Overview of GCAM
(Global Change Assessment Model)

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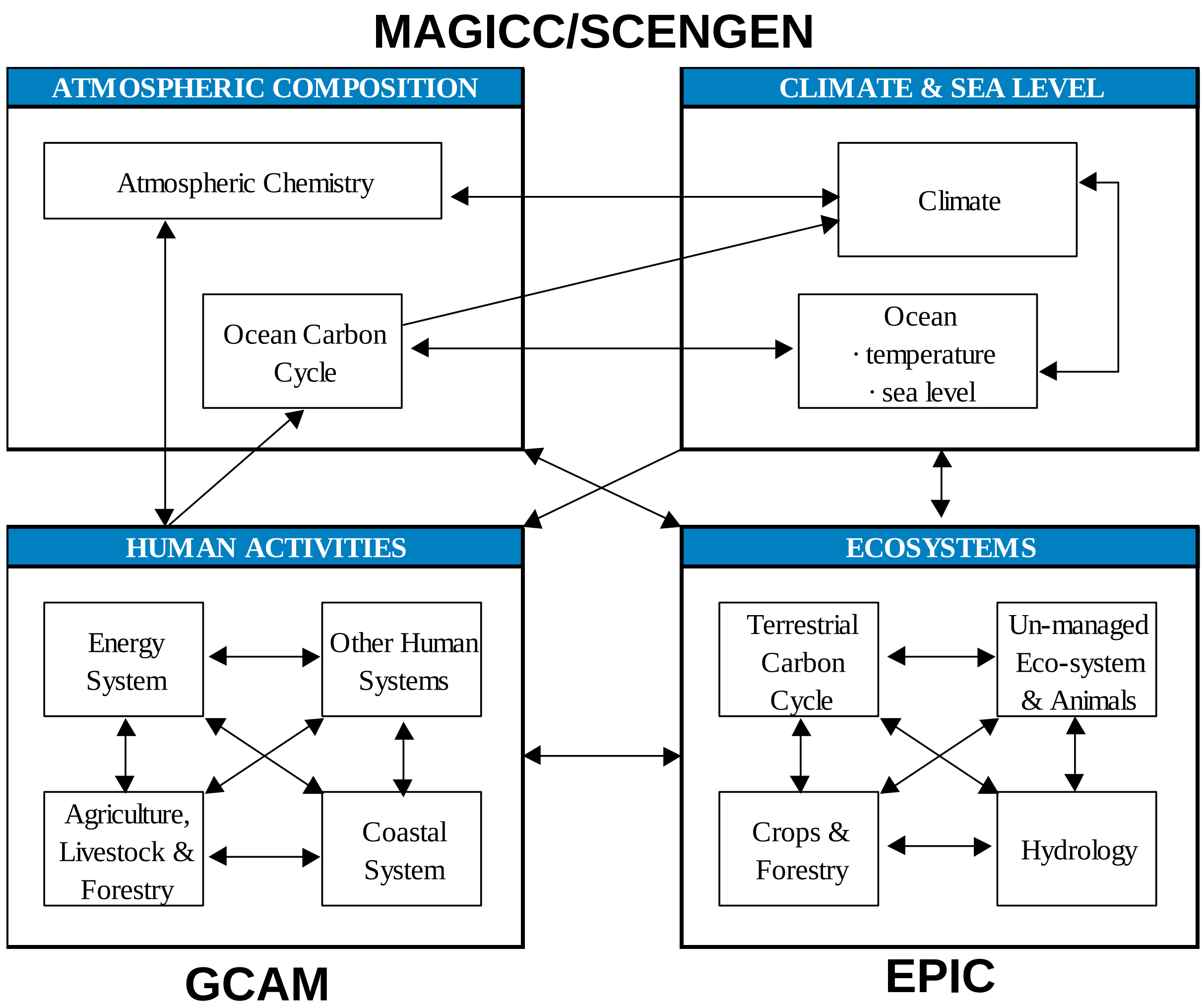
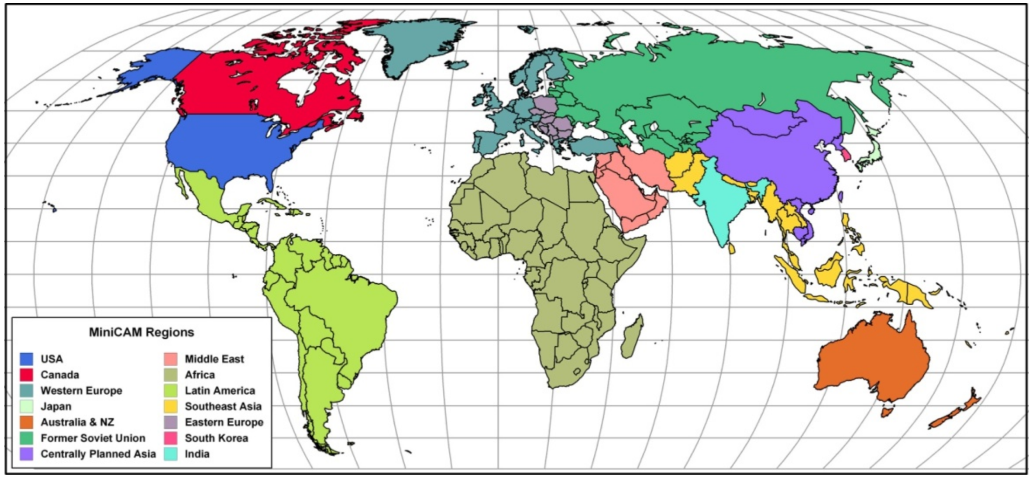
The Integrated Assessment Framework



Top-Level Design Characteristics of GCAM



- Builds on the energy/economy model of Edmonds and Reilly completed three decades ago.
- Combines economics-based energy, agricultural models with an Integrated Climate Assessment Model (MAGICC).
- Dynamic-recursive model.
- Partial equilibrium model (equilibrium in supplies and demands).
- Technologically detailed integrated assessment model.
- 14 geopolitical regions
- Emissions of 16 greenhouse gases and short-lived species: CO_2, CH_4, N_2O, halocarbons, carbonacious aerosols, reactive gases, sulfur dioxide.
- Runs from 1990 to 2095 in 15-year time steps (moving to variable time steps).

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The GCAM Model

- Origins in the DOE/SC Carbon Dioxide Research Program – 1st model designed specifically to calculate emissions from human activities for scientific assessment.
  - Workhorse of the U.S. science program since 1978.
  - Workhorse of the IPCC (every emissions scenario used this model or its predecessor).
- Recent uses include
  - U.S. Climate Change Science Program scenarios
  - U.S. Climate Change Technology Program scenarios
  - Developed most recent “central” scenario (RCP 4.5, Representative Concentration Pathway stabilizing radiative forcing at 4.5 W/m^2.
  - Technology and policy analyses for US DOE, EPA and others.

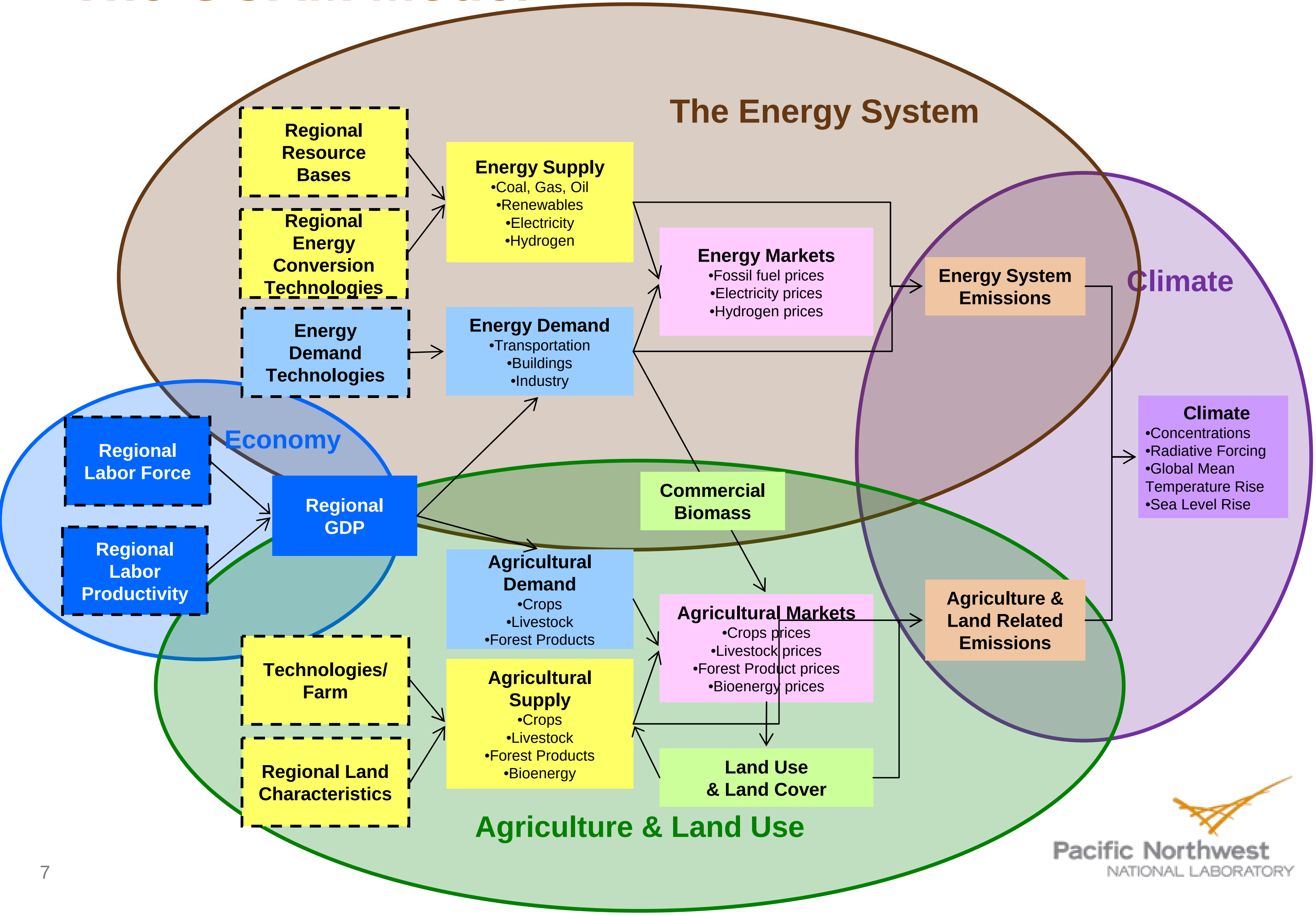
Integrated Assessment Models

- Integrated Assessment (IA) Models
  - Combine information from numerous disciplines into one framework.
  - For climate problem, must be both global and long-term in scope.
  - Model development strategy considers tradeoffs between completeness and complexity, depending on goals.
- IA Models Are Not “Truth Machines”
  - IA models are not predictive - but should be used as research and analysis tools to aid understanding of the complexities and interactions.
- IA Models Are Tools, useful to examine questions such as
  - possible futures with different assumptions for energy technologies, economic growth rates, etc. (thereby producing emission scenarios).
  - what are the important linkages: complementary, substitutes, feedbacks?
  - where are the lever points: technologies, resources, etc.?

GCAM Model Overview: Inputs and Outputs

- **Key inputs**
  - ***Demographics:*** population and labor force by region
  - ***Economic:*** labor productivity, price and income elasticities.
  - ***Resources:*** Depletable resources by grade (e.g. fossil fuels and uranium); renewable resources by grade (e.g. wind, solar).
  - ***Technologies:*** Technology representations of production, transformation and use technologies.
- **Key outputs**
  - ***Economic:*** GDP, World energy and agriculture prices (oil, gas, coal, wheat, rice, etc.)
  - ***Energy:*** Production, transformation, end use, and trade.
  - ***Agriculture:*** Production, consumption, trade, and land use.
  - ***Emissions:*** CO_2 emissions by source, non-CO_2 emissions (CH_4, N_2O, etc.), short-lived species emissions (S, BC, OC, CO, NMVOC, etc.).
  - ***Climate:*** GHG concentrations, climate change, sea level.

The GCAM Model



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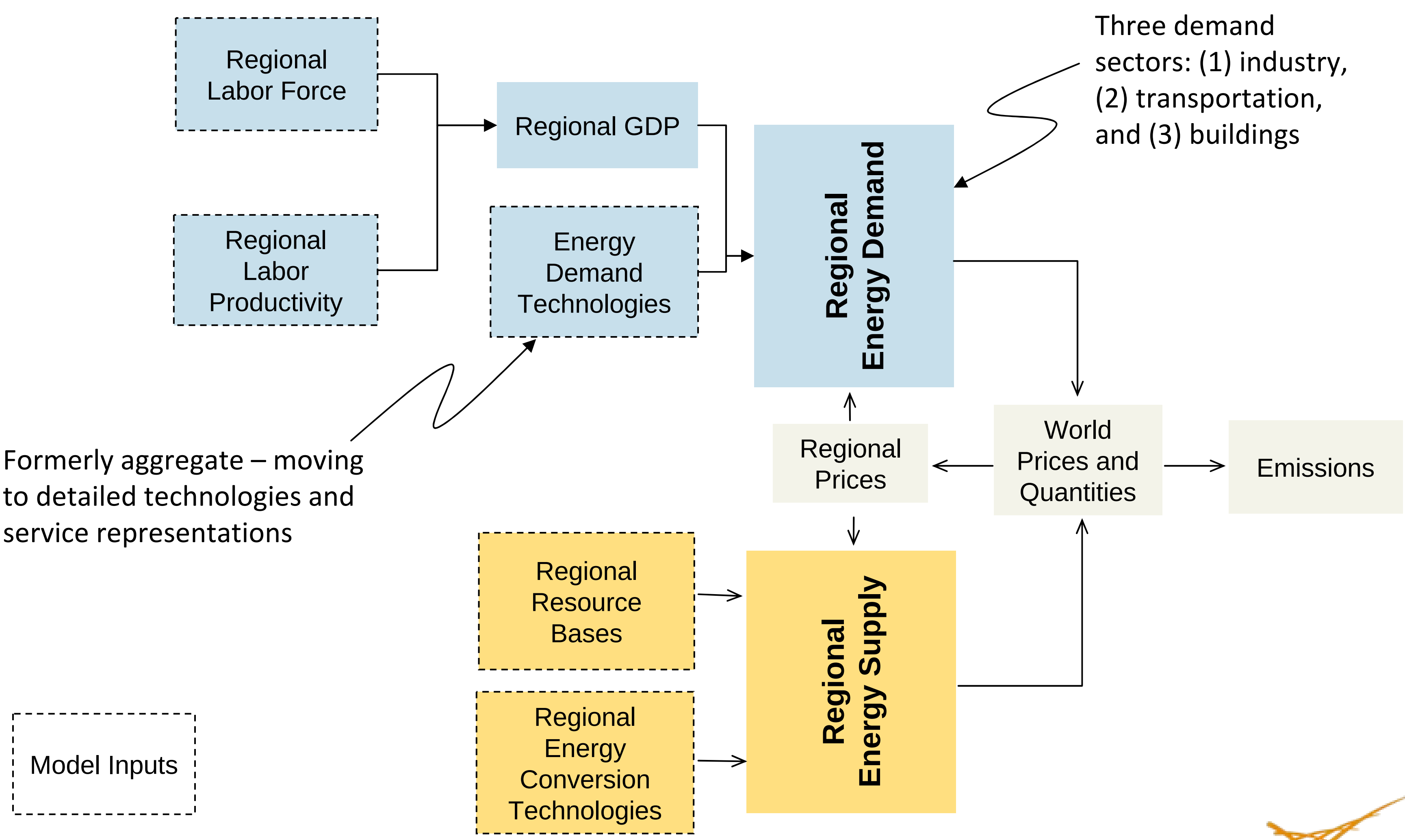
GCAM Model Structure: The Economy

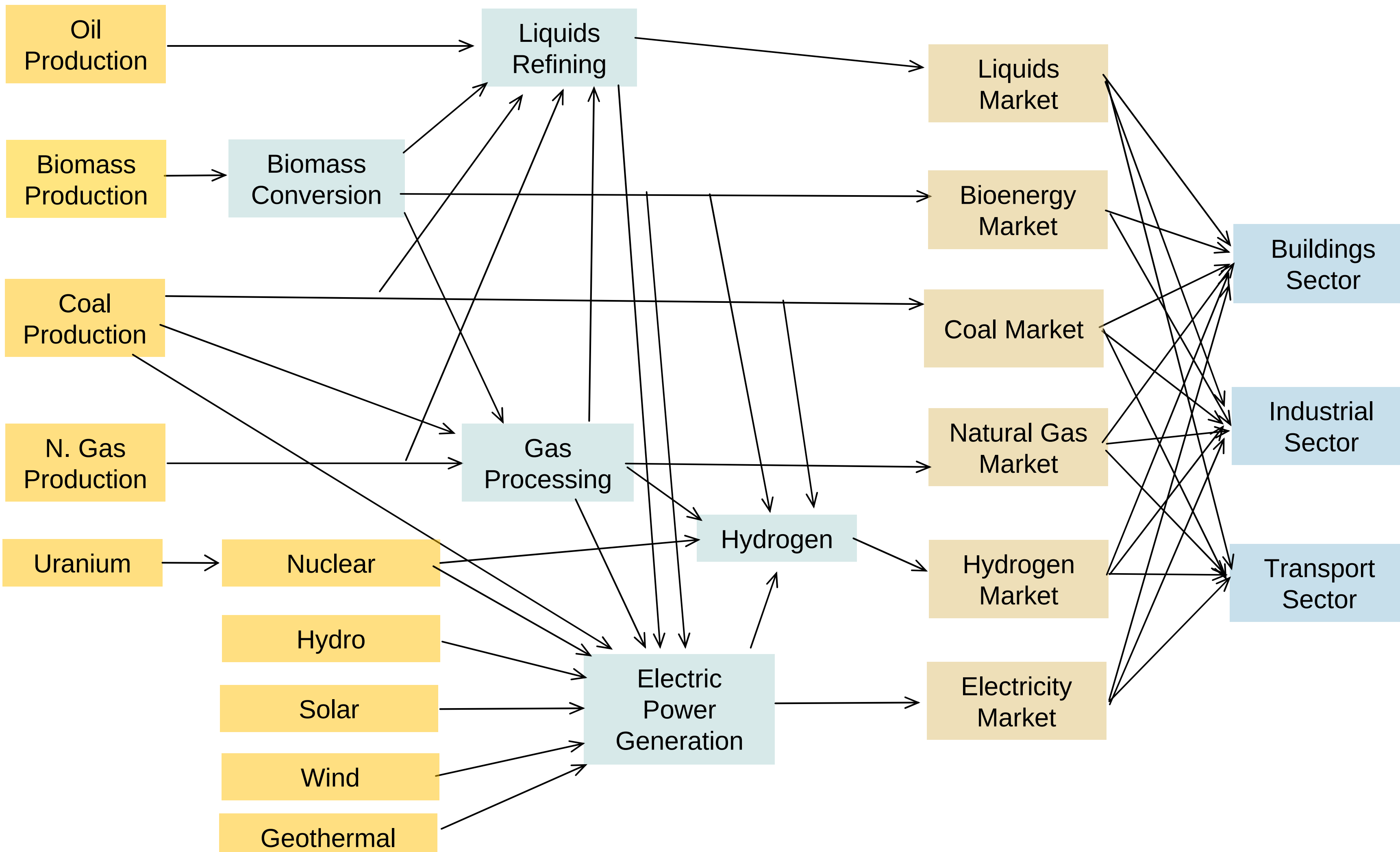
- Population and GDP are important drivers for the model and have significant impact on consumption and emissions.

- Population:
  - Exogenously specified for each region
  - Current core model scenario assumes global population peaks in 2065 at roughly 9 billion people and falls thereafter
    - Based on UN population projection
- GDP:
  - Exogenously specified with assumptions about labor force participation and labor productivity growth
  - 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.

Overview of the Energy System



The Current Structure of the Energy System



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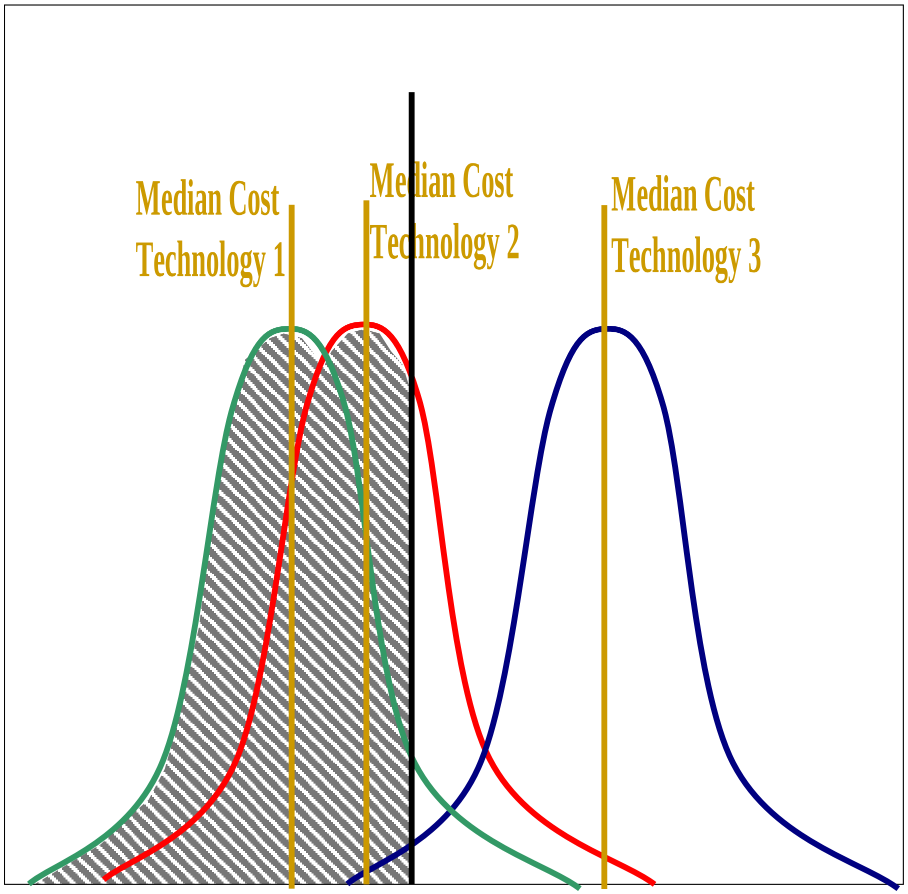
Energy Resources in GCAM

- Resources serve as inputs to conversion technologies to produce energy carriers such as electricity, liquid fuels, and hydrogen.
- Exhaustible Resources in GCAM
  - Coal
  - Natural Gas
  - Oil (conventional and unconventional)
  - Uranium
  - Resource supply curves are based on graded resources
  - Greater production moves to less desirable grades at higher extraction cost
- Renewable Resources in GCAM
  - Solar
  - Wind (onshore and offshore combined into one)
  - Geothermal
  - Bioenergy

GCAM Technology Competition – Based on Economics

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.

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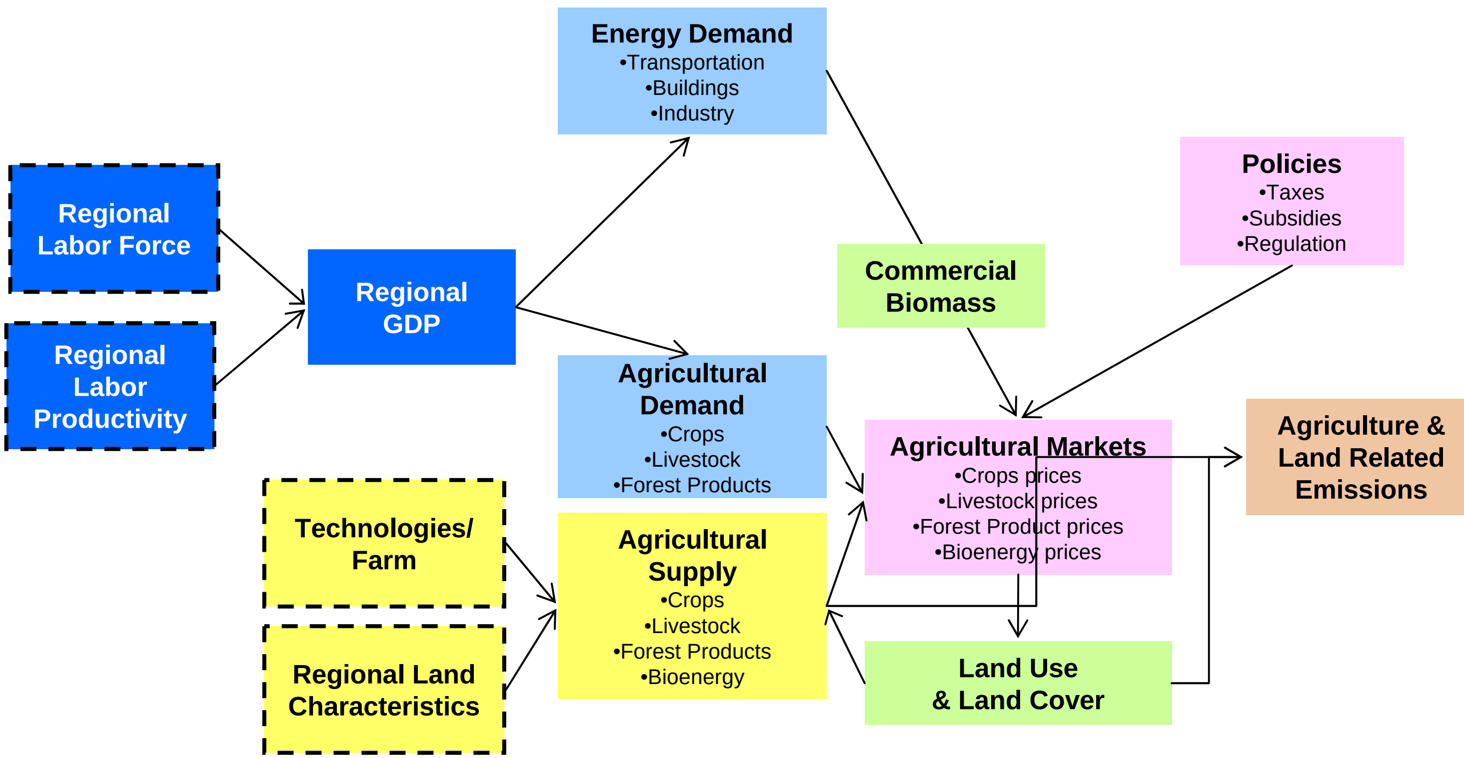
Emissions

- GCAM tracks emissions for several gases and species
  - CO_2, CH_4, N_2O, CF_4, C_2F_6, SF_6, HFC125, HFC134, HFC245fa, 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 non-CO_2 gas is associated with a specific sectoral 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 non-CO_2 GHGs as the carbon price rises
- Emissions are produced at a region level, but we can downscale them to grid cell level if necessary (e.g., RCPs)

Agriculture and Land-use in GCAM



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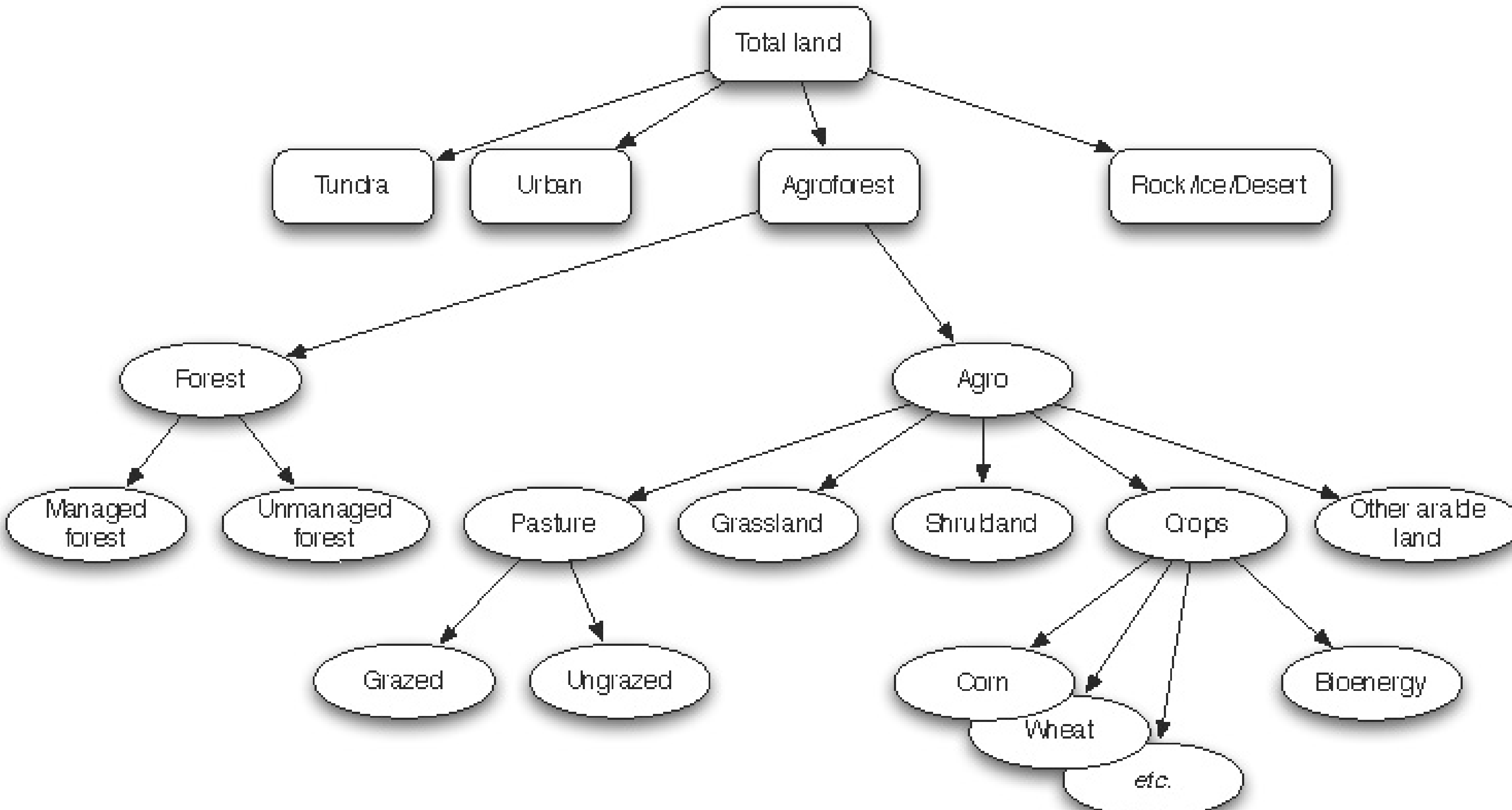
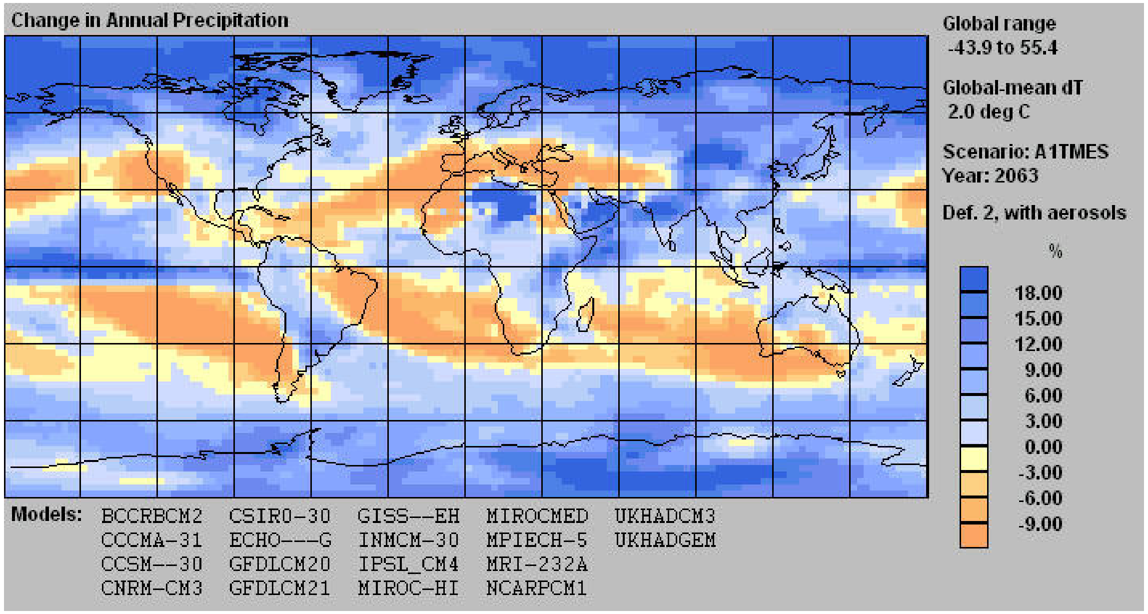
GCAM Land allocation based on profitability (representative structure shown here)



GCAM currently uses MAGICC as a Climate Model

- A gas-cycle, carbon, climate and ice-melt model used in IPCC assessments
- Treats various GHGs, halocarbons, SO_2, reactive gases
- When coupled to GCAM, is primarily used to provide estimates of atmospheric GHG levels and radiative forcing under a particular policy case



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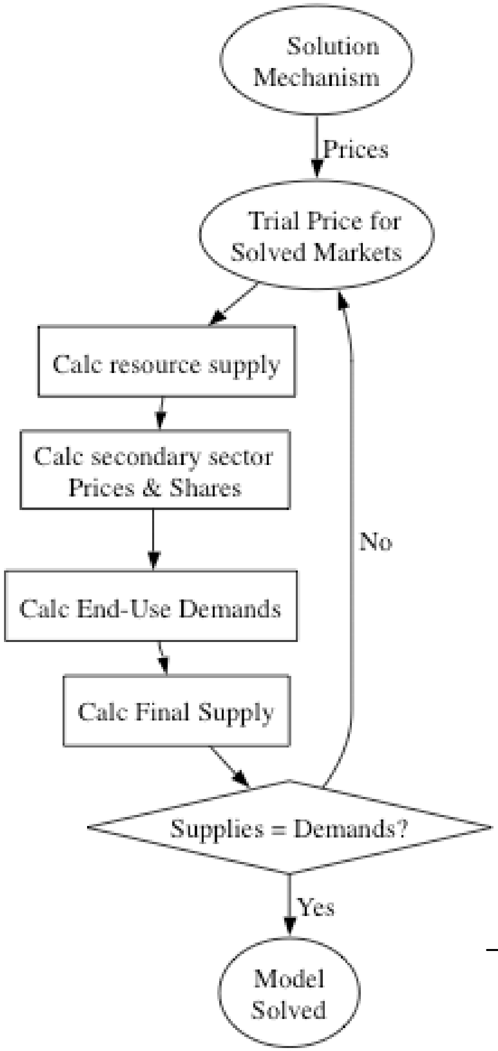
GCAM and Object-Oriented Programming

GCAM uses an object-oriented programming approach for implementing a modular, data-driven architecture to model energy and agricultural systems.

- Implemented in C++ with XML input data structure.
  - Hierarchical data structure is self describing and mirrors model structure.
- Flexible number of regions, sectors and technologies.
  - Dynamic memory allocation.
- Allows heterogeneity - enables varying degrees of detail where needed.
  - Classes and objects, inheritance and polymorphism.
- Model is data driven.
  - Input data determines the market structure, sector definitions, fuels, and linkages.

GCAM Solution Process



Solution Steps

Given a set of prices

- Primary production of resources computed (*i.e. coal, crude oil, biomass).*
- Each sector determines technology shares based on relative costs, computes sector prices.
- End-Use Demands computed (sector prices).
- Supply of secondary goods computed.
- Check for solution (do all supplies = demands).
  - If not, adjust prices and re-compute model.

Sectors communicate with each other through the marketplace

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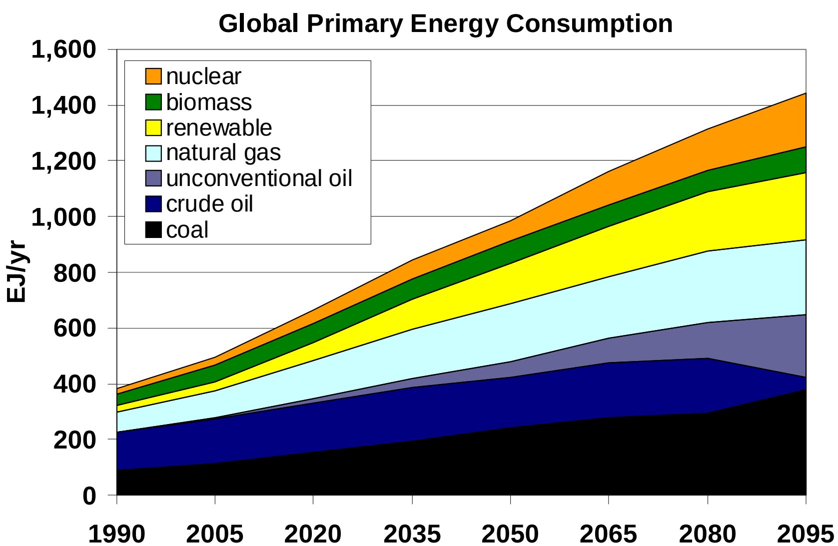
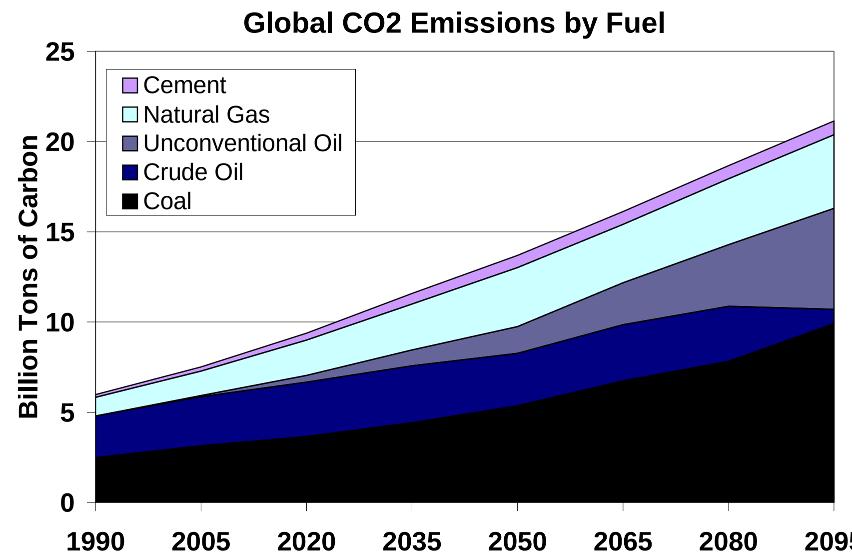
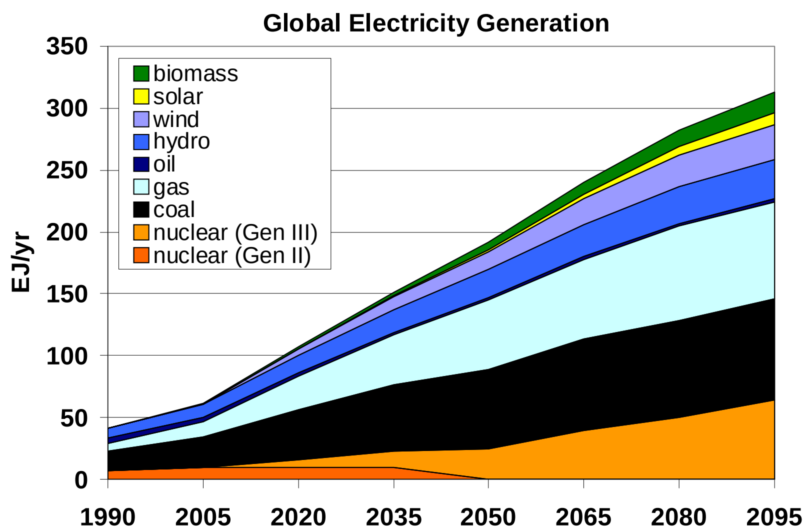
GCAM Scenarios and Sample Results

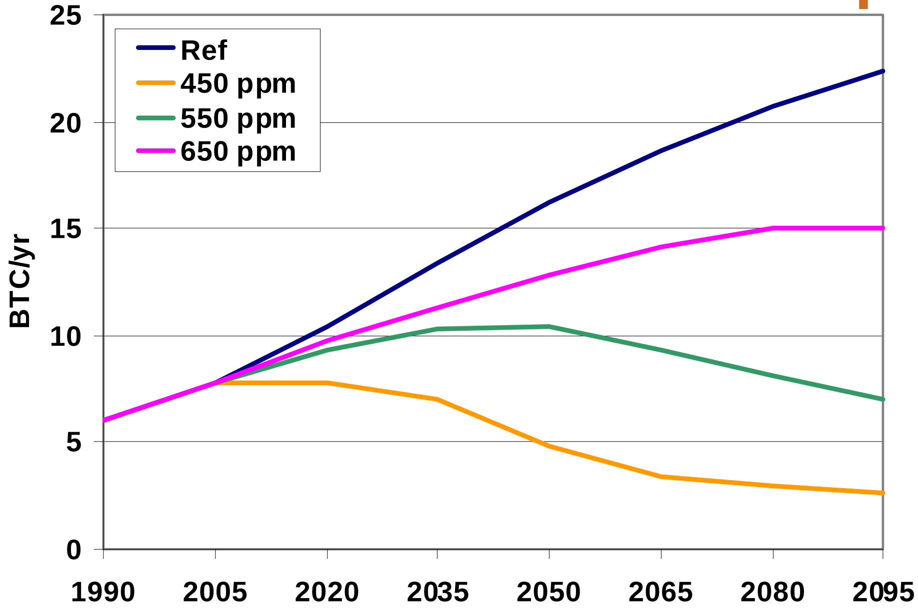
Global Primary Energy Consumption, CO_2 Emissions & Electricity Generation - Reference Scenario





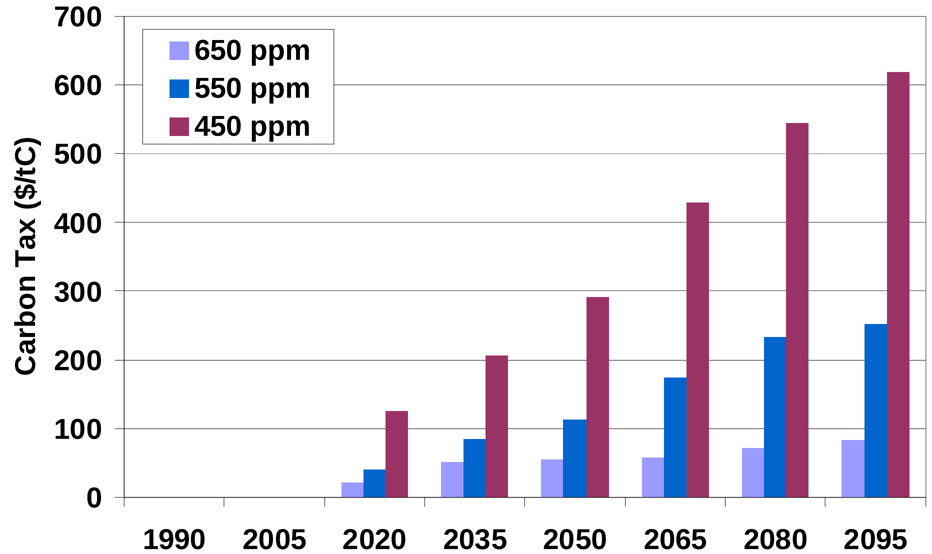


Global Carbon Policy
Stabilization of Atmospheric CO_2 Concentrations



CO2 Emission Coefficient:
Coal = 27.3 kg C/GJ
Oil = 19.6 kg C/GJ
N. Gas = 14.2 kg C/GJ

100 \$/tC carbon tax = 1.8 cents/kWh
= 26 cents/gal of gasoline
100 \$/tC = 27.3 \$/tCO_2 * (44/12) CO_2/C



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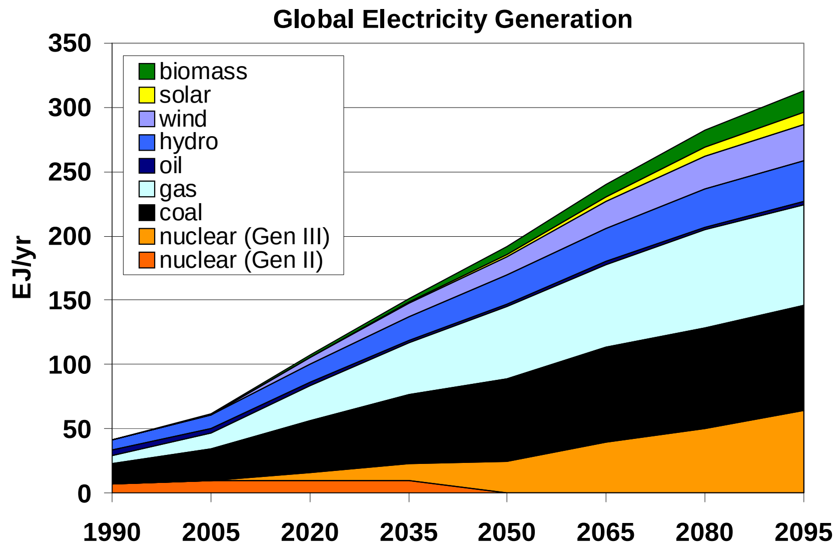
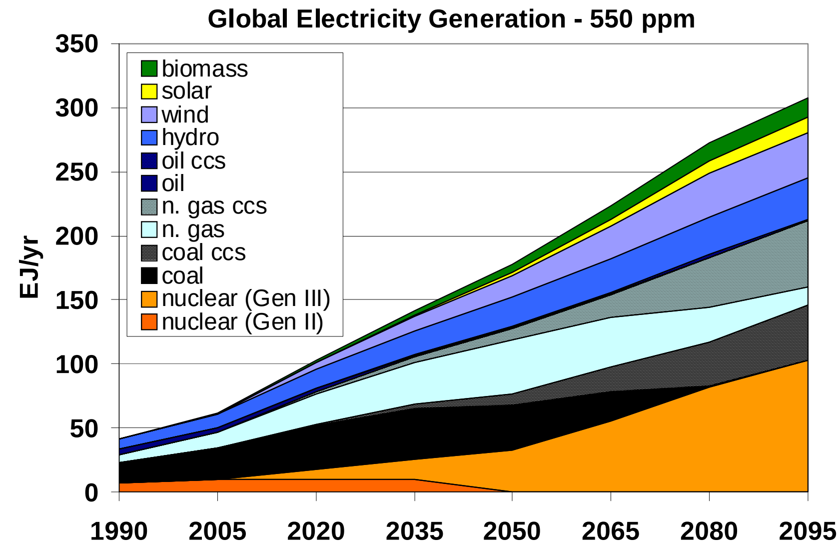
Global Electricity Generation
550 ppm Scenario

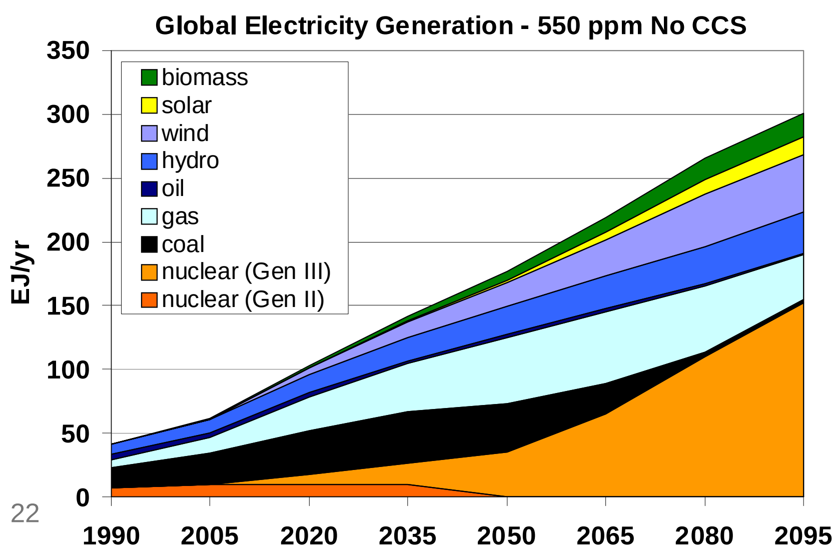
Reference



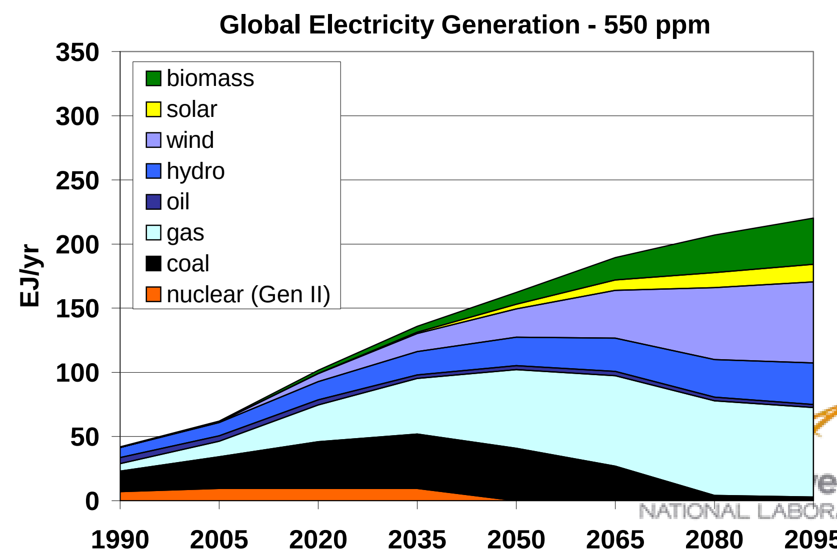
CCS & Nuclear



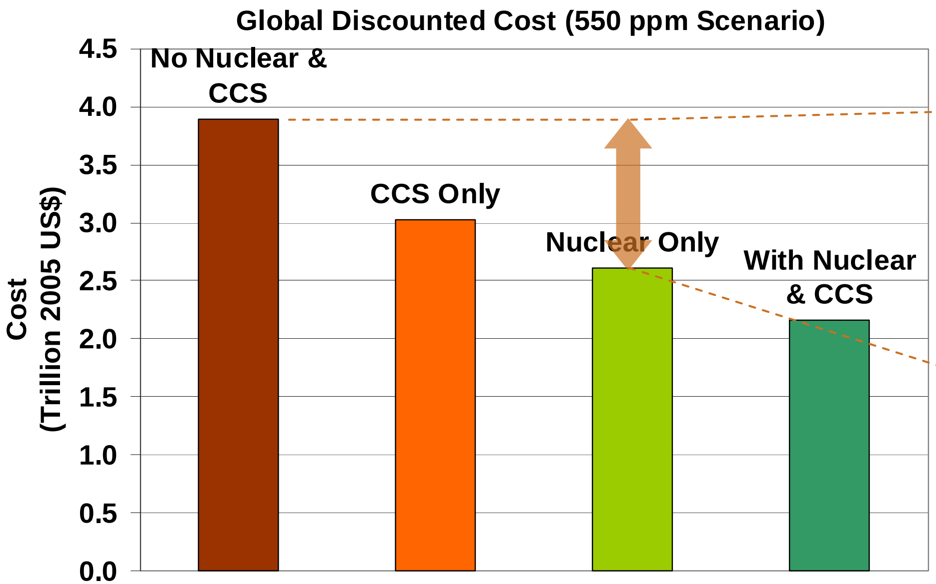
Nuclear & No CCS

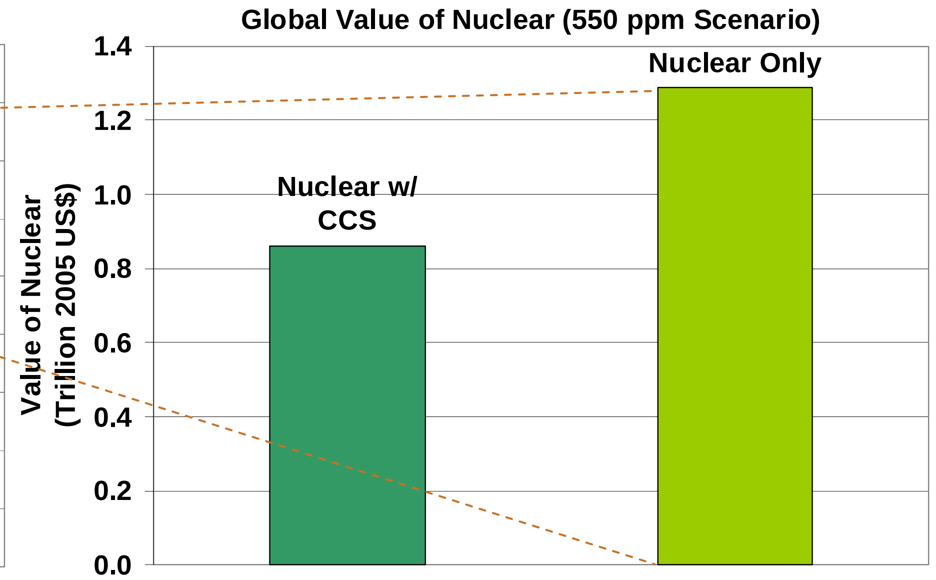


No CCS & No Nuclear



Global Cost of 550 ppm Scenario with Alternative Power Technologies





(Discounted @ 5% from 2095 to 2005)

Value of Nuclear =
(Cost without Nuclear)
– (Cost with Nuclear)

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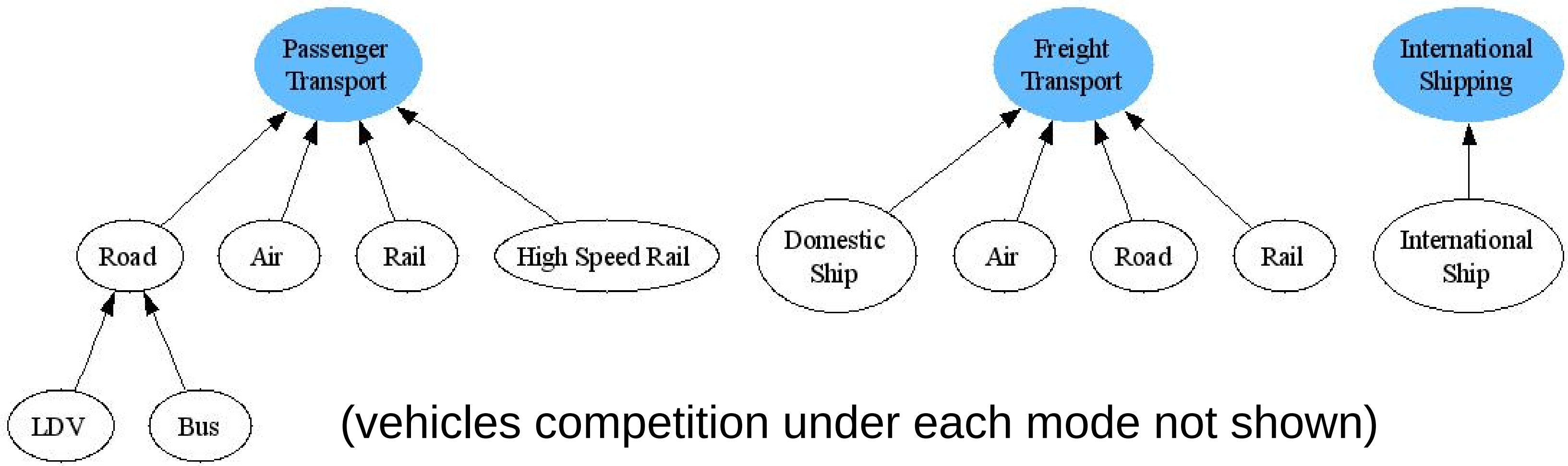
Transportation Scenarios

Modeling the Transportation Sector



(vehicles competition under each mode not shown)

Passenger Service Demand: $$D_{pass,L} = a_{pass,L} P_{pass,L}^{rp_{pass,L}} X_L^{ry_{pass,L}} Pop_L$$

Cost of Service by Vehicle: $$P_{v,i,L} = (P_{f,i,L} / Eff_{i,L} + P_{nf,i,L}) / LF_{i,L}$$

Cost of Service by Mode: $$P_{m,L} = \sum_{i}^{N} S_{i,L} (P_{v,i,L} + W_L / T_m)$$

Market Share: $$S_{i,L} = sw_{i,L} P_{i,L}^{r_L} / \sum_{i}^{N} sw_{i,L} P_{i,L}^{r_L}$$

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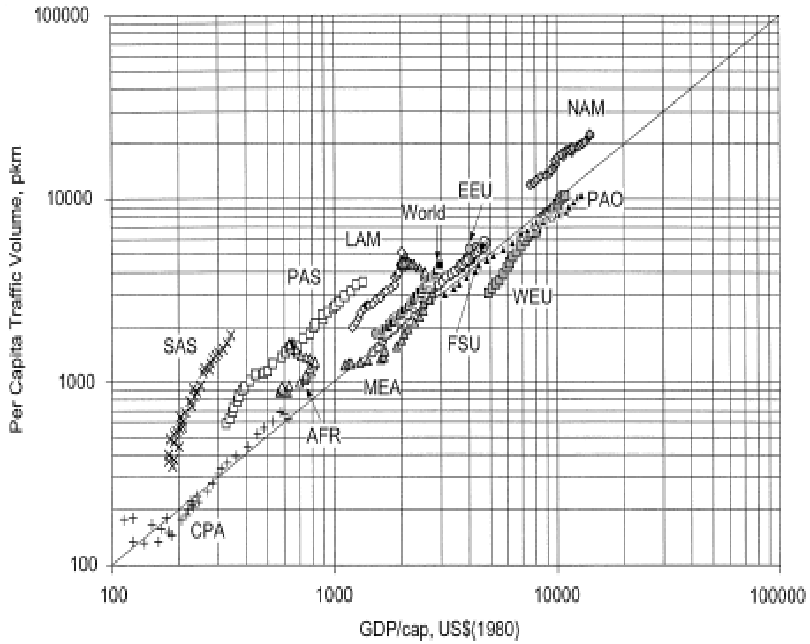
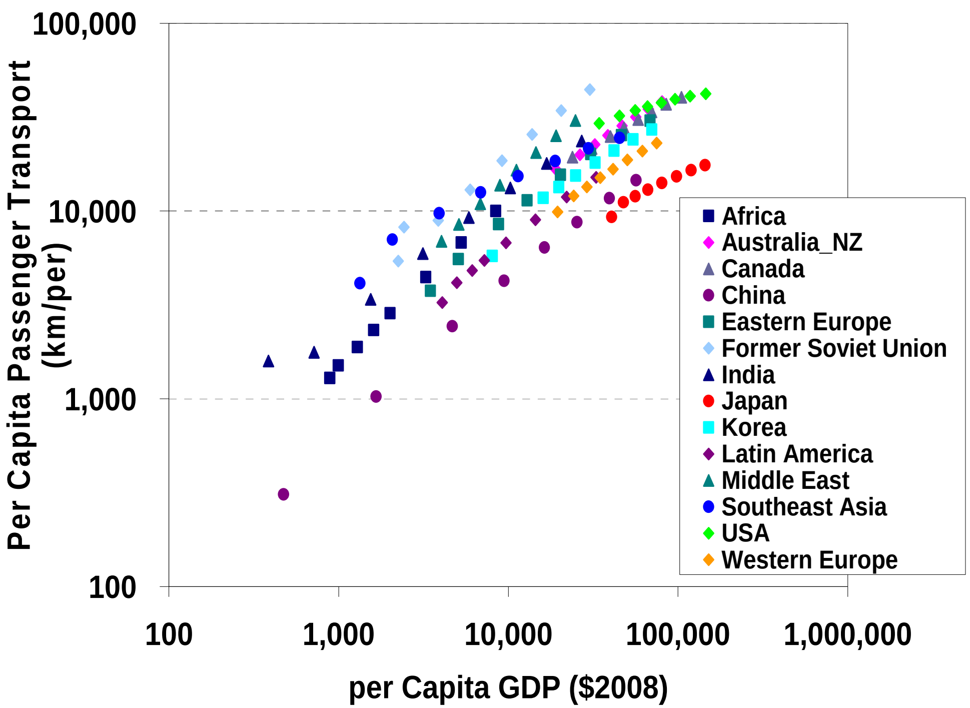
Comparison of Model Results Passenger Service Demand

Shafer (1960-1990)



GCAM (1990-2095)



Source: Fig. 5 in: Shafer, A. (1998). The Global Demand for Motorized Mobility. Transportation Res.-A, Vol. 32, No. 6, pp. 455-477.

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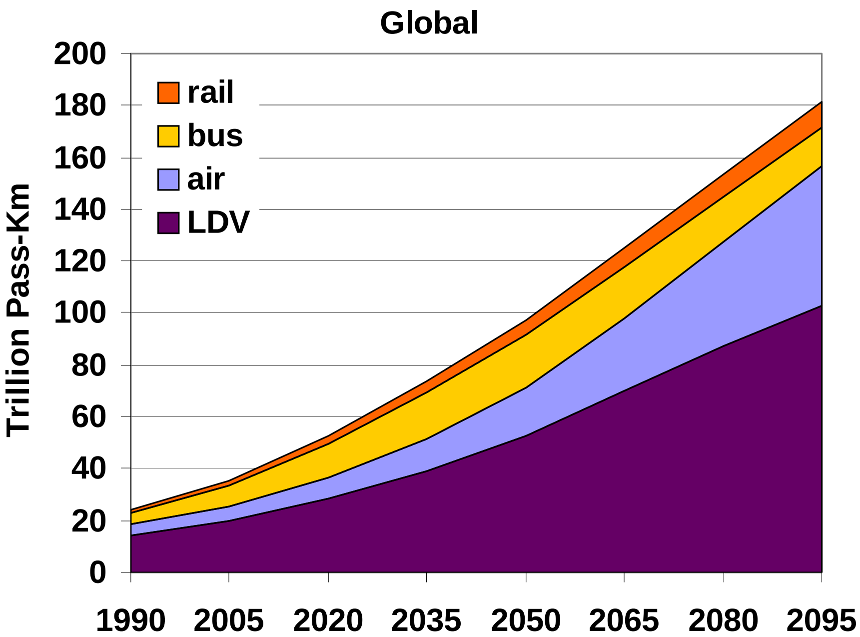
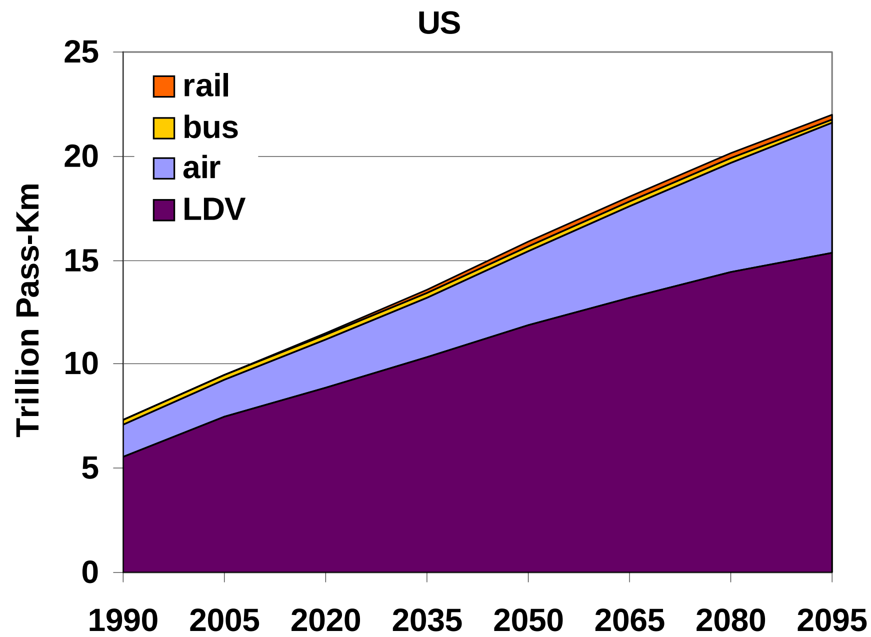
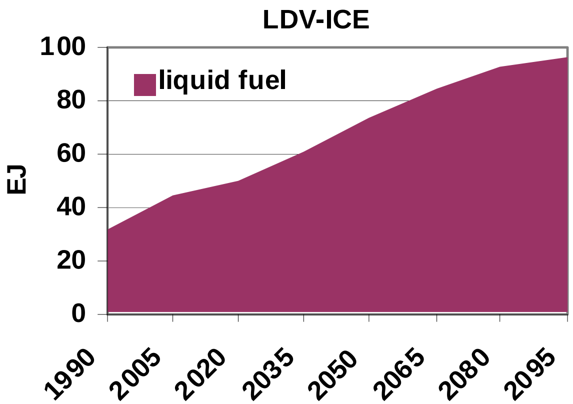
US and Global Passenger Service Reference Scenario (no carbon policy)

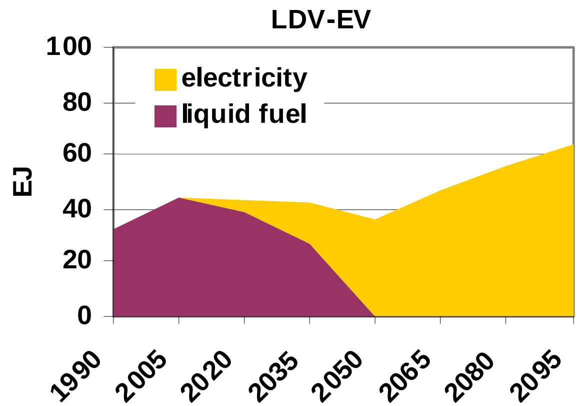


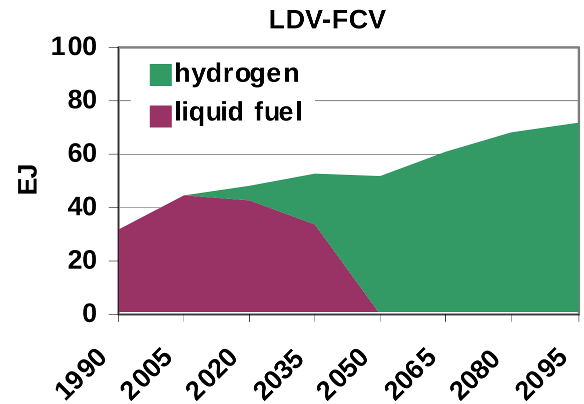


Lt-Duty Transport Energy Demand
450 ppm Scenario

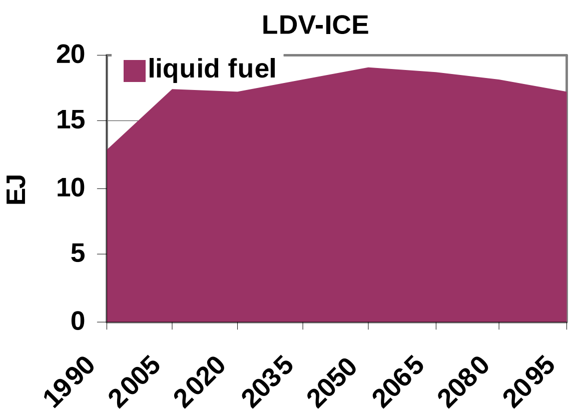
Global

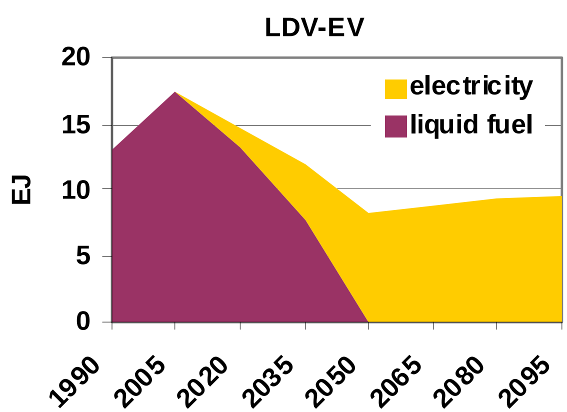


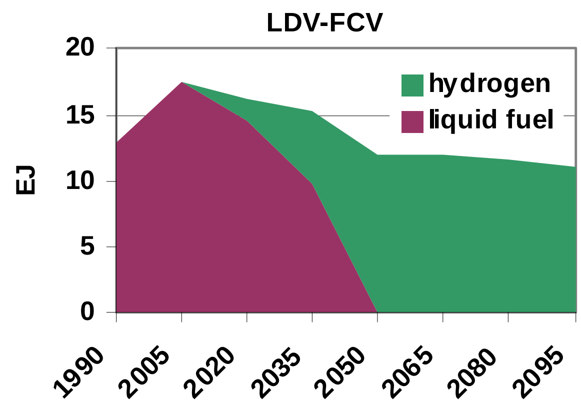




US

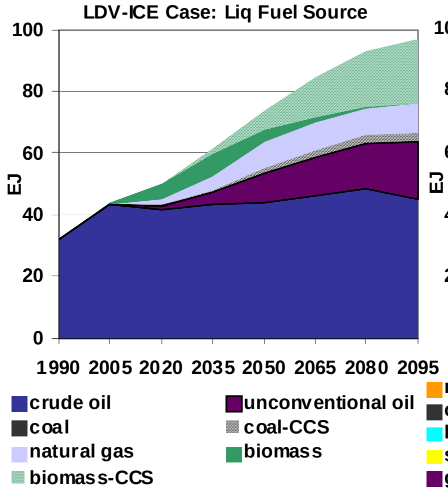


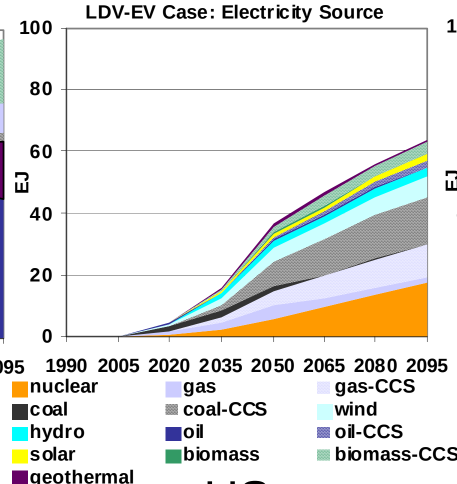


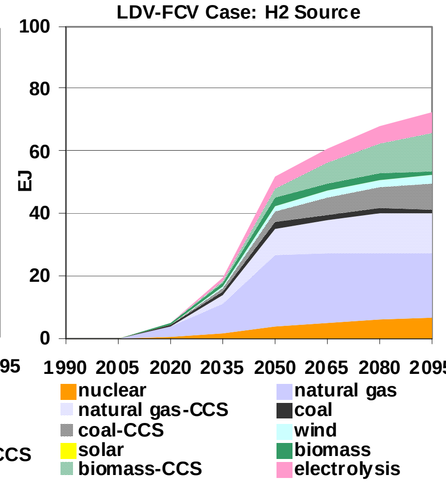


Sources of Lt-Duty Vehicle Fuel
450 ppm Scenario

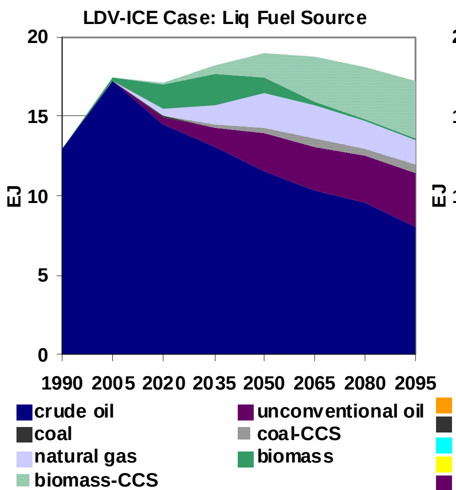
Global

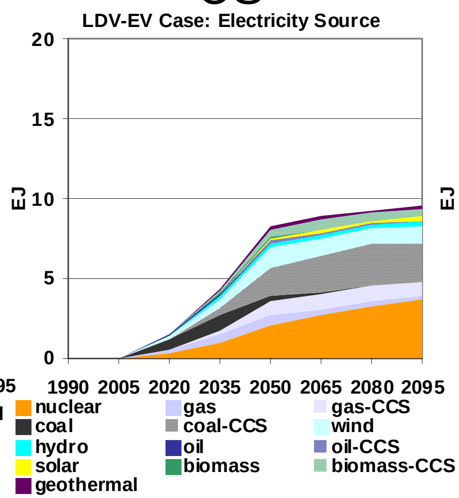


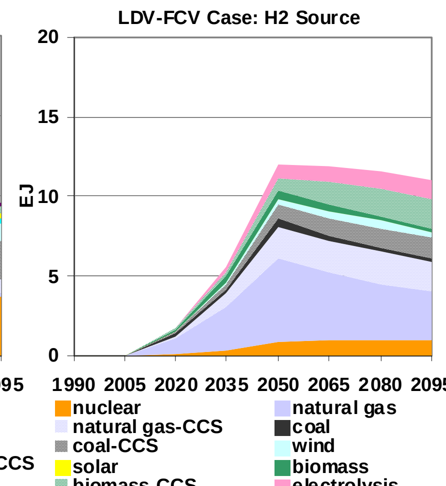




US







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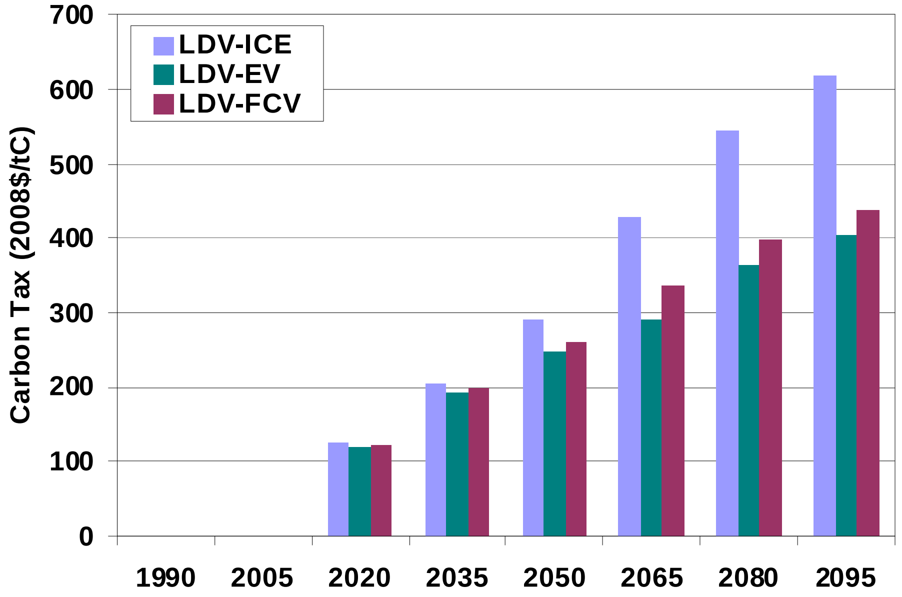
Carbon Taxes for Transport Cases
450 ppm Scenario



Summary of GCAM Results Shown

- Long-term projections of energy use and CO2 emissions
- Impact of climate policies: 450 and 550 CO2 ppm cases
- Carbon values for meeting climate targets
- Impact of technology options: electric power and transportation technologies
- Cost of carbon-constrained scenarios
- Value of technologies