The US Spent Nuclear Fuel Legacy
and
The Sustainability of Nuclear Power

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Caveats and Acknowledgements

- The conclusions and opinions presented are those of the authors and do ***not*** necessarily reflect those of Los Alamos National Laboratory, US DOE, or any agency of the US Federal Government.
- All errors of commission or omission are ours, and the usual caveats apply.
- We owe a tremendous debt to over 200 individuals who provided data and expertise in specialized areas of energy technology, supply, and consumption over a two year period. Without this "grass roots" community contribution, effort and support, we would not have been able to complete this work.

Issues for US Nuclear Electricity Generation

- In 2001, approximately 20.5% of the electricity generated in the US was provided by nuclear generation.
- Economics, reliability and safety have improved substantially over the last 20 years for nuclear electricity generation facilities.
- Currently, well over 31,000 metric tons of “legacy” spent nuclear fuel resides in cooling or interim dry storage. By the expiration of the majority of nuclear licenses in 2020, 1.5 Yucca Mountains will be required to store the waste for 10,000 years.
- Replacement of the existing nuclear technology with other sources will require substantial investments in new generation capacity, and should result in increases in prices of competing fuels (e.g., natural gas).
- The spent nuclear fuel will still to be be dealt with, and a potentially useful energy resource will be buried.

Questions we want to find answers for:

- What technologies could replace existing nuclear capacity, and be used to meet growing electricity demand?
- Will the resource base be sufficient to support the added capacity required?
- What happens to the emissions picture without nuclear generation?
- Is there a strategy for nuclear capacity development that minimizes spent nuclear fuel (including the 'legacy') to levels within the current statutory limit of 63,000 metric tons?
- Is there a net aggregate social surplus (Marshallian) or loss associated with each of the potential pathways?
- Can the Nuclear Waste Trust Fund be used to promote a sustainable nuclear future?
- Are nuclear technologies a necessary component for the potential development of a "hydrogen" economy?

Comparison of Nuclear in LA US MARKAL with Other Frameworks

- US MARKAL contains all of the steps in the nuclear fuel cycle including waste disposal. This is more complete than NEMS (EIA), or any model of this type since Joskow and Baughman, 1976.
- Depiction of reprocessing, and permanent disposal capture differences in radiotoxicity and heat of materials. This allows the determination of the benefits (e.g., reduced emissions, energy security) of reprocessing, waste partitioning and transmutation, and reduced volume and radiotoxicity disposal strategies for spent nuclear fuel.
- Longer forecast horizon than other models allows the evaluation of "new generation" nuclear technologies and the development of interim strategies for waste disposal in the face of legal caps on permanent disposal depositories.

Attributes of Model of LA-MARKAL

- All sources of energy represented.
- Expanded technology choice set of over 4000 technologies.
- Nine different emissions types (CO_2, SO_2, NO_x, N_2O, CO, VOC, CH_4, particulates, and mercury) tracked through the economy, along with depiction of regulations, and mitigation techniques.
- Inclusion of demand response to prices and incomes incorporates a response that results in a lower total cost of satisfying energy demand.
- Electricity and steam: Representation of centrally dispatched, distributed generation, and combined heat and power (including consumption of direct heat and steam).
- See article in IAEE Newsletter, Fourth Quarter 2003 (pages12-19), www.iaee.org. Table 1 provides a summary comparison with NEMS (EIA).

Embedded Assumptions in Linear Programming

- A linear program is a linear program . . .is a linear program!!
- Embedded economic paradigm in a cost minimization framework.
- The economic paradigm includes:
  - Homogeneous, linear cost functions.
  - Assumption of perfect competition, i.e., large number of economic agents and everybody is a "price taker."
  - Ease of entry and exit.
  - All markets are in equilibrium, i.e., market clearing assumed, with perfect foresight.
- Factors that drive energy use or consumption are "energy only." Other factors in the economy that drive energy consumption are excluded.

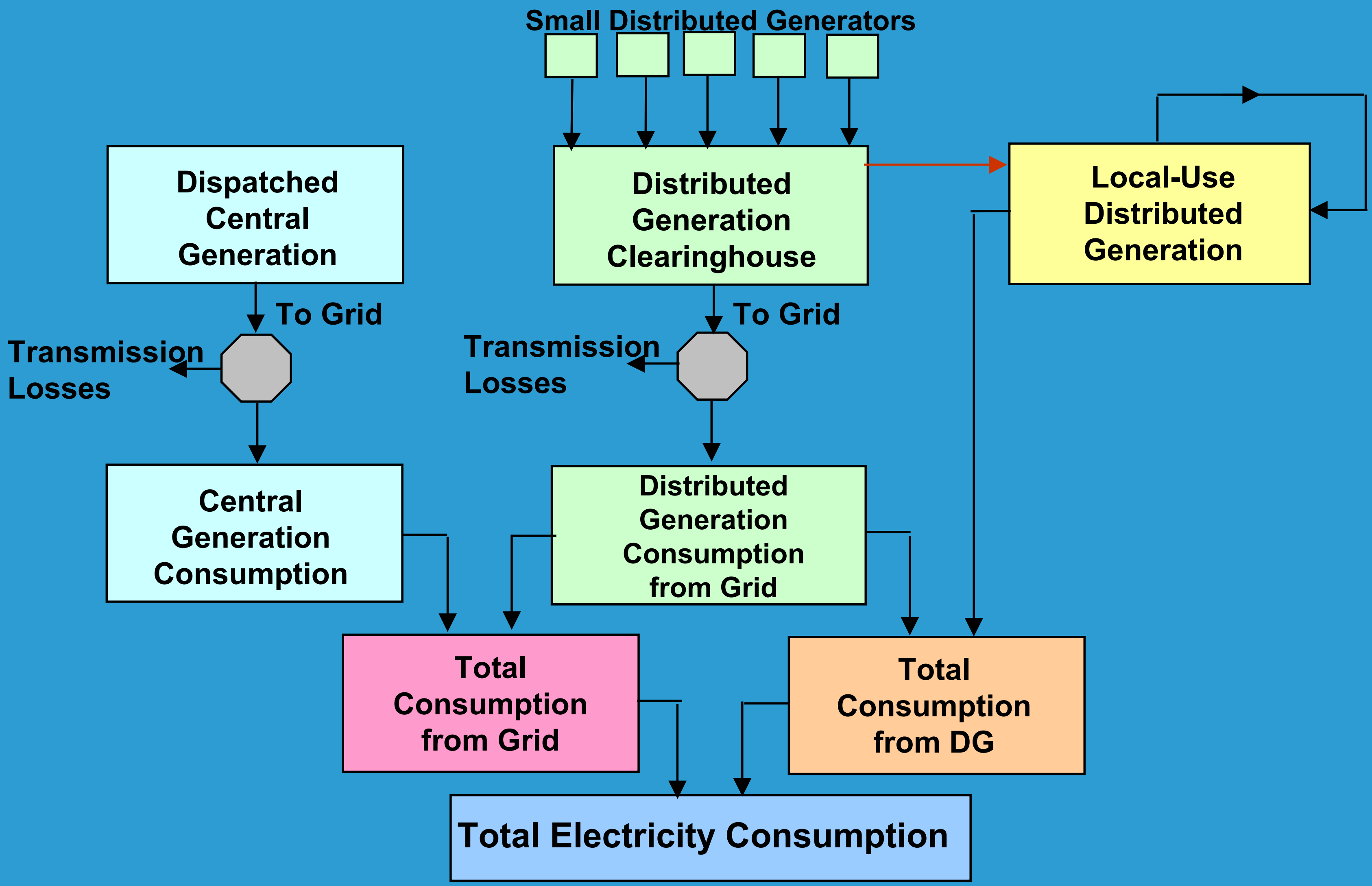
Electricity: Central Generation

- Over 90 centrally dispatched electricity generation technologies are characterized.
- Fuel/technology types represented include:
  - Fossil (oil, natural gas, coal, MSW) steam.
  - Combined cycle (natural gas, coal, biomass).
  - Conventional and advanced turbines (fossil and methanol).
  - Renewables including solar, wind, biomass, and waste.
  - Nuclear (light water reactors and MOX), and "next generation" including HTGR, HTGR-MOX, HTGR-TRU, Fast-spectrum TRU, CR-1, and MOX burners, and Accelerator-driven TRU and MA burners.
- Aggregation contracts for purchase by main grid of electricity from CHP/distributed generation.

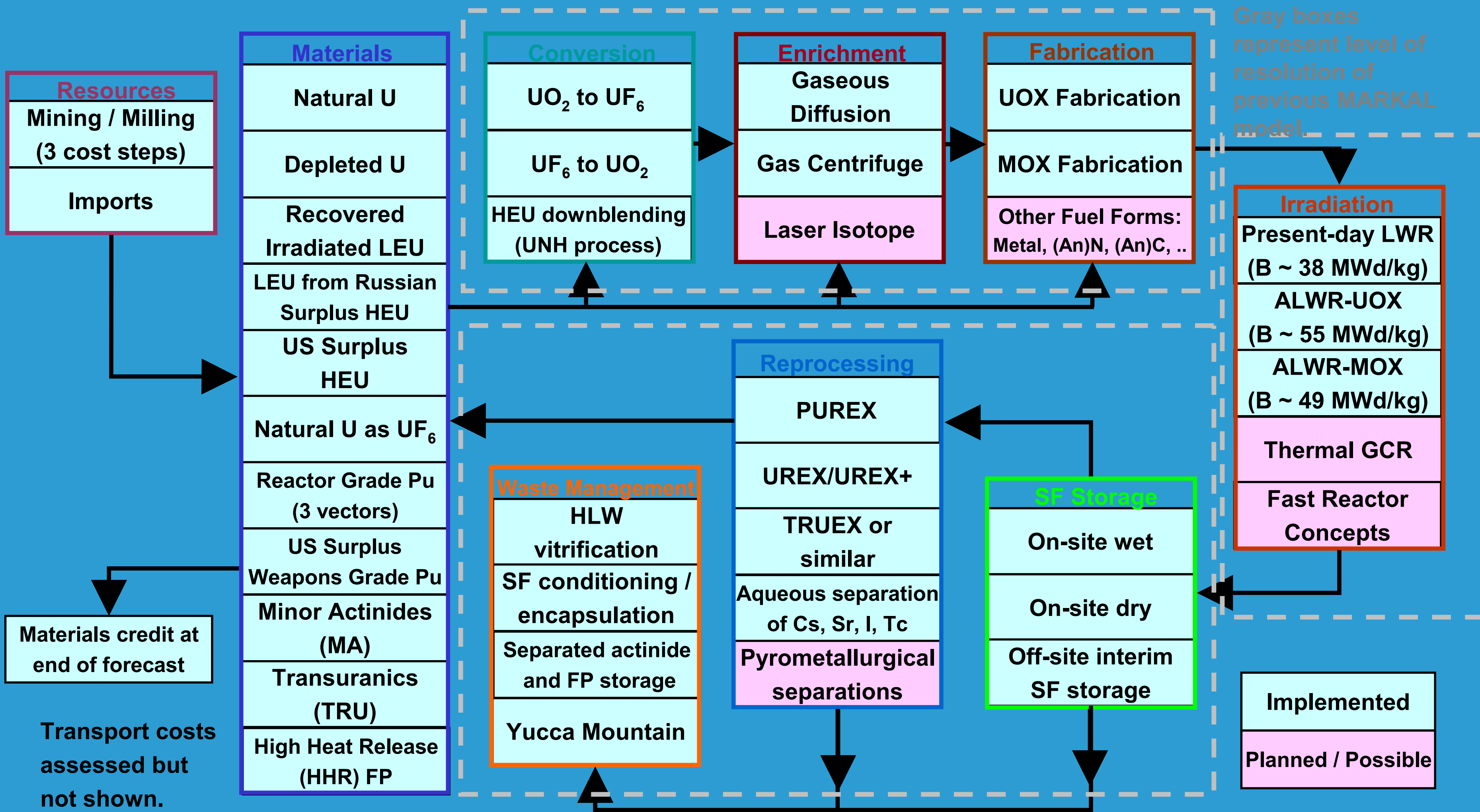
Electricity: Distributed Generation/CHP

- Each end-use sector has a sector-specific electricity and steam grid which is connected to the main grid with the option of selling (i.e., inter-sector trade).
- Each sector or end-use has up to 34 CHP/DG technologies using natural gas or renewables or other fossil fuels.
  - Industrial CHP: "pass-out" turbines (flexible heat/power ratios)
  - Commercial and residential: microturbines, fuel cells, reciprocating engines, and photovoltaic.
  - Transport: structured for the addition of "mobile" generation sources.
- DG and CHP are depicted as the "marginal" producer in the base case, i.e., these technologies compete in a market niche with central generation and more efficient end-use technologies.

Distributed Electricity Generation (DG) *versus* Central Electricity Generation (CG)



Nuclear Technologies and Materials Flows



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Disposal Costing Model Based Upon Repository Heat Load Limitations

- **Unit repository disposal costs for spent fuel, less transportation-related charges, are currently estimated by OMB as ca. $440/kgIHM.**
- **Disposal costs include vitrification – the glassification of high-level radioactive waste (HLW) in an inert matrix – as well well as emplacement of this waste in Yucca Mountain.**
- **The capacity of Yucca Mountain is governed not by the mass of material emplaced, but rather by the *total decay heat production* of that material.**
- **Comparing the heat production for high level waste of various compositions to that of spent nuclear fuel, one can estimate an 'effective' repository capacity and thus arrive at a cost estimate.**

Disposal Cost as a Function of Waste Content

- **The 'equivalent' heat load-based repository utilization of HLW is the amount [in kg] of the ca. 83000* tonHM Yucca Mountain capacity used by HLW of a given composition originating from 1 kgHM.**
- **This figure, as well as the derived volume of HLW glass, allows the disposal cost to be formulated based upon:**
  - **$300,000/m^3 HLW unit vitrification cost (Source: Hanford HLW vitrification program),**
  - **$332 per 'equivalent' kg HLW repository disposal cost, representing $440/kg less the YM cost component relating to waste package fabrication.**

***Yucca Mountain's *legislated* capacity is 63,000 tons; however DOE estimates its *actual* capacity at 83,000 tons.**

Example Disposal Cost Comparison

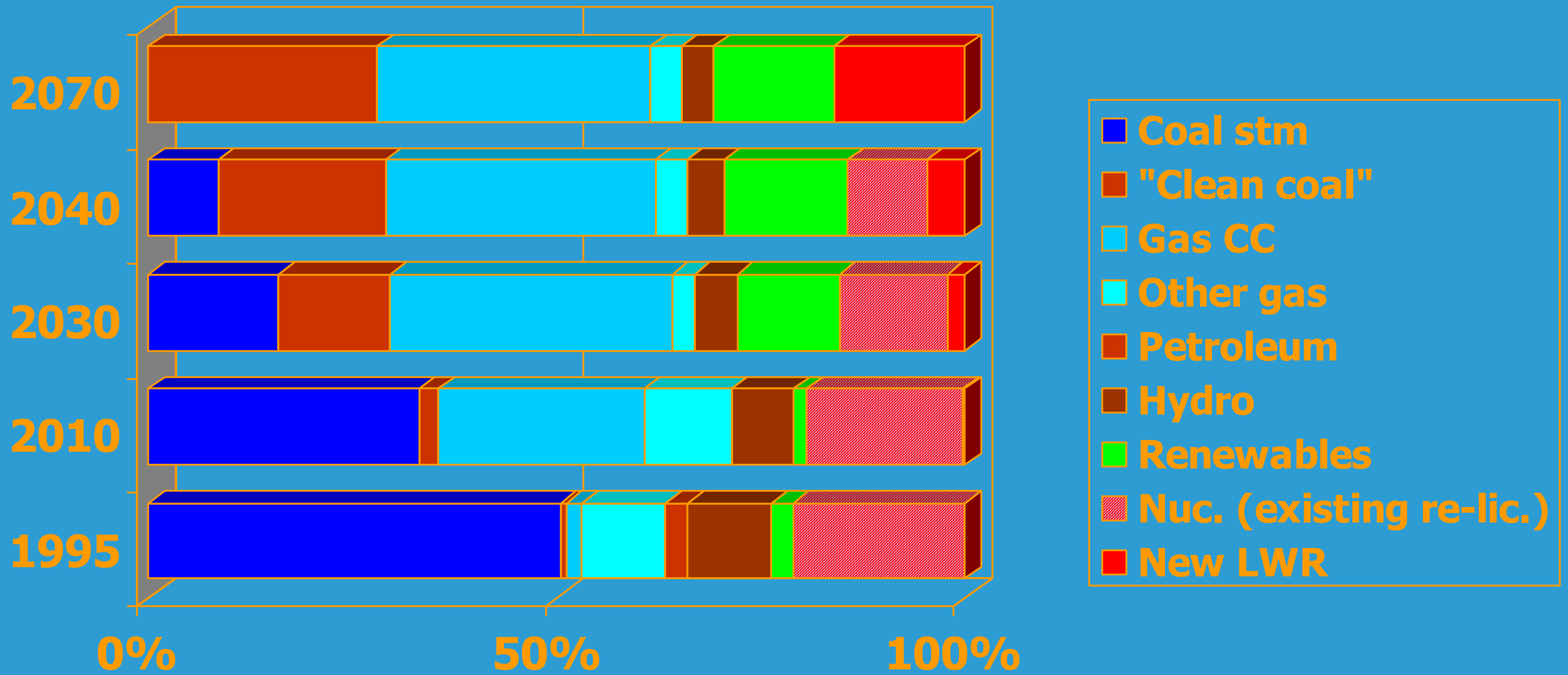
Waste Composition	Unit vitrifi. cost [$/kg waste]	Unit disposal cost [$/kg waste]	Total [$/kgIHM]	'Effective' capacity [kgIHM]
All Spent Fuel	N/A	440	440	83800
Transuranics (TRU and FP)	3231	6436	498	83800
TRU, Low Heat Release FPs (LHRFP)	922	4087	238	143300
Minor Actinides (MA), LHRFP	757	3484	161	210300
MA, all FP	3686	7052	451	93900

Further Gains from 'Advanced Nuclear Technologies'

Technology	Efficiency of generation	Tonnes SNF/Gwh
LWR: 38 MW/d (present)	32.93%	3.33
LWR: 49 to 55 MW/d	34.20%	2.22 to 2.49
HTGR: 121 to 470 MW/d	48.00%	0.18 to 0.72
Fast-spectrum: 127 to 185 MW/d	42.00%	0.54 to 0.71
Accelerator-driven: 150 to 250 MW/d	40.00%	0.42 to 0.69

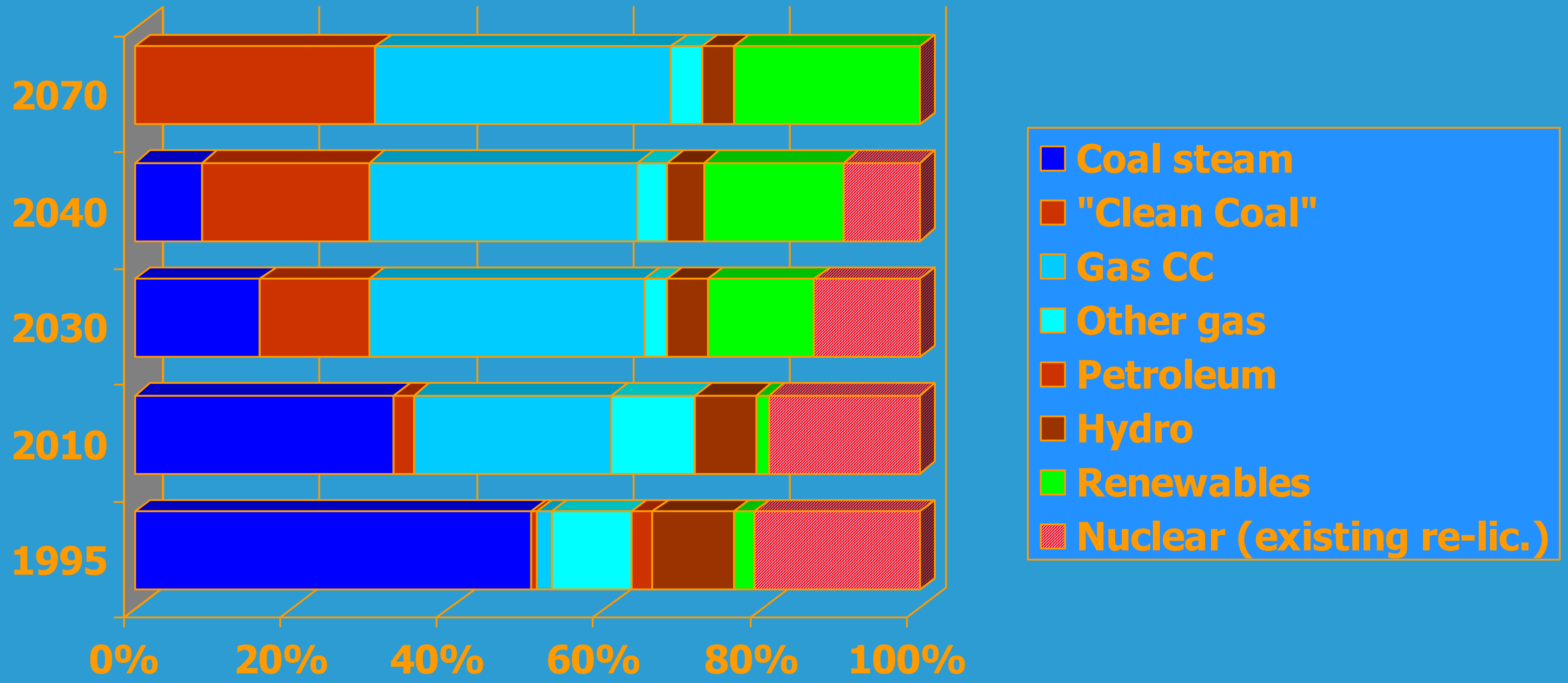
Reference Case
Shares of Central Generation

SNF: 5 to 6 YM



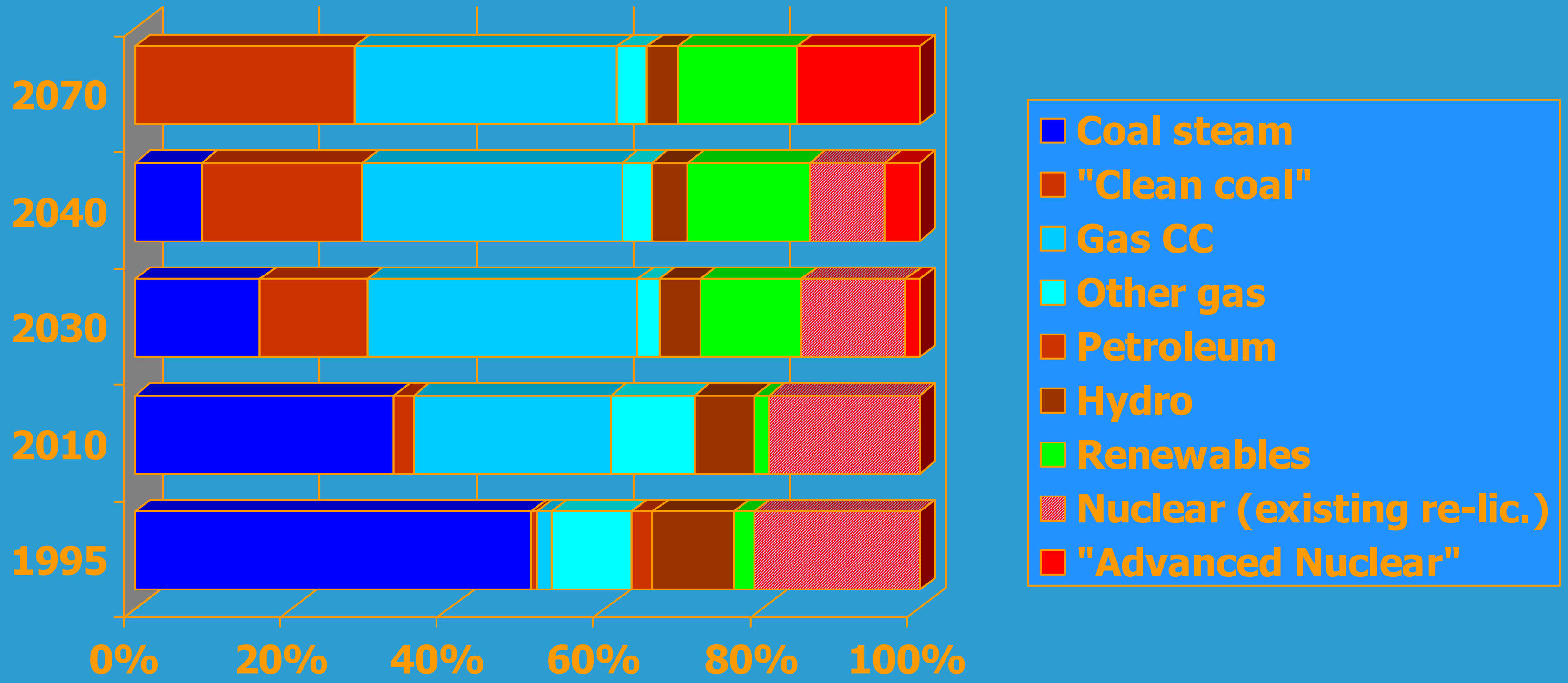
Phase-out of Nuclear
Shares of Central Generation

SNF: 1.5 to 2 YM

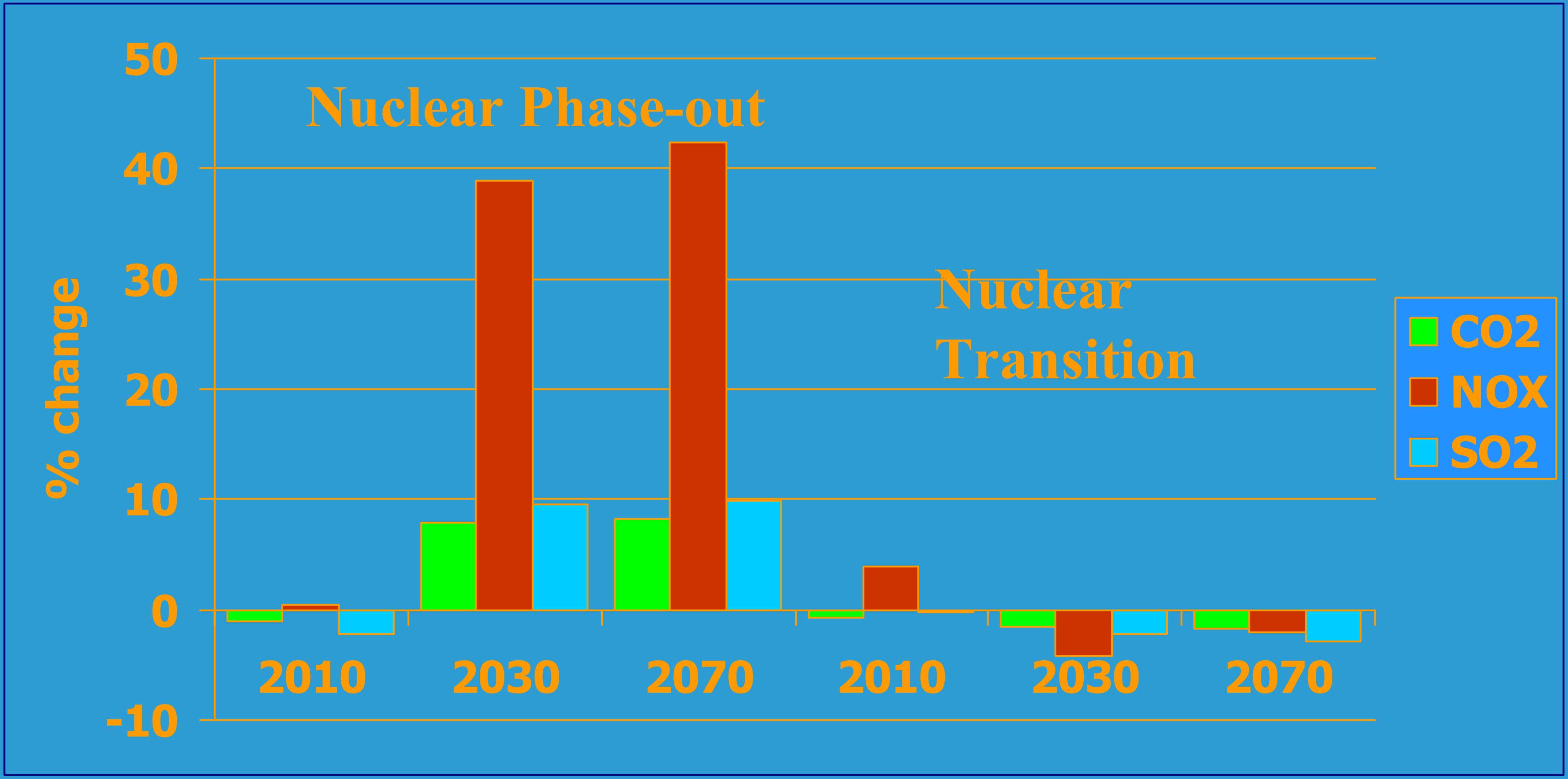


Transition Nuclear Strategy
Shares of Central Generation

SNF: Less than one YM



Emissions
Change in Annual Emissions



Annual Total Net Social Surplus Gains and Losses

The Nuclear "Conundrum"

- If nuclear generation is phased out:
  - emissions will increase.
  - existence of 60 years of 'legacy' waste.
  - probable loss of net total social surplus.
- Implementation of a 'closed fuel cycle':
  - reductions in emissions.
  - reductions in electricity costs and volumes of spent nuclear fuel.
  - probable gains of net total social surplus.

Parting Shot!

- Nuclear energy holds tremendous potential as an option for our long-term energy future.
- However. . .
  - Potential risks of proliferation, accidents, or other negative consequences of nuclear energy need to be fully examined and included in any public decision-making process.
  - A strategy for dealing with spent nuclear fuel should probably be included in any plan to expand nuclear capacity in the US.
- Additional research (both economic and engineering) on various aspects of the problem is underway.
- And. . .the spent nuclear fuel is still there (all 2.53 “cans of Friskies” of ‘legacy’ for every man, woman, and child in the US).