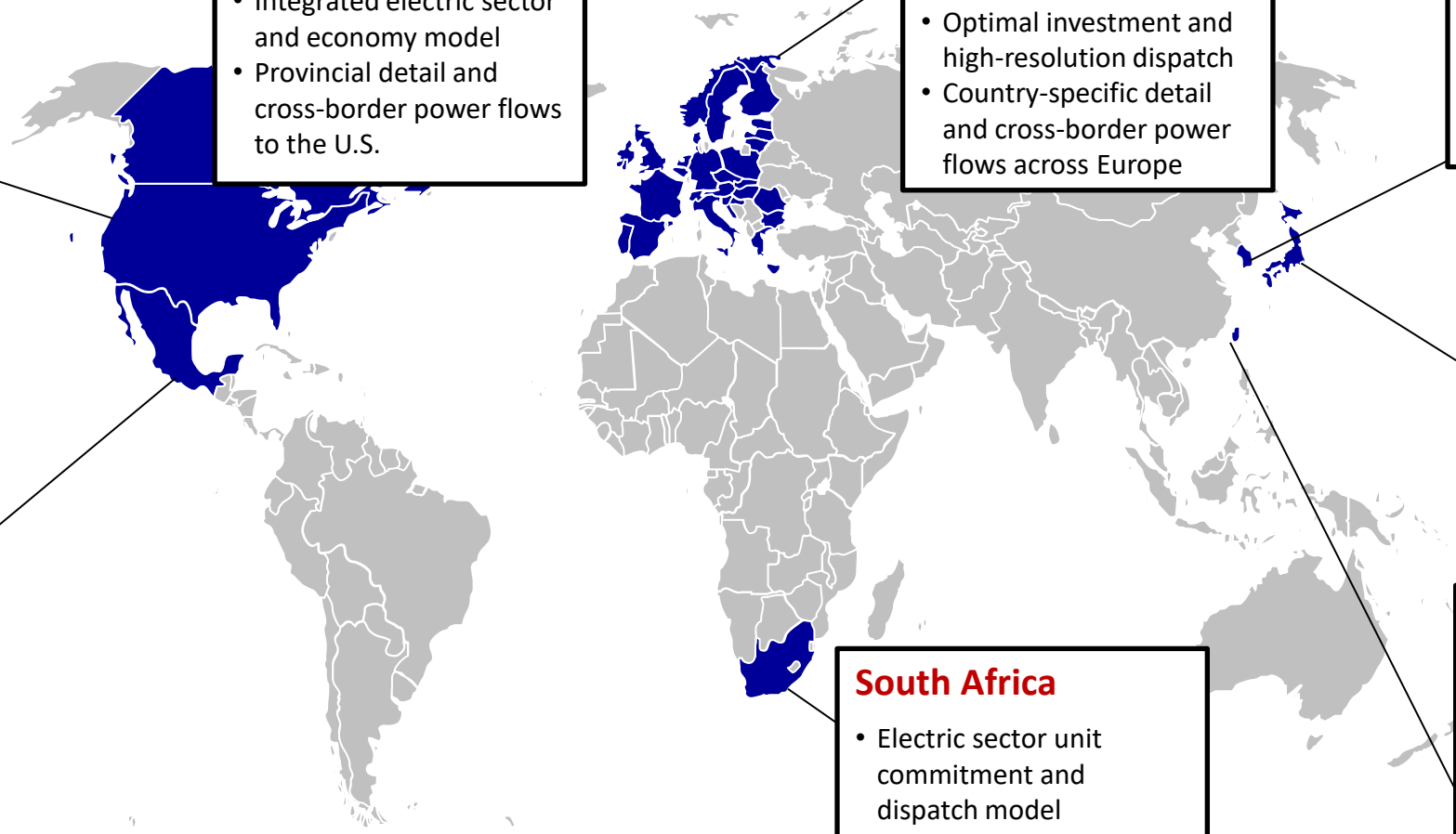
Global REGEN Energy-Economic Modeling Efforts



United States

- US-REGEN integrated electric sector and economy model
- Customizable regional and temporal detail
- Detailed end-use energy demand for exploring energy and climate policy

Canada

- Integrated electric sector and economy model
- Provincial detail and cross-border power flows to the U.S.

Europe

- Europe-REGEN detailed electric sector model
- Optimal investment and high-resolution dispatch
- Country-specific detail and cross-border power flows across Europe

South Korea

- Detailed electric sector model with investment and dispatch

Japan

- JP-REGEN full integrated electric, end-use, and low-carbon fuels model (in development)

Mexico

- MEX-REGEN
- 52-zone electric sector model with capacity planning and dispatch

South Africa

- Electric sector unit commitment and dispatch model
- Scenario analysis with exogenous capacity mixes

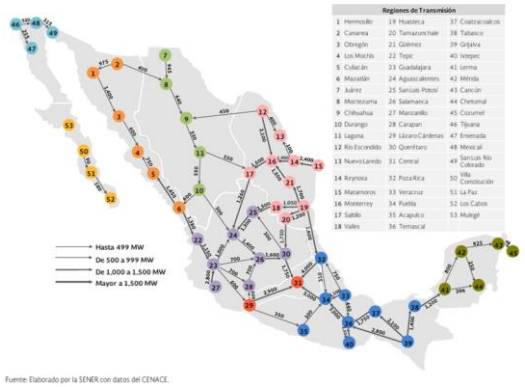
Taiwan

- High-level CGE representation of 18 economic sectors
- Technologically detailed power sector model
- Separate hourly / 40-year capacity expansion model for the Kinmen Islands

Every REGEN Model Is Customized to the Research Question

Mexico

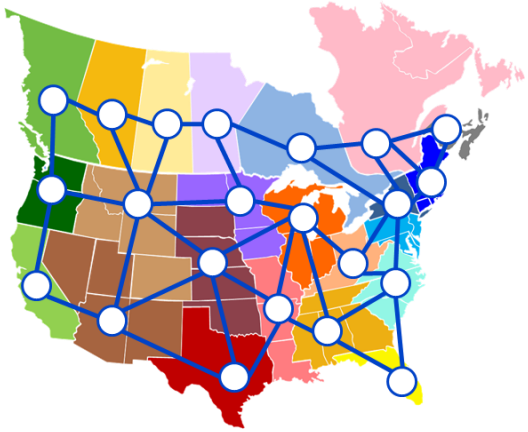
Assisting CFE strategy for decarbonization and renewable integration



- Electric model only
- 52 zones, 3-5 year steps to 2050
- Integration of renewables
- Value of natural gas
- Energy flows with the U.S.

Canada

Evaluating provincial and federal electrification opportunities and pathways to net-zero



- Electric and energy use model
- Canada provinces + 16 U.S. regions
- 5 year timesteps to 2050
- Climate zones, building types, end use technology detail
- Fuels model under construction

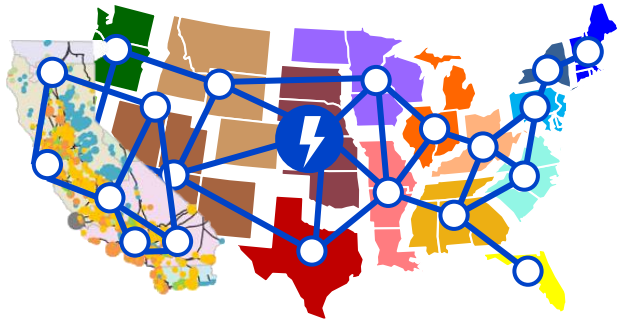
South Korea

Evaluating the 9th & 10th Basic Plan for Meeting South Korea CO_2 Reduction Goals

- Electric model only
- 9 regions, 2 year steps to 2050
- Integration of renewables
- Low carbon technologies and storage

Coming Soon: Open-Source REGEN

California-REGEN



Expected: Q4 2025

EPRI is developing the California-REGEN electric sector model for use by the California Energy Commission and linking it to PLEXOS to help the CEC understand the reliability implications of deep decarbonization policies such as California SB100 (Clean Electricity Standard). The model will be publicly available c. Q4 2025 after CEC completes a report on the work.

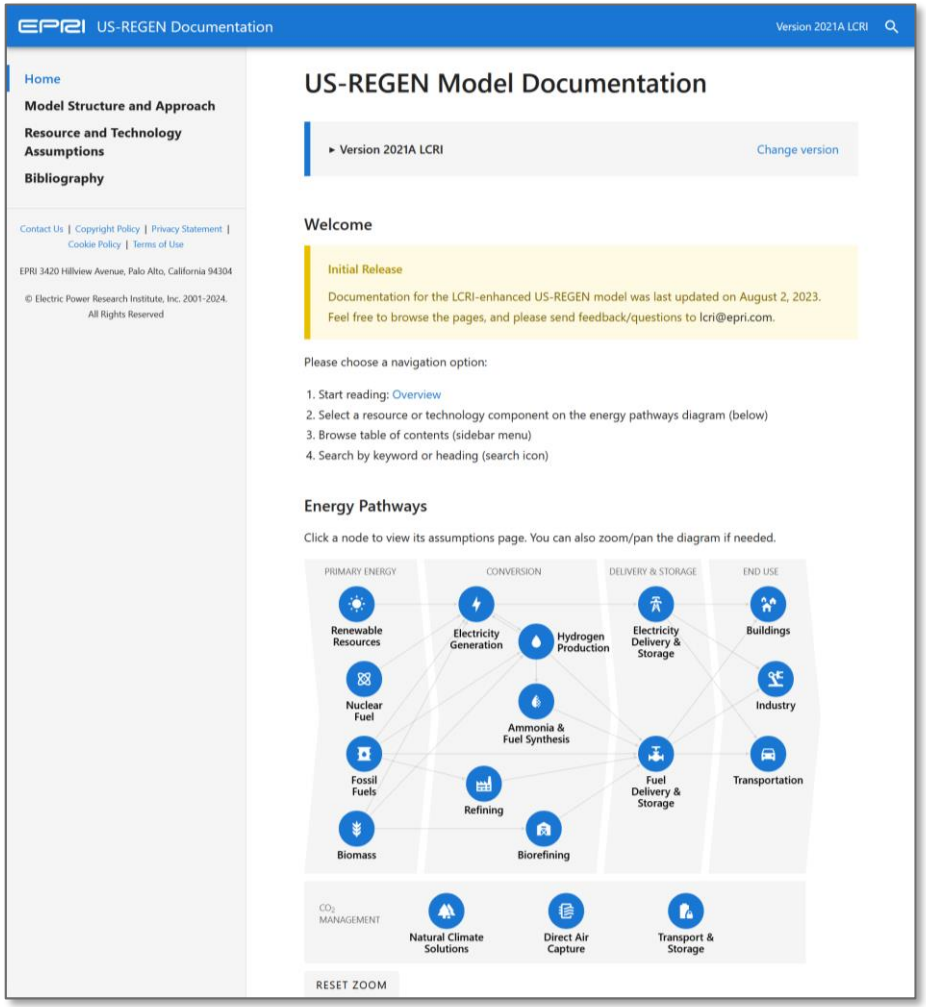
US-REGEN Electric/Fuels Model

Expected: Q2 2025

EPRI intends to make the full US-REGEN electric and fuels model open source in 2025, with user manual and updated documentation.

Other Resources

https://esca.epri.com/usregen



https://us-regen-docs.epri.com/

Acknowledgements

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  AEP, Duke, Entergy, FirstEnergy, Great River Energy, Kansas City Power and Light, NYPA, Oglethorpe, PacifiCorp, Progress Energy, Salt River Project, Southern Company, TVA
- Members of P178 and P201
- Members of the LCRI and Climate READi initiatives
- EPRI subject matter experts
- Participants in the Energy Modeling Forum and other multi-model comparison projects

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