Introduction to the Global Change Assessment Model (GCAM)

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(ON BEHALF OF THE ENTIRE GCAM TEAM)

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Outline

- Brief introduction to Integrated Assessment Models
- Overview of GCAM
- Detailed information on GCAM's
  - Economic assumptions,
  - Energy system,
  - Agriculture and land use system,
  - Emissions,
  - Policies,
  - Climate system, and
  - Solution algorithm.
- Frequently asked questions

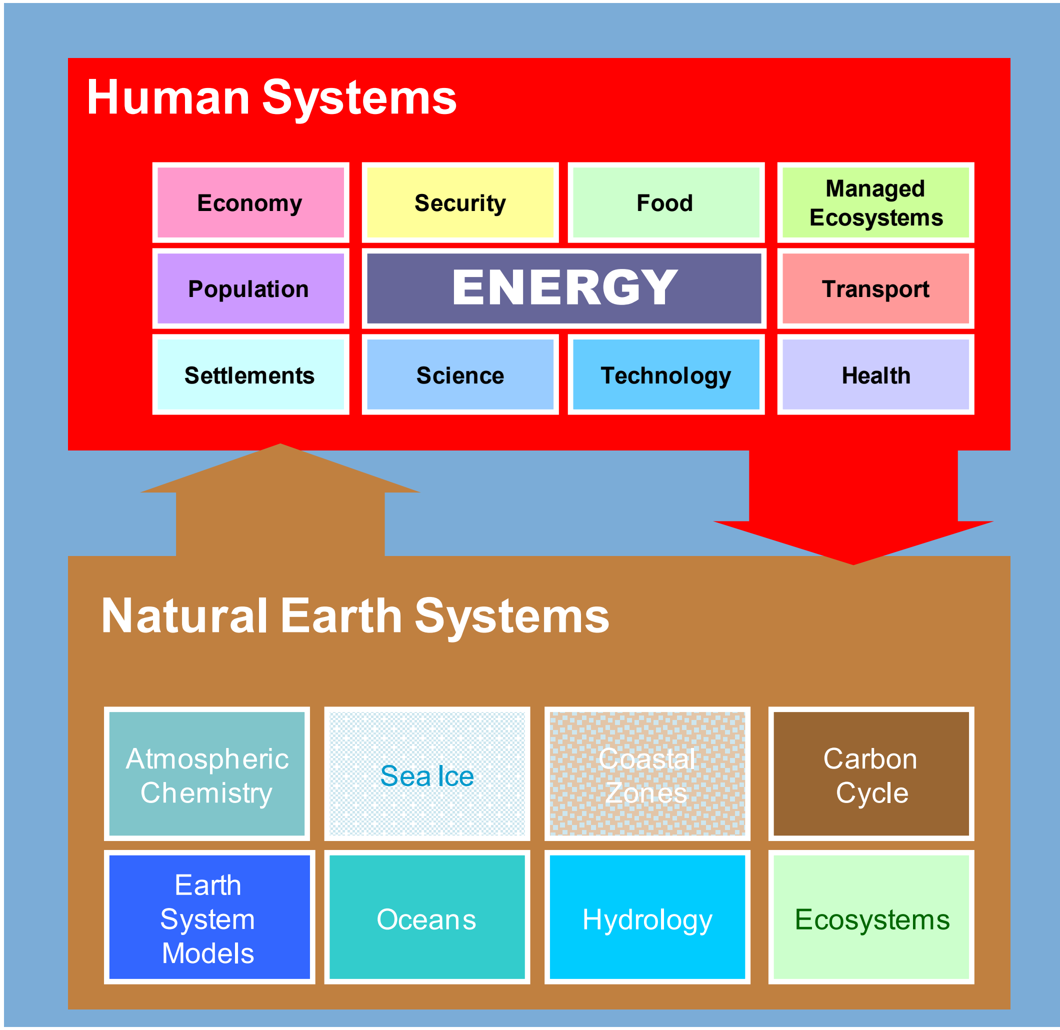
What is an Integrated Assessment Model (IAM)?

IAMs integrate human and natural Earth system climate science.

- IAMs provide insights that would be otherwise unavailable from disciplinary research.
- IAMs capture interactions between complex and highly nonlinear systems.
- IAMs provide natural science researchers with information about human systems such as GHG emissions, land use and land cover.

IAMs provide important, science-based decision support tools.

- IAMs support national, international, regional, and private-sector decisions.



IAMs Are Strategic in Nature

- IAMs were designed to provide strategic insights.
- IAMs were not designed to model the very fine details, e.g.
  - Electrical grid operation
  - Daily oil market price paths.
- IAMs are analogous to climate models in the sense that climate models don't forecast weather.
- However, climate models are moving higher resolution, and so is GCAM.
- There is a big difference between highly-aggregated IAMs used for cost-benefit analysis and higher-resolution IAMs used for analysis of system dynamics
  - GCAM is a higher-resolution IAM

General Principles

- IAMs are:
  - Global in scope,
  - Include all anthropogenic sources of emissions,
  - Include some representation of the climate system.

- However, there is significant variation across models as to their:
  - Spatial resolution
  - Inclusion of gases and substances
  - Energy system detail
  - Representation of agriculture and land-use
  - Economic assumptions
  - Degree of foresight
  - Sophistication of the climate model component

IAMs are a diverse set of tools

- The diversity of IAMs is a reflection of the diversity of problems for which the models were designed to address.
  - What is the optimal climate policy?
  - Implications of policy regimes for technology choice?
  - How do policy, energy, the economy, land use and terrestrial carbon cycle interact?
  - How does climate policy affect energy security, energy access, and air pollution?
- IAMs are evolving to address new questions
  - How will emissions mitigation and climate impacts interact?

GCAM has a long history…

- GCAM was one of four models chosen to create the representative concentration pathways for the IPCC's AR5.
- GCAM was one of three models used to create scenarios for the CCSP's scenario analysis.
- GCAM has been a prominent tool for analysis in the Climate Change Technology Program.
- GCAM has participated in virtually every major climate/energy/ economics assessment over the last 20 years:
  - Every EMF study on climate
  - Every IPCC assessment
- GCAM has been used for strategic planning by energy and other private companies.
- GCAM is now used by research institutions and governments internationally.

The Global Change Assessment Model

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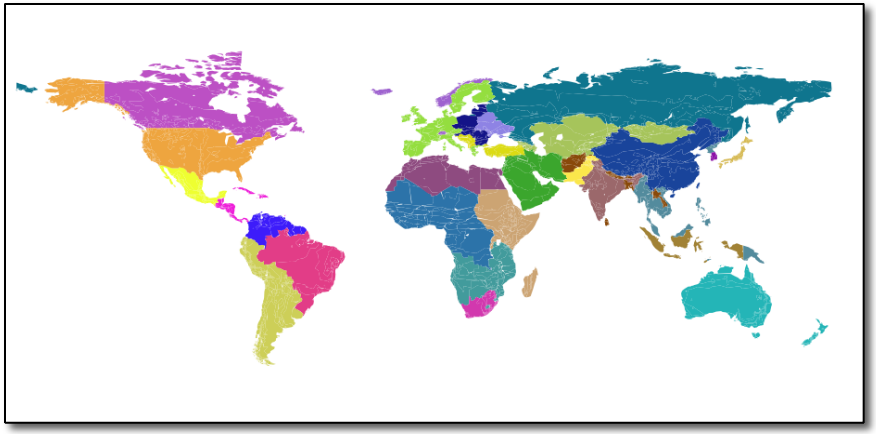
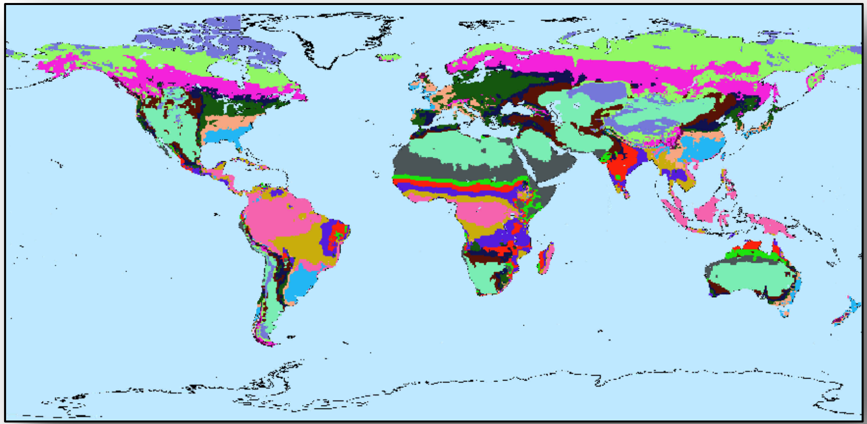
32 Region Energy/Economy Model



283 Agriculture and Land Use Model



- GCAM is a **global integrated assessment model**
- GCAM links **Economic**, **Energy**, **Land-use**, and **Climate** systems
- Typically used to examine the effect of technology and policy on the economy, energy system, agriculture and land-use, and climate
- Technology-rich model
- Emissions of 24 greenhouse gases and short-lived species: CO_2, CH_4, N_2O, halocarbons, carbonaceous aerosols, reactive gases, sulfur dioxide.
- Runs through **2100** in **5-year time-steps.**
- Documentation available at: **wiki.umd.edu/gcam**
- There is also a GCAM Community Listserve.

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BEFORE WE START…

Model version

- Everything included in this presentation is about the 2015 release version of GCAM (version 4.2)

- I am only describing elements of the model that are in that version. We do have research versions of GCAM that include other capabilities. These were discussed earlier in the week, but not this morning.

What’s new from the previous release

- Added the ability to use Hector as a climate model
- Included DDGS as a feed source (produced from biorefineries)
- Included the ability to use an absolute cost logit
- Updates to electric power plant costs
- BC-OC emissions updates
- Updates to residue biomass & crop vegetation carbon parameters
- Improvements to the solver

- Changes in model configuration/operation:
  - Changed the output file format from DBXML to BaseX
  - Adjustment to the configuration file to enable flexible output file writing
  - Proportional-tax-rate functionality merged into the linked_ghg_policy
  - Added a run-gcam script to quickly run GCAM (without re-compiling)

What's new from the previous release (continued)

- Various clean-up tasks:
  - Improvements to near-term refining behavior
  - Improvements to target finder
  - Correction to scavenging & OtherMeat_Fish resource curves
  - Correction to non-CO_2 pricing (doesn't affect MACs)
  - Enable policy cost calculation with regionally differentiated carbon prices
  - Corrections/additions to queries
  - Other bug fixes

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OVERVIEW OF GCAM

The Global Change Assessment Model

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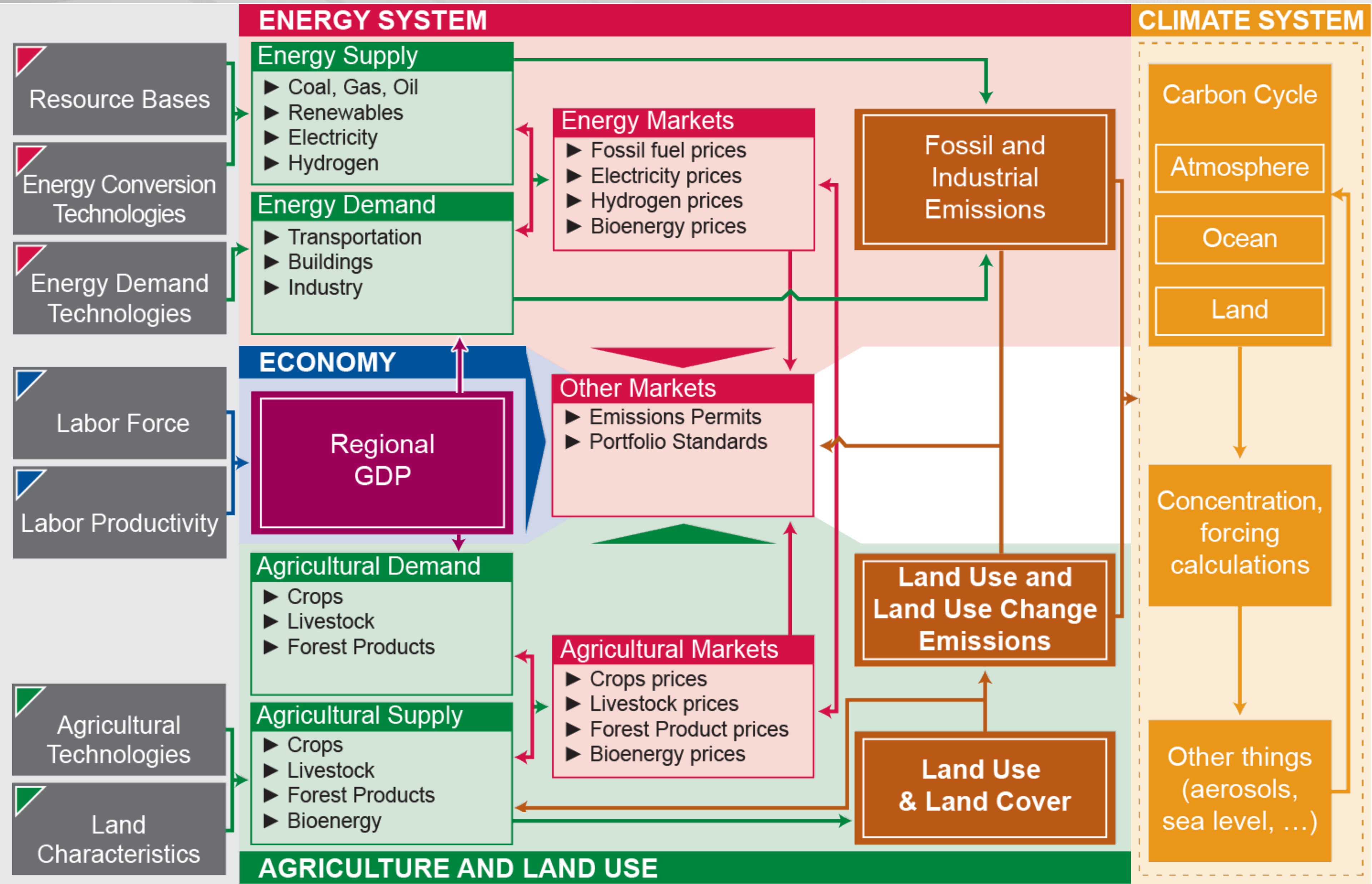
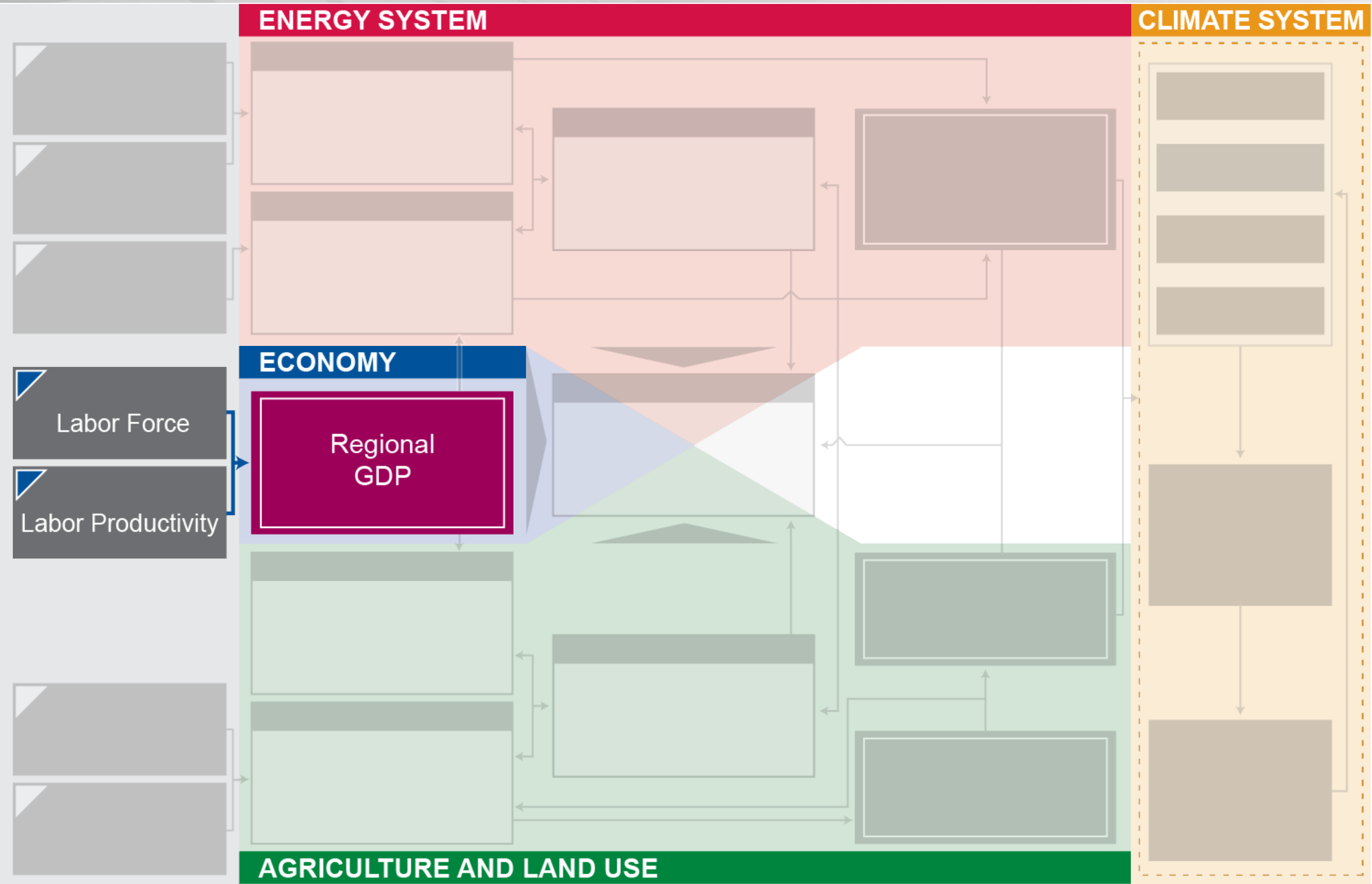


DETAILED MODEL DESCRIPTION

The Global Change Assessment Model

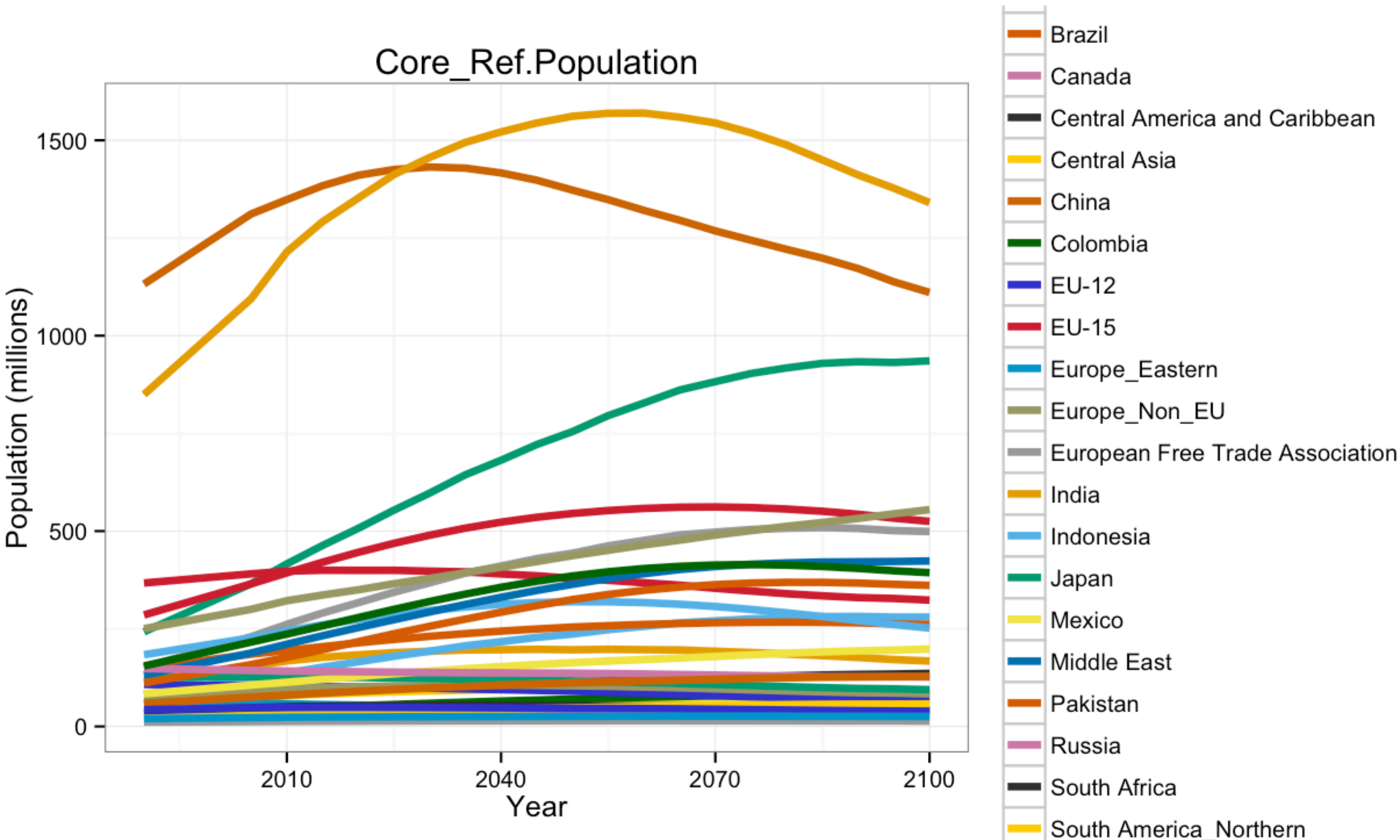


The Economy: Basic Assumptions

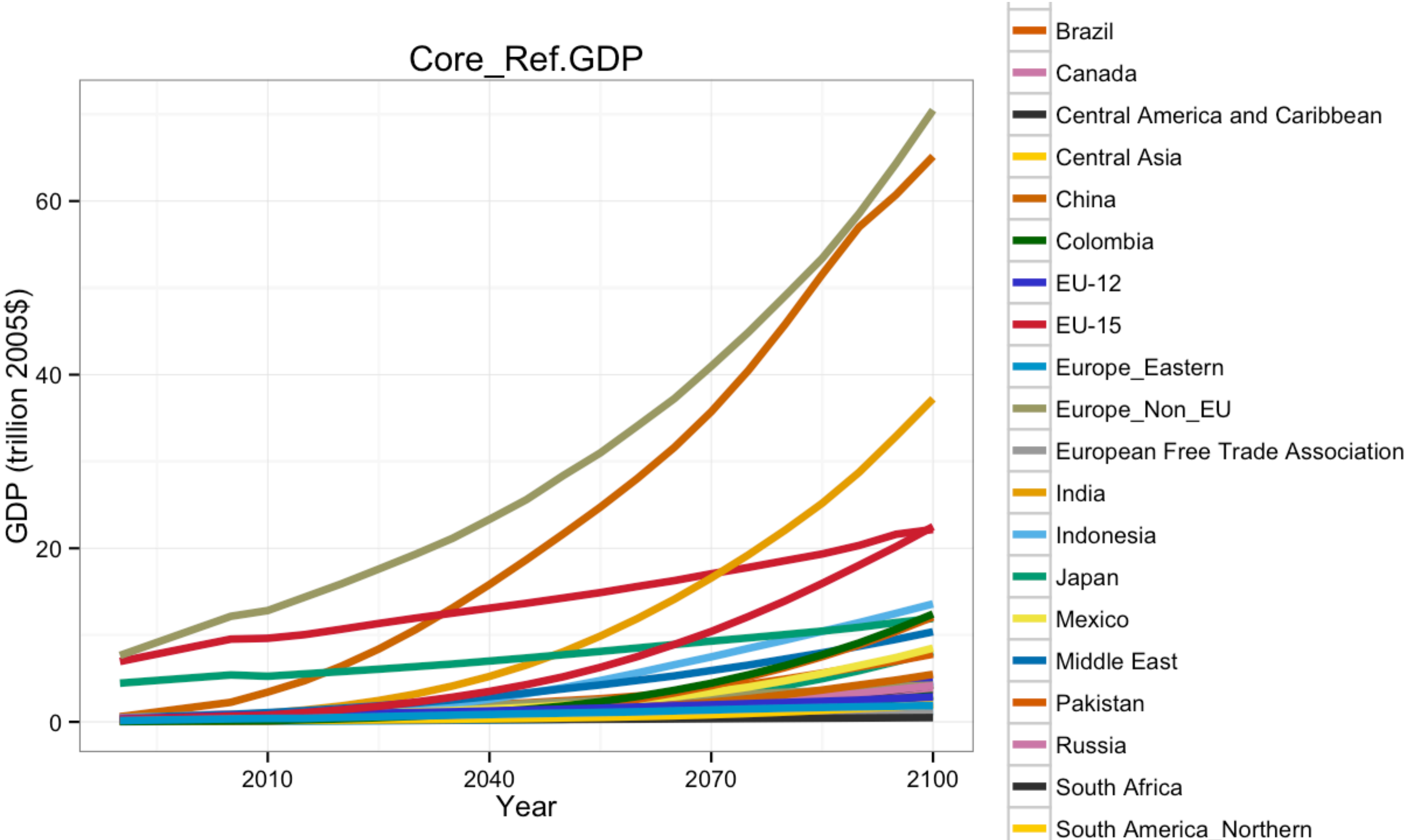
- Population:
  - Exogenously specified
  - Does not change in response to policy, technology, etc.
  - Current core model scenario assumes global population peaks in 2065 at roughly 9 billion people

- GDP:
  - Exogenously specified assumptions about labor productivity growth
  - Does not change in response to policy, technology, etc.
  - Current core model scenario assumes long-term labor productivity growth of approximately 1.5 percent per year in the developed world. Developing world growth is generally higher, with countries undergoing initially rapid growth which then slows toward the developed country levels over time.

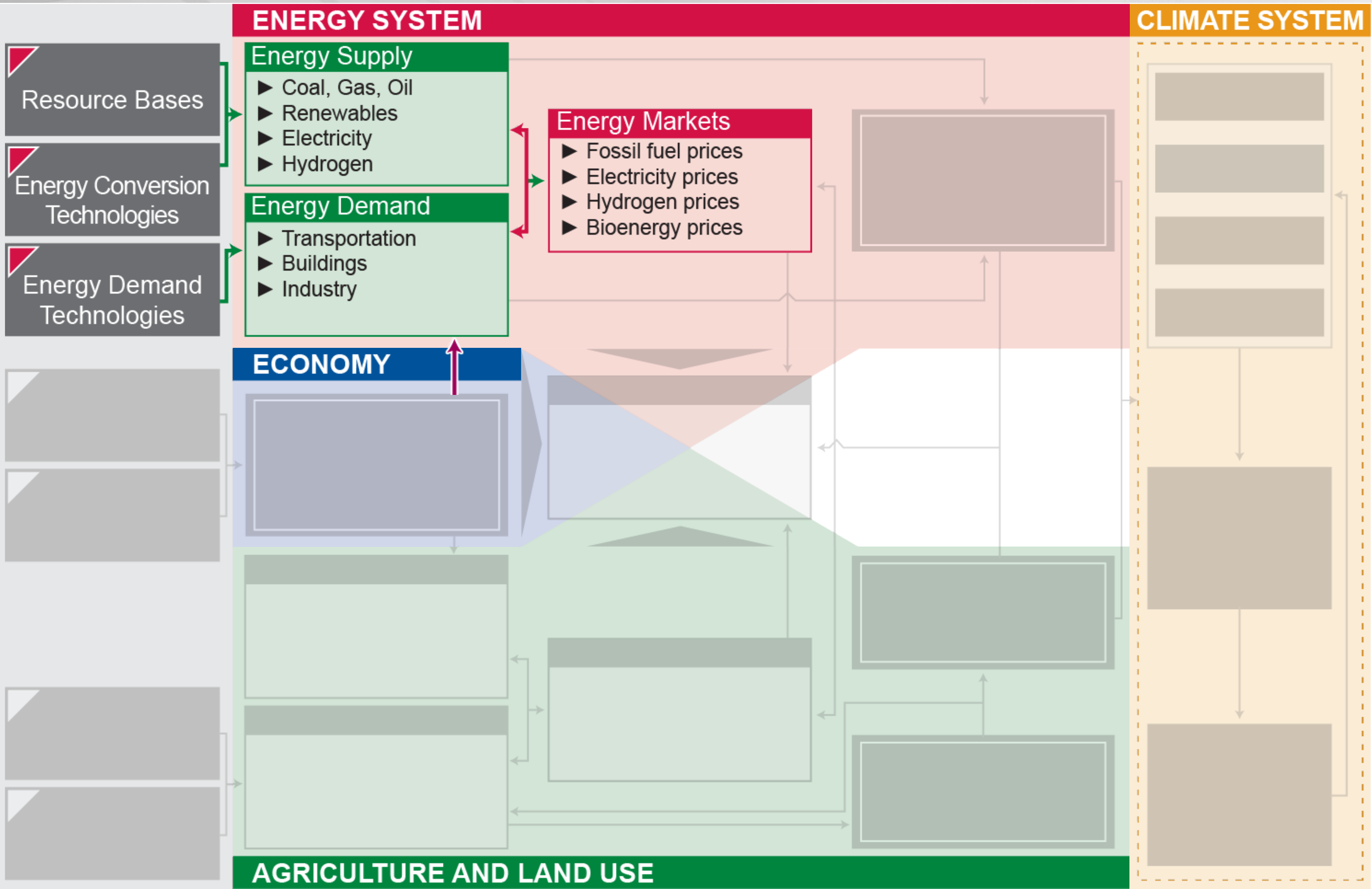
The Economy: Basic Assumptions



The Economy: Basic Assumptions



The Global Change Assessment Model



The Energy System: Structure

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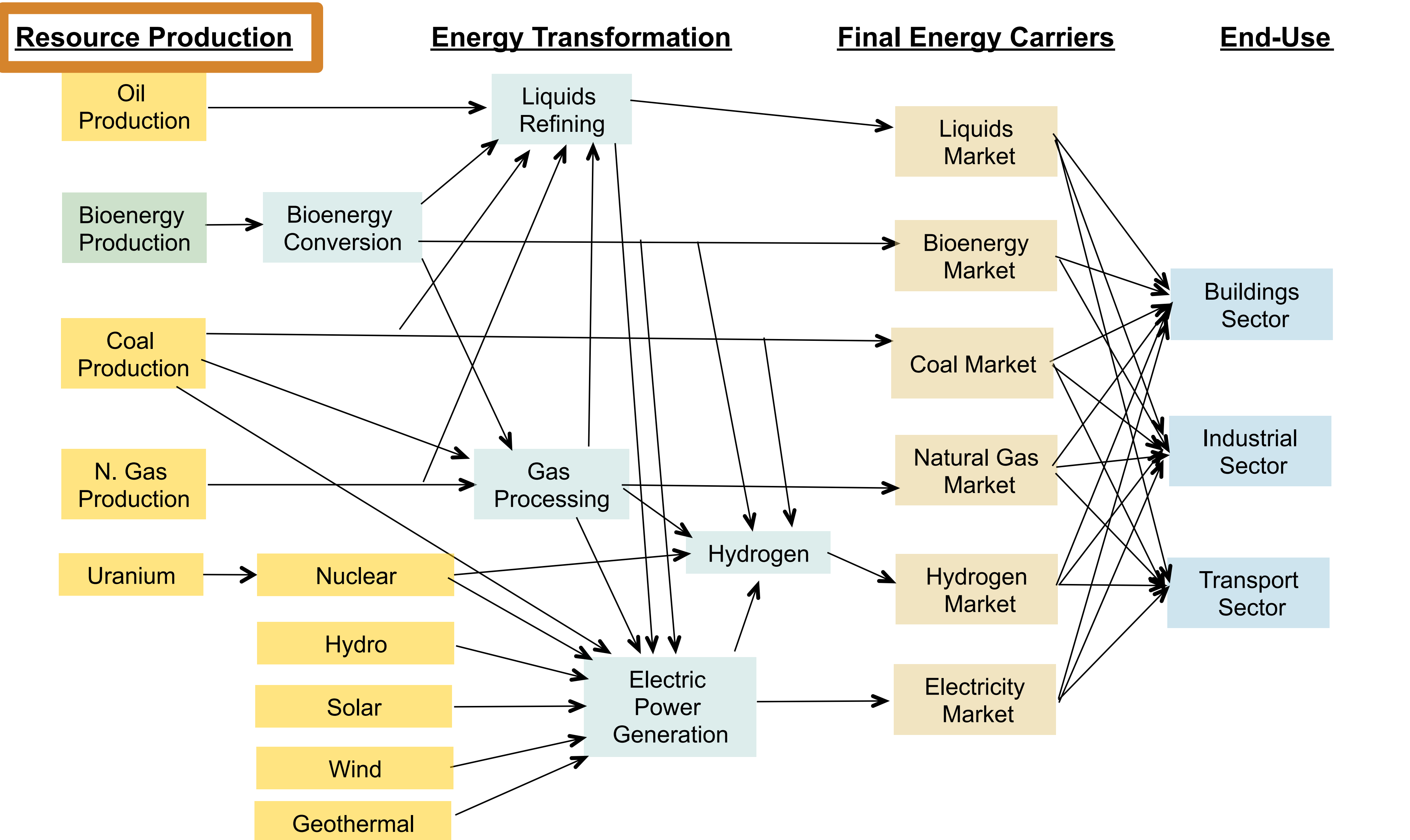
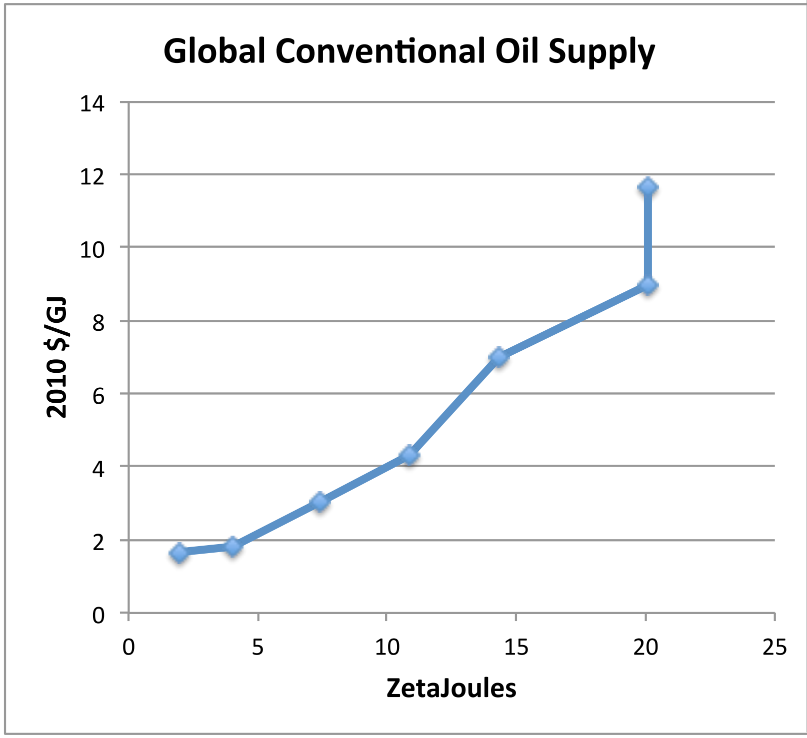
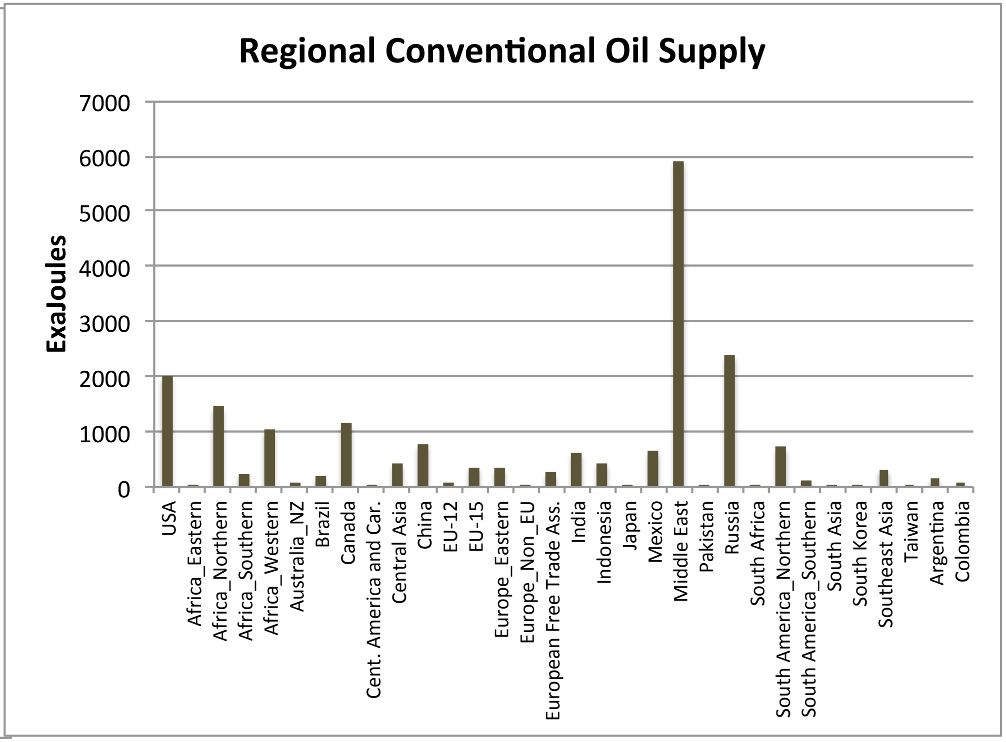


The Energy System: Resources

- Resources serve as inputs to conversion technologies to produce energy carriers such as electricity, liquid fuels, and hydrogen.
  - For example, several types of solar technologies – CSP, central PV, rooftop PV – draw from the solar resource to produce electricity.
- Exhaustible Resources in GCAM
  - Coal
  - Natural Gas
  - Oil (conventional and unconventional)
  - Uranium
- Renewable Resources in GCAM
  - Solar
  - Wind (onshore and offshore combined into one)
  - Geothermal
  - Bioenergy (several forms)

The Energy System: Resources: Conventional Oil





- Oil, Gas, and Coal Resources derived from Rogner 1997 (per the GCAM wiki), but please refer to that source for original data.
- Note: there is an additional 90 ZJ of unconventional oil in GCAM 4

The Energy System: Resources: Natural Gas

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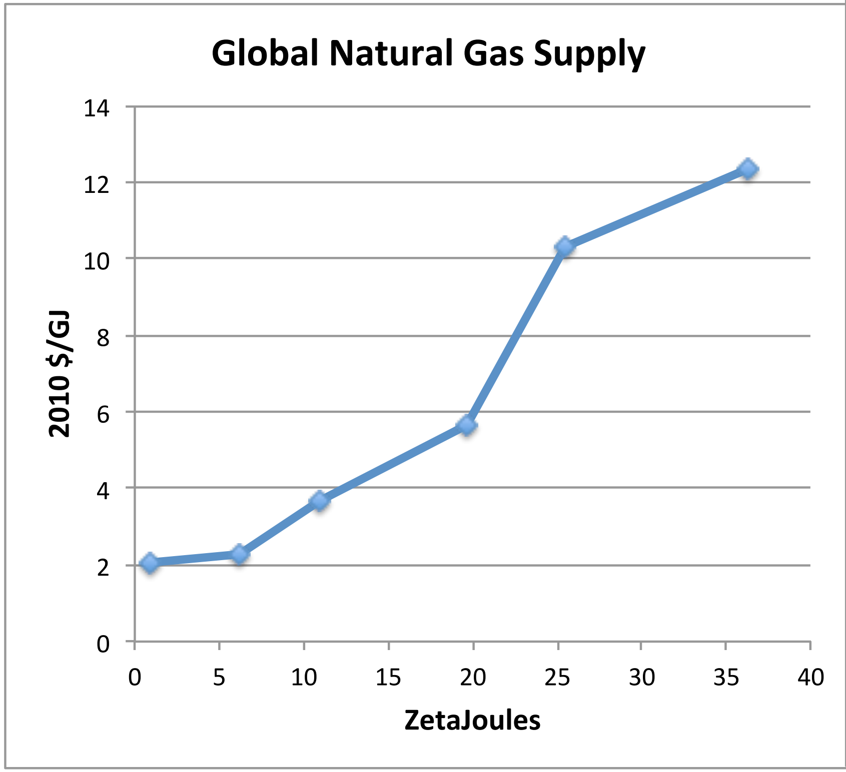
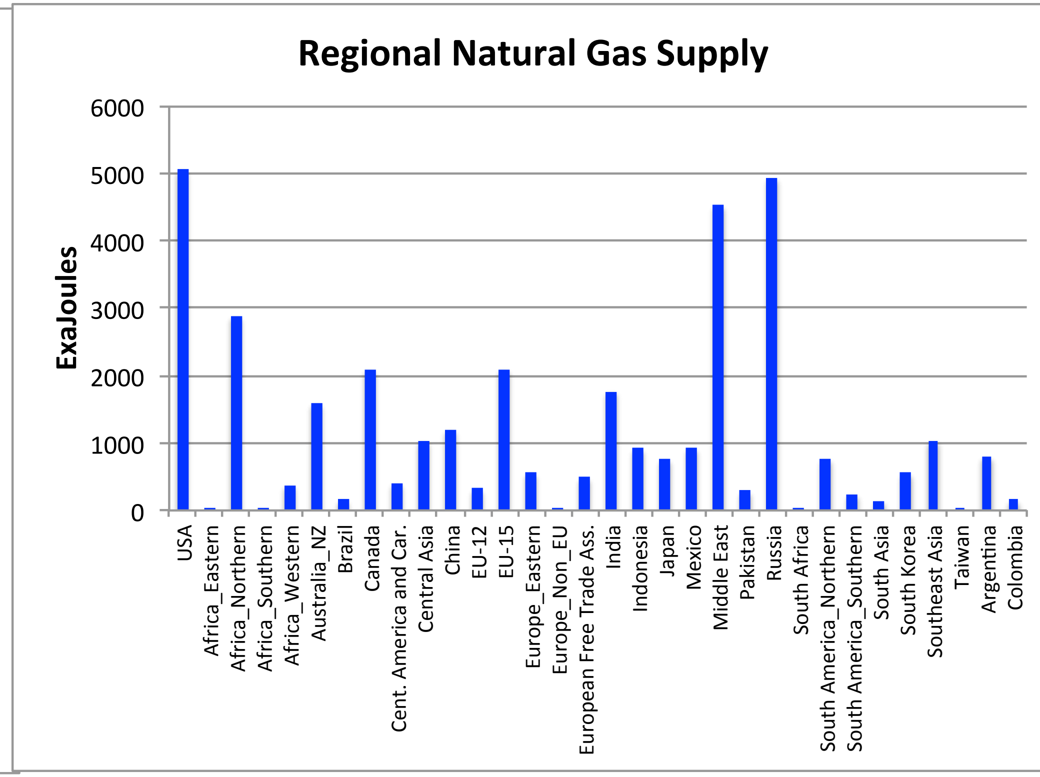
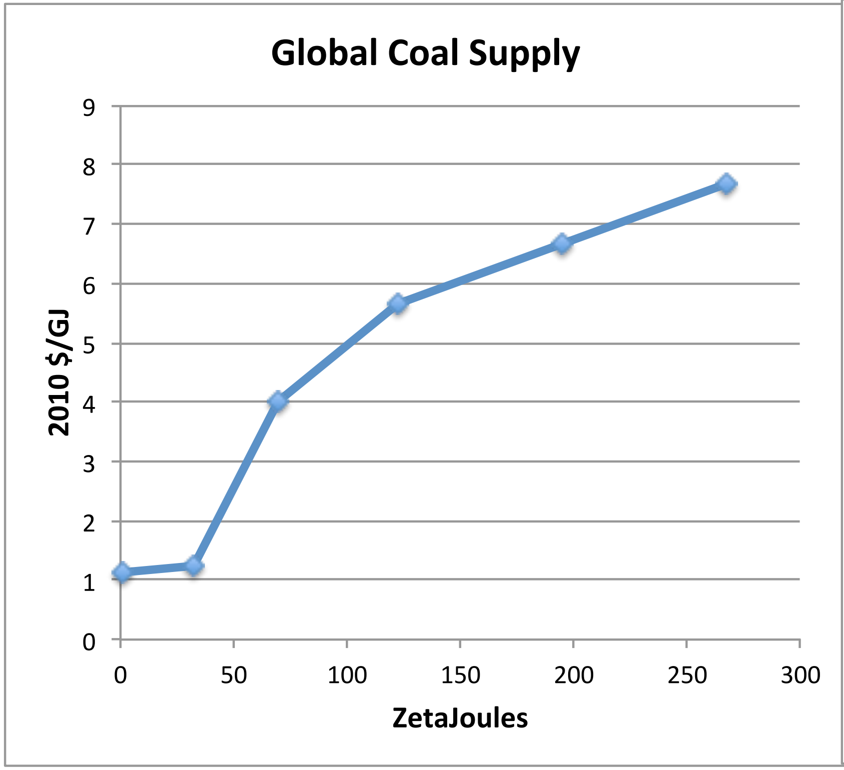
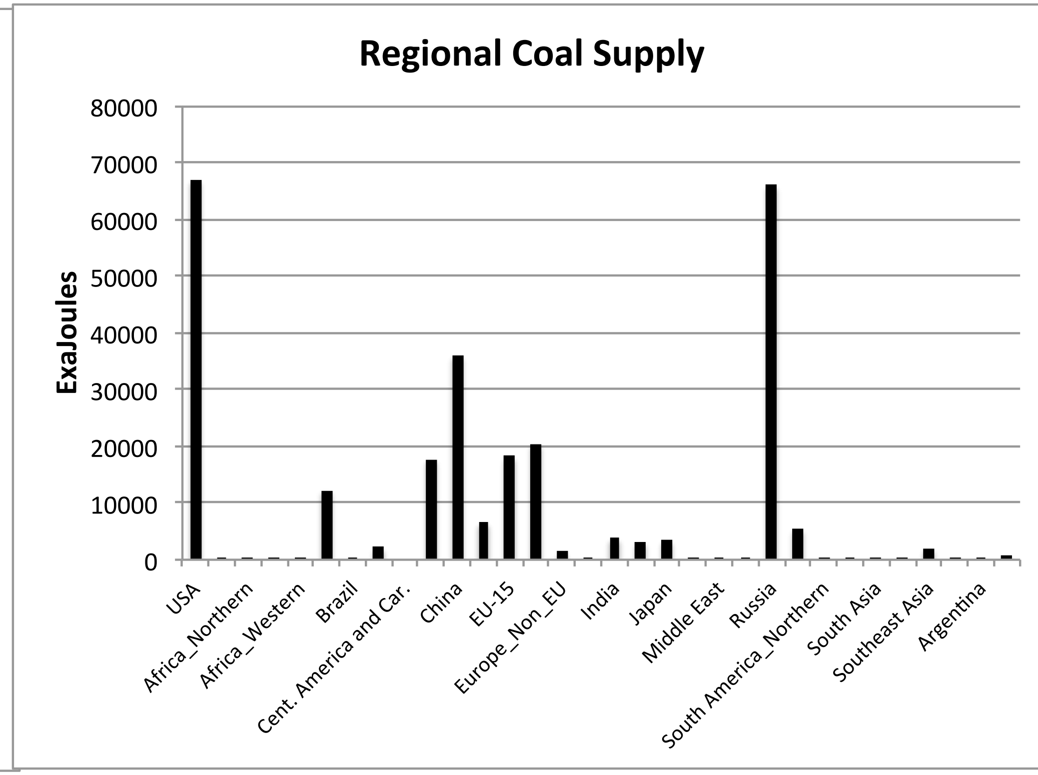




- Oil, Gas, and Coal Resources derived from Rogner 1997 (per the GCAM wiki), but please refer to that source for original data.
- Note: The highest cost grade of natural gas is not shown here. We have ~200 ZJ more natural gas available in the model (hydrates).

The Energy System: Resources: Coal





- Oil, Gas, and Coal Resources derived from Rogner 1997 (per the GCAM wiki), but please refer to that source for original data.

The Energy System: Renewable Resources

- In GCAM the capacity factors of wind turbines are based on detailed global supply curves [1, 2]. Similarly, the capacity factors of photovoltaic panels in GCAM are based on rooftop PV supply curves developed for the United States [3].

- [1] Y. Zhou and S. J. Smith, “Spatial and temporal patterns of global onshore wind speed distribution,” Environmental Research Letters, vol. 8, no. 3, p. 034029, 2013.
- [2] Y. Zhou, P. Luckow, S. J. Smith, and L. Clarke, “Evaluation of global onshore wind energy potential and generation costs,” Environmental science & technology, vol. 46, no. 14, pp. 7857–7864, 2012.
- [3] P. Denholm and R. Margolis, “Supply curves for rooftop solar pv-generated electricity for the united states,” 2008.

The Energy System: Structure

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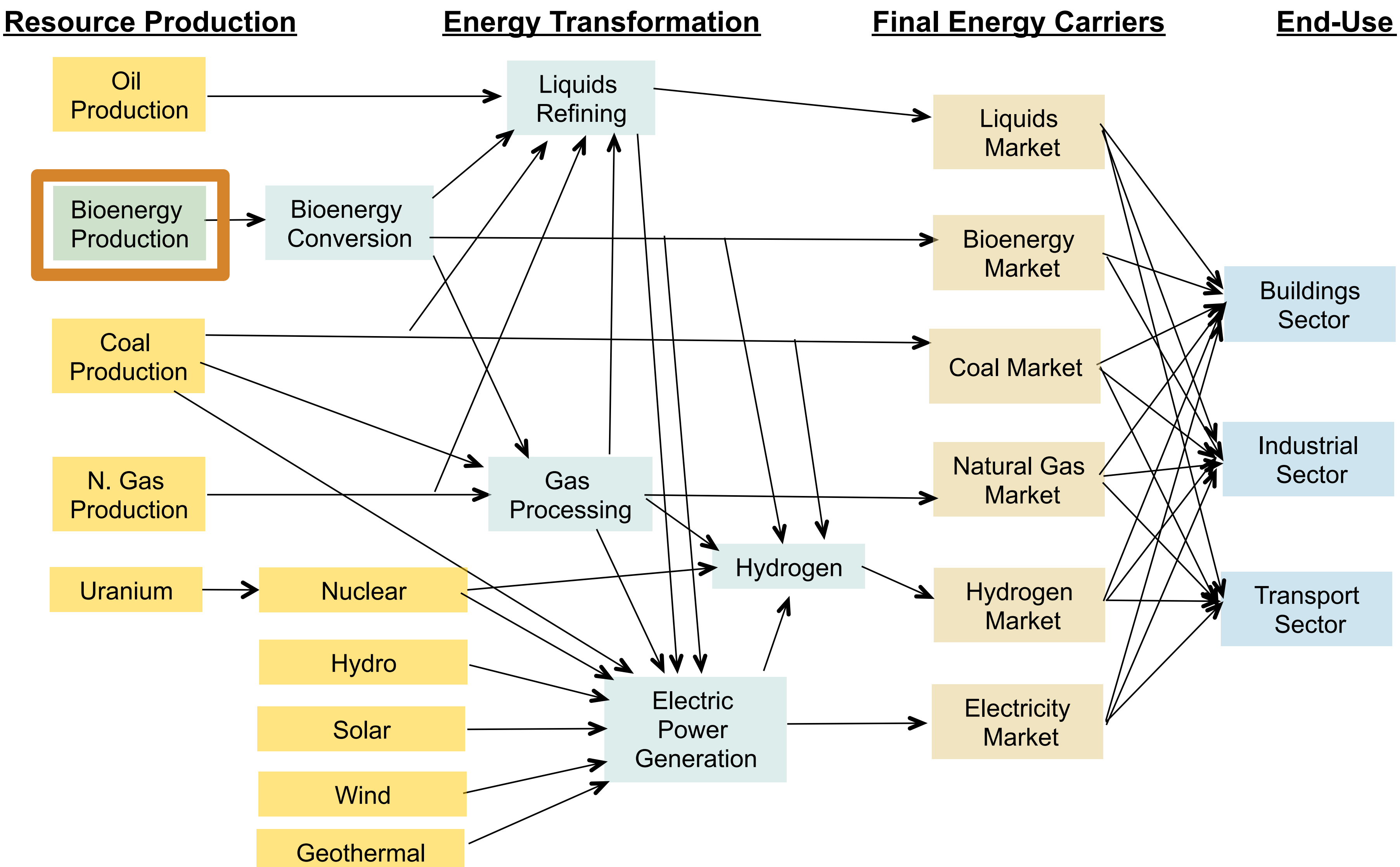
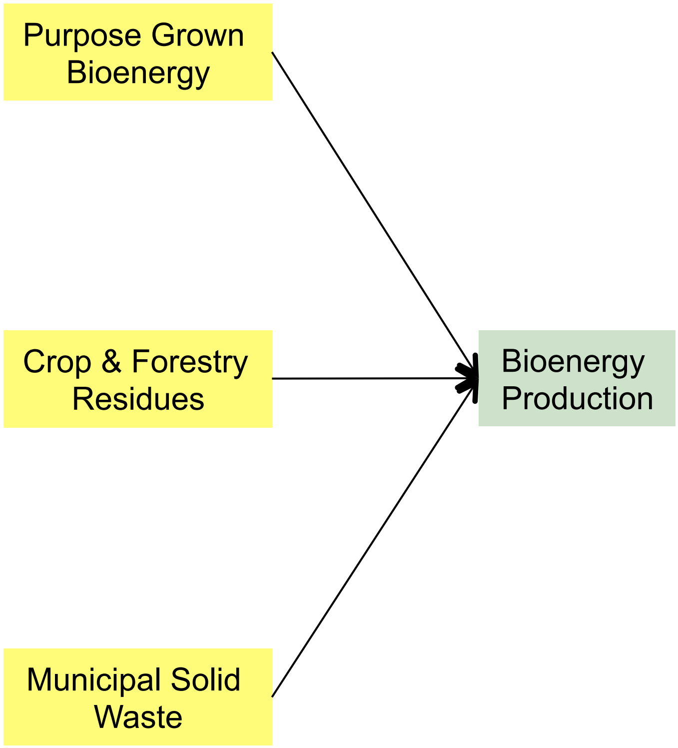


The Energy System: Structure

Purpose Grown Bioenergy:
• Production depends on land allocation and regional yield
• Land allocation depends on the profit rate of biomass AND all competing land uses
• Includes 1st and 2nd generation crops

Crop & Forestry Residues:
• Potential production depends on crop production
• Fraction harvested depends on the price of bioenergy; higher prices lead to more production
• Some amount of residue must remain on the field for erosion control

Municipal Solid Waste:
• Potential production depends population and income
• Fraction used for bioenergy depends on the price of bioenergy; higher prices lead to more production



Note: We also model traditional bioenergy. However, it is not added to the bioenergy resource pool and is instead consumed directly by the buildings sector. Similarly, we model 1st generation bioenergy (corn, sugar, oil crops), but it is converted directly to ethanol or diesel and not added to the bioenergy resource pool.

The Energy System: Structure

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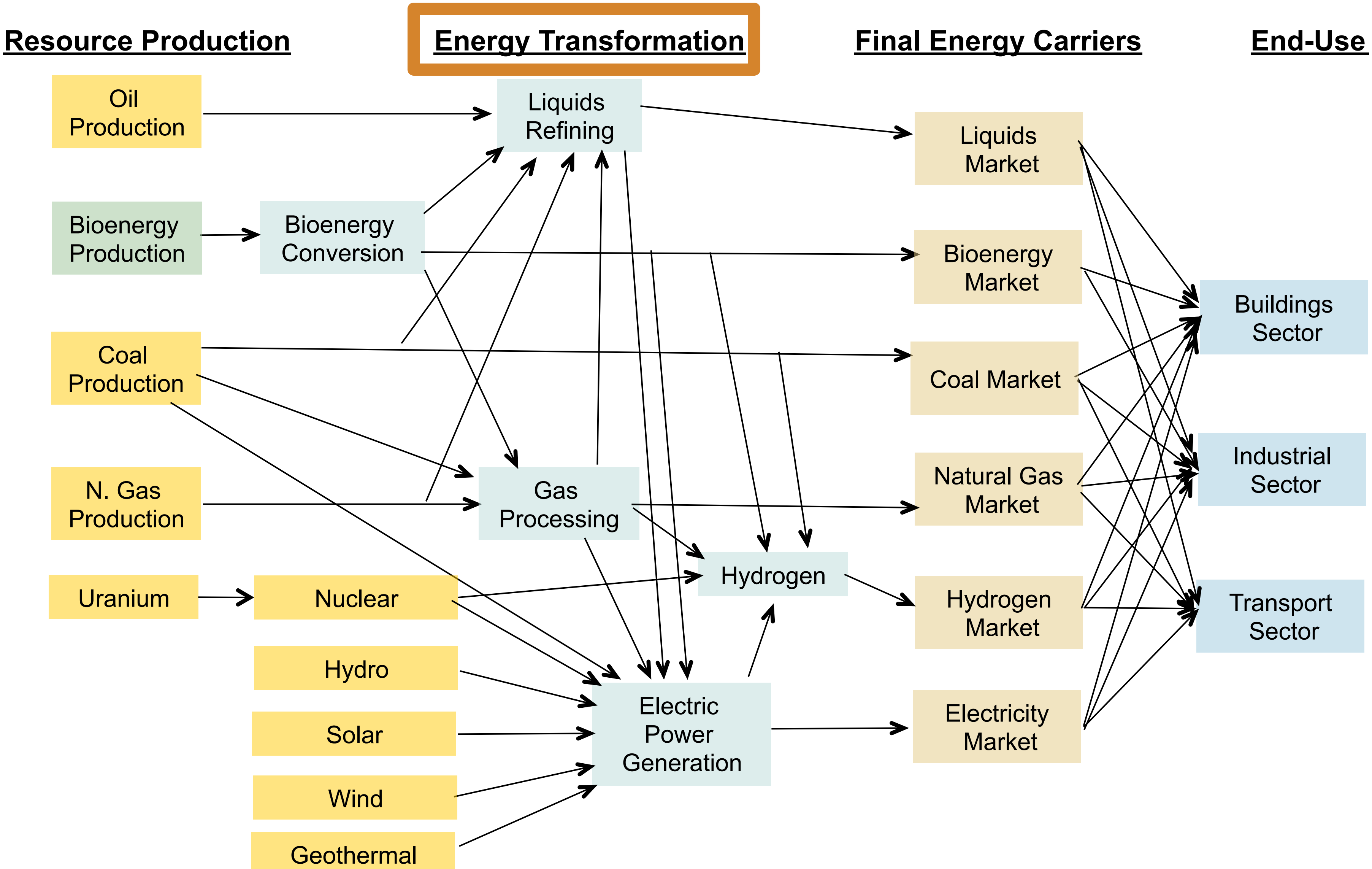

The Energy System: Energy Conversion

- Final energy sectors in GCAM consume several fuels:
  - Electricity
  - Liquid Fuels
  - Coal
  - Bioenergy
  - Gas
  - Hydrogen
- Corresponding to each of these is a conversion sector that takes as inputs various resources.
  - For example, liquid fuels are produced from bioenergy, conventional and unconventional oil, coal, and natural gas.
- Conversion sectors can utilize a number of technologies, even for a single input fuel.
  - Bioenergy-to-liquids, for example, can be produced through several different technologies, some with CCS options.

The Energy System: Structure

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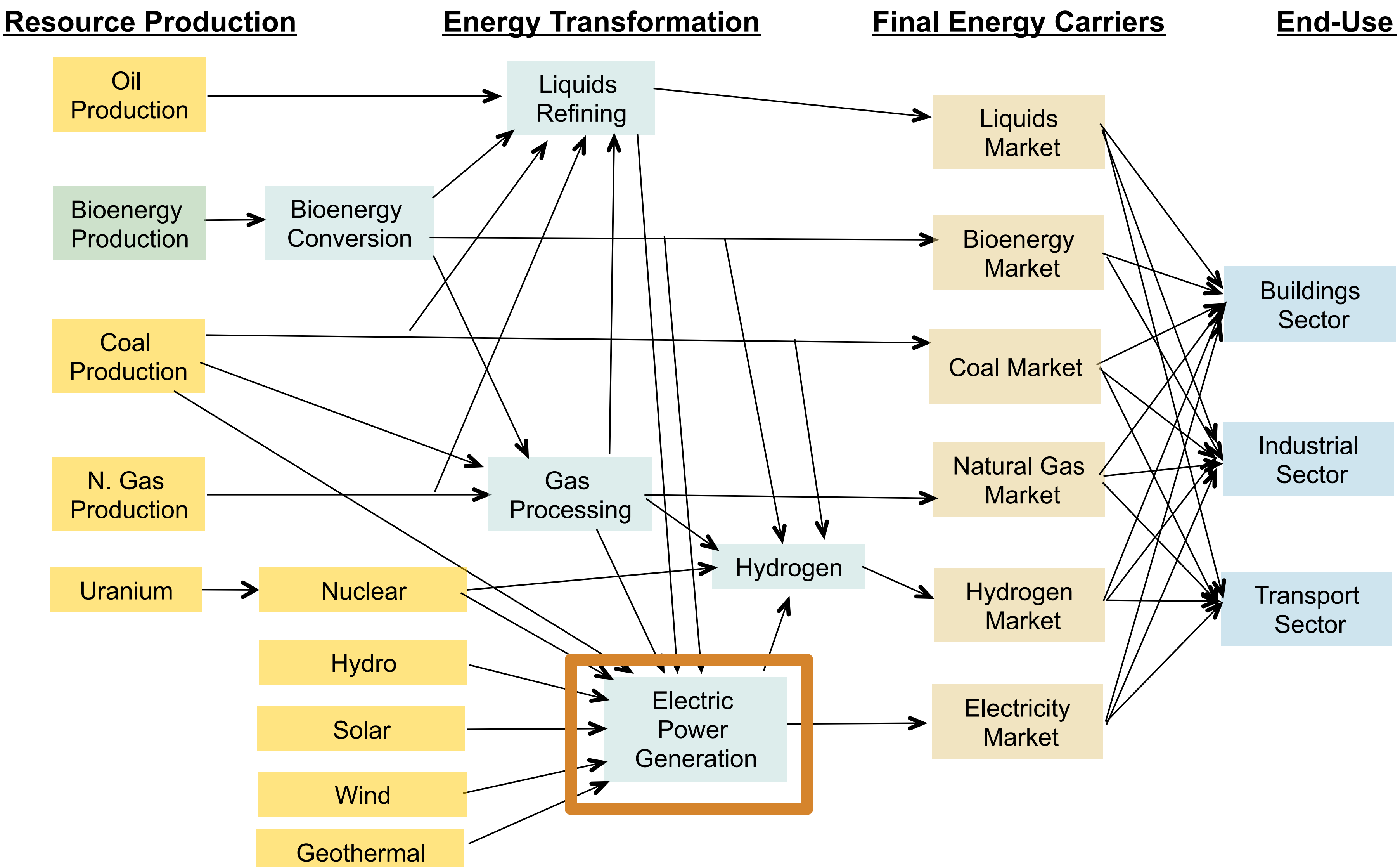
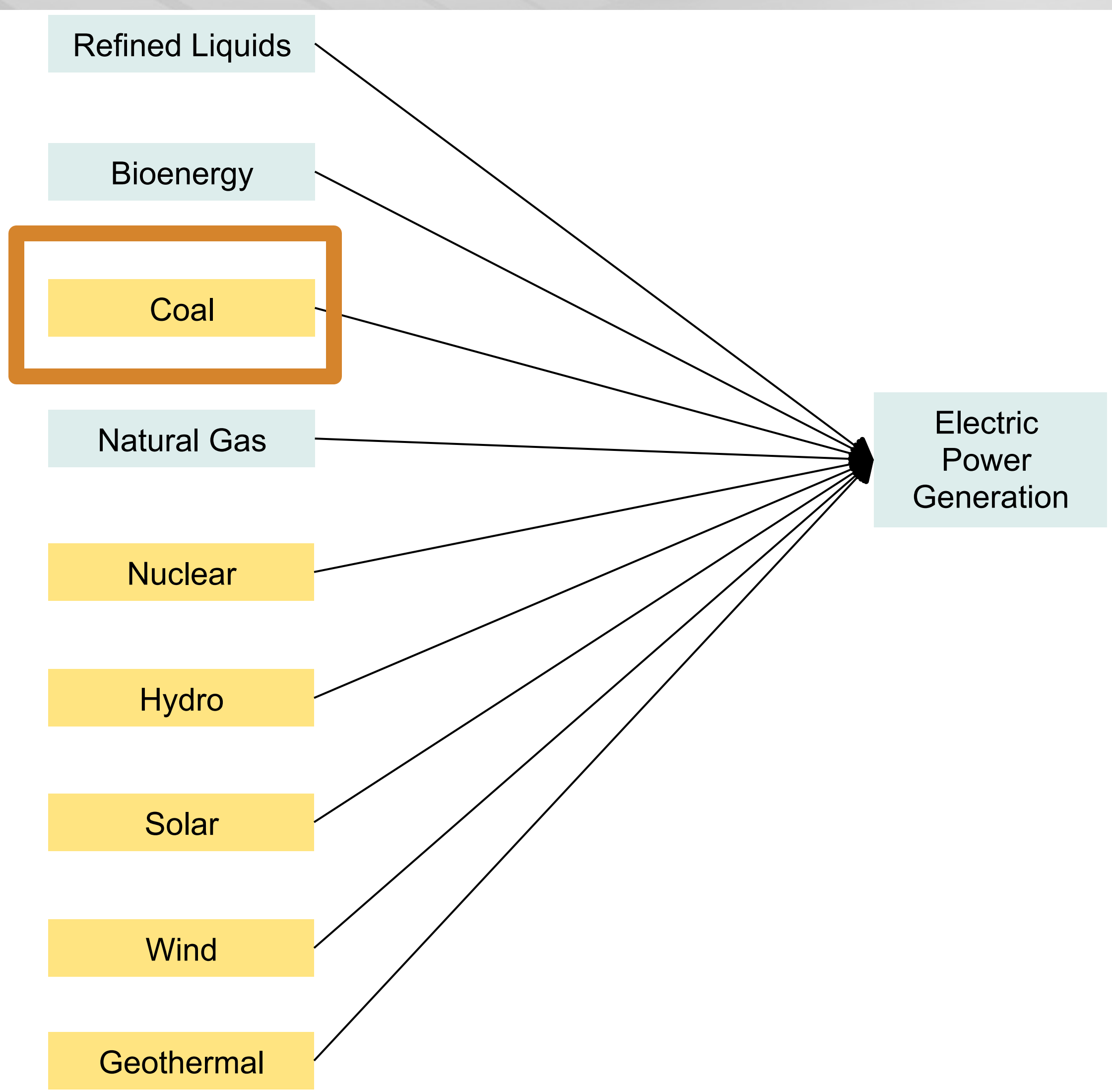


The Energy System: Electricity Generation



The Energy System: Electric Power Plants

- We model several fuels and technologies for generating electric power.

- For example, the current GCAM core has 4 different technology options for coal power plants:
  - Pulverized coal steam plants
  - Pulverized coal steam plants with CO_2 Capture and Storage (CCS)
  - IGCC
  - IGCC with CO_2 Capture and Storage (CCS)

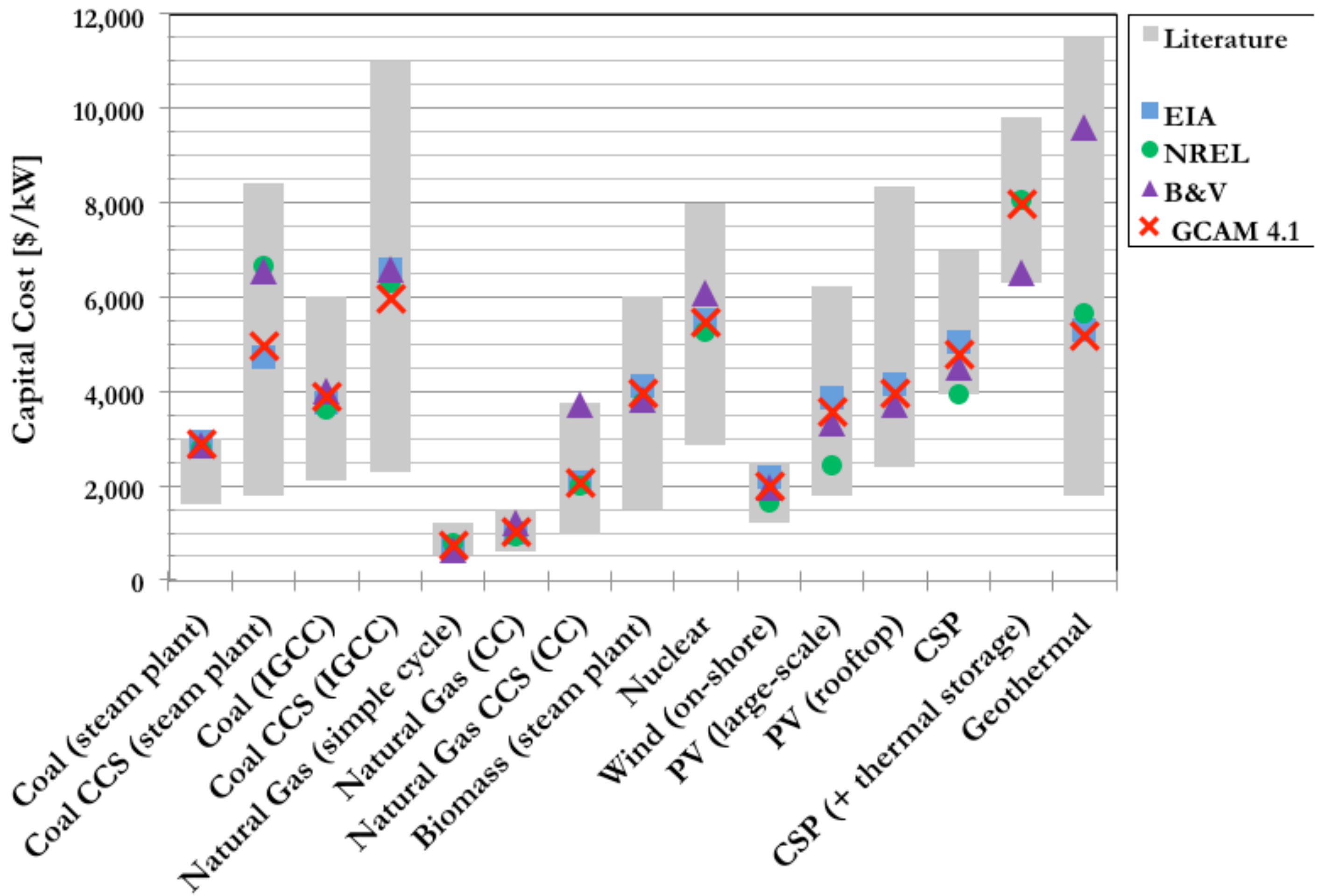
- Each power plant has a different efficiency, non-energy cost, and emissions factor.
  - Which technology is deployed depends on the trade-offs between emissions and other costs. For example, IGCC with CCS will only deploy with a higher value on CO2 – as in a climate policy scenario.

GCAM Electricity Capital Costs updated this year

TECHNOLOGY	Capital Cost [$/kW]	Fixed O&M Cost [$/kW-year]	Variable O&M Cost [$/kWh]
Coal (steam plant)	2900	25	4
Coal CCS (steam plant)	5800	50	8
Coal (IGCC)	4000	35	6.5
Coal CCS (IGCC)	6600	70	10
Natural Gas (simple cycle)	750	6	10
Natural Gas (CC)	1050	10	3.5
Natural Gas CCS (CC)	2100	20	7
Oil (simple cycle)	750	6	10
Oil (CC)	1050	10	305
Oil CCS (CC)	2500	24	8
Biomass (steam plant)	4000	95	10
Biomass CCS (steam plant)	6443	116	13.4
Biomass (IGCC)	6000	140	15
Biomass CCS (IGCC)	8190	170	18
Nuclear	5500	95	2
Wind (on-shore)	2000	50	0
Wind (on-shore + battery)	5800	60	0
PV (large-scale)	3000	40	0
PV (large-scale + battery)	6800	48	0
PV (rooftop)	4700	60	0
CSP	4800	55	0
CSP (+ thermal storage)	8000	65	0
Geothermal	5200	100	0

- Capital and operation and maintenance costs of different electricity-generating technologies in 2015. Cost are expressed in 2010USD. Draft from forthcoming paper by Muratori et al.

GCAM Electricity Capital Costs updated this year



- Draft figure from forthcoming paper by Muratori et al.
- Latest capital costs in GCAM higher for many technologies than in previous versions.

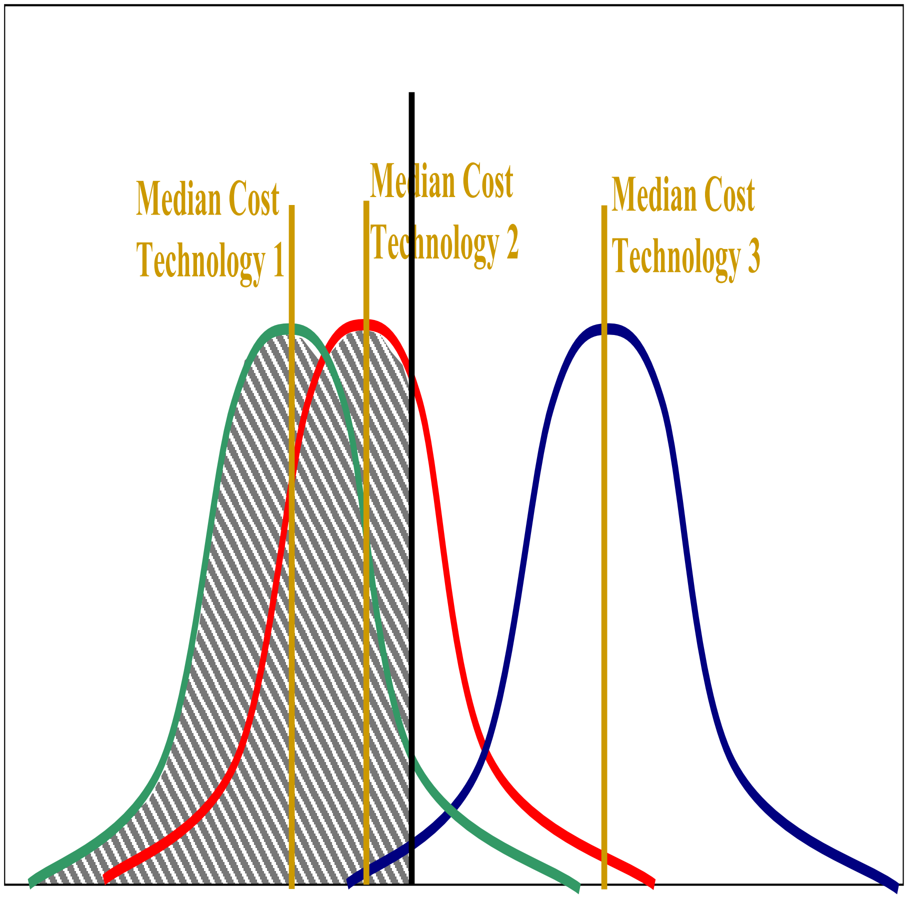
GCAM Electricity Efficiencies updated this year

TECHNOLOGY	HHV EFFICIENCY	HEAT RATE
Coal (steam plant)	0.38	8,979
Coal CCS (steam plant)	0.28	12,186
Coal (IGCC)	0.39	8,749
Coal CCS (IGCC)	0.32	10,663
Natural Gas (simple cycle)	0.34	10,035
Natural Gas (CC)	0.52	6,562
Natural Gas CCS (CC)	0.42	8,124
Oil (steam plant)	0.34	10,035
Oil (CC)	0.51	6,690
Oil CCS (CC)	0.39	8,749
Biomass (steam plant)	0.25	13,648
Biomass CCS (steam plant)	0.18	18,956
Biomass (IGCC)	0.3	11,373
Biomass CCS (IGCC)	0.25	13,648
Nuclear	0.33	10,339
Geothermal	0.1	34,120

- HHV efficiency and HR of different electricity-generating technologies in 2015. Draft from forthcoming paper by Muratori et al.

The Energy System: Technology Competition

A Probabilistic Approach



- Economic competition among technologies takes place at many sectors and levels.
- Assumes a distribution of realized costs due to heterogeneous conditions.
- Market share based on probability that a technology has the least cost for an application.
  - Avoids a "winner take all" result.
  - "Logit" specification.

The Energy System: Technology Competition

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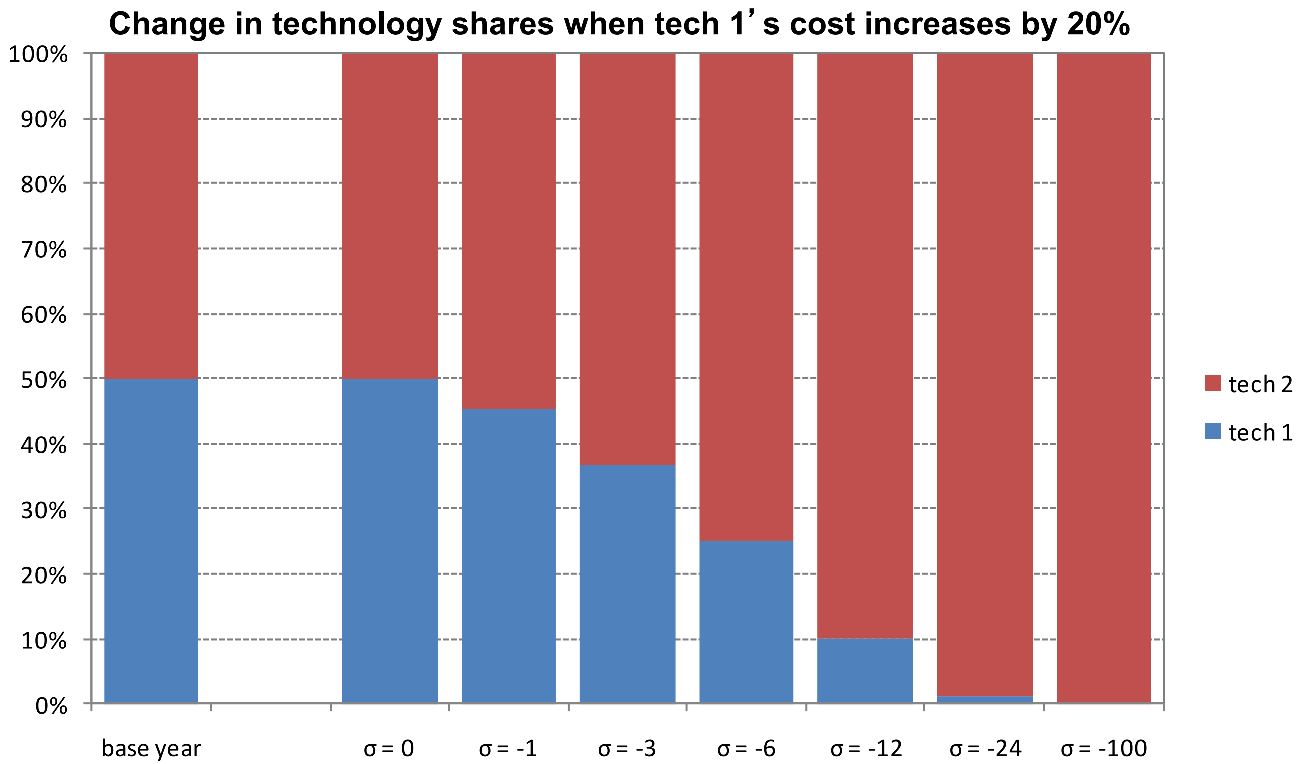
$$s_i = \frac{\alpha_i c_i^{\sigma}}{\sum_j \alpha_j c_j^{\sigma}}$$

Source: Clarke and Edmonds (1993), McFadden (1974)

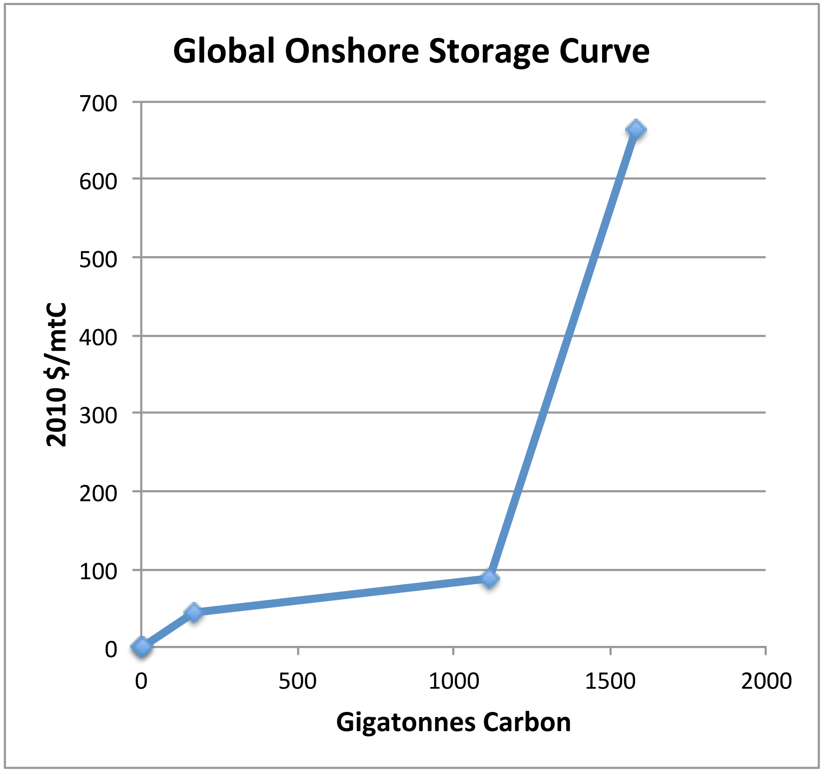


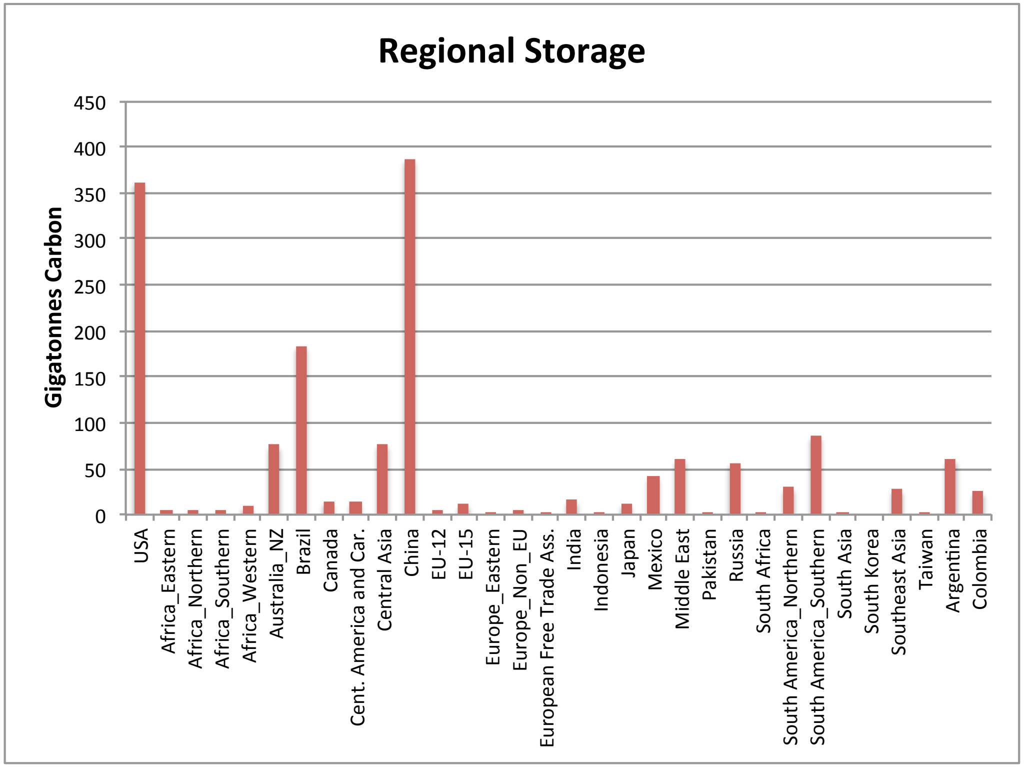
The Energy System: Vintaging of Capital

- We assume that capital stock in certain sectors (for example, electric power generation and oil refining sectors) is long-lived.
- This means that a power plant or refinery built in one model period *may* still be in operation many time periods later.
- However, we do not assume that existing capital is always in operation. Once the variable cost exceeds the market price, we begin to shut down existing units. This often occurs when a carbon price is applied.

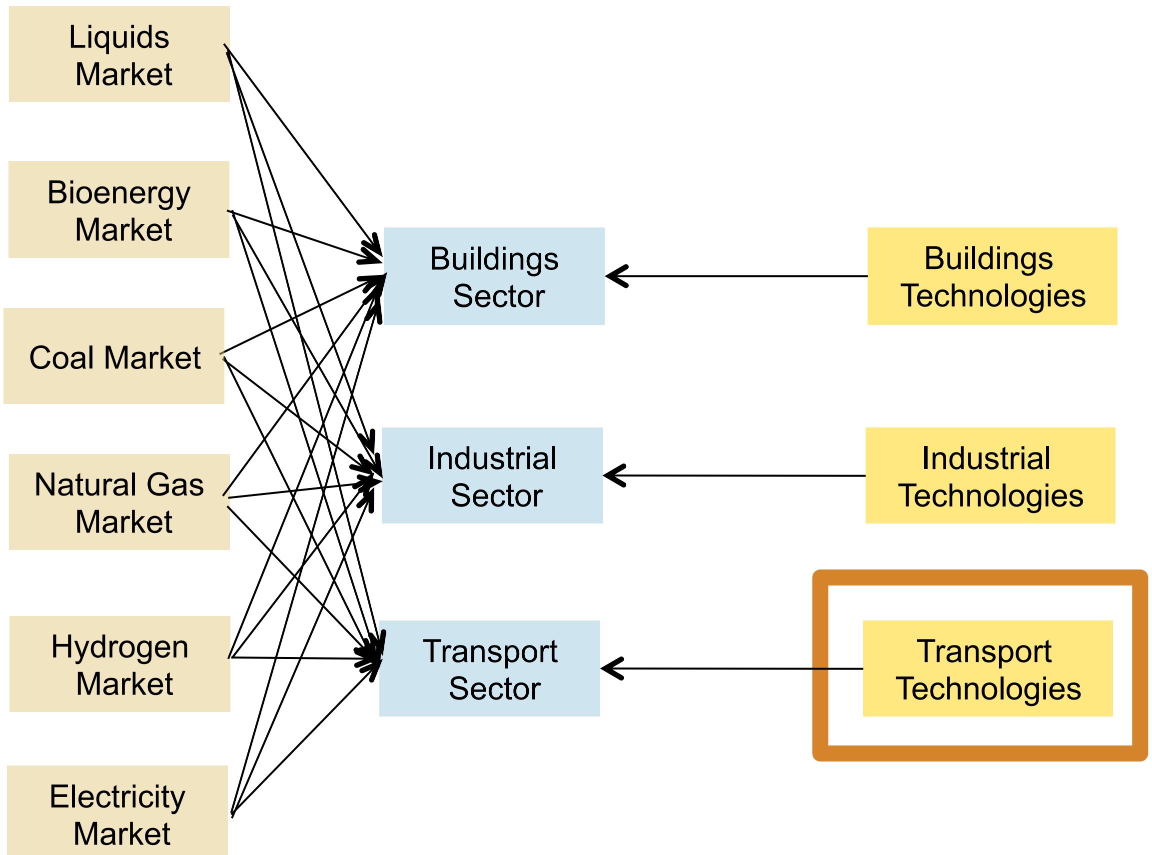
The Energy System: CO_2 Capture and Storage

- Onshore CO_2 storage capacity modeled at region level using supply curves
- Offshore CO_2 storage capacity is available to any region at a cost of \$96/tCO_2 (\$352/tC)





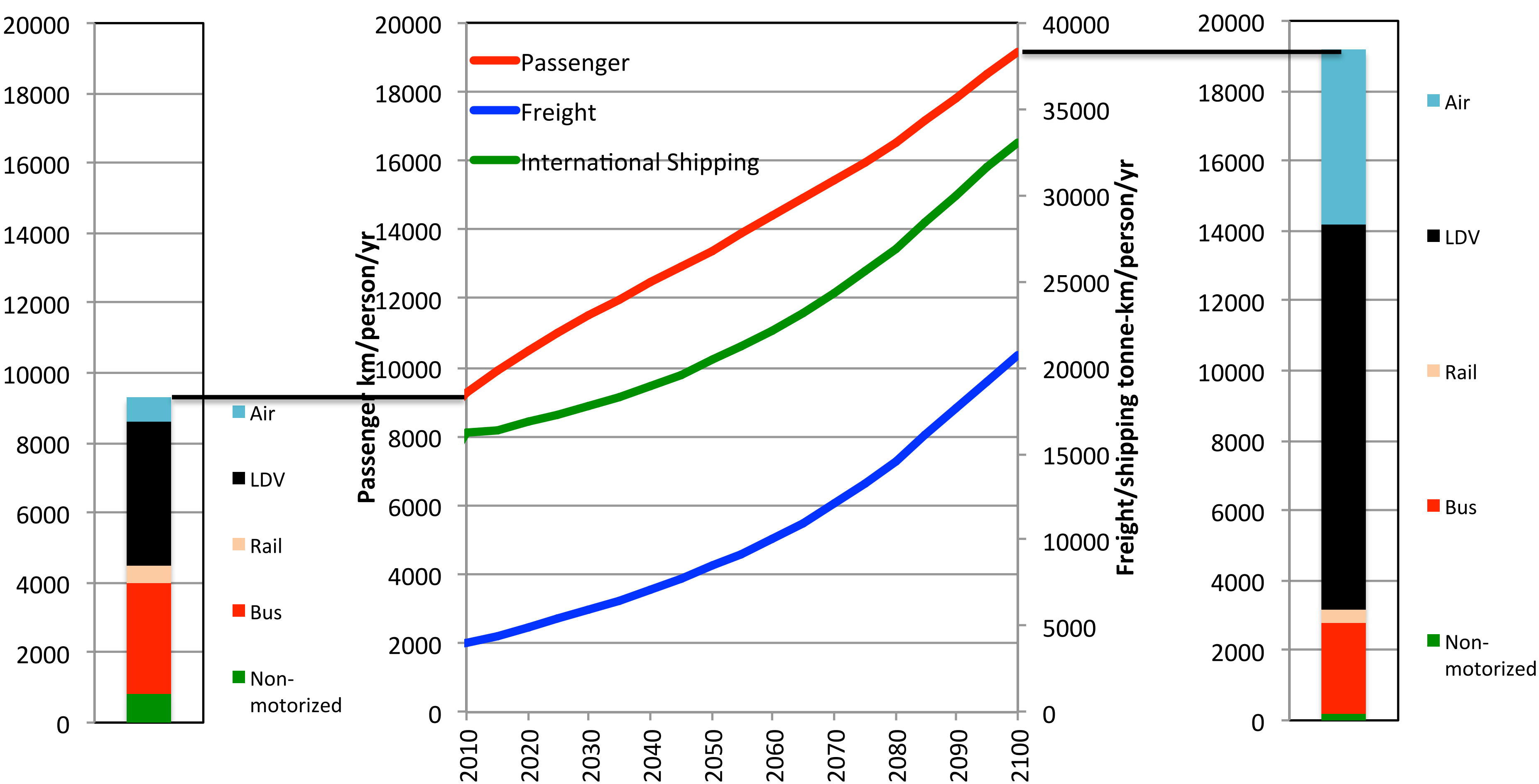
The Energy System: Energy Demand



We have detailed representations of transportation & buildings in all regions.

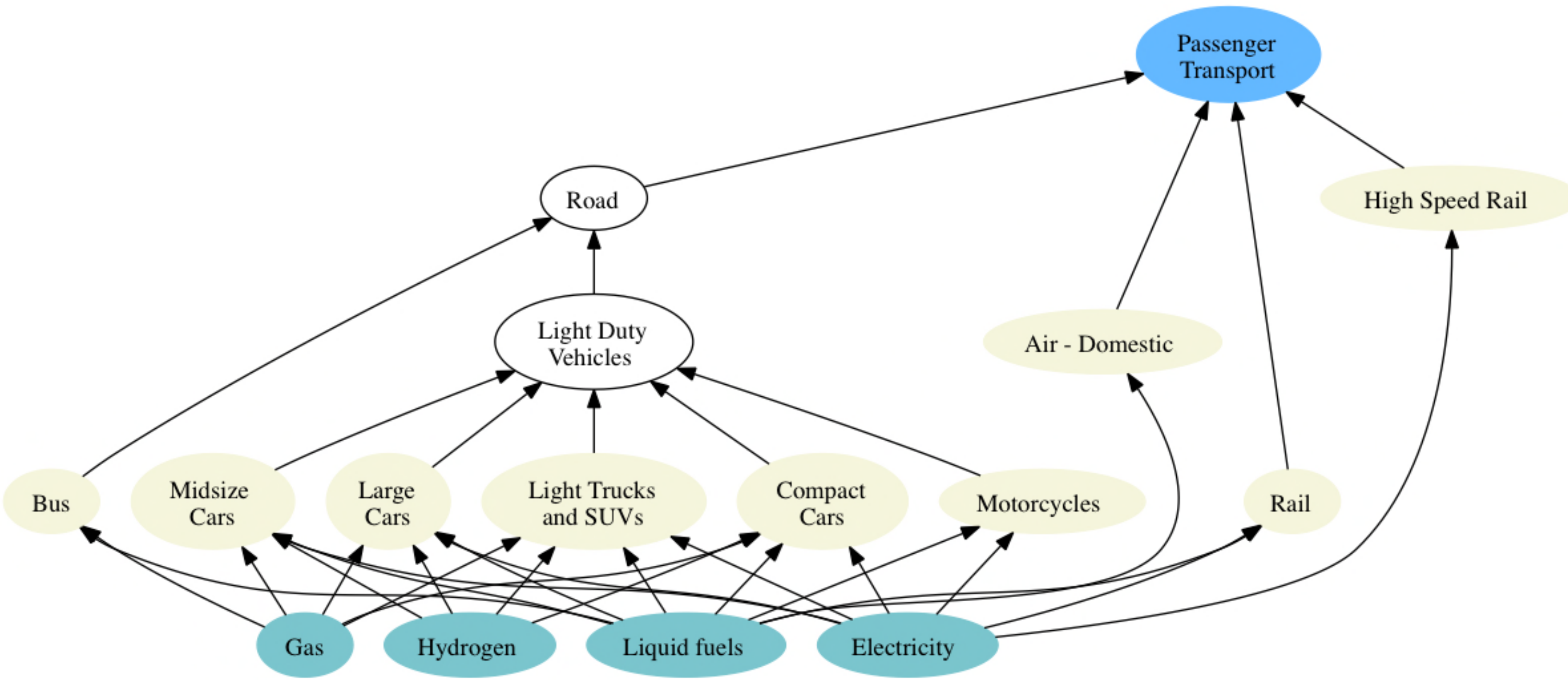
The Energy System: Transportation

- Per capita transportation service demands (measured in km/yr) are a function of income and the prices of services.



The Energy System: Transportation

- The choice among modes of transportation in the passenger sector is a function of the cost of travel, the time it takes, and income.



The Energy System: Transportation

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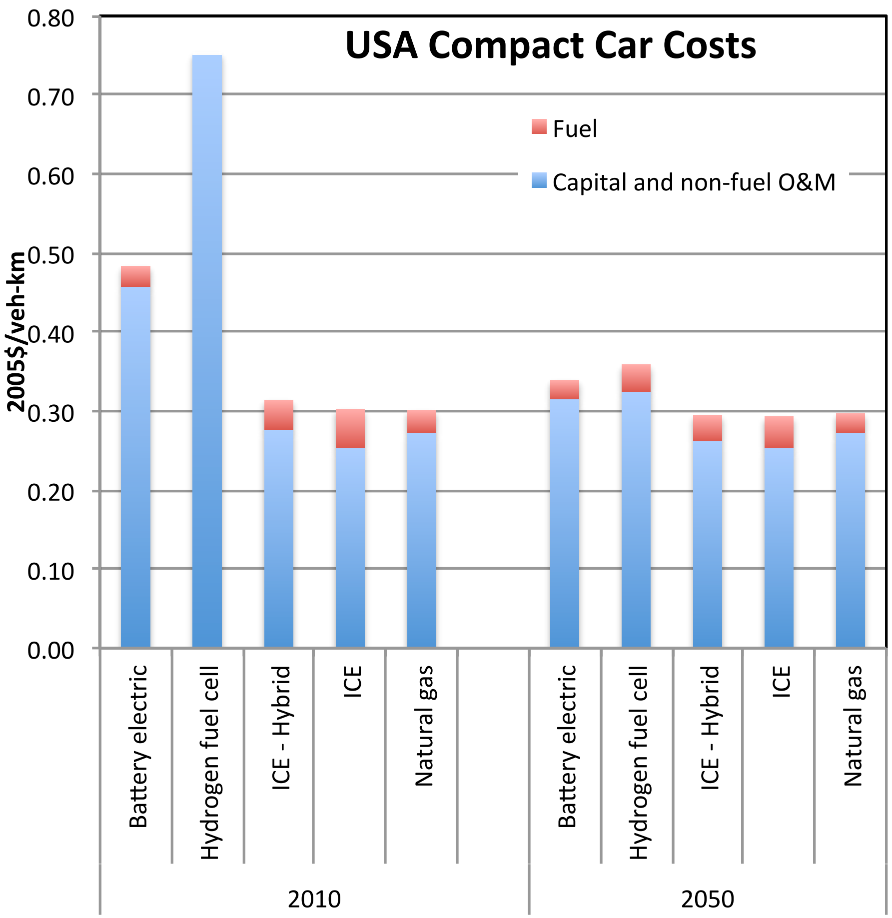
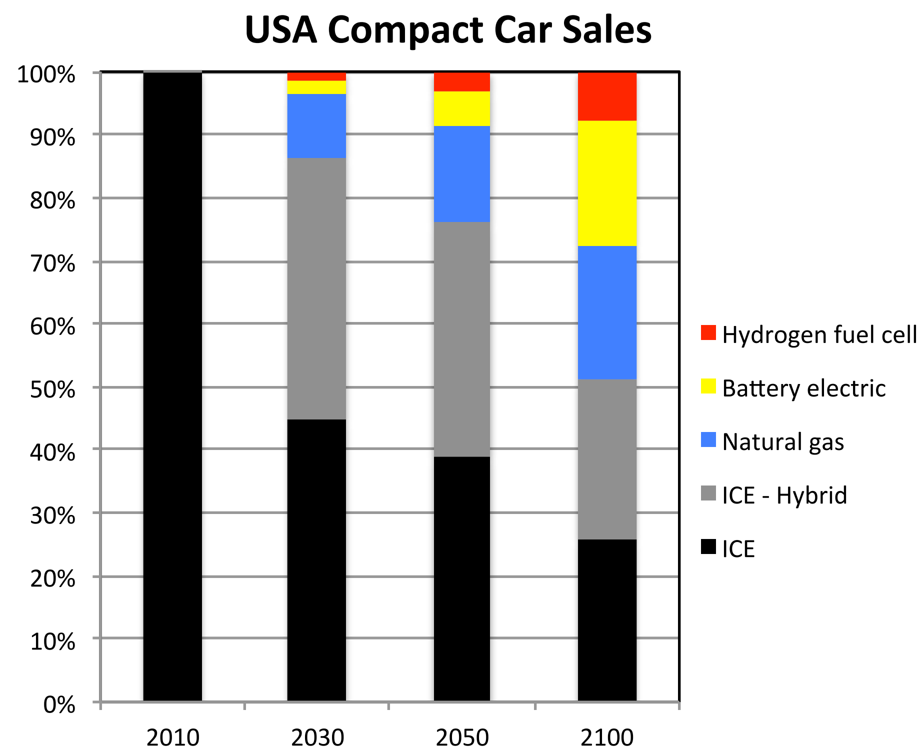
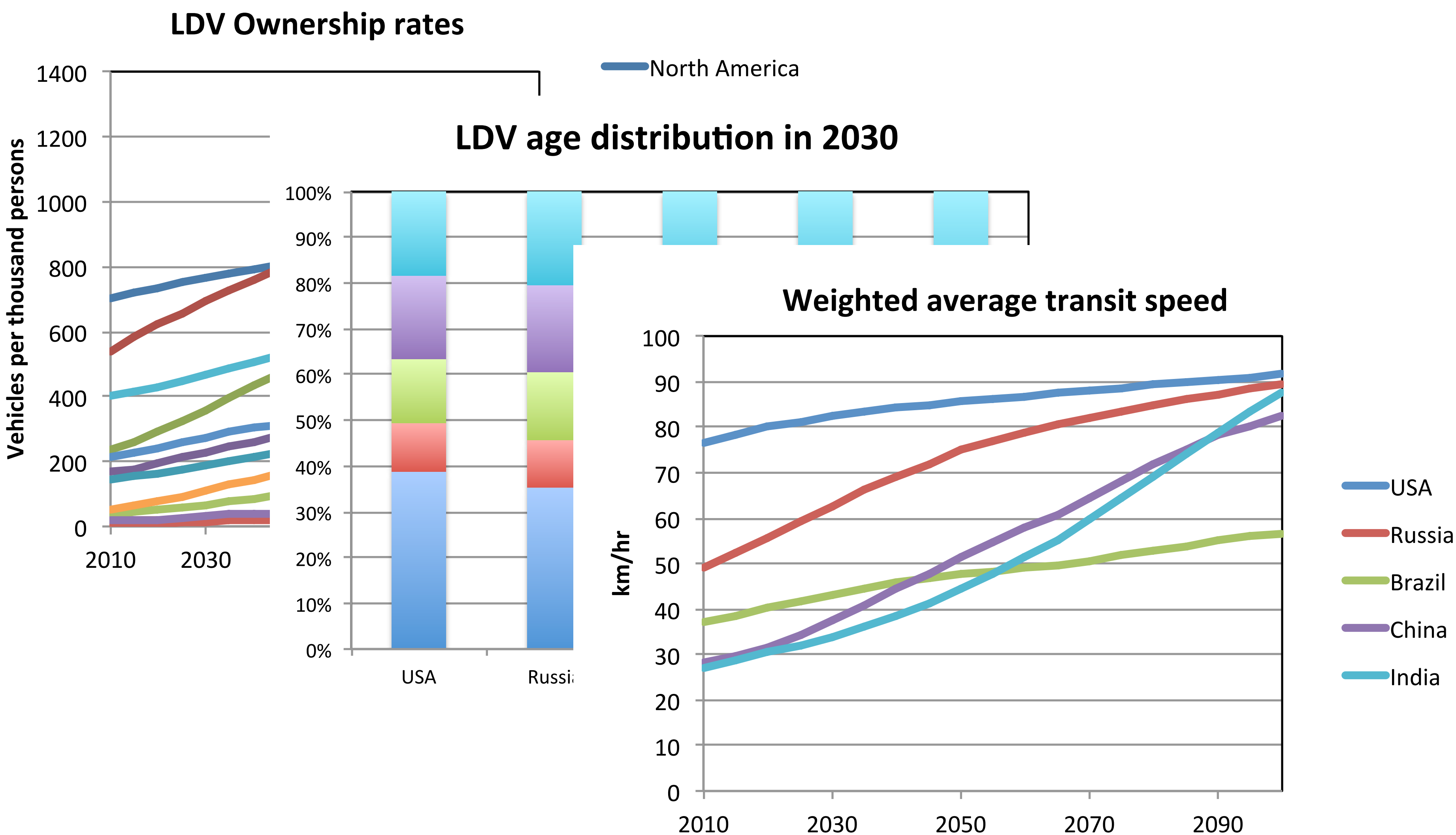
- The choice among fuels within a mode is a function of cost (including capital cost and the cost of fuel)



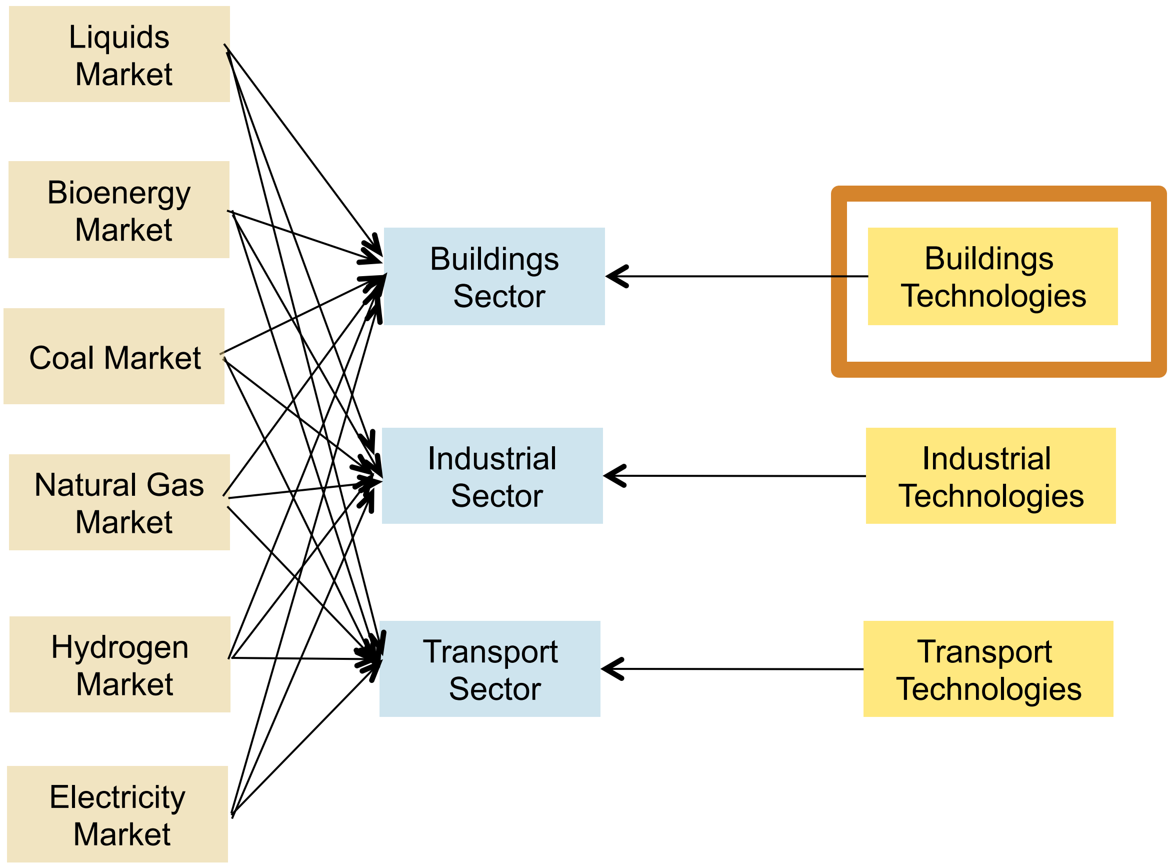


The Energy System: Transportation

- A wide variety of detailed output variables can be reported for the transportation sector



The Energy System: Energy Demand



We have detailed representations of transportation & buildings in all regions.

The Energy System: Buildings

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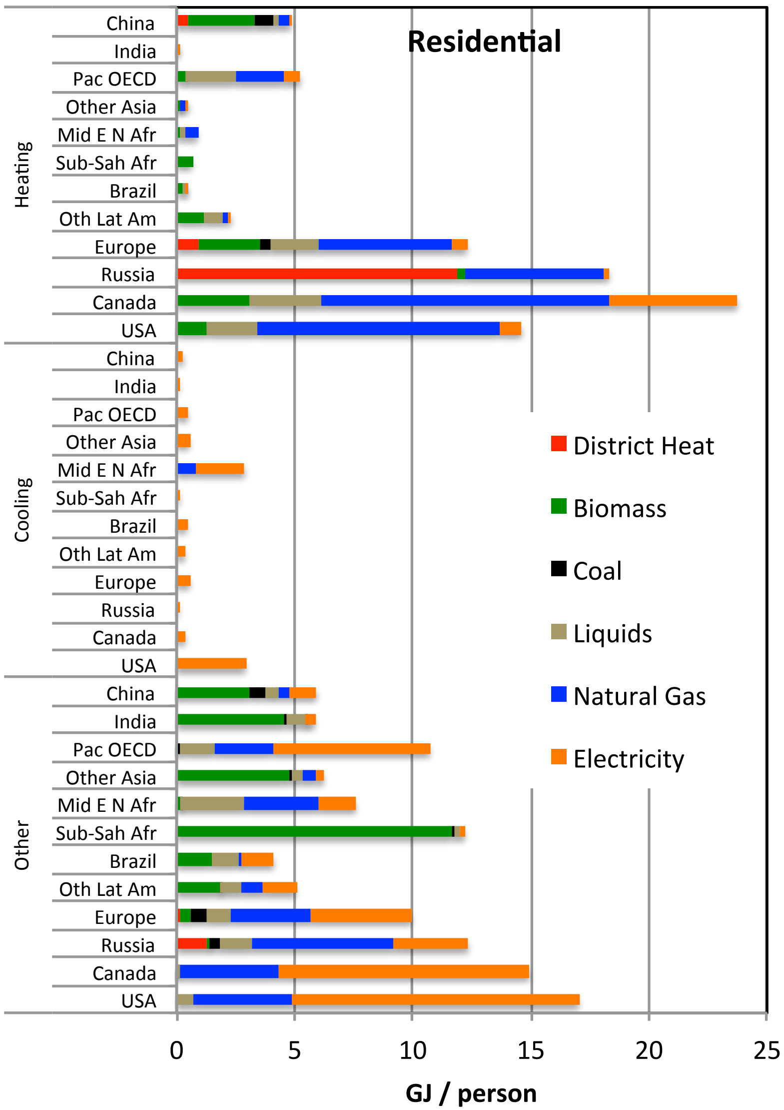
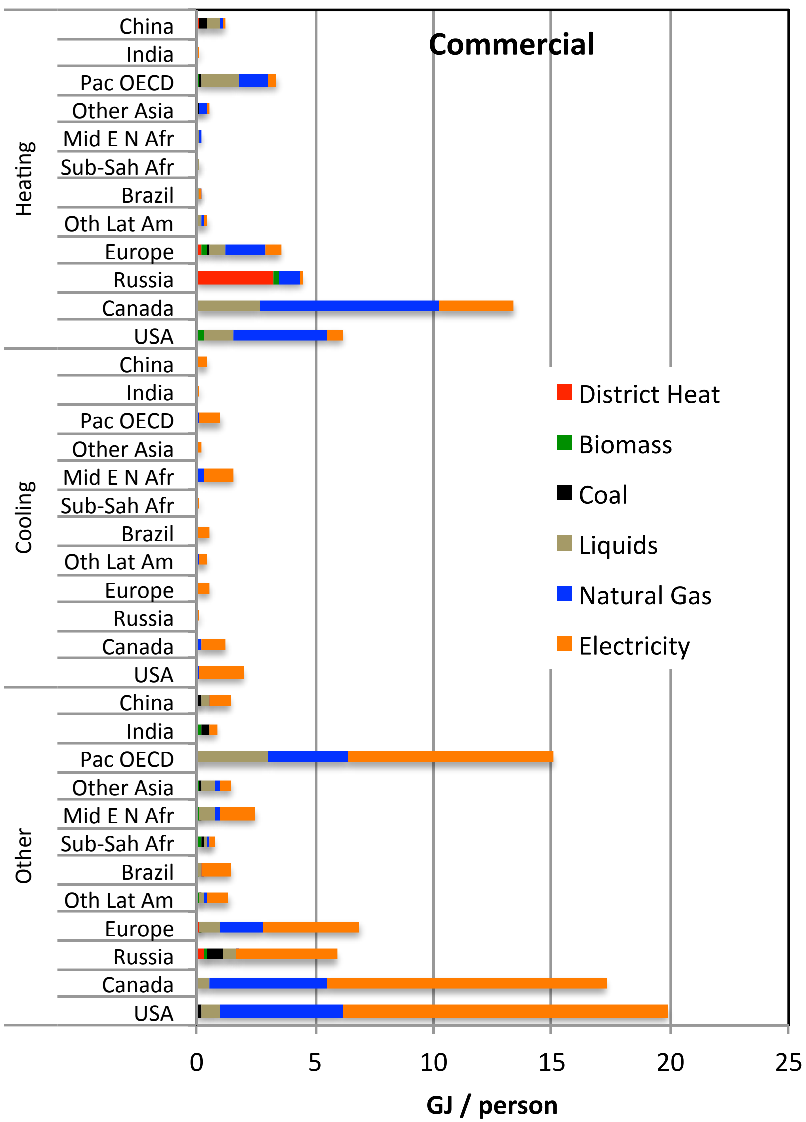
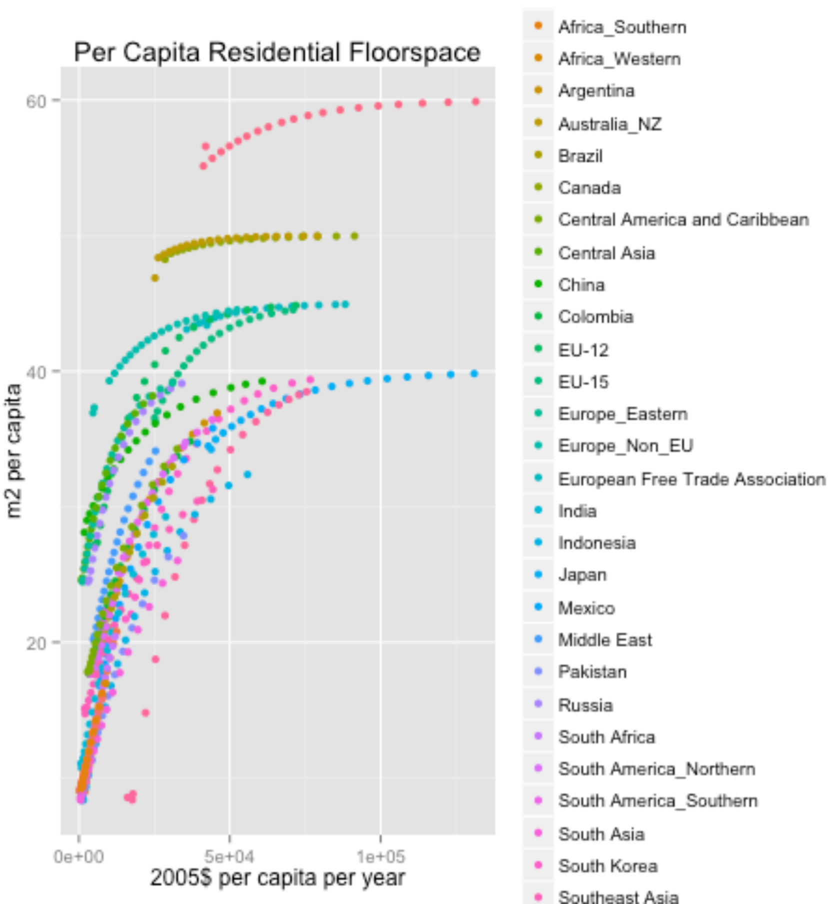
Per-capita Residential and Commercial Energy Use in 2010

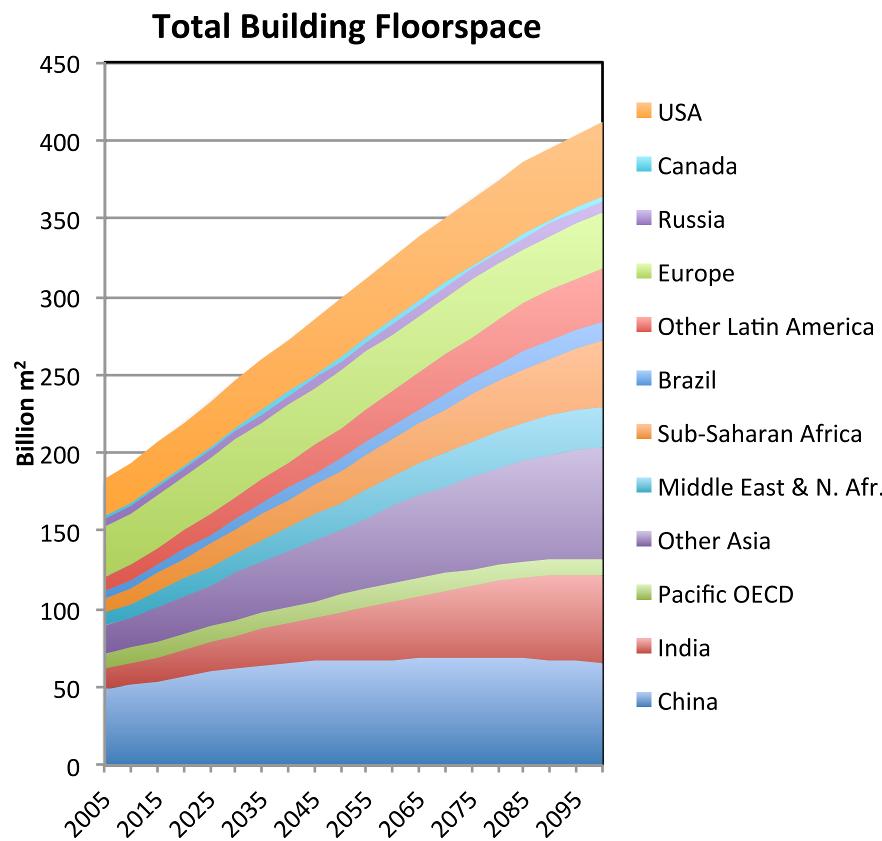




The Energy System: Buildings

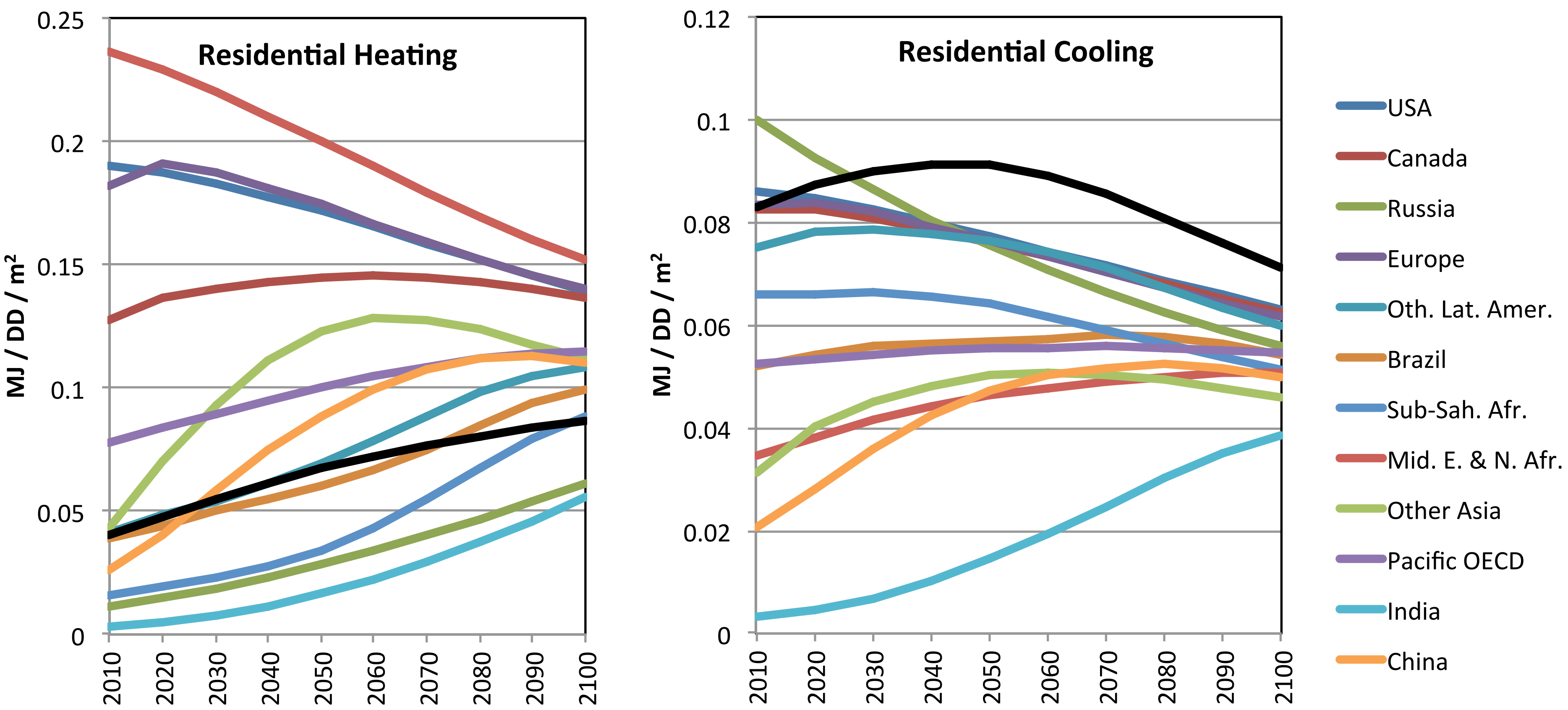
- Future evolution of building energy use is shaped by...
  - Residential and commercial floorspace
    - Population, GDP, and exogenous per-capita floorspace satiation levels





The Energy System: Buildings

- Future evolution of building energy use is shaped by...
  - Residential and commercial floorspace
  - Levels of building service demands per unit floorspace
    - Climate, building shell conductivity, GDP, and exogenous satiation levels



The Energy System: Buildings

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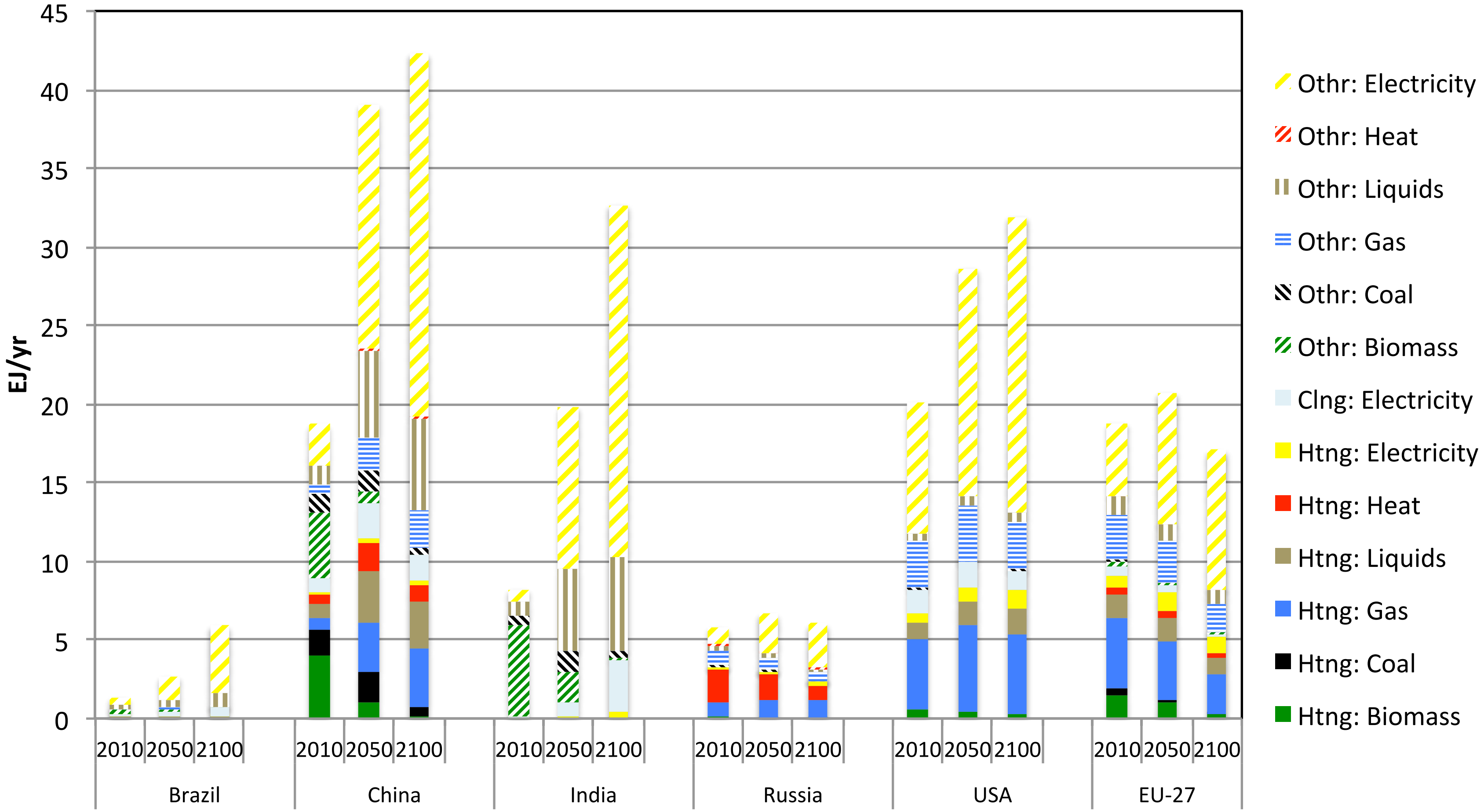
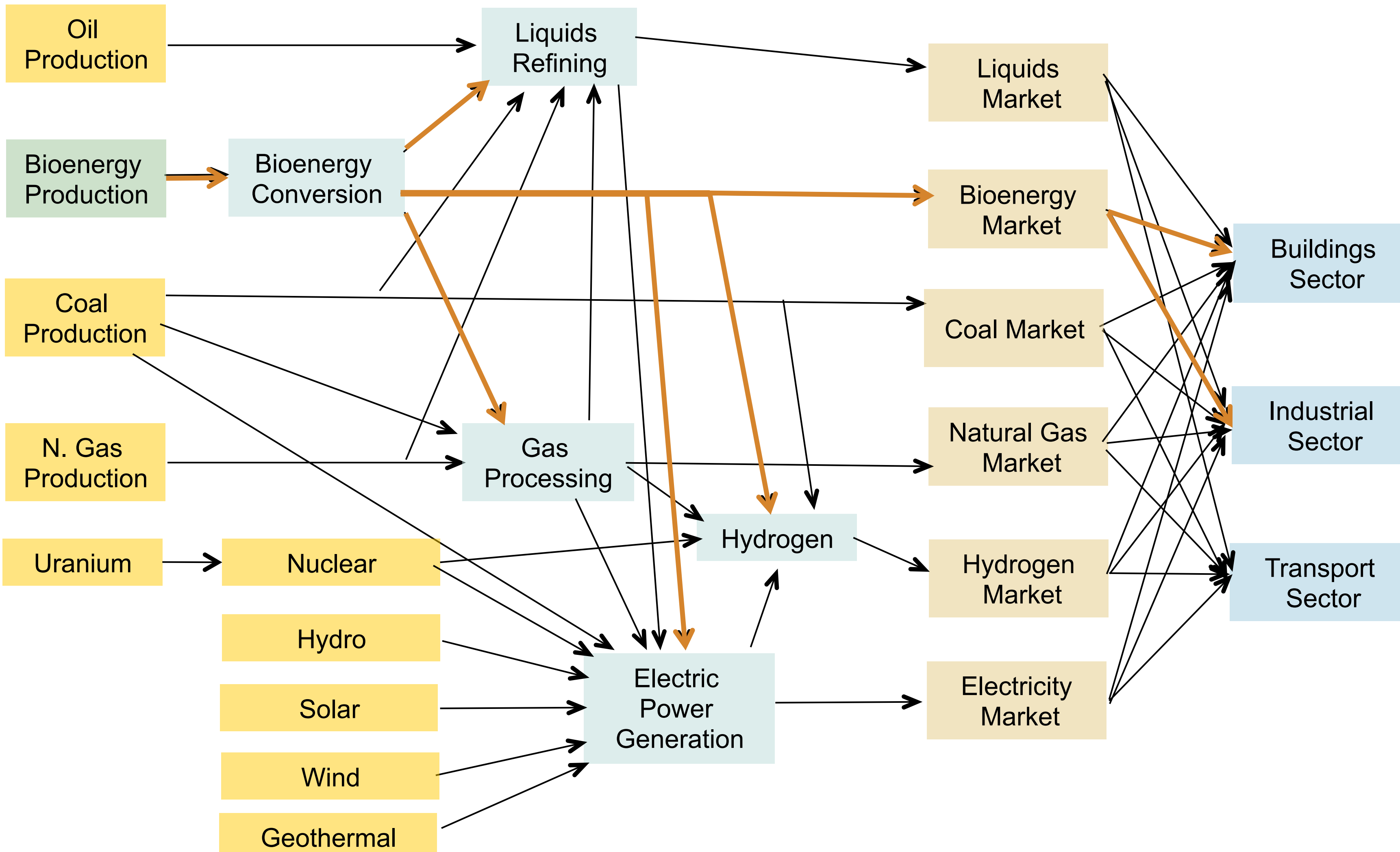
- Future evolution of building energy use is shaped by...
  - Residential and commercial floorspace
  - Levels of building service demands per unit floorspace
  - Fuel and technology choices by consumers

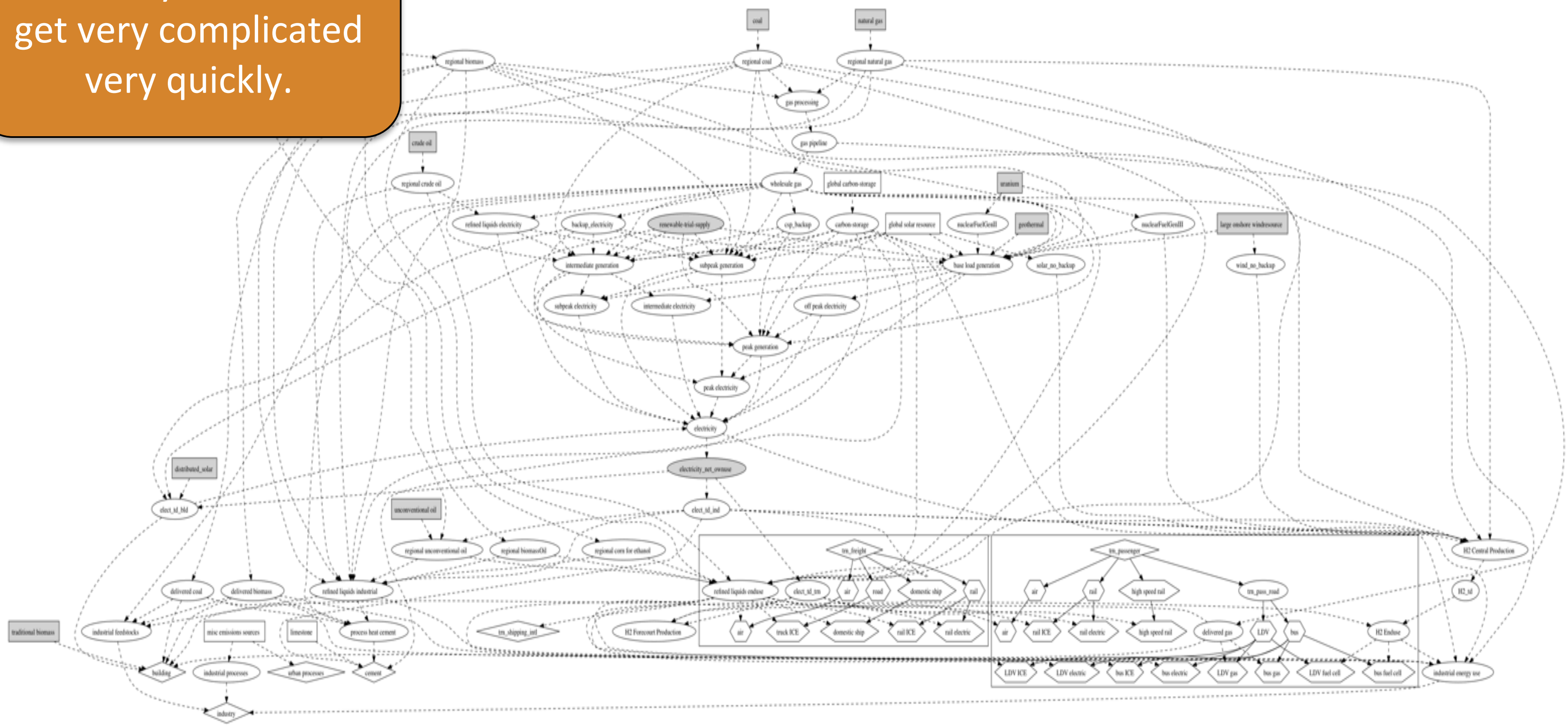


The Energy System: Structure



The Energy System: Structure

These systems can get very complicated very quickly.



The Energy System: Calibration

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- The current base year for the energy system is 2010.
- We use IEA energy balances as calibration data.
  - The calibration procedure calculates “share weights” such that the dataset derived from the IEA energy balances is reproduced.
  - These share weights reflect unmeasured and non-economic influences on decision-making.
    - If a technology has low costs but nevertheless has low market share (e.g. coal furnaces), then the model will compute a low share weight. If this base-year share weight is applied to future periods, then the market share of the technology will remain low even if it remains a relatively low-cost option.
  - In most cases, we retain these share weights in future years. In some cases (e.g. renewables in the electric sector, or alternative-fuel vehicles in the LDV sector), we have over-written them because the base-year shares do not reflect mature market equilibrium conditions.

The Energy System: Results

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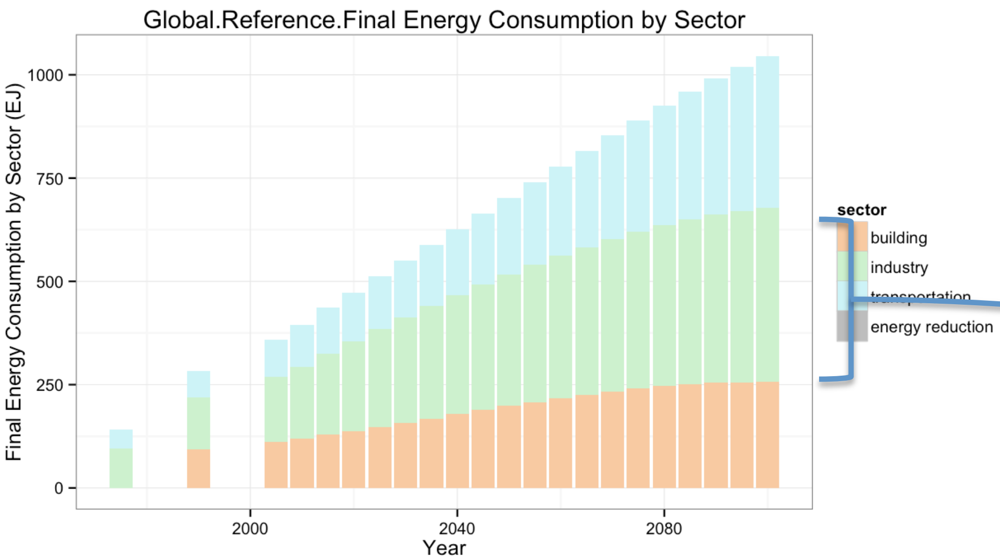

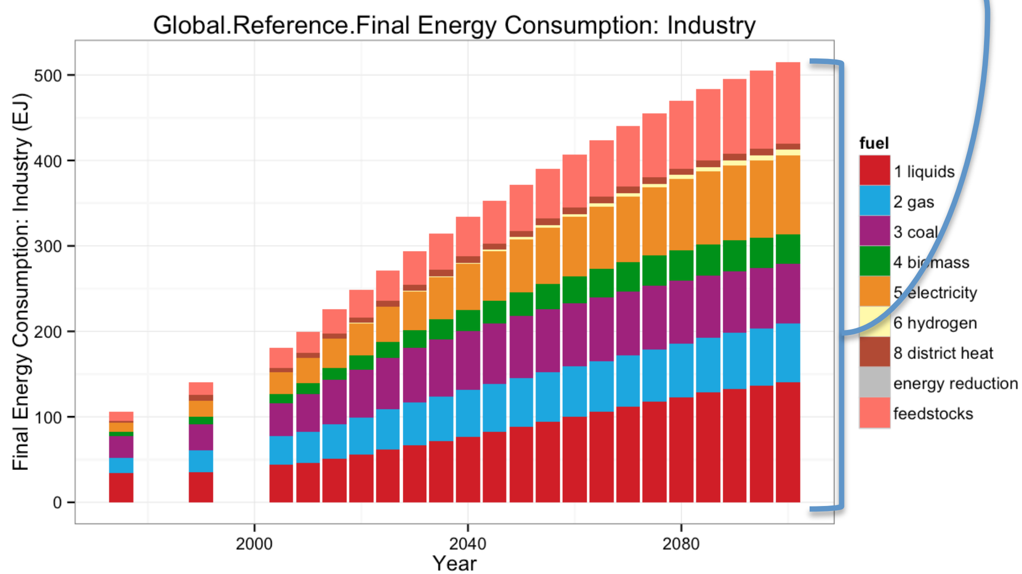

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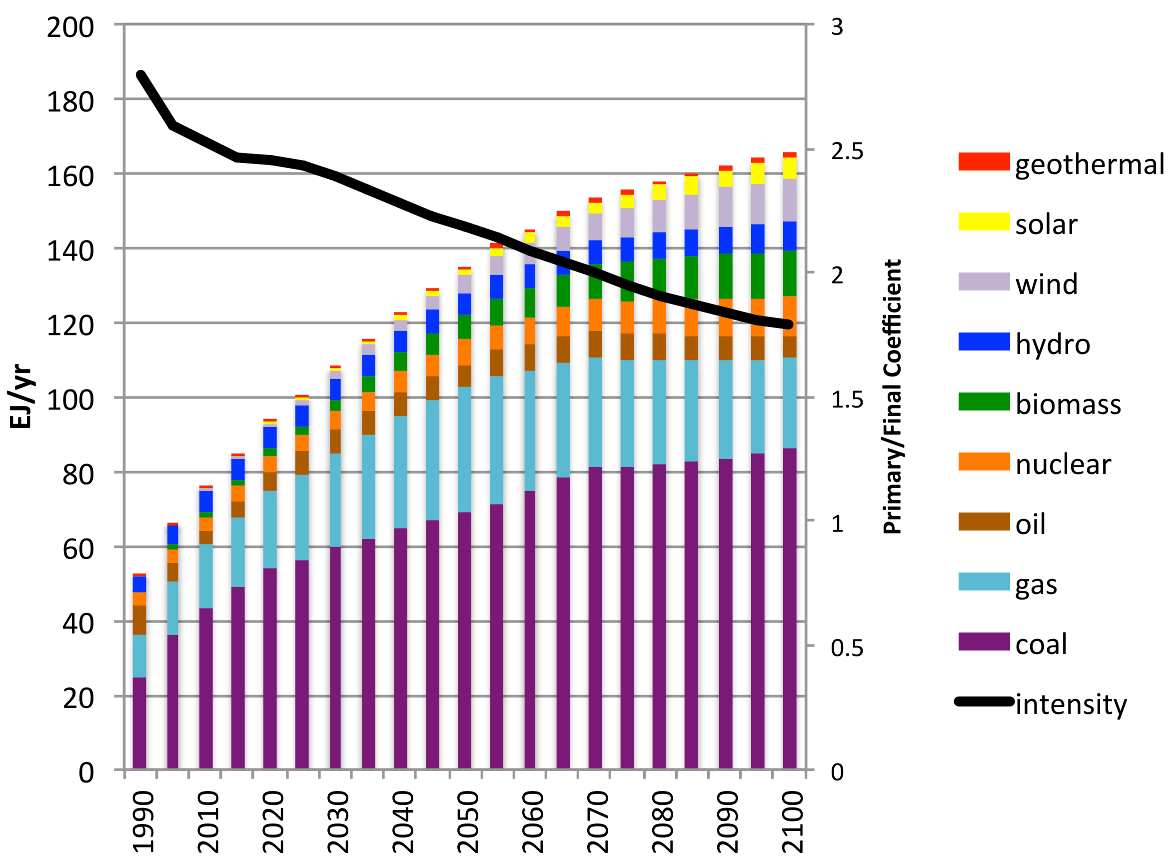
Primary Energy Inputs to Industrial Electricity



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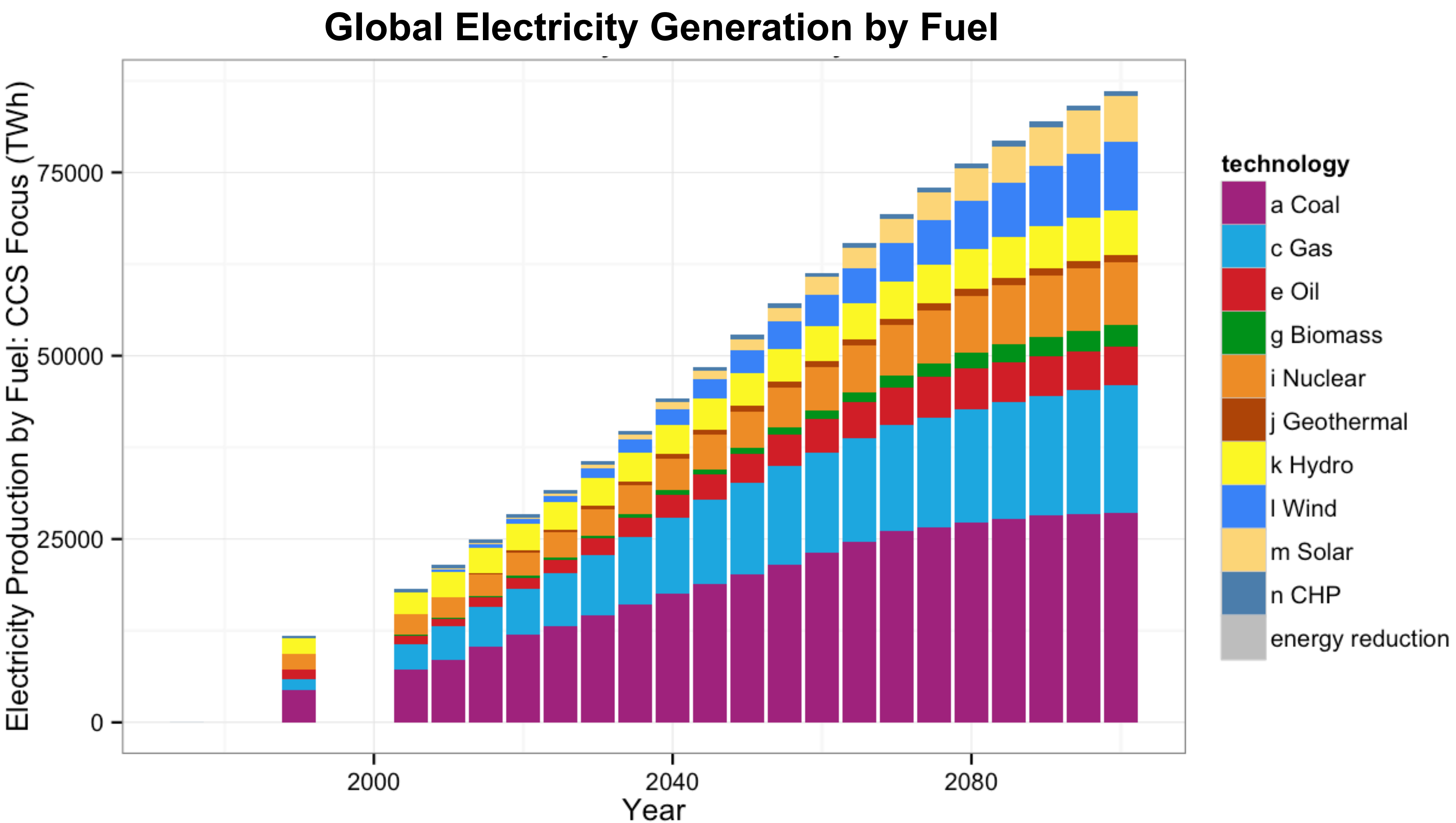

The Energy System: Results

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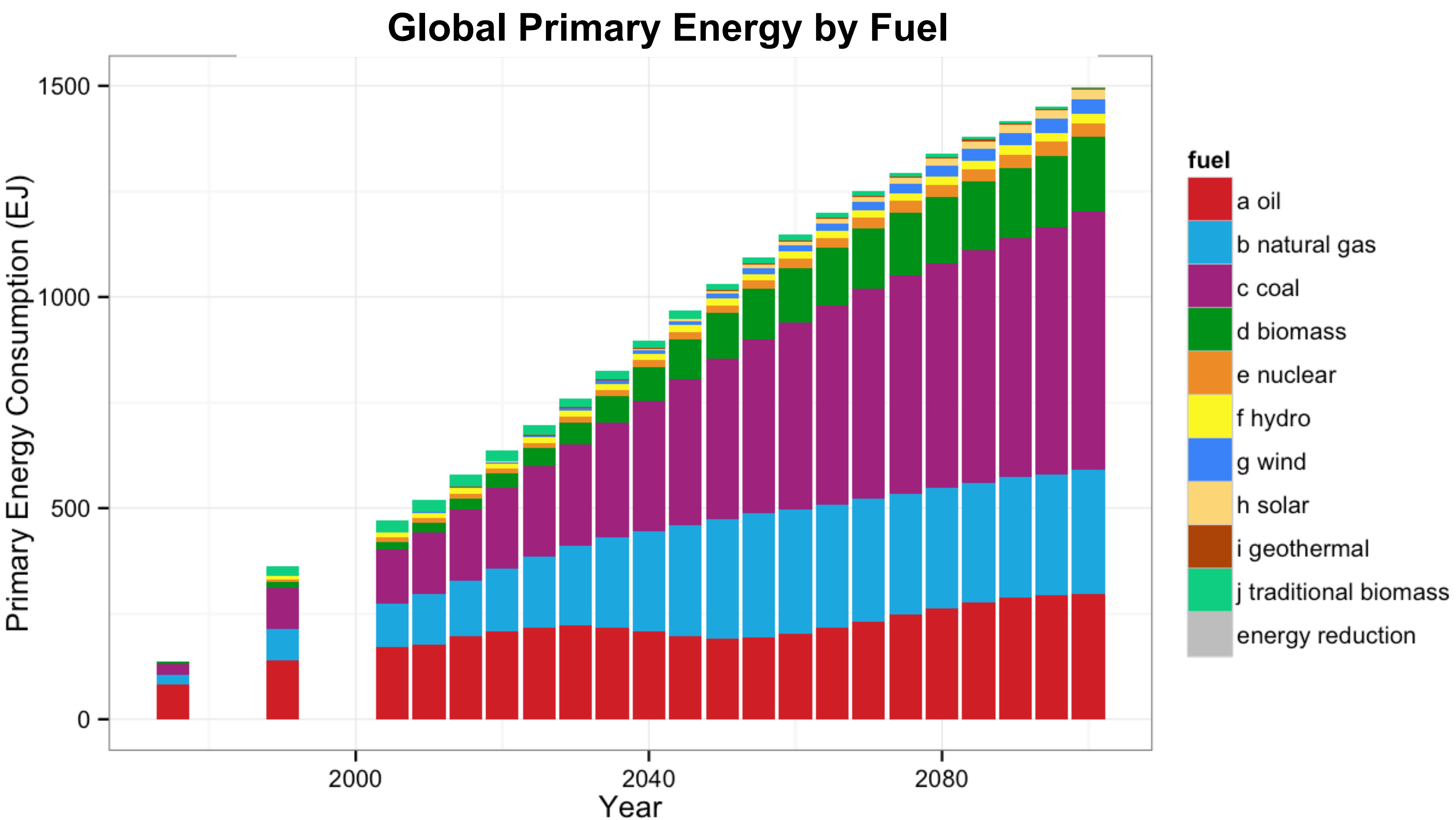
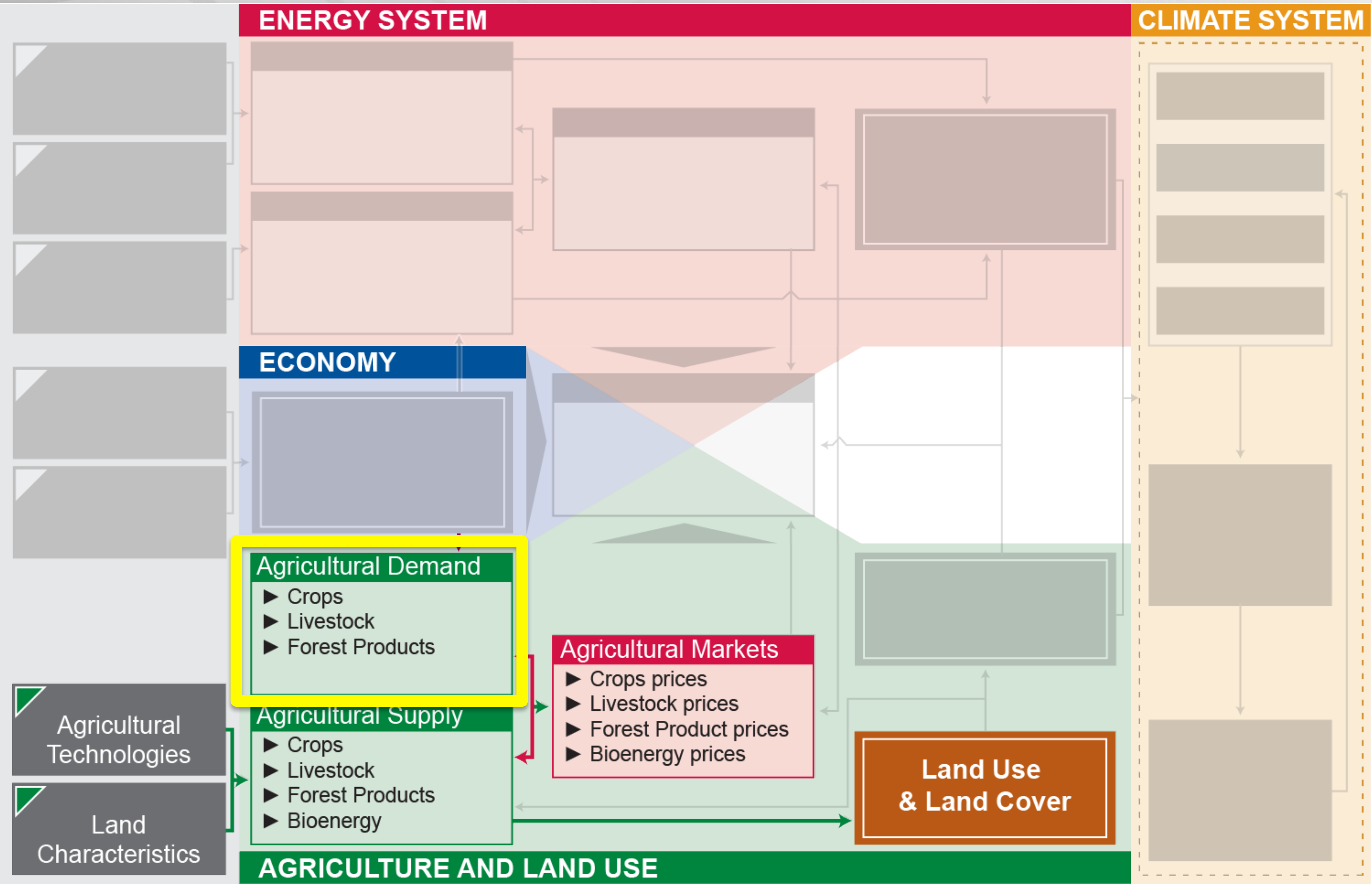


HALF TIME

The Global Change Assessment Model



The Agricultural System: Demand

- GCAM currently models supply and demand for 12 crops, 6 animal categories, and bioenergy:
  - Crops: corn, rice, wheat, sugar, oil crops (e.g., soybeans), other grains (e.g., barley), fiber (e.g., cotton), fodder (e.g., hay, alfalfa), roots & tubers, fruits & vegetables
  - Animals: beef, dairy, pork, poultry, sheep/goat, other
  - Forest: roundwood
  - Bioenergy: switchgrass, miscanthus, jatropha, willow, eucalyptus, corn ethanol, sugar ethanol, biodiesel (from soybeans and other oil crops)

- We account for both food and non-food demand, including animal feed.

- Demand is modeled at the 32 region level.

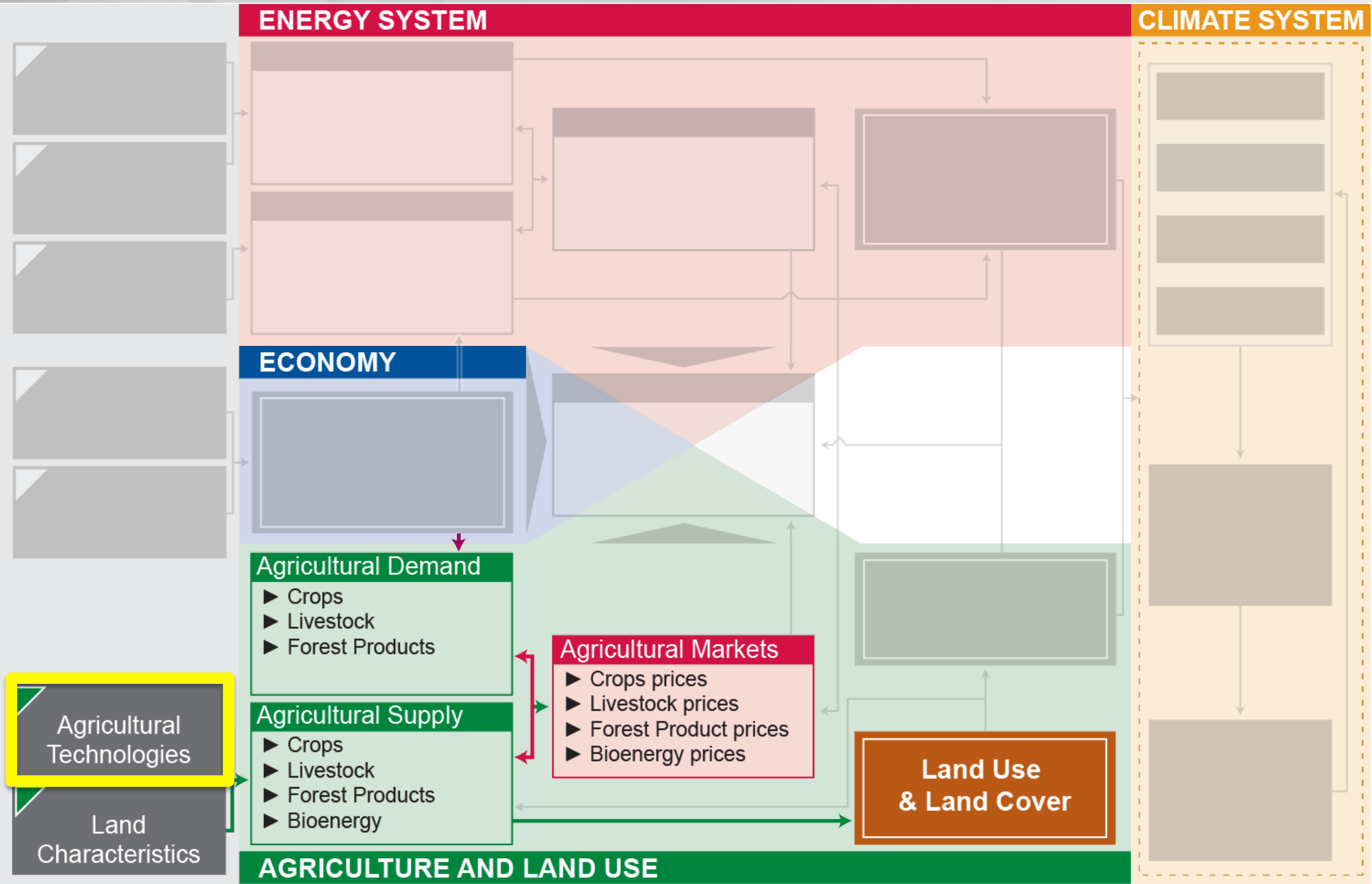
The Agricultural System: Demand

- Non-food, non-feed demand:
  - Base year demand for non-food, non-feed uses FAO statistics
  - Future demand:
    - Per capita demand for crops, animals, and forestry products is currently fixed.
    - Thus, demand grows proportional to population, regardless of income or price.
- Feed demand:
  - Base year demand for feed combines FAO statistics with data from the IMAGE model (PBL)
  - Future demand:
    - Depends on the growth in animal consumption, as well as the change in relative prices of feed options
    - Animal can either be grass-fed or grain-fed. The exact proportion of grass- vs. grain-fed depends on the price of pasture land as compared to the price of crops
    - Grain-fed animals can shift their diet as the relative prices of various crops change. However, the elasticity is relatively low to prevent dramatic shifts that may comprise an unsustainable diet.

The Agricultural System: Demand

- Food demand:
  - Base year demand for food uses FAO statistics
  - Future demand in the baseline is calibrated to match FAO projections of crop and meat demand through 2050. After 2050, we assume that per capita demand is constant.
  - Meat demand in GCAM is price responsive. As the price of meat increases, meat demand will decline.
    - The current price elasticity is very low (~0.25). This is consistent with USDA data for the USA and Australia. Developing countries typically have more elastic demand, but our default assumption is very conservative.
  - Crop demand is not price responsive.

The Global Change Assessment Model



The Agricultural System: Technologies

<u>Ongoing developments:</u>
Including multiple crops (irrigation & fertilizer)

- For each crop and region, we have started with a single production technology.
  - The yield for this technology is calculated from GTAP/FAO statistics, by dividing total production in a region by land area.
  - GCAM results are production per year, not per harvest. Thus, we use total physical crop land area to calculate yield and not harvested area. If a region actually harvests more than once a year, their “economic” yield (used by GCAM) will be larger than the actual physical yield.
- We exogenously specify technical change for agricultural technologies.
  - We use FAO projections through 2050.
  - After 2050, we assume that yields will improve by 0.25% per year for all crops and regions.

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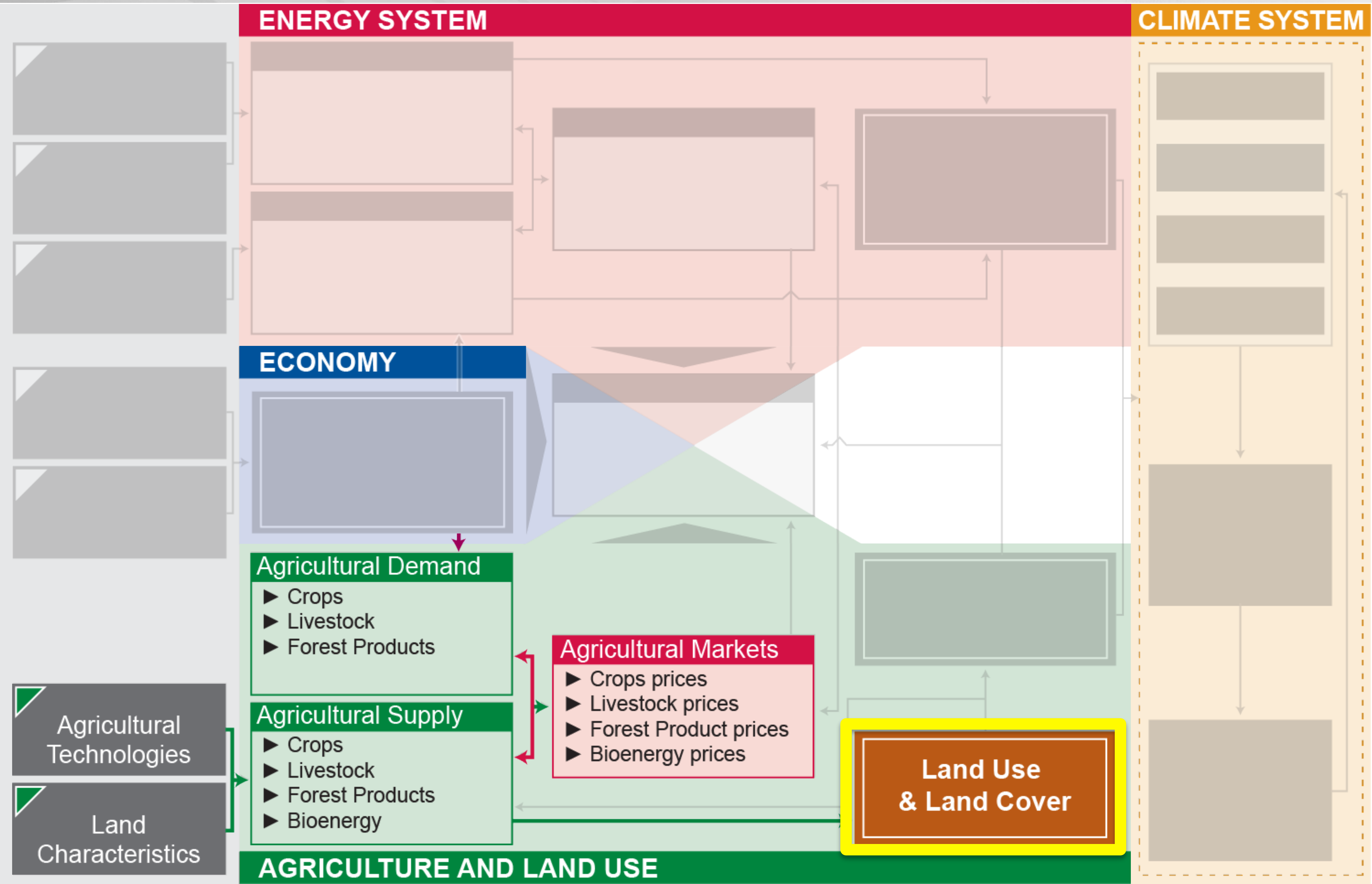
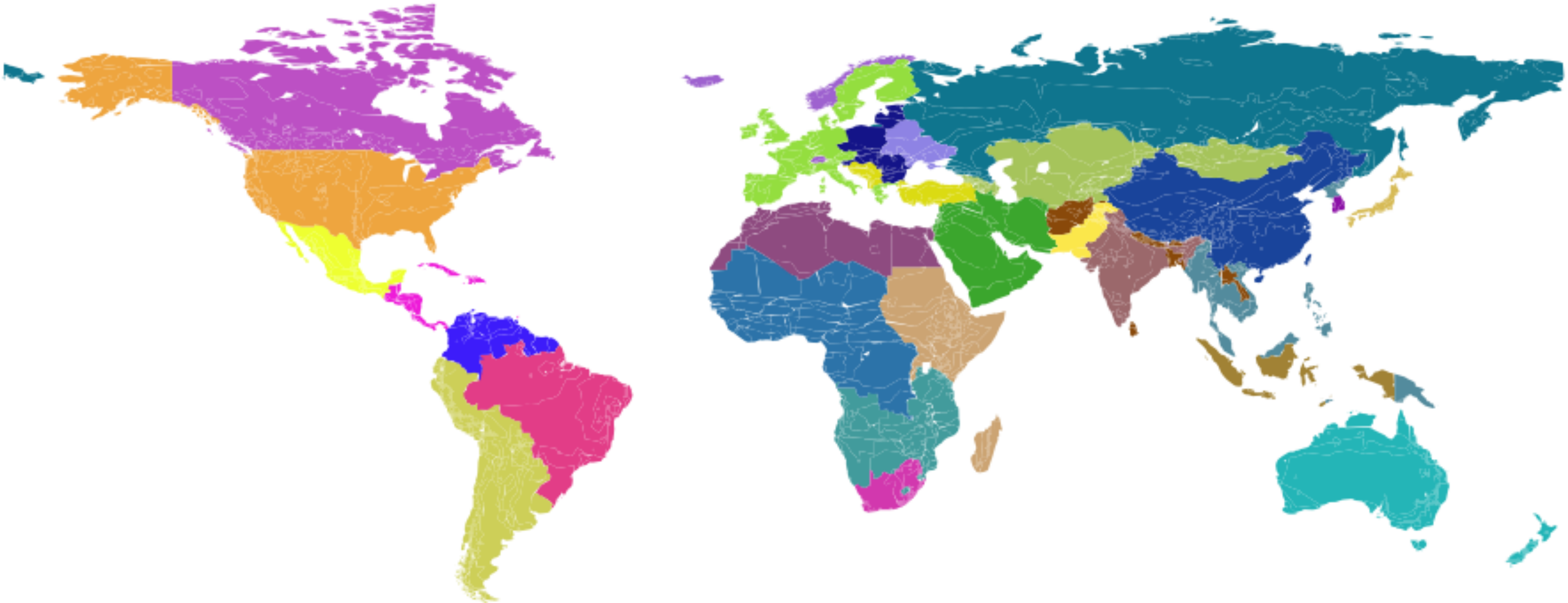


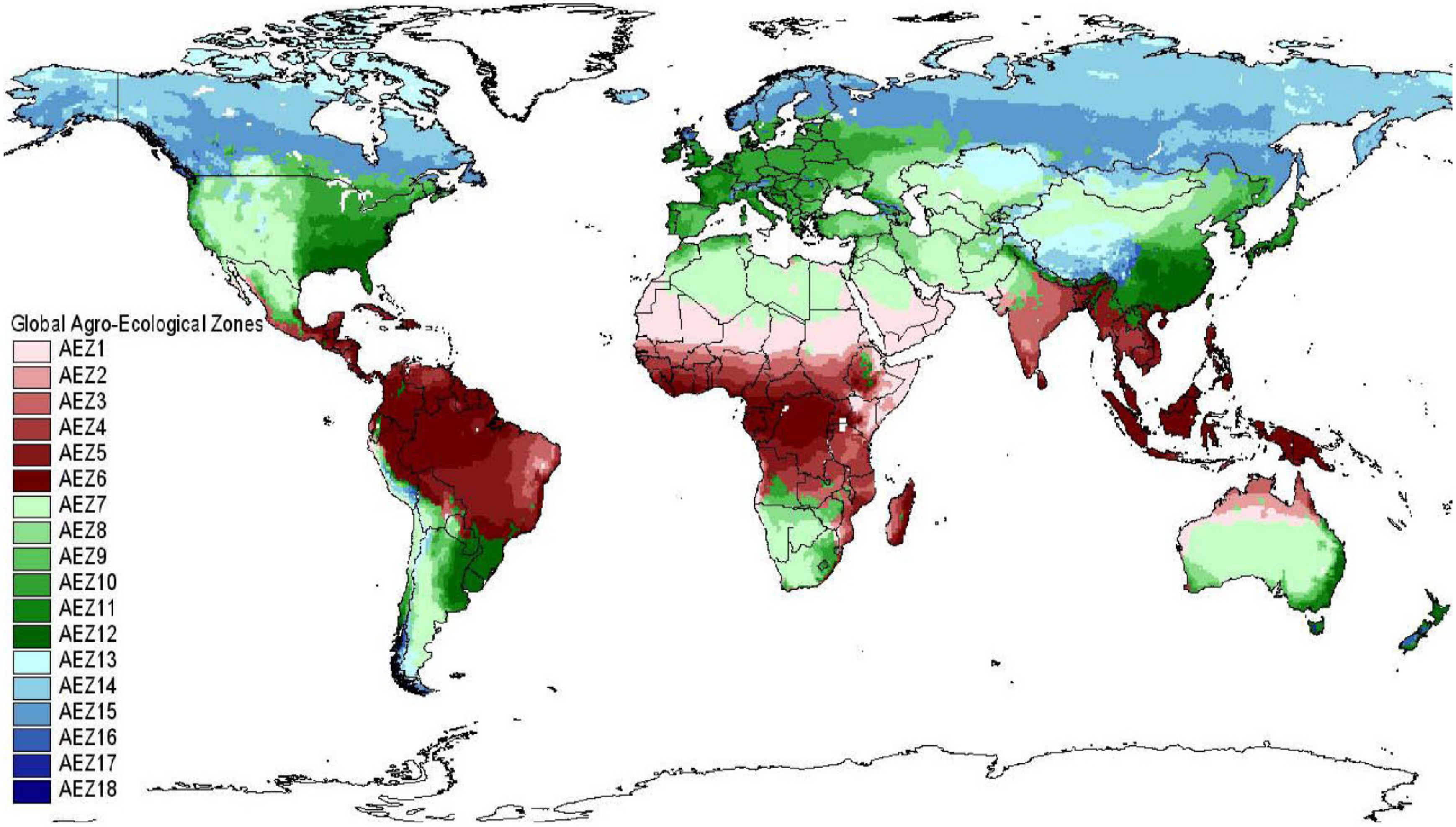
The Agricultural System: Basic Assumptions

- The world is divided into **283** regions

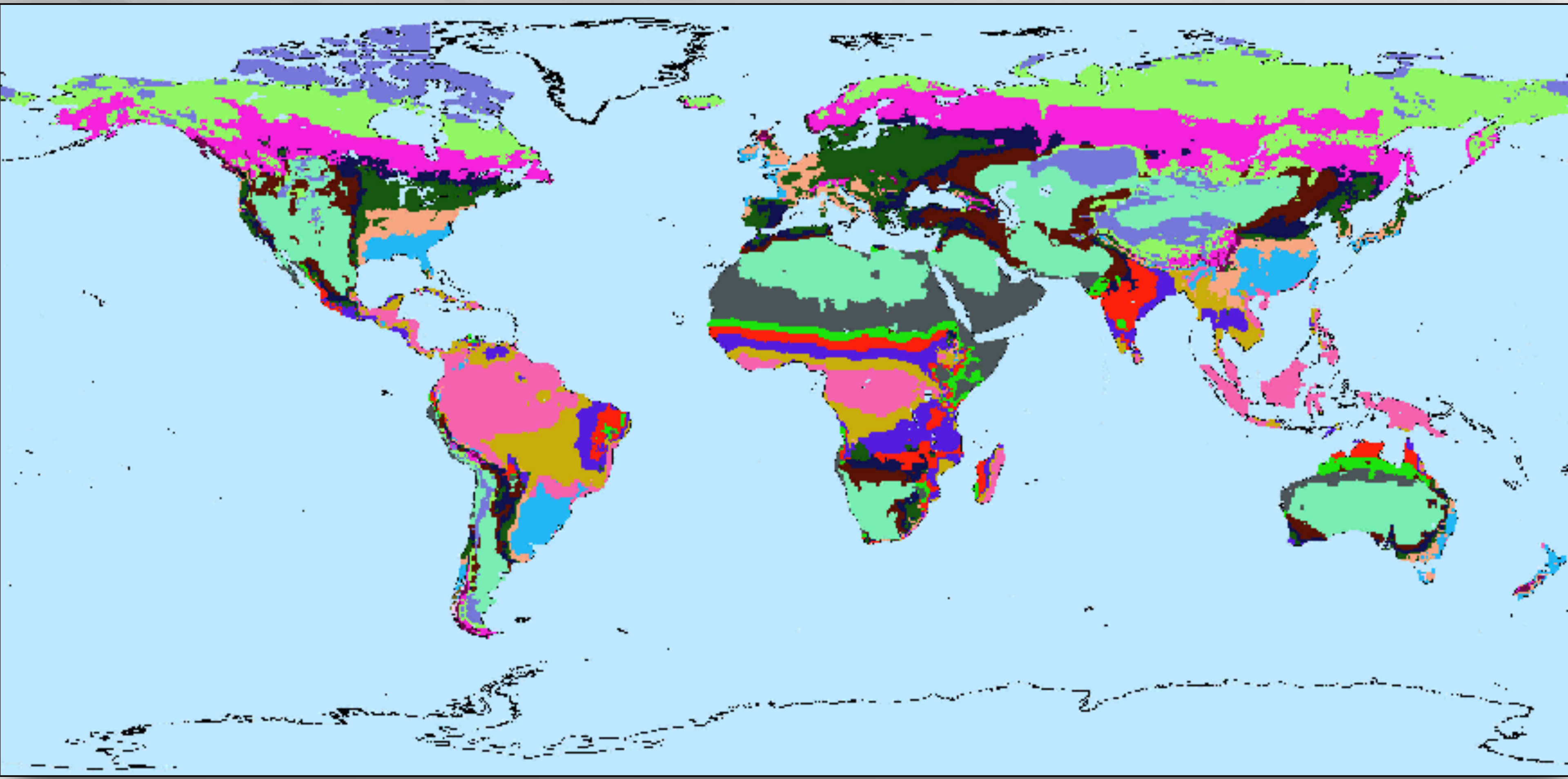
The Agricultural System: Regions



The Agricultural System: Regions



Monfreda et al. (2009)



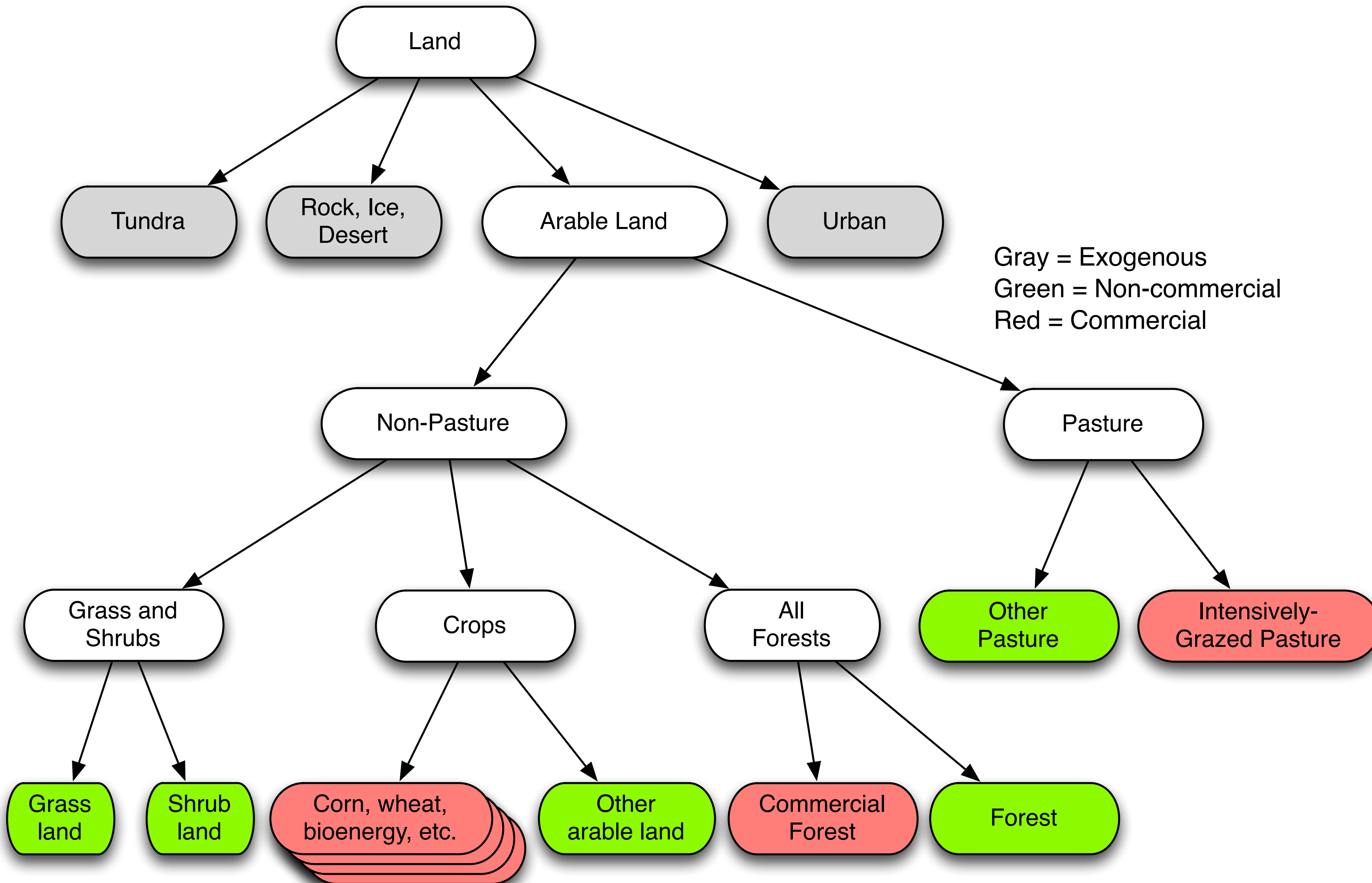
283 Different AgLU Supply Regions

The Agricultural System: Basic Assumptions

- The world is divided into **283** regions
- Farmers allocate land across a variety of uses in order to maximize profit
- There is a distribution of profits for each land type across each of the 283 regions
- The actual share of land allocated to a particular use is the probability in which that land type has the highest profit
- The variation in profit rates is due to variation in the cost of production
  - As the area devoted to a particular land use expands, cost increases
  - Yield is fixed within each region for each crop management practice

The Agricultural System: Nesting

<u>Ongoing developments:</u> Including multiple management technologies.



Gray = Exogenous
Green = Non-commercial
Red = Commercial

The Agricultural System: USA Wheat Yield

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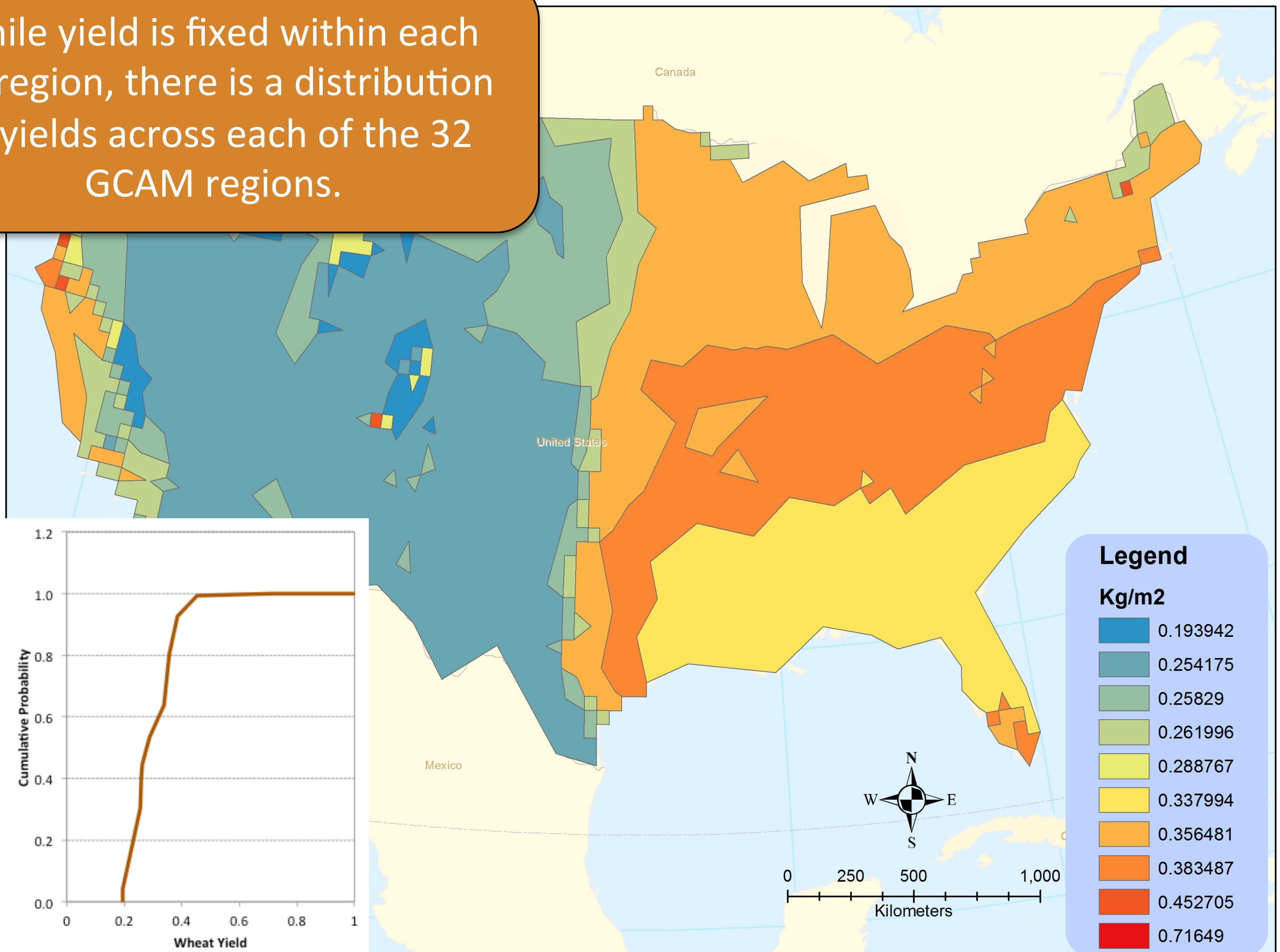
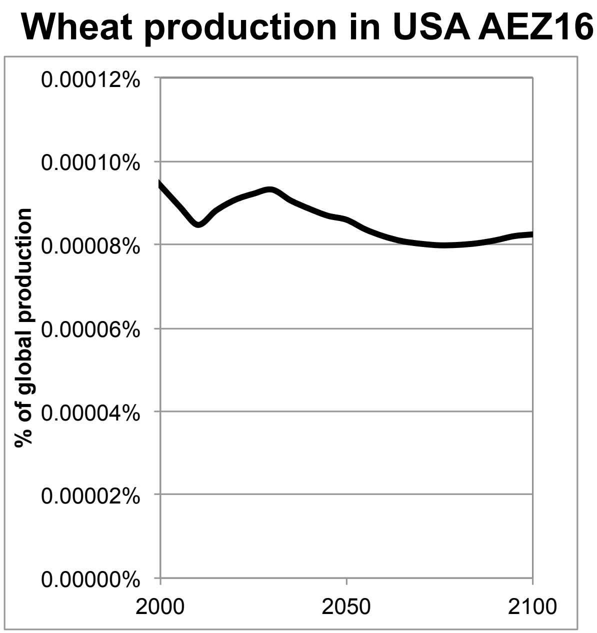
While yield is fixed within each subregion, there is a distribution of yields across each of the 32 GCAM regions.



The Agricultural System: Calibration

- Currently, we calibrate to an average of 2008-2010 data. This is to avoid using an anomalous weather year as a benchmark.
- During the AgLU calibration process, the model computes the average profit rate required to reproduce the base year land allocations. We assume that the difference between this profit and the observed profit (yield * (p – c)) is a cost to production that also applies in the future.
- Thus, if you have a region with a high crop yield, but low land allocation in the base year (e.g., Wheat in Alaska), the model assumes that there are some additional costs that must be considered when expanding its land area. As a result, that crop will continue to have a low share in the future in the absence of a technology or policy change.

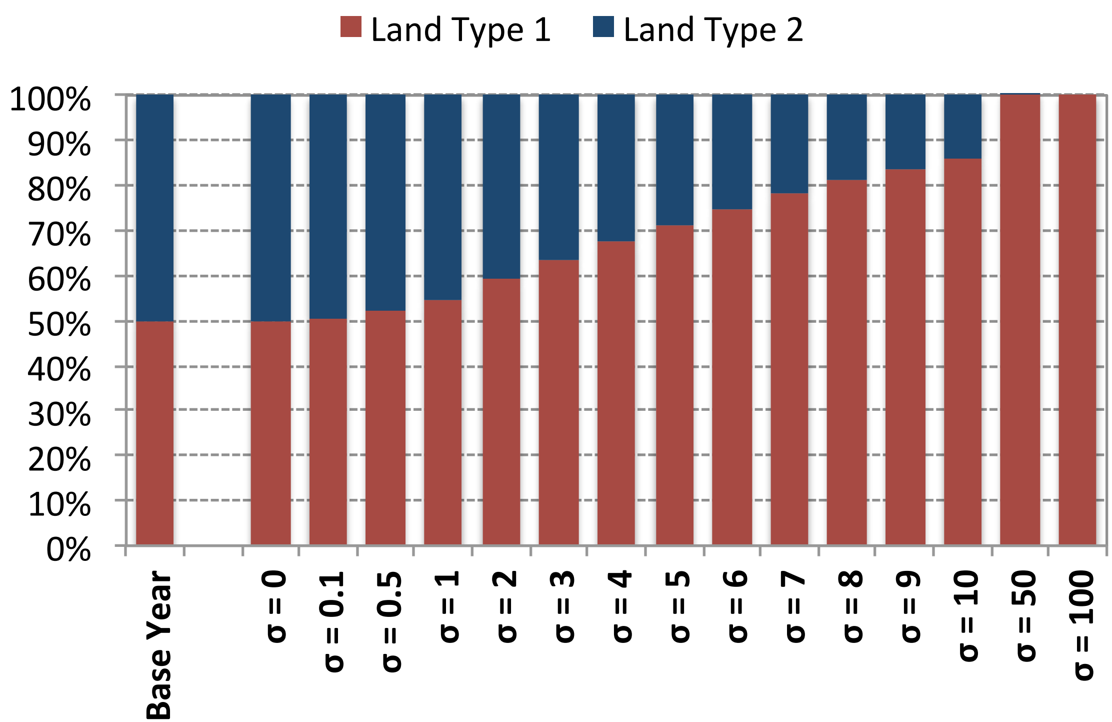


The Agricultural System: Land Competition

$$s_i = \frac{\left(\alpha_i \pi_i\right)^{\sigma}}{\sum_j \left(\alpha_j \pi_j\right)^{\sigma}}$$

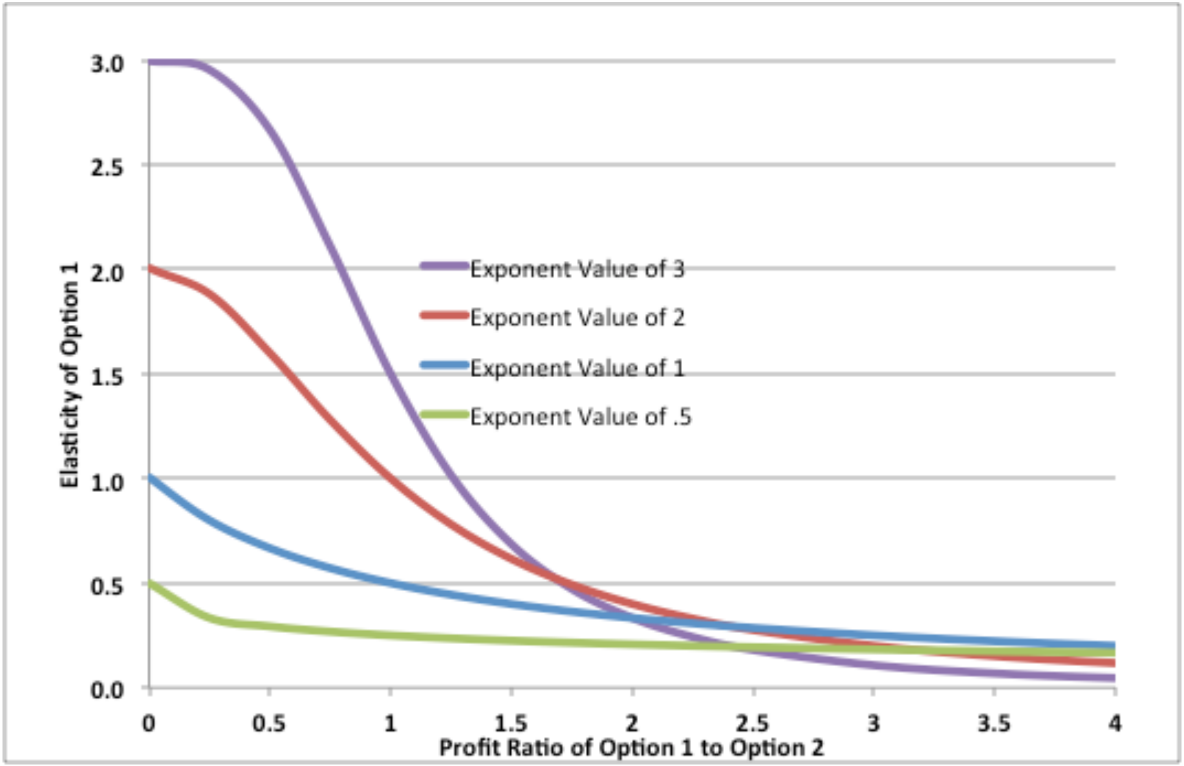
Source: Clarke and Edmonds (1993), McFadden (1974)

Change in land shares when land type 1's profit increases by 20%



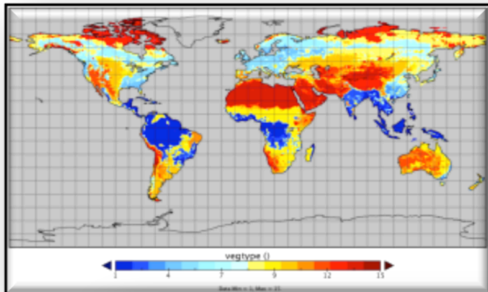
The Agricultural System: Land Competition

- Elasticities can be computed at each point, but
- By design, there is not a constant elasticity relationship with respect to changes in profit

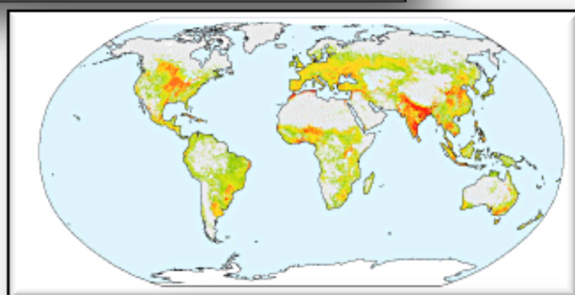


The Agricultural System: Land Cover Data

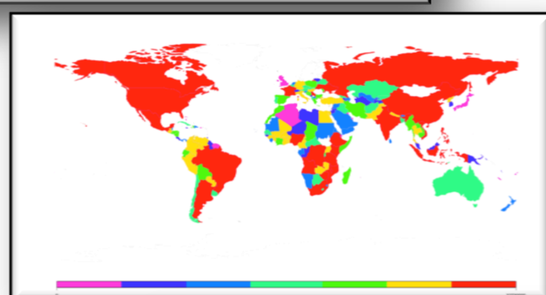
Potential Vegetation



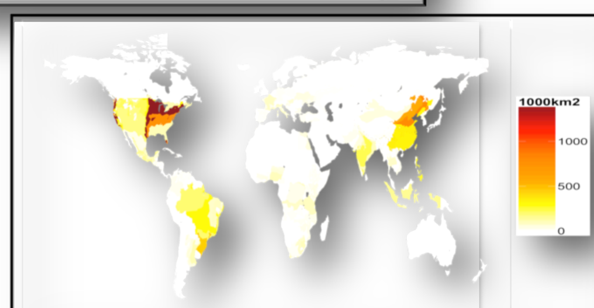
+ Cropland area



+ Crop-specific harvested areas

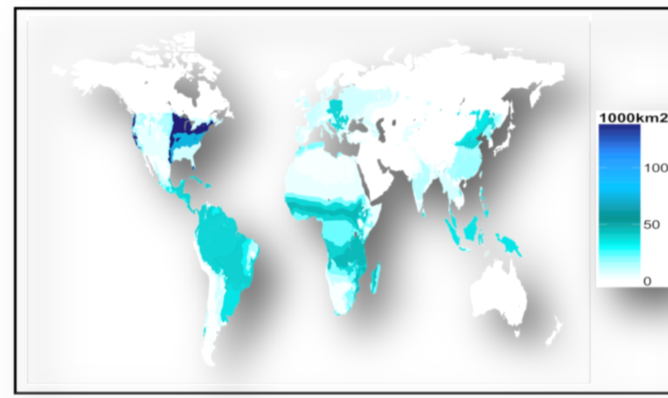


+ Sub-national Harvested areas



- GCAM needs land cover by type (e.g., forest, grass, maize, wheat, etc.) for each region/AEZ combination in each historical year.

Maize Area in 2010



- We have similar methodologies in other sectors:
  - Population: IIASA, US Census
  - Energy: IEA, EIA, country studies
  - Agriculture: FAO, GTAP, MIRCA
  - Emissions: EDGAR, EPA, RCP

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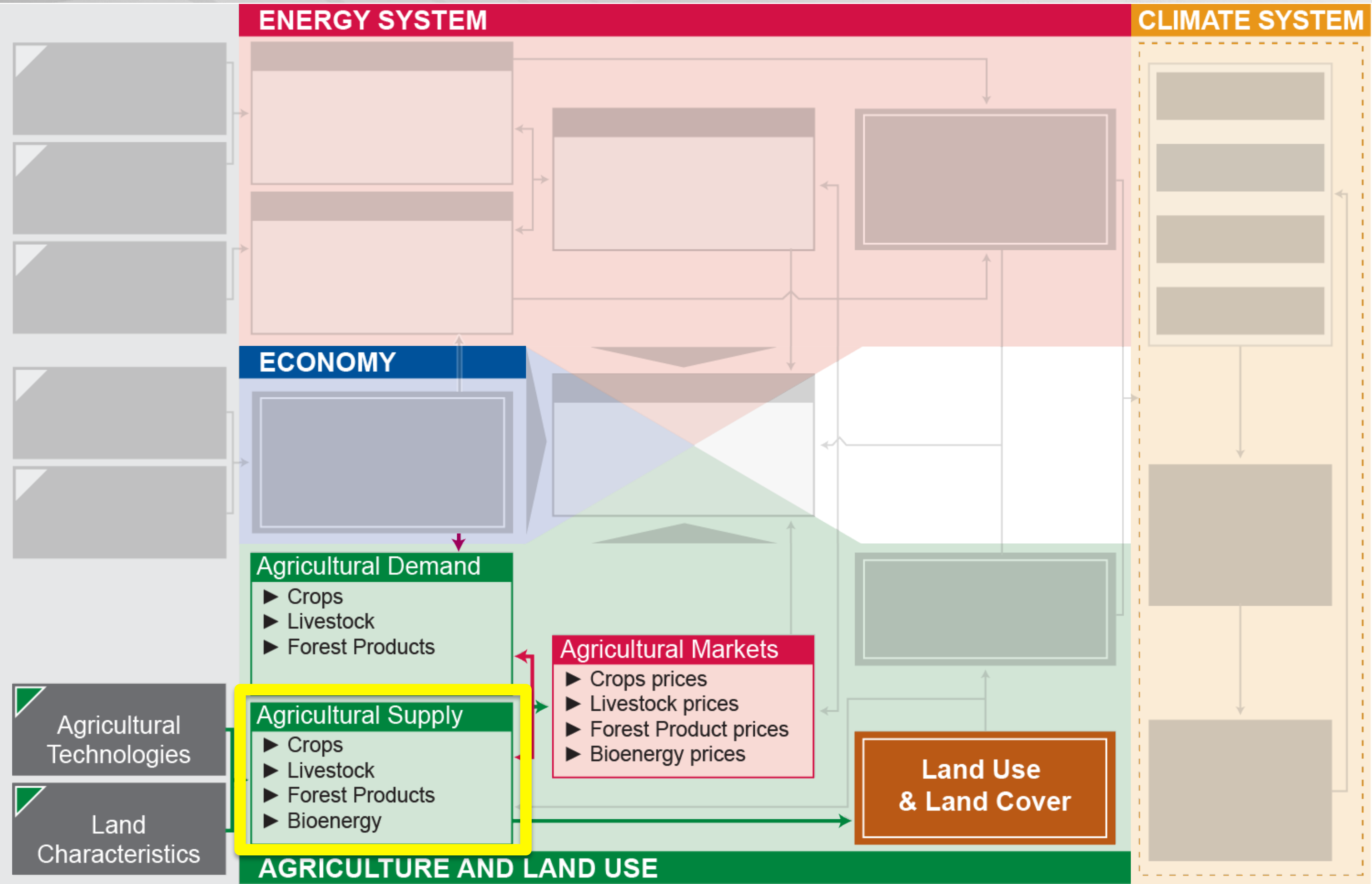

The Agricultural System: Supply

- Yield is exogenously calculated.
  - Base year derived from GTAP/FAO production and land area.
  - Yields increase over time based on exogenously specified technical change.
- Land area is endogenously calculated.
  - Each land types share of area in its region is the probability its profit is the highest in that region.
- Supply = land * yield

The Agricultural System: Results

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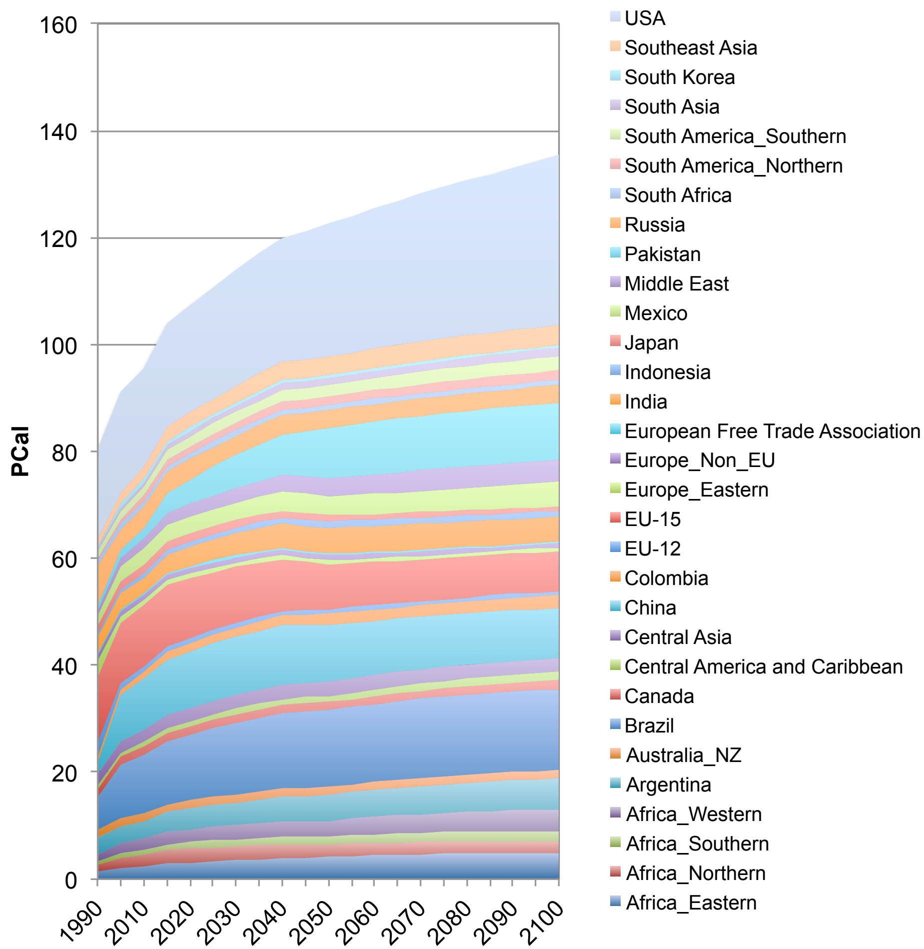
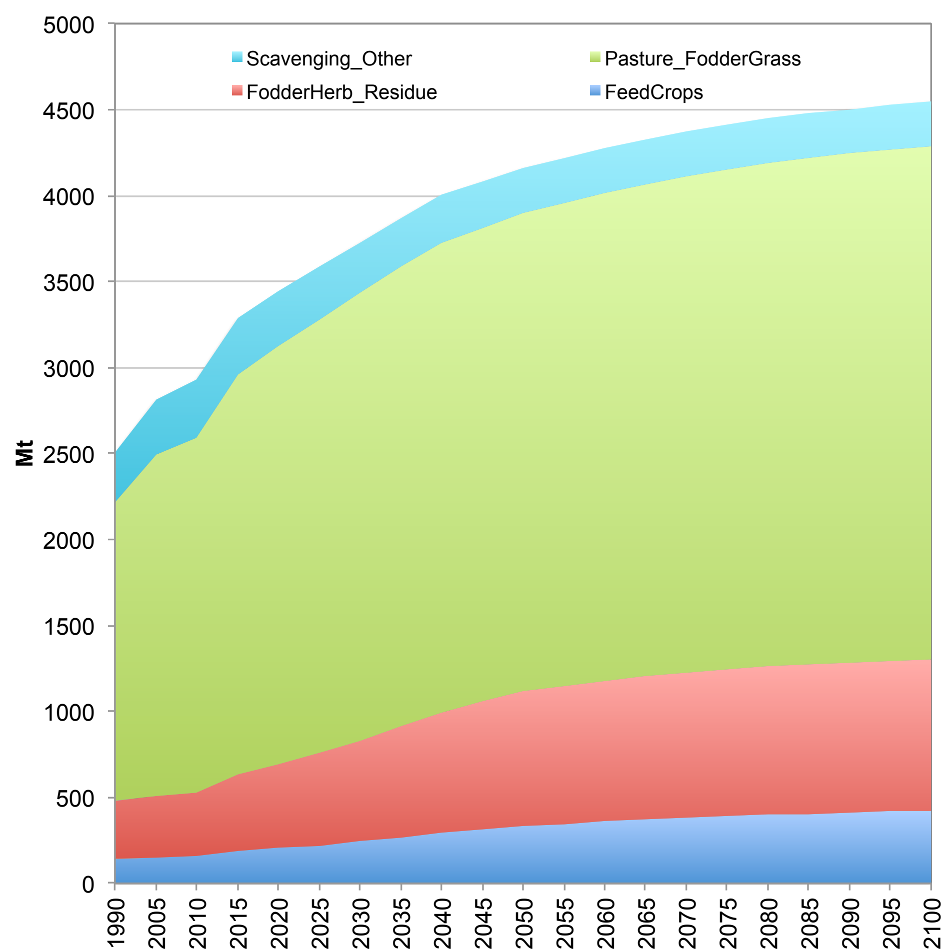
Beef Consumption by Region



Global Beef Feed



The Agricultural System: Results

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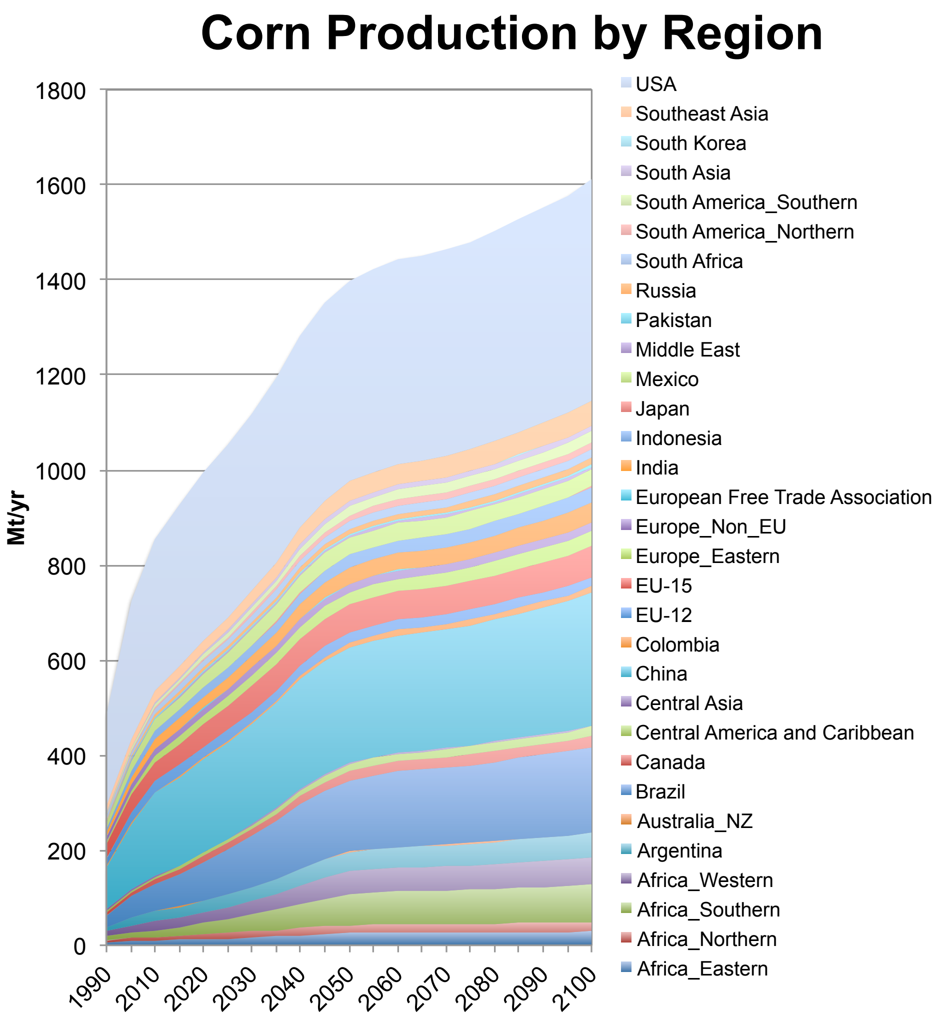

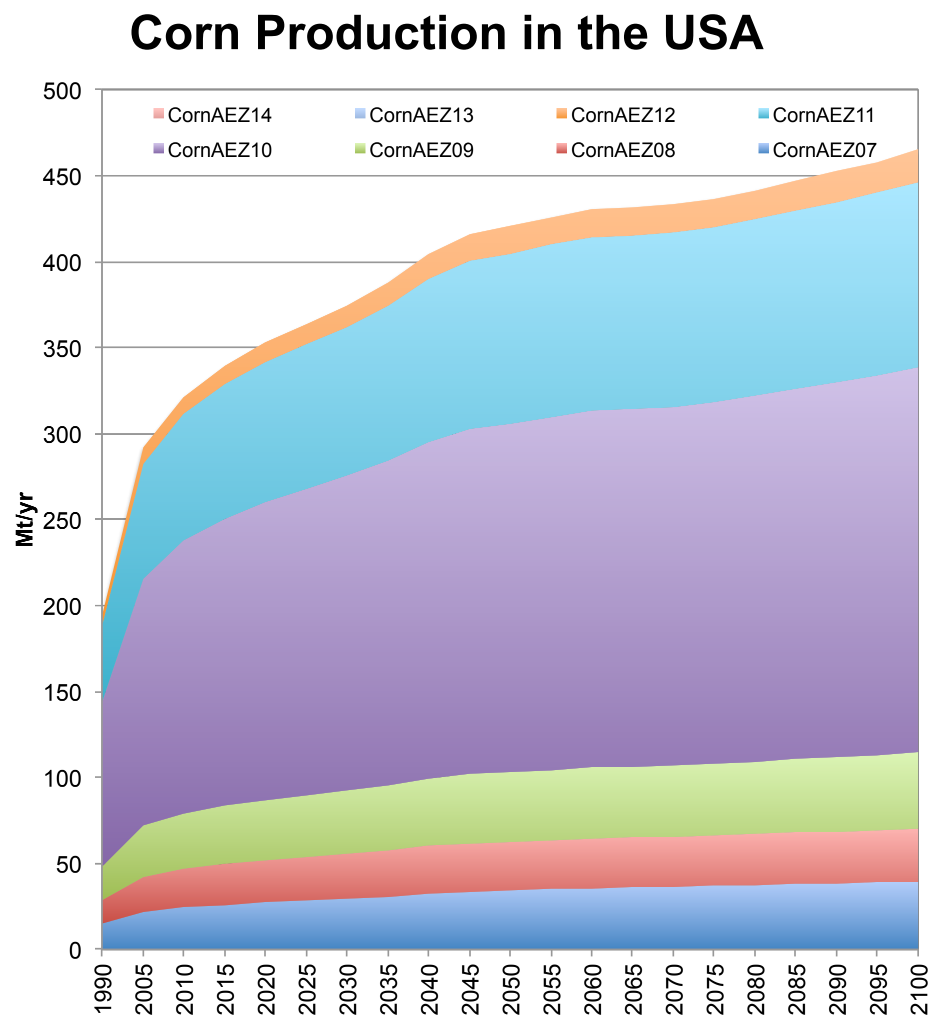

The Agricultural System: Results

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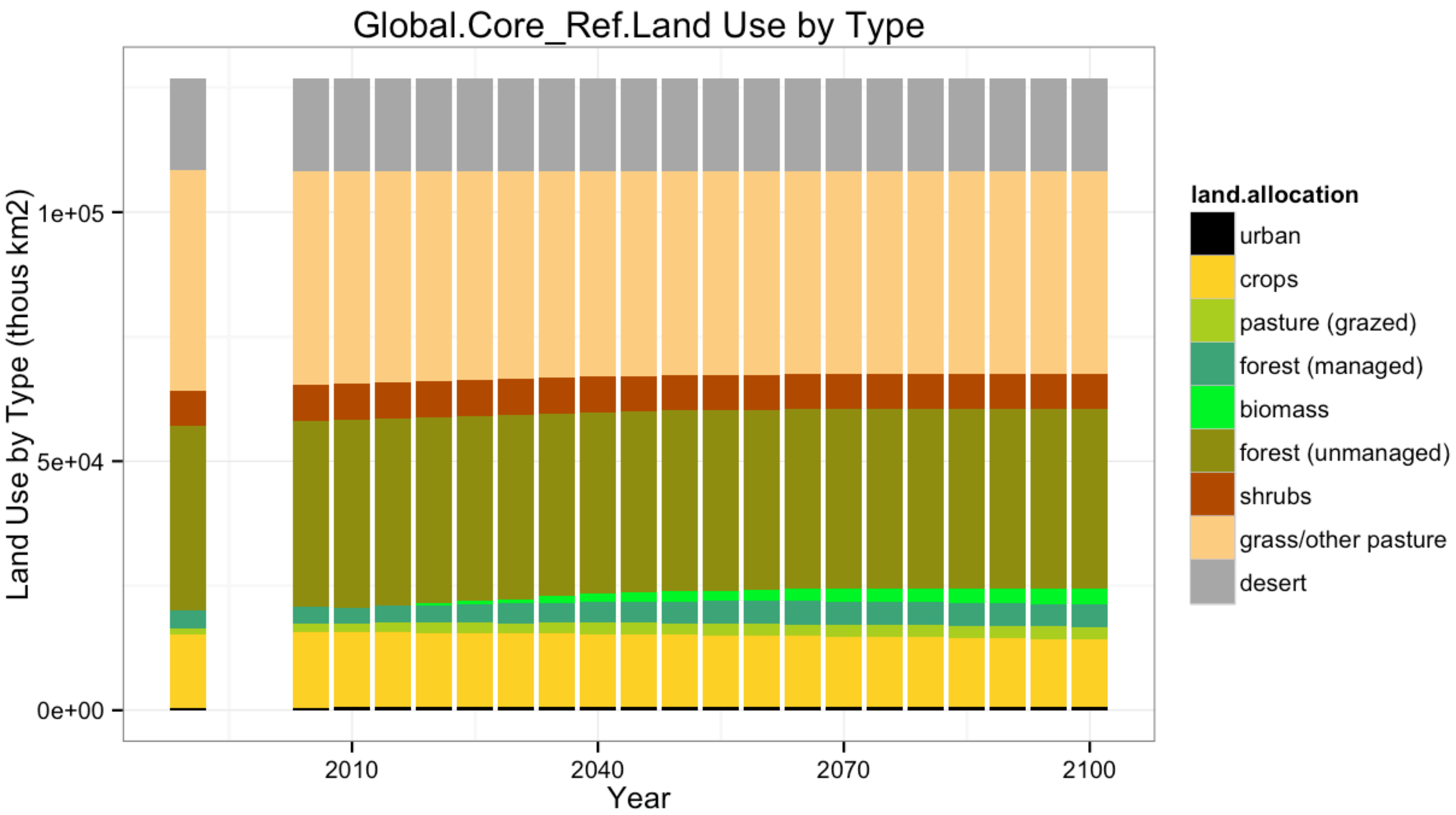

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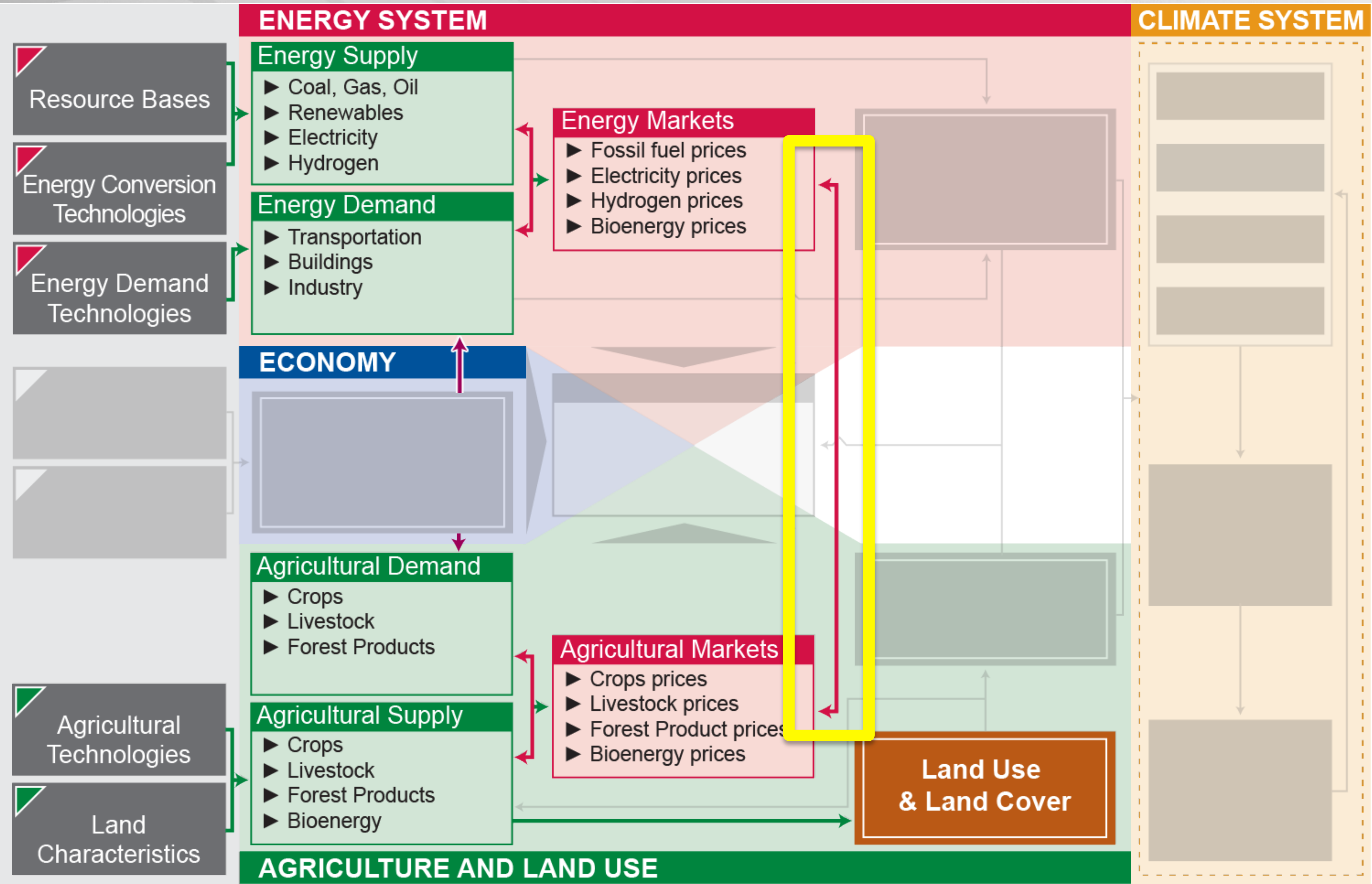


The Agricultural System: Linking the Energy & Agricultural Sectors

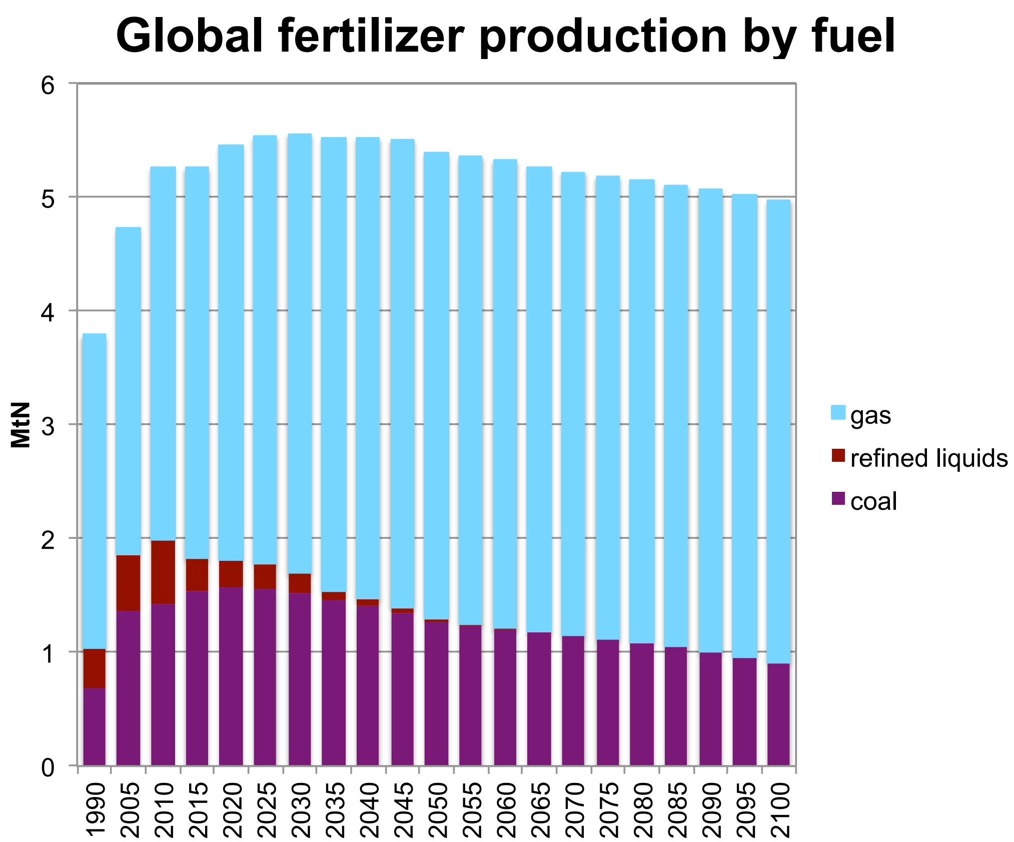
- While we can explain the energy and agricultural systems separately, these two systems cannot be separated in practice. Choices made in one sector affect outcomes in another sector.

- This is true both in the real world and in GCAM. You cannot run the different components of the model separately.

- GCAM currently has three means of linking the energy and agriculture systems:
  - Bioenergy: supplied by the agricultural system, demanded by the energy system
  - Fertilizer: supplied by the energy system, demanded by the agricultural system
  - DDGS: supplied by the energy system, demanded by the agricultural system

Fertilizer Supply

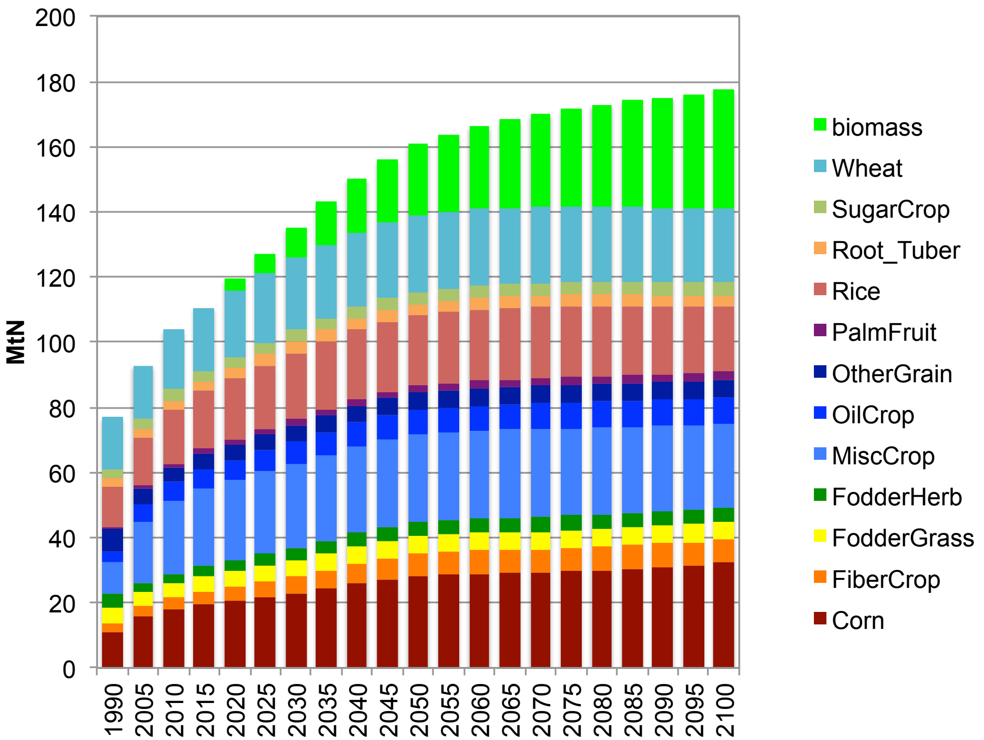
- We are modeling synthetic fertilizer production for use in the agricultural sector. We do not include non-agricultural uses of fertilizer or natural fertilizer.
- Production by technology is from IEA.



Fertilizer Demand

- Consumption by country (and therefore region) are from FAO ResourceSTAT.
- Consumption by region is first downscaled to crops according to a dataset put together by the International Fertilizer Industry Association working in collaboration with the FAO, and then downscaled to AEZ on the basis of crop production.

Global fertilizer consumption by crop



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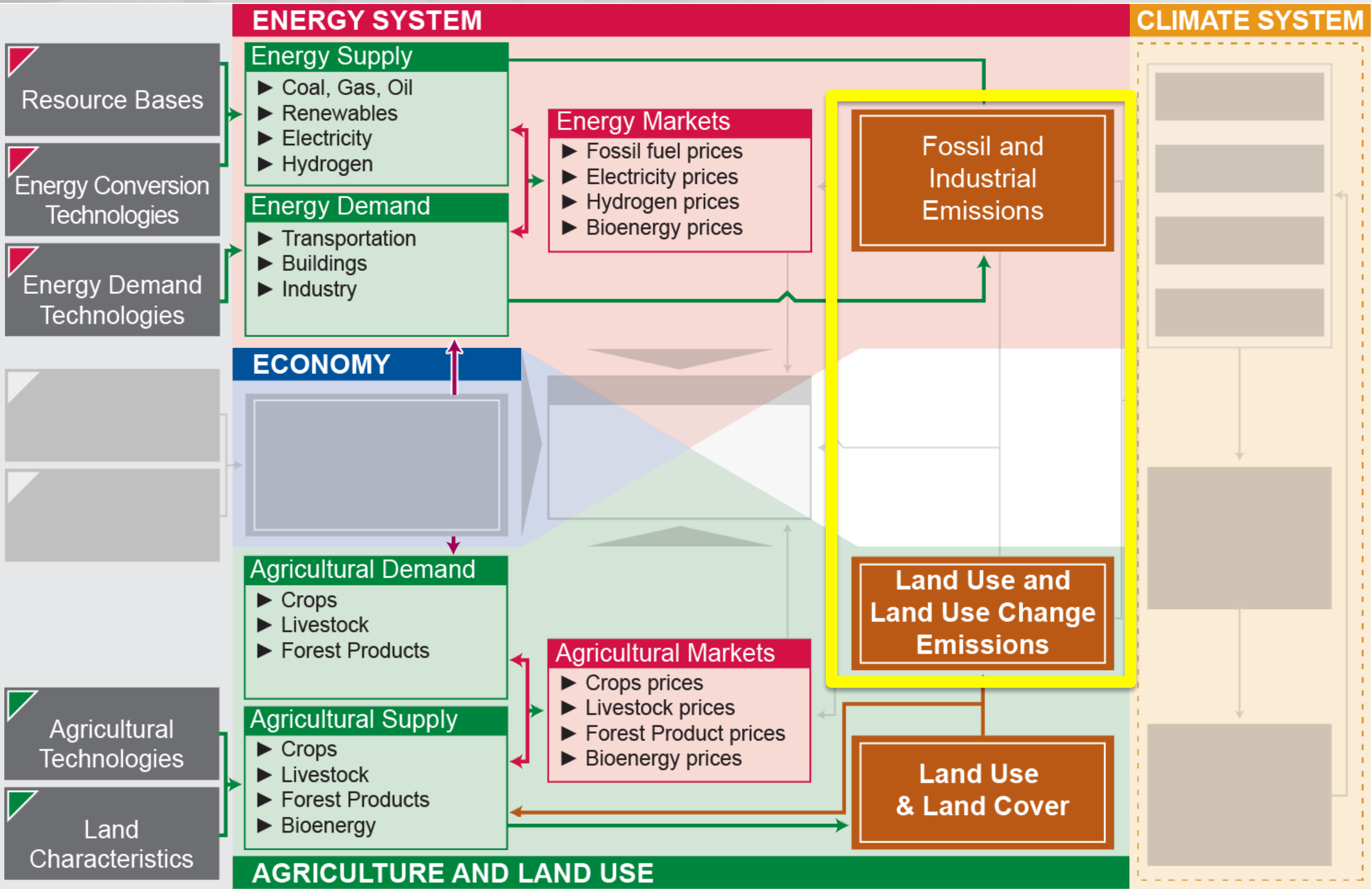

Emissions: General Structure

- GCAM tracks emissions for several gases and species
  - CO_2, CH_4, N_2O, CF_4, C_2F_6, SF_6, HFC23, HFC32, HFC43-10mee, HFC125, HFC134a, HFC143a, HFC152a, HFC227ea, HFC236fa, HFC245fa, HFC365mfc, SO_2, BC, OC, CO, VOCs, NOx, NH_3
  - We calculate CO_2 from fossil fuel & industrial uses, as well as from land-use change
- Each gas is associated with a specific activity and changes throughout the coming century if:
  - The activity level changes
    - Increasing the activity increases emissions
  - Pollution controls increase
    - As incomes rise, we assume that regions will reduce pollutant emissions
  - A carbon price is applied
    - We use MAC curves to reduce the emissions of GHGs as the carbon price rises
- Emissions are produced at a region level (32 regions for energy, 283 regions for agriculture & land-use).

Emissions: Base Year Emissions

- CO_2:
  - Energy system: we read in carbon contents for all fuels (e.g., coal, gas, oil). These carbon contents are chosen so we match global emissions from CDIAC in the base year. These carbon contents are used to compute emissions in all years (including the base year).
  - LUC: we read in carbon density, growth parameters, and historical land allocation and compute emissions in all years (including the base year).

- Non-CO_2:
  - Base year emissions are calibrated to match the EDGAR* data set for most emissions (exceptions are BC & OC, where we still use RCP inventories). We use this data to calculate emissions factors (emissions per unit of activity) for all emissions sources. In some cases (e.g., electricity), we supplement EDGAR with EPA to get technology-specific emissions.

* Note: EDGAR only provides data through 2008. So, our final calibration year for non-CO_2 emissions is 2005.

Emissions: Vegetation CO_2 Emissions

- First, we determine the total change in carbon stock for each land type and region.
  - Δ C Stock = [Land Area (t)]*[C density (t)] - [Land Area (t-1)]*[C density (t-1)]

- Then, we allocate that change across time.
  - If change in land area decreases the carbon stock (e.g., deforestation), then all carbon is released into the atmosphere instantaneously.

  - If the change in land area increases the carbon stock (e.g., afforestation), then carbon accumulates slowly over time, depending on an exogenously specified mature age.
    - The mature age varies by land type and region.

Emissions: Forest Carbon Uptake

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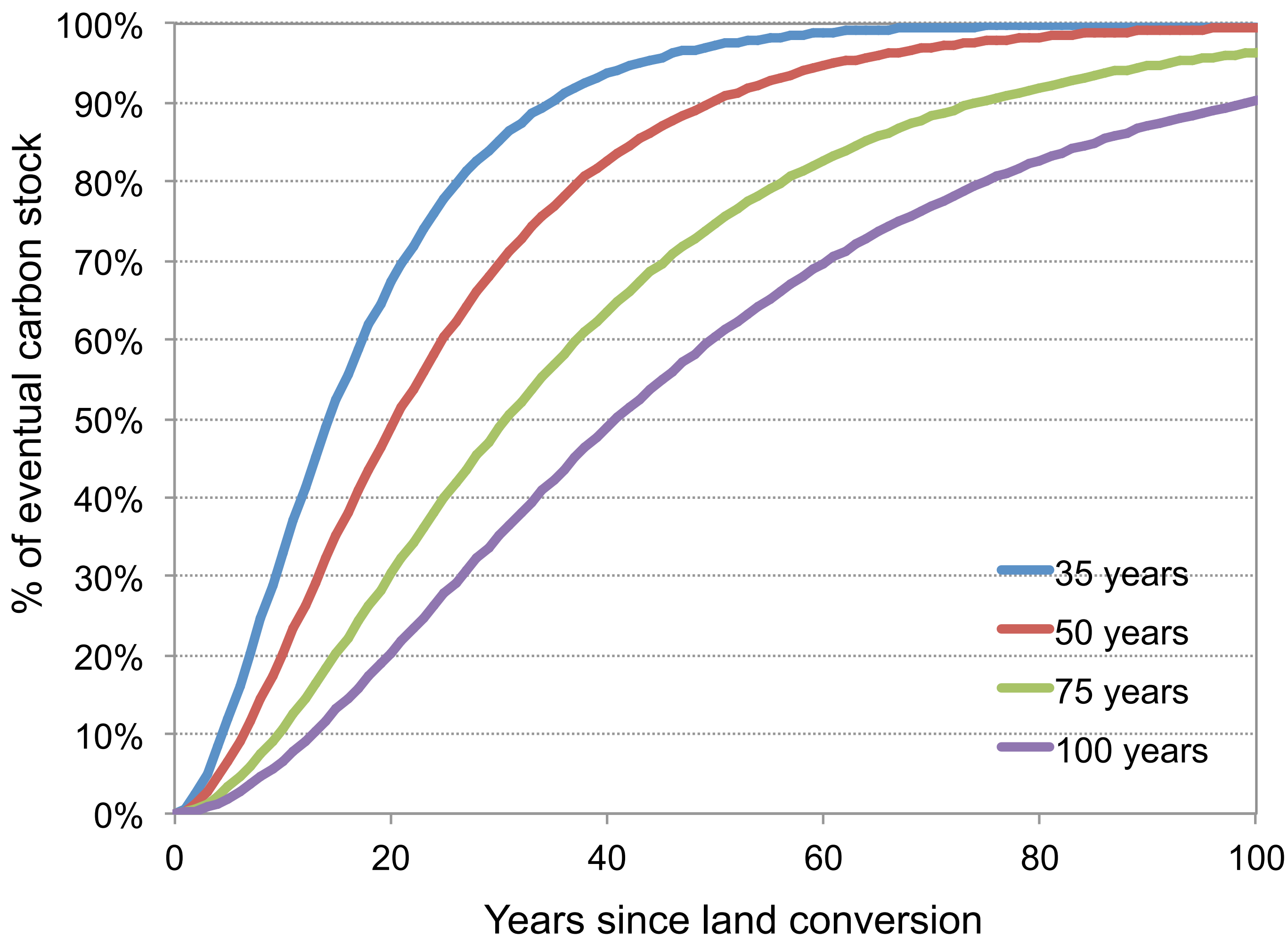


Emissions: Soil CO_2 Emissions

- First, we determine the total change in carbon stock for each land type and region.
  - Δ C Stock = [Land Area (t)]*[C density (t)] - [Land Area (t-1)]*[C density (t-1)]

- Then, we allocate that change across time.
  - Whether carbon stock increases or decreases, we use the same formula.
    - $SoilCarbon(t) = SoilCarbon(0) + \Delta SoilCarbonStock_{i,j} \cdot (1 - e^{-\lambda t})$
  - The half life, λ, varies by region.
  - In general, colder regions have longer soil carbon half lives.

Emissions: Energy System Non-CO_2

- Emissions in the energy system can be driven by input (e.g., fuel consumed by a particular technology) or output (e.g., fuel produced by a particular technology).

- Emissions information is technology-specific. As a result, different technologies that produce the same output can have different emissions per unit of activity.

- For most gases and species, we model drivers of emissions in detail. However, for some F-gases, the driver data (e.g., fire extinguishers) depends only on GDP.

Emissions: Agricultural Non-CO_2

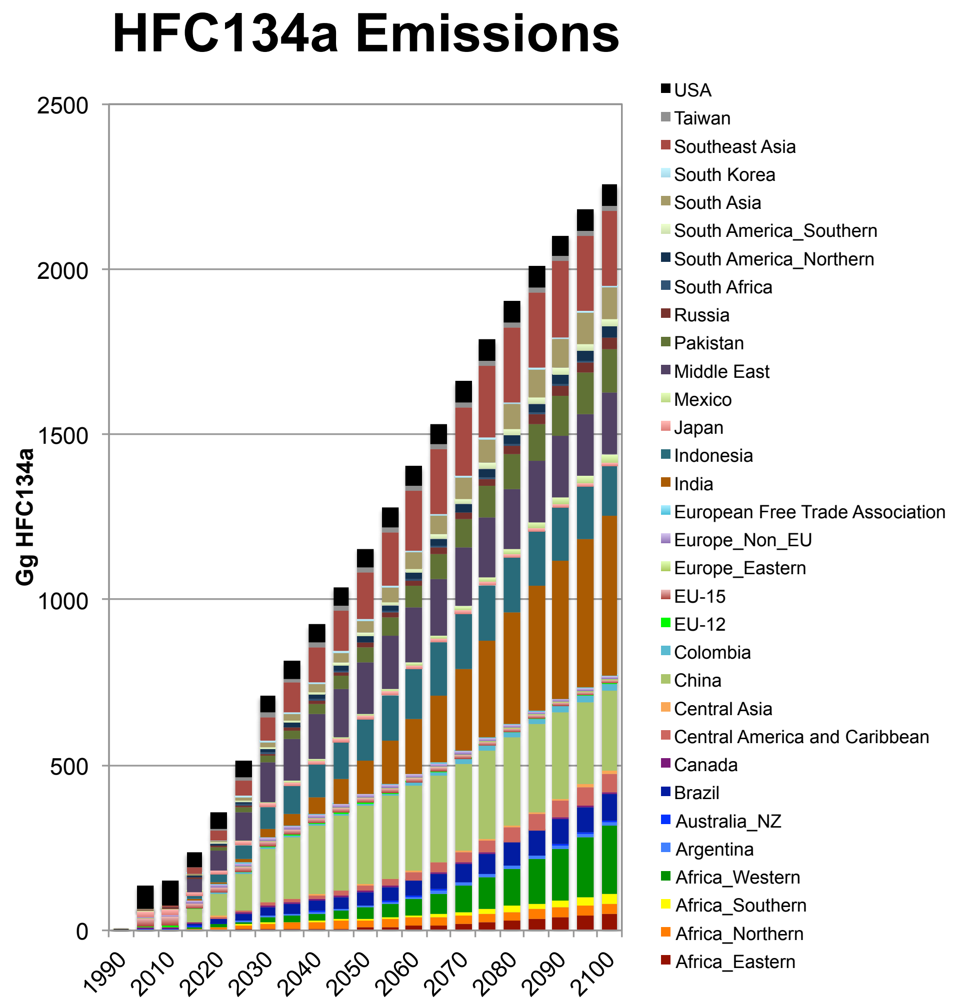
- Emissions in the agricultural system can be driven by output (e.g., for crop production) or land area (e.g., for open burning).

- Emissions information is crop and region specific in GCAM. However, inventory data is region specific, but not crop specific (or AEZ specific).

Emissions: Fluorinated Gases

- Fluorinated gas emissions are linked either to the size of the industrial sector (e.g., semiconductors) or to GDP (e.g., fire extinguishers). As those drivers change, emissions will change. Additionally, we include abatement options based on the EPA's most recent MAC curves.

- For HFC134a from cooling, we make additional adjustments to emissions factors in the developing regions to reflect their continued transition from CFCs to HFCs (see EPA report).



Emissions: Results

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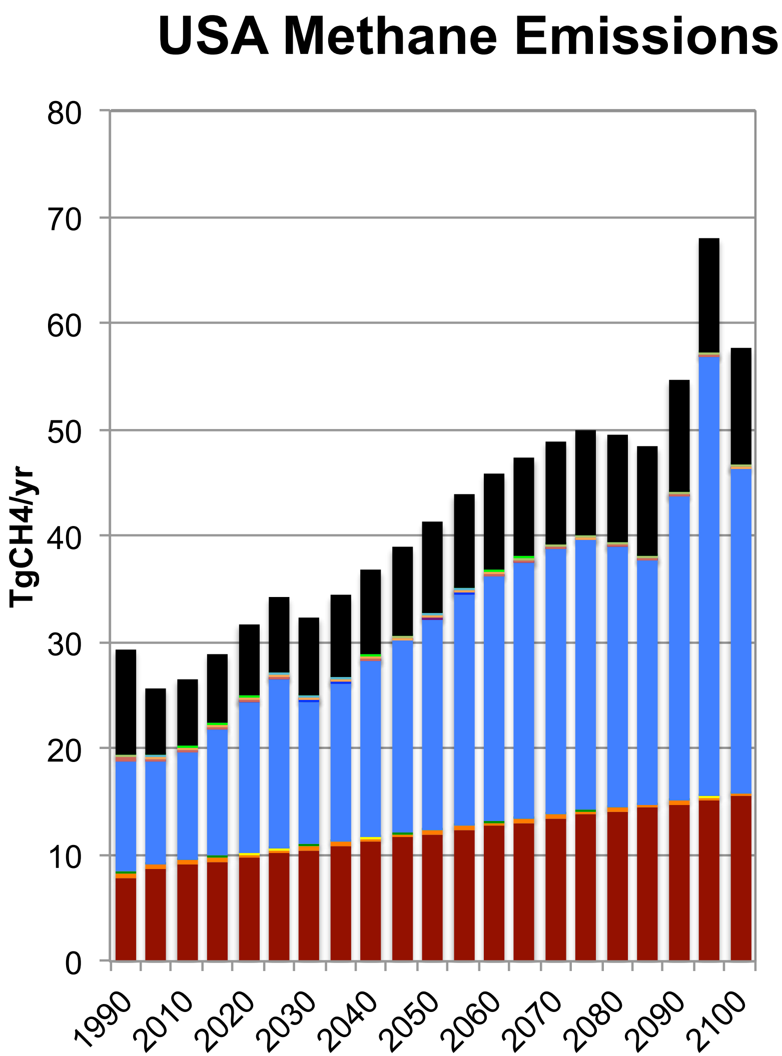

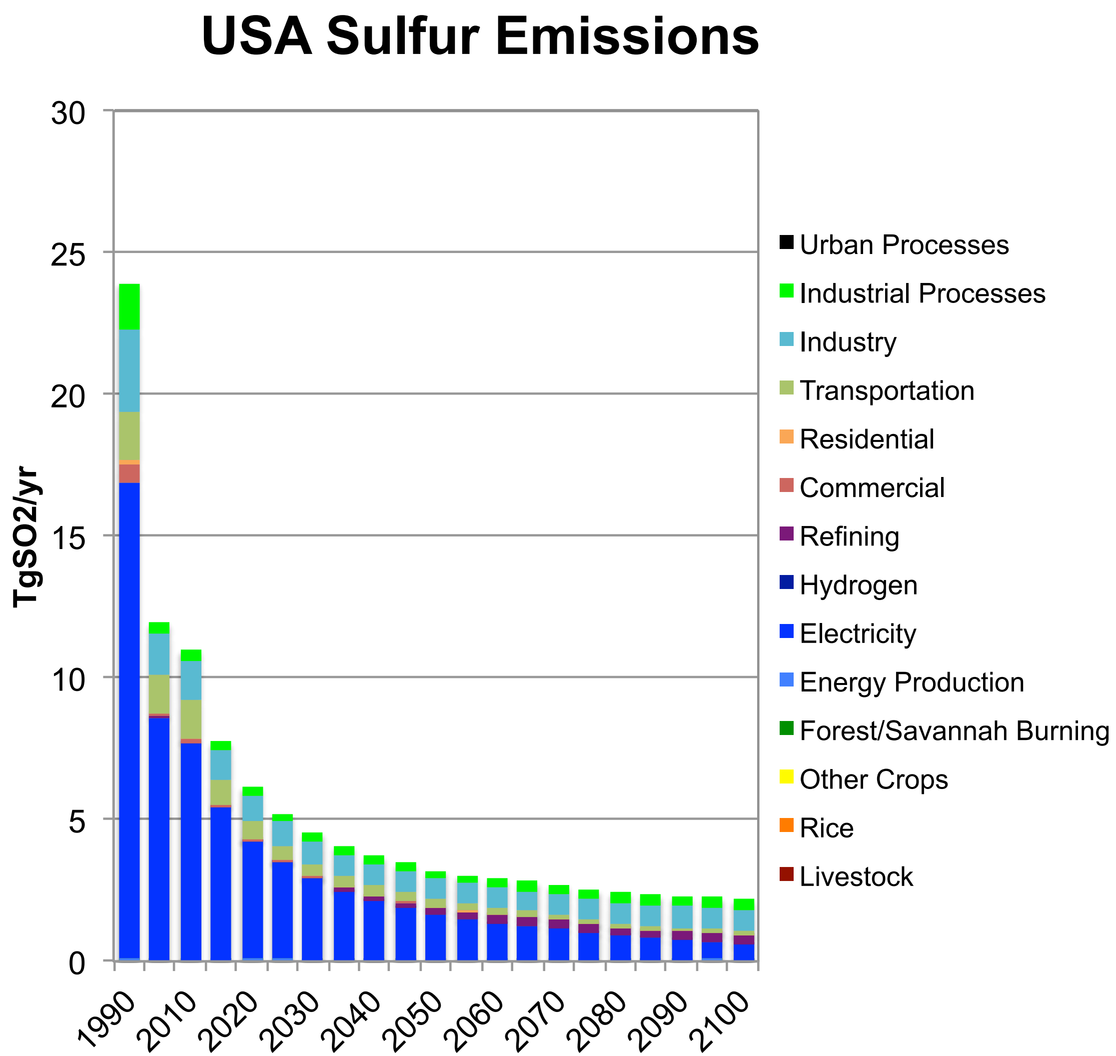

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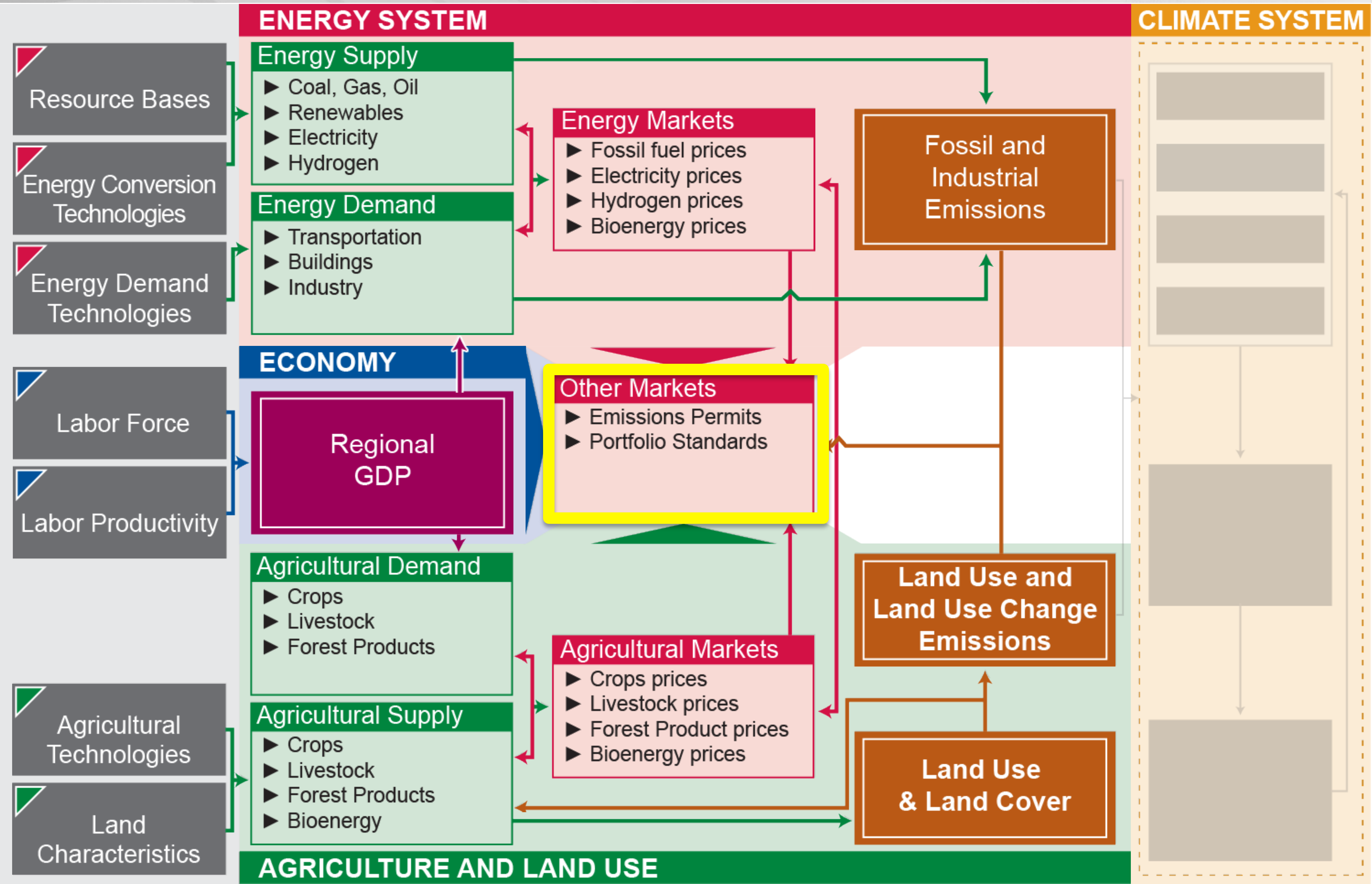


Other Markets: Climate Policy

- Carbon or GHG prices:
  - Users can specify the price of carbon or GHGs directly
  - Emissions will vary depending on other scenario drivers
- Emissions constraints:
  - Users can specify the total amount of emissions (CO_2 or GHG)
  - Model will calculate the price of carbon needed to reach the constraint
- Climate constraints:
  - Users can specify a climate variable (e.g., concentration or radiative forcing) target for a particular year
  - Users determine whether that target can be exceeded prior to the target year
  - Model will adjust carbon prices in order to find the least cost path to reaching the target
  - (This type of policy increases model run time significantly)

Other Markets: Energy Policy

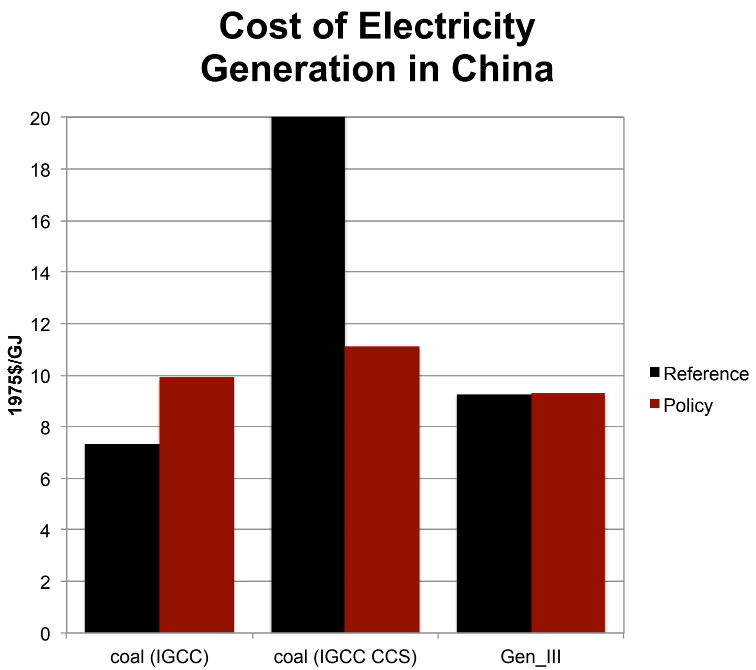
- We can impose constraints (lower & upper bounds) on energy consumption.
  - The model will solve for the tax (upper bound) or subsidy (lower bound) required to reach the given constraint.
  - Within an individual sector, these constraints can be share constraints (e.g., fraction of electricity that comes from solar power).
    - This allows us to model renewable portfolio standards and biofuels standards.
  - Across sectors, these must be quantity constraints.

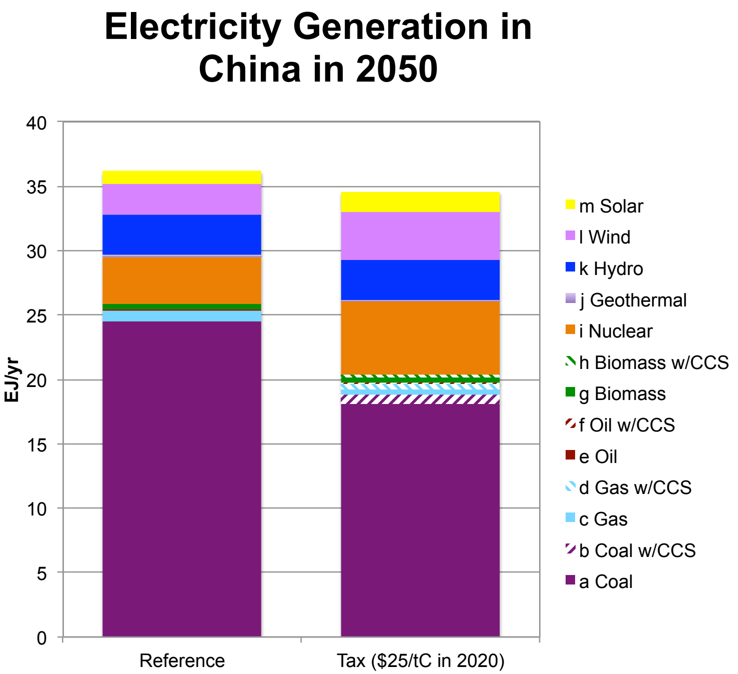
Other Markets: Land-Use Policy

- REDD:
  - In this policy, we set aside some land from economic competition. This land cannot be converted to crops, pasture, or any other land type.
  - Currently, this is the core assumption in GCAM when running a carbon policy.
    - We have protected 90% of non-commercial ecosystems.
- Valuing carbon in land:
  - In this policy, we assume that land use change emissions are taxed at the same rate as fossil fuel and industrial emissions.
  - Land owners receive a subsidy proportional to their carbon content.
- Bioenergy constraints (upper or lower):
  - We can also constrain biomass to a particular level. This is implemented in GCAM as a tax or subsidy on bioenergy consumption. The tax/subsidy is adjusted until the constraint is met.
- Bioenergy taxes:
  - We can impose a tax on bioenergy that is linked to the carbon price.

Other Markets: The Effect of Climate Policy on the Energy System

- Imposing a climate policy affects the cost of energy production for carbon-intensive fuels. This induces a shift toward lower emitting technologies.





Other Markets: The Effect of Climate Policy on the Agriculture & Land-Use System

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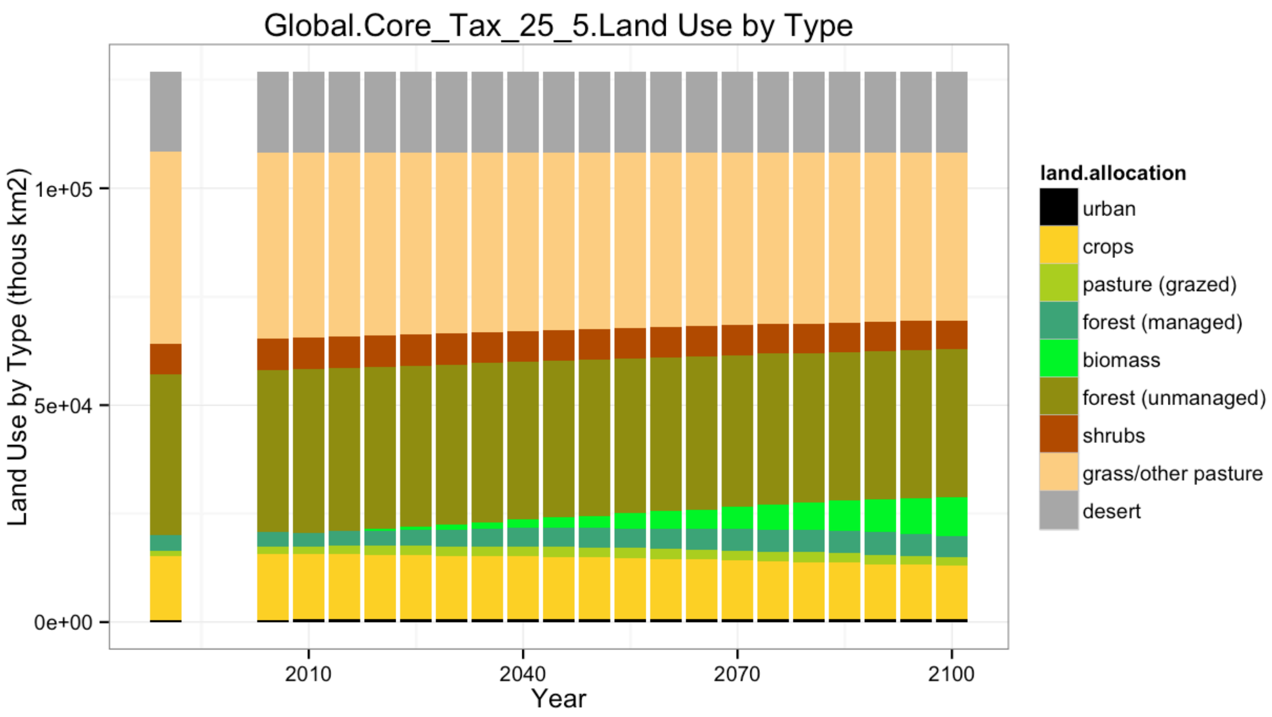
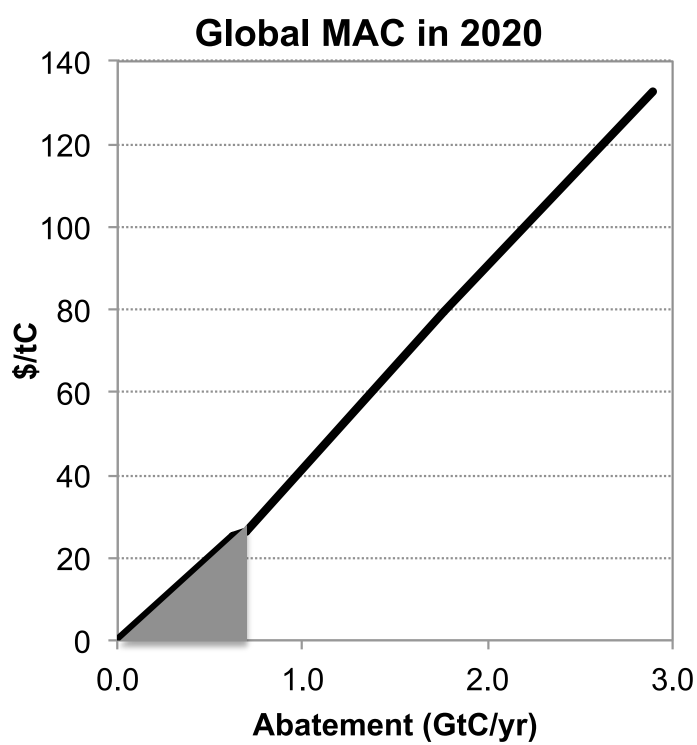
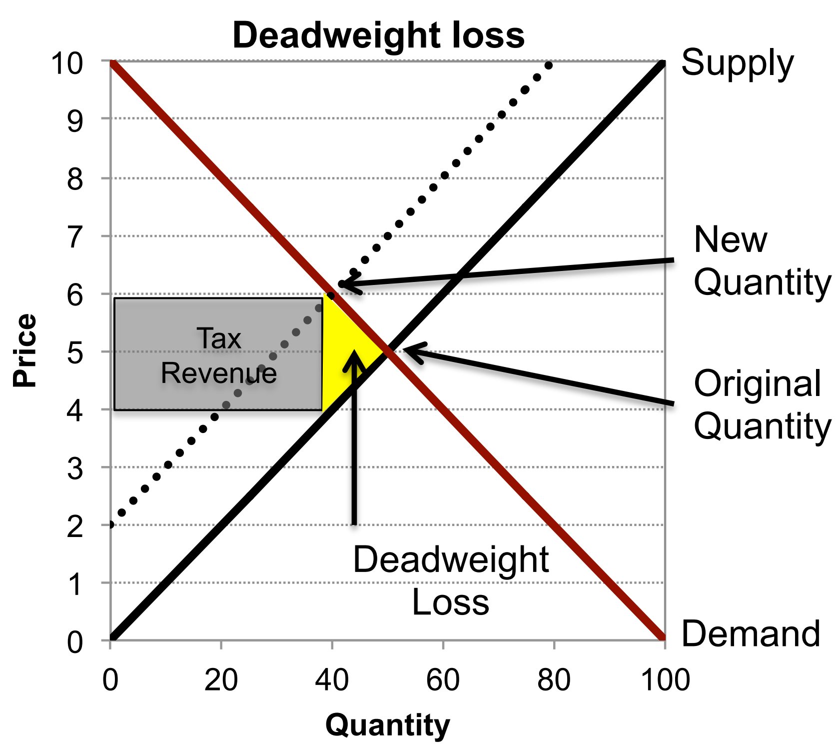
- Under the default assumption in GCAM, 90% of non-commercial ecosystems are protected in GCAM. This means that they cannot be used for crop or bioenergy production.



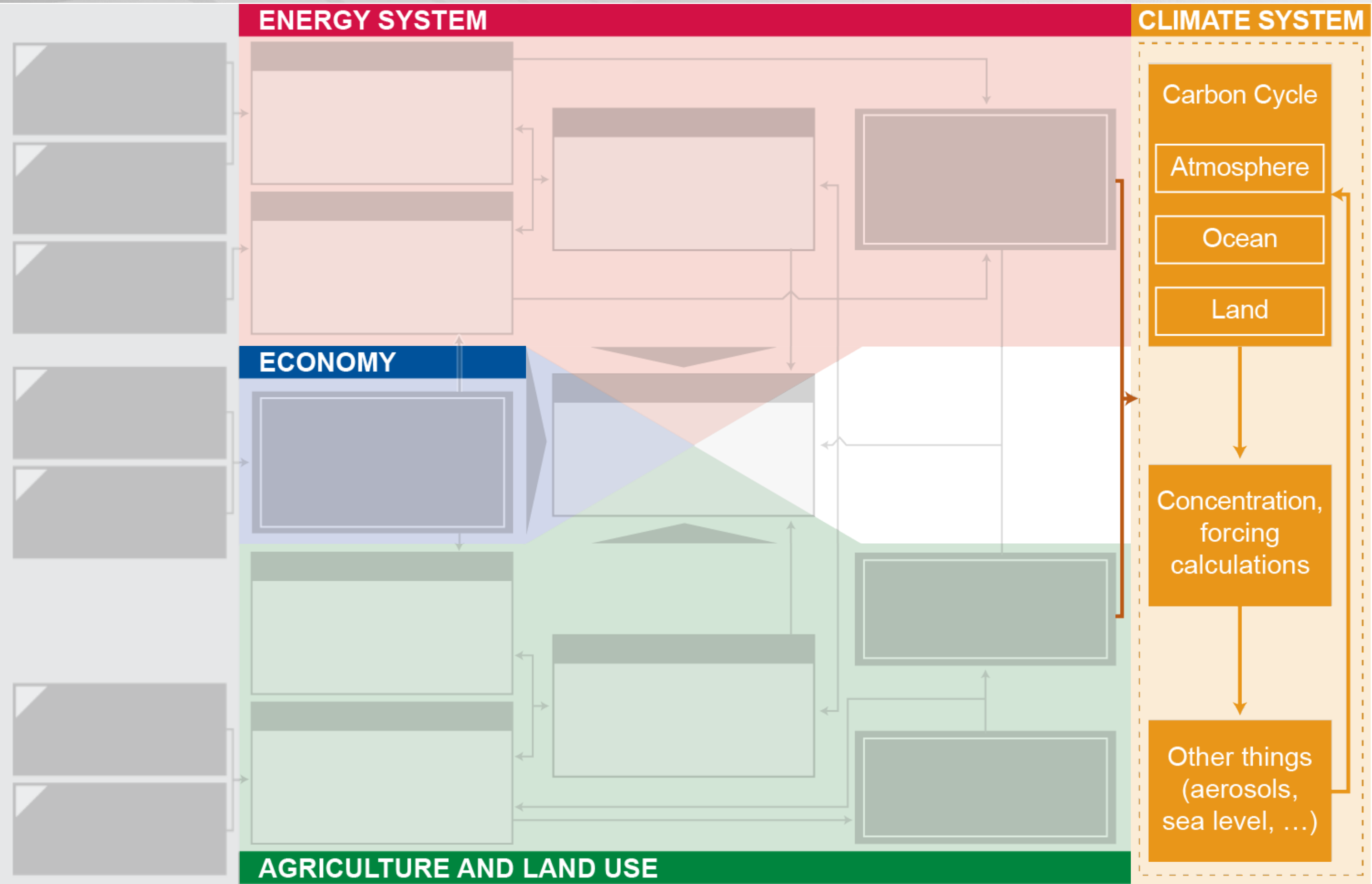
Other Markets: Climate Policy Cost

- GCAM can compute the cost of a climate policy endogenously.
- The cost metric used is the area under the marginal abatement cost (MAC) curve. This area under the MAC curve is deadweight loss (i.e., the loss in producer and consumer surplus.)
- Currently, we are not modeling this cost as affecting GDP in GCAM.





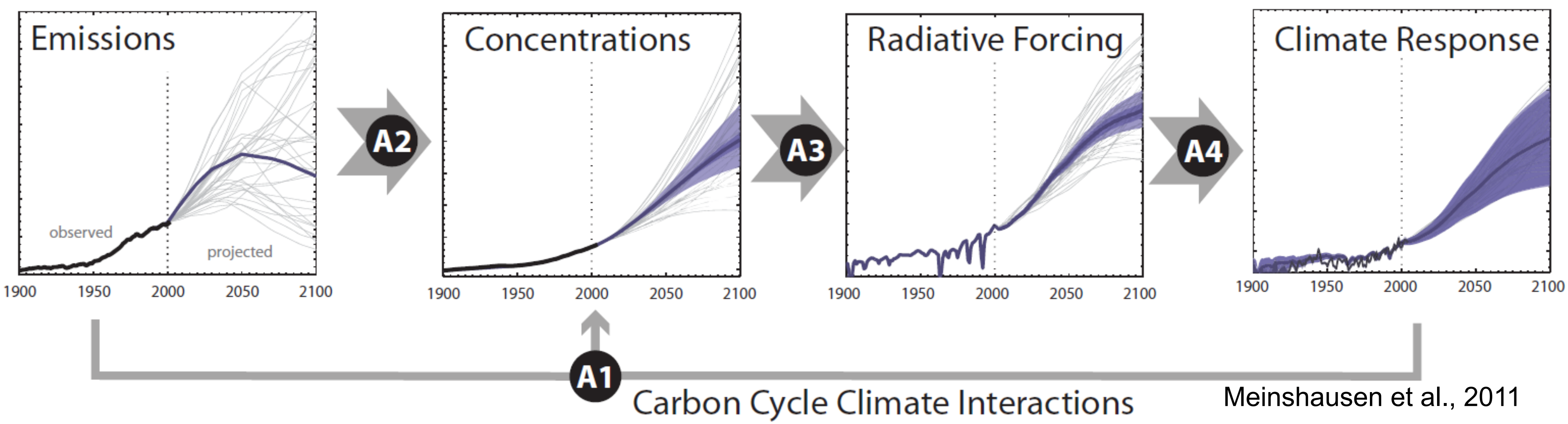
The Global Change Assessment Model



The Climate System: Approach

<u>Ongoing developments:</u>
Continual development of Hector

- GCAM has the option to use MAGICC 5.3 or ***Hector v1.1.2*** to compute climate related outputs – simply
- Inputs:
  - GCAM passes emissions into MAGICC or Hector.
  - MAGICC: Fossil fuel & Industrial CO_2, Land-Use Change CO_2, CH_4, N_2O, SF_6, C_2F_6, CF_4, HFC125, HFC134a, HFC143a, HFC227ea, HFC245fa*, SO_2, CO, NO_x, NMVOCs, BC, OC
  - Hector: includes more HFCs
- Outputs:
  - MAGICC and Hector compute concentrations and radiative forcing
  - Computes atmospheric CO_2, temperature change, air-land/air-sea fluxes, SLR



Meinshausen et al., 2011

Why develop a new simple climate model?

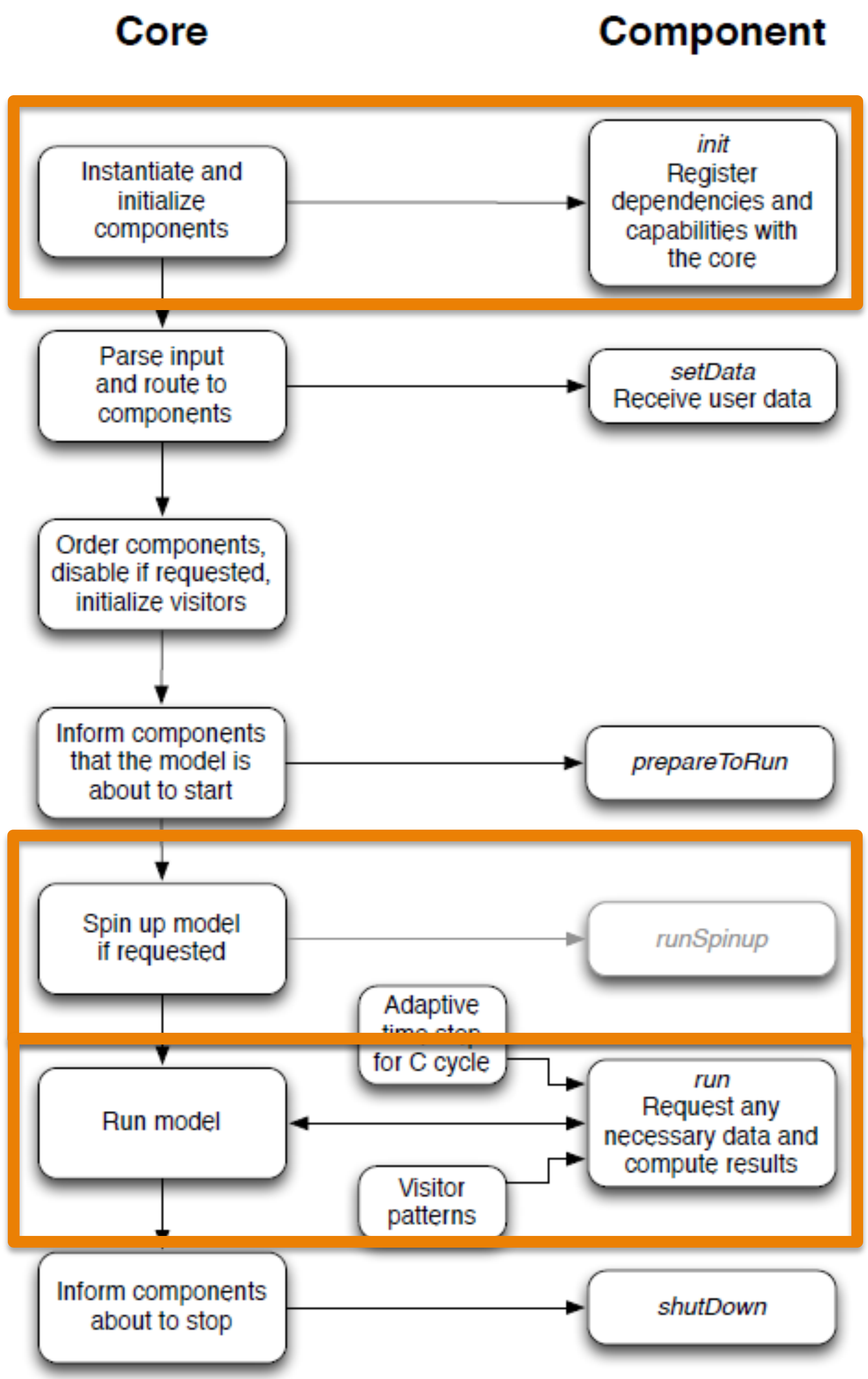
- MAGICC
  - Used across many scientific and policy communities – instrumental in the IPCC
  - Many strengths
  - Old code to work with
  - Not open source, legal issues unclear
- Developed Hector
  - Free and open-source – community model
    - www.Github.com/JGCRI/hector
  - Easy to use and well documented
    - Hartin et al., 2015 - GMD
    - Hartin et al., submitted - BGS
  - Modular

Hector philosophy and structure

- Complexity only where warranted
- Components can be enabled/disabled via inputs
  - E.g. you can test two different ocean submodels against each other
- Modern, clean structure
  - E.g. coupler enforces unit checking between submodels
- R backend for summarizing and analyzing results
  - Ships with MAGICC, CMIP5, and observational data for comparison

Hector: open and object – oriented architecture

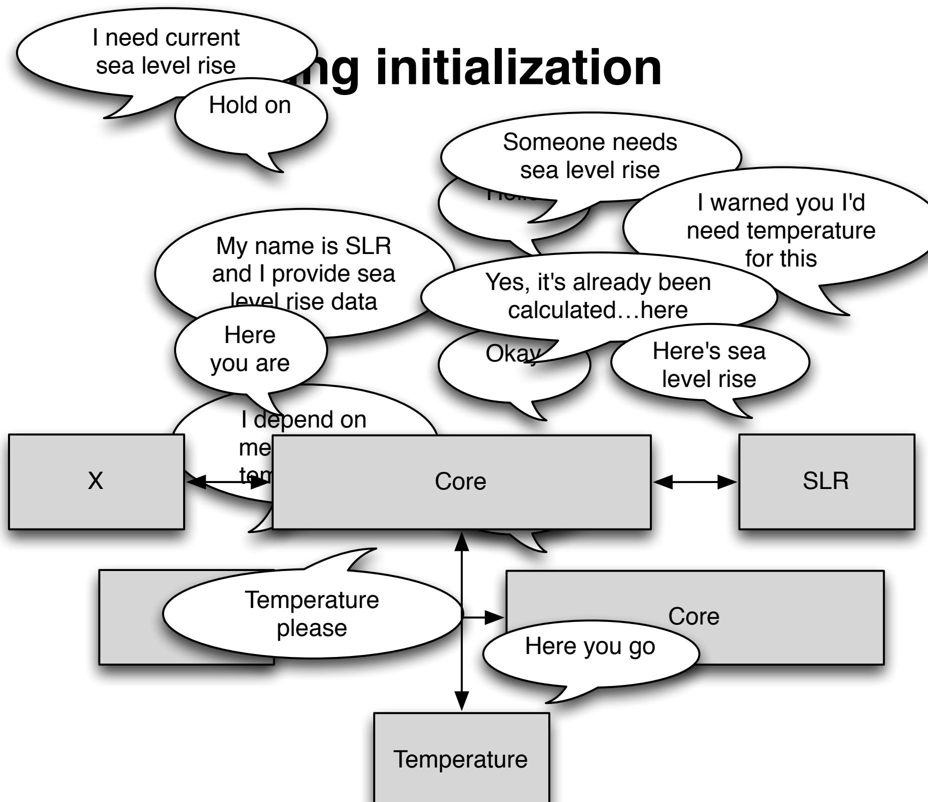
- Initialization
  - Input data are routed to model *components* via the model *core*
- Spin up
  - the carbon cycle is in equilibrium before the main run starts
- Main run



Hector: open and object – oriented architecture

- Components have a defined interface (API)
- They register their *dependencies* and *capabilities* with the core
  - e.g., sea level rise depends on temperature
- Core orders components by their dependencies
- Components query the core for data
  - Core routes request to appropriate component

As the model runs

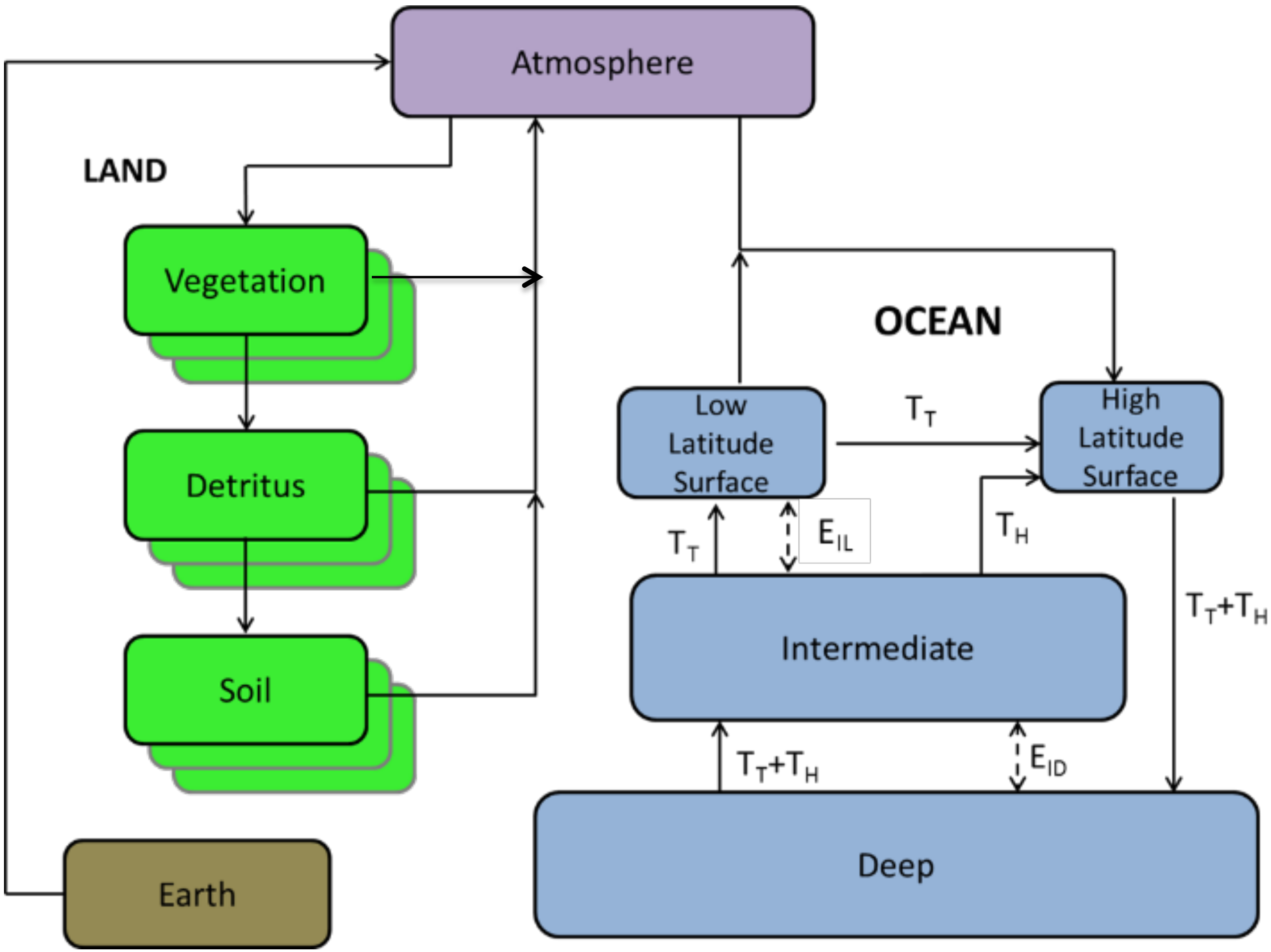


Sample Input File


```
; Config file for hector model: RCP4.5
[core]
run_name=rcp45
startDate=1745
endDate=2100
do_spinup=1             ; if 1, spin up model before running (default=1)
max_spinup=5000         ; maximum steps allowed for spinup
(default=2000)

[onelineocean]
enabled=0               ; putting 'enabled=0' will disable any component
ocean_c=38000, Pg C

[ocean]
enabled=1               ; putting 'enabled=0' will disable any component

spinup_chem=0           ; run surface chemistry during spinup phase?
tt  = 72000000           ; 7.2e7 thermohaline circulation, m3/s
tu  = 49000000          ; 4.9e7 high latitude overturning, m3/s
twi = 12500000           ; 1.25e7 warm-intermediate exchange, m3/s
tid = 200000000         ; 2.0e8 intermediate-deep exchange, m3/s

k = 0.2                 ; ocean heat uptake efficiency  (W/m2/K)

[simpleNbox]
; Initial (preindustrial) carbon pools
atmos_c=588.071                ; Pg C in CO2, from Murakami (2010)
veg_c=550                      ; Pg C
detritus_c=55                  ; Pg C
soil_c=1782                    ; Pg C
```

Initial values for the ocean and land components

Hector: Science

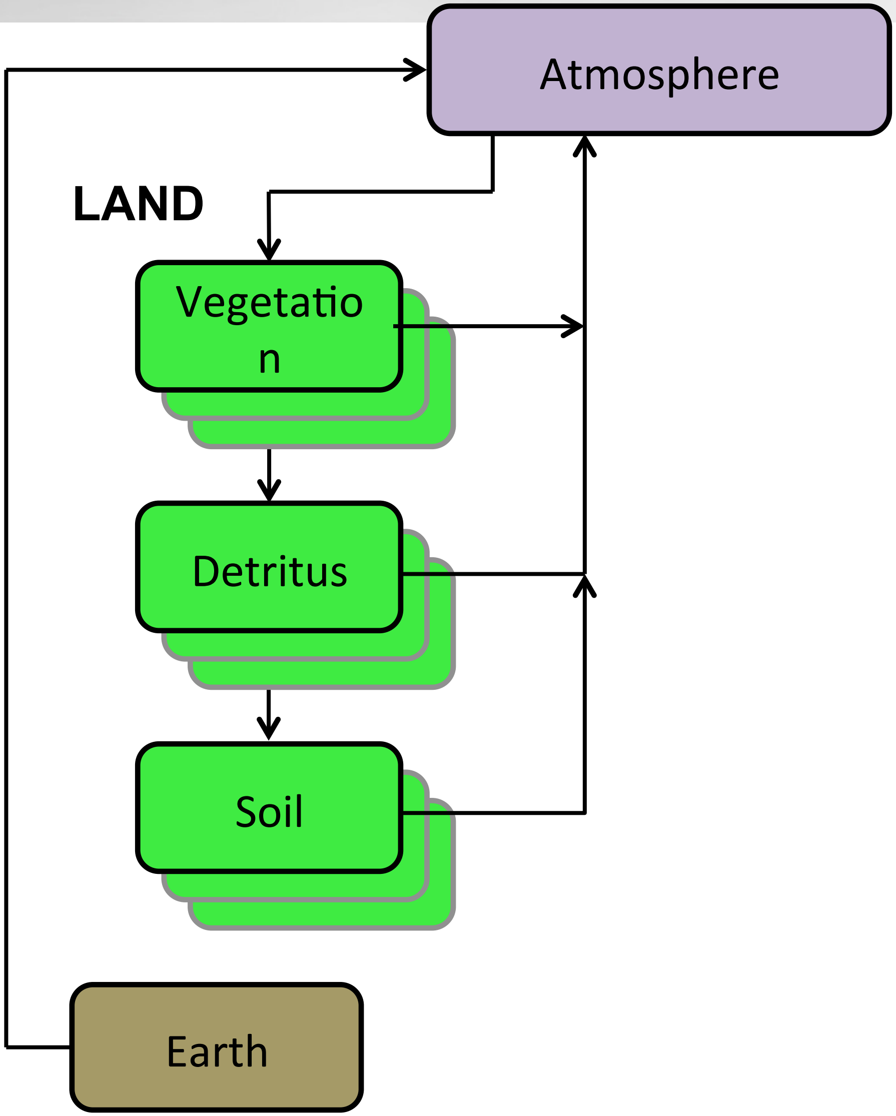


Hector: atmosphere

- Well mixed globally averaged atmosphere
- Forced with emissions from RCP scenarios
  - CO_2 – anthropogenic & LUC
  - BC/OC
  - CH_4/N_2O
  - 26 halocarbons
  - Sulphate aerosols
  - Volcanic emissions
- Calculate:
  - Stratospheric H_2O
  - Tropospheric O_3
- Radiative forcing
  - include both indirect and direct effects on radiative forcing

Science: land

- A classic simple design: five boxes
- NPP, R_H, litter fluxes scaled by global temperature and CO_2
- Optional biomes – ex. Boreal and tropical
- Continual mass balance to check for 'leaks'



Science: ocean

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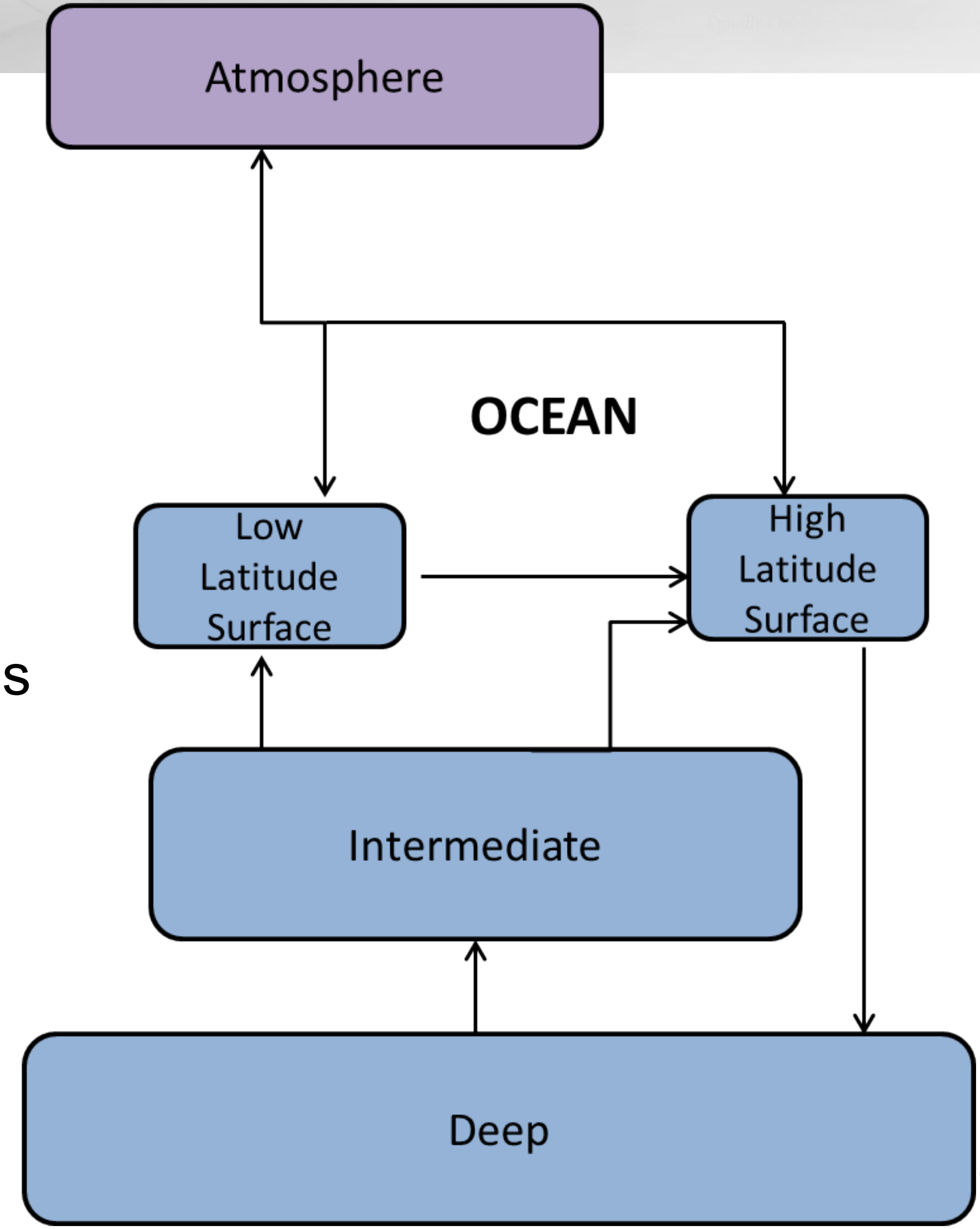
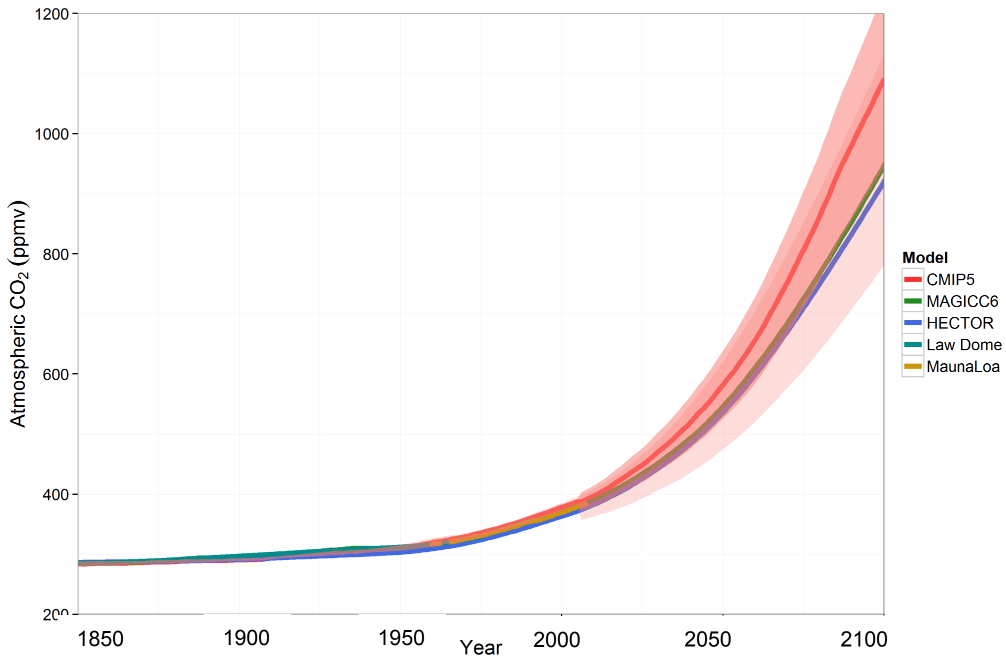
- 4 boxes
  - 2 surface boxes (100m)
  - Intermediate box
  - Deep box (~3777m)
- Advection and water mass exchange
- Heat uptake in surface boxes
- Carbon chemistry in surface boxes (e.g., atmosphere-ocean flux, pH, $CaCO_3$ saturations)

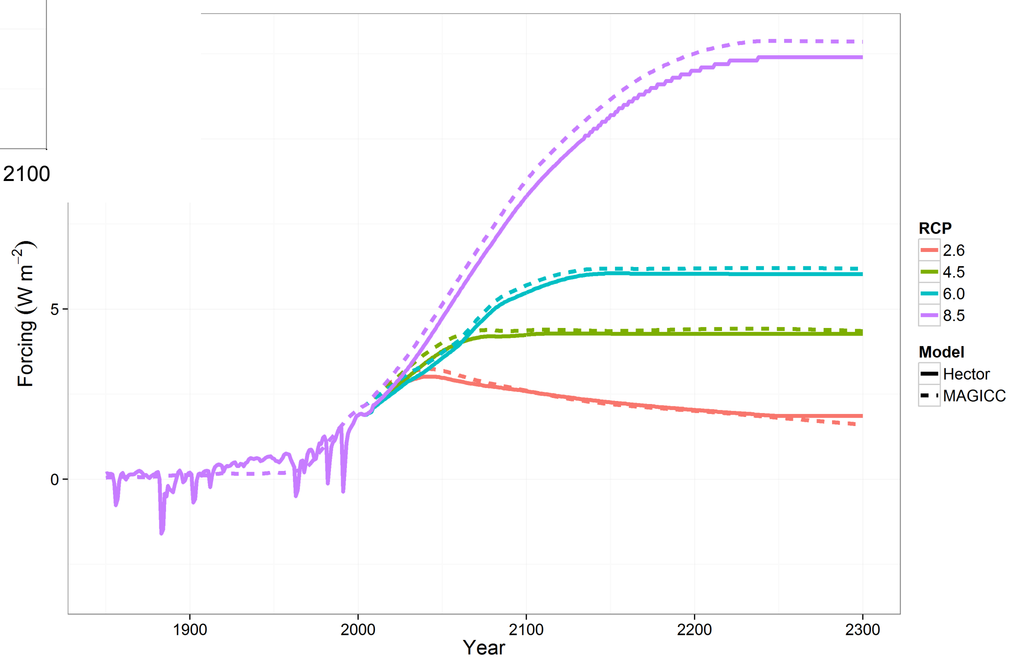


The Climate System: Results



Atmospheric CO_2

Radiative Forcing



Hartin et al., 2015 - GMD

The Climate System: Results

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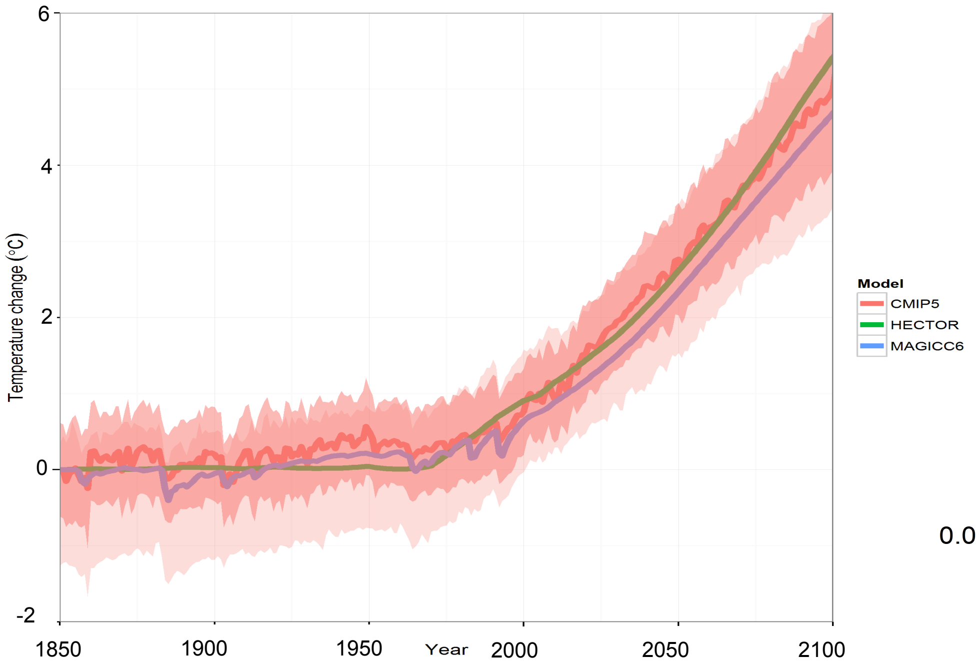
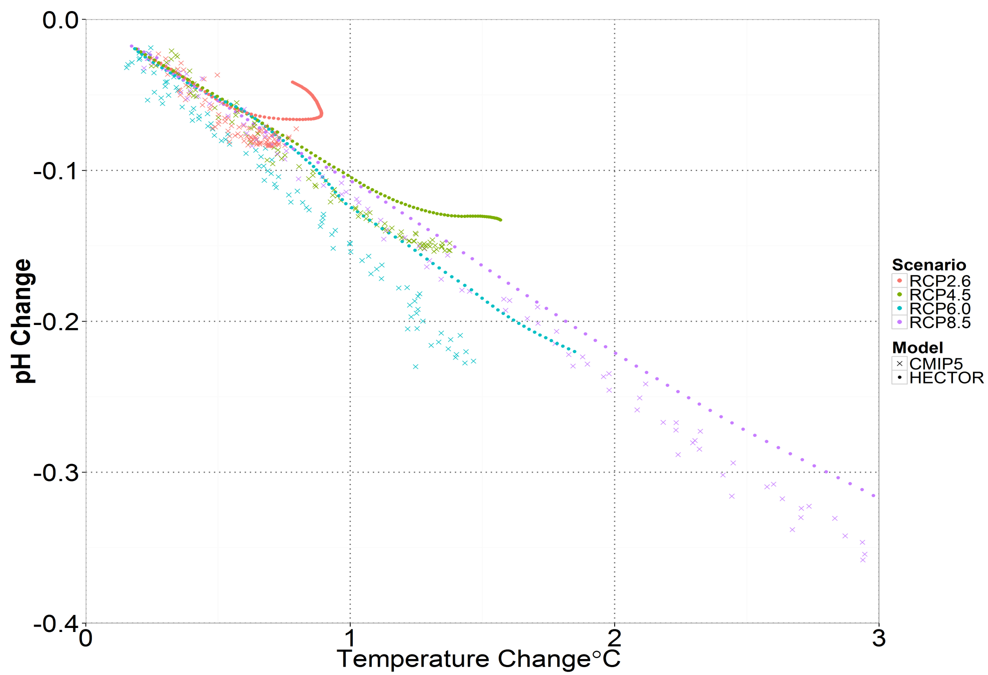
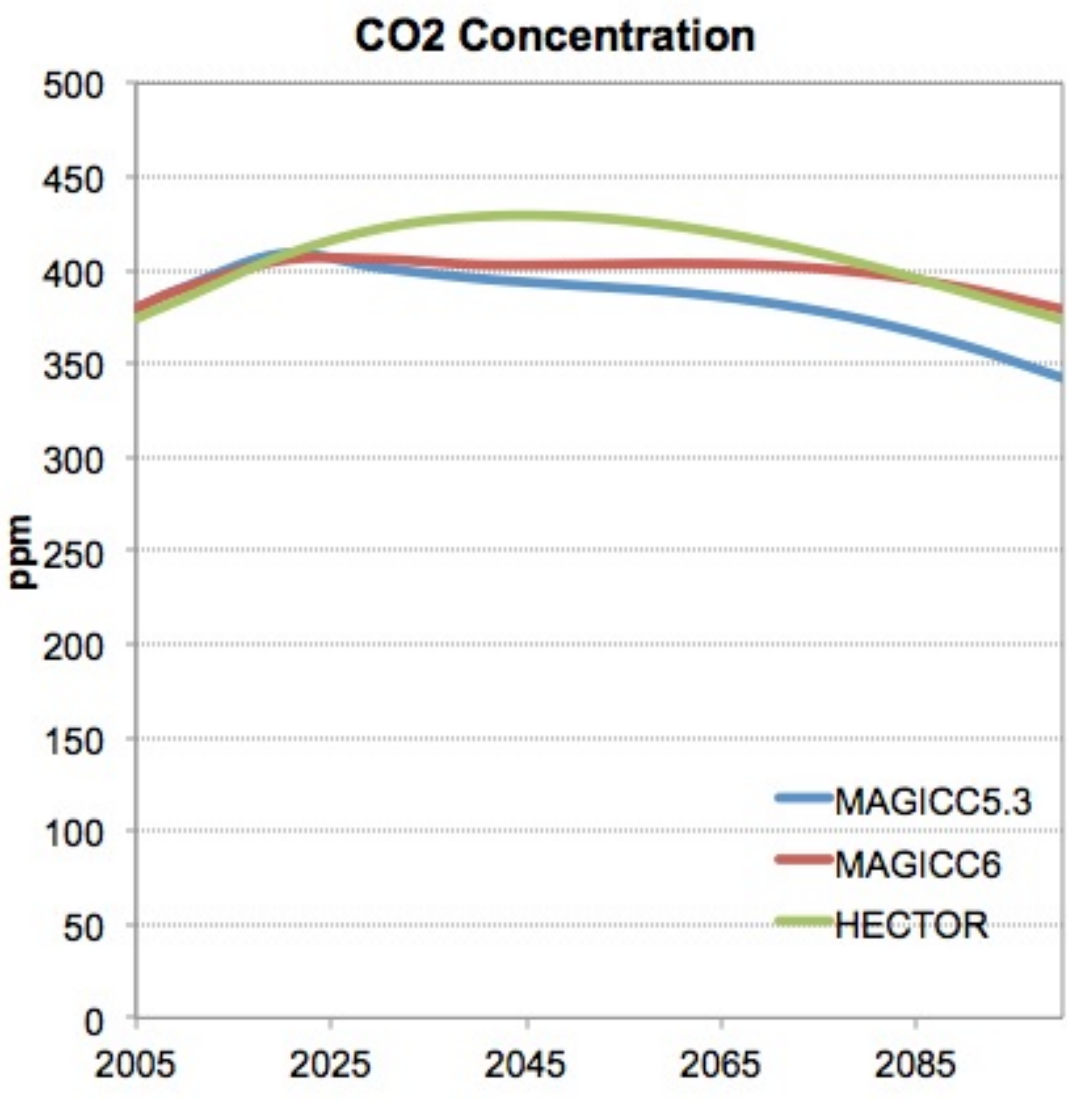


Atmospheric Temperature



GCAM integration of Hector



Atmospheric [CO_2] from 3 different emulators, Hector (green), MAGICC5.3 (blue), and MAGICC6 (red). The emission pathway is developed using the SSP4, attempting to limit radiative forcing to 2.6 W m^{-2} in 2100.

GCAM integration of Hector

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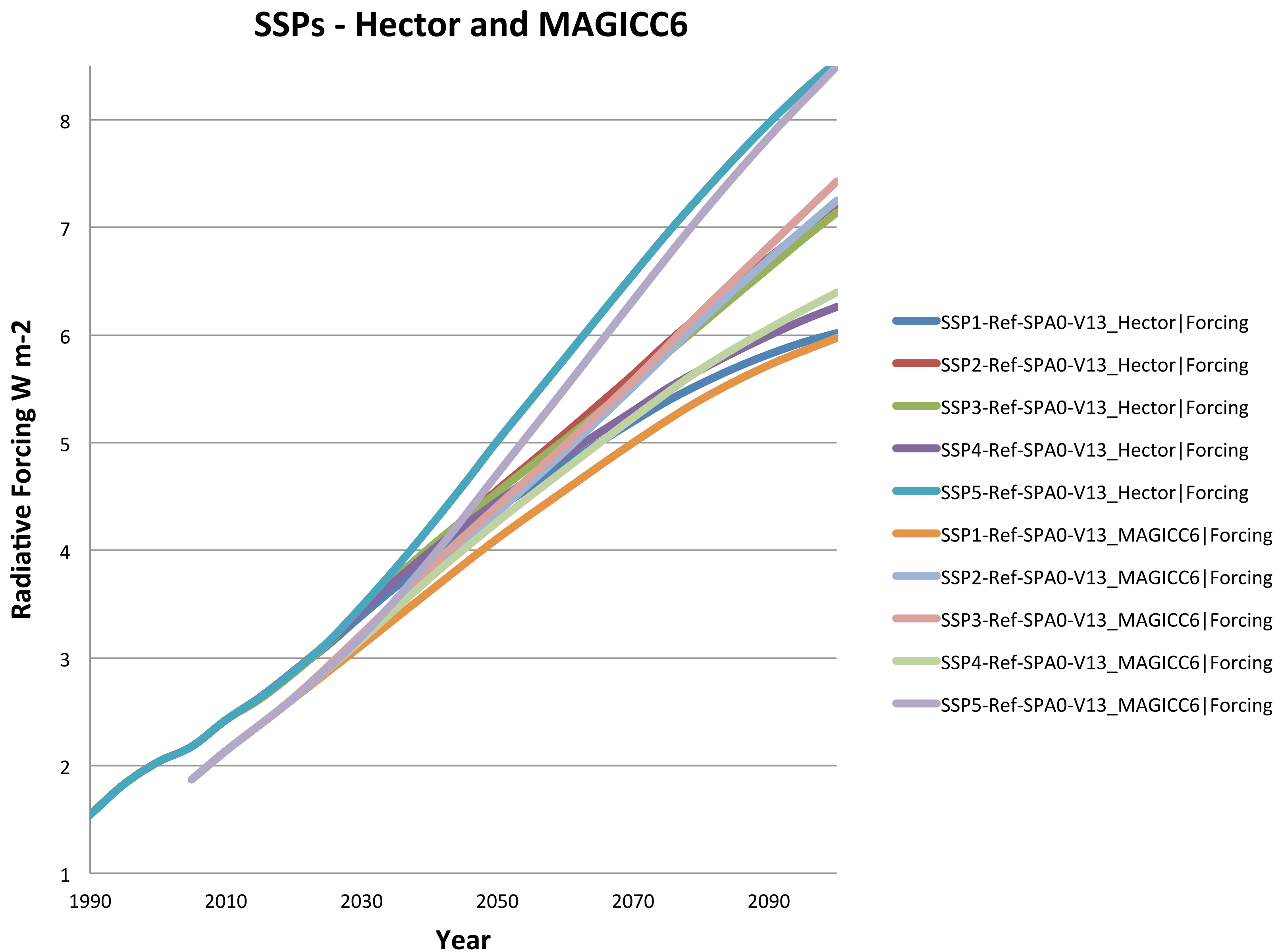

The Global Change Assessment Model

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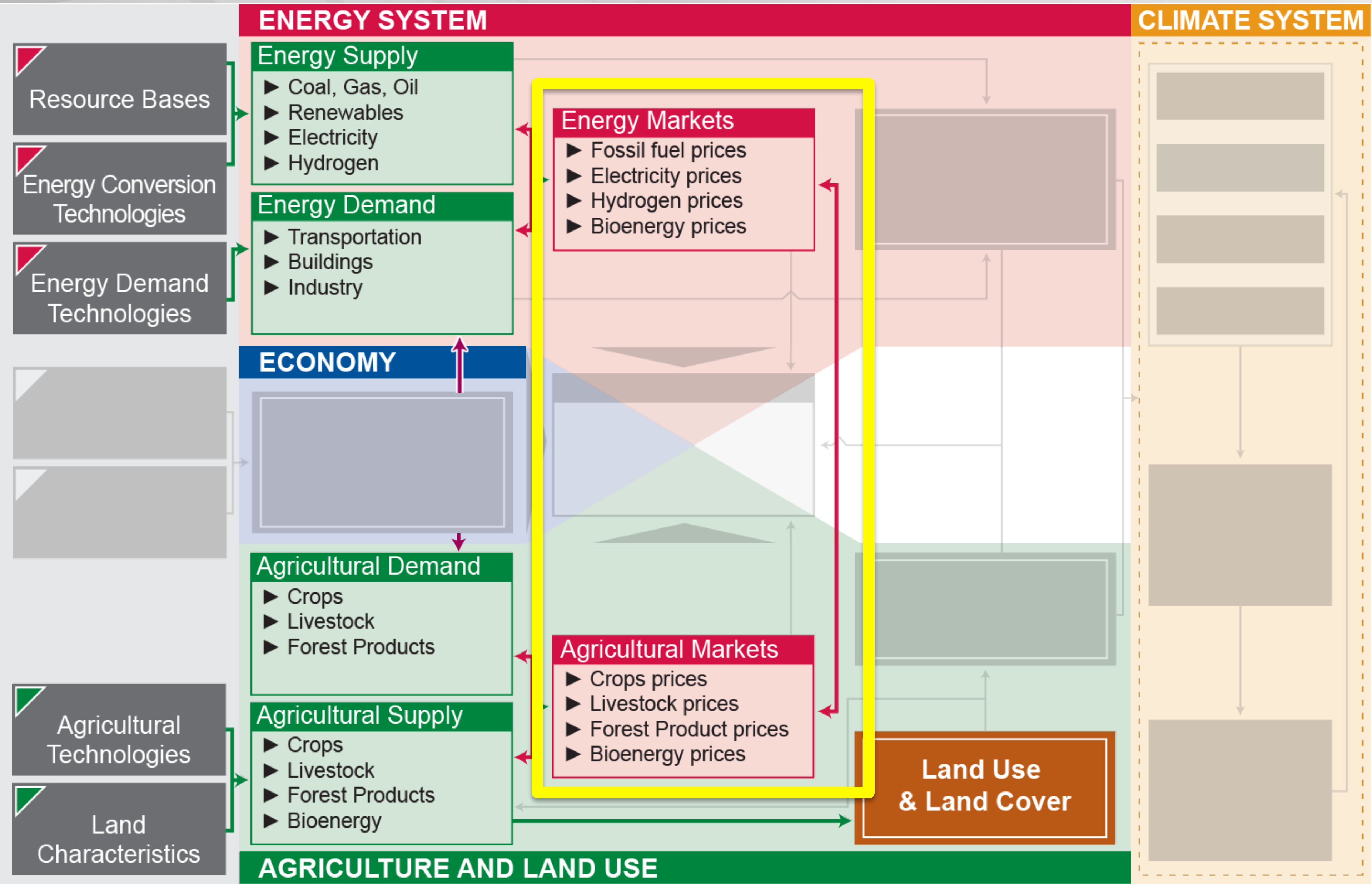
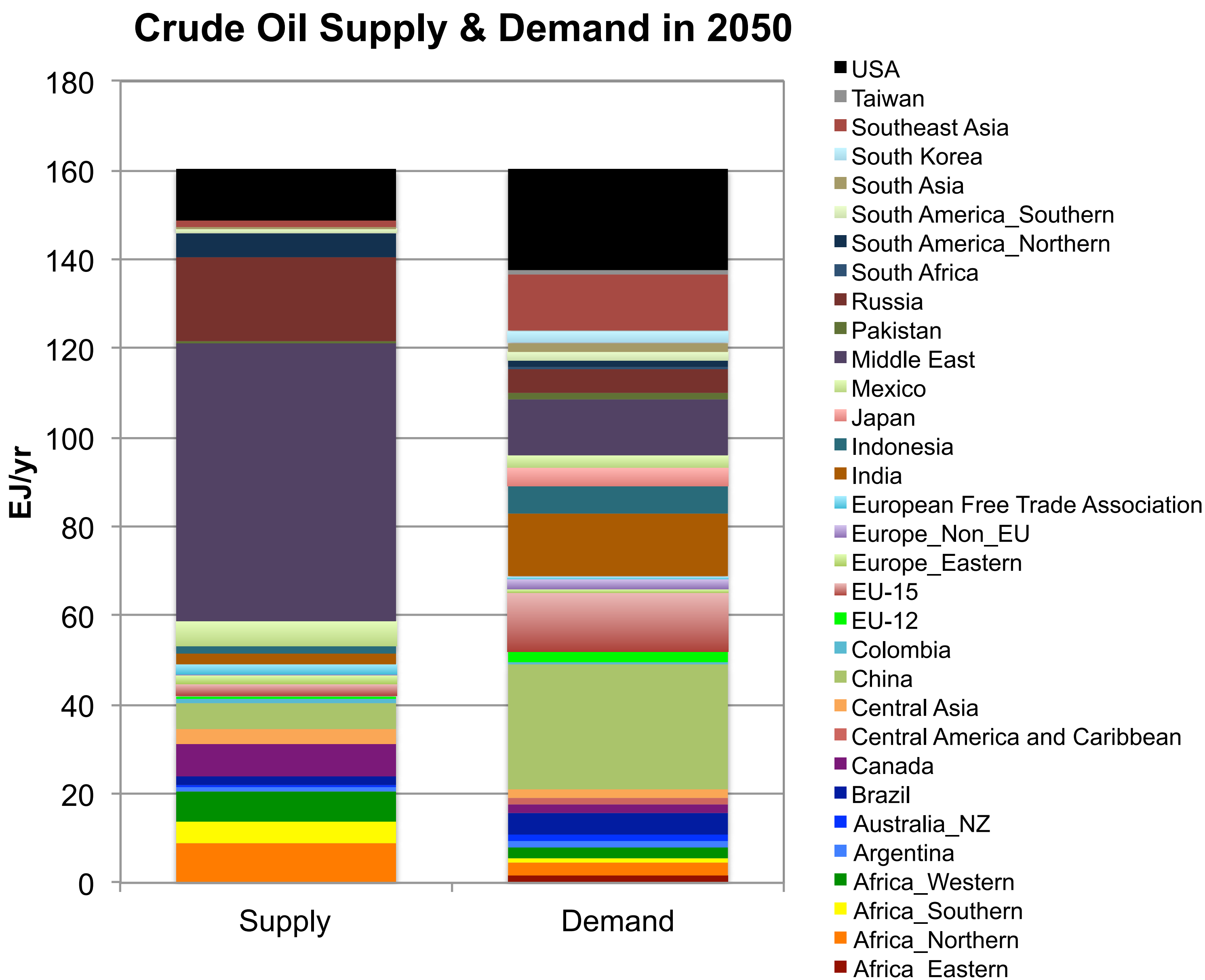


Trade: Assumptions

Ongoing developments:
Adjusting natural gas trade assumptions.

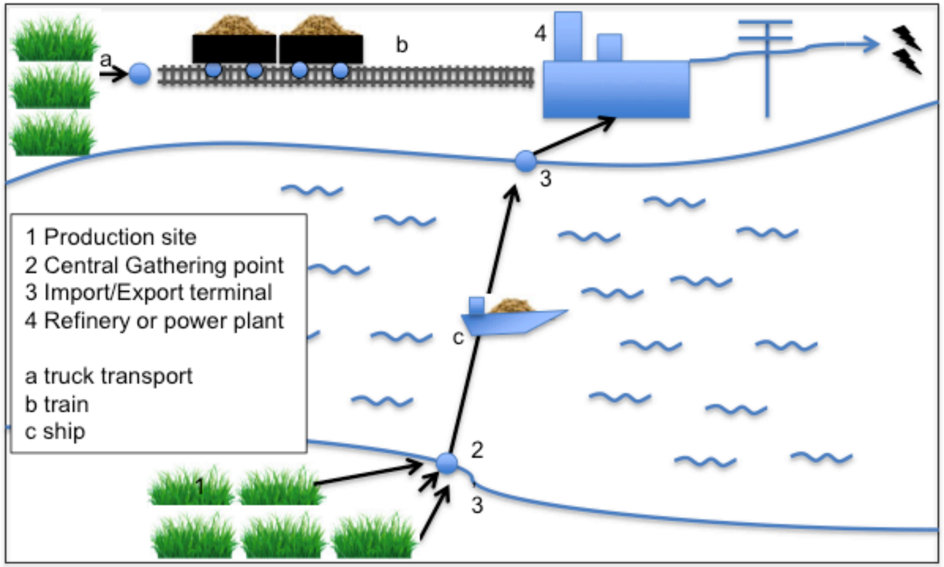
- We model Heckscher-Ohlin trade. We have not focused on bilateral trade.
- For many products, we assume that trade is free and global. These products include coal, gas, oil, bioenergy, food, and fiber.
  - However, we can have differences in regional prices by including an "adder" to account for transportation costs, etc.
- For other products, we assume that no interregional trade is allowed. These products include solar, wind, geothermal, meat, and dairy.
  - In this case, each region must produce enough to meet demand.
  - In some sectors (e.g., beef), we exogenously specify trade to match base year statistics. This trade is held constant over time.

Trade: Results



We model large scale bioenergy systems

- Collection and Processing
  - Pelletizing important to increase the energy density of the fuel and facilitate transportation
  - Average cost to transport to local collection facility and pelletize of **$2.18/GJ** (2005$)
    - 85% of cost is in pelletizing
    - compare to **$1.33/GJ** for Coal (Edwards).
  - International transport cost of **$0.31/GJ** (2005$) added to all regions (assumes large ocean bulk carriers)



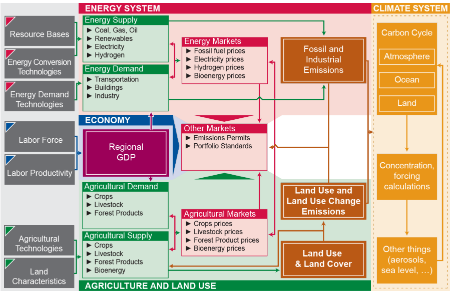
(Van Vliet, 2009, consistent with Wolf 2006)

The Solution Process: Algorithm

Step 1: Choose a vector of prices.

We use a combination of bracketing/bisection and Broyden's method to update prices.

Step 2: Run GCAM.



Step 3: Test whether supply = demand for all markets.

If no

2 + 2 = 5?

If yes

We're done!

The Solution Process: Results

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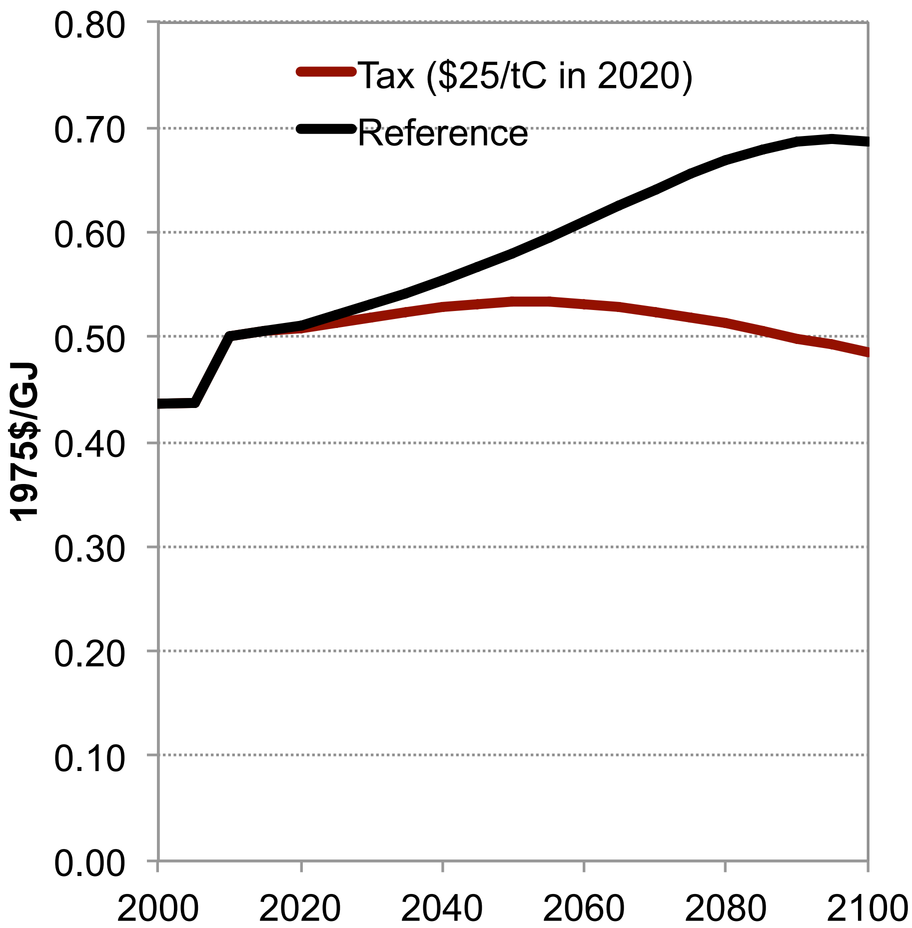
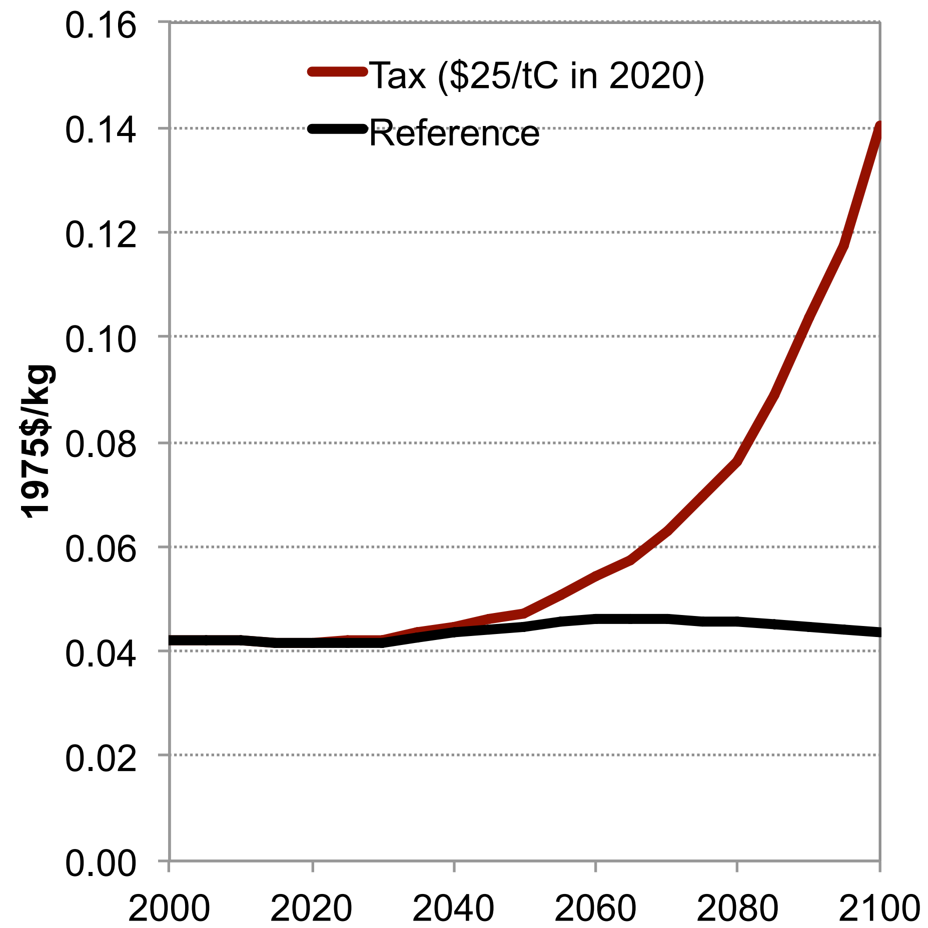
Coal Price



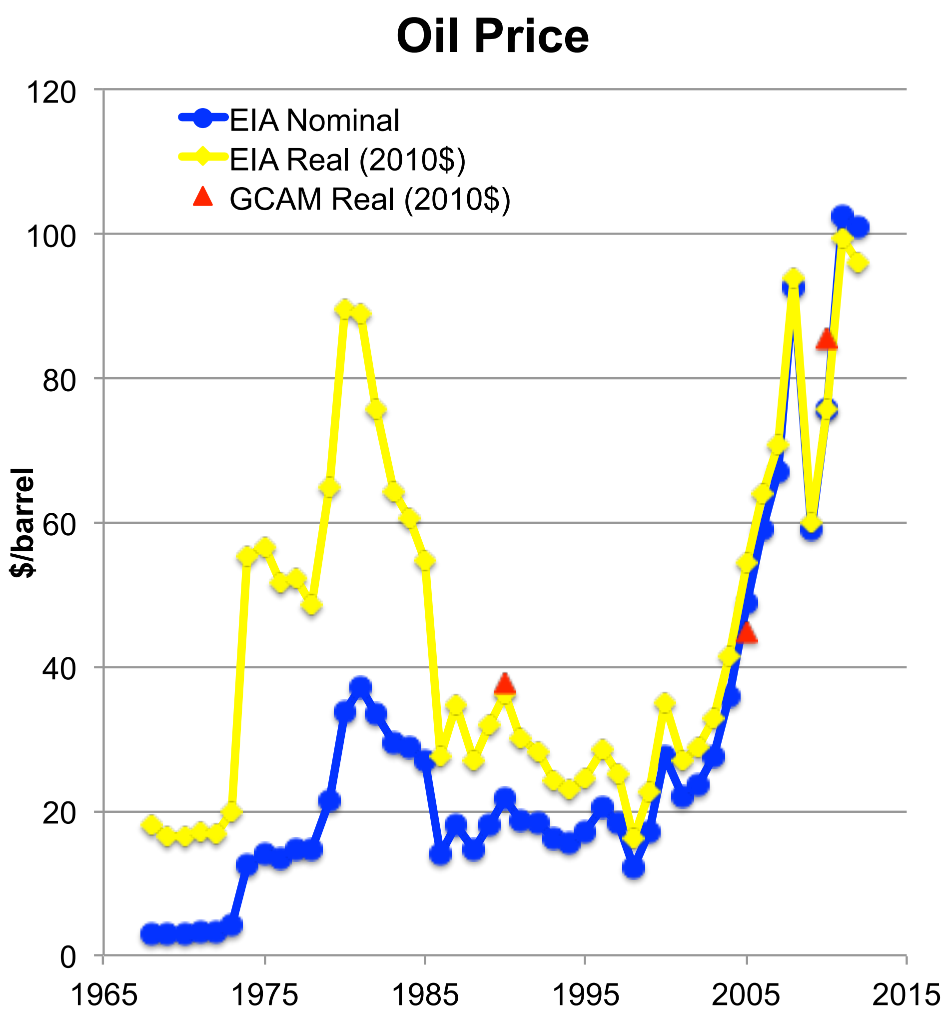
Wheat Price



FREQUENTLY ASKED QUESTIONS

Frequently Asked Questions

- Common question:
  - Why are some of the energy prices in GCAM lower than recent history or other projections?
- Answer:
  - We are a long-term equilibrium model. We do not attempt to capture short-term market fluctuations or market behavior.
  - In the case of oil, we do not sustain higher oil prices because the cost of substitutes (e.g., CTL, GTL) is lower than the current market price.

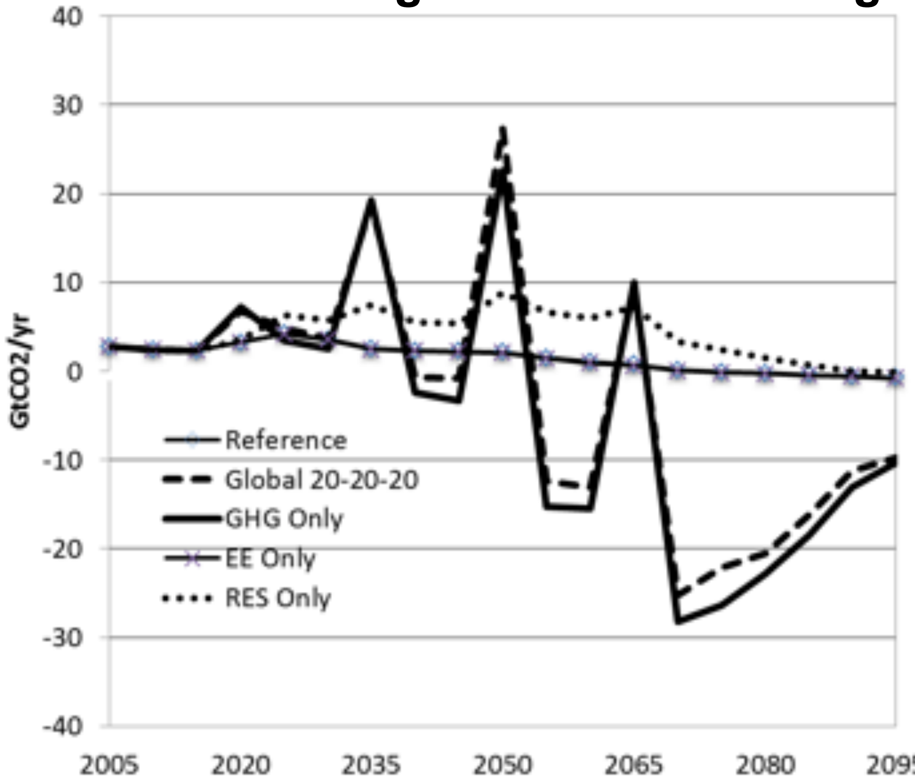


Frequently Asked Questions

- Common question:
  - Does GCAM include foresight?

- Answer:
  - For long-term investment decisions, we assume that decision-makers think about the future. That is, they may consider the costs and profits over the full lifetime of an electricity generation unit before building.
  - However, we are myopic in that we uses current prices when making these decisions.
  - Decision-makers do not know future prices!

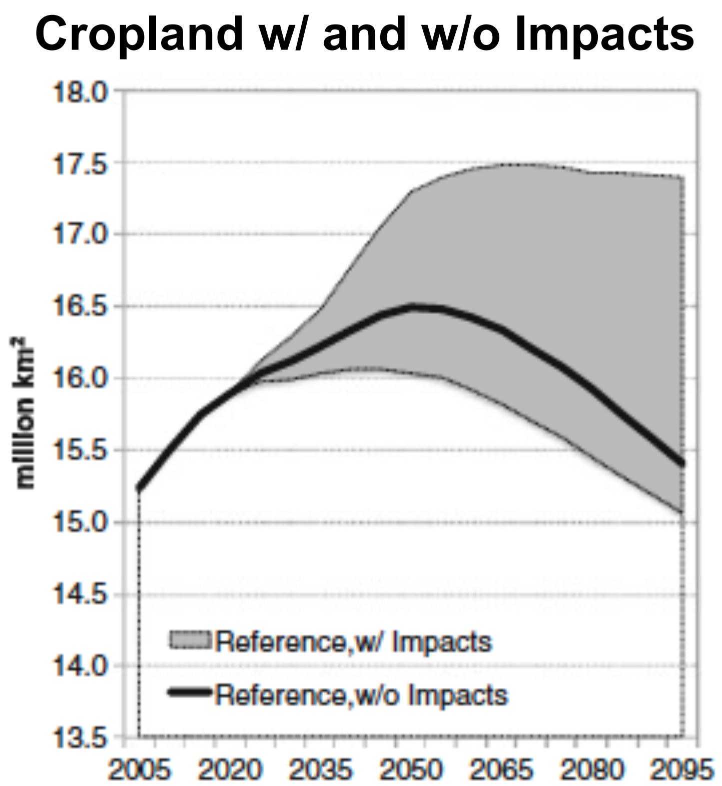
Land Use Change Emissions Leakage



Source: Calvin et al. (2014). The EU20-20-20 Energy Policy as a Model for Global Climate Mitigation. *Climate Policy.*

Frequently Asked Questions

- Common question:
  - Does GCAM include climate change impacts?
- Answer:
  - We do have several studies including impacts. In most cases the model is equipped to estimate the effect of climate change impacts easily (e.g., building energy demand, agricultural yields). All that is needed is an input data set.
  - No, at least not in the core model.



Source: Calvin et al. (2013). Implications of simultaneously mitigating and adapting to climate change: initial results using GCAM. *Climatic Change 117 (3).*

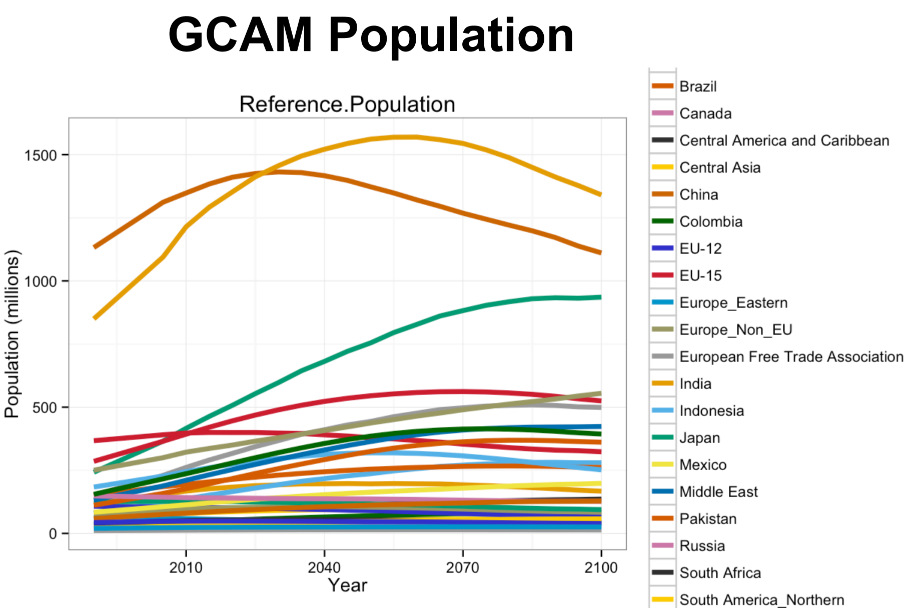
Frequently Asked Questions

- Common question:
  - Does the GCAM reference scenario include other climate and energy policies?
- Answer:
  - To the extent that these exist in the base year, they will be calibrated into the GCAM reference scenario.
  - However, we do not explicitly include any climate or energy policies in the core reference scenario.

Frequently Asked Questions

- Common question:
  - Where do your population estimates come from?

- Answer:
  - We use an older version of UN's medium population through 2050, then IIASA technogarden post-2050. We update the USA population to be consistent with Census projections.
  - Population in the core is similar to the UN medium or SSP2 population estimates.



Frequently Asked Questions

- Common question:
  - Does GCAM include shale gas?

- Answer:
  - Yes, GCAM includes conventional and unconventional resources of natural gas.
  - However, these are currently aggregated into a single resource supply curve, so you cannot determine how much shale gas is produced in a given scenario.
  - We are working on separating shale gas from other types of gas.

Frequently Asked Questions

- Common question:
  - Does GCAM optimize?
- Answer:
  - Not exactly.
  - GCAM is a market equilibrium model, so it adjusts prices until supplies and demands are equal.
  - However, GCAM assumes that producers maximize profit and consumers minimize cost.
  - And, under certain conditions, welfare economics tells us that market equilibria are (Pareto) optimal.
  - Also, as previously stated, we are not intertemporally optimizing.

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QUESTIONS?