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.
  - Popular myths and misconceptions about hydrogen.
  - Technical issues impeding the penetration of hydrogen.
  - Where can hydrogen come from?
  - The economics, emissions, and security aspects of various pathways.
- Summary of preliminary results.
- Discussion of the means of analysis:
  - Overview of 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.

Popular Myths and Misconceptions

- Myth one: Hydrogen is an ‘energy source.’

  Fact: Hydrogen is an ‘energy carrier’ just like electricity.

- Myth two: We are running out of oil, and have or are about ready to go over ‘Hubbert’s peak.’

  Fact: At this point in time, we have only used about 1/6 of the world’s petroleum resources. A better statement might be that we are running out of ‘cheap oil.’

- Myth three: Hydrogen is a non-polluting, more-secure substitute for carbon-intensive fuels in any number of applications—particularly transportation.

  Fact: It depends. . .and, here lies the problem.

Myth One

- Although roughly 90% of all particles in our universe—and that's over 15 billion years after the 'big bang'--are hydrogen, this simplest of elements is usually found bound to other atoms, e.g., H_2O, hydrocarbons, biomass, coal.
- As a result, in order to obtain pure hydrogen, hydrogen-bearing substances must under go a conversion process usually involving heat or electricity. In other words, we input one form of energy into the process to obtain another form.
- This is no different than the process we undergo in the generation of electricity—another energy carrier. And, we have been and are now routinely using hydrogen in the production of ammonia fertilizers and refining of gasoline.

Myth Two

If you believe the methods of analysis for 'Hubbert's peak' for world conventional oil production, then you agree with the following:

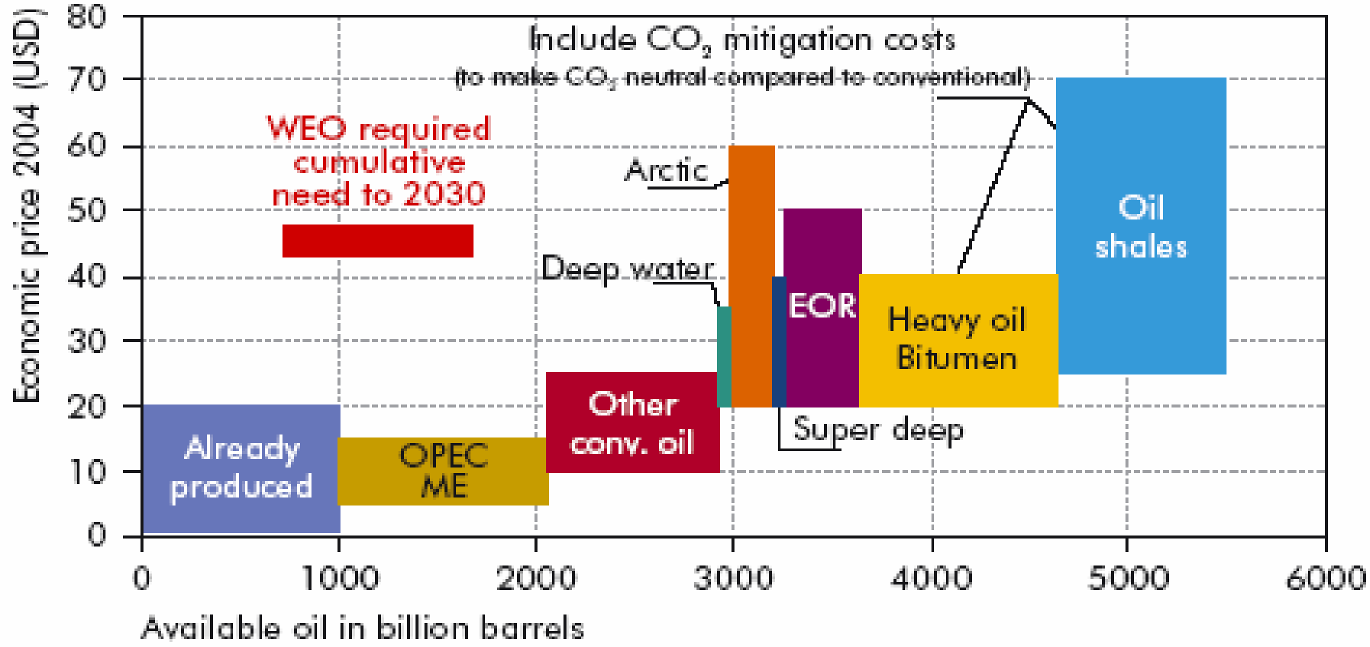
	Peak Point	Cumulative Percentage
Production	2005	49%
Initial finds	1964	94%

Taken from: Hubbert's Peak: The Impending World Oil Shortage and Beyond Oil: The View from Hubbert's Peak by Kenneth S. Deffeyes

Assuming slightly over 2 trillion barrels, then we have pretty well discovered all of the possible resource, and have used about half of our reserves in about 150 years. This was before we start facing the increase in demand from China, India, and the rest of the developing world.

Myth 2: The Alternative View of World Petroleum Resources

Oil cost curve, including technological progress: availability of oil resources as a function of economic price



The x axis represents cumulative accessible oil. The y axis represents the price at which each type of resource becomes economical.

Source: IEA.

Resources to Reserves: Oil & Gas Technologies for the Energy Markets of the Future

More Than Just Petroleum Supplies

- If our concern is security and oil:
  - Canada with its oil sands ranks second after Saudia Arabia for world reserves.
  - The US has on the order of 620 billion barrels of recoverable oil with today's technology in the form of oil shales.
- If our concern is security:
  - Low-grade coal supplied approximately 80% of the German fuel requirements during WWII.
  - Technologies for the conversion of coal to liquid fuels have substantially improved and costs have declined since the last serious consideration of this option in the late 1970s.
  - Based on current usage, the US has on the order of 225 to 240 years of coal resource available.

Myth Three: A summary

- Hydrogen has a lower energy 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.

Hydrogen: The Stasis (or ‘chicken versus egg’)

Reality of introducing alternative fuels learned from previous experience:

“. . .if hydrogen is going to make it in the mass market as a transport fuel, it has to be available in 30 to 50% of the retail network from the day the first mass manufactured cars hit the showrooms. We know that the customer must be able to fill the tank in about a minute . . . safely with no leaks while telling the kids to keep quiet in the back of the car.”

Bernard Bulkin, Chief Scientist for British Petroleum, presentation to the National Hydrogen Association’s Fourteenth Annual U.S. Hydrogen Conference and Hydrogen Expo, Washington, DC, March 4-6, 2003

Hydrogen Distribution

- A distribution network initiating a ‘hydrogen transportation economy’ would require refitting or building between 4500 and 17,700 stations with a capital investment of between $7 and $25 billion. (Melaina, 2003, International Journal of Hydrogen Energy, 27:1103-11.)
- To retrofit or build 30 to 50% of a retail network in the US would require an estimated 50,000 to 90,000 service stations at an estimated investment of half a trillion dollars. (Mintz, et al., ANL, www.transportation.anl.gov/pdfs/AF/224.pdf)
- Hydrogen requires additional safety regulation due to flammability over a wide range of concentrations; hydrogen has a minimum ignition energy twenty times smaller than that of natural gas or gasoline. As a result, modifications would need to be made to garages, maintenance facilities, and on-road infrastructure (e.g., tunnels).

Hydrogen Storage

- Hydrogen storage systems need to enable a vehicle to travel 300 to 400 miles, but can not compromise passenger comfort or trunk space.
- Such a driving range with current technology would require a tank holding approximately 5 kg of hydrogen.
- Three methods with novel storage methods (e.g., nanotubes) developing:
  - Liquid: Relatively compact and lightweight vessels are available, however, approximately 40% of the hydrogen energy is required for liquefy for storage. For 1 kg of hydrogen, this would result in a release of 17.5 to 21 pounds of CO_2, while a gallon of gasoline releases about 20 pounds.
  - Compressed hydrogen: Compression is a mature technology, however, approximately 10 to 15% additional energy is required. Further, a tank <u>ten times greater in volume</u> to the average gasoline tank would be required and would cost an estimated 100 times ($2100 per kg of capacity) more.
  - Metal hydrides: A large volume of hydrogen (5 kg) can be stored in one-third the volume of compressed hydrogen, however, hydrides are heavy (e.g., a tank carrying 6 kg of hydrogen could weigh as much as 300 kg or 660 lbs). Further, hydrides are slow to re-fuel, and slow to release.

Hydrogen Transportation

- A well-developed hydrogen economy would probably evolve into a supply chain including centralized production with a transportation component.
- Three methods for delivery to distribution points are currently envisioned:
  - Tanker trucks: Liquefied hydrogen is currently delivered to industrial sites using this method. Liquefaction is initially energy-intensive, but fueling stations would require pressurization equipment (another 10 to 15% of usable energy or a total of 50% more for the entire chain).
  - Hydrogen pipelines: Hydrogen pipelines have special materials requirements; capital costs have been estimated at $1 million per mile for a 9 to 14-inch diameter pipeline. However, only about 6 to 10% of usable energy is used for compression.
  - Trailers carrying compressed hydrogen canisters: A 40 MT truck would be required to deliver 400 kg of hydrogen; the same size truck can deliver 26 MT of gasoline (10,000 gallons).

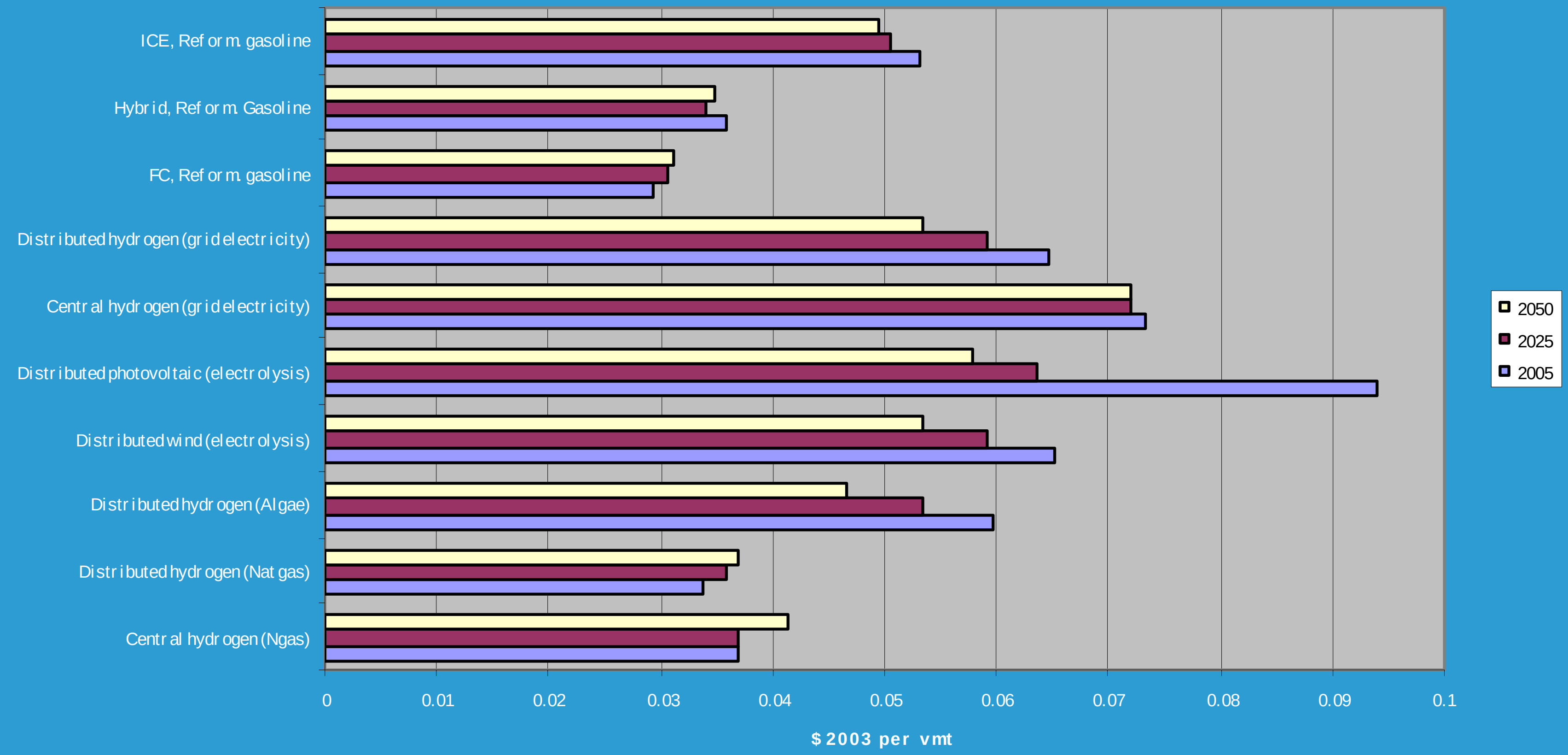
Hydrogen Production

- Hydrogen can be produced from any number of feedstocks, and with a variety of methods. Currently, the majority (98%+) of hydrogen is produced through the reformulation of natural gas or other hydrocarbons with efficiencies of around 72% to slightly less than 80%.
- Much of the initial work on the economics of hydrogen as a transportation option has focused on central production with pipeline transportation. However,
  - This pathway results in greater emissions of greenhouse gases (more energy-intensive along each step of the path).
  - And depends on readily available supplies of relatively inexpensive natural gas. According to the EIA, by 2025, approximately 1/3 of US natural gas will be imported in the form of LNG, and average costs to the end-user will increase somewhere in the range of 5% to 10% (in real terms). Gasoline prices in the same forecast are expected to remain constant or decline slightly.

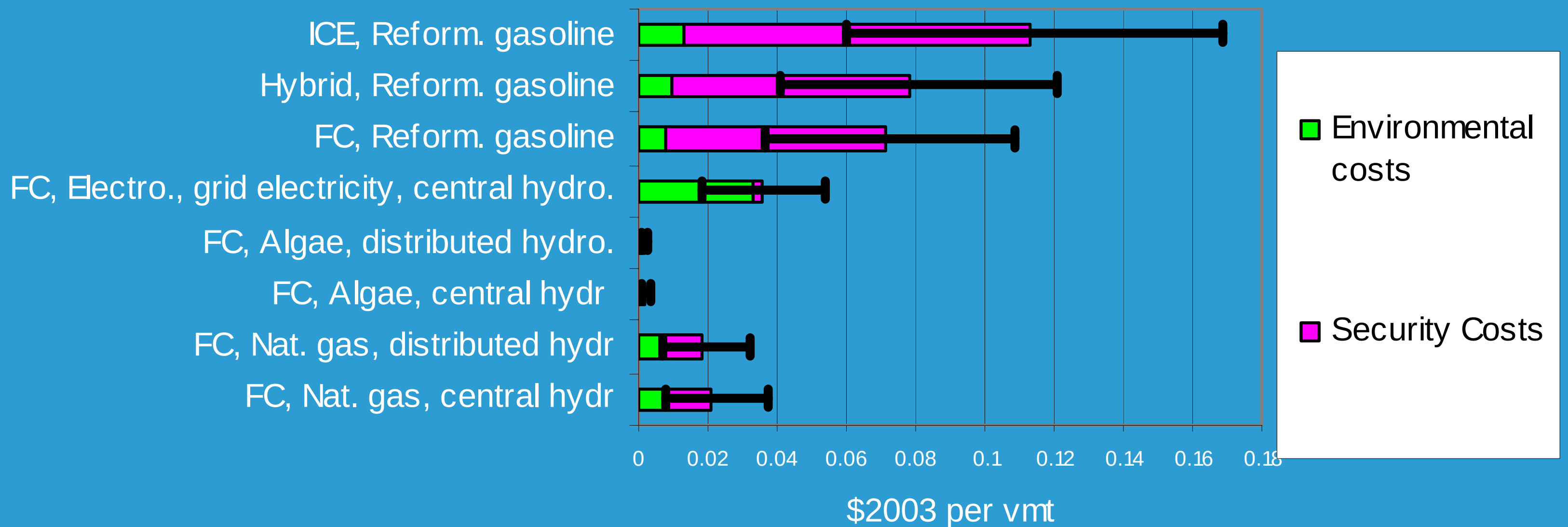
Comparing Options

- To do a valid comparison of different hydrogen pathways and personal transportation options, costs on a vehicle mile traveled basis (the actual derived demand) need to be performed.
- These types of comparisons need to incorporate price and technology uncertainty.
- The following are excerpts from:
  Greening, L.A., 2005. "Hydrogen Strategies Under Uncertainty: Risk-averse Choices for 'Hydrogen' Pathway Development." pages 22-28 (http://www.iaee.org/documents/05win.pdf)
- Assumptions:
  - Vehicle costs and efficiencies are those underlying the Annual Energy Outlook for 2004 and analysis performed by OTT/DOE.
  - Vehicles are assumed to be mid-sized with future costs and technical efficiencies forecast by the EIA. Different vehicle types are assumed to have different trajectories for costs and technical efficiency improvements.
  - Fuel price uncertainty is treated through projection of a spread of prices for each fuel commodity over a forecast horizon extending from 2000 to 2050.
  - Some of the unpriced externalities associated with transportation are included—GHG and increased dependence on foreign sources of imports.

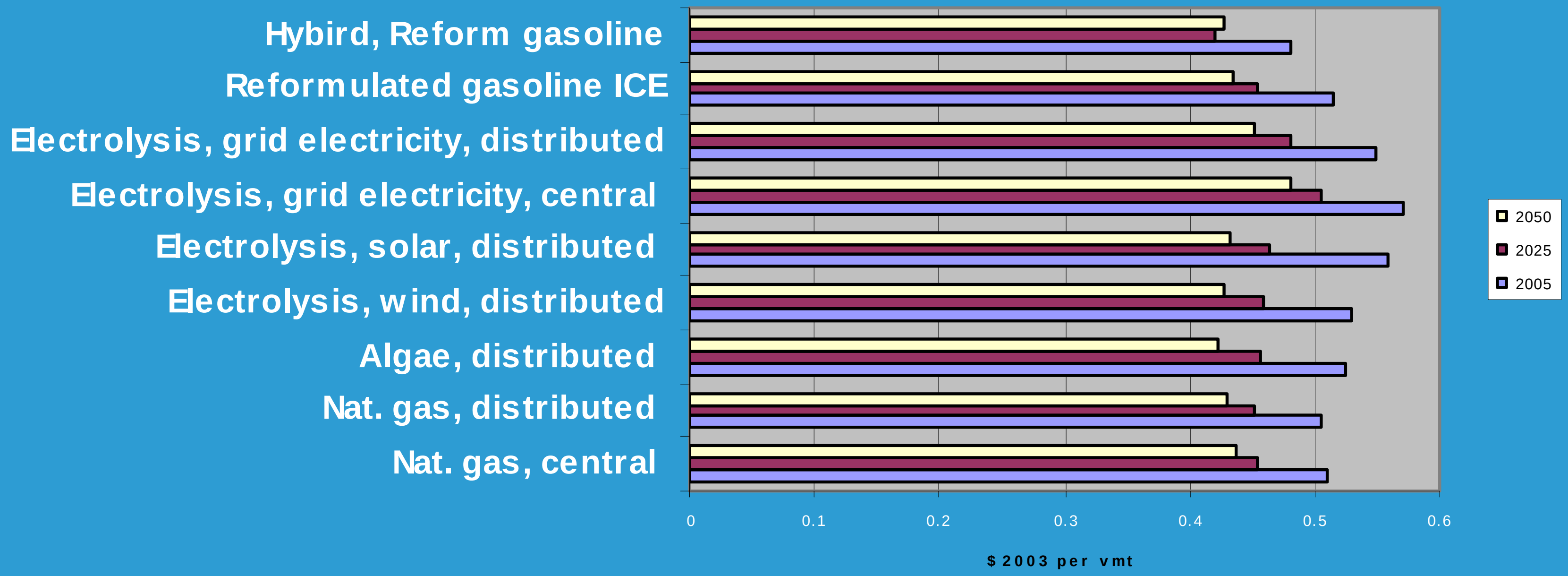
Fuel Costs for Selected Technologies



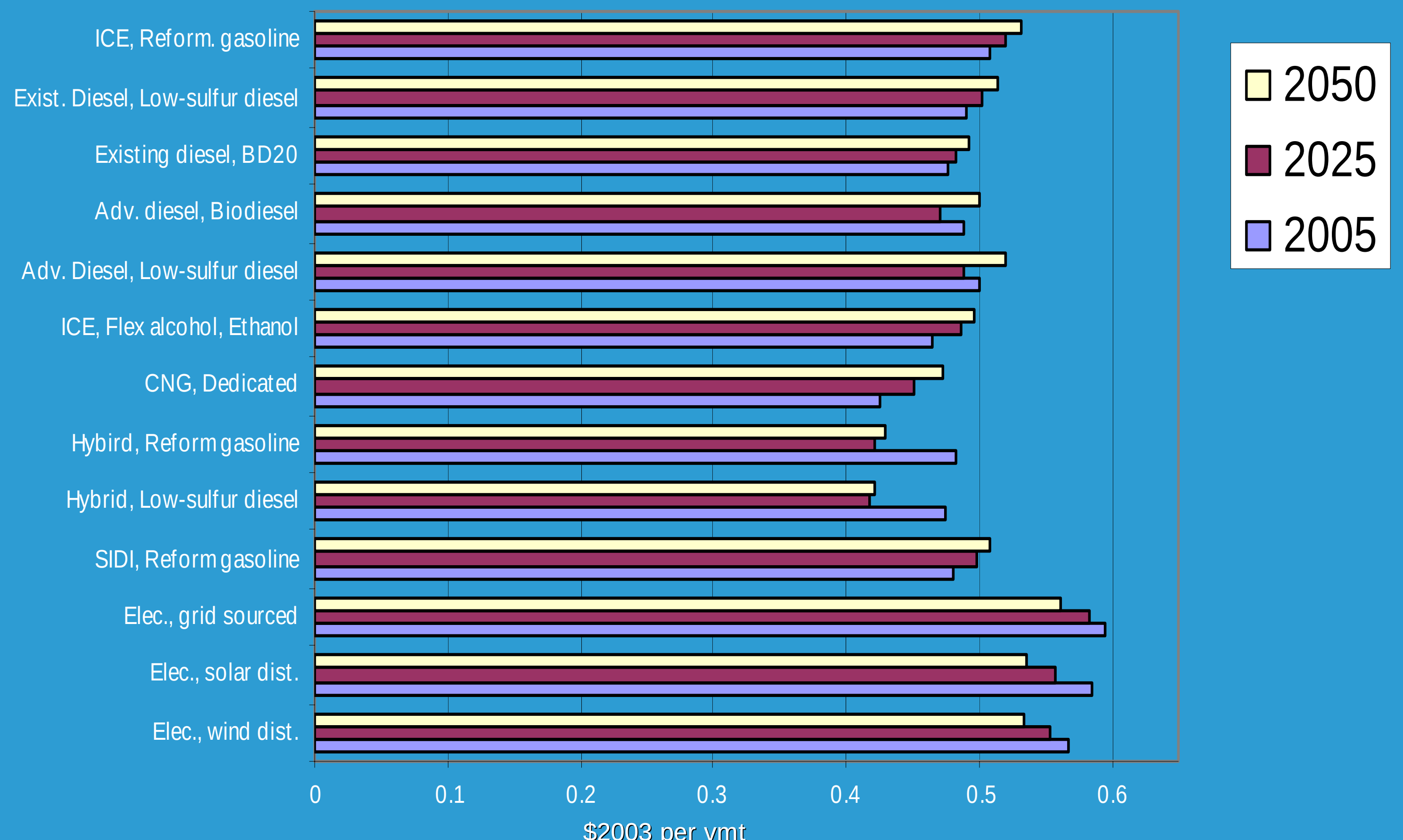
Environmental and Security Costs for Selected Technologies in 2050



Total Costs:
Reformulated Gasoline vs. Fuel Cells



Total Costs of Other Potential Personal Transportation Options in Comparison to Hydrogen FC



Some Thoughts From Preliminary Analysis

- 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 paradigm for the supply chain of central production/transportation/local 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.
  - 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.
  - Nuclear and renewable technologies also provide the greatest energy security benefits—and, energy security seems to be a greater driver than environmental considerations.

- Other alternative fuels such as bio-diesel are also very economically competitive with gasoline and are closer substitutes. To be competitive, costs of hydrogen FC vehicles would need to fall to at least current costs of hybrids.

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.

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

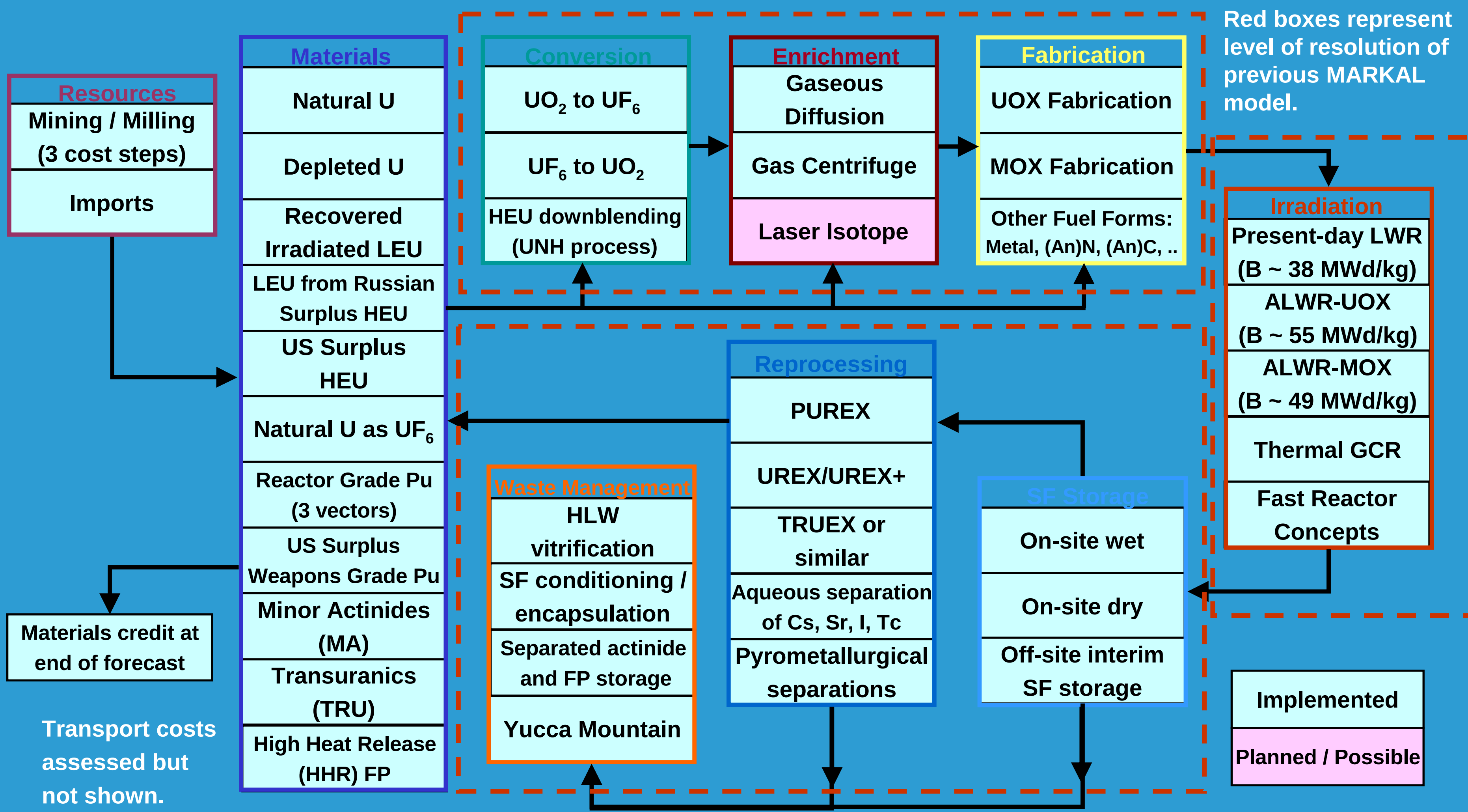
- Industrial Sector: Possibilities for development of new markets or expansion of current uses as a chemical feedstock, flux material, or similar applications.
- Transportation Sector: Hydrogen powered (on-board reformers and external sources) FCs vehicles competing against ICEs, existing and advanced 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.

    (For details on the NFC see Greening and Schneider, pages 12-19 www.iaee.org/documents/03fall.pdf)
  - Carbon capture and sequestration, and methane recovery feedback loops help determine the share of carbon-intensive fuels in the long-term energy mix.

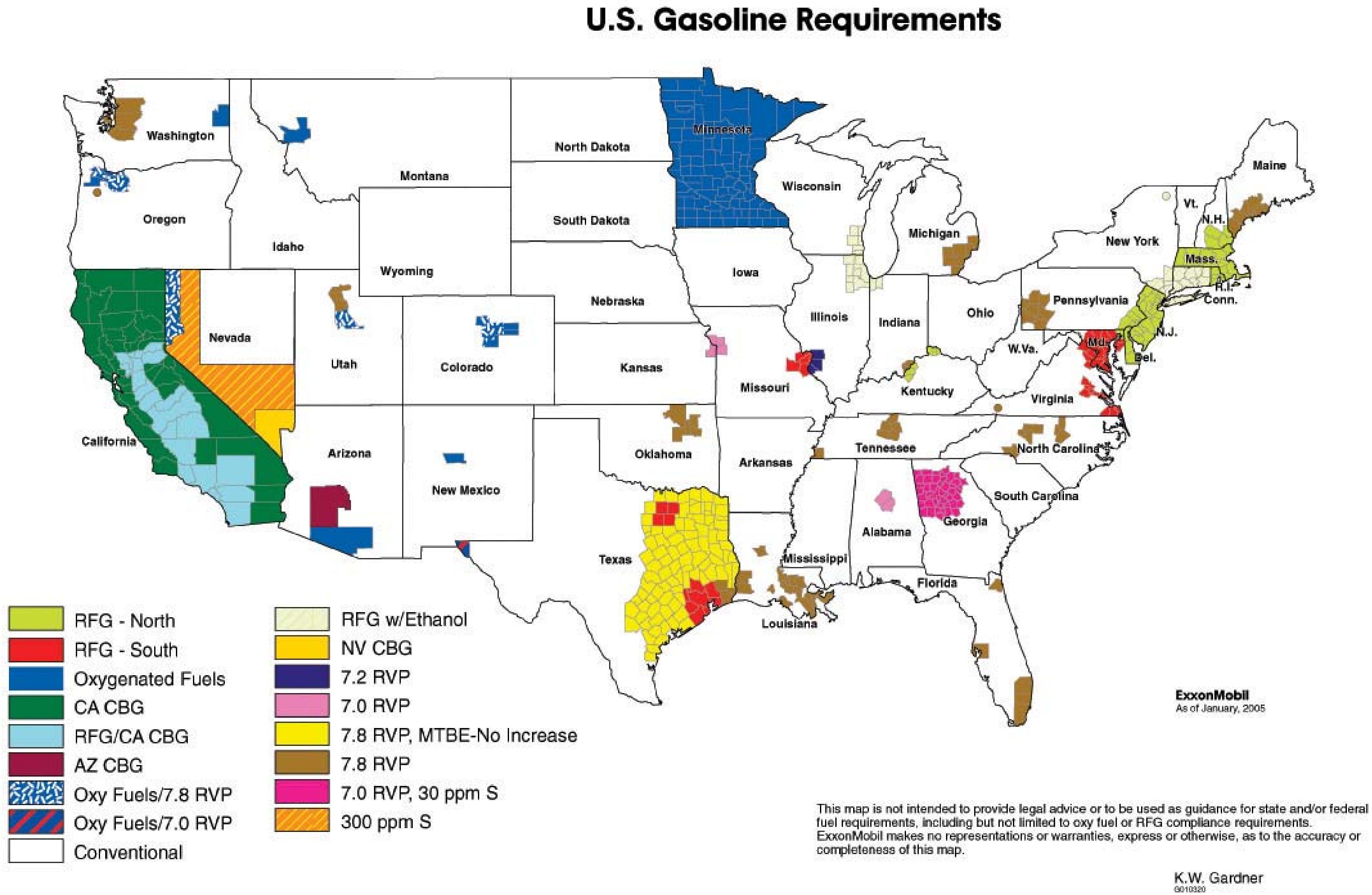
Expanded Nuclear Representation with Materials Flows



Conflicts between Energy and Environmental Policy

- US policy formulation in both areas has been historically narrow-focused on specific aspects.
  - Energy policy has focused on reliability, sufficiency, security, energy demands, and energy prices.
  - Environmental policy has focused on emissions reductions.
- As a result a policy in one area can offset the benefits of a policy in another. For both sets of policies costs may be higher than anticipated and results can be suboptimal.
- Both energy and environmental issues or policies embody uncertainties evolving from:
  - Long, but very different time frames.
  - Magnitude of capital investment.
- Development of each type of policy involves potential if not inherent conflicts, which are characterized by technical, social, economic, and political value judgements.

An Example of a Very Real Conflict Between Energy and Environmental Policy



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

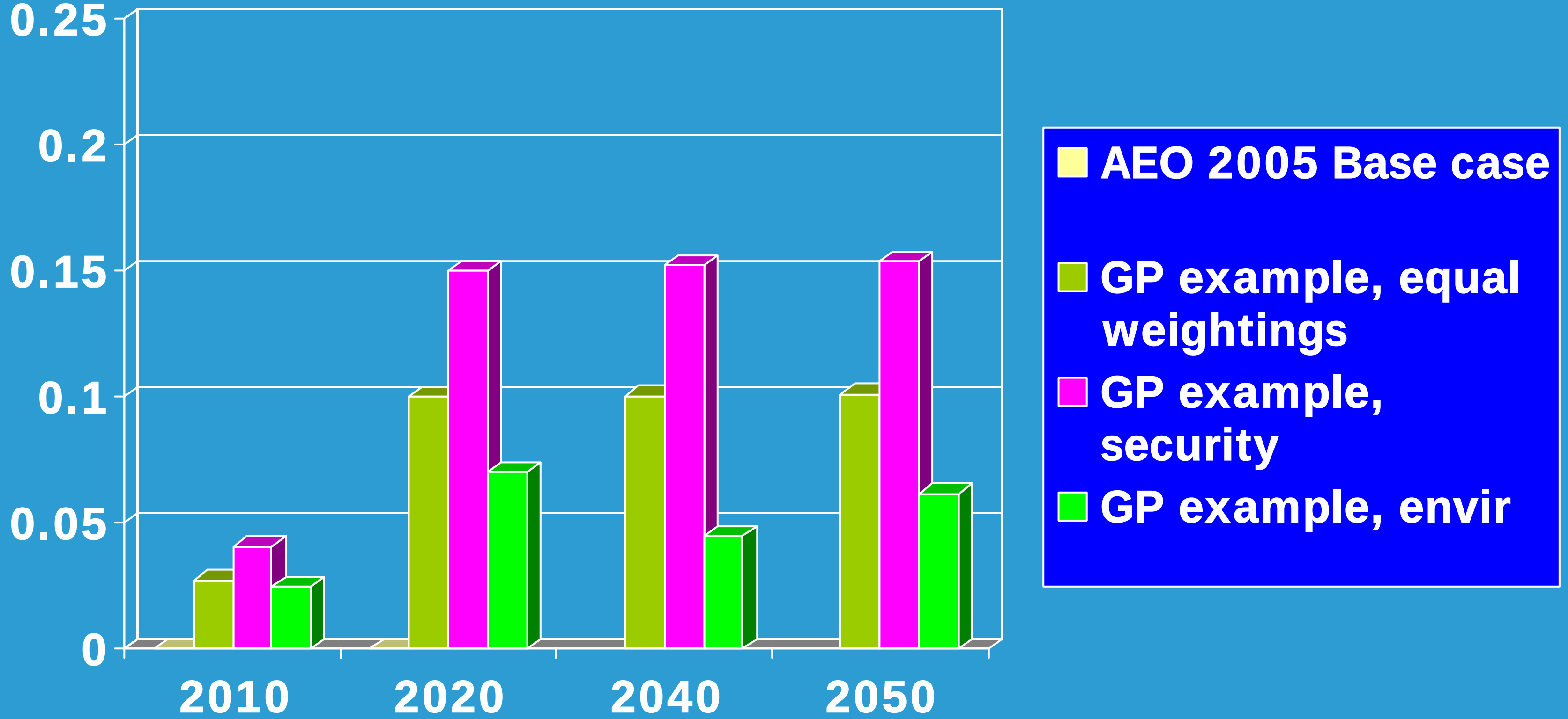
u_i and v_i are preference weightings;

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, 'fore-court' generation using renewables or natural gas will probably be 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.
- Coordinated policies—environmental and energy—coupled with a stable regulatory environment are necessary to attract the levels of capital required for any type of major transformation of the US energy system.