Analysis of Market Penetration of Renewable Energy Alternatives under Uncertain and Carbon Constrained World

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Abstract

- Future energy prices and supply, availability and costs of emerging technologies including CCS, wind, solar and bioenergy can have significant impact on how fast and cost effectively we could abate carbon emissions. Various carbon policies have been proposed and analyzed, however the adequacy of these policies is highly uncertain due to uncertain pace of the climate change. This study investigates how the uncertainty in future energy supply and prices, and various carbon abatement policies will affect the market penetration of CCS and renewable energy alternatives including bioenergy, wind, and solar. Two-staged decision making methods embedded in U.S. EPA's Markal modeling system will be utilized to find most robust mitigation strategy under carbon constraint world. A range of technology availability and cost scenarios are analyzed to capture the uncertainty in the R&D progress.

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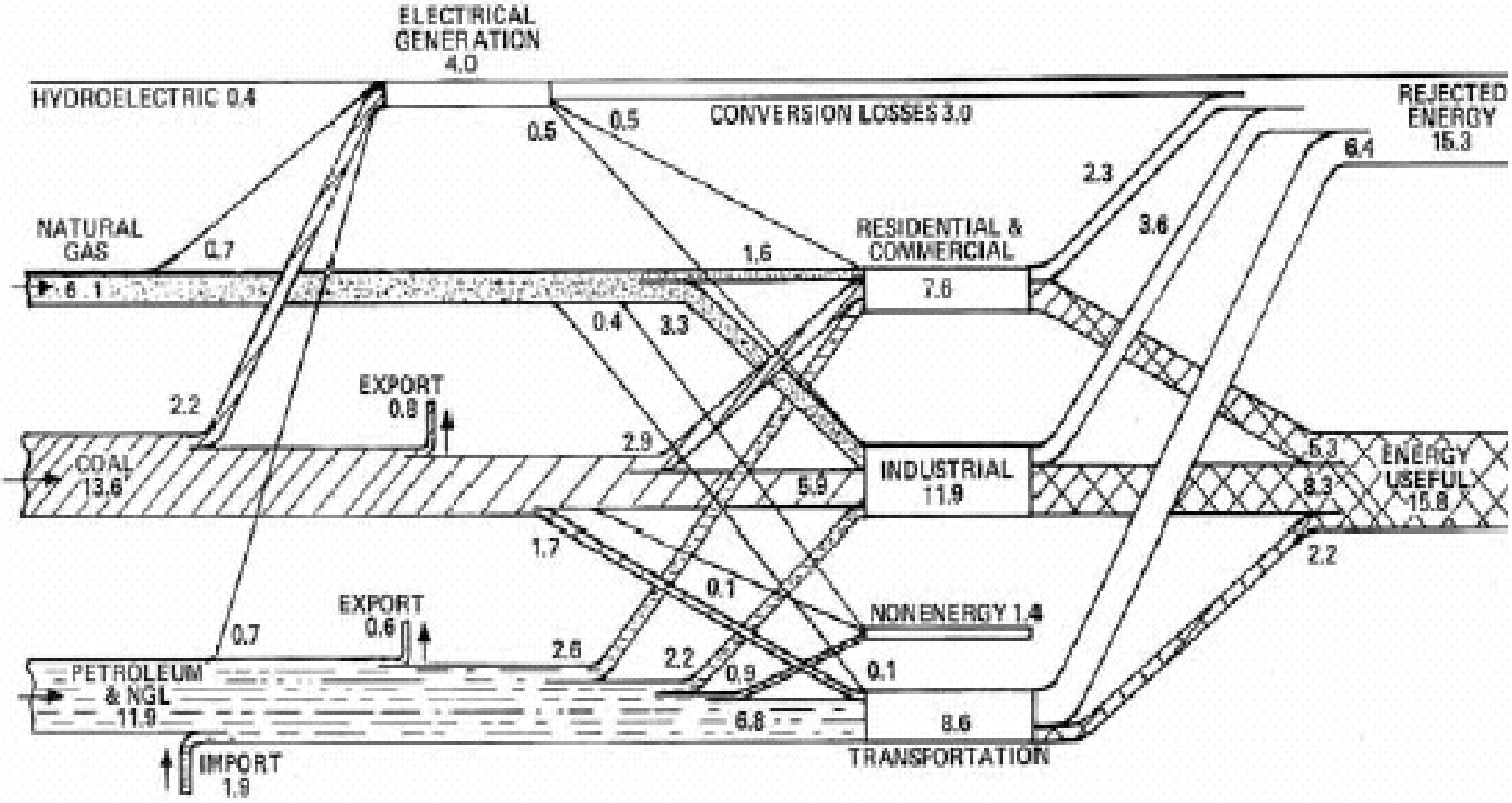


U.S. Energy Flow – 1950

All values in 10^{15} Btu (2.12×10^{15} Btu = 10^6 bbl/day oil)

Total energy consumption = 33.9×10^{15} Btu.

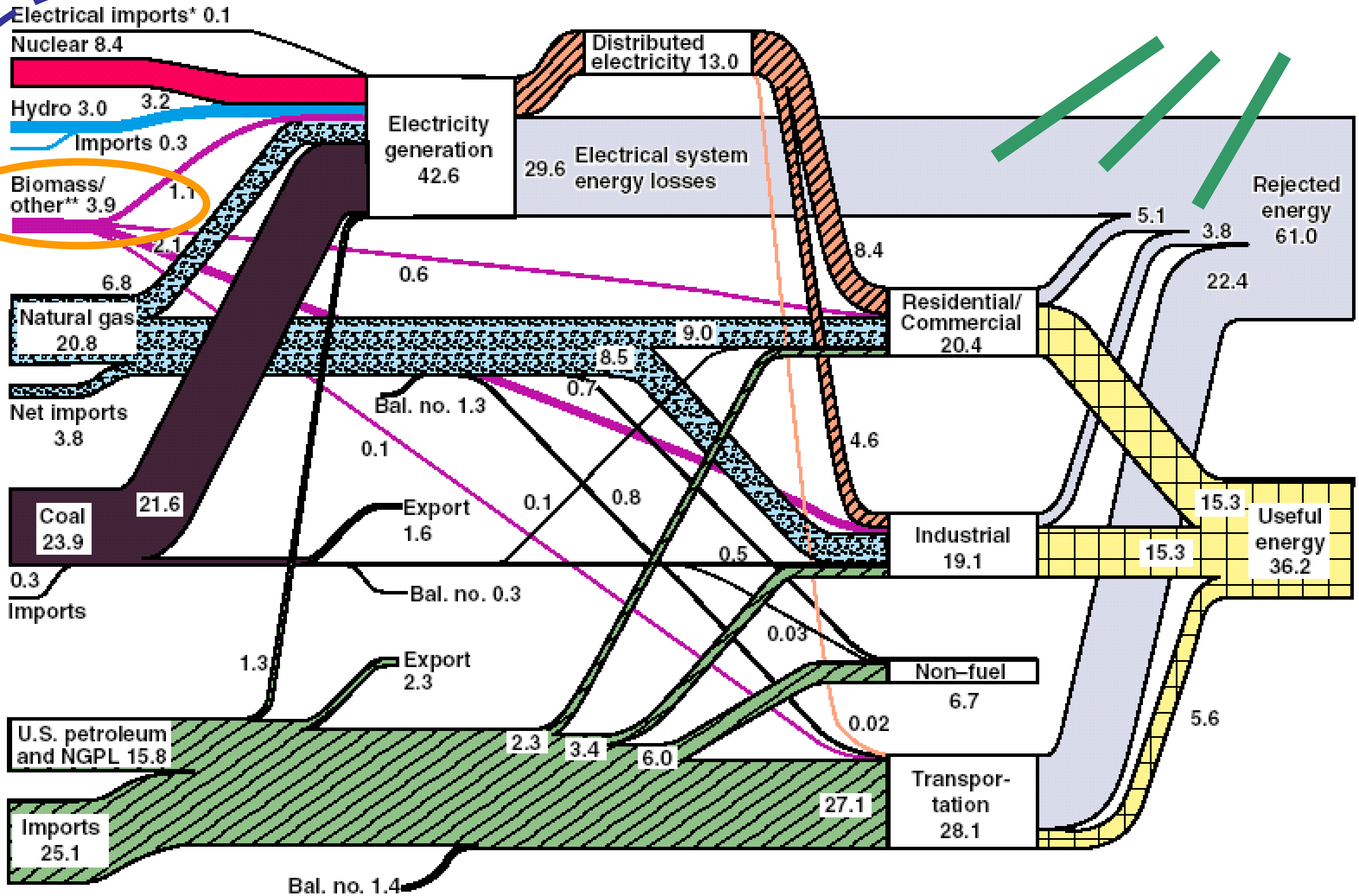
Ref: Lawrence Livermore Laboratory UCRL-51487

Total Energy Consumption = 35,765 PJ

U.S. Energy Flow Trends – 2000
Net Primary Resource Consumption

2050?

Emissions?



Source: Production and end-use data from Energy Information Administration, *Annual Energy Review 2000*
*Net fossil-fuel electrical imports
**Biomass/other includes wood and waste, geothermal, solar, and wind.

December 2001
Lawrence Livermore
National Laboratory

MARKAL

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Why Energy and the Environment?

In 2000:

- Air and Water Quality
  - Contributions to U.S. anthropogenic emissions
    - *NOx – 95%*
    - *SO_2 – 89%*
    - *CO – 95%*
    - *Hg – 87%*
- Climate Change
  - Contributes 94% of U.S. anthropogenic CO_2 emissions
- Water Supply and Use
  - 89% of U.S. electricity production uses water for steam or cooling
    - *39% of U.S. water withdrawals (agriculture ~ 41%; domestic ~ 12%)*
    - *132 trillion gallons of water per day is required*
    - *2 gallons/kWh evaporates from thermoelectric plants*
    - *18 gallons/kWh evaporates from hydroelectric plants*
  - One gallon of ethanol may require four or more gallons of water

Project Goals

- Developing and examining **internally consistent scenarios** of energy system evolution and anticipating environmental consequences
- Exploring the **energy and environmental implications** of current, proposed, and potential policies
  - Climate policies
- Identifying important system interactions and potential **unintended consequences**
- Developing **robust solutions** while including consideration of **uncertainties** in fuel prices, technologies, and policy
  - Carbon capture and sequestration

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What is MARKAL?

- Developed in cooperative multinational International Energy Agency (IEA) project in late 70s
- Selects the **optimal mix of technologies and fuels** at each time step to minimize the net present value of energy system capital and O&M costs
- Subject to:
  - Current and projected technology costs and efficiencies
  - Resource supply costs and competition for fuel across sectors
  - Resource supply constraints
  - Trade costs and constraints
  - Emission limits
  - Other constraints (e.g., policies)
- Currently used by ~200 institutions and governments in 70 countries
  - *Including Department of Energy and U.S. Environmental Protection Agency*

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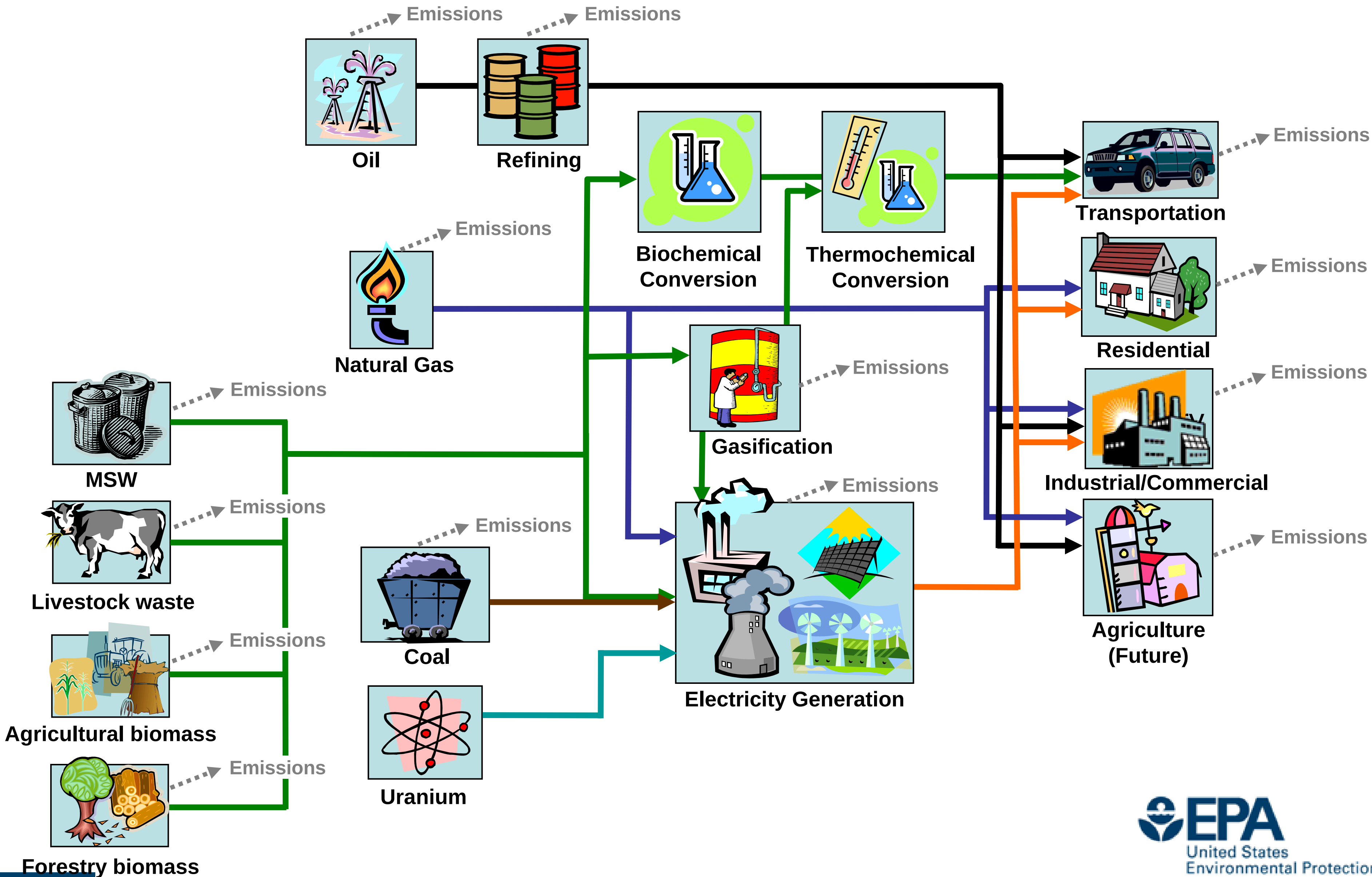
Modeling Energy *System* Interactions



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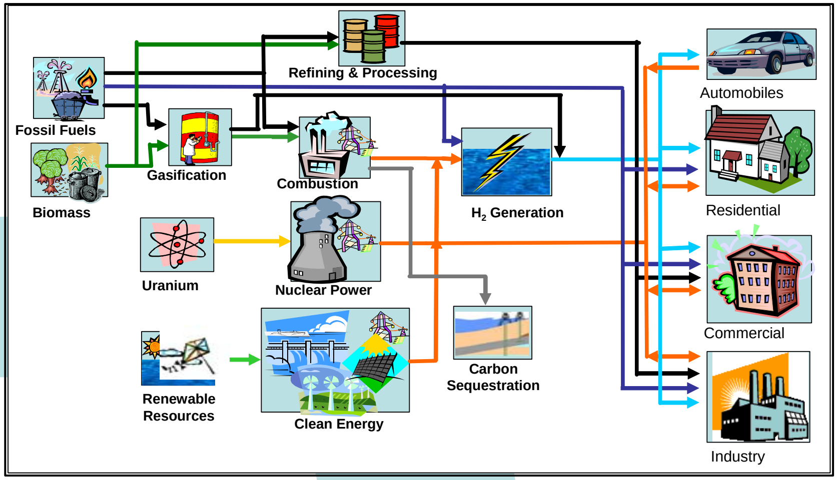
Modeling Technology Change with MARKAL

MARKAL Inputs:

• Future-year energy service **demands**
• Primary energy resource **supplies**
• Current & future **technology characteristics**
• Emissions and energy **policies**



•Through linear optimization MARKAL finds the **least cost set of technologies**

MARKAL Outputs:

• **Technology penetrations** for meeting industrial, residential, commercial, and transportation demands
• **Fuel use** by type and region
• Sectoral and system-wide **emissions**
  NOx, SO_2, PM_{10} and CO_2
• Marginal fuel and emissions reduction prices

Soon will add Hg, CH_4, and N_2O as outputs

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Factors Driving Energy System Evolution

- **Population** growth and migration
- **Economic** growth and transformation
- **Land use** change
- **Technology** innovation
- **Climate change** impacts on energy use and production
- Availability and cost of **fuel resources**
- Consumer and firm **behavior**

Policy
- *Climate*
- *Energy security*
- *Environmental*
- *Other*
  - *- R&D*
  - *- Trade*
  - *- Smart growth*

Many uncertainties when projecting to future

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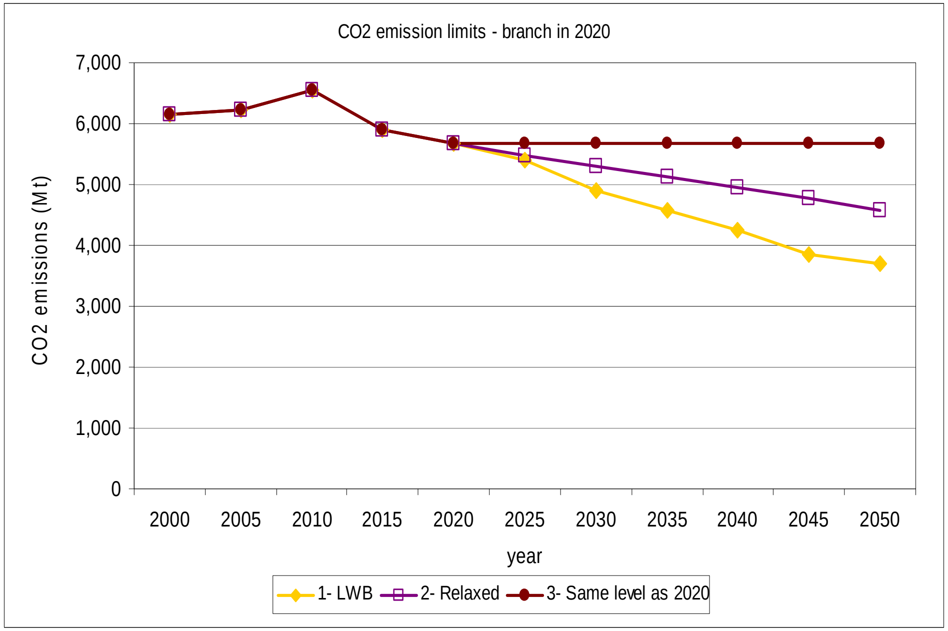
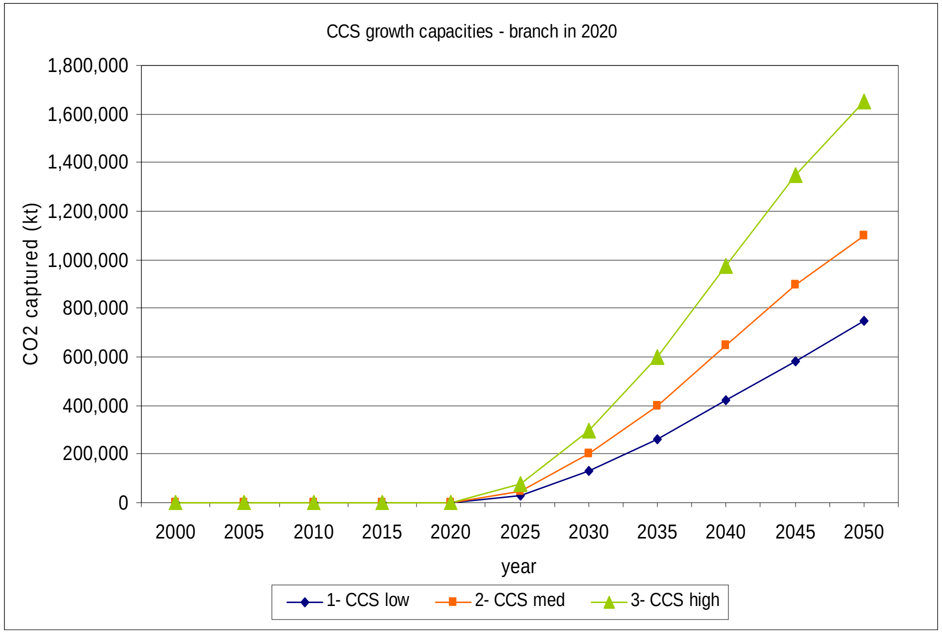
Scenario Analysis

- Examine hedging scenarios under an uncertain GHG policy considering different assumptions about the availability of advanced technologies such as CCS
  - Follow a historical CO2 emission path until 2010
  - In 2010, Lieberman-Warner-Boxer CO2 abatement policy is implemented.
  - In 2020, more information could be attained regarding climate change which could change the CO2 emission limits

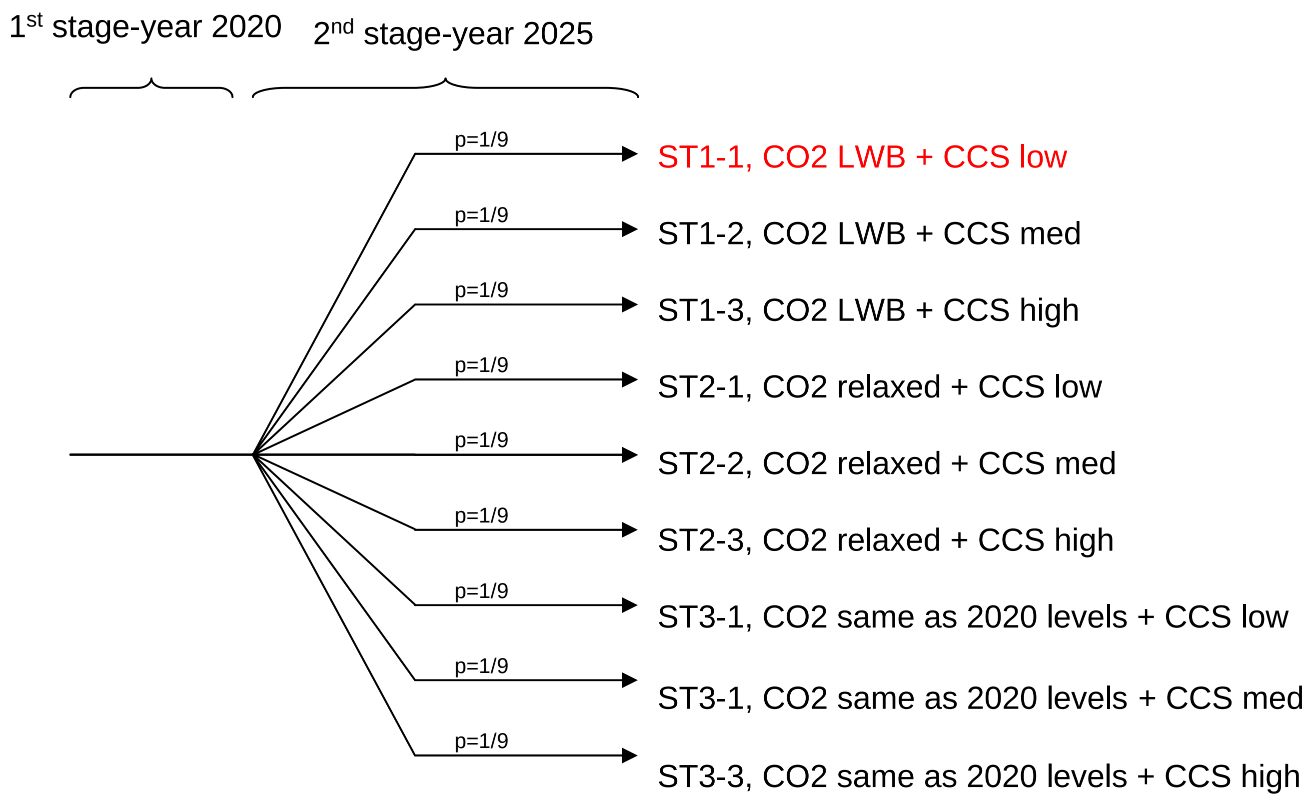




Results generated with U.S. EPA National Model database

Methodology

- Utilized two-stage stochastic optimization feature embedded in MARKAL framework
- Constructed the scenarios as multiple realizations of the future
- Run the stochastic model
- Run the deterministic (perfect foresight) models (9 runs)
- Compare the results from stochastic vs deterministic models



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Hypothesis

- Expect to see short-term differences between 2000 and 2020 to help prepare for the risk of change in 2020 for stochastic version
- Expect technologies to be chosen that are a reasonable price but have low CO2 output
  - Coal is cheap, but is a large CO2 emitter
  - Coal depends on CCS to be viable for CO2 reduction
  - Natural gas allows for reasonable CO2 emission levels without CCS → Could serve as a transition fuel
  - Natural gas w/CCS is a good solution for extreme CO2 reduction
- The deterministic run knows what to expect in the future, but the stochastic version has to be more robust to minimize cost while having the ability to reduce CO2 emissions
  - the cost of having perfect information

Technology Assumptions

Technology	Availability Year	Capital $M/GW	Fixed $M/GW	Variable $M/kWh	Heat Rate
Natural Gas - Advanced Combined-Cycle (Turbine)	2005	486	9.73	1.66	6333
Natural Gas - Advanced Combustion Turbine	2005	335	8.76	2.64	8550
Geothermal - Binary Cycle and Flashed Steam	2005	1919	68.52		35460
Biomass Integrated Gasification Combined-Cycle	2010	1516	44.37	13.74	8911
Pulverized Coal Steam - 2005	2005	1066	22.90	3.82	8600
Supercritical Coal Steam - 2010	2010	1100	22.90	3.82	7200
Integrated Coal Gasif. Combined Cycle	2015	1232	32.17	2.42	7200
Integrated Coal Gasif. Combined Cycle -- CO2 Capt.	2015	1873	41.44	4.03	8538
Oxyfuel Coal Steam -- CO2 Capture	2015	1873	41.44	4.03	8538
Natural Gas Combined Cycle -- CO2 Capture	2015	1021	18.12	2.66	7957
Nuclear LWRs in 2010	2010	1440		5.00	*0.65* *
Pebble-Bed Modular Reactor (PBMR)	2020	1250		2.50	*0.36* *
Gas Turbine - Modular Helium Reactor (GT-MHR)	2020	1122	26.48	0.64	*0.22* *
Solar PV Centralized Generation	2010	3436 - 3931			
Solar PV Distributed Residential Generation	2010	4512 - 6771			
Solar PV Distributed Commercial Generation	2010	3760 - 4870			
Solar Thermal Centralized Generation	2015	2325 - 2465			
Wind by Generation and Cost Category	2005	1381- 4214			

* tons of U45/ PJ ELC

Most cost data is adopted from AEO 2006.

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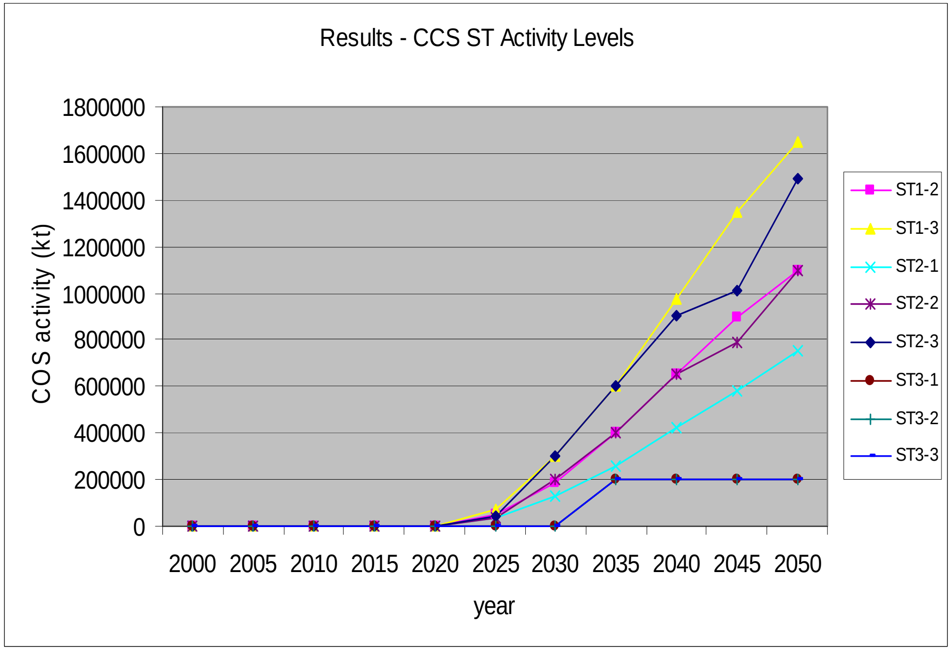
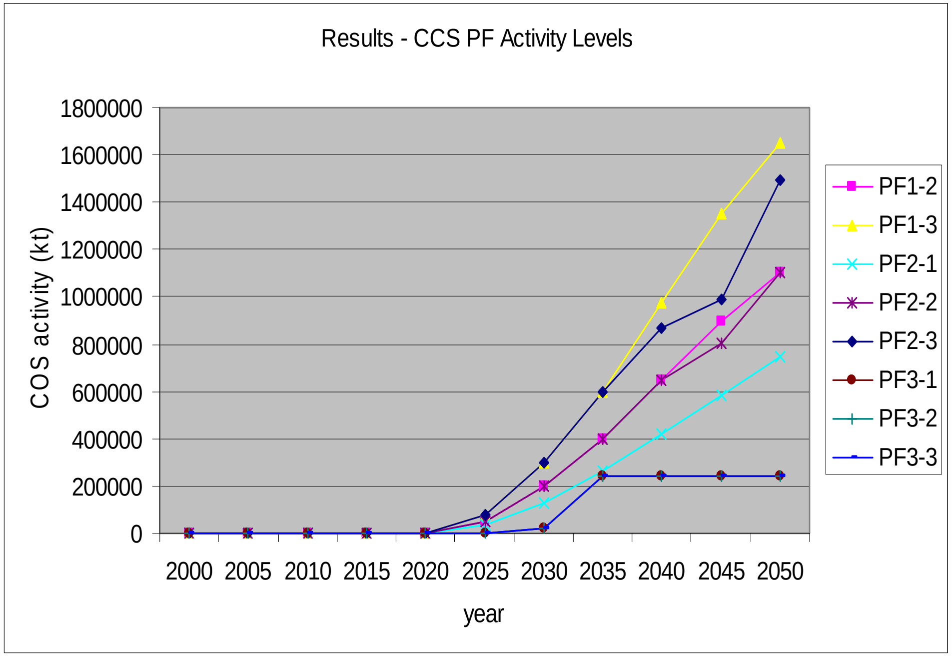
Stochastic vs. Deterministic?

Stochastic



Perfect Foresight



Results

- CCS Activity levels are nearly the same
- All available CCS is used in strict CO2 emission scenarios
  - An important technology in the face of CO2 abatement

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Illustrative Results

Total Costs and Value of Perfect Information

Variations of Scenarios

1-CO2 LWB

2-CO2 relaxed

3-CO2 same as 2020 levels

1-CCS low

2-CCS medium

3-CCS high

Nomenclature

PF is Perfect Foresight

ST is Stochastic

e.g, 1-1 is CO2 tight-CCS low

	D.TOTCOST	D.TOT.EMIS.TAX	Total Cost (M$)
PF1-1	60,026,452	38,236	60,064,688
PF1-2	53,098,505	60,680	**53,159,185**
PF1-3	52,449,626	91,020	**52,540,646**
PF2-1	51,600,767	39,881	**51,640,648**
PF2-2	51,510,752	59,154	**51,569,906**
PF2-3	51,461,141	81,144	51,542,285
PF3-1	51,245,155	18,496	51,263,651
PF3-2	51,245,155	18,496	51,263,651
PF3-3	51,245,155	18,496	51,263,651
ST1-1	60,394,425	39,881	60,434,306
ST1-2	53,096,677	60,276	**53,156,953**
ST1-3	52,514,519	91,020	**52,605,539**
ST2-1	51,732,280	39,868	**51,772,148**
ST2-2	51,664,567	58,332	**51,722,899**
ST2-3	51,620,980	80,785	51,701,765
ST3-1	51,415,262	15,214	51,430,476
ST3-2	51,415,262	15,214	51,430,476
ST3-3	51,415,262	15,214	51,430,476

Comparing costs

- D.TOTCOST + D.TOT.EMIS.TAX = Total Cost
- Value of perfect information = Stochastic – Deterministic

	Stochastic	Deterministic	Cost of Perfect Information
SW 1-2	53,156,953	53,159,185	-2,232 ?
SW 1-3	52,605,539	52,540,646	64,893
SW 2-1	51,772,148	51,640,648	131,500
SW 2-2	51,722,899	51,569,906	152,993

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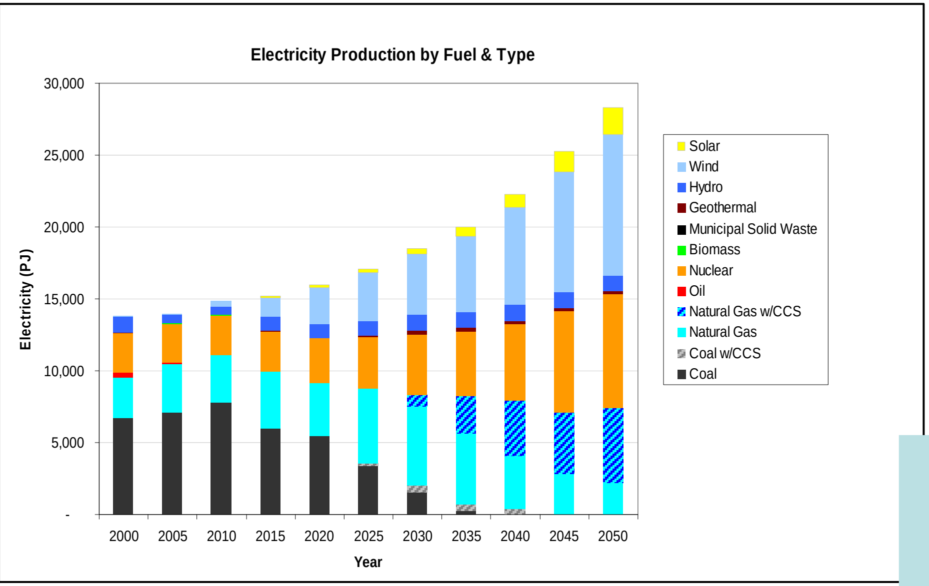
Illustrative Results

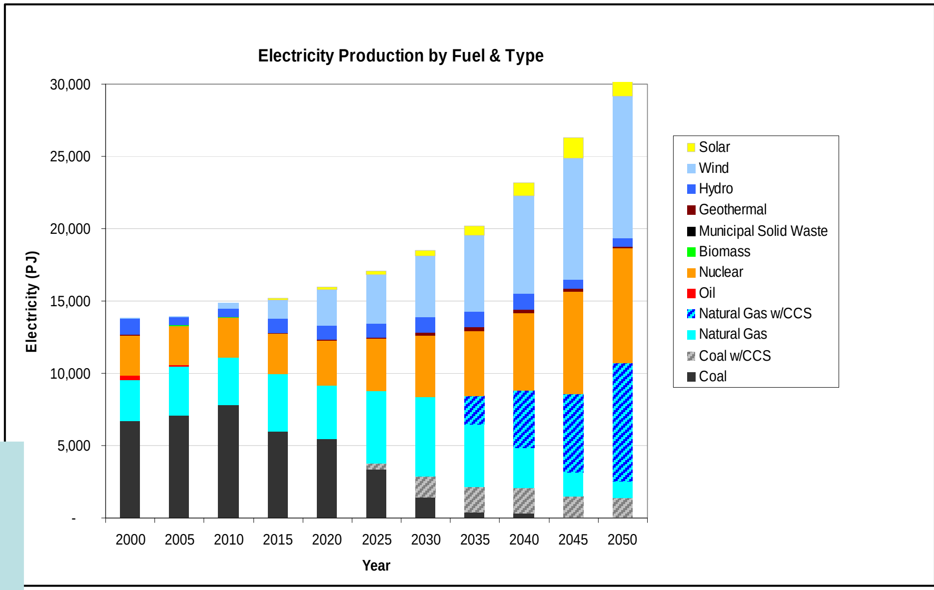
ST1-2 (selected)

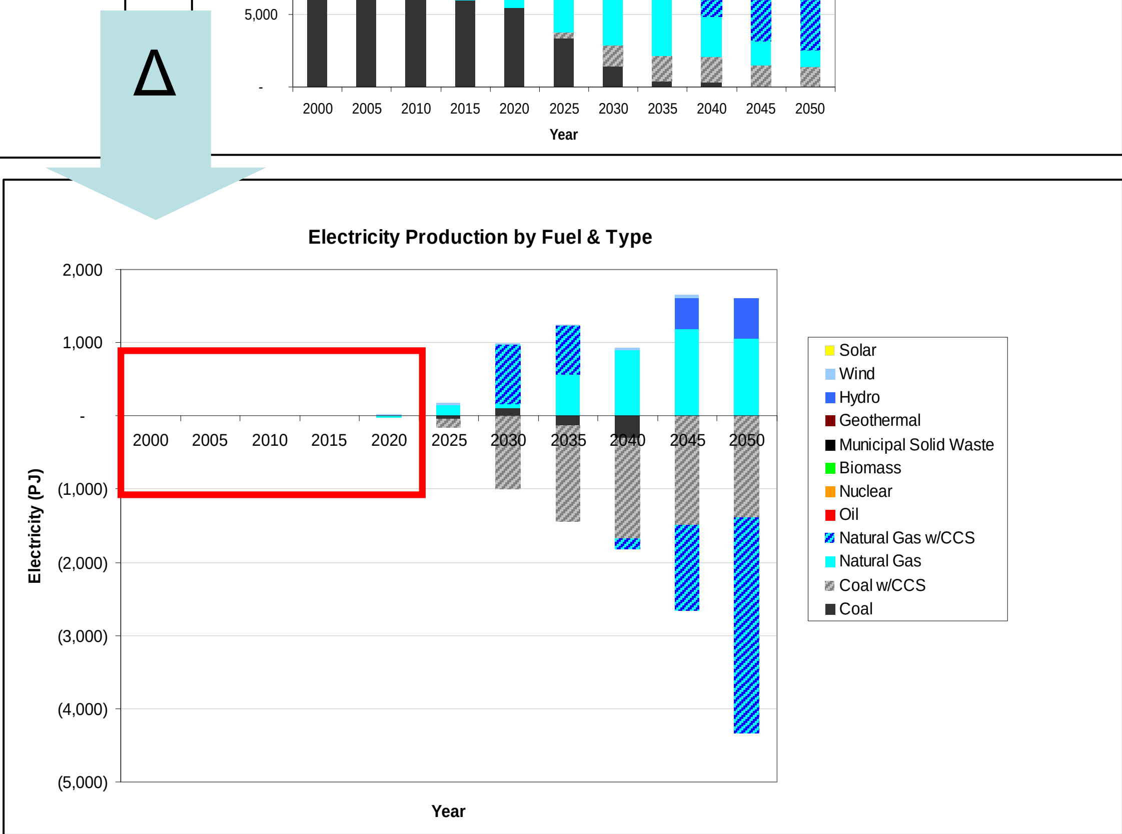
CO2 LWB with medium CCS



ST1-3 (baseline)

CO2 LWB with high CCS



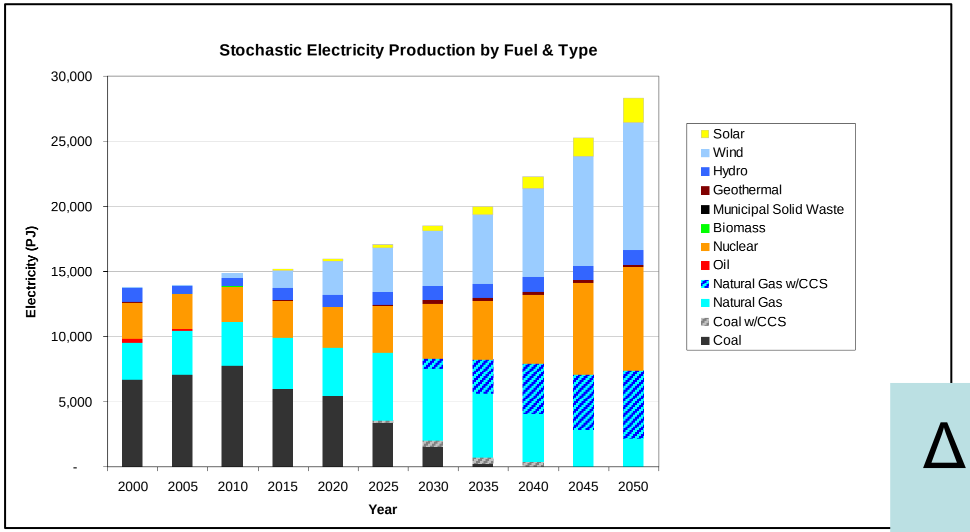


- Less CCS (positive), natural gas is necessary to meet CO2 constraints.
- With more CCS available (negative), Coal w/ CCS is cheapest, but as CO2 limits become tighter, Natural Gas w/CSS is necessary.

Illustrative Results

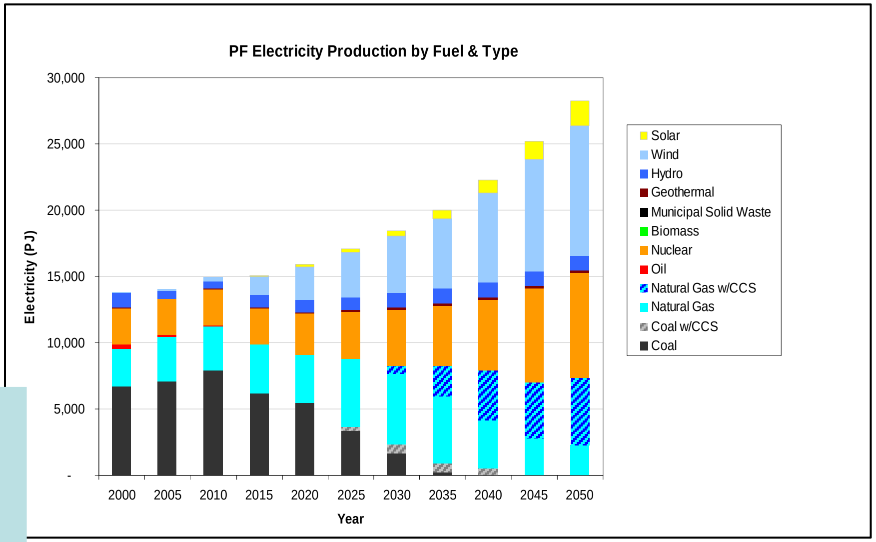
ST1-2

CO2 LWB -CCS medium



PF1-2

CO2 LWB -CCS medium



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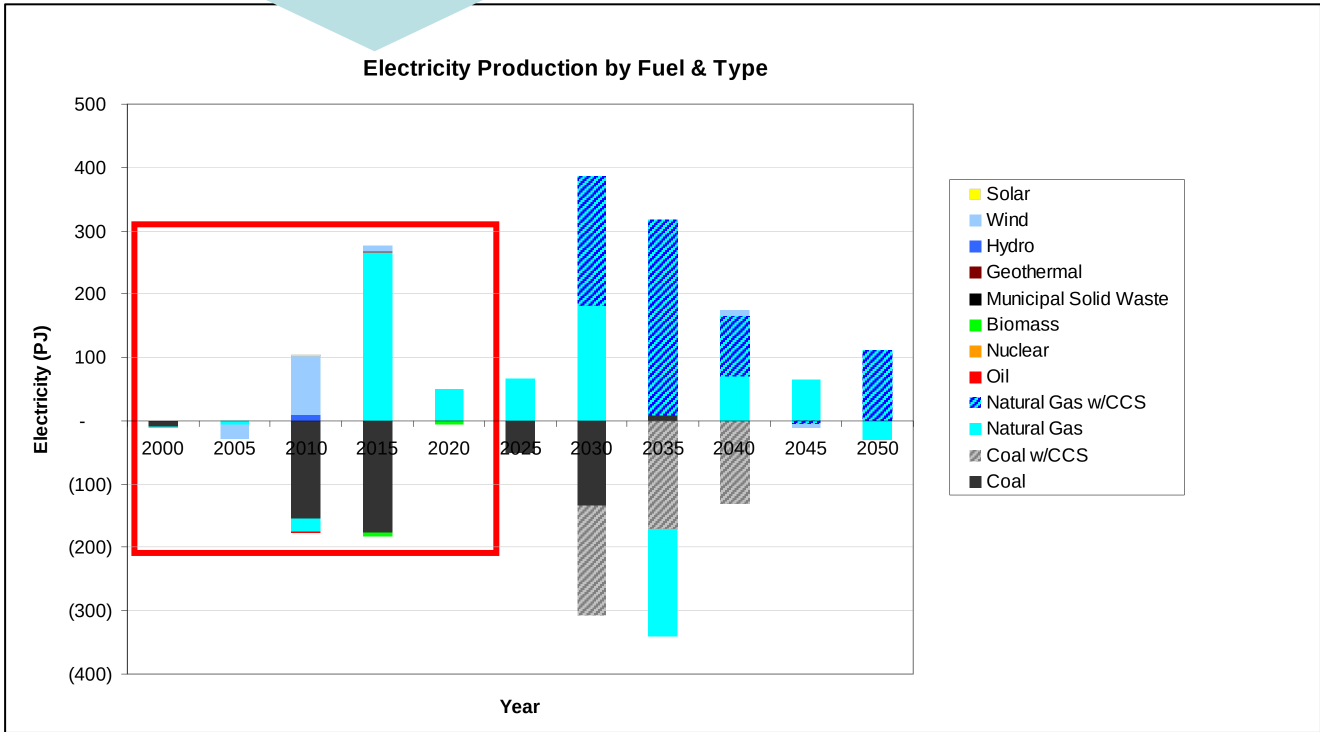
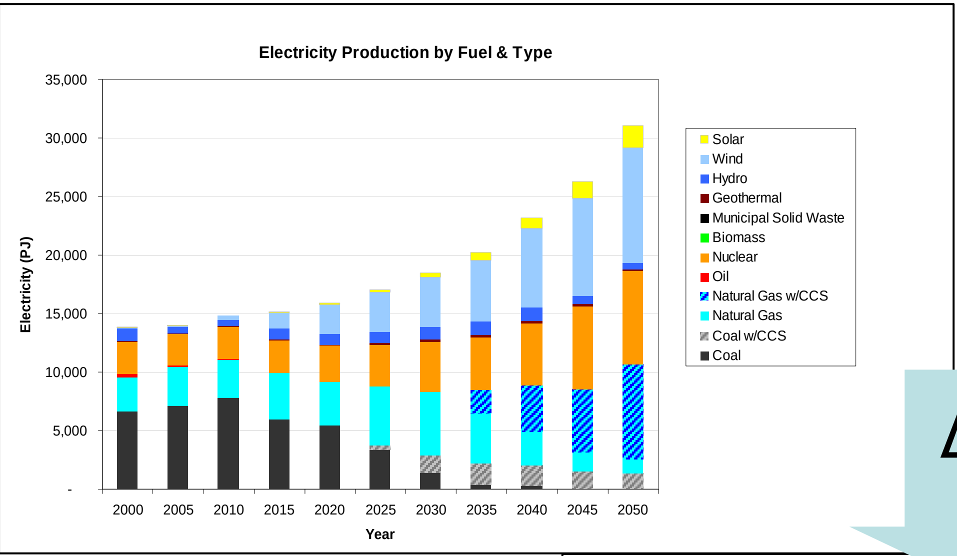


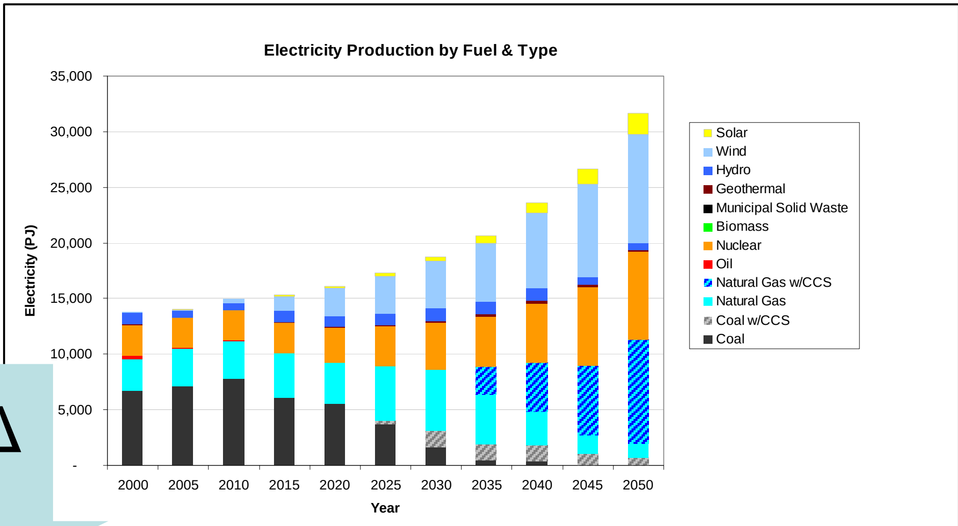
- Wind and natural gas utilized more in ST1-2 than PF1-2

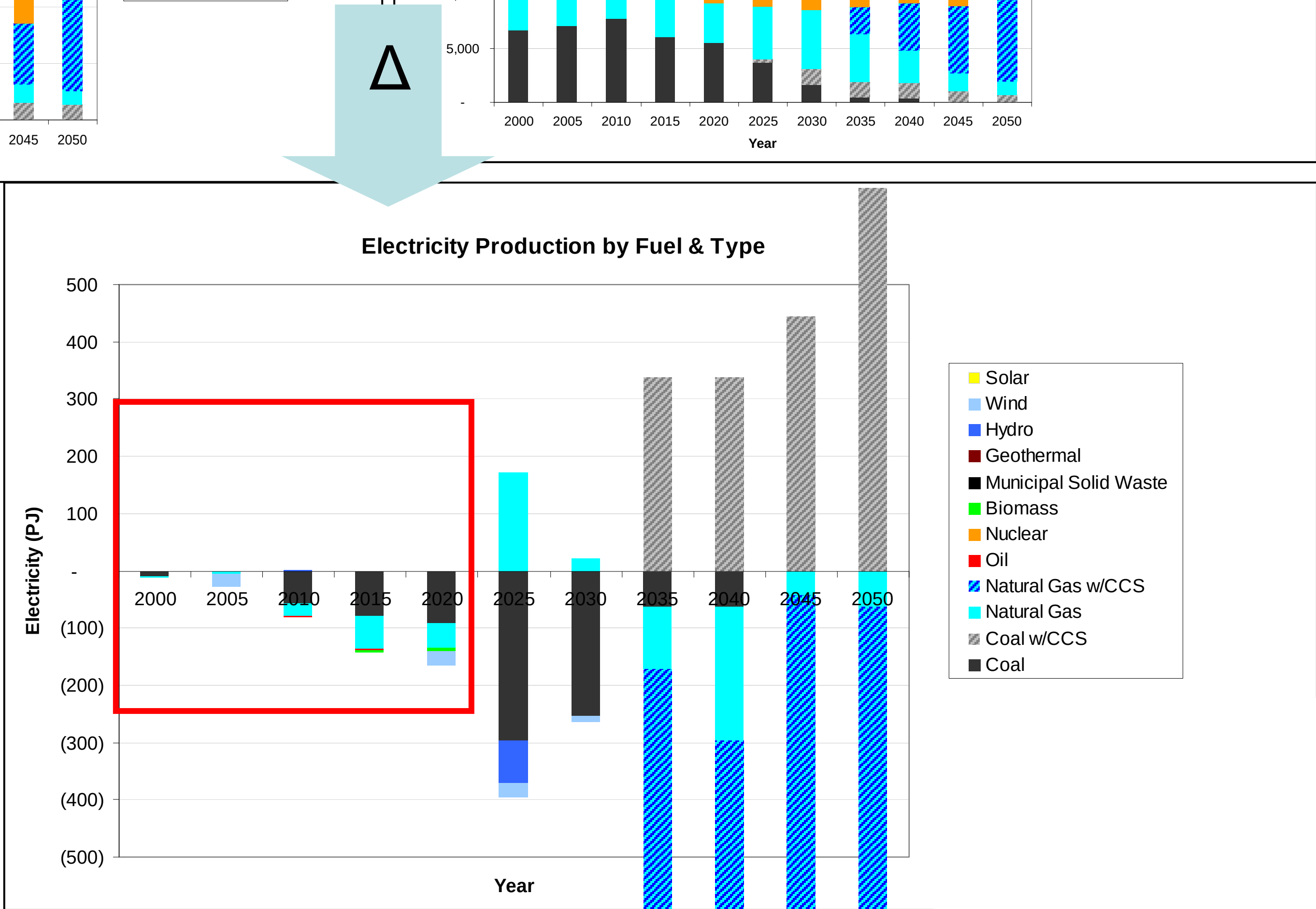
Illustrative Results

ST1-3 CO2 LWB-CCS high

PF1-3 CO2 LWB-CCS high



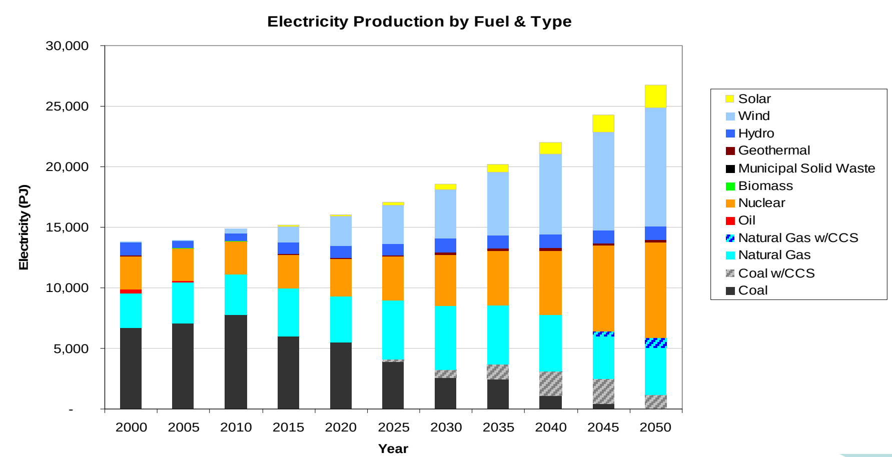




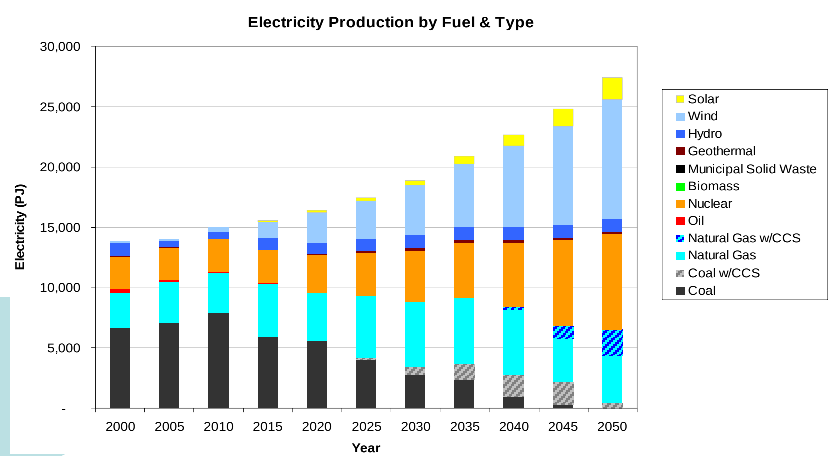
- Trade-off between coal and natural gas CCS

Illustrative Results

ST2-1 CO2 relaxed - CCS low



PF2-1 CO2 relaxed - CCS low



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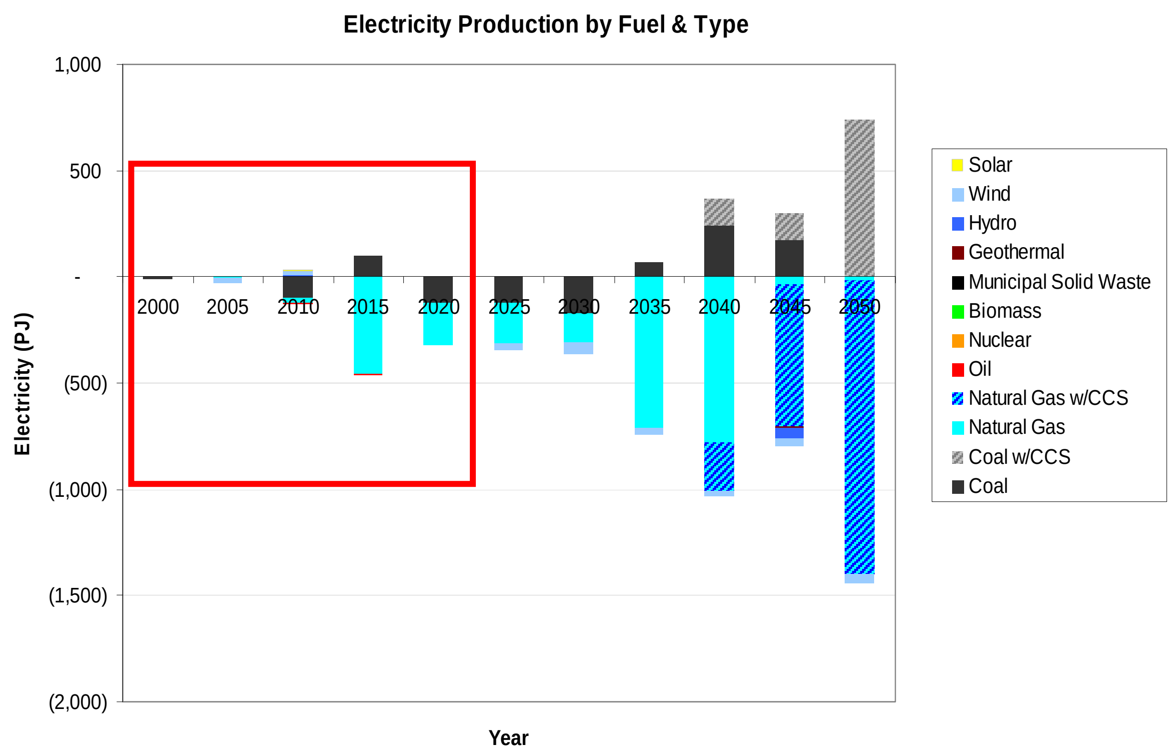
- Low CCS results in increased use of natural gas in PF2-1



Analysis of results

- Scales of differences were much smaller than expected between stochastic and perfect foresight
- Observed a trade-off between natural gas and coal
- New nuclear did not play a critical role

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What's next?

- Updating the results with the latest AEO projections and recent technology cost projections
- Extend the analysis to include additional drivers
  - Fossil fuel prices, especially natural gas prices
  - Availability and costs of coal and natural gas technologies
  - Availability and costs of renewable energy technologies
- Tinker with stochastic parameters to get different results
  - Vary probabilities of branches
  - Apply a risk aversion level to a parameter
    - Weights the cost of specified parameter, giving the modeler control of the uncertainty
    - λ = risk level, $\lambda = 0$ is Perfect foresight, $\lambda > 0$ is risk averse

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THANK YOU

QUESTIONS?

Team and Contact Information

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