Argonne NATIONAL LABORATORY

... for a brighter future

U.S. Department of Energy

THE UNIVERSITY OF CHICAGO

A U.S. Department of Energy laboratory managed by The University of Chicago

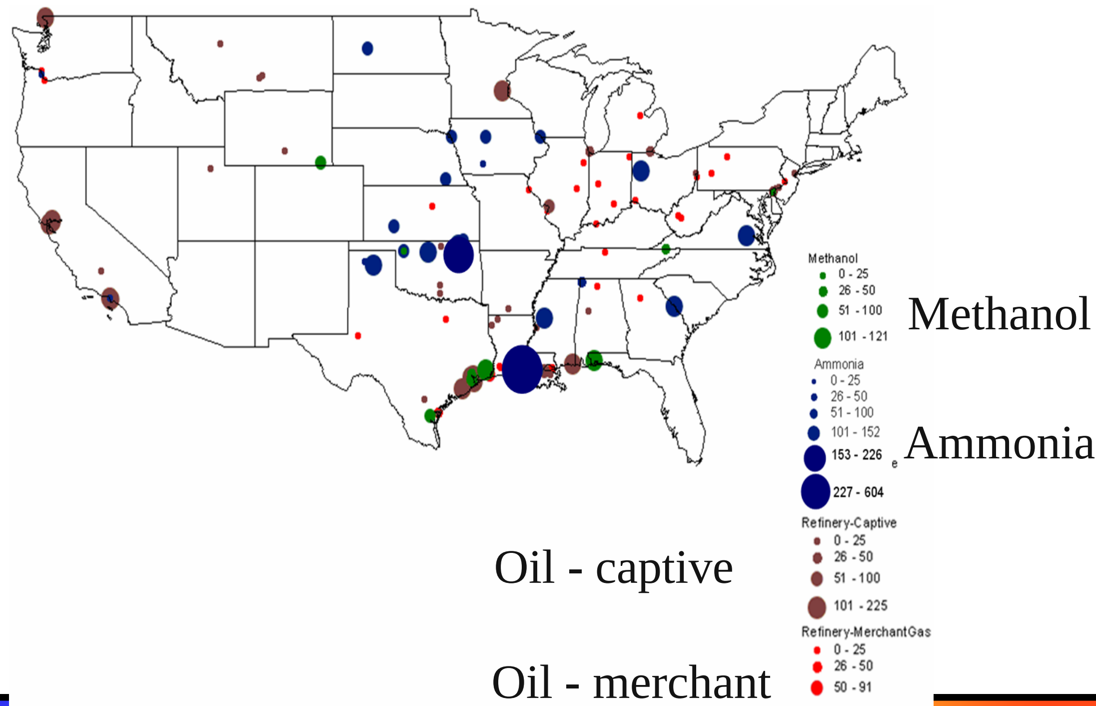
The Value of Product Flexibility in Nuclear Hydrogen Technologies: A Real Options Analysis

Audun Botterud,
Bilge Yıldız,
Guenter Conzelmann,
Mark C. Petri

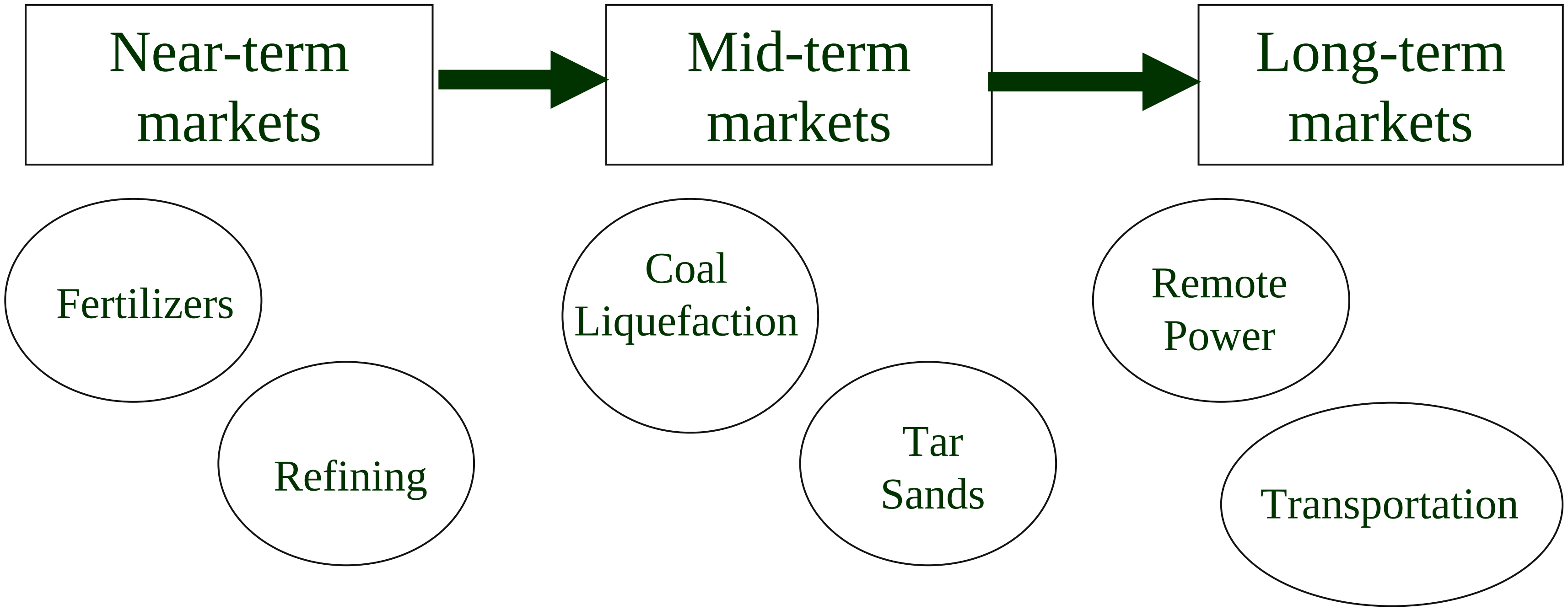
International Conference on Non-Electric Applications of Nuclear Power
Oarai, Japan
April 16-19, 2007

Current U.S. Hydrogen Markets

- Oil refining (4.1M tonnes H_2).
- Ammonia (2.6M tonnes H_2).
- [Canadian oil sands (0.5M tonnes H_2)].
- Methanol (0.4M tonnes H_2).
- Chemical, metal, food, etc. (0.1M tonnes H_2).



An Evolving Hydrogen Economy



Each market will have different hydrogen needs.

Alternative technologies must compete in each market.

Hydrogen Production Options

- Almost all H_2 today comes from steam reforming of CH_4.
  - Costs rising with natural gas prices. — >750°C. — *CO_2 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 H_2 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 H_2 production process at the exit of the reactor or the turbine.

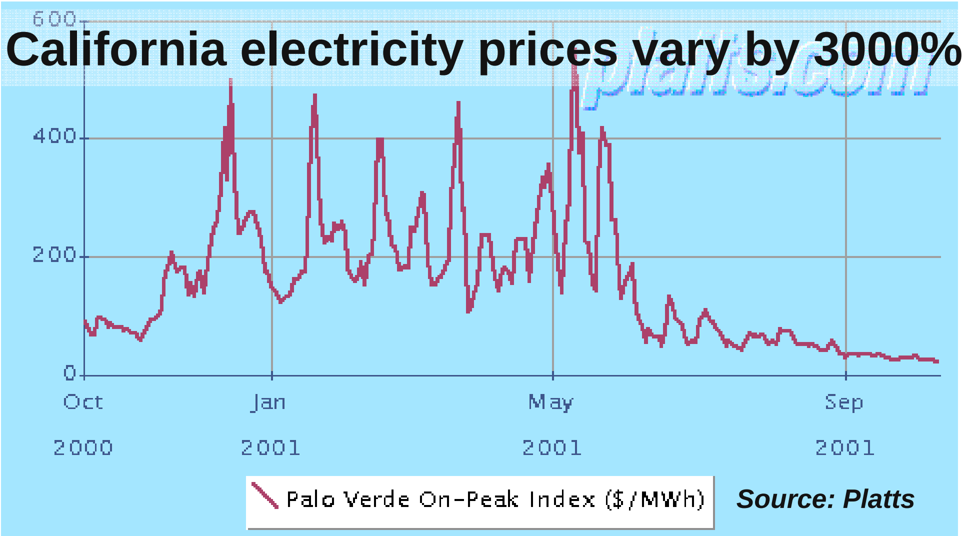
Implications for

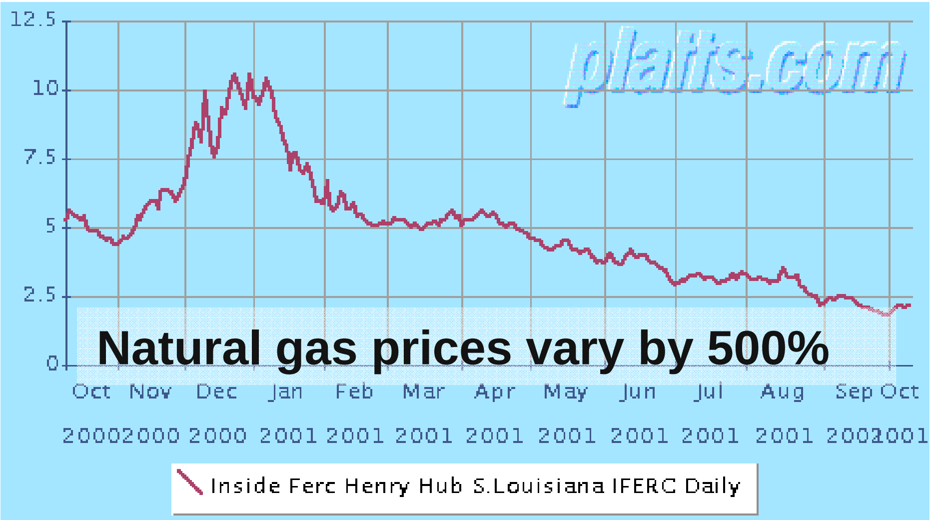
- Efficiency
- Cost
- Location requirement

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

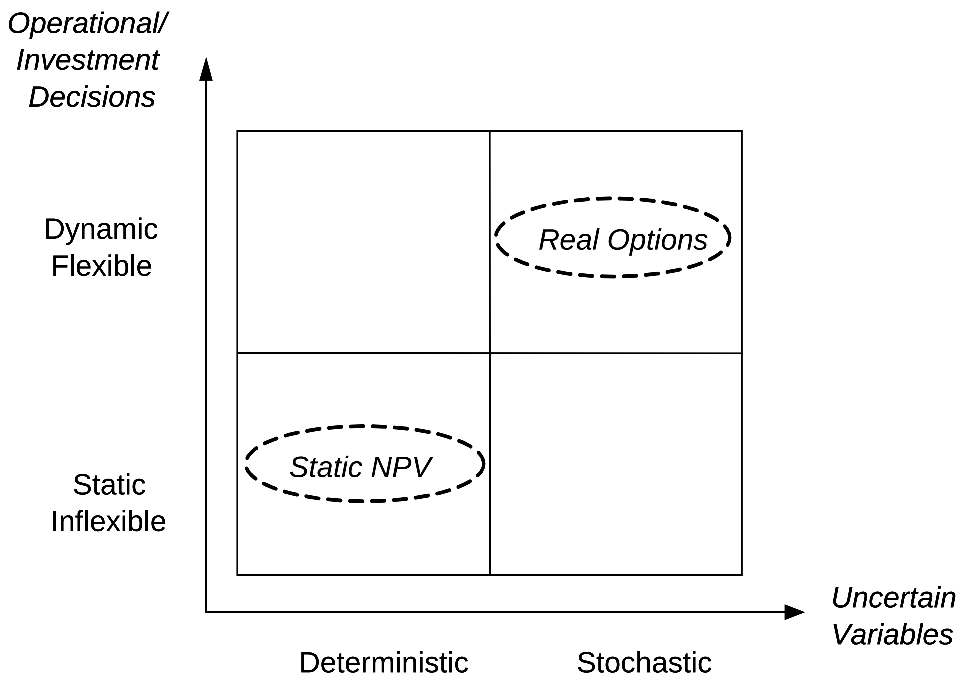
- Several plant configurations are being considered for nuclear H_2 production.
  - Electrochemical cycles.
  - Thermochemical cycles.

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 H_2 Plants

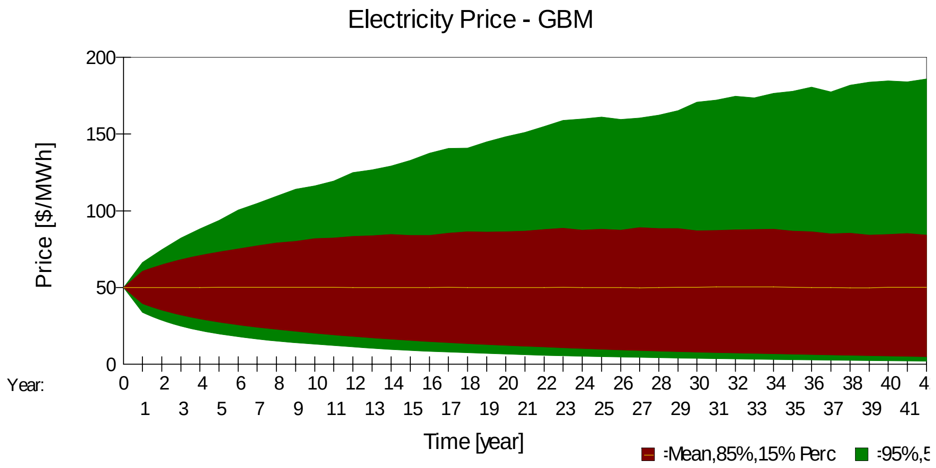
- Cash flow analysis of nuclear hydrogen options.
  - Spreadsheet model calculates annual revenues and costs.
  - Revenue depends on H_2 and electricity prices, which are uncertain.
  - Same cost structure as Technology Insight's levelized cost analysis.
  - No additional capital cost for flexible co-generation 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 H_2 or only electricity.
  - Electricity price varies within the three sub-periods, but the H_2 price is constant.
  - Prices do not include transmission and distribution costs.

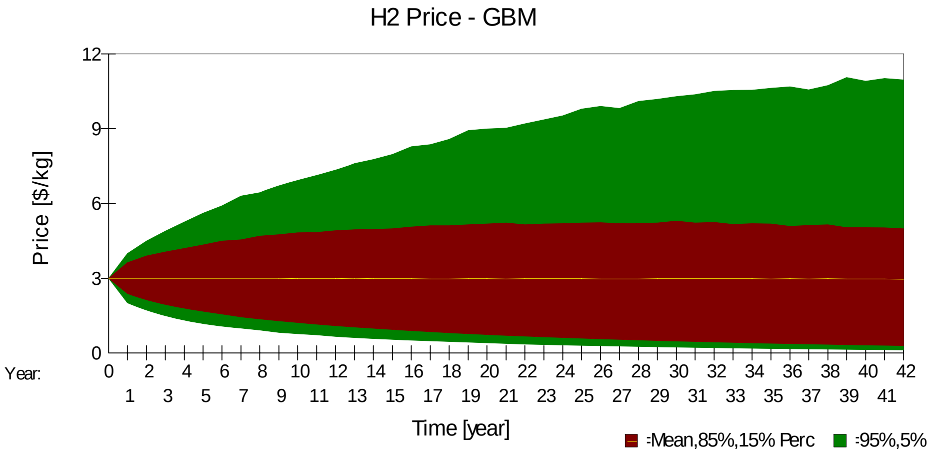
A Model for Financial Assessment of Nuclear H_2 Plants

- Two operational modes.
  1) *Inflexible*: Pure H_2 production.
  2) *Flexible*: H_2 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 H_2 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 H_2 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 H_2 Technologies

- The model is used to analyze three potential nuclear H_2 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 H_2 price: 3 $/kg.
  - Electricity and H_2 price volatilities: 20 %/year.
  - Electricity and H_2 price correlation: 0.5.

- Expected lifetime profits with real options analysis (GBM):

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

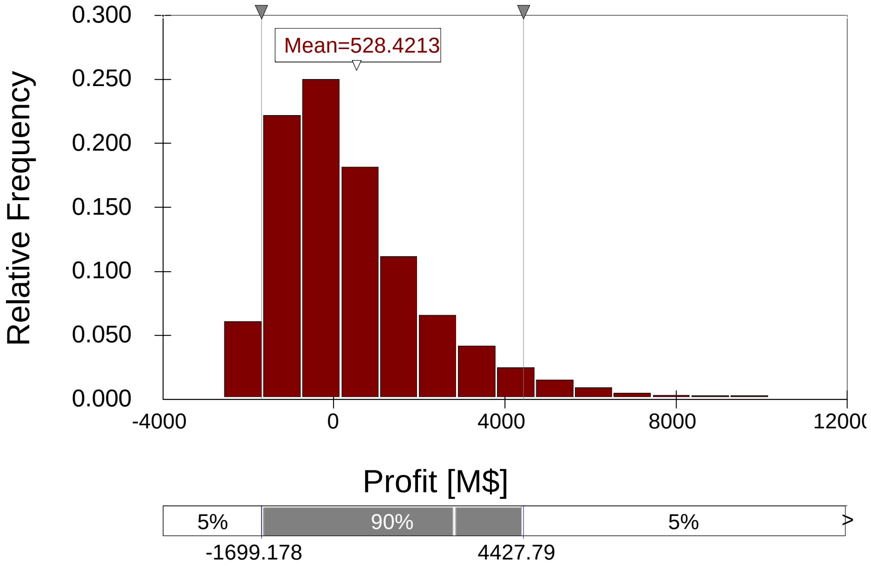
HPE-ALWR Inflexible vs. Flexible: $670M

HTE-HTGR Inflexible vs. Flexible: $340M

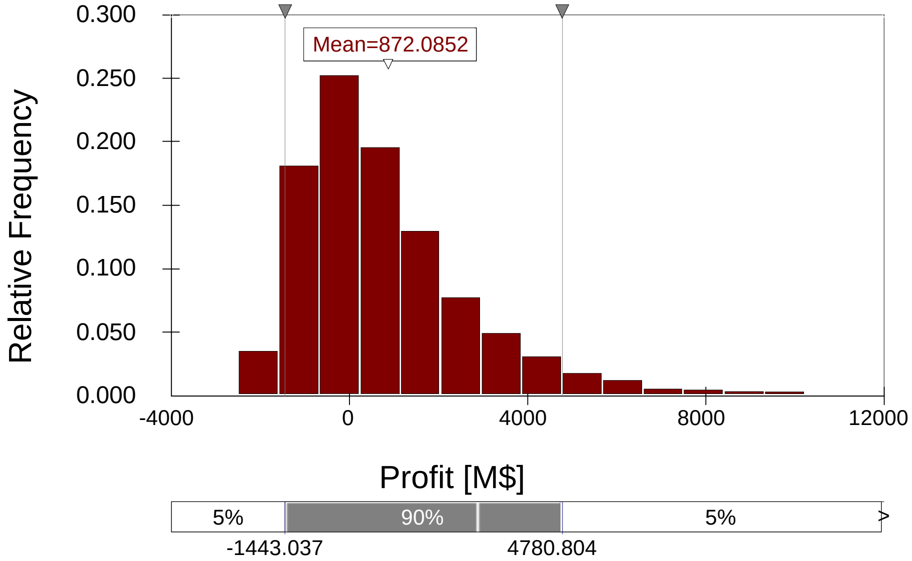
Flexibility adds substantial value to production technologies.
Stochastic analysis is needed to capture the full option value of flexibility.

Results – Profit Distributions for HTE-HTGR

Inflexible (Mean = $530M)



Flexible (Mean = $870M)

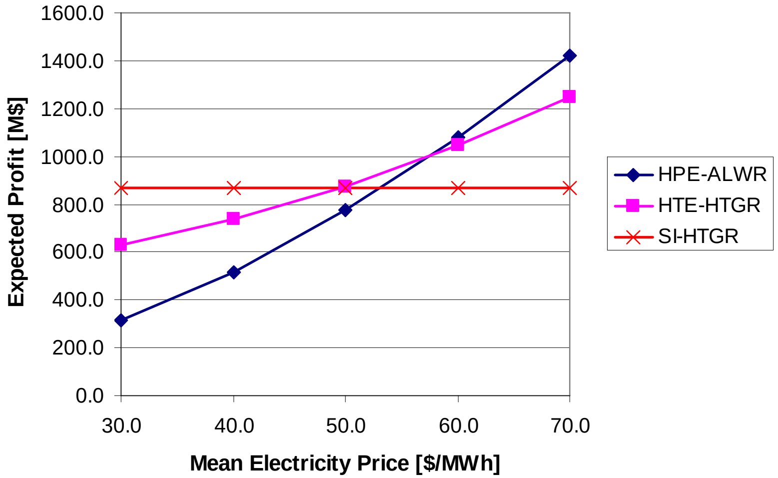


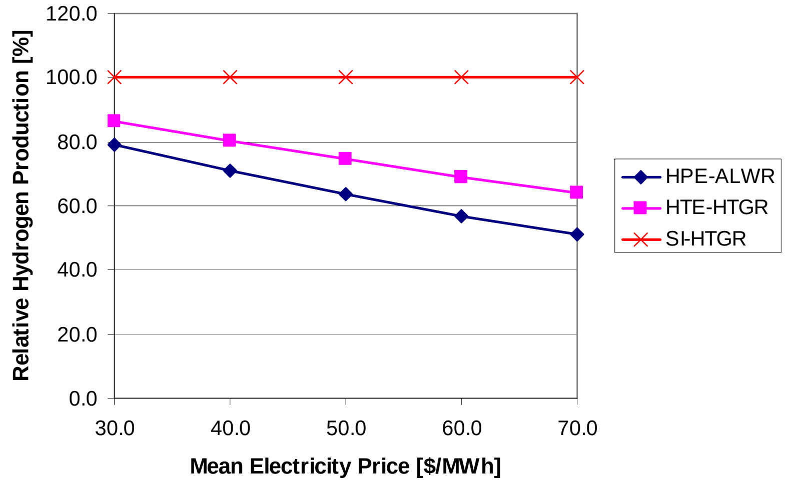
- Flexibility in output product
  - Increases upside of profit distribution and expected profits.
  - Reduces downside of profit distribution.
  - Lowers risk for investor.

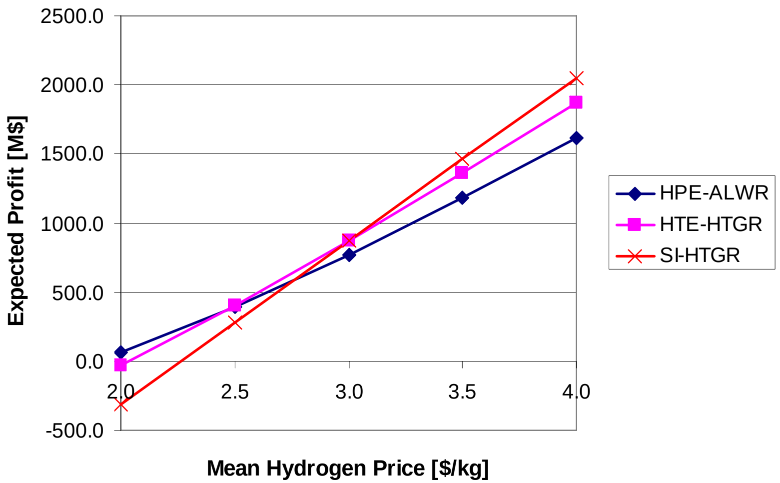
Results – Sensitivity Analysis: Mean Prices

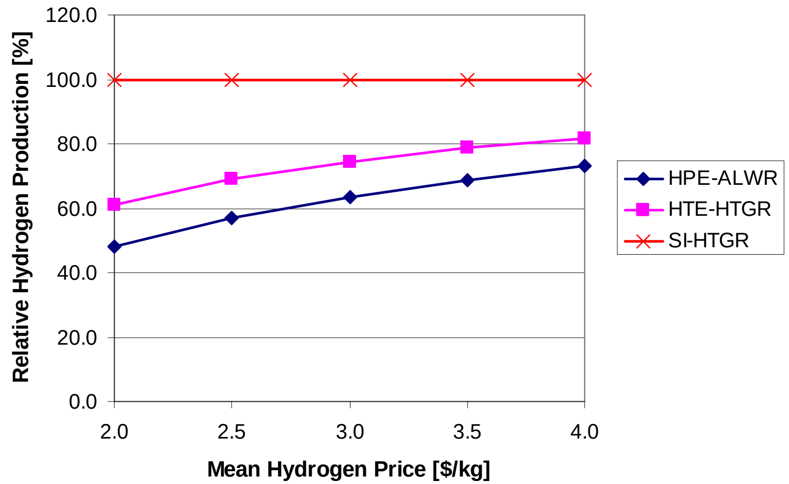
Expected profits

Expected H_2 production

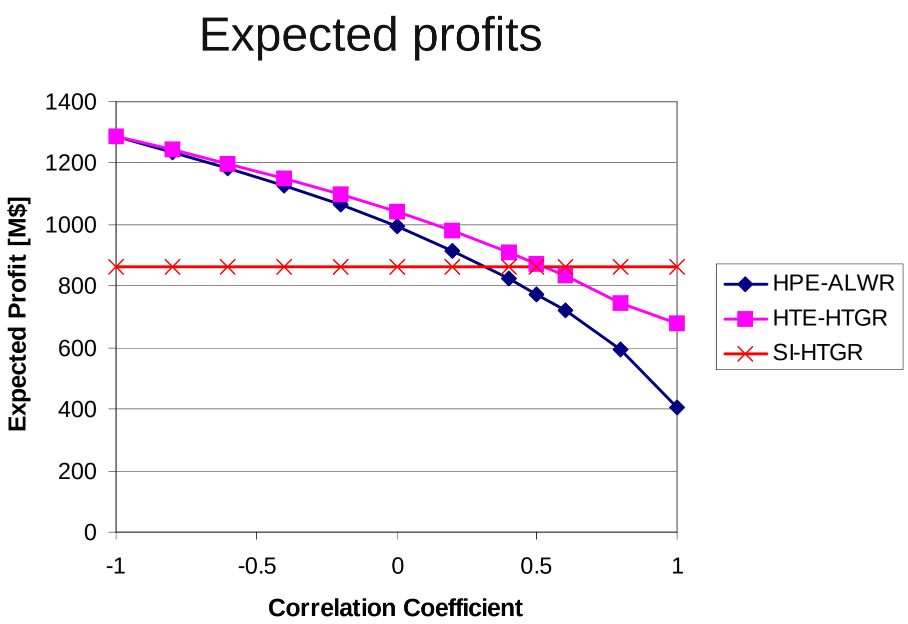


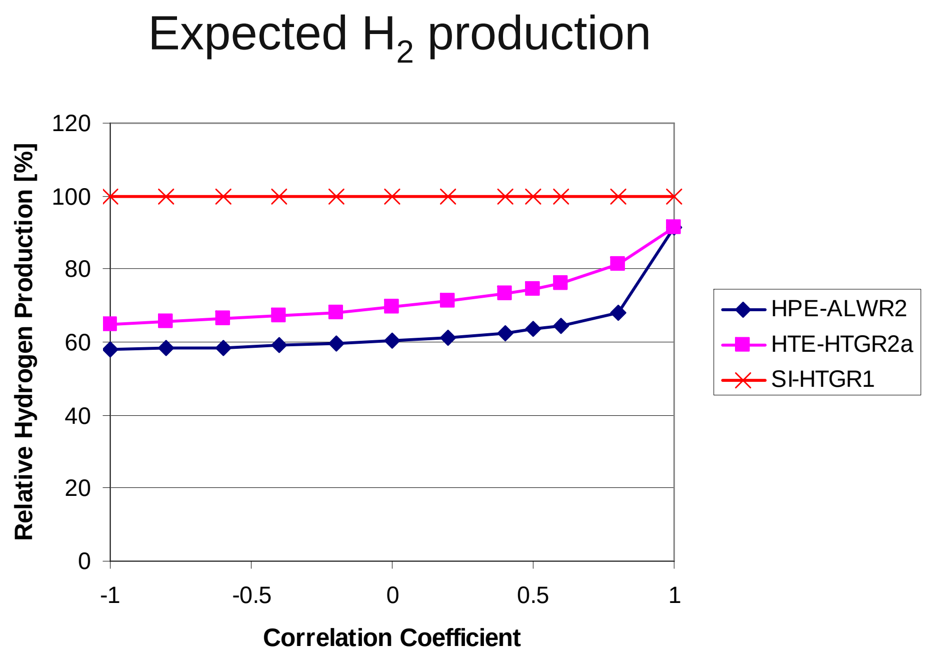






Results – Sensitivity Analysis: Price Correlation





- The value of flexible plants is higher for a low price correlation.
- The amount of H_2 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 H_2 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 H_2 demand, intra-year variations in H_2 price).
  - Extension of real options model (e.g. modular expansion, investment timing, on-site H_2 storage).