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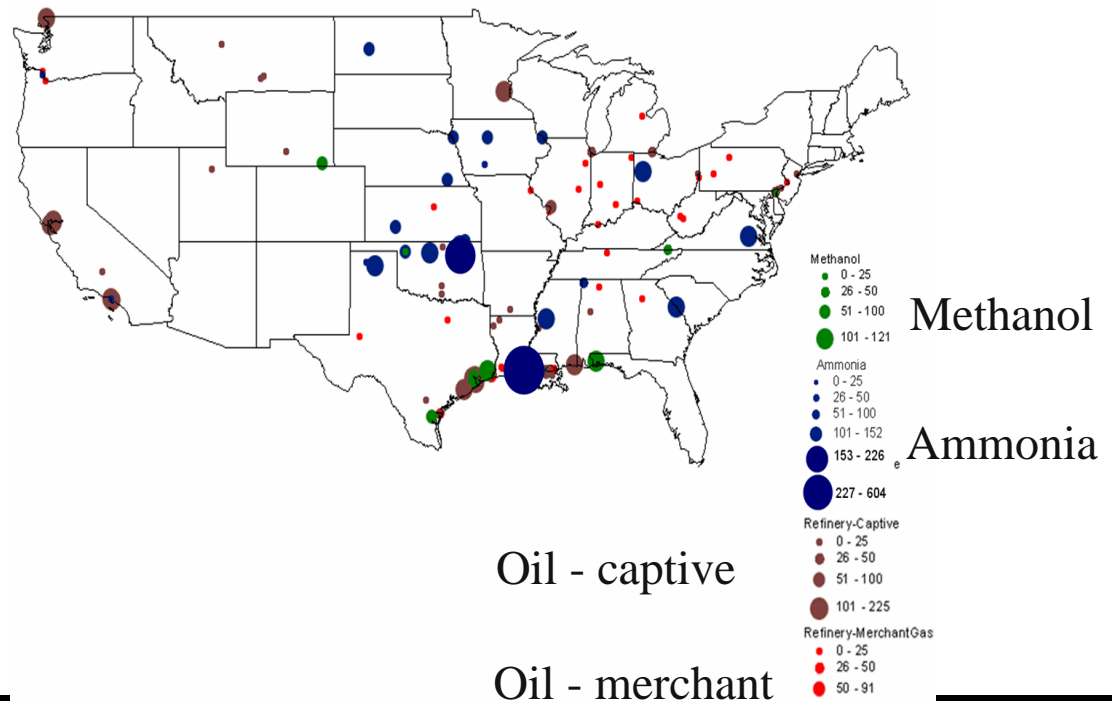
The Value of Product Flexibility in Nuclear Hydrogen Technologies: A Real Options Analysis

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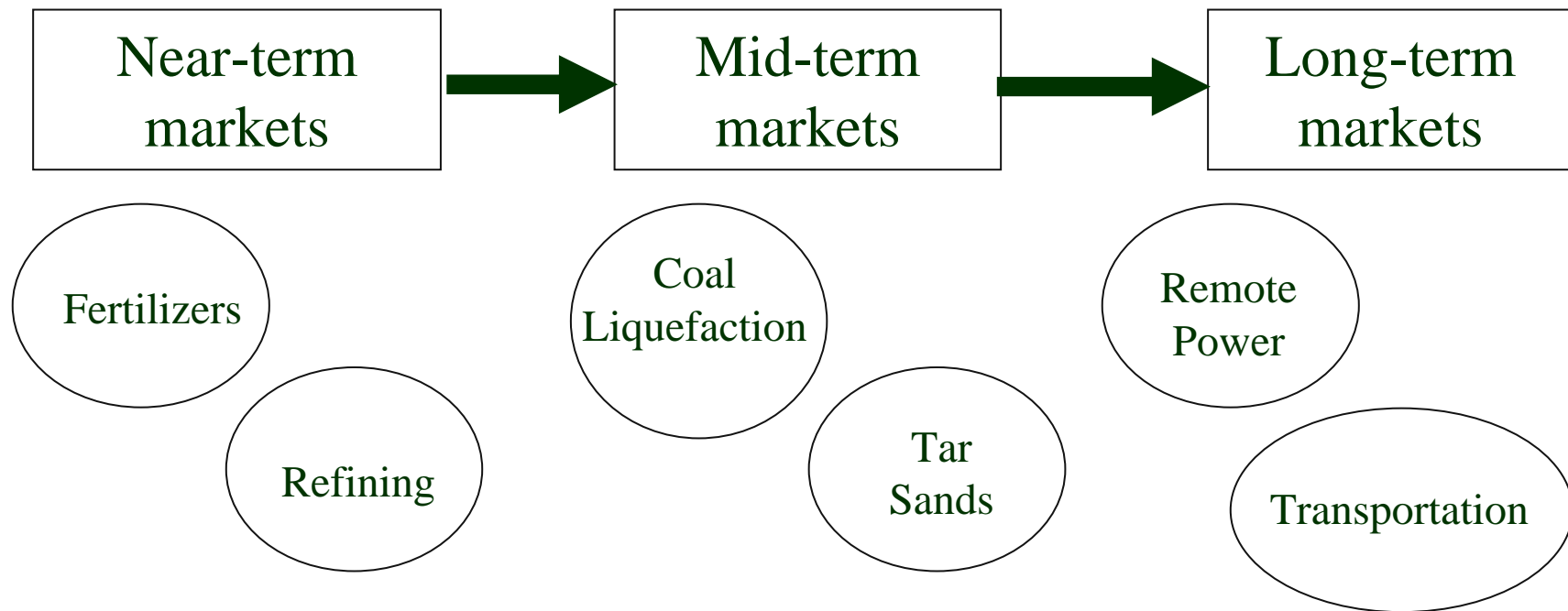
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Current U.S. Hydrogen Markets

- Oil refining (4.1M tonnes H₂).
- Ammonia (2.6M tonnes H₂).
- [Canadian oil sands (0.5M tonnes H₂)].
- Methanol (0.4M tonnes H₂).
- Chemical, metal, food, etc. (0.1M tonnes H₂).



An Evolving Hydrogen Economy



Each market will have different hydrogen needs.
Alternative technologies must compete in each market.

Hydrogen Production Options

- Almost all H₂ today comes from steam reforming of CH₄.
 - Costs rising with natural gas prices. — >750°C. — CO₂ emissions.
- Low-temperature water electrolysis.
 - Energy intensive (i.e., costly). — Production decoupled from heat source.
 - Precious-metal catalysts.
- Thermochemical cycles.
 - 550°C - 2000°C.
- High-temperature steam electrolysis.
 - Solid-oxide fuel cell technology. — Durability?
- Solar hydrogen.
 - Direct solar production: photo-electrochemical cells; artificial photosynthesis.
 - Biomass as feedstock.
- Other options under investigation:
 - Biological/biomimetic hydrogen production.
 - Coal gasification.
 - Direct ceramic-membrane separation of water.

Nuclear Hydrogen Production Plant Configuration Options

- Multiple energy products.
 - Dedicated H₂ vs. hydrogen plus electricity.
- Plant size.
 - Large-scale vs. modular/distributed.
- Flexibility of changing product output rate in co-generation.
 - Load following on either electricity or hydrogen rate without changing the reactor power.
- Direct vs. indirect heating of the electricity production cycle (if electricity is produced).
- Parallel vs. series arrangement of heat loads.
 - Heat transfer to the H₂ production process at the exit of the reactor or the turbine.

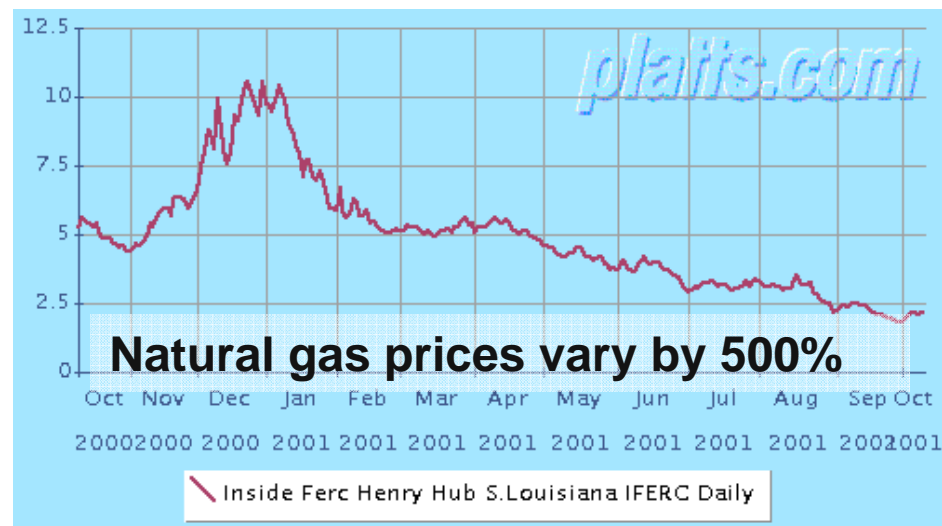
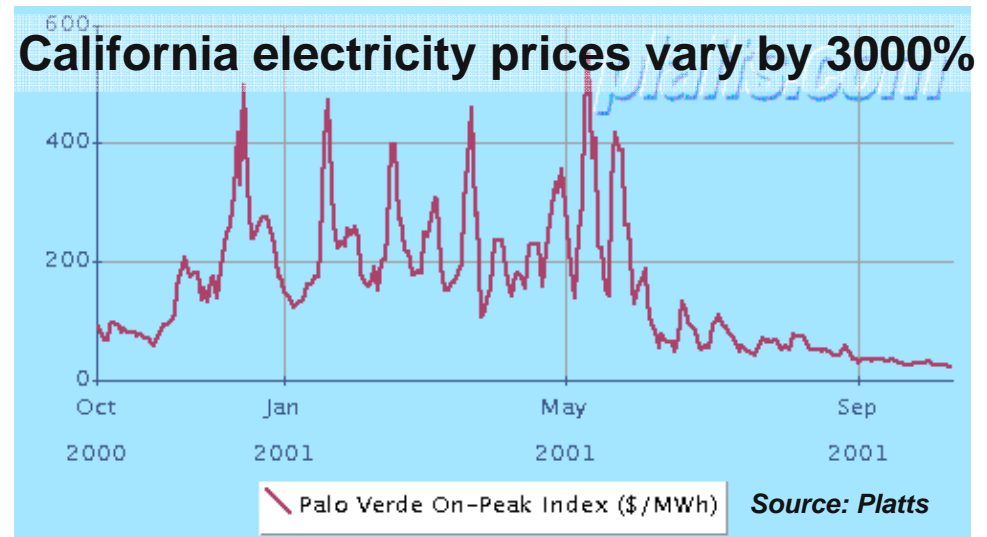
Implications for

- Efficiency
- Cost
- Location requirement

for the specific technology in a specific market.

Electricity (and Hydrogen) Costs Can Vary Widely

- There's great promise in taking advantage of price fluctuations.
- But price variations are not predictable.
- A hydrogen production system based on off-peak (low-price) electricity would have to be flexible enough to adapt to changing market conditions.



Investment Decisions

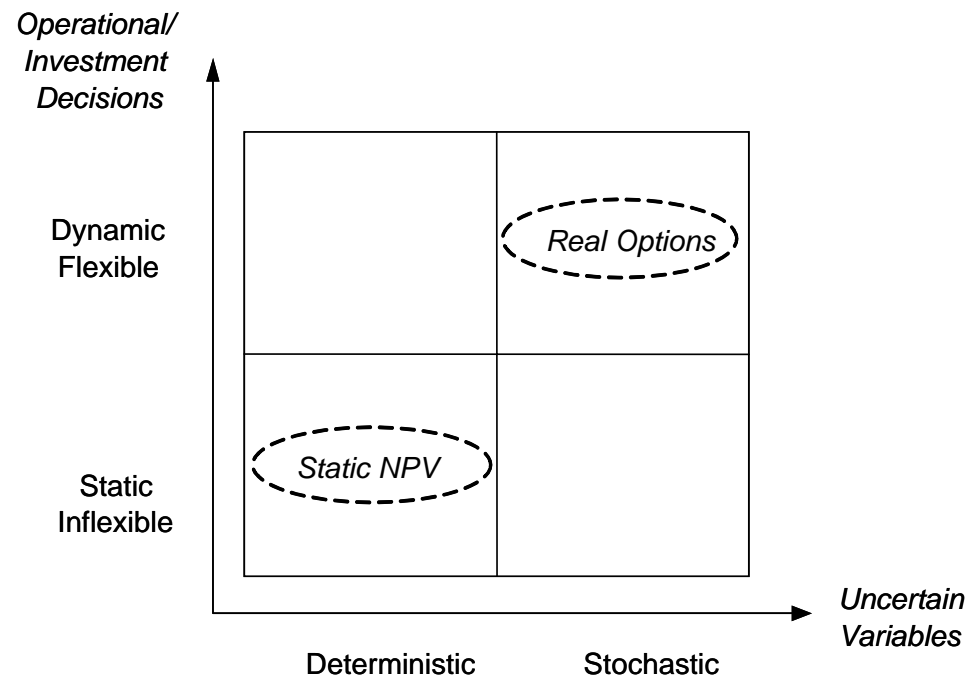
- Several plant configurations are being considered for nuclear H₂ production.
 - Electrochemical cycles.
 - Thermochemical cycles.

How does an investor decide?

- Cost analysis is important, but
 - Levelized cost is not the only input factor for potential investors.
 - The cheapest plant may not be the most attractive investment alternative.
- Investments in these plants will be based on *profitability assessments*.
 - Future cash flows are exposed to a high degree of uncertainty.
 - Real options analysis is a convenient tool for this type of analysis.

Real Options Analysis

- Developed for financial analysis of investments under uncertainty.
- Estimates the value of flexibility in future decisions regarding operations or investment.
- The *option value of flexibility* is not included in traditional Net Present Value (NPV) calculations.



A Model for Financial Assessment of Nuclear H₂ Plants

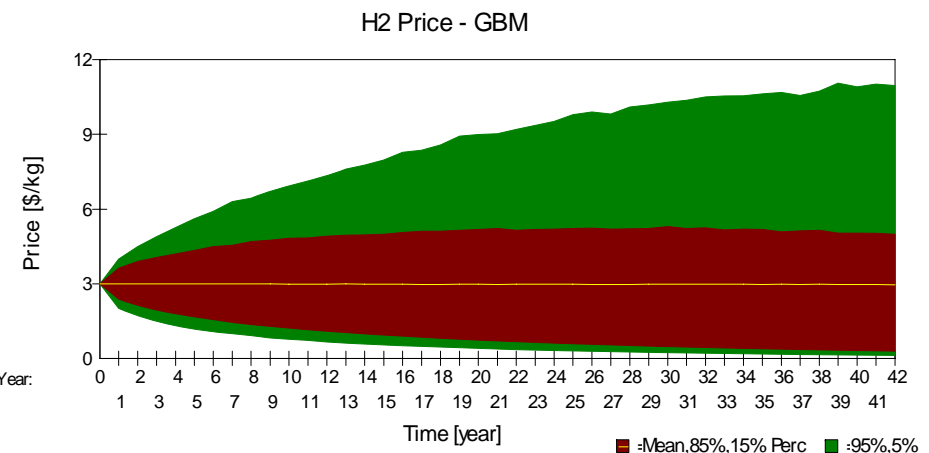
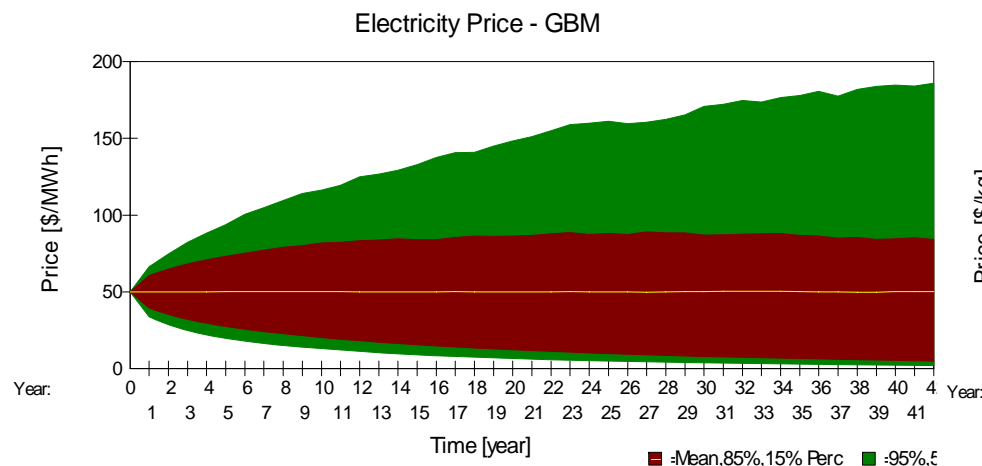
- Cash flow analysis of nuclear hydrogen options.
 - Spreadsheet model calculates annual revenues and costs.
 - Revenue depends on H₂ and electricity prices, which are uncertain.
 - Same cost structure as Technology Insight's levelized cost analysis.
 - No additional capital cost for flexible co-generation plants.
- Demand and prices.
 - Three demand/price sub-periods within each year (low, medium, high).
 - A flexible plant can switch output product instantaneously between sub-periods with no additional operational cost, producing either only H₂ or only electricity.
 - Electricity price varies within the three sub-periods, but the H₂ price is constant.
 - Prices do not include transmission and distribution costs.

A Model for Financial Assessment of Nuclear H₂ Plants

- Two operational modes.
 - 1) *Inflexible*: Pure H₂ production.
 - 2) *Flexible*: H₂ or electricity, depending on what is more profitable at any time.
- The value of flexibility in output product.
 - The difference in profits between flexible and inflexible operations.
 - Not all nuclear H₂ technologies have the switching flexibility (e.g., SI – HTGR).

Uncertainty in Hydrogen and Electricity Prices

- Two stochastic processes used to represent future prices (annual average).
 - Geometric Brownian Motion (GBM). — Mean Reversion (MR).
 - Correlation between H₂ and electricity prices is represented.
- Monte-Carlo simulations are used for discrete sampling of prices.
 - Example: GBM – 10,000 M-C iterations:



Analysis of Nuclear H₂ Technologies

- The model is used to analyze three potential nuclear H₂ technologies:

Hydrogen Production Process	Nuclear Reactor Type	Cogeneration of Hydrogen and Electricity?
High-pressure, low-temperature water electrolysis (HPE)	Advanced Light Water Reactor (ALWR)	Yes
High-temperature steam electrolysis (HTE)	High-Temperature Gas-Cooled Reactor (HTGR)	Yes
High-temperature sulfur-iodine cycle (SI)	High-Temperature Gas-Cooled Reactor (HTGR)	No

- Levelized cost, pure hydrogen production:

	ANL model
HPE – ALWR	\$2.91/kg
HTE – HTGR	\$2.51/kg
SI - HTGR	\$2.26/kg

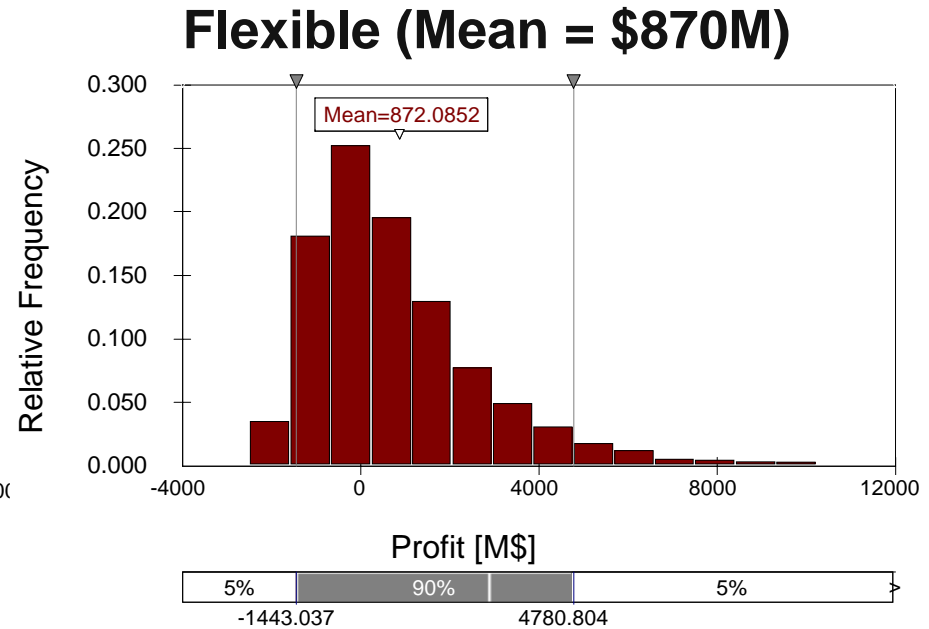
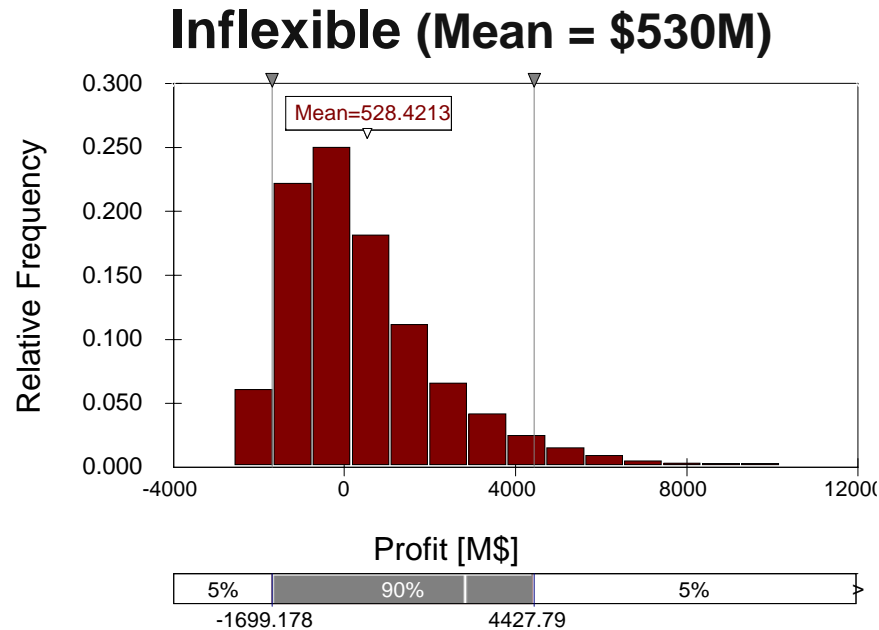
Results – Expected Profits

- Price assumptions for GBM (subjective)
 - Average electricity price: 50 \$/MWh.
 - Average H₂ price: 3 \$/kg.
 - Electricity and H₂ price volatilities: 20 %/year.
 - Electricity and H₂ price correlation: 0.5.
- Expected lifetime profits with real options analysis (GBM):

	Expected Profit (M\$)	
HPE-ALWR, Inflexible	96	} \$670M
HPE-ALWR, Flexible	770	
HTE-HTGR, Inflexible	530	} \$340M
HTE-HTGR, Flexible	870	
SI-HTGR, Inflexible	860	

Flexibility adds substantial value to production technologies.
Stochastic analysis is needed to capture the full option value of flexibility.

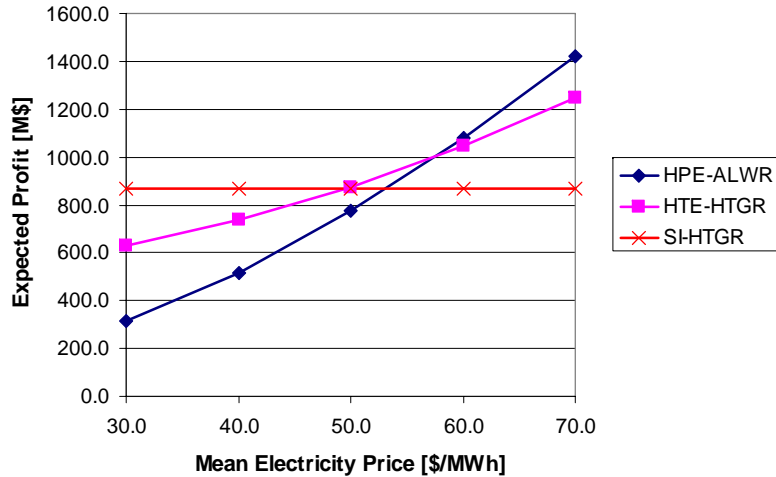
Results – Profit Distributions for HTE-HTGR



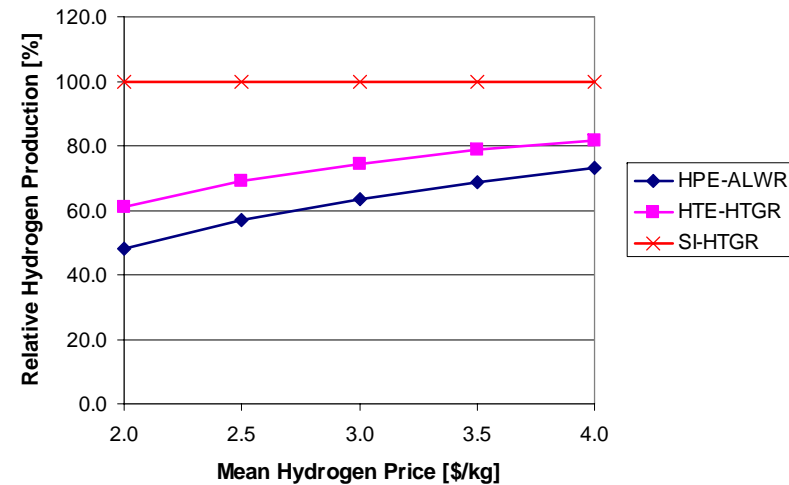
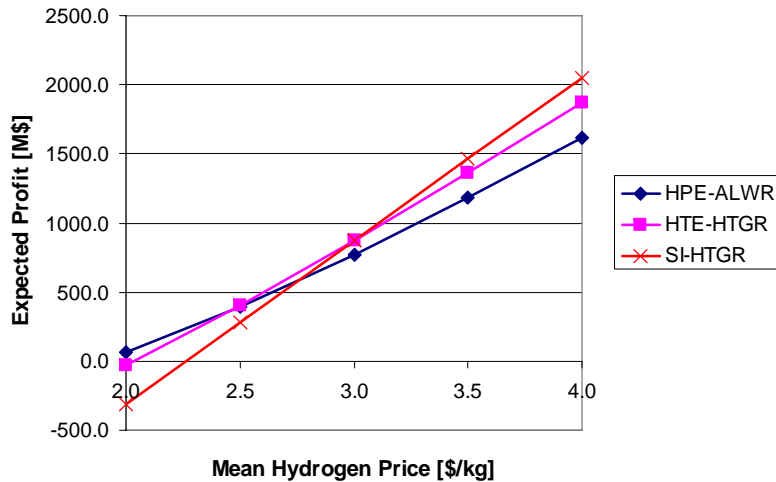
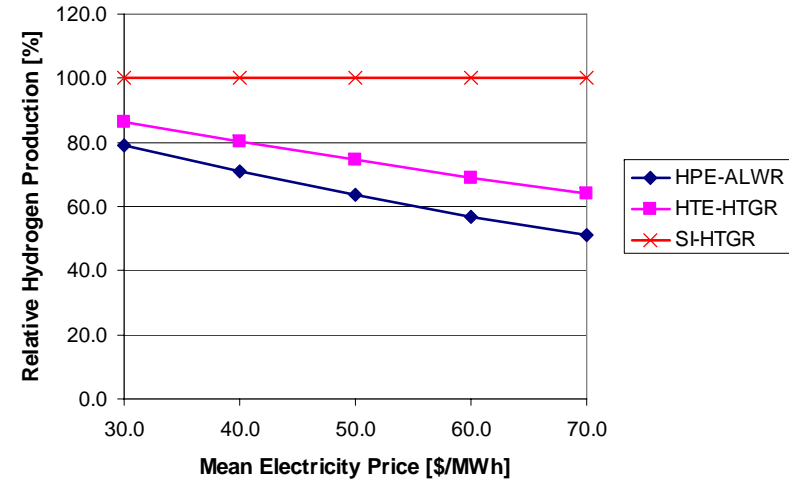
- Flexibility in output product
 - Increases upside of profit distribution and expected profits.
 - Reduces downside of profit distribution.
 - Lowers risk for investor.

Results – Sensitivity Analysis: Mean Prices

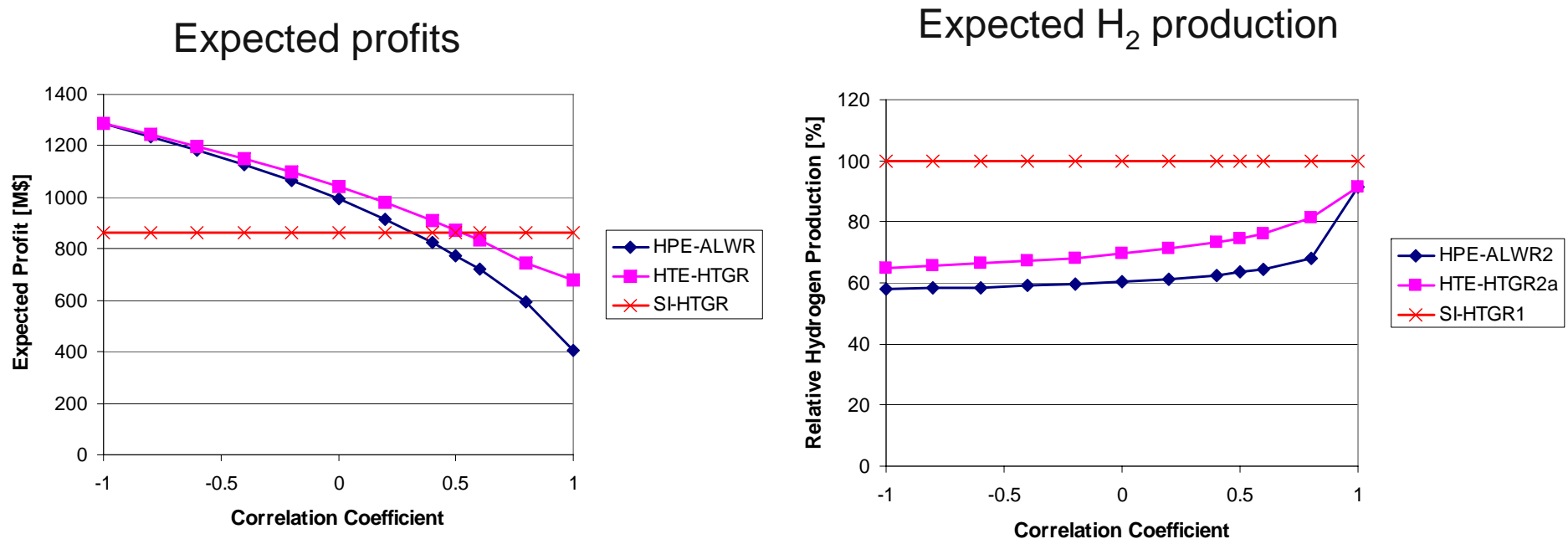
Expected profits



Expected H₂ production



Results – Sensitivity Analysis: Price Correlation



- The value of flexible plants is higher for a low price correlation.
- The amount of H₂ production increases with price correlation.

Conclusions and Future Work

- Main conclusions
 - In addition to cost estimates, it is important to consider profit opportunities and risks.
 - Flexibility to switch between H₂ and electricity can have substantial value for a potential investor.
 - Assumptions about costs and price distributions are highly uncertain.
 - DOE should consider R&D efforts towards developing processes and durable materials that can enable co-generation.
- Future work
 - Refinement of real options model (e.g. cost sensitivity analysis, switching costs, firm H₂ demand, intra-year variations in H₂ price).
 - Extension of real options model (e.g. modular expansion, investment timing, on-site H₂ storage).