The Princeton-Tsinghua Collaboration on Low Emission Energy Technologies and Strategies for China

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China's Energy Challenges

Air Pollution

- Outdoor urban air pollution is severe.
- ~ 700 million Chinese living in rural areas rely in part or wholly on solid fuels for cooking and heating, with high levels of CO and PM_{10} pollution.

Energy Resources

- The demand for energy services is growing rapidly: a tripling is expected by 2050. Domestic energy production will be unable to meet demand without substantial efficiency improvements.
- Coal and biomass are the most abundant domestic fuels in China. Domestic oil and natural gas resources are modest. Renewables and nuclear can provide only modest contributions in the future.

Energy Security

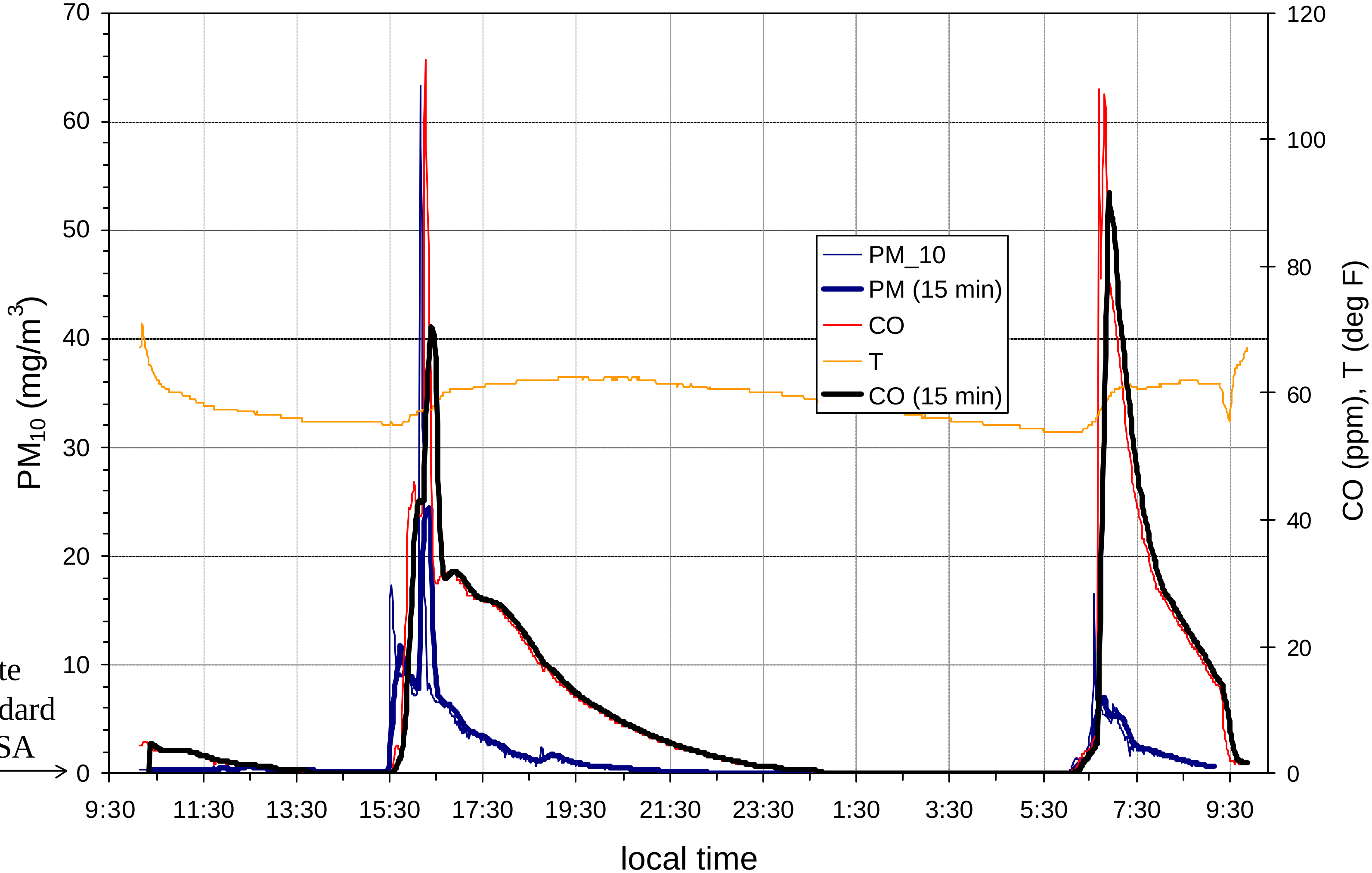
- An especially rapid increase in transportation energy demand is leading China toward over-dependence on imported liquid fuels.

Greenhouse Gas Emissions

- CO_2 emissions will out-strip even those of the USA by 2020 with continued "business-as-usual" energy development.

CO and PM_{10} concentrations in a village home in Jilin Province (29-30 Nov 2001)

15-minute PM standard in the USA



Source: Susan Fischer, UC Berkeley, School of Public Health

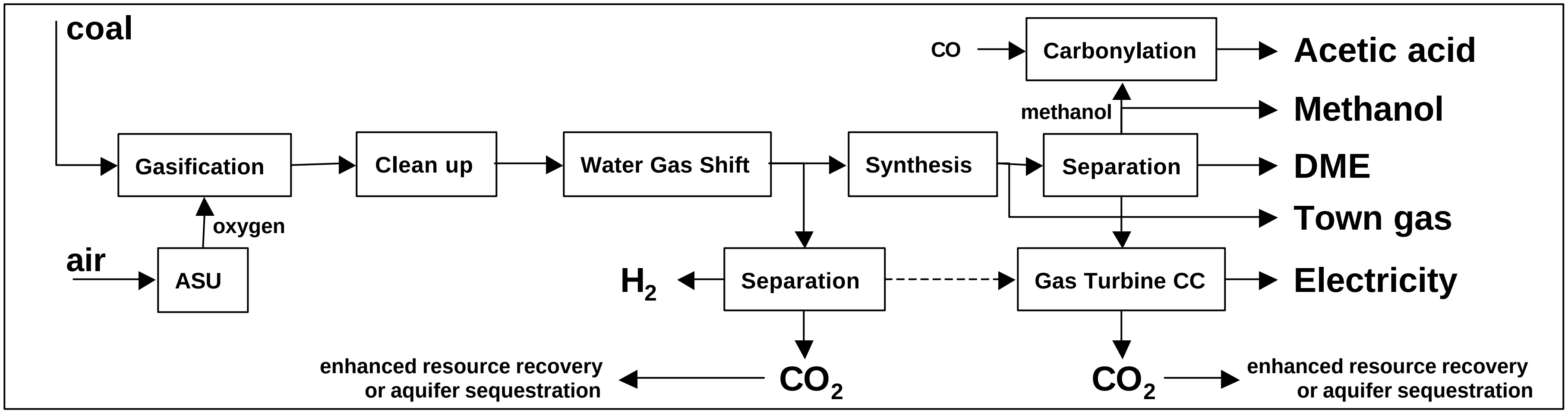
Tsinghua-Princeton Research on Low-Emission Energy Futures

- **Vision**
  - China's energy system could evolve over several decades to one based largely on solid fuels (coal and biomass) and having near-zero emissions of local air pollutants and CO_2. The three main energy carriers would be H_2, electricity, and a clean hydrocarbon such as DME.
- **Objectives**
  - Explore via detailed modeling how China could evolve a clean, low-emission energy future around solid fuels.
  - Catalyze demonstration projects in the near term.

Energy Evolution for China

- The energy system in China is relatively immature, which offers opportunities for establishing infrastructure that could lead to a low-emission H_2-electricity economy based on solid fuels.
- Are there technologies and strategies for the near term that are consistent with such an evolution?
  - Technologies must compete at present energy prices.
  - Technologies must address immediate air pollution problems, especially outdoor urban and indoor rural.
- Gasification-based polygeneration is promising.

Polygeneration



- Polygeneration
  - Higher efficiency and more effective use of capital.
  - Good prospects for cost-competitive production of clean energy carriers and chemicals.
  - Possible CO_2 capture for enhanced HC resource recovery
- Polygeneration could meet most requirements for centralized production of electricity and clean fuels.

Making DME from Coal

Methanol synthesis + dehydration: $CO + 2H_2 \rightarrow CH_3OH \rightarrow ½CH_3OCH_3 + ½H_2O$

➔ DME synthesis requires synthesis gas with overall H_2/CO ratio = 2

Gasification of bituminous coal (with Destek gasifier):

$CH_{0.82}O_{0.06} + 0.27H_2O_{(g)} + 0.41O_2 \rightarrow 0.85CO + 0.15CO_2 + 0.68\ H_2$ ($H_2/CO = 0.8$)

Gasification + Water gas shift ($CO + H_2O_{(g)} \rightarrow CO_2 + H_2$) to achieve $H_2/CO = 2$:

$CH_{0.82}O_{0.06} + (0.27+0.34)H_2O_{(g)} + 0.41O_2 \rightarrow 0.51(CO + 2\ H_2) + 0.49CO_2$

Gasification + WGS + MeOH synthesis:

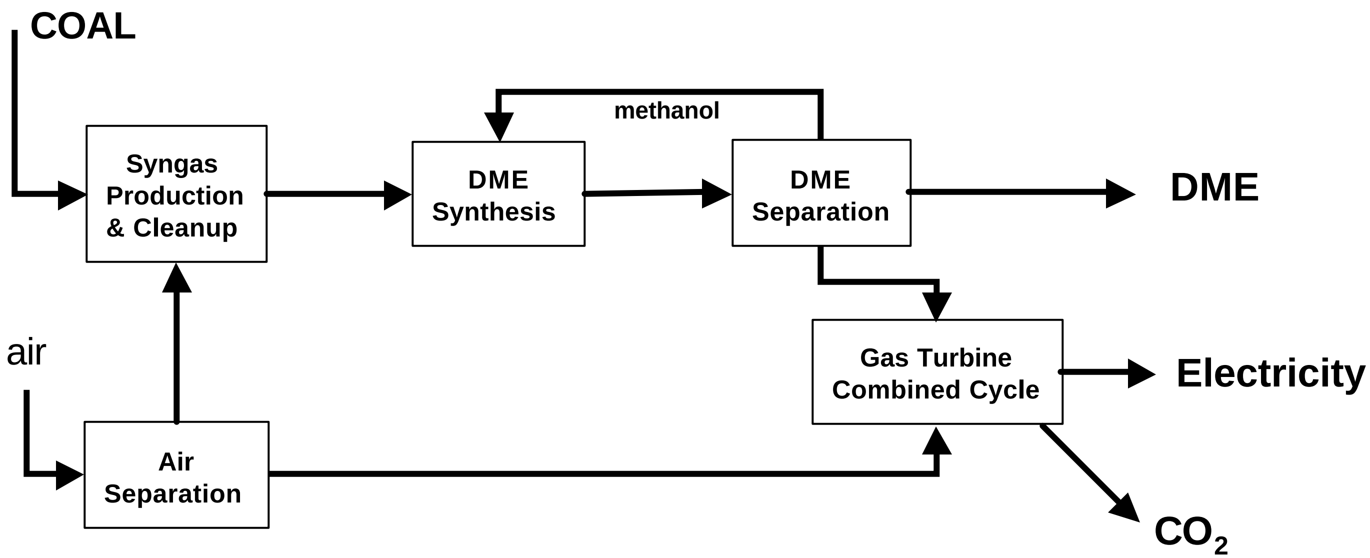
$CH_{0.82}O_{0.06} + 0.61H_2O_{(g)} + 0.41O_2 \rightarrow 0.51CH_3OH + 0.49CO_2$

Gasification + WGS + MeOH synthesis + MeOH dehydration:

$CH_{0.82}O_{0.06} + 0.61H_2O_{(g)} + 0.41O_2 \rightarrow 0.255H_2O + 0.255CH_3OCH_3 + 0.49CO_2$

➔ **At least ½ of C in coal is potentially recoverable as CO_2 for sequestration. Higher recovery possible with polygeneration using "once-through" synthesis.**

Once-through DME from Coal with Co-Production of Electricity



- Fraction of energy in coal converted to DME = 33%
- Fraction of energy in coal converted to electricity = 17%
- Fraction of coal's carbon captured as CO_2 > 70%

Based on preliminary analysis by Air Products and Chemicals.

Polygen Environmental Outlook

- Near term
  - Town gas for cooking and CHP in buildings and factories (piping infrastructure costs are much less for gas than for district heating).
  - Coal IGCC cogenerated power – as clean as natural gas CC power.
  - DME and F-T middle distillates as superclean fuels for diesel engines.
  - DME: superclean fuel for rural cooking
  - Environmentally-friendly production of methanol, acetic acid, and other high-value chemicals.
- Longer term
  - Coal-derived H_2 for fuel cells for transportation and distributed CHP – zero air pollution. Co-production of electricity plus sequestration of CO_2.
  - DME for rural distributed generation and cooking.

Polygeneration Outlook for China

- China's chemical process industry has over 20 oxygen-blown gasifiers in operation, under construction, or on order, making China technologically well-positioned to launch a polygeneration energy strategy.
- The chemical process industries will play a key role in implementing a polygeneration energy strategy.
- Some leading coal processing companies are interested in polygeneration for future expansions.
- Market reform to encourage competition in power generation would be beneficial, since the most favorable polygeneration systems will involve electricity co-production.

A Polygeneration Strategy

- *Phase 1*: Establish polygeneration technologies in the market using petroleum residuals as feedstock and/or making higher value products from coal.
- *Phase 2*: Shift to polygeneration from coal over time; emphasis on production of high-value chemicals and process heat, as well as fuels and electricity.
- *Phase 3*: As chemicals and heat markets saturate, shift new construction to dedicated fuels and electricity production, with some sequestering of CO_2 (possibly for enhanced recovery of CBM).
- *Phase 4*: Polygeneration of H_2 and electricity, with full CO_2 sequestration.

Tsinghua-Princeton Activities

- Detailed performance and cost modeling of polygeneration systems with coal, biomass, or natural gas feed.
  - Products will include process heat, F-T liquids, DME, MeOH, H_2, towngas, electricity, chemicals.
  - With and without CO_2 recovery/sequestration.
- Case studies
  - "Syncity" (synthesis gas city): model coal-based polygeneration energy supply and demand for an actual Chinese city for the near-term (2005-2015 time frame) and long-term (2030-2050).
  - Biomass-polygeneration: model production of DME/electricity from biomass in rural areas with substantial crop residue resources, e.g. Jilin Province (corn stalks).
  - Carbon sequestration case studies for near-term (with enhanced resource recovery, e.g., coal-bed methane) and long-term (deep aquifer storage).
- Identify potential demonstration projects to help launch a zero-emission energy future for China.

Tools

- Process design and modeling
  - ASPEN+
  - Tsinghua process simulation (dynamic)
  - GS (Milan)
- Cost and engineering inputs
  - Chinese feasibility studies, engineering companies, and coal-related companies.
  - BP engineers.
  - Other industry experts, e.g., Bob Moore (APCI, retired).
  - Princeton CMI database.

Plans for 2002

- Development of process modeling tools
  - ASPEN library of unit operations for design-point analysis
  - Cost database for unit operations
  - Explore modeling of dynamic processes
- Process and cost modeling and assessment (MeOH, DME focus)
  - Polygeneration vs. stand-alone single-product plant configurations – design point.
  - Liquid-phase synthesis vs. gas-phase synthesis for polygeneration – design point.
  - Load-following plant configurations with liquid-phase vs. gas-phase synthesis.
- Syncity data collection/analysis and energy system modeling
  - Data collection: present air quality, future economic development objectives, population projections, current and projected demand for energy services, current energy production structure, magnitude and quality of coal reserves.
  - Model and evaluate overall energy/economic impact of alternative polygeneration systems for Syncity.
- Outreach
  - Advise Yanzhou Mining Group, Ltd. on polygeneration expansion plans.
  - Workshop in Yanzhou or Jingchen in January 2003 to report first-year results.
- Initiate studies of C storage by enhanced oil or CBM recovery?

Princeton-Tsinghua Project: Modeling Coal Syngas-Based Energy Systems – "Syncity"

Princeton Tasks

- Polygeneration process design and cost modeling: DME,F-T liquids, methanol, H_2, syngas, chemicals, heat, electricity.
- Carbon sequestration analysis for near-term EOR and CBM; aquifer CO_2 storage for long term.
- Integrated strategic analysis.

Tsinghua Tasks

- Energy-data collection for Yanzhou and Jincheng.
- Coal-based polygeneration process design, simulation.
- Lifecycle environmental impact and cost analysis.
- Integrated strategic analysis.
- Outreach to Yangzhou Mining Group Ltd., Shanxi Jincheng Anthracite Coal Mining Group Ltd., and other decision makers.

Future Implications of China’s Energy-Technology Choices

(a Markal Modeling Exercise)

- Summary of a report commissioned by the Working Group on Energy Strategies and Technologies (WGEST) of the China Council for International Cooperation on Environment (CCICED).*
- Modeling and analysis carried out by Tsinghua University (Professors Wu Zongxin and Chen Wenying; graduate student Gao Pengfei), Princeton University (Eric Larson), and Clean Energy Commercialization (Pat Delaquil).
- Objective of the analysis: Identify and analyze alternative energy-technology scenarios for China that will allow continued economic development and energy security while promoting a healthy environment.

* Z. Wu, P. DeLaquil, E.D. Larson, W. Chen, and P. Gao, *Future Implications of China’s Energy-Technology Choices*, prepared for the Working Group on Energy Strategies and Technologies of the China Council for International Cooperation on Environment and Development, 24 July 2001, 50 pp.

Energy Challenges for China

- How can China meet its projected demand for energy services? (Conventional projections show a domestic energy shortfall of 2000 Mtce in 2050.)
- How can China meet projected liquid fuel needs, especially for transportation, while not becoming over-dependent on imported energy?
- How can China reduce urban and rural air pollution while meeting its projected demands for energy services?
- How can China meet requirements for lower carbon emissions that may arise from global warming concerns?

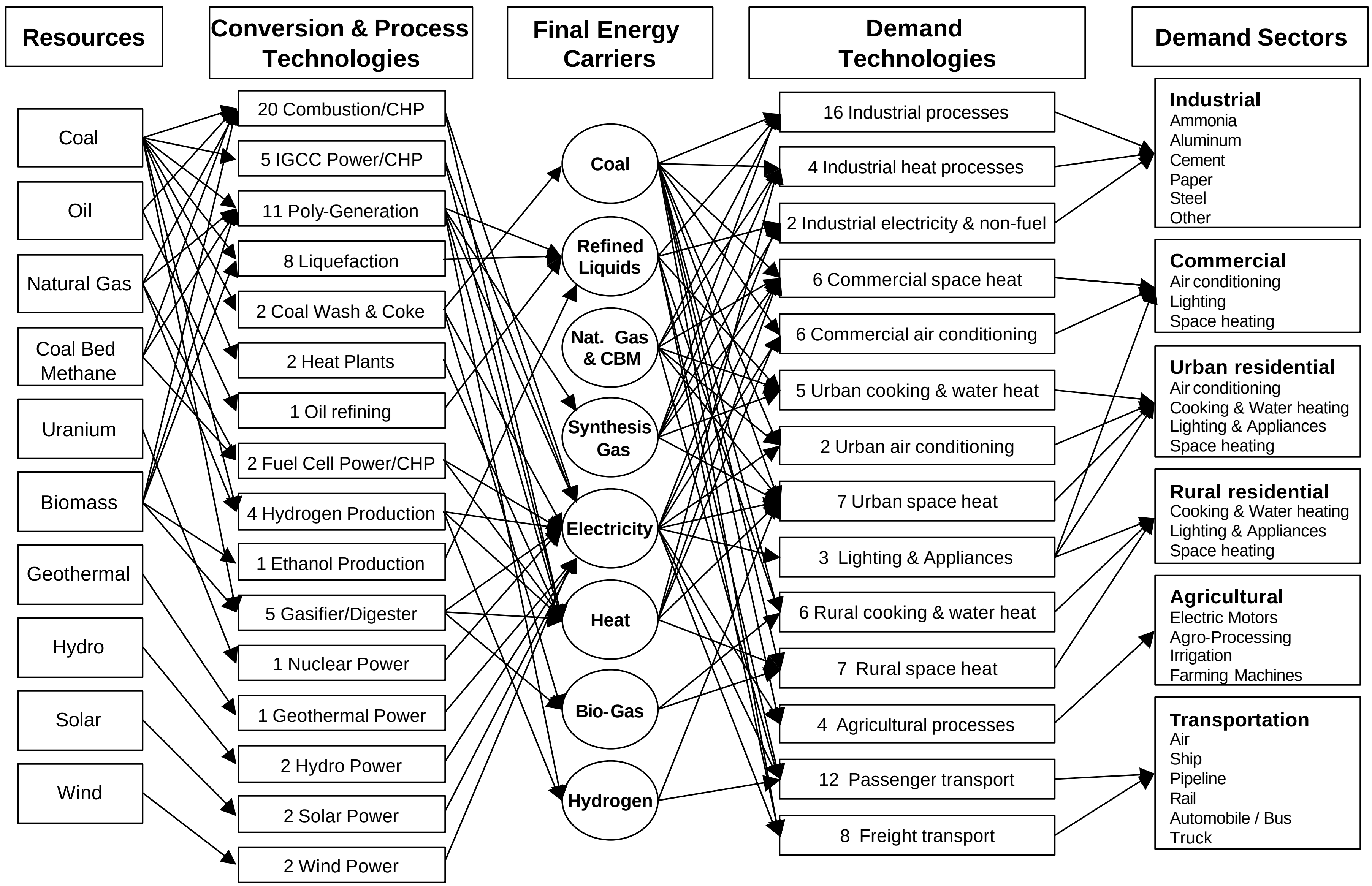
What can MARKAL do?

- Markal software uses a linear programming solver to identify the least-costly mix of primary energy resources and conversion and end-use technologies (chosen from within a set of technologies defined by the user) that will satisfy a user-specified set of energy service demands.
- Markal selects technologies that minimize total cumulative system cost over the specified analysis period, subject to:
  - Meeting all energy demand requirements,
  - Capital stock turnover of equipment,
  - Environmental/policy constraints imposed by the user.
- Markal makes choices based on life-cycle costs
- Enables “what if?” analysis, e.g. for alternative sets of technologies or environmental constraints.

MARKAL Input Requirements

- End-use energy-demand projections
- Technology profiles
  - Efficiency, availabilities, emissions characteristics, first-use dates, maximum allowed new investment rates, capital and operating costs
- Primary energy resources: production rates and cumulative exploitation limits.
- Policy-related constraints (environmental, energy security, etc.)

China MARKAL Model (simplified)



Two Technology Scenarios

(emphasis on exploring impact of alternative conversion-technology choices)

BASE TECHNOLOGIES

- Representing continuation of current trends:
- Modern energy end-use (“demand”) technologies.
- Current and advanced coal combustion technologies.
- Current town gas technologies.
- Current renewable energy technologies.
- Most technologies area available starting in 1995 or 2000.

ADVANCED TECHNOLOGIES

- High-efficiency industrial processes.
- Distributed fuel cells for urban residential demands.
- Hybrid-electric and fuel cell vehicles.
- Advanced polygeneration with coal, NG, and biomass for fluid fuels and electricity production.
- Advanced renewable energy technologies.
- Carbon capture and sequestration options (with and without enhanced resource recovery).
- Advanced technologies available starting between 2005 and 2015.

Energy Conversion Technologies

- Specific configurations for technologies chosen to represent broader technology class
- Costs and efficiencies for existing Chinese technologies based on current data
- All other technologies are from U.S.-based studies
- SO_2 emissions for Chinese technologies assume an average of 1.2% sulfur in raw coal
- Coal washing: 18% in 1995 rising to 80% in 2050.
- Advanced-technology emissions are estimated from Chapter 8 in World Energy Assessment

Coal Technologies

BASE

- Electric
  - Conventional coal, 100, 200, 300 MW (with and without emissions controls)
  - Pulverized coal (PCC), 500 MW
  - AFBC, PFBC, Ultra-supercritical steam
  - Cogeneration
    - Conventional steam w/ district heat (trad. & adv.)
    - Modern PCC w/ industrial heat
- Heating
  - Conventional and Advanced boilers
- Process
  - Coke making
  - Coal washing
  - Town gas systems with coke co-product
  - Advanced coal gasification

ADVANCED

- Electric
  - IGCC and IGCC with shift reactor and CO2 capture/sequestration
  - Solid-oxide fuel cell with CO_2 capture/sequestration
  - IGCC with H_2 separation membrane reactor, w/ & w/o CO_2 capture/sequestration
  - Cogeneration
    - IGCC with industrial process heat
  - Polygeneration
    - DME, w/ and w/o CO_2 capture/seq.
    - H_2, w/ and w/o CO_2 capture/seq.
    - Methanol and industrial heat
    - Methanol, town gas, and industrial heat
- Process
  - Indirect liquefaction: F-T liquids (w/ and w/o CO_2 capture/seq.), methanol, and DME
  - Hydrogen: conventional and with augmentation by CBM conversion (CBM by CO_2 injection)

Renewable Technologies

BASE

- Electric Conversion
  - Biomass Combustion (AFBC Steam Cycle)
  - Village-scale Biomass Gasifier-IC Engine Cogeneration
  - Local Wind Farms
  - Solar Residential PV Systems
  - Hydro
    - Larger Than 25 MW
    - Smaller Than 25 MW
  - Geothermal
- Process
  - Biomass Digesters
  - Village-scale Cooking Gas Systems

ADVANCED

- Electric
  - Village-scale Gasifier-Microturbine Cogeneration
  - Village-scale Gasifier SOFC Hybrid Electric
  - Remote Wind Farms With Long-distance Transmission
  - Central Solar PV Systems
- Process
  - Ethanol from cellulosic biomass (crop residues)
  - Biomass Polygeneration
    - Once-through F-T Liquids, With IGCC Electricity
    - Once-through DME, With IGCC Electricity

Other Technologies

BASE

- Electric
  - Gas turbine simple cycle peaking
  - Gas turbine combined cycle (GTCC)
  - GTCC for industrial cogeneration
  - OIL Steam-electric
  - Oil Combined cycle
  - Nuclear
- Process
  - Oil Refinery

ADVANCED

- Electric
  - GTCC, with CO_2 capture/sequestration
  - GTCC with once-through F-T liquids
  - Distributed fuel cell cogeneration (Natural gas and H_2)
- Process
  - Natural Gas conversion: F-T liquids (w/ and w/o CO_2 capture/sequestration), methanol, and DME
  - Hydrogen: conventional technology (w/ and w/o CO_2 capture/sequestration)
  - CBM Stimulation by CO_2 injection

Demand Technologies

- Specific configurations for technologies chosen to represent broader technology class
- Inputs for existing Chinese technologies based on current data
- Other technology costs and efficiencies are based on data published in World Bank, ERI, LBNL and other U.S.-based studies of China energy sector
- Conservation technologies used to model specific end-use efficiency improvements

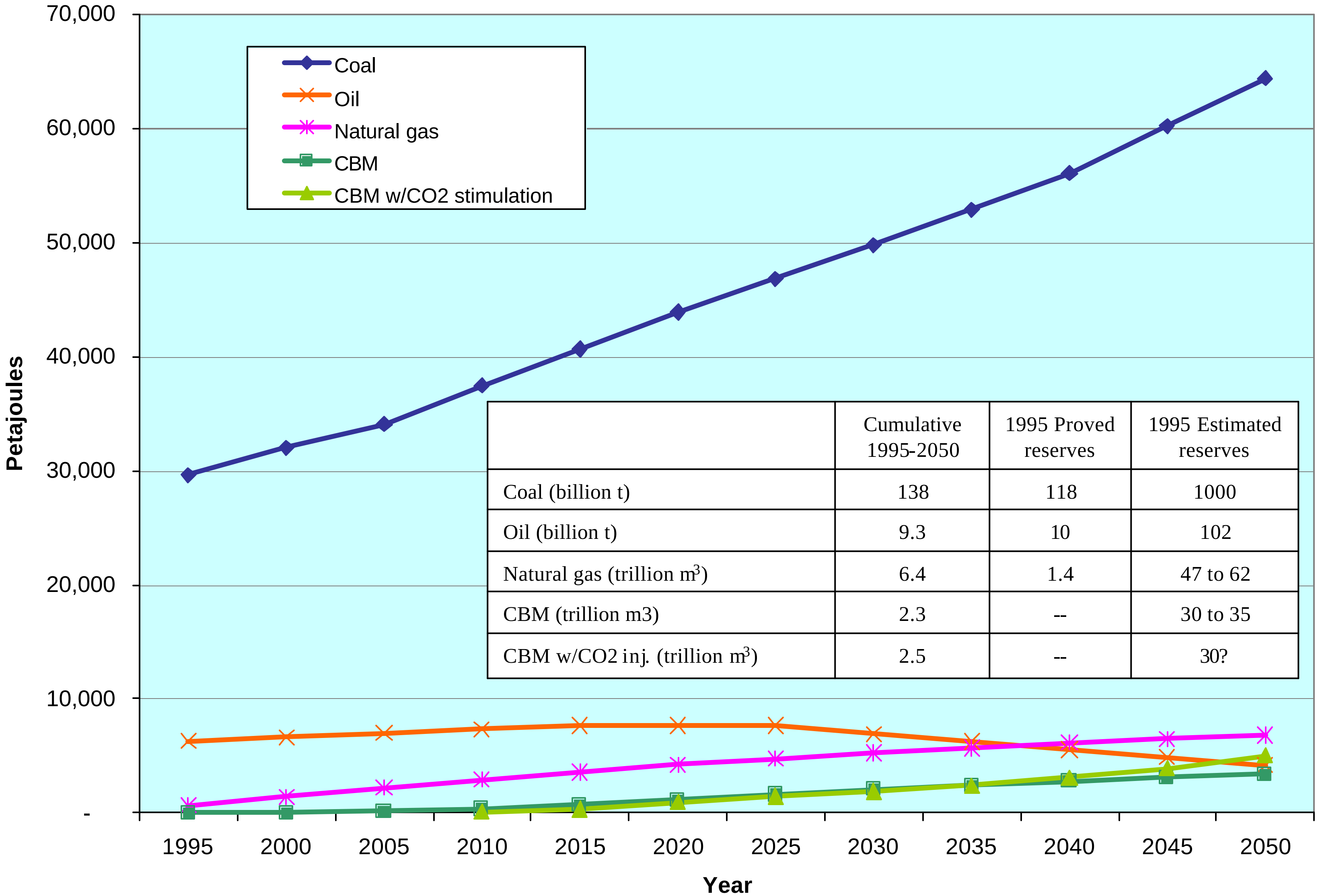
Industrial & Commercial Demand Technologies

- **Industrial**
  - **Steel**: Existing BOF, modern DRI/EAF, advanced smelt reduction, assumptions on scrap recycle
  - **Ammonia**: Coal, oil and natural gas
  - **Aluminum**: Existing, modern, advanced, assumptions on scrap recycle
  - **Paper**: Existing, modern, advanced
  - **Cement**: Small, wet, dry and advanced dry
  - **Other**: Electric, heat, non-fuel
- **Commercial**
  - Space heat, cooking and water heating: Coal, oil and gas boilers, electric heaters, district heat
  - Air conditioning
  - Lighting and appliances

Residential and Transport Technologies

- **Urban Residential**
  - Air conditioning
  - Cooking and water heating (coal, gas, electric and LPG/DME stoves)
  - Space heating (coal and gas boilers, coal stoves, electric heaters, district heat)
  - Lighting and appliances
- **Rural residential**
  - Cooking and water heating (coal, biomass, biogas and LPG/DME stoves, solar)
  - Space heating (coal, biomass, biogas and DME stoves, solar houses and solar panels with coal backup, village CHP/district heat)
  - Lighting and appliances
- **Transport**
  - **Passenger**: Air, ship, train (diesel and electric), bus (diesel and fuel cell), car (gasoline, hybrid, and H_2 fuel cell)
  - **Freight**: Pipeline, air, ship, train (coal, diesel, and electric), truck (diesel and gasoline)

Fossil Fuel Supply Constraints

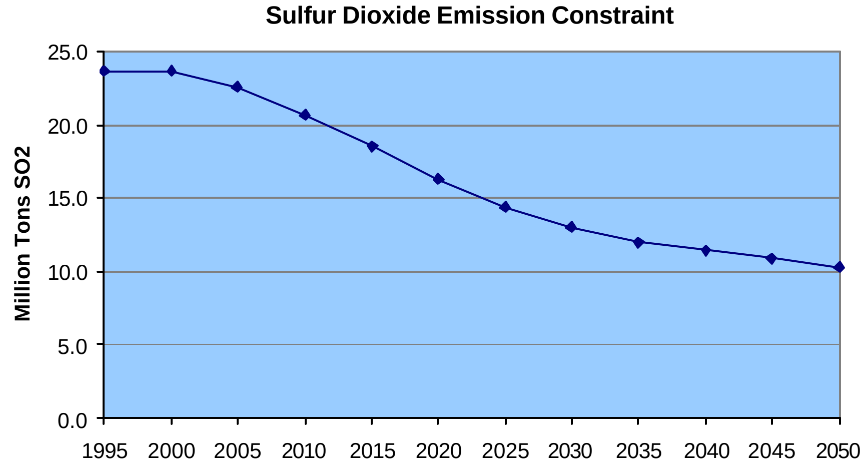


	Cumulative 1995-2050	1995 Proved reserves	1995 Estimated reserves
Coal (billion t)	138	118	1000
Oil (billion t)	9.3	10	102
Natural gas (trillion m^3)	6.4	1.4	47 to 62
CBM (trillion m3)	2.3	--	30 to 35
CBM w/CO2 inj. (trillion m^3)	2.5	--	30?

Environmental and Energy-Security Constraints

Sulfur Emissions Constraint

- SO_2 emission level for 2020 is government target of 16.5 Mt
- 2050 constraint of 10.4 Mt brings China to same level of SO_2 emission per GJ of coal consumption as US in 2000



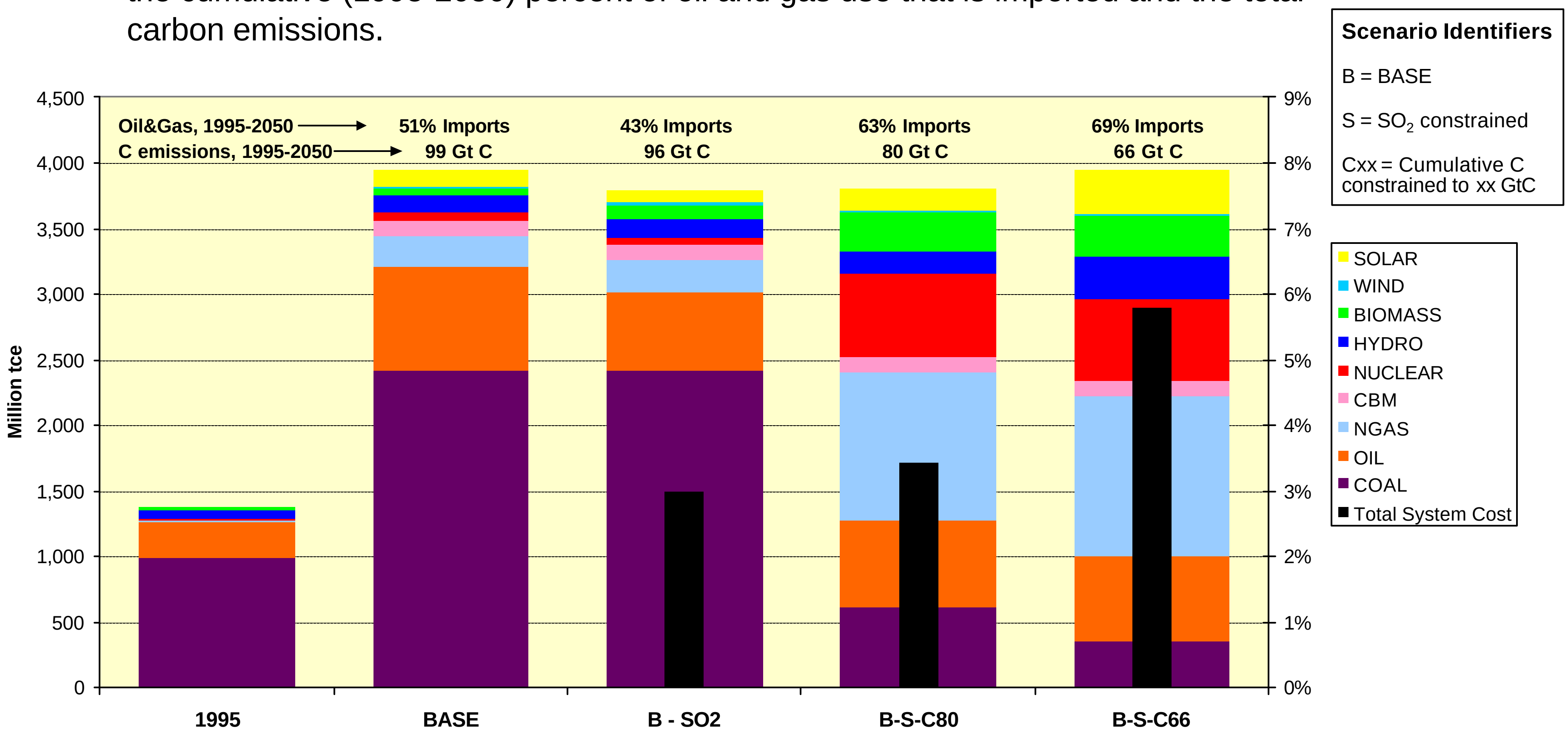
Energy Security Constraint

- Imported oil and gas constrained to be between 20% to 40% of total liquid and gas fuel consumption in any given year.

Carbon Emissions Constraint

WRE emissions scenario		Cumulative CO_2, 1990-2100 (Gt C)		China's "allowance" 1995-2050 (Gt C)
	Stable CO_2 (ppmv)	Global	China's "allowance"	
High	750	1400	301	89
Medium	550	1100	237	80
Low	450	750	161	66
Very low	350	380	82	46

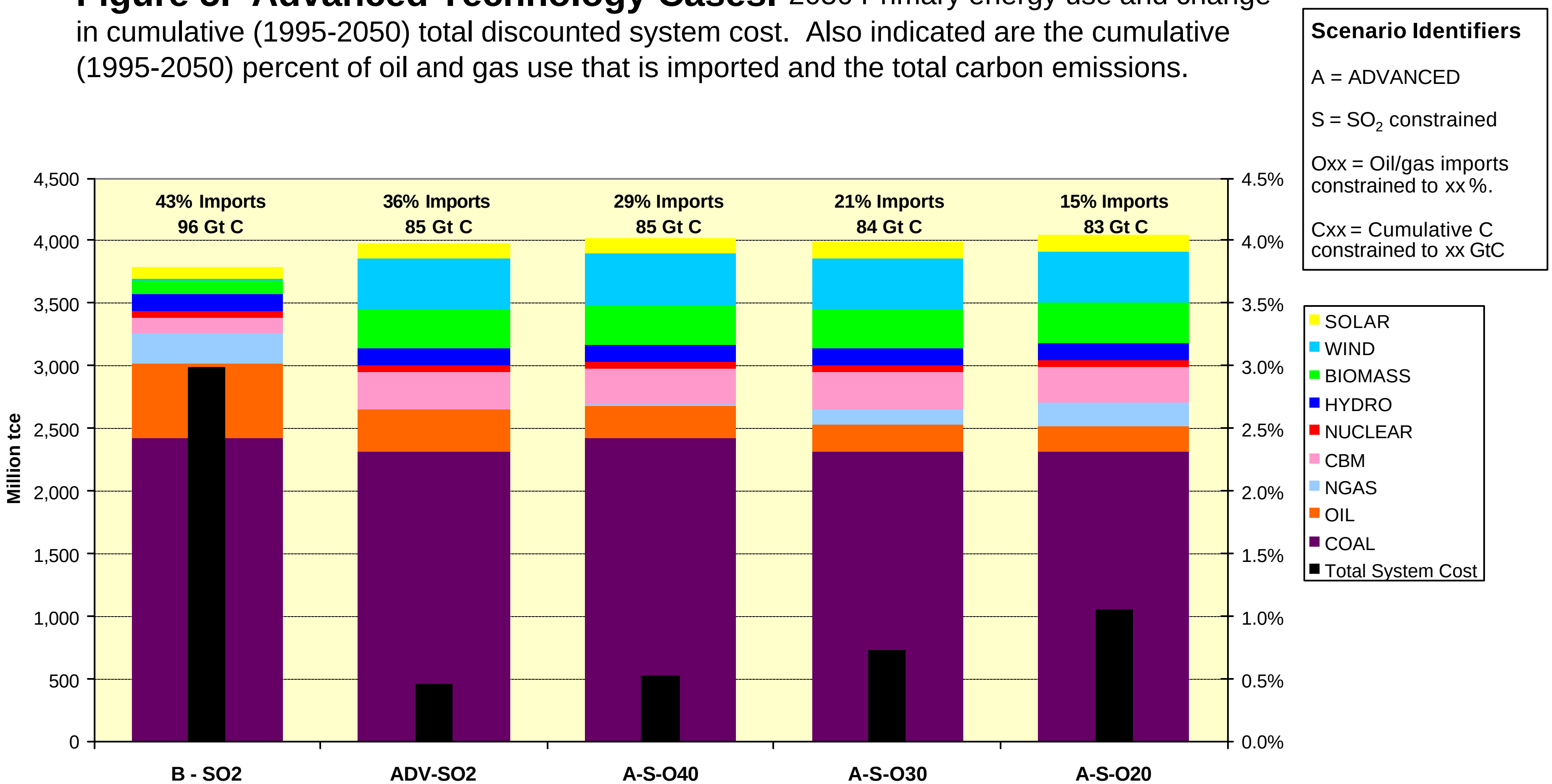
Figure 4. BASE Technology Scenarios. 2050 primary energy use and change in cumulative (1995-2050) discounted total system cost. Also indicated are the cumulative (1995-2050) percent of oil and gas use that is imported and the total carbon emissions.



BASE Technology Scenarios

- **SO_2 constraints can be met with no fundamentally new technology.**
- **Reducing CO_2 emissions requires a drastic reduction in coal use, NG imports of 60 to 70%, maximum use of nuclear and biomass, and significant hydro and solar use.**
- **The 46 Gt CO_2 limit (350 ppm world) cannot be achieved.**

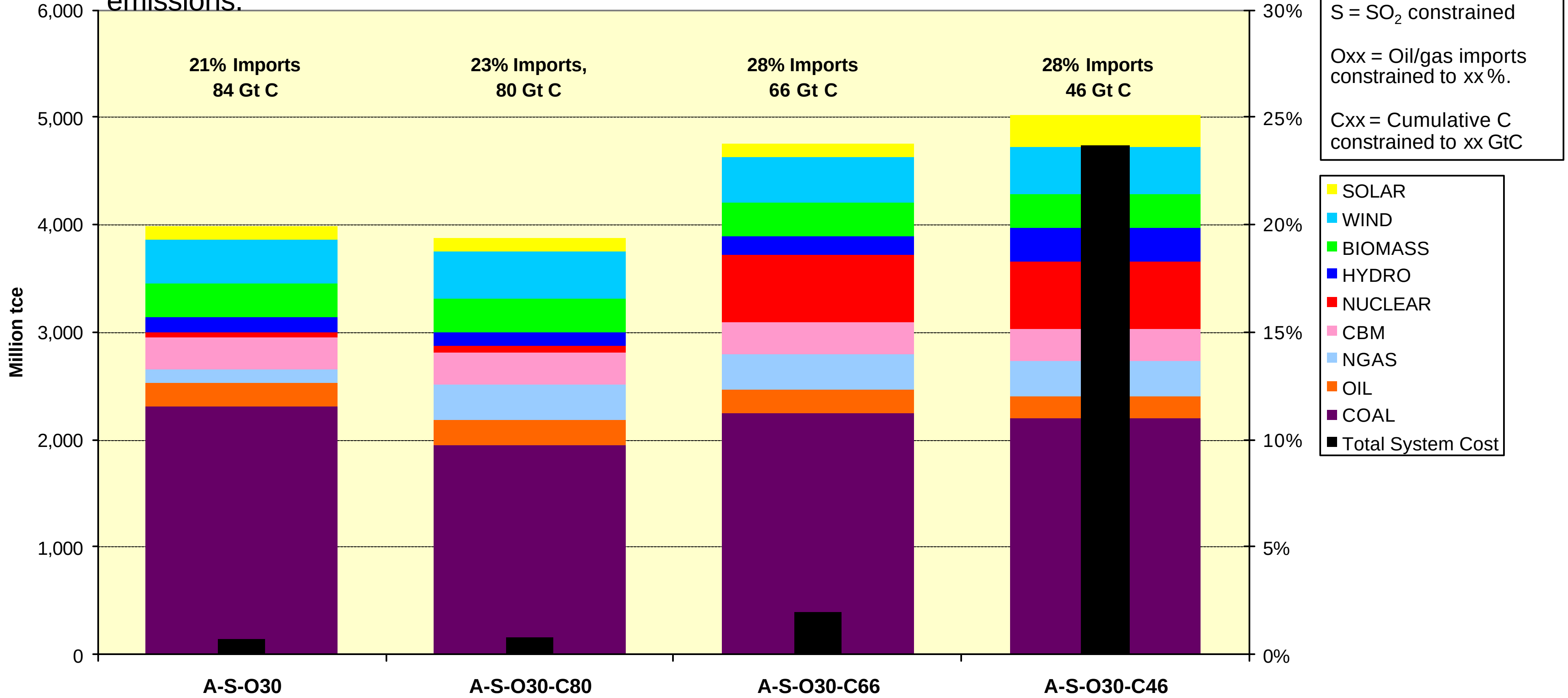
Figure 5. Advanced Technology Cases. 2050 Primary energy use and change in cumulative (1995-2050) total discounted system cost. Also indicated are the cumulative (1995-2050) percent of oil and gas use that is imported and the total carbon emissions.



ADVANCED Technology Scenarios

- **SO_2 constraints can be met at lower cost than in BASE scenario.**
- **With no explicit constraint on energy imports or carbon emissions, oil and gas imports are reduced to 36% of total oil/gas, and carbon emissions are reduced by 16% relative to BASE.**
- **Oil/gas imports can be reduced to below 20%, with little cost increase, primarily by increasing use of domestic natural gas.**

Figure 6. Advanced Technology and Carbon Constraint Cases. 2050 Primary energy use and change in cumulative (1995-2050) total discounted system cost. Also indicated are the percent of oil and gas use that is imported and the total carbon emissions.



ADVANCED Scenarios with Carbon Constraints

- SO_2 constraint, and any allowable cumulative C emissions (corresponding to 750 ppm to 350 ppm CO_2 world) can be achieved with less than 30% oil/gas imports.
- 550 ppm world requires some CO_2 capture for enhanced oil/gas recovery.
- 450 ppm world requires either maximum use of nuclear or maximum hydro, along with CO_2 sequestration in addition to that for enhanced resource recovery.
- 350 ppm world requires significant solar penetration and significant cost increase.

Detailed Comparisons of Two Scenarios

- BASE technologies with SO_2 cap.
- ADVANCED technologies with SO_2 cap, 30% oil/gas imports, and 66 Gt CO_2 cap (450 ppm world).

Figure 7. Total Primary Energy Comparison

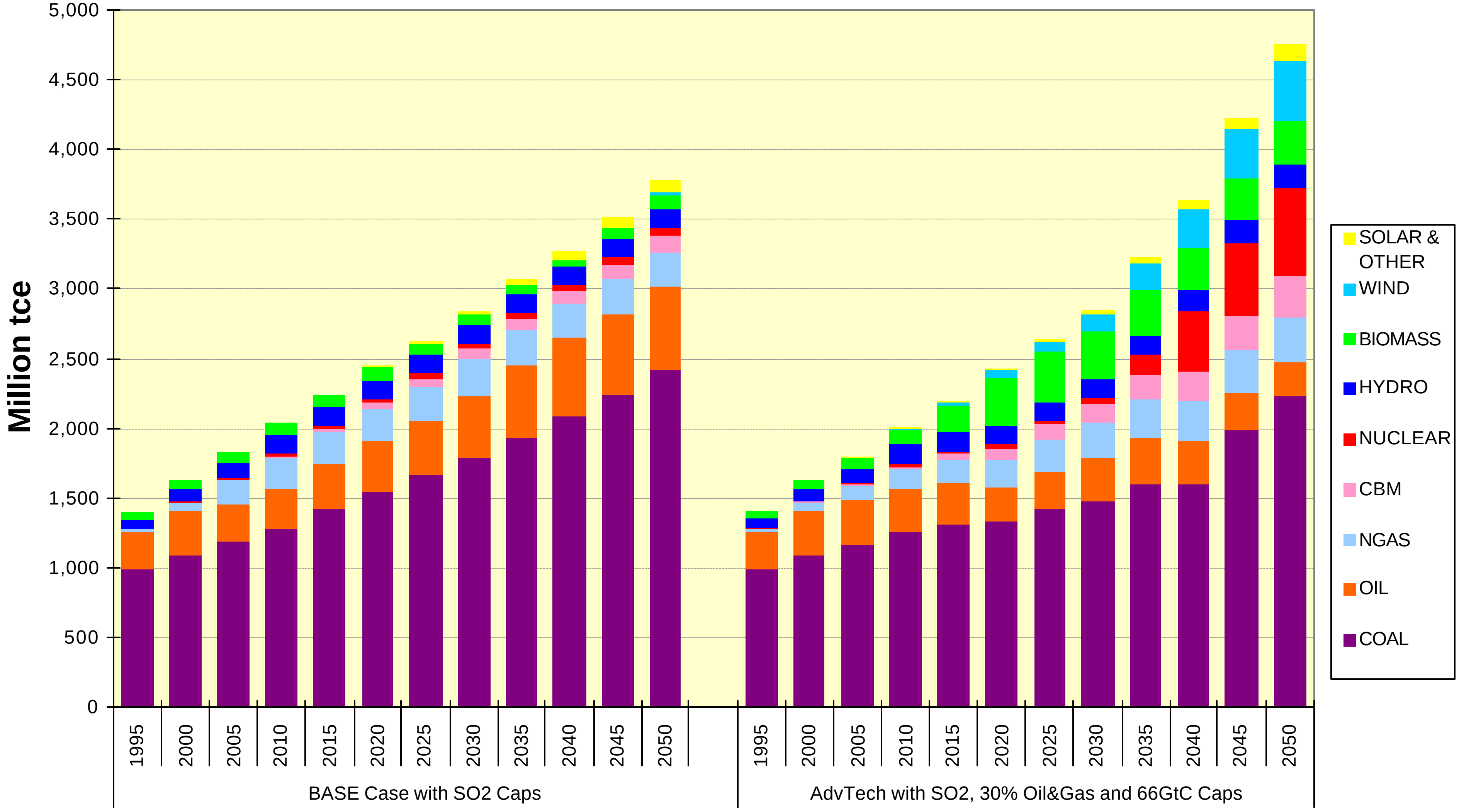


Figure 9. Gas & Synthetic Liquid Fuels

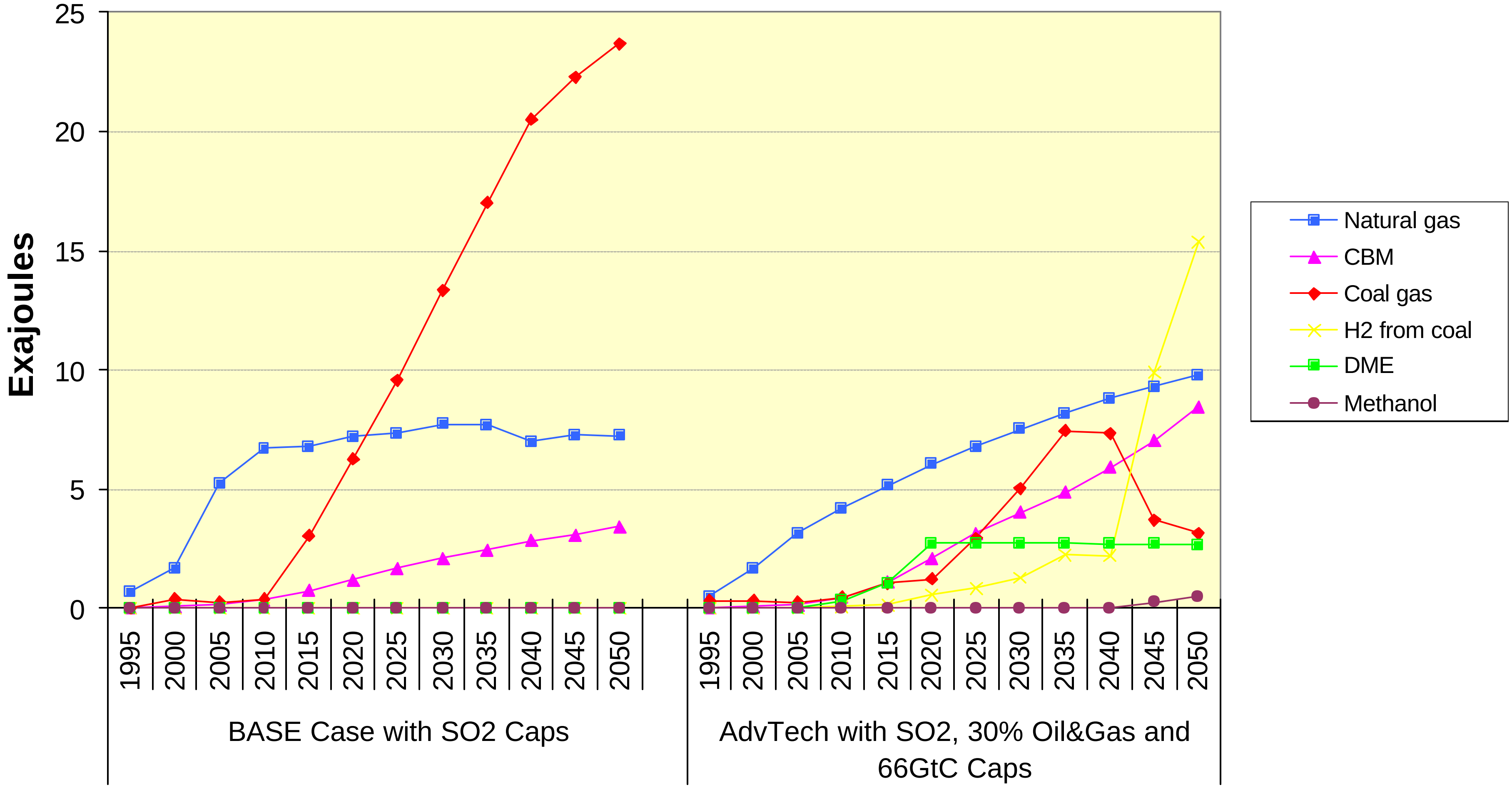
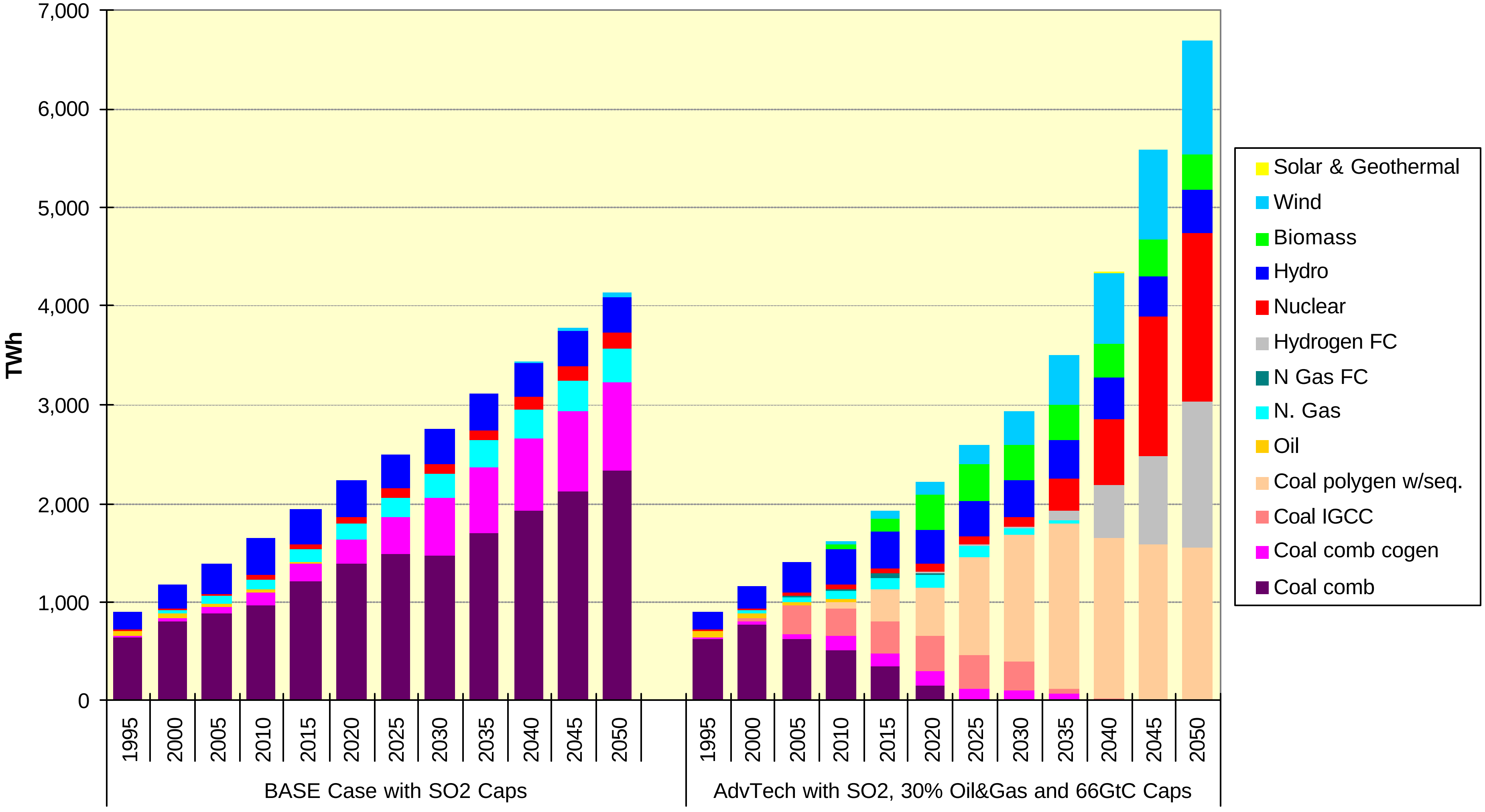


Figure 12. Comparison of Electricity Production Fuel/Technology Selections



Conclusion - Base Technologies

- A “business-as-usual” approach to energy supply will not enable China to achieve its economic development aspirations while simultaneously meeting energy-security and local air pollution reduction goals.
- This is true even if end-use energy efficiency improvements are aggressively pursued and a high level of nuclear electricity enters the economy.
- Moreover, a business-as-usual energy-supply strategy does not provide the possibility for achieving meaningful reductions in carbon emissions without very high levels of energy imports.

Conclusion - Advanced Technologies

- An advanced-technology strategy based on energy efficiency, renewables, and synthetic fuels would enable China to continue social and economic development while ensuring energy security and improved local and global environmental quality.
- Such a strategy would require policies in China that
  - Encourage utilization of a wider variety of primary energy sources (especially biomass and wind) and secondary energy carriers (especially synthetic fluid fuels from coal and biomass)
  - Support the development, demonstration and commercialization of new clean energy conversion technologies, especially for coal gasification, to ensure that they are commercially available beginning in the next 10 to 20 years
  - Support aggressive end-use energy efficiency improvement measures