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The Global Change Analysis Model (GCAM) and Multisector Dynamics

Dr. Nazar Kholod

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U.S. DEPARTMENT OF ENERGY BATTELLE

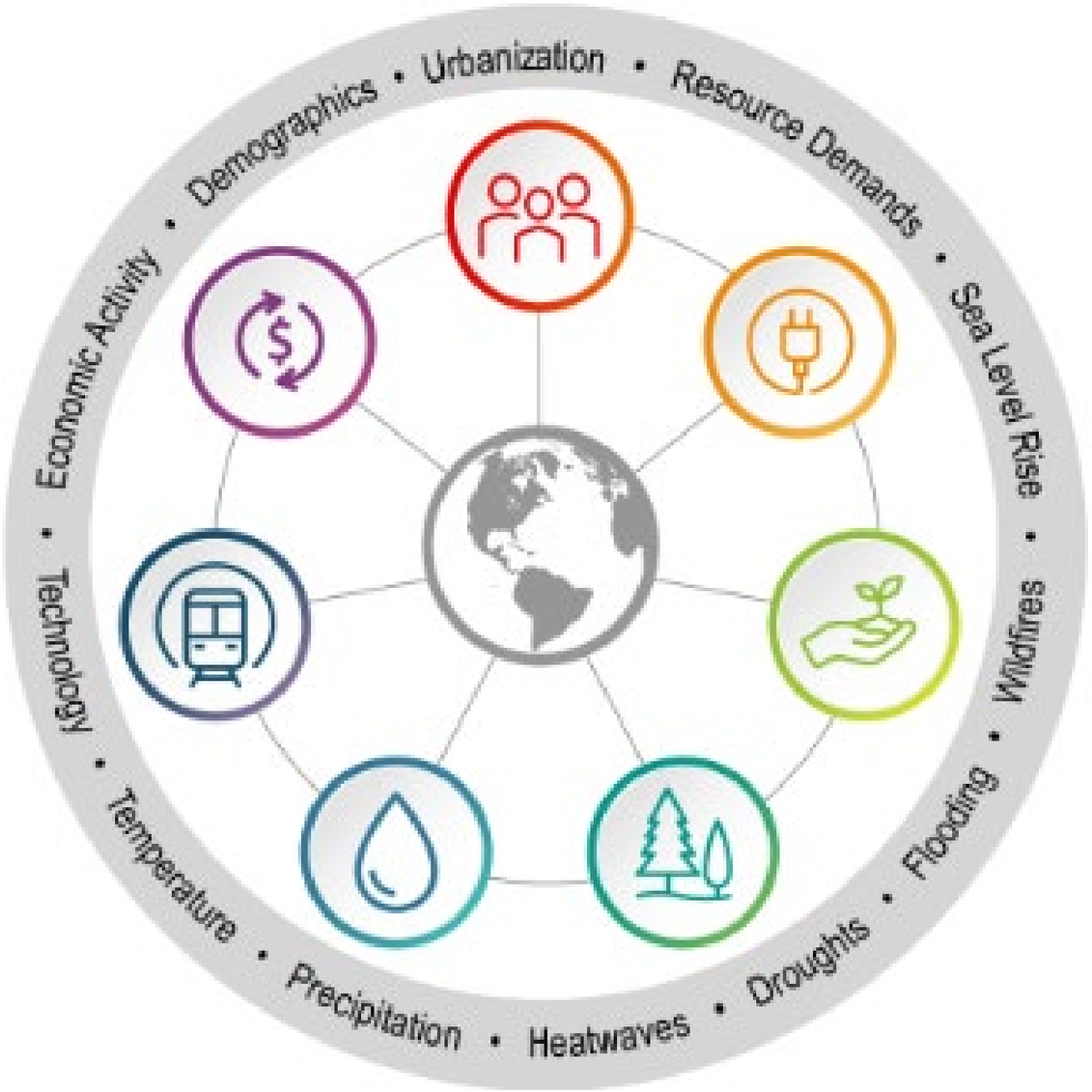
PNNL is operated by Battelle for the U.S. Department of Energy

Outline

- Introduction to GCAM
- Energy system
- Land use
- Water system
- Practical use of GCAM
- How to run GCAM
- Development of GCAM-Ukraine
- Q&A

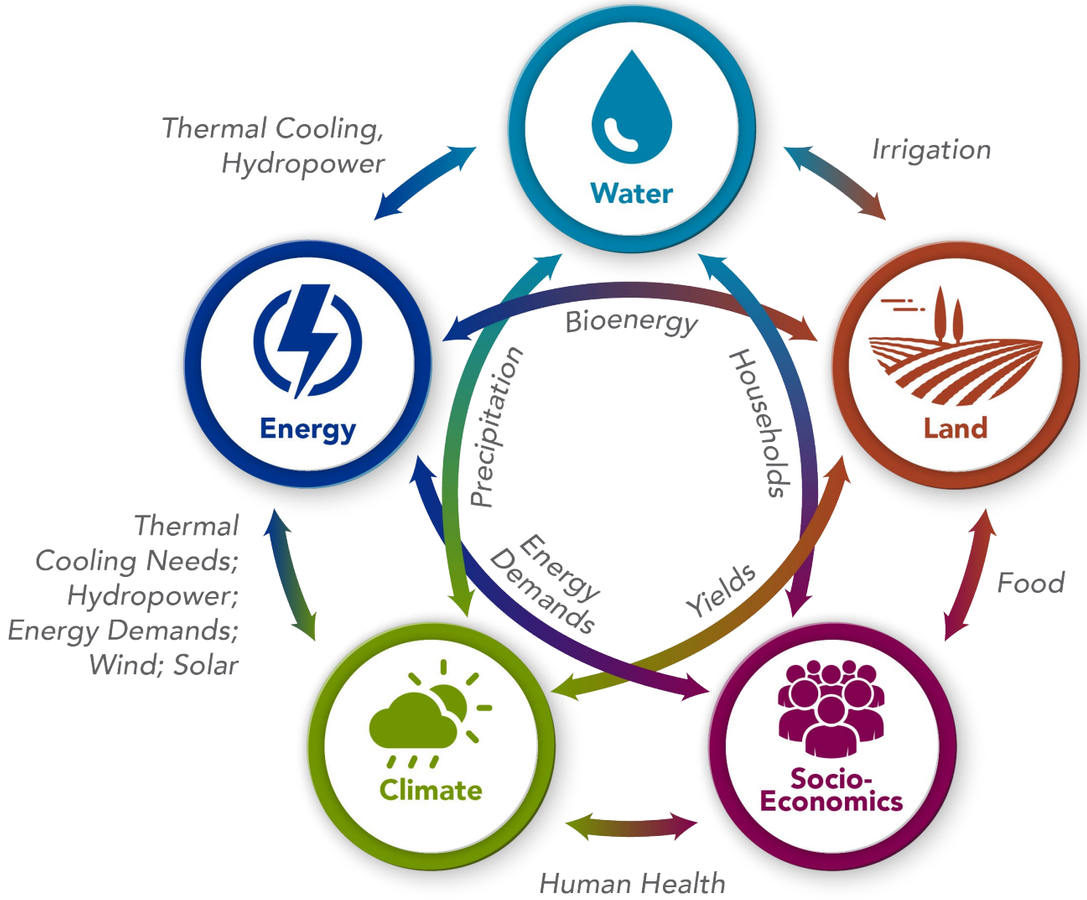
Multisector Dynamics

- Interactions among energy, water, land, climate, socioeconomics, and other important human and natural systems are very complex



Global Change Intersectoral Modeling System (GCIMS), sponsored by DOE's Earth & Environmental Systems Modeling Program

Global Change Analysis Model (GCAM)



- GCAM explores the interactions between multiple systems
- Pacific Northwest National Laboratory / Joint Global Change Research Institute is the developer and host of GCAM

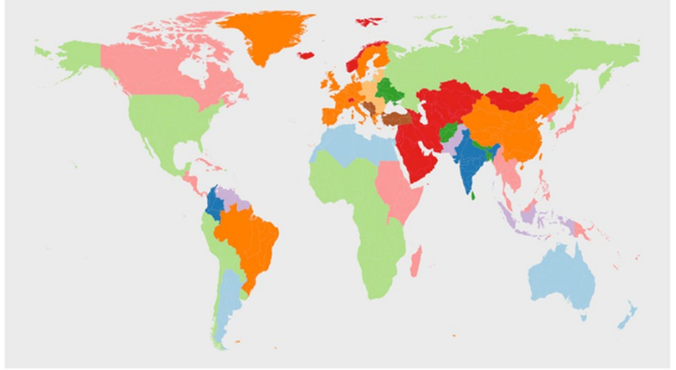
History of GCAM

- Oil crisis in the 1970s: How much oil the world will need in 10 years? In 20? In 50?
- In 1978, Jae Edmonds began what has developed into an integrated model of energy, economy, water, land and climate interactions
- The model was renamed MiniCAM in the mid-1990s, and GCAM in the mid-2000s. The model was renamed from “assessment” to “analysis” in 2020
- GCAM was used in all IPCC reports
- U.S. government invested about one billion dollars in GCAM development
- “GCAM is the national treasure” – model became open source in 2010
- GCAM can be run on Windows, Linux, Mac, and high-performance computing systems

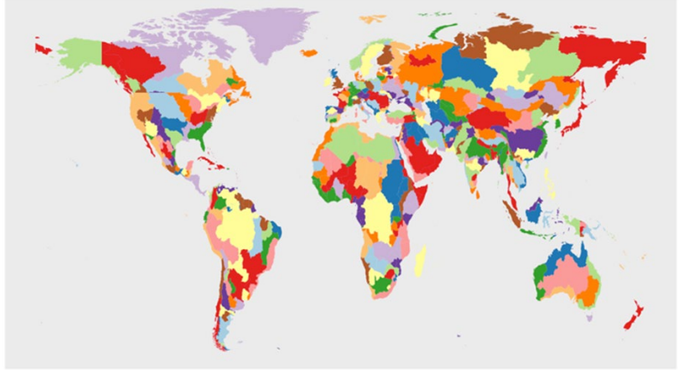
The Global Change Analysis Model (GCAM)

- GCAM is a **global integrated assessment model**
- GCAM links **Economic**, **Energy**, **Land-use**, **Water,** and **Climate** systems
- 32 socioeconomic regions in core GCAM and **Ukraine** is under development

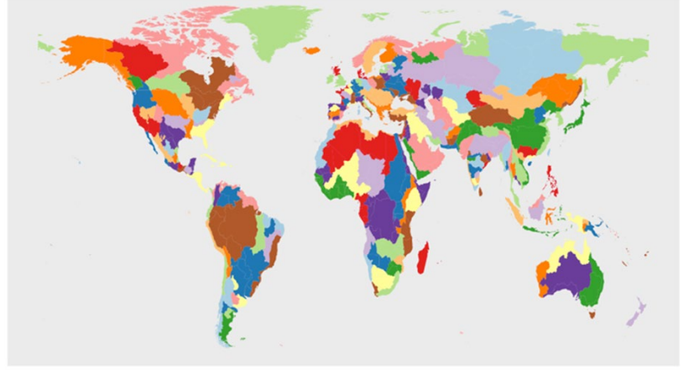
32 Energy Economy Regions



384 Land Regions

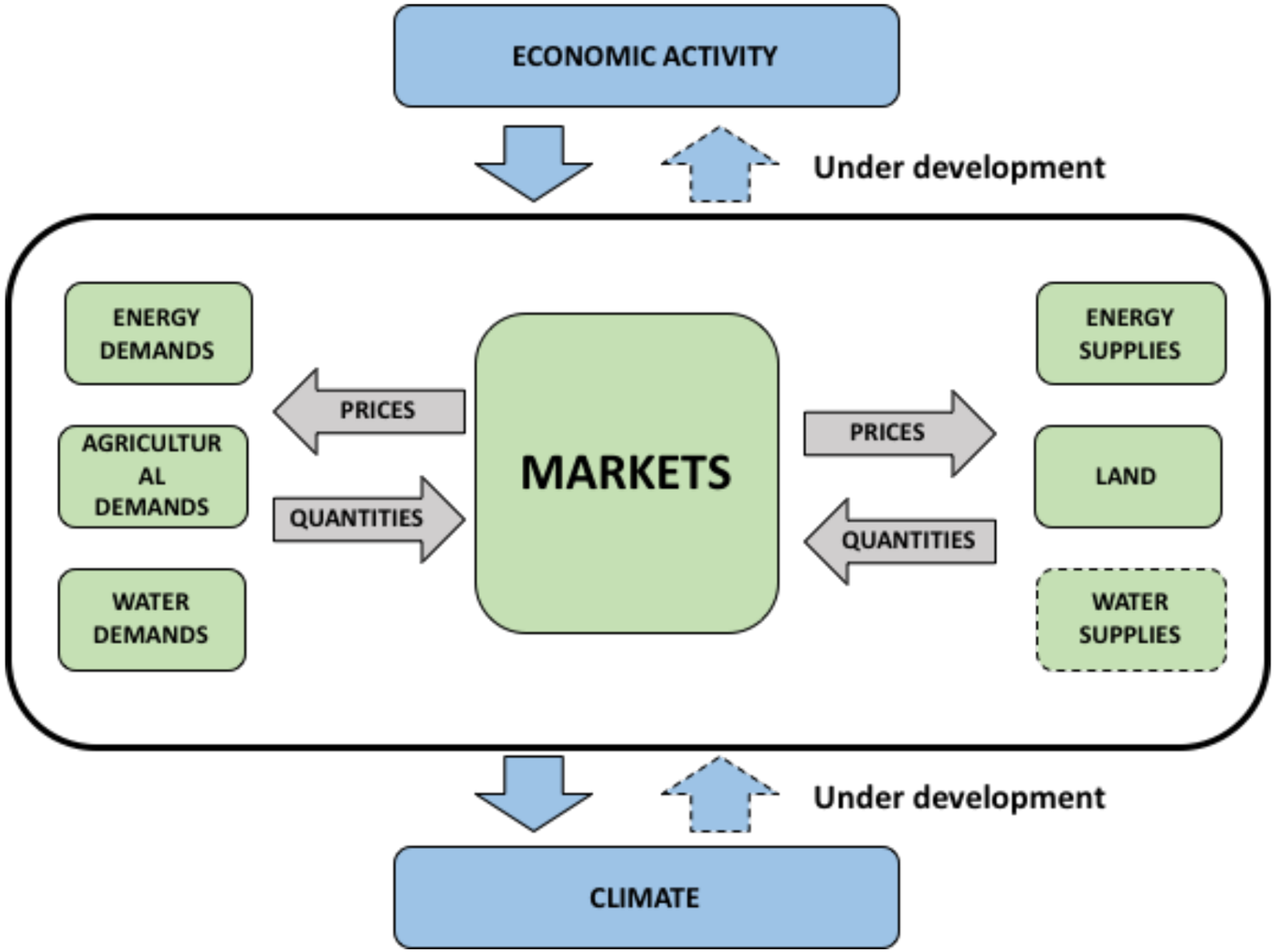


235 Water Basins

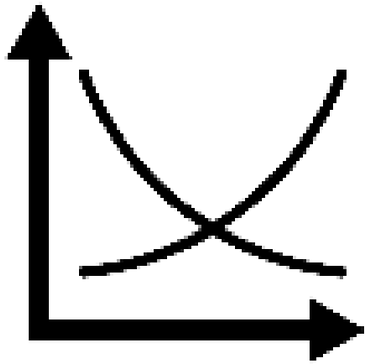


- GCAM is a community model -- Documentation available at: **https://github.com/JGCRI/gcam-core**
- Typically runs in **5-year time-steps**
- Used to evaluate impacts of *socioeconomic development, technology and resource developments, energy policies, etc.*

Integrated Assessment Modeling Framework

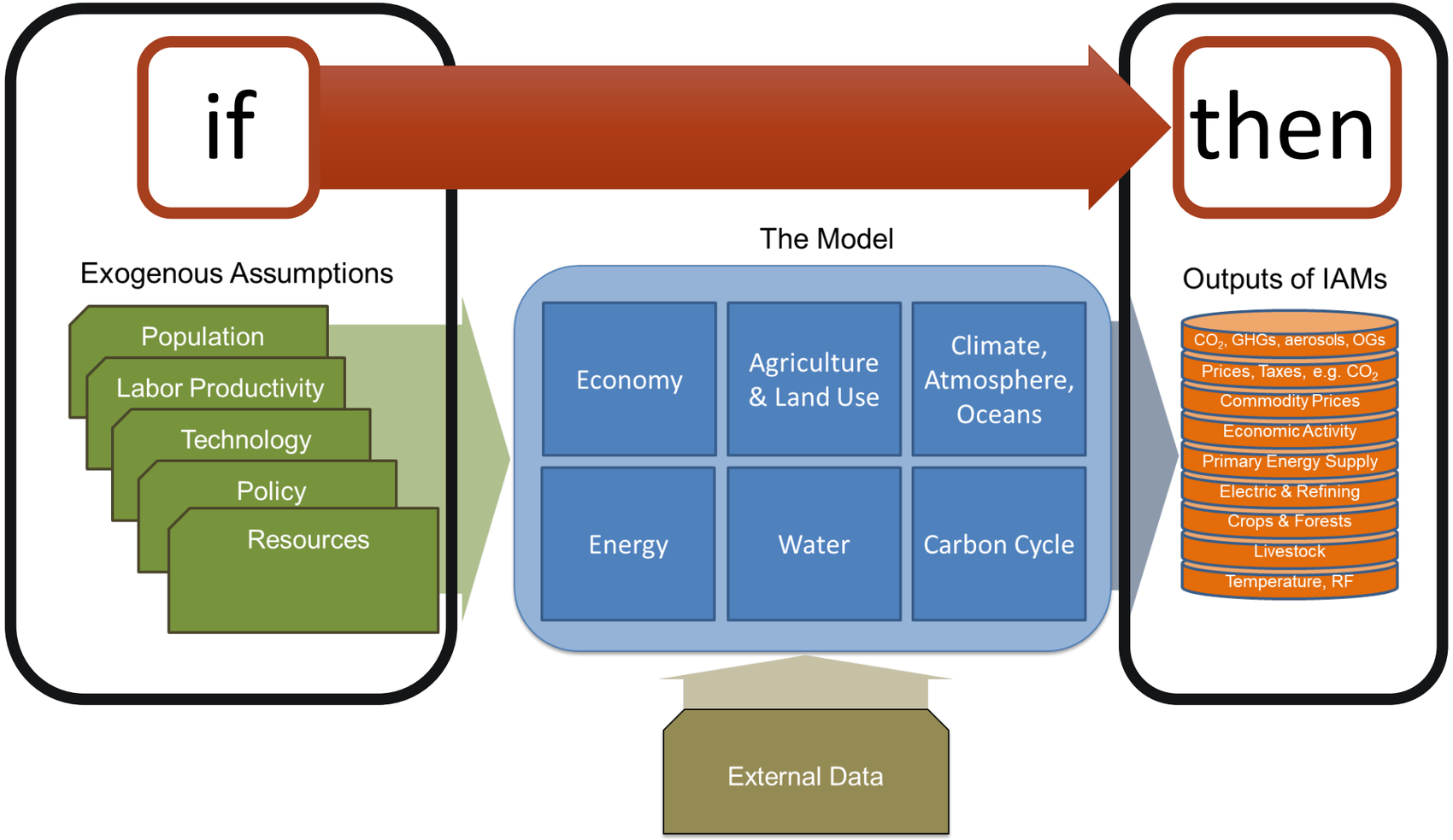


Market Equilibrium Solution



GCAM is used to produce internally consistent "scenarios" or "pathways" of the future

- Scenarios are conditional forecasts
- Scenarios describe how the future may develop based on a coherent and internally consistent set of assumptions about key relationships and driving forces



Some questions that GCAM can address

Supply

- How can distributed solar contribute to the power supply?
- How will a shift to renewable energy impact electricity prices?
- What investment costs are needed to transition to clean energy?

Demand

- How will electricity and energy demand change as technology shares shift?
  - Transport electrification
  - Efficient buildings & technologies
  - Industrial efficiency

Decarbonization

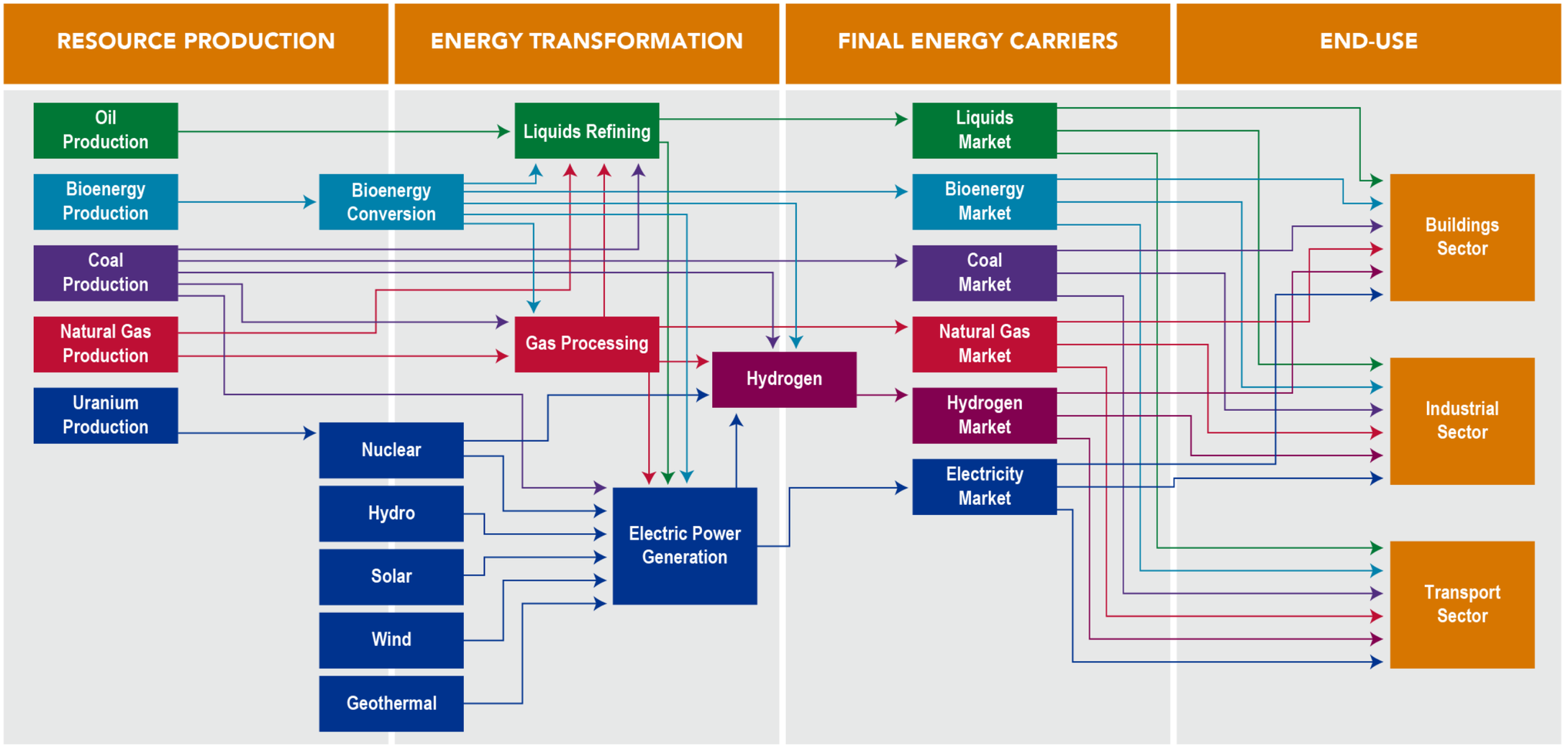
- How can specific policies contribute to national decarbonization goals?
- Which policies will have the most impact?

Nexus issues

- How much water is used to produce crops and food from land?
- How much water is withdrawn for electricity generation?

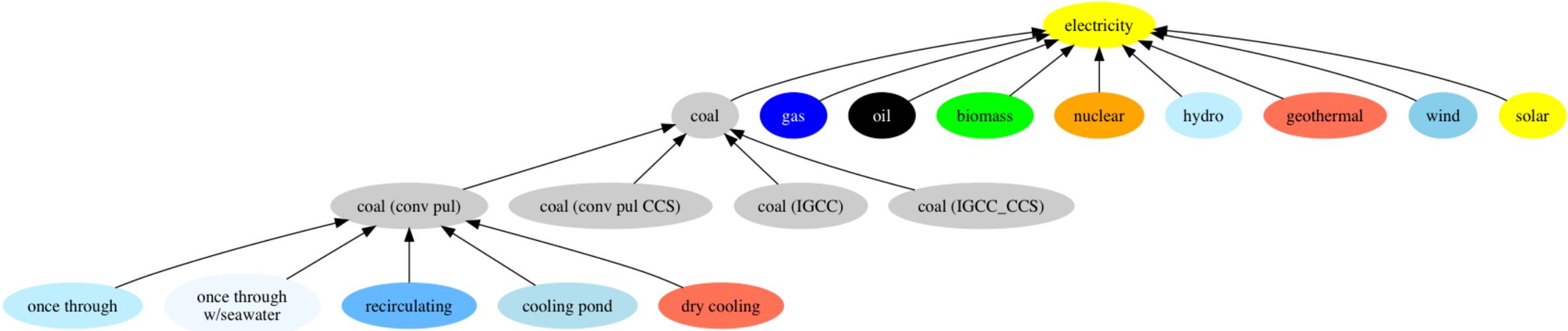
Energy System

GCAM Energy System Module



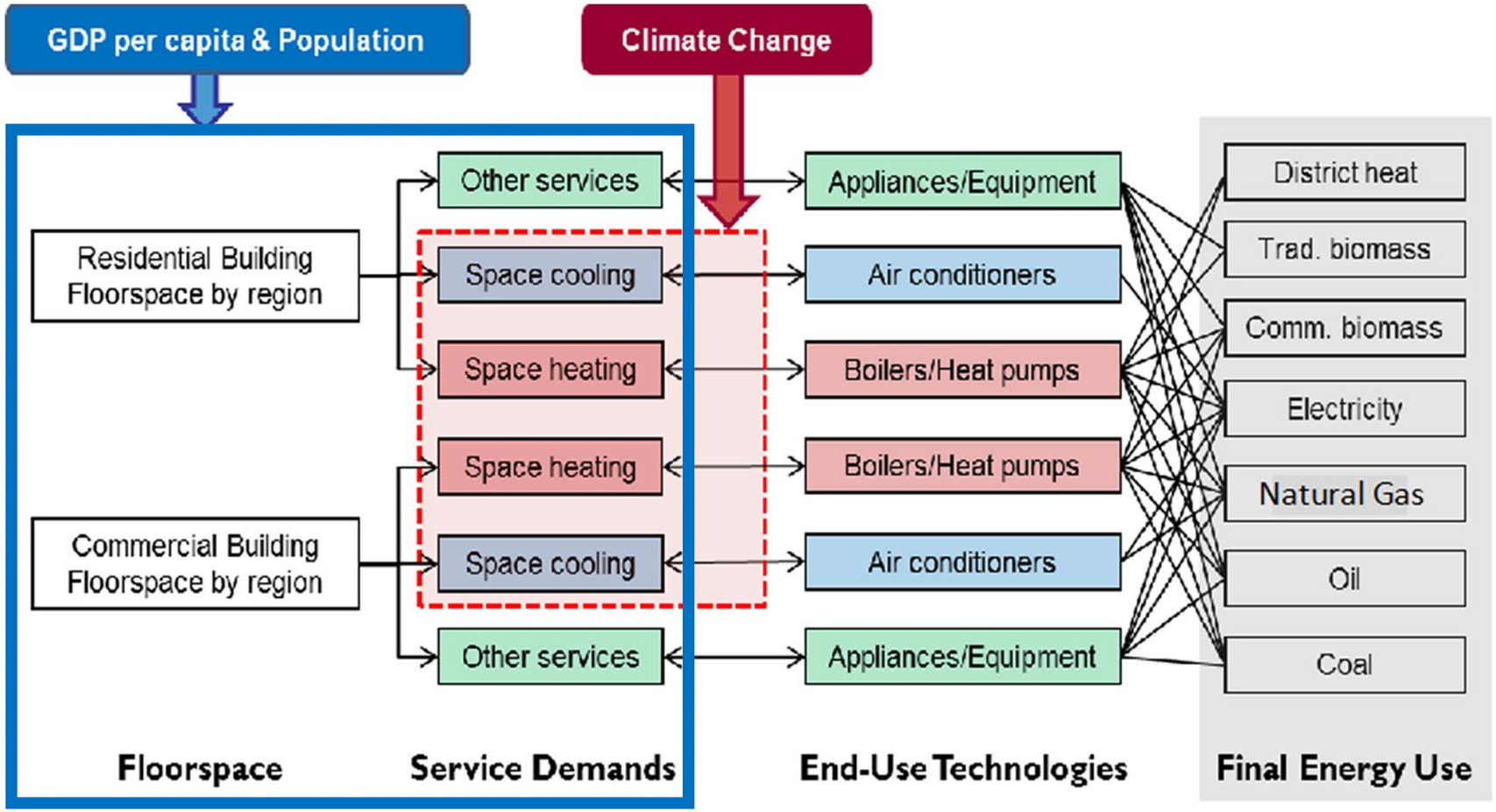
GCAM Documentation: http://jgcri.github.io/gcam-doc/toc.html

GCAM Power Sector



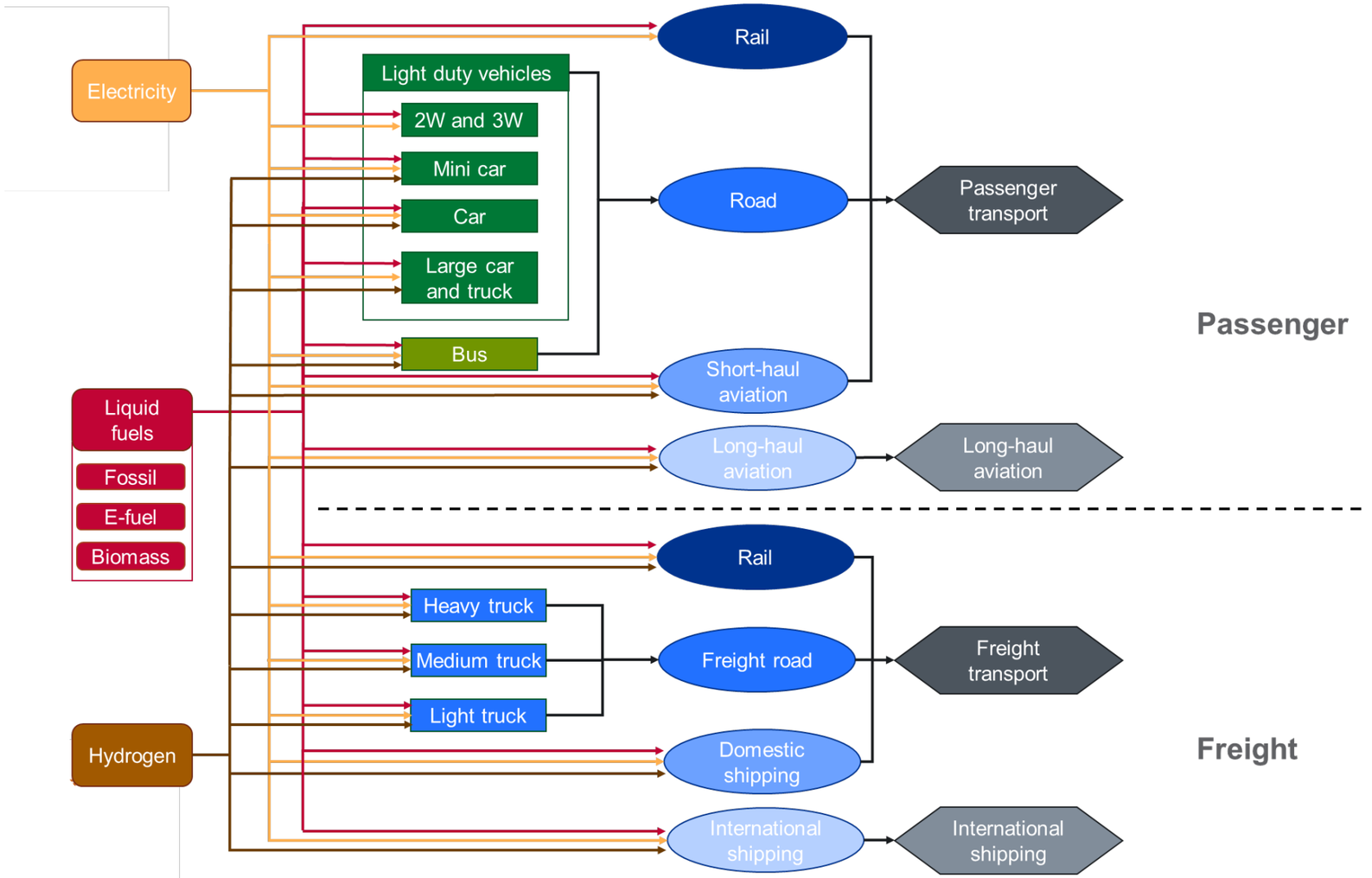
The GCAM power sector models the conversion of primary fuels to electricity

GCAM Buildings Sector



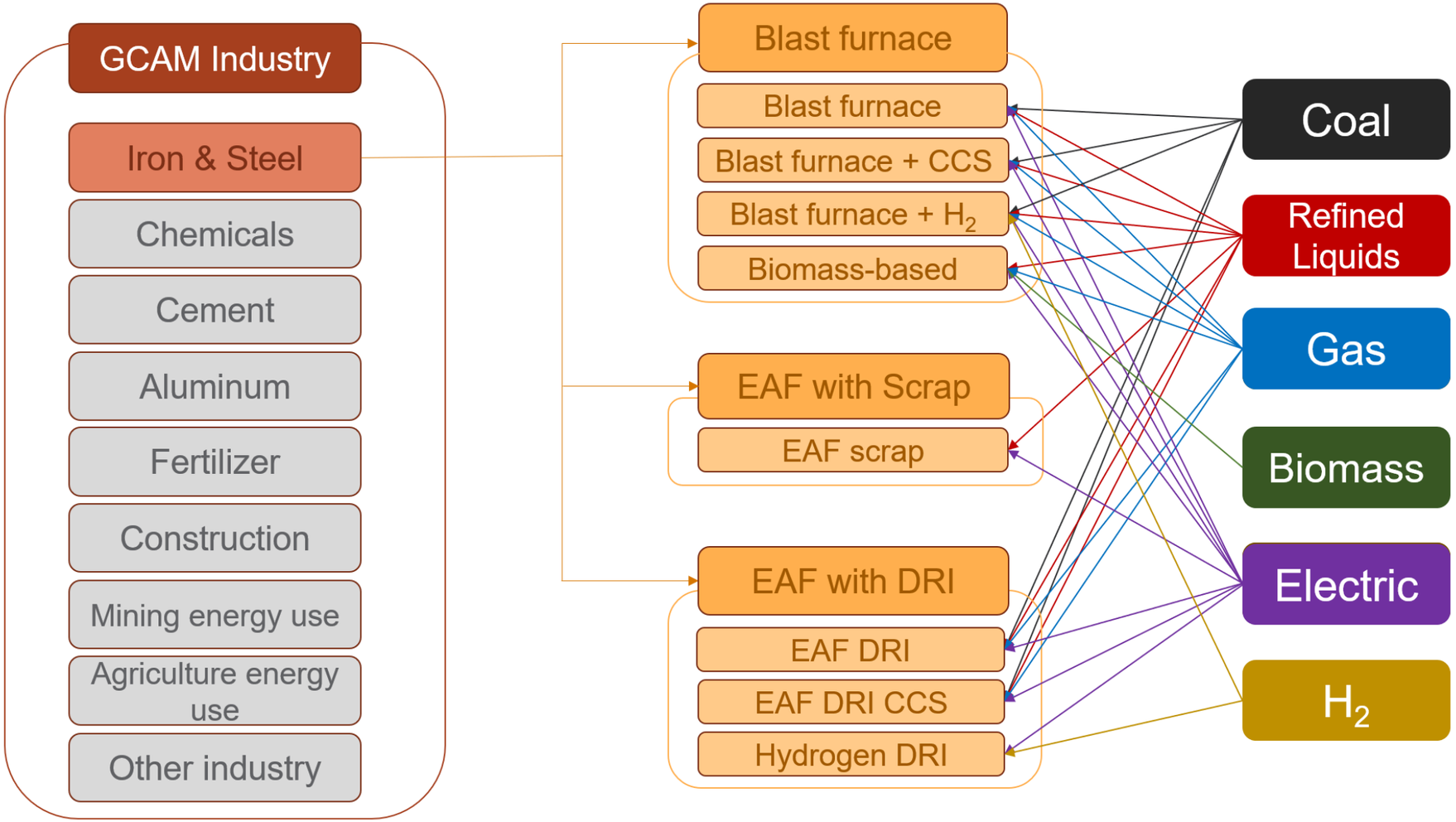
Source: Clarke, Leon, et al. "Effects of long-term climate change on global building energy expenditures." Energy Economics 72 (2018): 667-677

GCAM Transportation Sector



Source: McJeon, Haewon, et al. "A zero-emissions global transportation sector: Advanced technologies and their energy and environmental implications." (2023).

GCAM Industry Sector

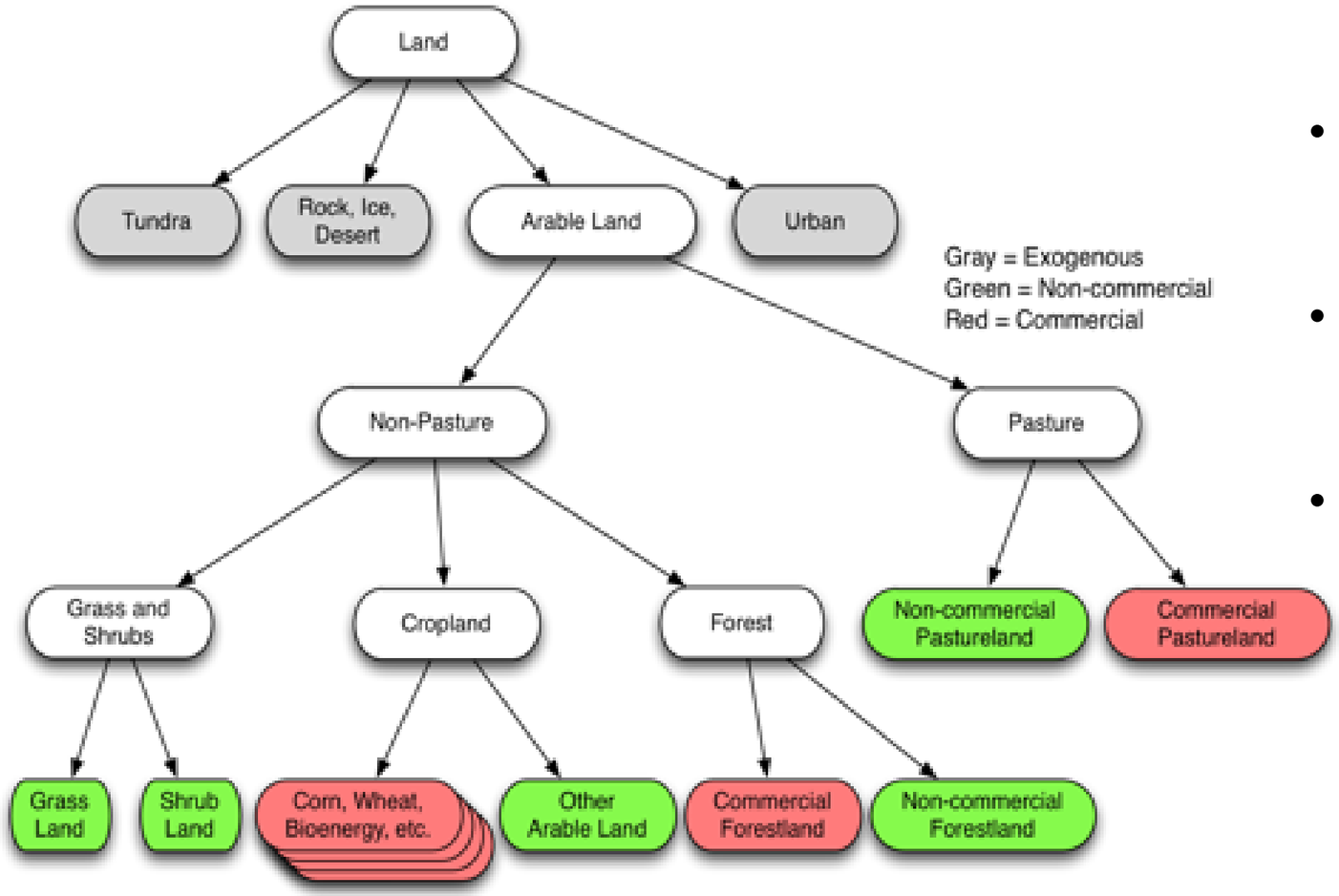


Modeling Land Use and Water

Input data to the land system

- Food and Agriculture Organization (FAO):
  - Production and harvested area, 1973-2020
  - Primary Ag production quantity and value by area, 2010-2020
  - Supply and utilization accounting for all FAO items, 2010-2019
  - Fertilizer production…
- US Department of Agriculture (USDA): Itemized costs by crop and sub-region of USA
- gcamfaostat: R package is designed for the preparation, processing, and synthesis of the FAOSTAT agroeconomic data
- Demeter: Python package that was built to disaggregate projections of future land allocations
- Moirai: Average annual water consumption and irrigated harvested area
- … and many more

GCAM Land Module



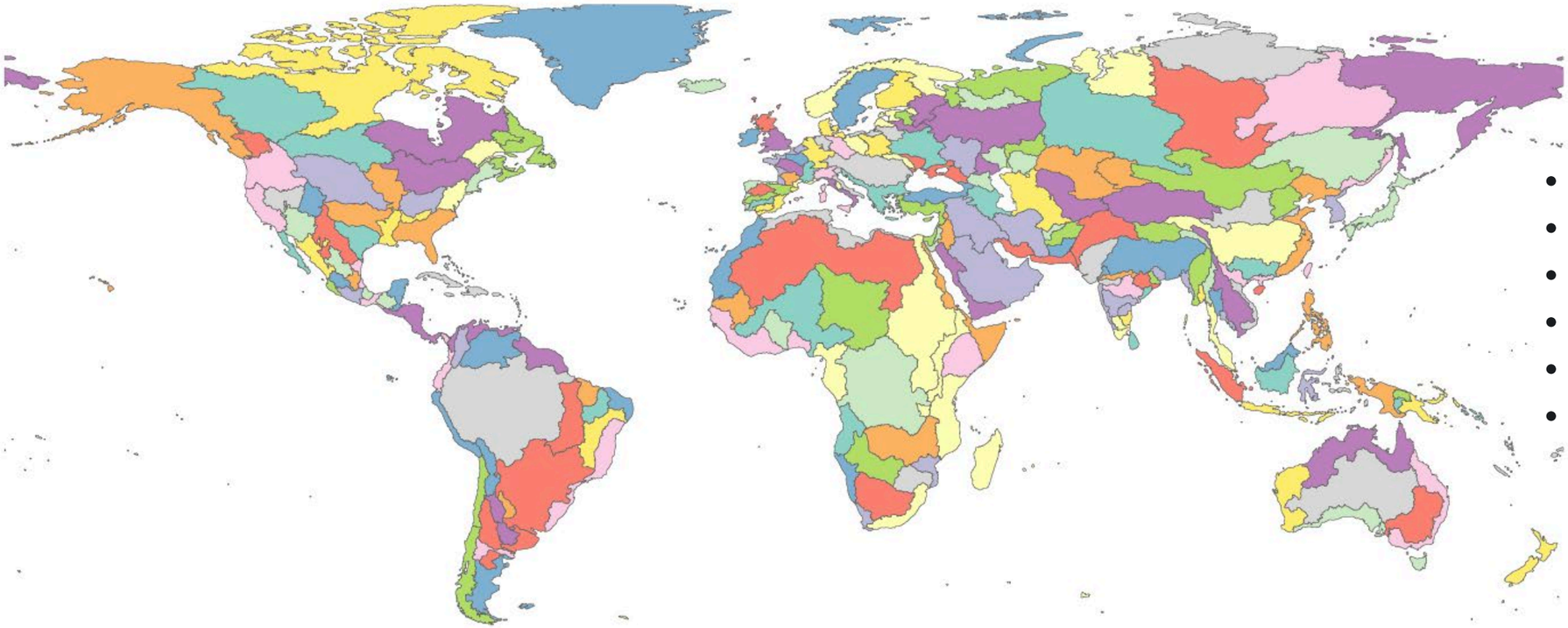
- Food demand modeled at the 32-region level
- Land use / land use change at the 384 land-use region level
- Supply at the 384 land-use region level
- Supply and demand for 15 crops, 6 animal categories, and forest products

Input data to the water system

- FAO AQUASTAT:
  - Municipal water withdrawals
  - Industrial water withdrawals
  - Desalinated water production by country and year
- Xanthos: open-source hydrologic model, written in Python, designed to quantify and analyze global water availability
  - Maximum runoff by basin
  - Accessible runoff
- … and many more

GCAM Water Module

- Global water supply by 235 major river basins
- Supply and demand are economically-balanced in each river basin



- Agriculture
- Livestock
- Electric power sector
- Industrial manufacturing
- Municipal
- Primary energy production

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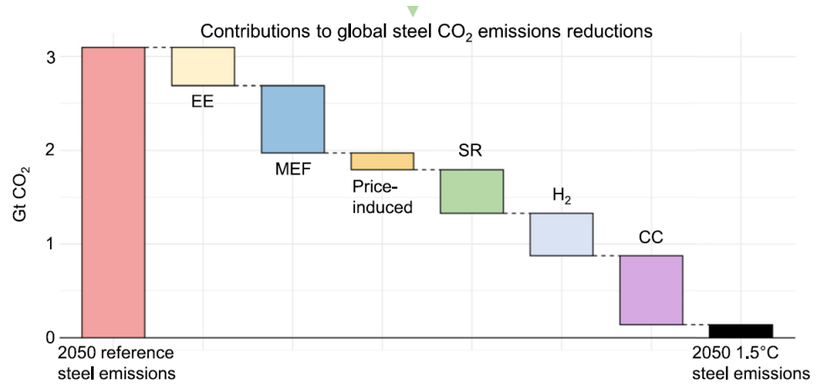
Case studies: energy, land, water, climate

Energy

- Production and use of energy resources
- Climate change impact on energy use
- Policies for reducing energy use by industry, buildings and transportation
- GHG emissions



Energy system analysis of cutting off Russian gas supply to the European Union — Energy Systems Reviews

Three different directions in which the European Union could replace Russian natural gas — Energy

Effects of long-term climate change on global building energy expenditures — Energy Economics

Limited increases in Arctic offshore oil and gas production with climate change and the implications for energy markets — Scientific Reports

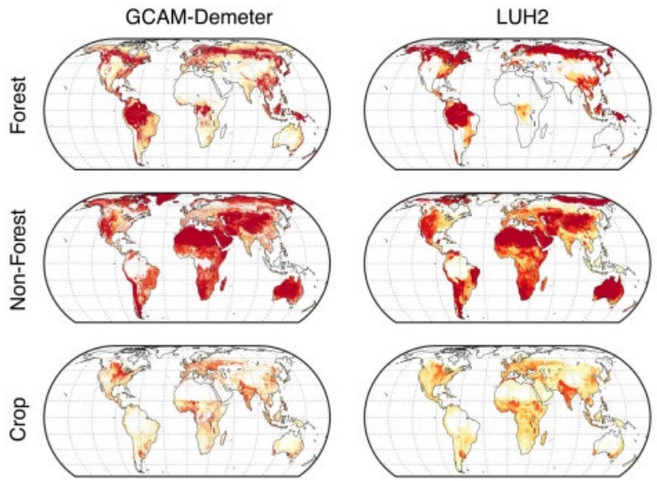
One Earth — The hydrogen economy can reduce costs of climate change mitigation by up to 22%

Integrated assessment modeling of a zero-emissions global transportation sector — Nature Communications

Rapid implementation of mitigation measures can facilitate decarbonization of the global steel sector in 1.5°C-consistent pathways — One Earth

Land use

- Land use allocation
- Sustainable agriculture
- Future of forests
- Production of food
- Impact of climate change on agriculture



Global land use for 2015–2100 at 0.05° resolution under diverse socioeconomic and climate scenarios

Scientific Data

Assessing Multi-Dimensional Impacts of Achieving Sustainability Goals by Projecting the Sustainable Agriculture Matrix Into the Future

Earth's Future

Traceable and Scalable Food Balance Sheets from Agricultural Commodity Supply and Utilization Accounts (2010-2022)

https://www.researchsquare.com/article/rs-5860715/v1

Global agricultural responses to interannual climate and biophysical variability

Environmental Research Letters

Land-based climate change mitigation measures can affect agricultural markets and food security

Nature Food

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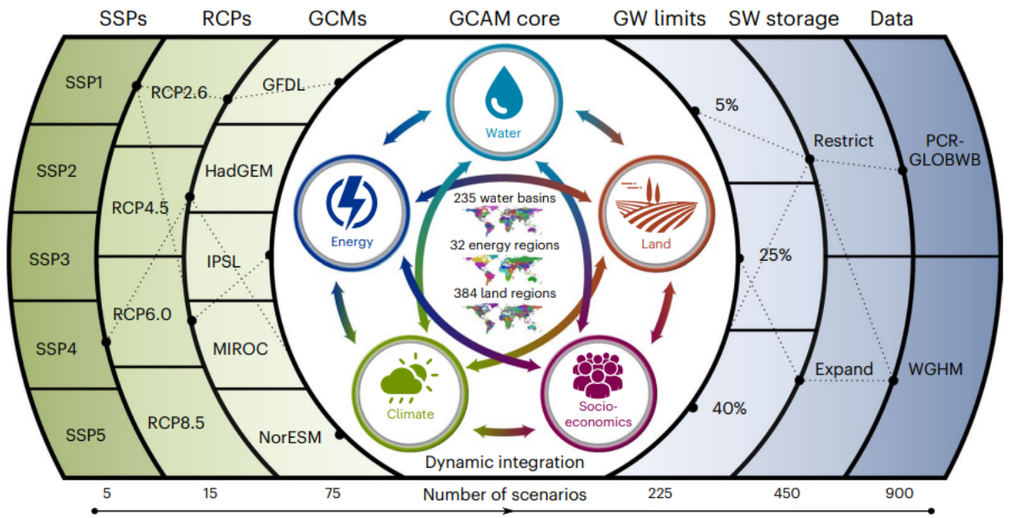
Water

- Assessment of surface and ground water availability
- Climate change impacts on water availability
- Water use by sector
- Trade of virtual water



nature sustainability

Article

https://doi.org/10.1038/s41893-024-01306-w

Global peak water limit of future groundwater withdrawals

LETTER • OPEN ACCESS

Assessing the future of global energy-for-water

To cite this article: Page Kyle *et al* 2021 *Environ. Res. Lett.* **16** 024031

LETTER • OPEN ACCESS

Characterizing the multisectoral impacts of future global hydrologic variability

To cite this article: Abigail Birnbaum *et al* 2024 *Environ. Res. Lett.* **19** 074014

A pathway of global food supply adaptation in a world with increasingly constrained groundwater

Sean W.D. Turner [a,*], Mohamad Hejazi [b], Katherine Calvin [b], Page Kyle [b], Sonny Kim [b]

ARTICLE

https://doi.org/10.1038/s41467-020-17400-4 OPEN

Check for updates

Future changes in the trading of virtual water

Neal T. Graham [1,2,3✉], Mohamad I. Hejazi [1,3], Son H. Kim [1], Evan G. R. Davies [4], James A. Edmonds [1] & Fernando Miralles-Wilhelm [1,2,3,5]

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GCAM-USA

- GCAM-USA was developed in 2020 and is embedded within the global GCAM model
- Core GCAM model was used to model the 2016 Mid-term strategy
- GCAM-USA was used for the Long-term strategy

High-ambition climate action in all sectors can achieve a 65% greenhouse gas emissions reduction in the United States by 2035

Renewable Energy and Efficiency Technologies in Scenarios of U.S. Decarbonization in Two Types of Models: Comparison of GCAM Modeling and Sector-Specific Modeling

The domestic and international implications of future climate for U.S. agriculture in GCAM

Potential long-term, global effects of enhancing the domestic terrestrial carbon sink in the United States through no-till and cover cropping

The role of electrification and the power sector in U.S. carbon neutrality

Relative Cost-Effectiveness of Electricity and Transportation Policies as a Means to Reduce CO_2 Emissions in the United States: A Multi-Model Assessment

Power sector impacts of the Inflation Reduction Act of 2022

State-by-state energy-water-land-health impacts of the US net-zero emissions goal

Other GCAM versions

- Many researchers are developing their versions of the model with additional details
- GCAM-Europe represents all EU-27 member states & other countries (e.g., UK, Norway)
- GCAM-China separates the energy and economic systems in China into provinces
- GCAM-India provides data on energy use and emissions by state
- GCAM-Canada provides information about 10 provinces and 3 territories
- GCAM-Korea is applied to reflect provincially different emission patterns

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How to Run GCAM

GCAM Documentation

GitHub: GCAM code and files also available here; users outside of PNNL can access it and ask questions

GCAM: https://github.com/JGCRI/gcam-core/releases

Links

- GCAM Documentation: http://jgcri.github.io/gcam-doc/
- GCAM Training Resources: https://jgcri.github.io/gcam_training/
- GCAM issues on GitHub: https://github.com/JGCRI/gcam-core/issues/

Running GCAM

Software

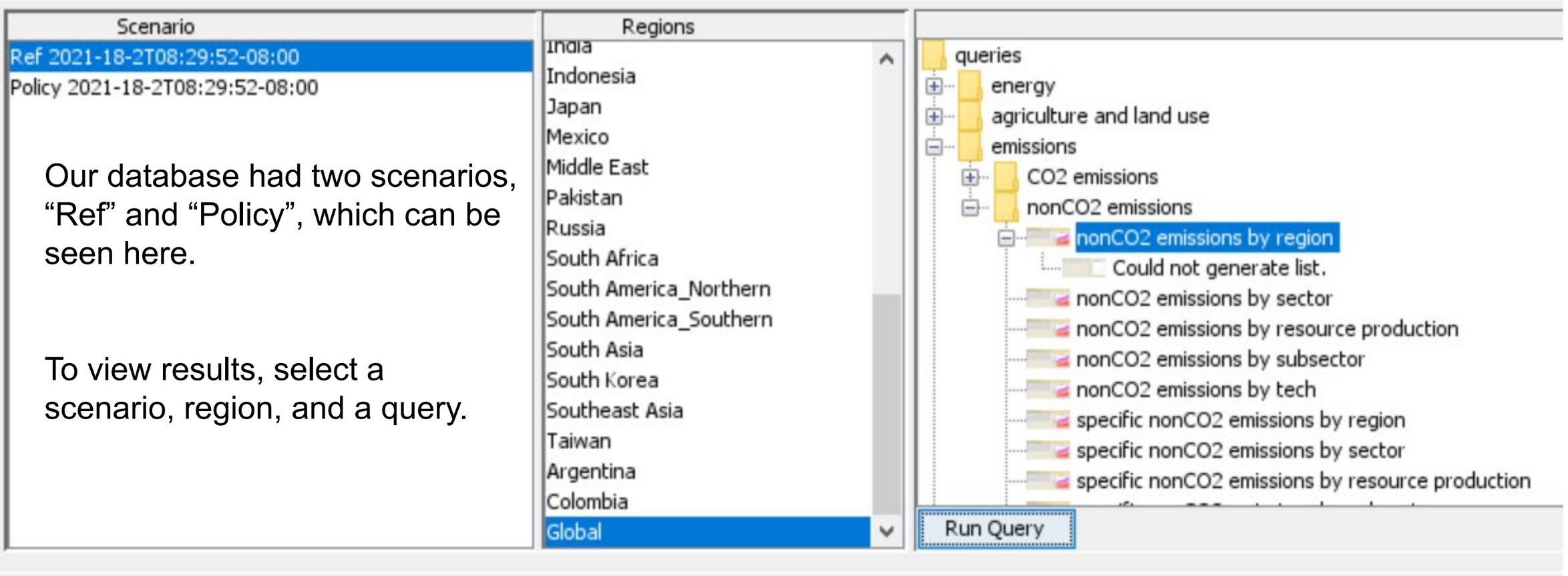
- Java Runtime Environment (64 bit): https://openjdk.org/
- On Windows you may need the Visual Studio Redistributable (for 2015/2017/2019/2022 x64): https://learn.microsoft.com/en-us/cpp/windows/latest-supported-vc-redist?view=msvc-170

Additional Software

- R program used for running the data system local https://cran.r-project.org/bin/windows/base/old/4.1.0/
- Rstudio https://www.rstudio.com
- XML Marker: http://symbolclick.com/xmlmarker_1_1_setup.exe

Model Interface

ModelInterface run-model-interface.bat
File > Open > DB Open



Our database had two scenarios, “Ref” and “Policy”, which can be seen here.

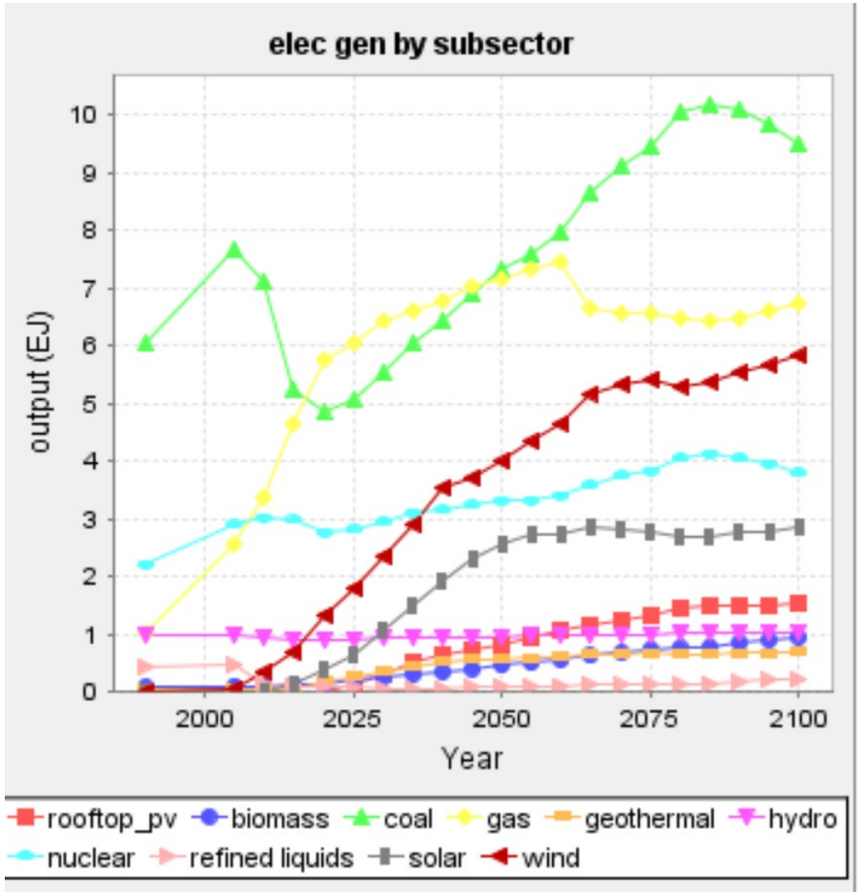
To view results, select a scenario, region, and a query.

The current selections would show nonCO_2 emissions, globally, for the Reference scenario.

Model Interface

elec gen by subsector

scenario	region	output	subsector	1990	2005	2010	2015	2020	2025	2030
Reference,...	USA	elect_td_...	rooftop_pv	0	0	0	0	0.015	0.12	0.317
Reference,...	USA	electricity	biomass	0.079	0.111	0.113	0.125	0.155	0.214	0.269
Reference,...	USA	electricity	coal	6.029	7.68	7.105	5.236	4.839	5.059	5.54
Reference,...	USA	electricity	gas	1.026	2.569	3.384	4.639	5.772	6.042	6.416
Reference,...	USA	electricity	geothermal	0.058	0.06	0.063	0.067	0.182	0.266	0.358
Reference,...	USA	electricity	hydro	0.983	0.981	0.944	0.904	0.912	0.92	0.929
Reference,...	USA	electricity	nuclear	2.201	2.918	3.02	2.988	2.761	2.815	2.961
Reference,...	USA	electricity	refined liquids	0.451	0.455	0.145	0.11	0.093	0.072	0.065
Reference,...	USA	electricity	solar	0.002	0.004	0.014	0.128	0.378	0.648	1.064
Reference,...	USA	electricity	wind	0.011	0.064	0.343	0.694	1.338	1.8	2.362



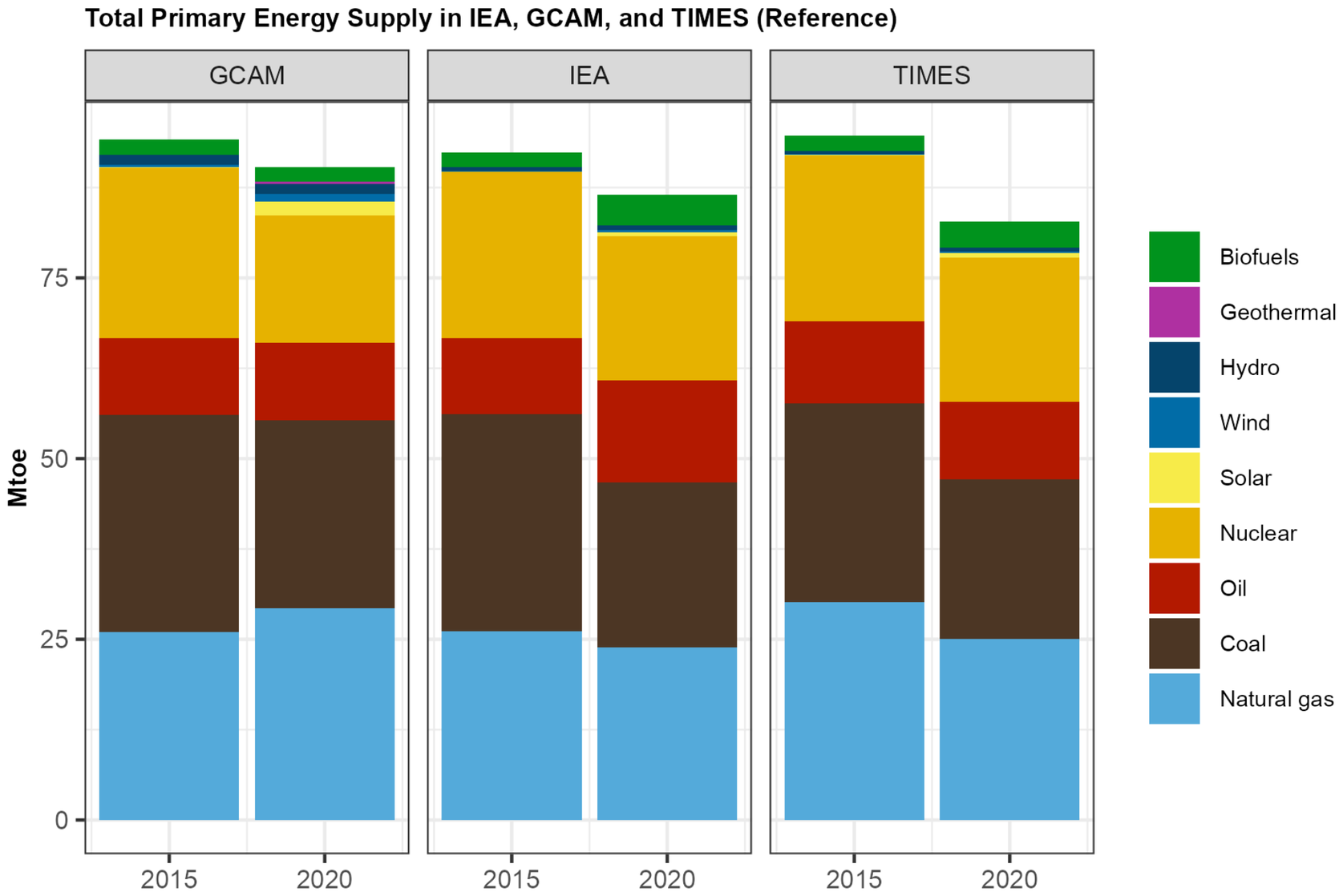
- After pressing the “Run Query” button, MI will generate a table and figure.
- MI is a great initial visualization tool, but we have better ways to analyze the results

Development of GCAM-Ukraine

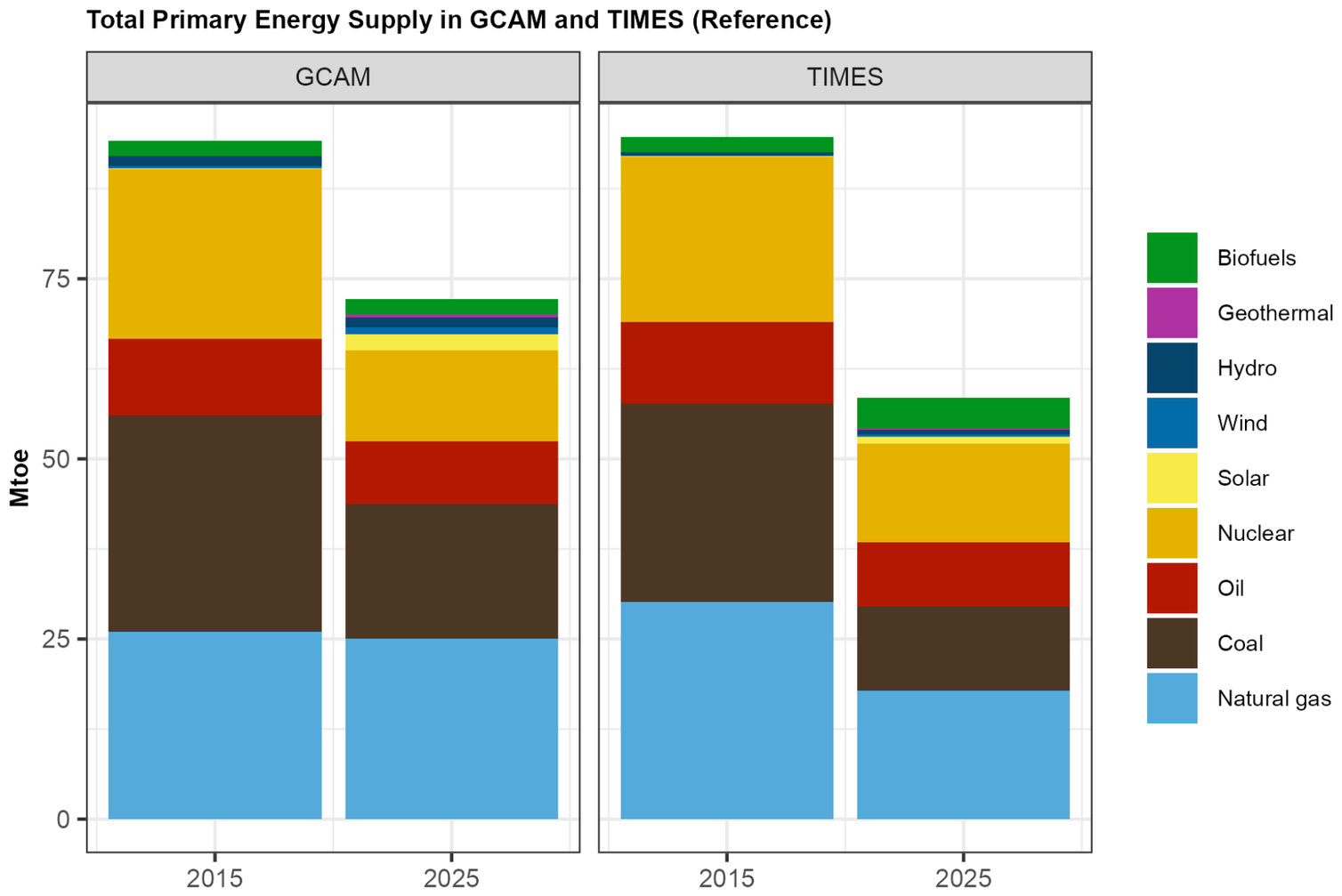
Breaking out Ukraine from GCAM 7.3

- GCAM-Ukraine 6.0 was used to model the Building Retrofit Strategy in 2022
- PNNL has broken out Ukraine from GCAM 7.3 (research branch)
- After calibration and checks, Ukraine will be included in the next model release as the 33d region
- Ukraine will stay as a separate region in all future releases with all new additional model capabilities
- The model will be free and open-source
- Ukrainian researchers will be able to modify inputs and run different policy scenarios

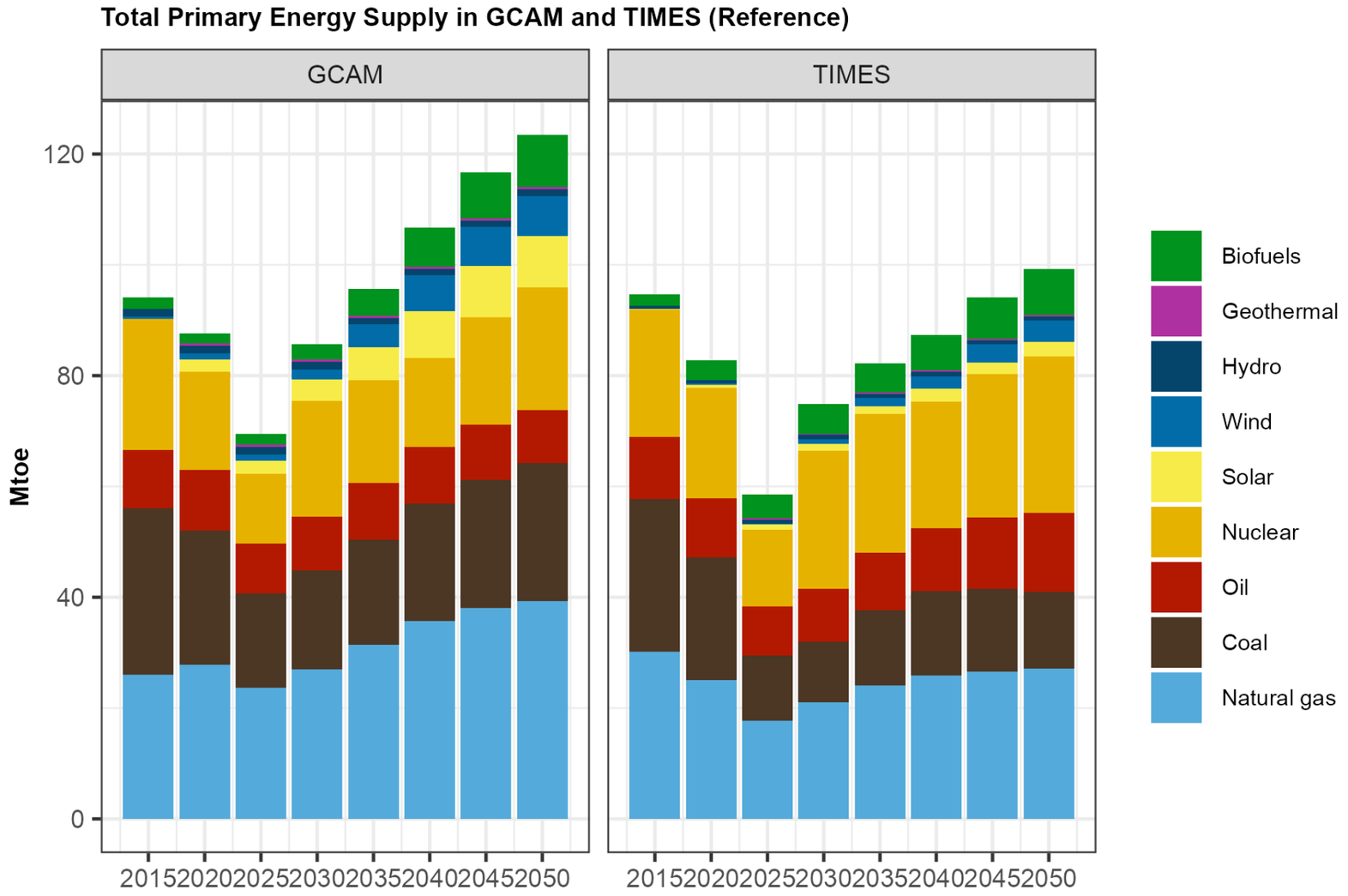
Primary energy supply



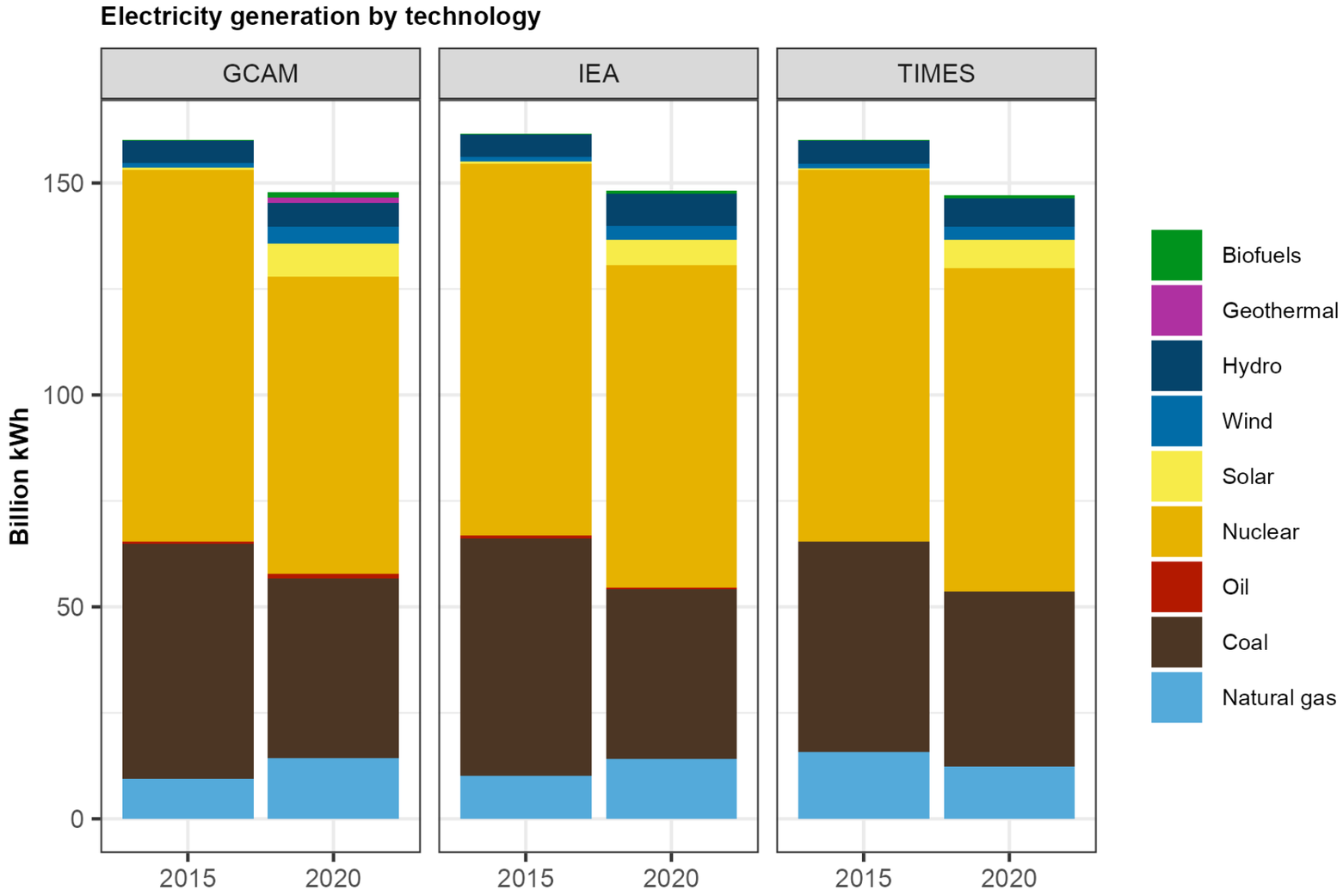
Primary energy supply



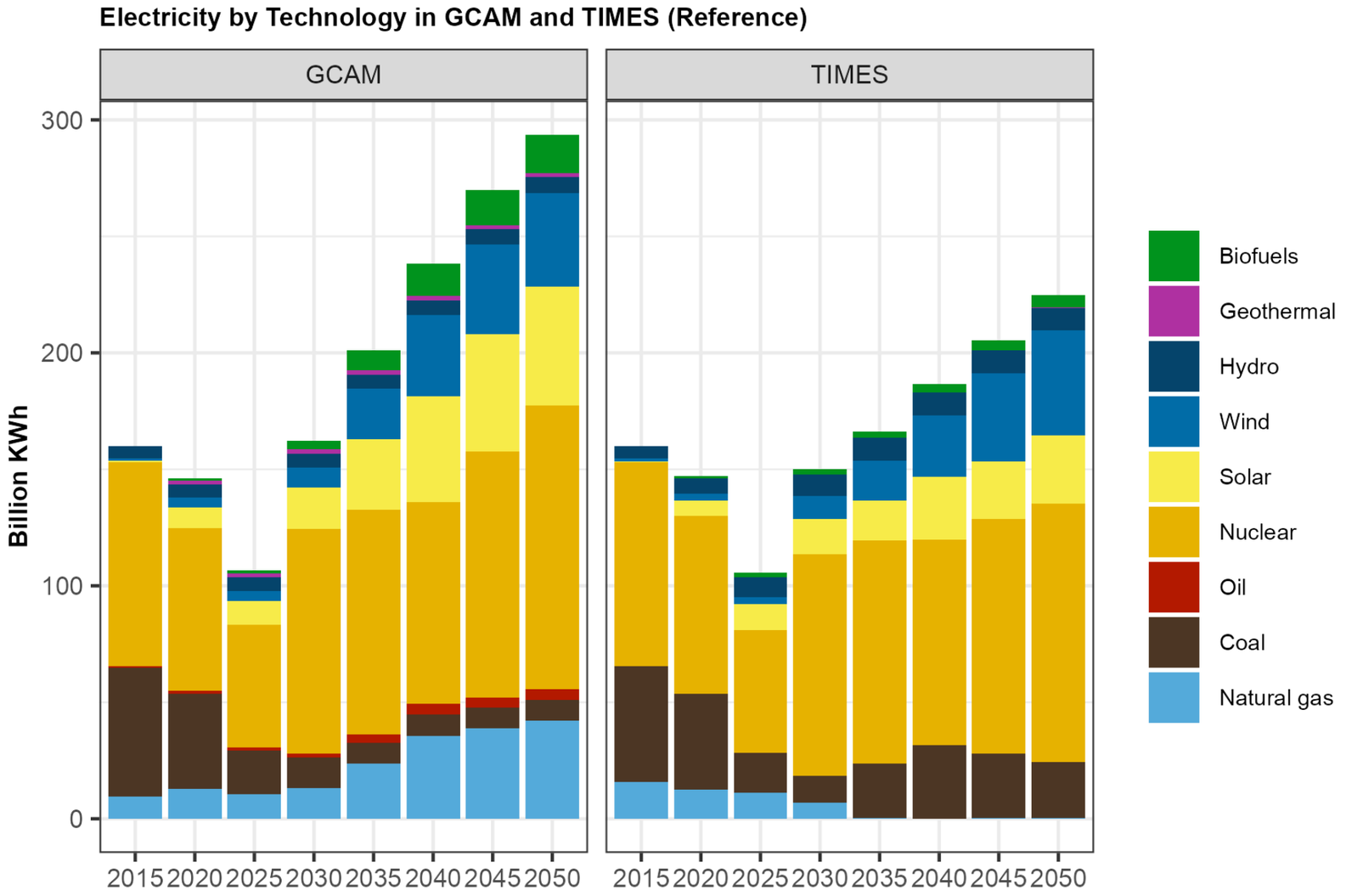
Primary energy supply



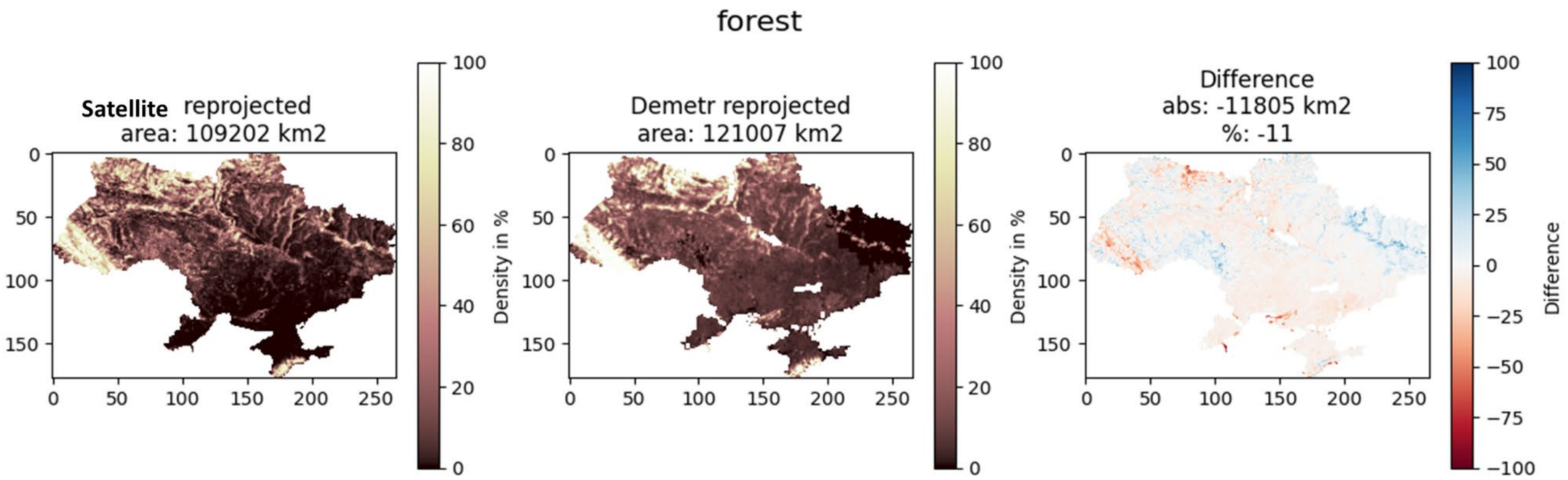
Electricity production



Electricity production



Land use



PNNL, in collaboration with NTUU 'Igor Sikorsky KPI,' is calibrating land use in GCAM using satellite-derived products

Special thanks to Volodymyr Kuzin for his contribution

Potential research topics

- Analysis of future energy mix in Ukraine
- Analysis of electricity generation (role of nuclear, gas, bioenergy) and corresponding emissions
- Role of small modular reactors for electricity generation
- Production and export of hydrogen
- Land use and agricultural output under different political and climate scenarios
- The role of Ukraine in global food security
- Water use to produce food crops and bioenergy crops
- Water withdrawn for electricity generation

Next Steps

- GCAM 7.3. (without Ukraine) is available here https://github.com/JGCRI/gcam-core/releases
- GCAM 7.4. (with Ukraine) will be separately available in a few months
  - ✓ The model will be publicly available
  - ✓ We will inform all interested researchers when the model is posted online
  - ✓ If someone is interested in the current branch, we can discuss this separately
- Modeling partners in Ukraine:
  - ✓ Institute for Economics and Forecasting of the National Academy of Sciences of Ukraine – to calibrate energy system
  - ✓ Department of Mathematical Modeling and Data Analysis of the Kyiv Polytechnic Institute - to update the land-use system

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Questions and answers

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Thank you

Nazar Kholod
nazar.kholod@pnnl.gov