Where Does the Hydrogen Come From: Potential Market Penetration in the US of Low- or No-Carbon, Energy Secure Sources

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Caveats and Acknowledgements

- The conclusions and opinions presented are my own and do not represent any one else.
- All errors of commission or omission are mine, and the usual caveats apply.
- I 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, this work would not have been possible.

Today's Discussion

- Framing of the issues and the questions.
- Summary of preliminary results.
- Discussion of the means of analysis:
  - Overview of hydrogen supply technologies and end-use technologies in LA-US MARKAL.
  - Use of goal-programming as a technique for identifying solutions to multi-objective problems.
  - Some preliminary results and conclusions.
- Some wrap-up comments and next steps.

Issues Surrounding Hydrogen

- Hydrogen has a lower density than gasoline, and is more flammable.
- We have not solved or resolved various technical issues associated with transporting, storing or distributing large quantities of this energy carrier economically. In addition, fuel cell technologies (the end-use technology) currently have limitations, such that FCs are not an equivalent technology to (or perfect substitute for) the internal combustion engine.
- Hydrogen, like other previously proposed alternative fuels, competes against a well-established infrastructure.
- Hydrogen can be produced by any number of methods using any number of feed stocks. However, very few produce lower emissions or are close to being economically competitive with gasoline.

Issues for "Hydrogen Economy"

Questions in the policy debate over hydrogen and transitioning to a hydrogen economy:

- Will hydrogen ever be a cost-competitive substitute for gasoline?
- Are some sources of hydrogen less carbon-intensive than others?
- Are some sources of hydrogen more secure than others?

Goal of this work:

- To identify the hydrogen supply chains that best move the US towards these three goals, simultaneously.
- To suggest a timing.
- To identify the sustained or long-run price for a barrel of oil and other conditions under which hydrogen transitions into the market.

Preliminary Results and/or Conclusions

- The paradigm for the supply chain of central production/transportation/local distribution is probably not going to initiate market penetration of hydrogen.
- Small and local will probably initiate the hydrogen economy, i.e., forecourt or by-product production will “leap-frog” other methods.
- True reductions of emissions, particularly CO_2, are only going to be possible when hydrogen is produced with either renewable or nuclear technologies.
- Those technologies also provide the greatest energy security benefits—and, energy security seems to be a greater driver than environmental considerations.
- With this view, assuming that the costs of hydrogen-fueled vehicles fall to current cost levels of hybrid vehicles, we can probably expect the development of a hydrogen segment in the transportation market beginning as early as 2010.

Attributes of Model of LA-US MARKAL

- Expanded technology choice set of over 4500 technologies.
- Expanded set of resources including conventional (e.g., coal, oil,), renewables (e.g., wind, solar, MSW), and unconventional (e.g., methane hydrates, shale oil).
- Detailed process specification used in nine of ten industrial sectors.
- Use of materials in industrial sectors and nuclear fuel cycle.
- Expanded depiction of electricity generation capturing potential interactions between centrally dispatched generation and distributed generation.
- Complete nuclear fuel cycle including spent nuclear fuel disposal and reprocessing.
- Nine different emissions types (CO_2, SO_2, NO_x, N_2O, CO, VOC, CH_4, particulates, and mercury) tracked through the economy.
- Inclusion of demand response to prices and incomes incorporates a response that results in a lower total cost of satisfying energy demand.

Hydrogen Production in LA-US MARKAL

- Forty different fuel/technology/distribution pathways have been depicted in LA US MARKAL.
- Technologies depicted include:
  - Central with distribution by pipeline, cryogenic tanker truck, and gas tube trailer to stations.
    - Gasification of biomass, petroleum coke, coal, and petroleum residue
    - Electrolysis
    - Steam methane reforming
    - Photo-biologic
    - Nuclear: HTGR-GT to electrolysis and plasma arc; HTGR-PH to SMR, Sulfur-iodine, Modified HTGR-GT to SMR, Modified Steam Cycle HTGR to SMR, and Steam Electrolysis.
  - Forecourt (or de-centralized)
    - Steam reforming of natural gas, methanol, and gasoline
    - Electrolysis using all sources of electricity (e.g., grid), wind-specific, and solar-specific.
    - Photobiologic.

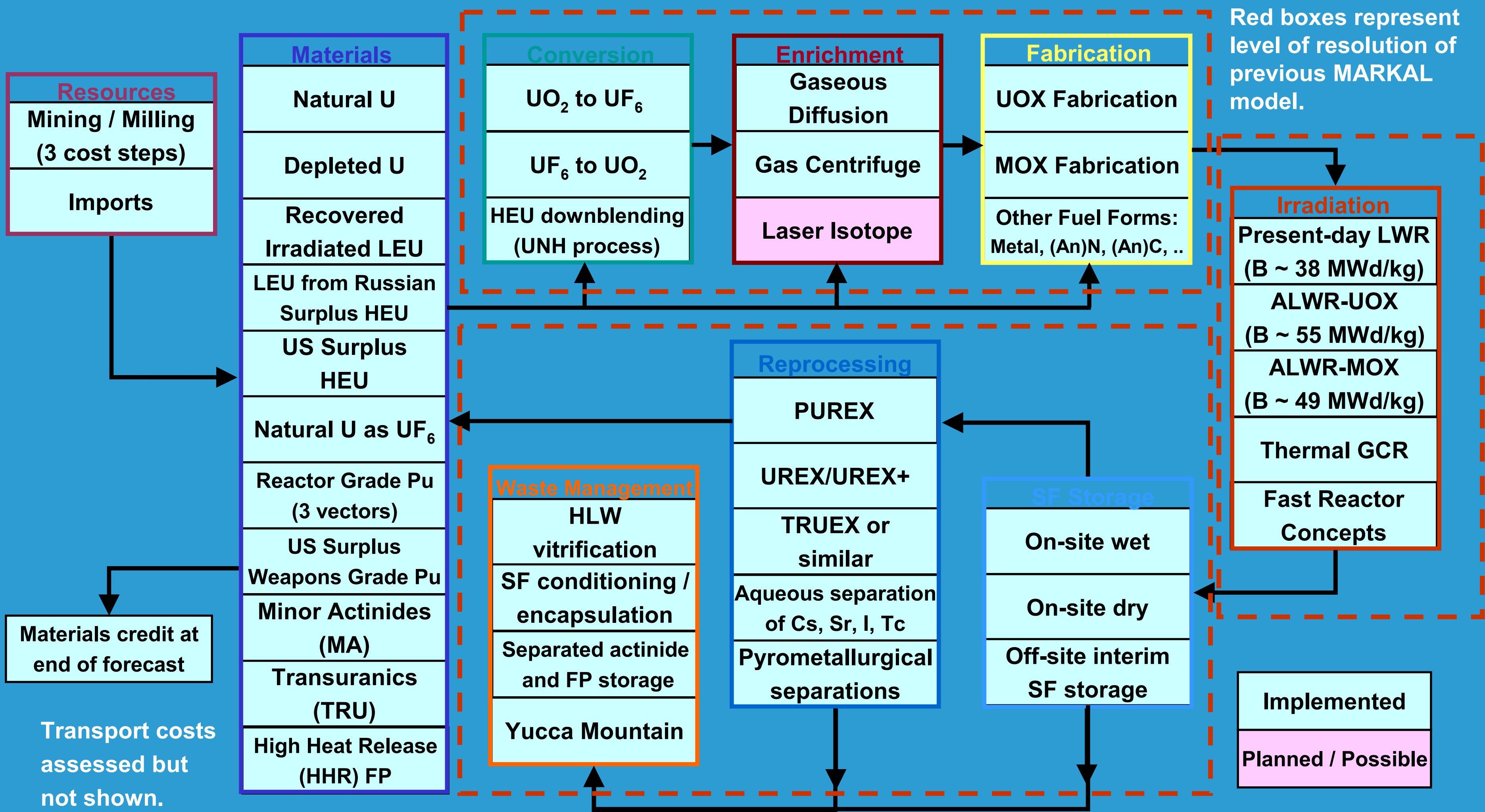
Hydrogen End-uses Currently Identified in LA-US MARKAL

- Industrial Sector: Possibilities for development of new markets or expansion of current uses as a chemical feedstock, flux material, or similar applications.
- Transportation Sector: Hydrogen powered (on-board reformers and external sources) FCs vehicles competing against ICEs, existing and advanced diesel, ICE flex alcohol, dedicated CNGs, hybrids, and similar alternatives.
- Residential, commercial, industrial, and electrical generation sectors: Fuel cells for the generation of electricity and heat for various end-uses in these sectors. Currently, these FCs are assumed to be fossil-fueled, however any source of hydrogen could be used. And, if the market developed, these end-uses could rely on central production/pipeline distributed sources.

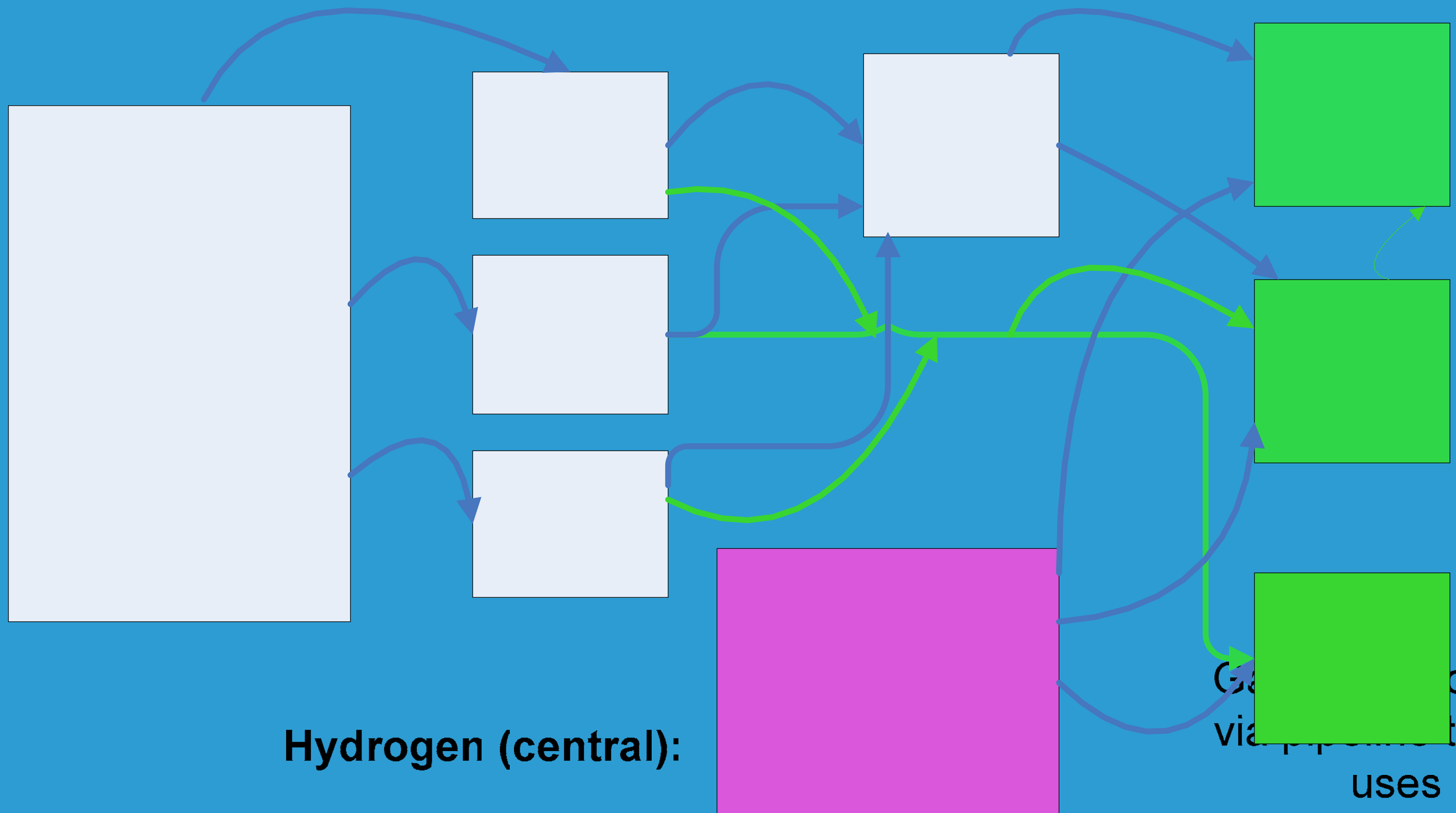
Feedback Loops

- Feedback loops play an important role in promoting/impeding technology penetration.
- Examples developed in LA-US MARKAL:
  - Complete nuclear fuel cycle designed to consider the question of how a spent nuclear fuel policy (or lack thereof) will impede or promote new nuclear technologies as hydrogen sources.
  - Carbon capture and sequestration, and methane recovery feedback loops help determine the share of carbon-intensive fuels in the long-term energy mix.

Expanded Nuclear Representation with Materials Flows



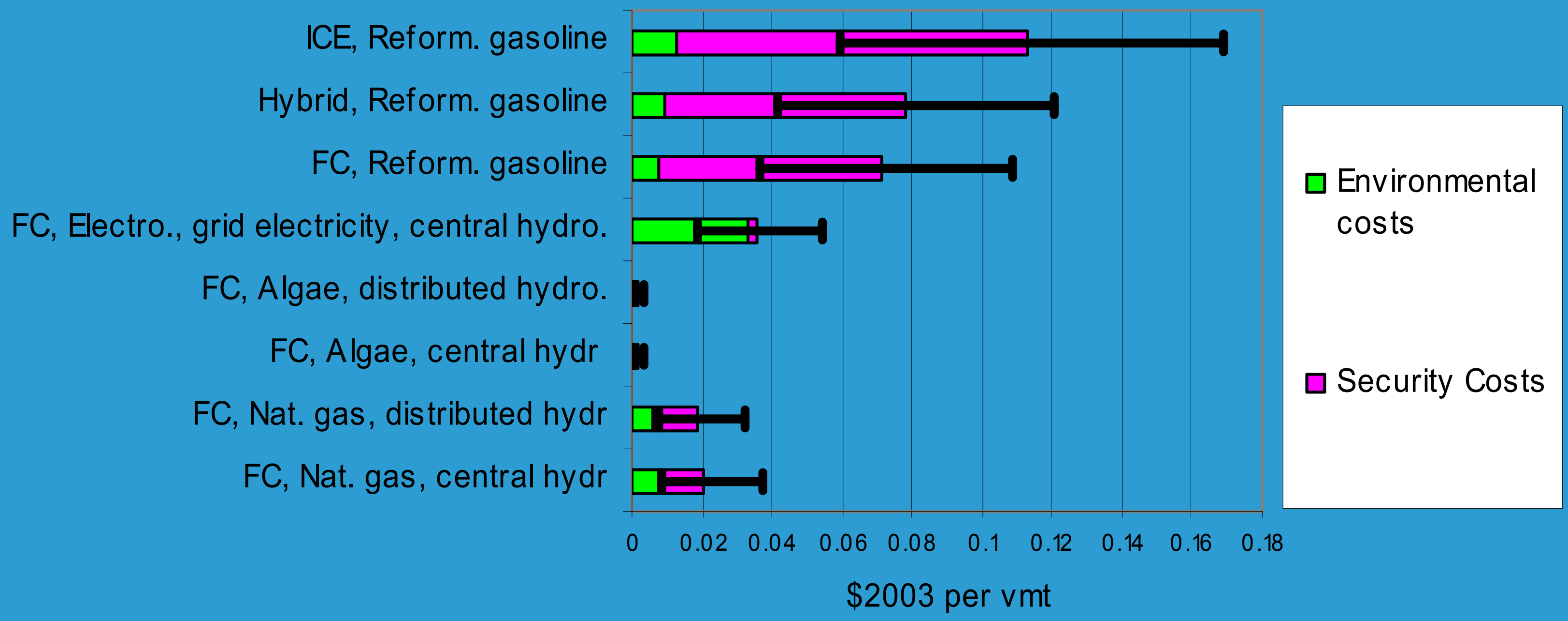
Schematic of Hydrogen in LA-US MARKAL



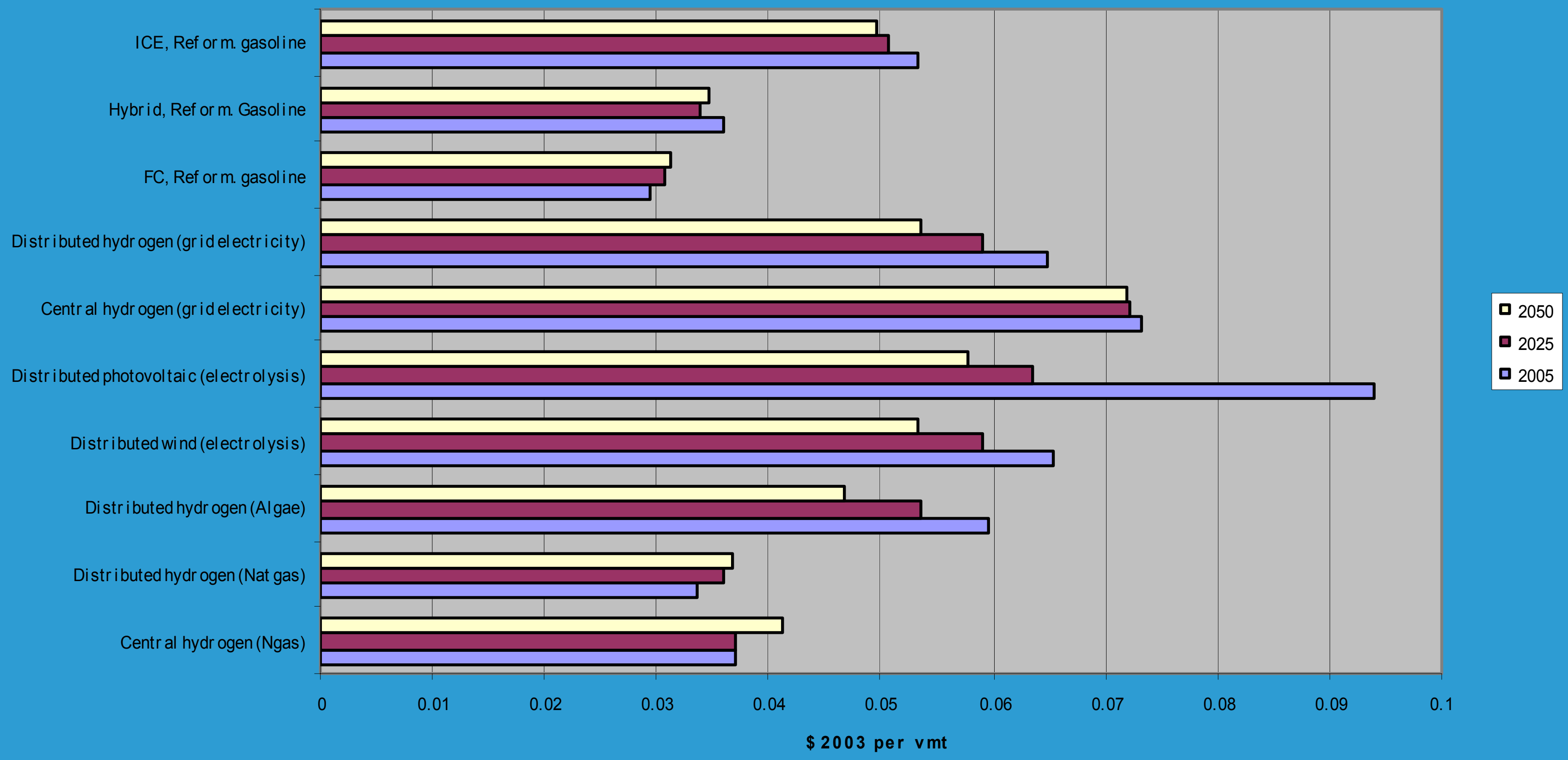
Hydrogen (central):

- Electrolysis
- Coal gasification
- Petroleum coke

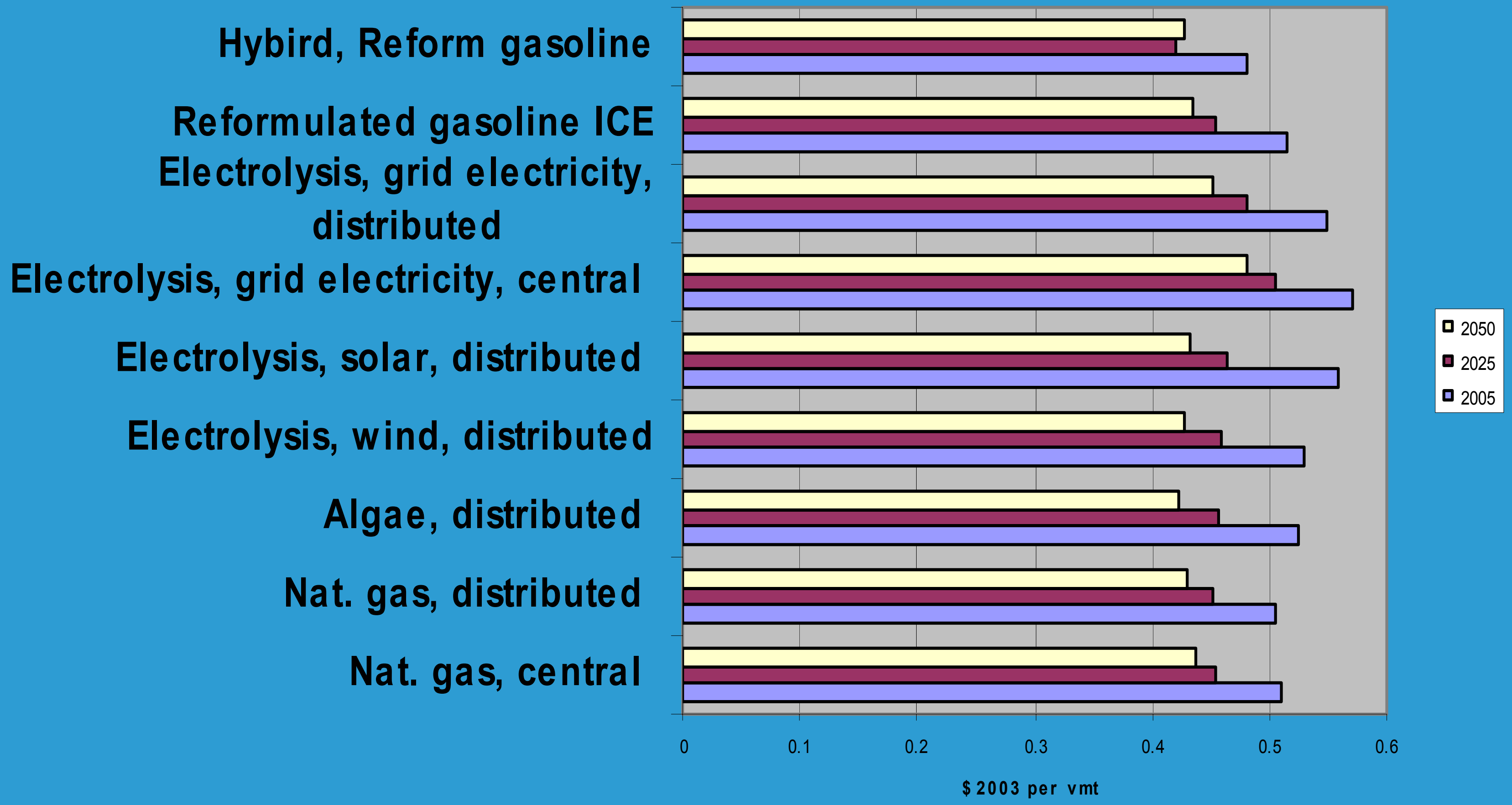
Environmental and Security Costs for Selected Technologies in 2050



Fuel Costs for Selected Technologies



Total Costs:
Reformulated Gasoline vs. Fuel Cells



Some Thoughts From the Data

- Based on total costs, including some externalities, hydrogen is in the 'ball park.'
- Distributed generation of hydrogen is less costly than central generation coupled with transmission and distribution. The cost difference, even with the economies of scale of central production, can be explained by fuel losses along the supply chain and the costs primarily of transmission.
- Renewable sources (wind, PV, photo-biologic) definitely appear to have potential in the mid- to longer-term.
- Not included on these graphs, is the use of 'advanced nuclear' for the production of hydrogen. The complexity of issues surrounding this pathway illustrate the value of more detailed analytical frameworks.
- However, other alternative fuels such as biodiesel are also very economically competitive with gasoline and are closer substitutes.
- An expanded discussion of the derivation of these numbers and additional comparisons can be found in:
  Greening, L.A., 2005. "Hydrogen Strategies Under Uncertainty: Risk-averse Choices for 'Hydrogen' Pathway Development." IAEE Newsletter, 14(First Quarter): 22-28.

What is Goal Programming?

- Goal programming is a mathematical programming tool of the class referred to as MCDM. For more on the application of MCDM methods to the solution of energy/environmental planning problems:

  Greening, L.A., and S. Bernow. 2004. "Design of Coordinated Energy and Environmental Policies: Use of Multicriteria Decision Making." Energy Policy, 32: 721-35.

- Mathematical programming methods are the most data intensive and the most widely used of all Multi-Criteria Decision-making Methods (MCDM).

- GP is a prescriptive method based on minimizing the distance from a goal for each attribute represented in the objective function.

- As with other MCDMs, weightings represent the preferences of decision makers.

- Solution of a GP can provide the Pareto optimal alternative.

Mathematical Formulation of a Goal Program

$$\min z = \sum_{i=1}^{k} \frac{100}{b_i}(u_i n_i + v_i p_i)$$

$$s.t.\ f_i(x) + n_i - p_i = b_i,\ i = 1 \ldots Q,\ x \in C_s$$

where

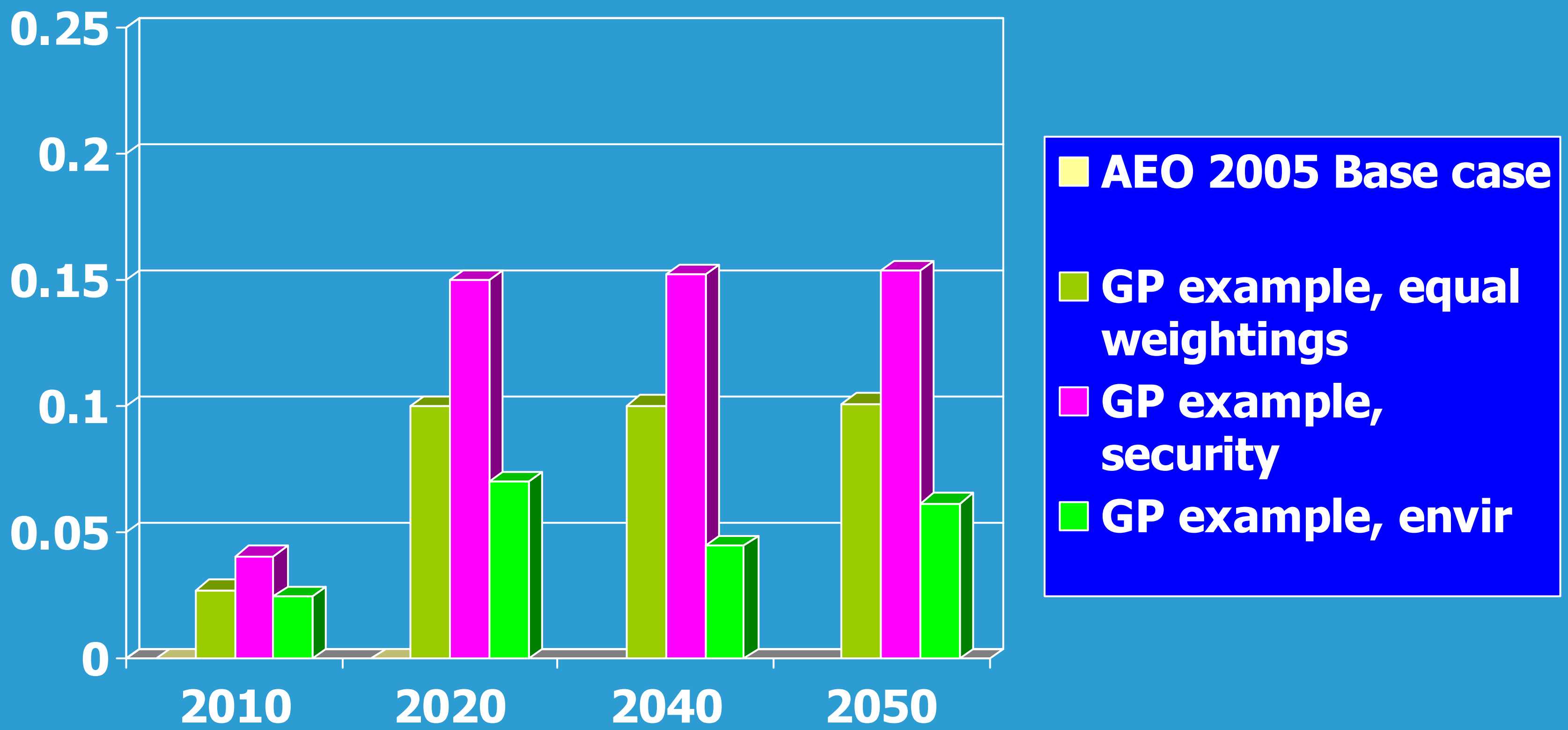
u_i and v_i are preference weightings;

n_i and p_i represent negative and positive deviations from a target value, b_i;

and

$f(x_i)$ is a linear function (the original objective function).

Potential Share of Personal Transportation Energy Provided by Hydrogen: Goal Programming in Comparison to Cost Minimization



Added Comments on Preliminary Results

- Using a goal programming formulation, hydrogen fuel cells do enter the solution. That is, because other goals besides cost minimization have been included in the analysis, a broader set of viable alternatives are considered.
- Prior to 2020, as the market for hydrogen initiates, distributed generation using renewables or on-board reforming is the 'technology of choice.'
- With the advent of 'advanced nuclear technologies' central production via nuclear generation (process heat from HTGRs) is cost competitive with methane reforming and dominates this set of choices. However, this analysis does not include preferences towards reprocessing and permanent disposal of nuclear waste.

Conclusions

- Minimizing total financial costs does not capture all facets of new technology adoption. Other factors very often drive the choice or market penetration.
- Goal programming is one of a set of tools that can be employed to incorporate other preferences or factors into an analysis.
- Without incorporation of preferences for security and emissions reductions into a decision-making process, such technologies as hydrogen probably won’t be adopted spontaneously.