# Overview of the GCIMS Project and a Dive into the GCAM Model

**E3SM Webinar**

**Marshall Wise**
Principal Investigator

On behalf of the GCIMS Project Team

July 24, 2025

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GLOBAL CHANGE INTERSECTORAL MODELING SYSTEM

Pacific Northwest NATIONAL LABORATORY

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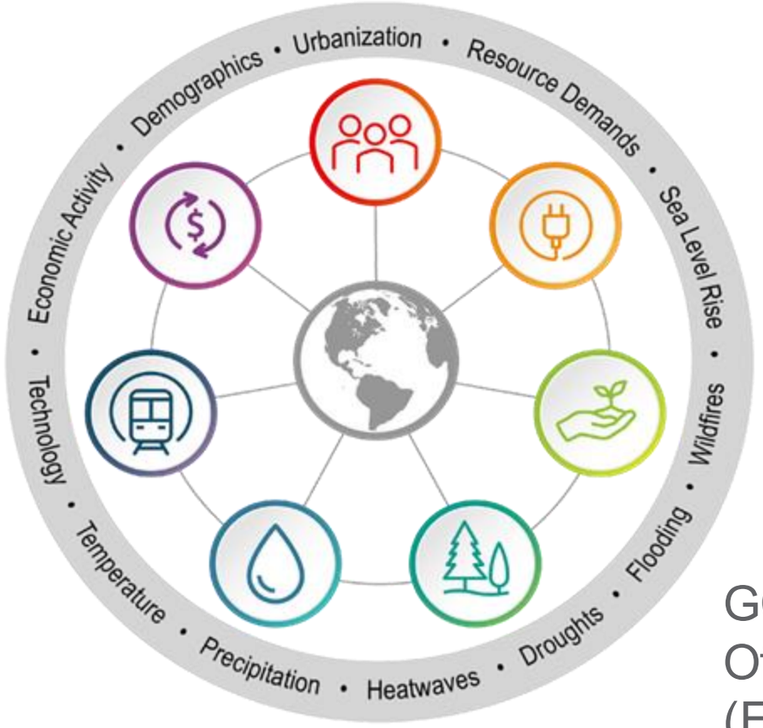
# GCIMS Project: Objective and Team

**The long-term objective is** *to improve understanding of the complex interactions among energy, water, land, economics, and other important human and physical Earth systems*




- *at regional to global scales,*
- *with an emphasis on developing and applying an internally consistent, open-source, computationally efficient modeling framework*
- *that captures the evolution of the integrated human–Earth system.*

GCIMS is supported by the U.S. Department of Energy, Office of Science, Earth and Environmental System Modeling (EESM), MultiSector Dynamics Program Area

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# GCIMS FY25-26 Research Focus Areas

- **Energy.** Analysis of the potential scales, roles, and impacts of energy resources, technologies, and applications in the multisector, domestic and global economic context of energy production, transformation, demand, trade, and energy security.
- **Critical Minerals/Materials.** Multisector modeling quantifying and exploring the demands, resources, supply chains, and domestic and global markets for the critical minerals and materials needed to meet the energy and computational needs of the evolving economy.
- **AI/ML-Integrated Modeling/Analysis.** Novel computational techniques for AI-assisted facile model integration, rapid model emulation of complex system behavior, and ML approaches for exploring large ensembles of scenarios quantifying the impact of uncertain drivers.
- **Data Centers as a key Multisector Use Case.** Analysis of the future growth of data centers - modeling the drivers of demand, the requirements for electricity, water, capital, and critical materials, and the potential impacts both from and on technological and economic change.

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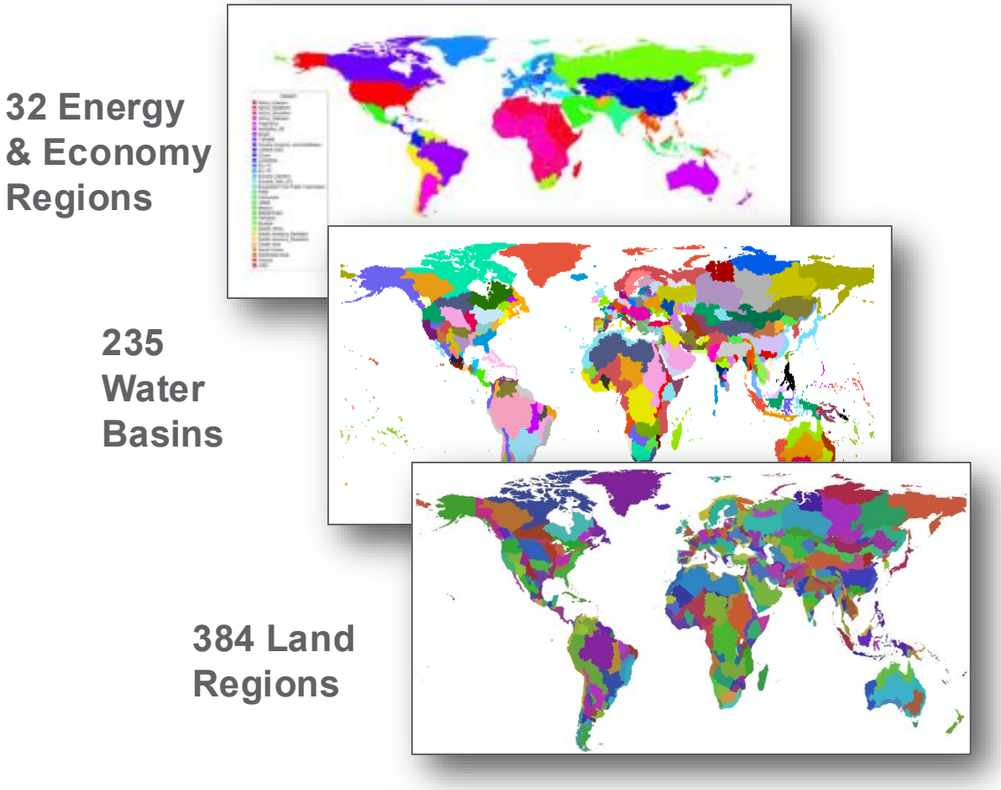
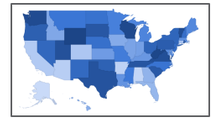
# Global Change Analysis Model (GCAM)

- GCAM is a ***multisector, multi-regional, dynamic model*** focusing on energy, agriculture, water and critical minerals and materials (CMM) production, consumption, and trade.
- GCAM ***economically and physically links*** activity in Energy, Agriculture, Land, Water, and CMM, with annual resolution typically at 5-year intervals to 2100.
- GCAM includes ***technology detail in energy*** production, transformation and final demand sectors.
- GCAM includes ***physical representations of crop management practices*** in the agriculture sector.
  - Includes all commercial and natural lands in each land region.
- GCAM includes ***dynamic economic modeling of the water*** sector at basin levels linked to energy and agriculture.
- GCAM dynamically computes ***international trade in energy, agriculture, and CMM*** (CMM in development)***.***

## Global Coverage




- 32 Energy/Economic regions
- 384 Land regions based on water basins



GCAM-USA (50 State)

# GCAM is the central MSD model of the GCIMS suite of open, modular, integrated tools

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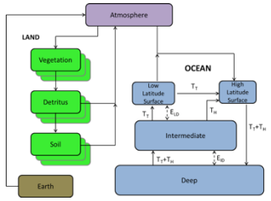
## Data Development

**gcamdata (consolidation)**

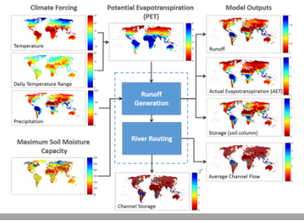
**Moirai (gridded land)**

## Physical System Models

**Hector (Earth systems)**




**Xanthos (global hydrology)**



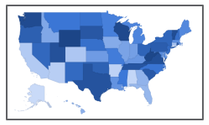

## MSD Integration

### GCAM

32 Energy Economy Regions

235 Water Basins

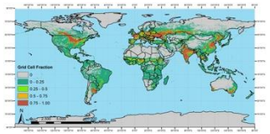
384 Land Regions



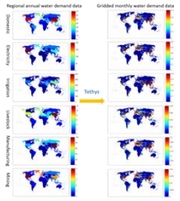
GCAM-USA (50 State)

## Regional Resolution

**Demeter (land)**

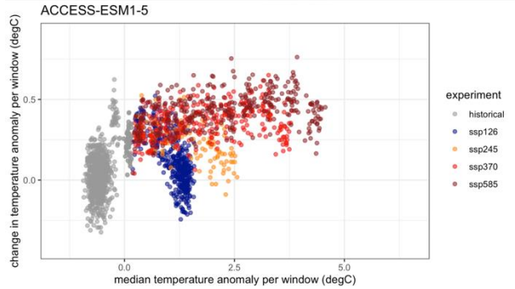


**Tethys (water)**



## Earth System Model Emulation

### STITCHES




GCIMS: Global Change Intersectoral Modeling System: Not all GCIMS models shown above.

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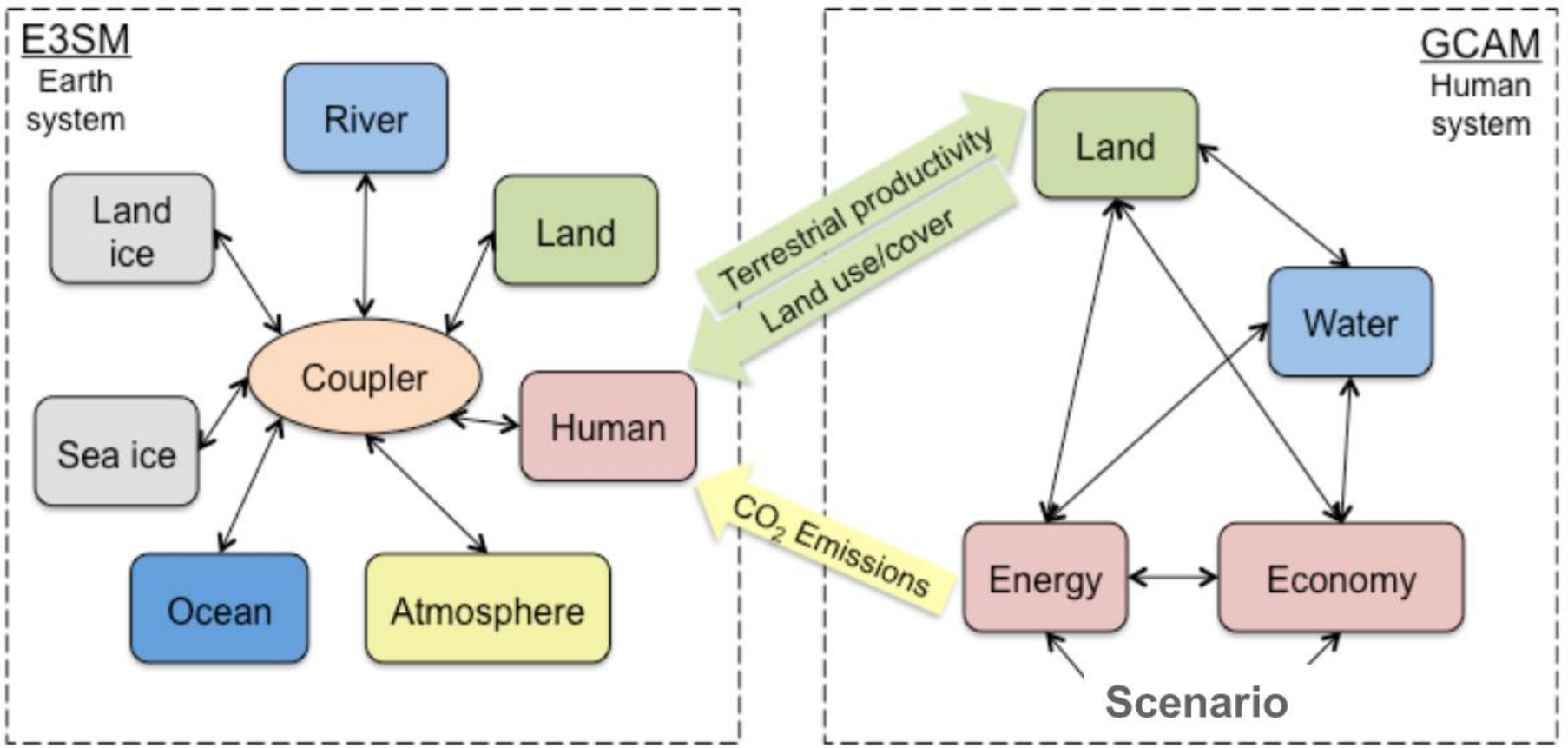
# GCAM is the Human System Model in E3SM




- Land and Terrestrial Carbon coupling:
  - GCAM Land Use/Cover sent to E3SM for its terrestrial carbon computations.
  - GCAM Energy Sector CO2 emissions sent to E3SM
  - GCAM makes economic land use decisions using productivity from E3SM.

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# GCAM is an Open-Source Community Model

- GCAM is an open source and open data community model built and maintained by PNNL.
- GCAM has been used for analysis for the US DOE, other US Administration, and in the energy industry.
- GCAM has an international user base and has been downloaded thousands of times.
- DOE’s Office of Science MSD program is the largest current and historical funder of GCAM development.

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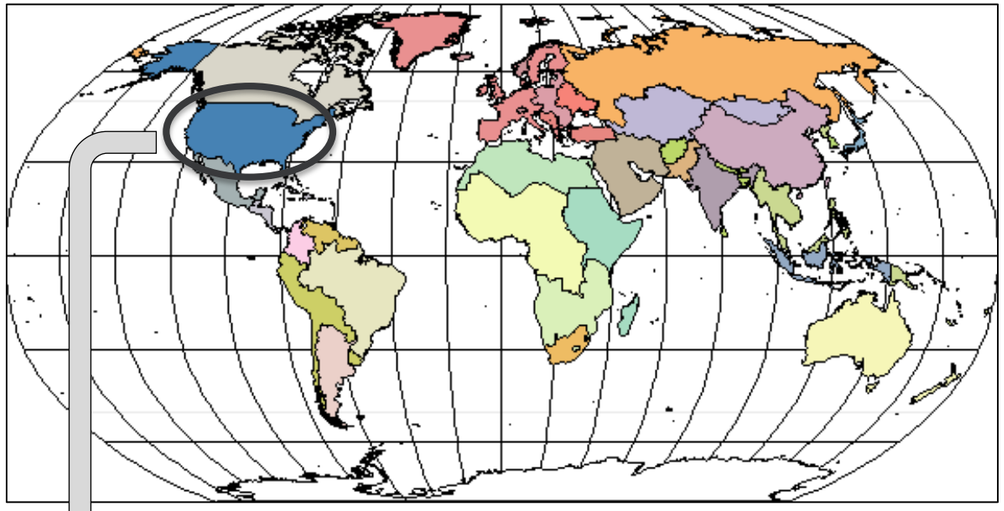
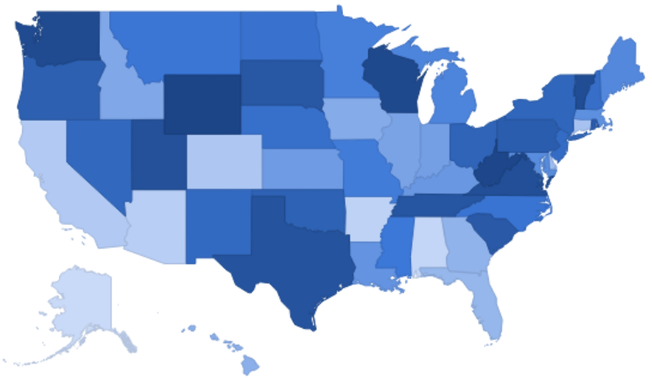
# GCAM-USA: Integrating higher resolution modeling with consistency at larger scales

- GCAM-USA: GCAM with subnational detail in the United States (50 states)
- GCAM-USA is embedded within the global version of GCAM
  - State-level energy systems both affect and respond to conditions in the domestic and global energy systems.
  - Scenarios of state-level energy are physically and economically consistent with US and global energy sectors.
- GCIMS/GCAM can contribute to ***digital testbeds*** with flexible, heterogeneous regional scales for MSD modeling while capturing feedbacks to and from US and global regions.

**GCAM: 32 geopolitical regions**



**GCAM-USA: 50 states + D.C. in the U.S.**



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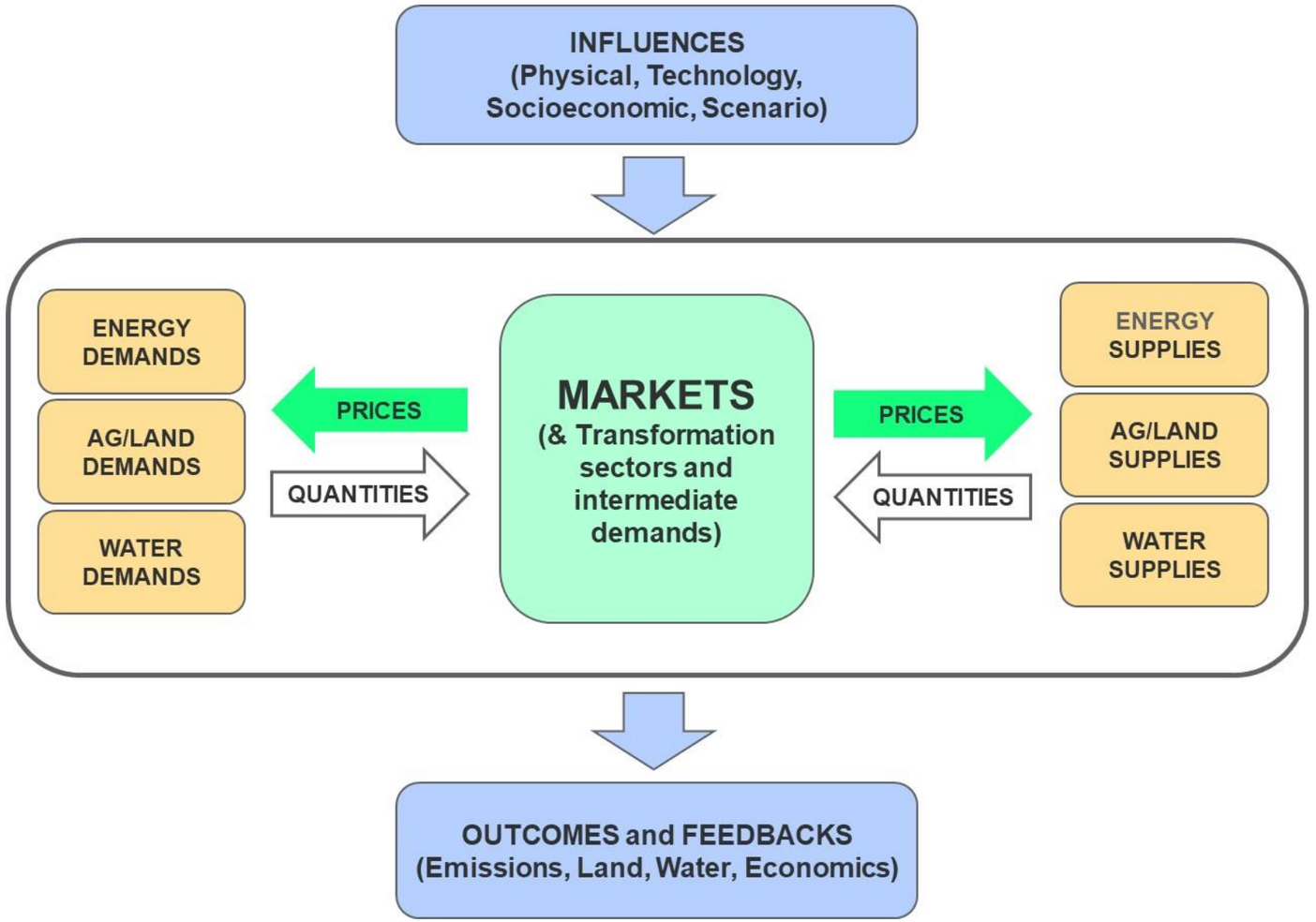
# GCAM Modeling Approach: Economic Equilibrium with Physical Detail




- GCAM ***solves*** each future period by finding the set of ***prices*** so that all modeled ***markets are "cleared."***
- GCAM uses a ***recursive dynamic*** rather than an ***intertemporal optimal*** approach.
- GCAM's ***non-linear*** system of equations is solved by finding the set of ***prices*** so that all supplies equal all demands.
- ***Economic equilibrium*** in GCAM means that physical quantities ***of the sectors it covers*** are balanced and allocated economically efficiently.
- ***Prices*** are the signals by which the multiple ***sectors*** communicate scarcity and demands and ***dynamically*** respond to each other.

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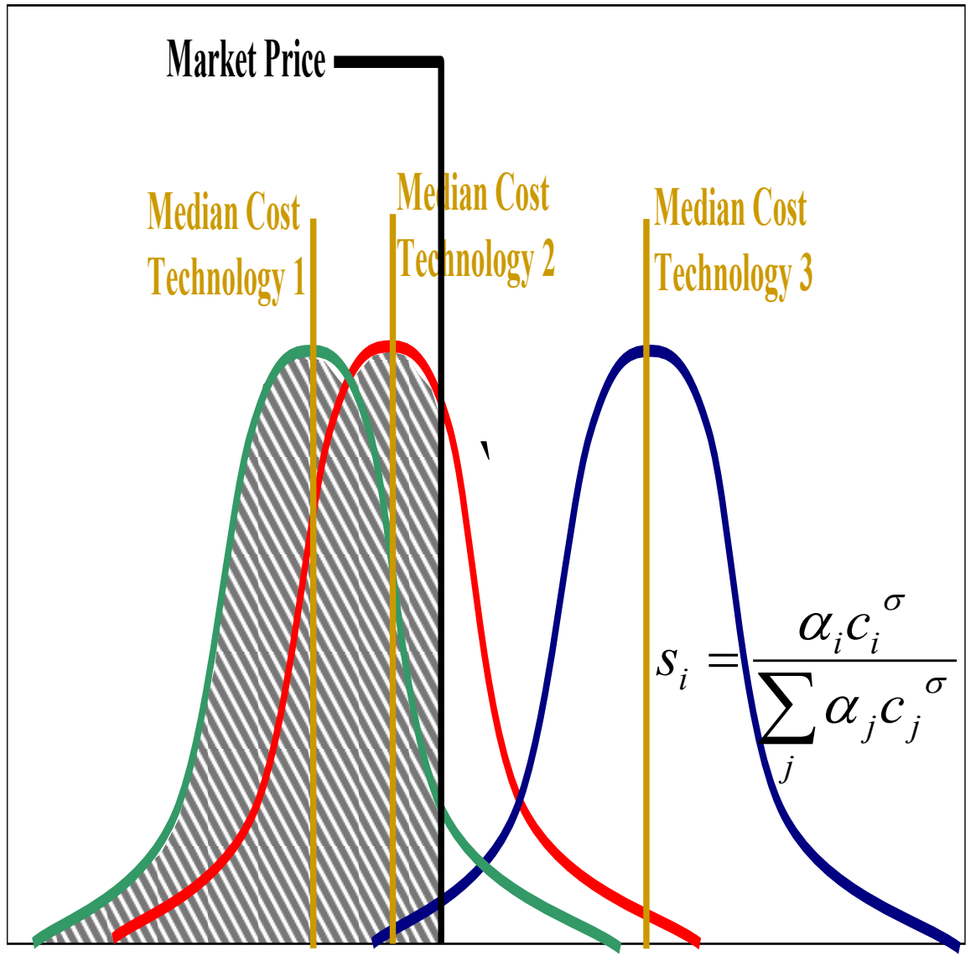
# Logit Choice Mechanism for Economic Decisions

## A Probabilistic Approach




- Logit approach infers a distribution of realized costs/profits due to heterogeneous conditions rather than a fixed point.
- Market share based on probability that a technology has the least cost.
  - Non-linear technology competition.
  - Historical calibration influences future competition through the $\alpha$ coefficient ("share-weight").
  - Exponent reflects a (non-constant) elasticity.
- In general, GCAM production functions, supplies and demands, and markets are non-linear.
  - Increasing marginal costs.
  - Diminishing returns to scale.
  - Linear constraints are not needed to bound solution.

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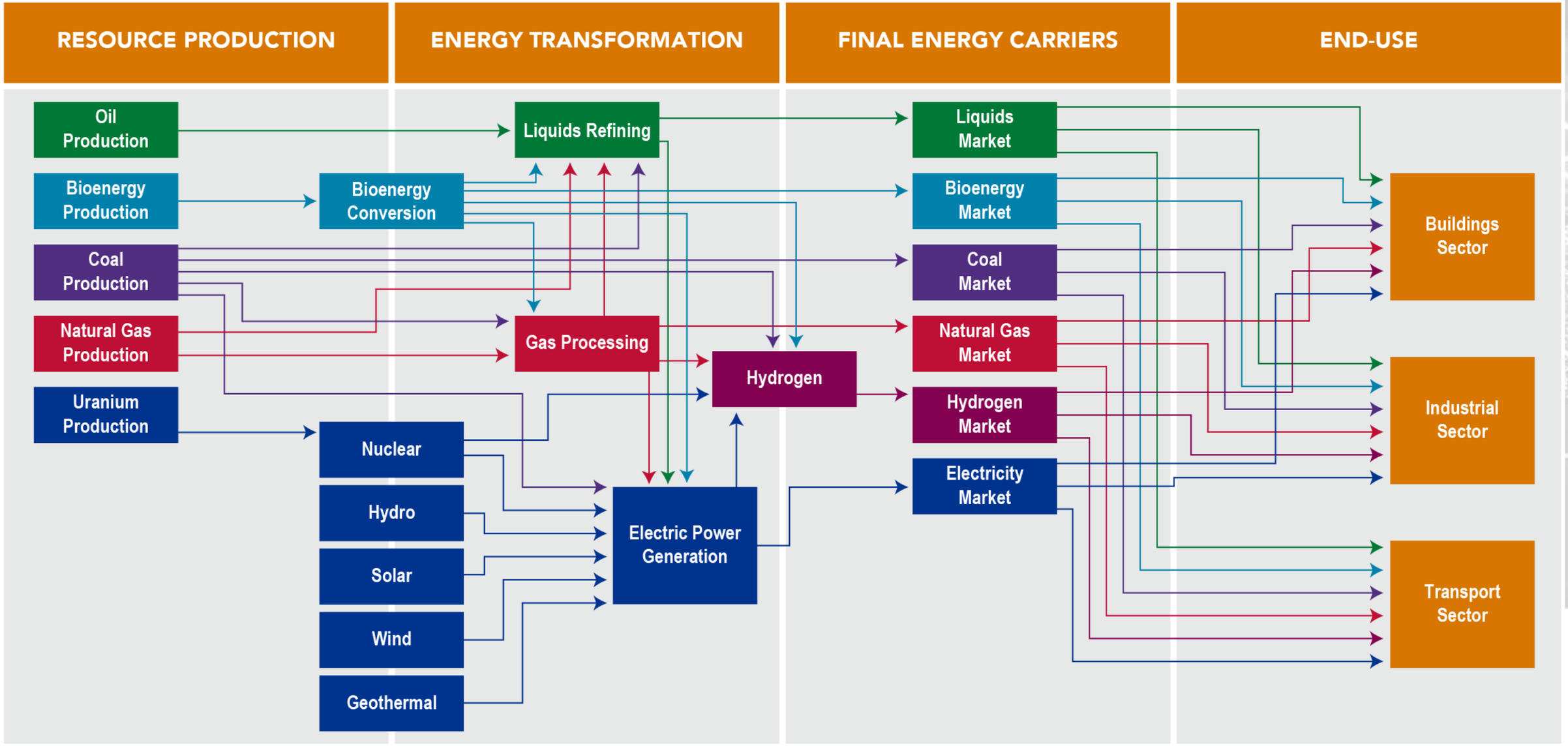
# GCIMS Energy Focus: Energy sector coverage in the GCAM model - from production to use



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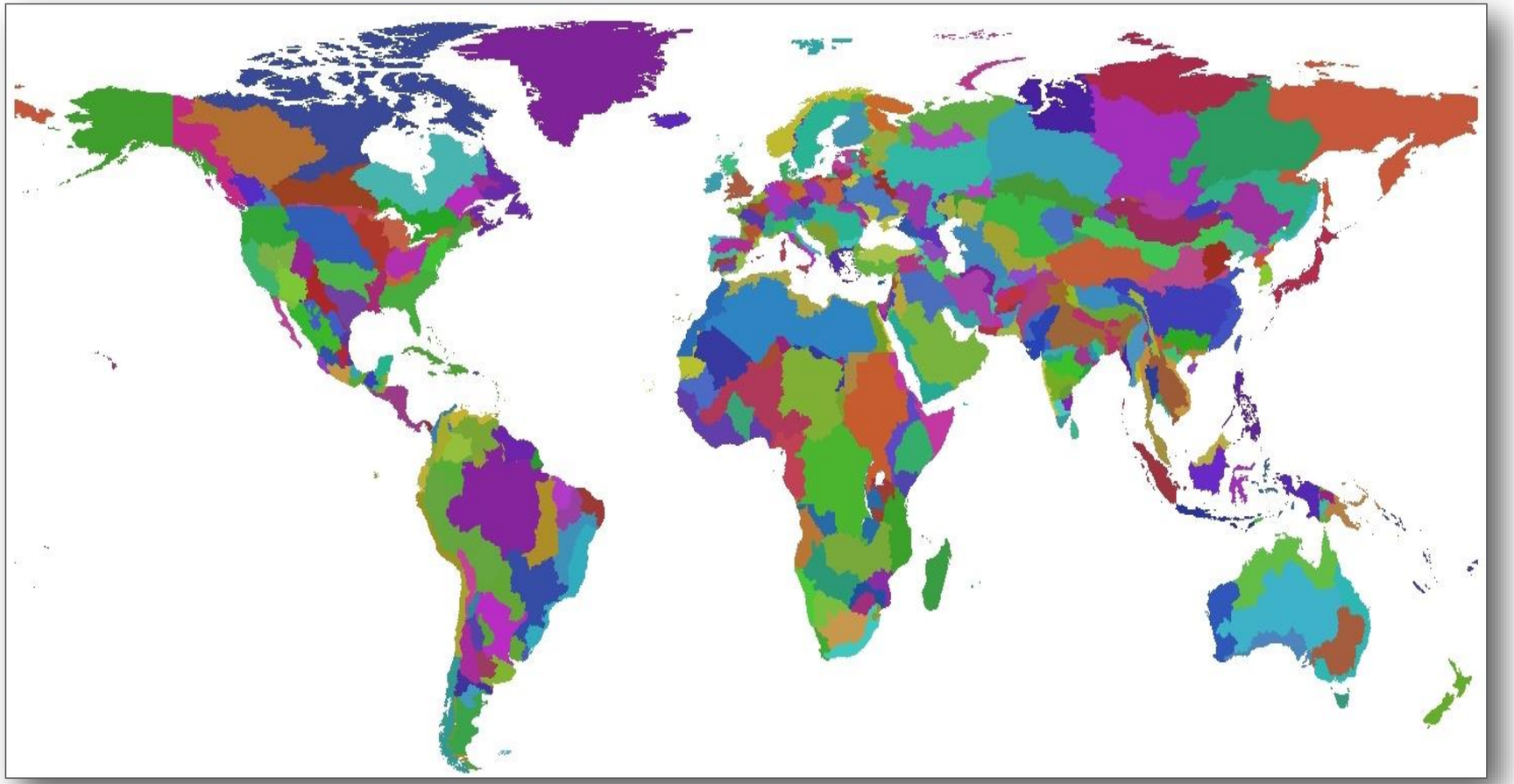
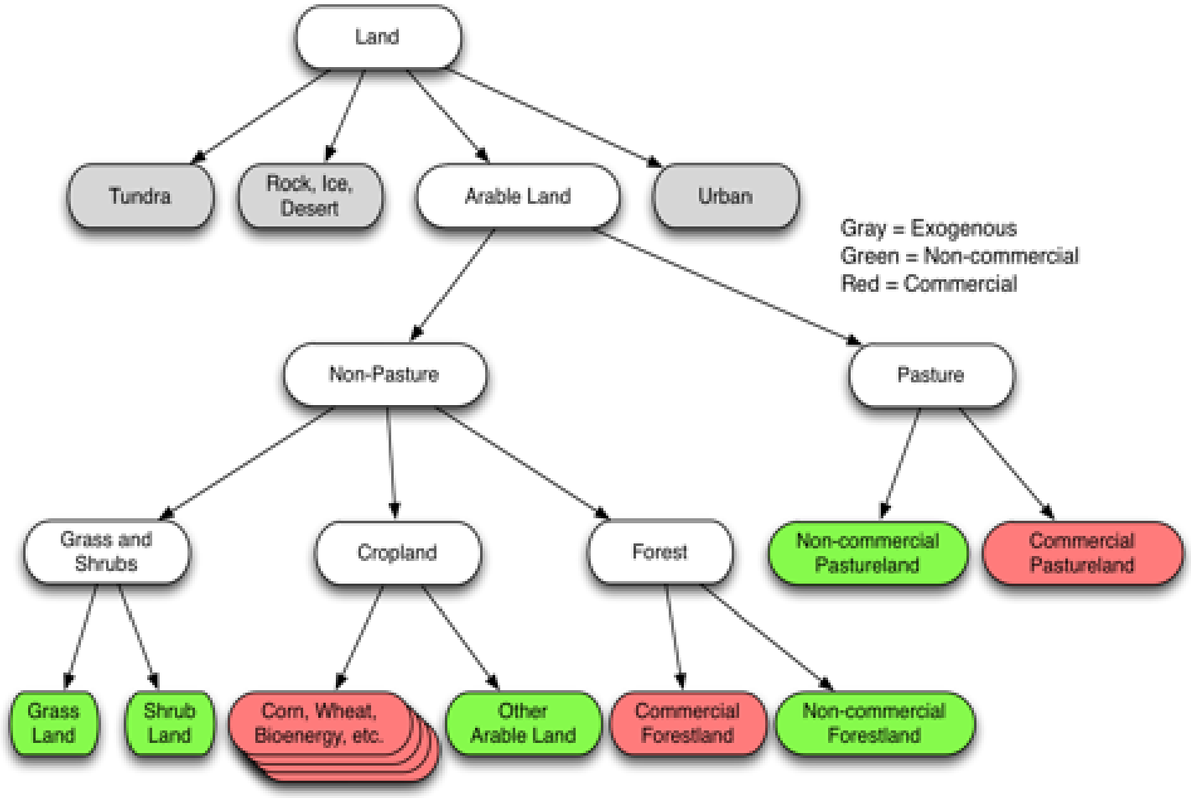
# GCAM Land Use Regions



GCAM has 384 land use regions, formed by the intersection of geopolitical regions and water basins.

# GCAM Land Use Categories (within each land use region)




- All land cover and use, including all commercial land uses as well as non-commercial natural lands, are represented in GCAM.
- These land categories are represented in each of the 384 land regions (where applicable) and calibrated to match a historical base year.
- Economics drive future changes in cropland, pasture, forest, and other land uses.

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# Agricultural Supply and Demand

- GCAM currently models supply and demand for approximately 13 crops, 6 animal categories, bioenergy, as well as wood products from forests.
- Agricultural Production (and all land use) is modeled at the 384 land use region level.
- Agricultural Markets and Demand are modeled at the 32 region level.
  - Market Producer Prices differ in each of the 32 regions.
  - Regional Consumer Prices are based on mix of consumption of local production and imports

- We account for both food and non-food demand, including animal feed.
  - Demand for a given commodity changes over time in response to income, its price, and the price of substitutes.
  - Demand for food, feed, and energy uses of crops are price responsive.

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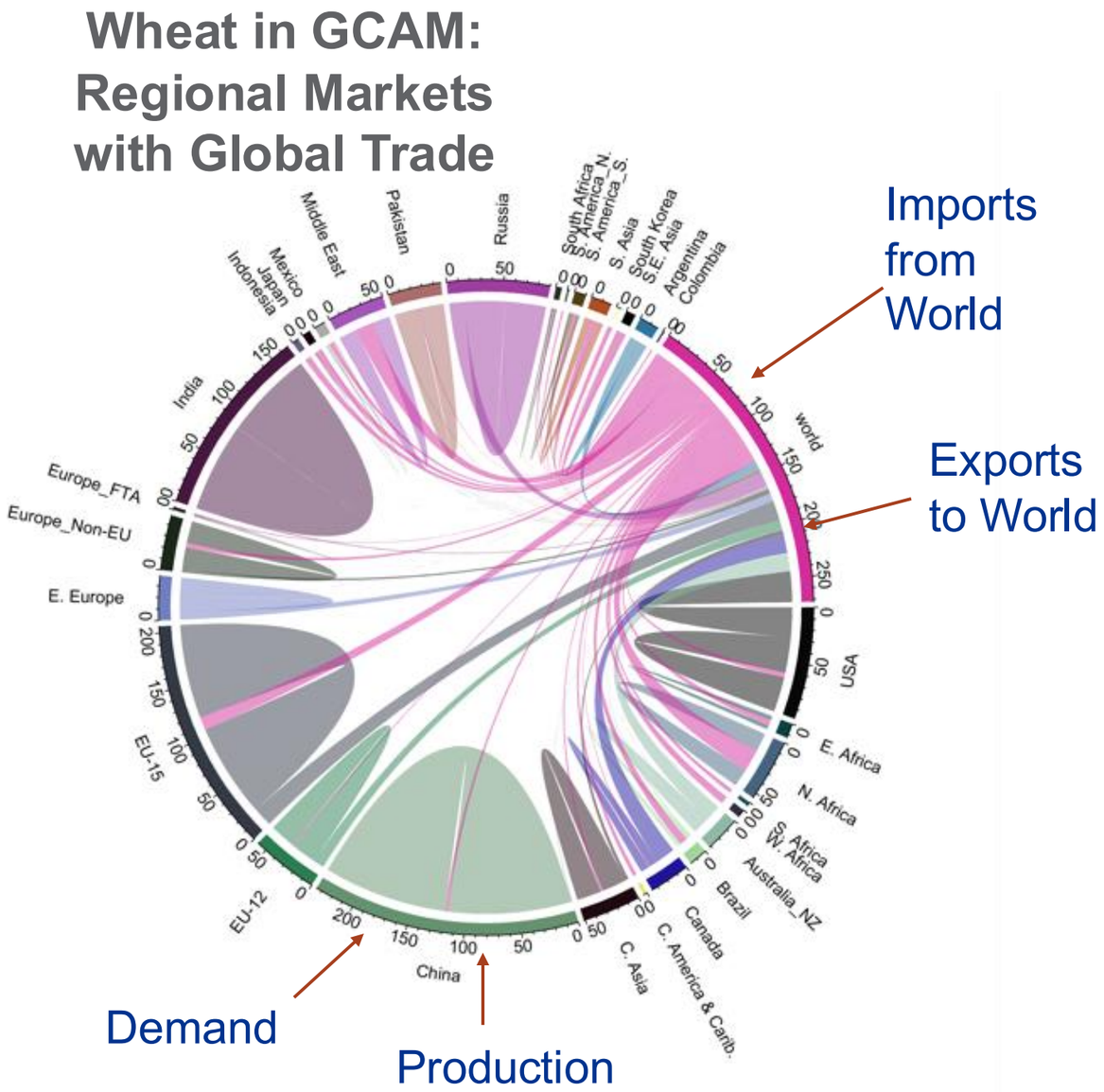
# Regional Teleconnections and Economic Trade

- Trade and teleconnections are key to understanding dynamic impacts and outcomes: globally and in the US.
- Critical to several research areas:
  - Trade in energy and important minerals,
  - Regional energy and food prices/access,
  - Regional resilience/impacts.
- GCAM now has trade capabilities on par with prominent trade models.

- ***GCAM can parameterize the full range from simple global trade, detailed bilateral trade, regional trading blocs, to Zero trade.***



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# GCAM Results are a function of scenario input assumptions

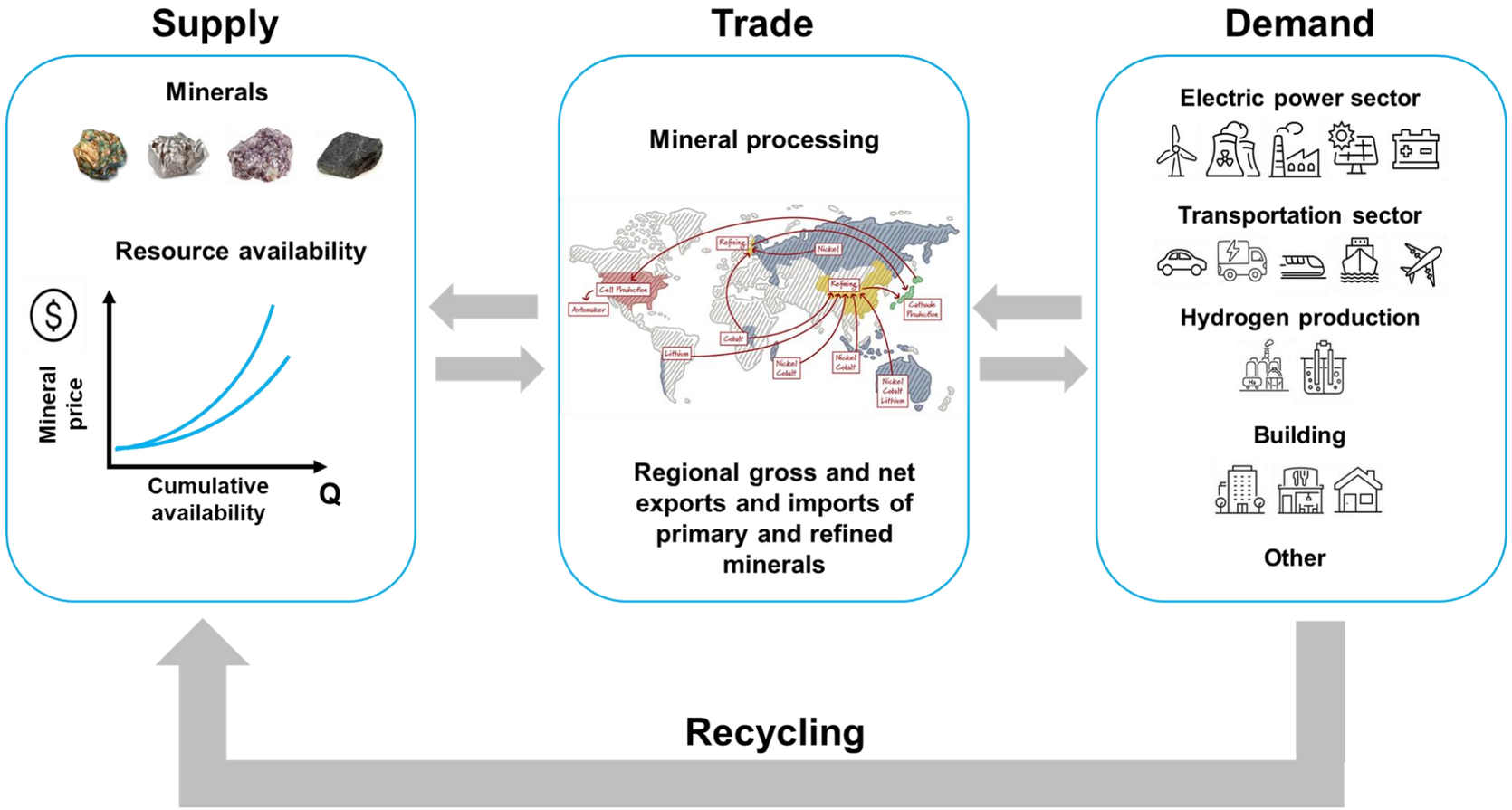
- Design Philosophy – flexible, data-driven modeling so that the input assumptions and parameters are open to users and can generate very different scenario results.

- Examples.
  - When given very different assumptions about cost and resources for renewable, fossil, and nuclear power, GCAM can generate very different scenarios of the future energy mix.
  - When given very different projections about regional crop yield, GCAM will generate very different scenarios of regional crop production and trade

- GCAM goal: make important “constraints” and “drivers” based on visible user-controlled input assumptions rather than hardwired into the model structure.
  - For example, assumptions about amount of land allowed for commercial expansion for agriculture and bioenergy production.
  - Or hardwired maximum “reasonable” market share for one crop in a region or for one fuel choice in the electric sector.

# Multisector Dynamic Modeling of Critical Minerals and Materials (CMM) in GCAM: Domestic and Globally

- Objective is to explore CMM demands, supplies, and trade dynamically within GCAM to capture the multisectoral interactions between material markets and technology deployment in various sectors of the economy, both domestically and globally.




Qiu, Y., Iyer, G., Graham, N., Binsted, M., Wise, M., Patel, P., & Yarlagadda, B. (2024). The impacts of material supply availability on a transitioning electric power sector. *Cell Reports Sustainability*, 1(10), 100221. https://doi.org/10.1016/j.crsus.2024.100221

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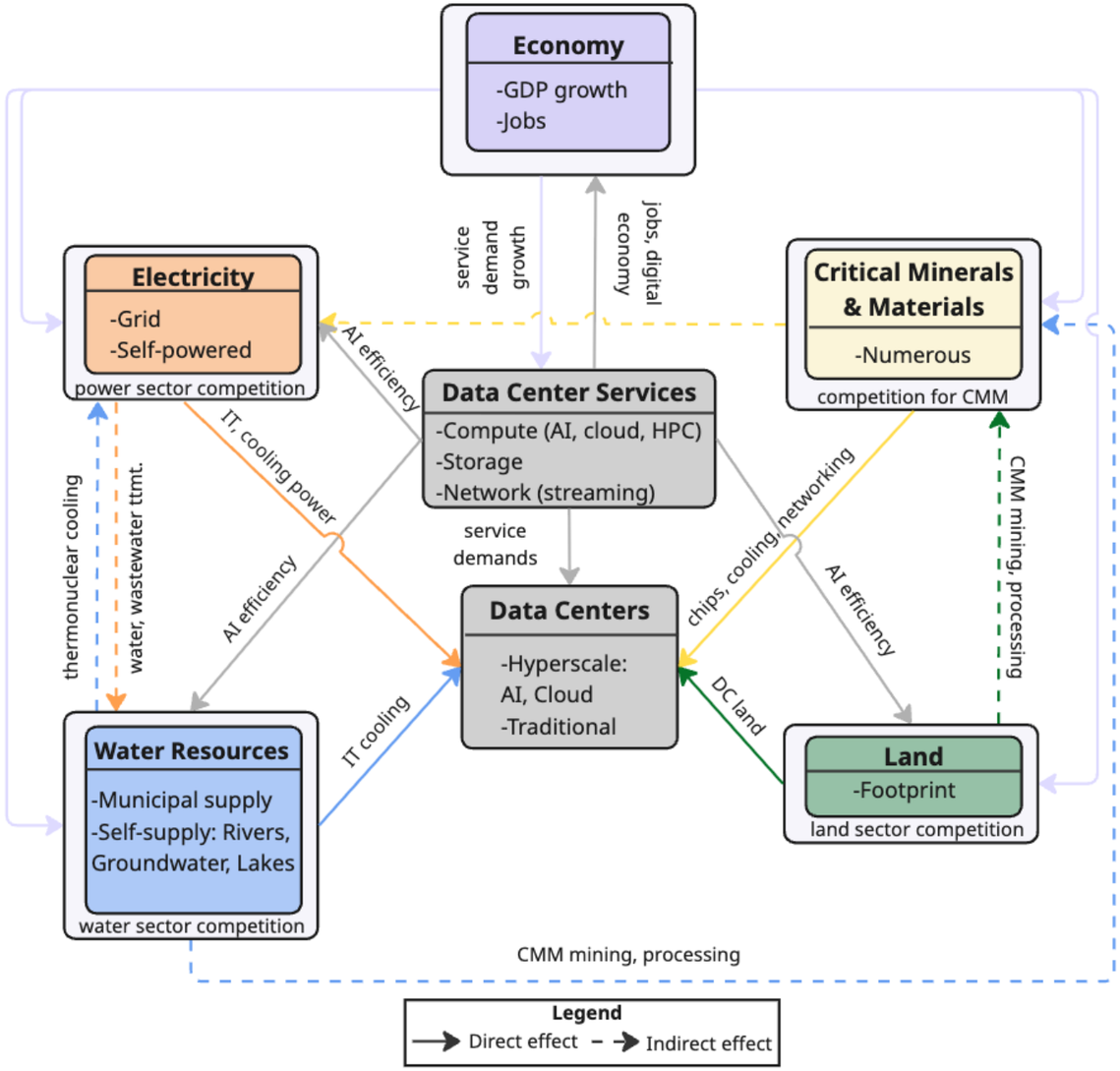
# Current Focus: GCAM modeling of Data Centers and the many implications for energy, water, land, critical minerals, and the economy

- *Demand for data center services and facilities will change in the coming years, with implications for multiple sectors, both in competition for resources and potential feedbacks to the economy.*
- Data centers exist to provide services, such as storage, streaming, cloud and HPC, and AI
- Different types of DCs to provide different services, with differing resource use intensities
  - Co-located/traditional
  - Hyperscale
- DCs require electricity, water, land, and critical minerals and materials
  - Competition with other demands: residential, industry, municipal, transportation, agriculture
  - Interactions across sectors: e.g., water demands for DCs are both direct (onsite cooling) and indirect (electricity generation)
- DC services feedback to the economy through labor productivity, jobs



# Thank You!

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