Title: Nuclear technology R&D strategies in an era of energy price uncertainty
Technical Work Scope Identifier No.: FC-5 (Fuel Cycle Option Analysis)
Team: Principal Investigator (**PI**) at Lead University (**LU**); Co-Investigator #1 (**Co-I1**) at University Partner (**UP**), Co-Investigators #2 and #3 (**Co-I2, Co-I3**) at Industry Partner (**IP**)

Proposed Scope Description

The past decade has seen dramatic shifts in prospects for a new generation of nuclear power plants (NPPs). The surge and recession in planned NPP builds has mirrored the ascent and fall of North American natural gas (NG) prices. Figure 1 shows that the combined license (COL) applications of 2007-08 followed a period of elevated NG prices. Although the loan guarantee program incentivized construction at four plants, the fall in NG prices has coincided with the withdrawal or freezing of many other COL applications. But **NG prices** are not the only factor that will shape the viability of nuclear power. **Coal-fired** and **renewable generation costs**, particularly those of **wind** and **solar**, strongly affect electricity markets and dispatch.

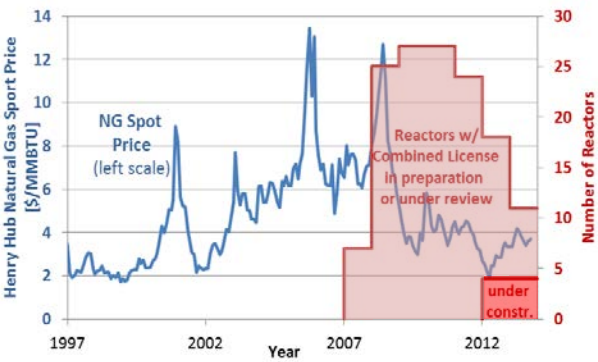


Figure 1. NG spot prices (left axis), nuclear plant builds (right). Data: NG prices, EIA; nuclear plants, WNA.

The growth of **intermittent** generators, especially the **non-dispatchable renewables**, benefits technologies with strong **load following** capabilities. For this reason, flexible generators such as combined cycle gas turbines (CCGT) may out-compete baseload even if NG prices do not remain low, and nuclear units are facing load reductions or even early retirement. In one example, Exelon has warned that it may shut down its Quad Cities plant due to a large increase in the number of "…hours when negative pricing occurs and baseload generating units have to pay to operate," which Exelon attributes largely to non-dispatchable, subsidized wind [Daniels 2013]. Future nuclear plants may increase revenues by avoiding sales when electricity prices are low, for instance by directing their heat or electricity to a **hybrid NG-nuclear system** or into **energy storage**. Figure 2 illustrates hourly electricity prices on the Texas ERCOT grid in 2012 and depicts the load following strategy that energy storage enables.

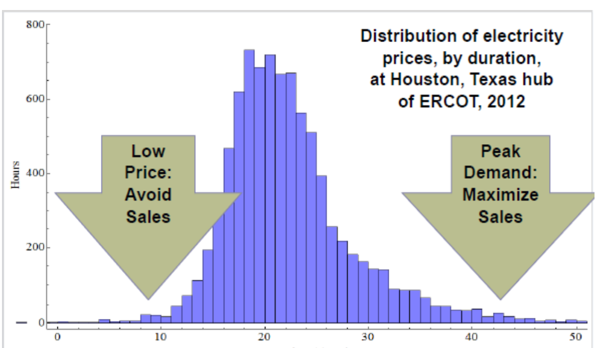


Figure 2. Histogram of hourly electricity prices, ERCOT grid, 2012. Source: Co-I1 publication.

The aim of this research project is to identify nuclear technology options that are competitive over a wide range of plausible future business environments. No single nuclear technology or business practice will be the best choice across all future conditions. Instead, a hedging strategy incorporating a set of technologies is envisioned. Energy storage and conversion as well as a hybrid nuclear-fossil technology will be the **nuclear strategies** considered in this work. Energy storage technologies are certain to come into wide use whether the nuclear industry adopts them or not. California has mandated that 1,325 MW of storage capacity be in place by 2020 [Sweet 2013] in order to minimize costly reserve capacity in the solar and wind-heavy California ISO. Current storage technology development is largely directed toward smaller-scale systems, so storage technologies that offer favorable economies of scale for 100 MW – 1 GW plants will be a focus of this work. High-Temperature Reactors (HTRs) will be considered along with Generation 3+ light water reactors (LWRs).

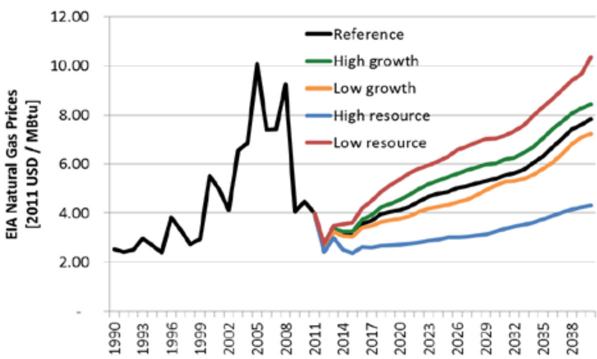
Energy sector scenarios will be defined that represent plausible future fossil and renewable costs and penetration for selected US electricity grids. The economic value of each nuclear strategy will be assessed for every energy sector scenario. This work will result in two key products. First, it will rank order the nuclear strategies for each energy scenario, illustrating strategies that succeed under each set of future market conditions. Second, it will identify a limited number of strategies that represent the best hedge across the range of future energy scenarios.

Logical Path to Accomplishing Scope (Tasks and Descriptions)

Task 1: Define energy sector scenarios. The aim of this task is to define scenarios covering a range of time periods, electricity grids, generation technologies, and market regulation conditions. This is primarily a literature review of plausible future energy scenarios from highly-regarded sources (e.g., [WEC 2013][IAEA 2013][EIA 2013]). Subtasks relating to scenario selection are as follows.

1a. Obtain market data over scenario time frame. Each scenario will specify electricity market conditions through 2040, the end date for projections in the Energy Information Administration (EIA) Annual Energy Outlook. Conditions include fuel prices, technology availability and characteristics (e.g. overnight capital and operating costs), and uncertainties. The uncertainties are important as they drive the concept of hedging against multiple plausible outcomes. NG prices provide an example. Figure 3 shows that five US NG price scenario forecasts in [EIA 2013] differ by a factor of 2.5 by 2040, while Figure 4 compares NG forecasts issued by the EIA since 1995 to historical prices. The historical price is notable for its volatility, which will be quantified in Task 2. The uncertainties will be used in the nuclear strategy decision analysis of Task 5.

1b. Select grids, technologies, and markets. Three regional electricity grids will be selected for the scenario studies. The grids offer distinct generation technology mixes, demand profiles and regulatory environments. The California grid (CAISO) will feature heavy solar penetration, while wind plays a key role in Texas' ERCOT. Solar and wind differ in the frequency and predictability of their intermittency. A third grid, perhaps PJM, will provide a representative East Coast demand and technology mix. As a base case, nuclear capacity that is present in any scenario will be given the characteristics of the reference Gen-3+ LWR to be defined in Task 3. The alternate nuclear strategies will be inserted into the scenarios in Tasks 4 and 5.



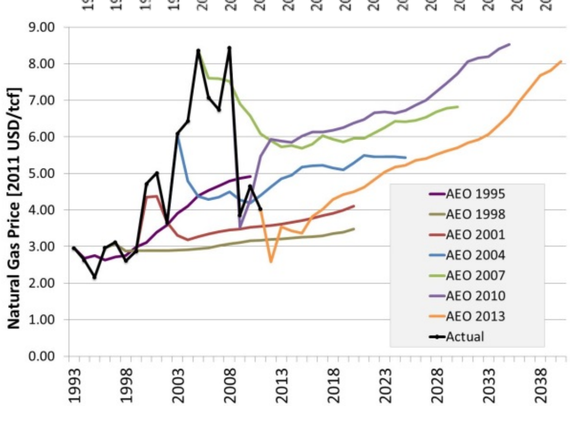


Figure 3. (top) NG spot price history and EIA forecasts to 2040.
Figure 4. (bottom) Past EIA NG price forecasts (colors), historical data (black)

Task 2: Model hourly electricity load profiles and prices. In order to assess the nuclear strategies specified in Task 3, it is necessary to quantitatively depict the markets in which they will be operating. This task will use an electricity market simulation tool to model hourly electricity prices (e.g., Fig. 2) and generation mixes for the energy scenarios defined in Task 1. The model's key performance requirement is that it solves the optimization problem of economic electricity load dispatching. Figure 5 uses

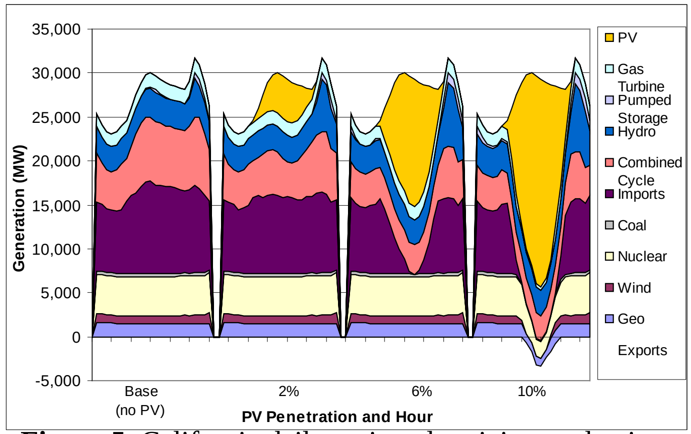


Figure 5. California daily spring electricity production with different levels of solar PV generation. Source: PI and Co-I1 publication.

California ISO hourly demand data to illustrate dispatching and highlight its importance to this project. The four vertical 'slices' of the figure show hourly generation mixes calculated for a representative day as non-dispatchable solar photovoltaic (PV) penetration is increased. In the slice at far right, high afternoon PV production pushes dispatchable sources (gas turbine, imports) offline. The grid system operator only dispatches the lowest cost generators, so the electricity price would decline to nearly zero and can even become negative. But nuclear, which is unable to go offline for just a short period, must stay on the grid and accept the low prices. The value of nuclear strategies involving energy storage or hybridization with natural gas can only be obtained from this hourly depiction of the market. Equally importantly, the nuclear strategy may change the market once it is deployed. This task therefore focuses on adapting an existing electricity market modeling and optimization tool to the needs of the project.

2a. Choose modeling tool and construct scenarios. Two widely-used wholesale electricity market simulators will be used: EnergyPLAN [Lund 2013] and PLEXOS (Energy Exemplar Pty Ltd.). Both models meet the basic performance requirement of depicting the hourly wholesale electricity market.

EnergyPLAN uses an iterative procedure to minimize electricity costs given a merit order stack for electricity generators as well as a set of installed energy storage and combined heat/power (CHP) technologies. It is open source but most of its existing databases focus on European energy markets. PLEXOS formulates the energy market clearing problem as a linear program and can incorporate uncertainty and volatility via a stochastic programming approach. It has been used in the US to quantify the economic value of a generic small-scale energy storage technology for renewable generators [Denholm 2013]. PLEXOS is proprietary but available to universities through an educational license. It features contemporary data sets (generation stations, demand profiles) for ERCOT and the Eastern Interconnect (EI) as well as forecasted (2020) data provided by the Western Electricity Coordinating Council (WECC). While this data is from publicly available sources, for model validation and quality assurance purposes it is advantageous to begin work with an externally-vetted database.

As a first step, Both EnergyPLAN and PLEXOS will be used to model one grid, likely ERCOT. This will allow quality assurance and cross-validation of key results such as forecasted hourly electricity price. Since the models employ distinct methodologies for solving the dispatched electricity cost minimization problem, identical results are not expected. Instead, differences will be explained and the model which is judged most suitable for this work will be retained. The selected model will then be employed to simulate the rest of the energy market cases that were defined in Task 1.

Criteria that will be used in model selection are listed below.

- *The models must be able to simulate each nuclear strategy.* PLEXOS has modeled a range of energy storage strategies; EnergyPLAN includes a generic storage technology but its suitability for a nuclear-NG hybrid is unknown. The down selection will be conducted in parallel with nuclear strategy definition (Task 3), as feasibility of modeling must play a role in determining the strategies. *The model that imposes the fewest constraints on Task 3 is preferred.*
- Both models effectively model the day-ahead electricity market, on which a large majority of electricity production is contracted. However, the real-time market is a significant outlet for

many of the nuclear strategies to be studied in Tasks 4 and 5. For example, a nuclear/natural gas hybrid plant has the flexibility to capitalize on a shortfall resulting from a less windy than expected day, which would be filled on the real-time market. *The ability of both models to depict the appropriate marketing for all nuclear strategies will be assessed.*

- As mentioned, the results are expected to be sensitive to the degree of volatility in natural gas and other energy commodity prices. An extensive literature applies well-known methods – Geometric Brownian Motion (GBM) and/or trend line-reversion with jump – to depict commodity price volatility (see [Mastrangelo 2007]). *The quality of both software packages' implementation of volatility models will be assessed.*

2b. Populate model with technology data. In future decades, nuclear will be competing against advanced wind, gas, solar and coal. Our industrial partner not only has extensive experience in nuclear power generation, but also maintains a portfolio of generation technologies that includes renewables. Therefore, IP will provide technical and economic data that is based on its experience in advanced wind, solar, and biomass generation. Past experience will be used to extrapolate future expectations for these technologies, taking into account trends in efficiency, availability, and capital and maintenance costs.

Some of these technologies, such as off-shore wind, are still in the nascent stages of development, with steep learning curves yet to be overcome before optimal designs and deployment strategies are realized. Therefore, the historical data for these systems are not necessarily a good indicator of future performance. With this in mind, IP will apply technology learning curve analyses augmented by engineering judgment to predict how these technologies mature as lessons learned result in performance improvements.

Task 3. Define and quantify nuclear 'strategies'. The nuclear strategies represent R&D-enabled market-driven decisions to deploy technologies for flexible use of nuclear heat. The technology classes to be studied are energy storage and hybrid nuclear-fossil. Since some technologies are enabled by or perform more efficiently with high temperature heat, reference Gen-3+ LWR and HTR technologies will be considered. A strategy comprises a reactor technology paired with an energy conversion and storage option, with conventional electricity generation also considered as a base case. Table 1 summarizes the two reactor types, nuclear-fossil hybrid and three energy storage technologies to be assessed.

Table 1. Reactor and energy conversion and storage technologies

Reactor Technologies (Task 3a)	
Large (1 GWe) Gen-III+ LWR: Technical-economic characteristics developed with input from IP as well as the Advanced Fuel Cycle Cost Basis report [INL 2013].	*Small (100 MWe) High temperature reactor (HTR):* Down select a design from salt and gas coolants. Characteristics from 2012 INL technical evaluation study [INL 2012], UP design study, input from IP.
Energy Conversion and Storage Technologies (Task 3b)	
Nuclear-energy storage strategy #1: *Daily load following.* Down select from technologies suitable for 4-8 hours of storage with limited carryover including molten salts (e.g. sodium nitrate), pressurized hot water storage, trans/supercritical CO_2 heat pump [Fuller 2013]	*Nuclear-energy storage strategy #3*: *Fast discharge.* Down select from the fastest response technologies to capitalize on brief periods of peak demand or swings in real-time market prices: steam accumulators, molten salts, flywheels
Nuclear-energy storage strategy #2: *Multi-day or multi-week storage.* Respond to weekly or seasonal price changes. Down select from technologies including pressurized underground hot water, heating of large rock formations	*Nuclear-fossil hybrid strategy* HTR (gas or salt cooled) with nuclear air-Brayton combined cycle, natural gas boosted, operating above natural gas autoignition temperature (see [Co-I1 2014] and Figure 6).

3a. Define reactors. Reactor costs and characteristics will be defined with input from the IP and data from the Advanced Fuel Cycle Cost Basis report. The IP will work with the UP to develop credible pre-conceptual designs for coupling the reactors to the energy storage strategies. The purpose of these simple designs will be to serve as a basis for scaling the major cost components of the storage systems. The data for the reference LWR and HTR will be based on IP's current portfolio of commercial reactor designs, which are in various stages of maturity. These designs include PWRs and BWRs as well as an HTR.

3b. Define energy conversion and storage technologies. This subtask will collect technical and economic characteristics for the nuclear-fossil hybrid and energy storage technologies.

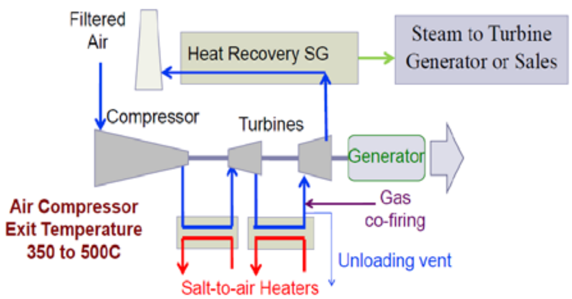


Figure 6. Nuclear air-Brayton cycle operating above NG autoignition temperature. Source: Co-I1 publication.

The nuclear-fossil hybrid featuring a nuclear-NG Brayton cycle is a new option made possible by advances in NG combined cycle plant design. A high-temperature reactor is coupled to an air gas turbine with heat recovery boiler that produces steam for added electricity production or industrial sale (Fig. 6). The plant can operate as a baseload nuclear plant or in peaking mode where after nuclear heating NG is injected to boost the temperature of the compressed air before it enters the turbine. Because the NG is used on top of 'low-temperature' nuclear heat, the NG to electricity efficiency is above 66%, better than any stand-alone NG plant, and the hybrid will be dispatched before stand-alone NG.

As the first step in the energy storage part of this subtask, three storage technologies will be down selected from the larger set of options delineated in Table 1. Table 2 summarizes technical and economic characteristics of a subset of the energy storage technologies. Using existing studies as a starting point, the subtask will develop engineering estimates of the round-trip efficiency and capital and operating costs of the storage technologies when scaled up in size to be commensurate with the capacity of nuclear plants.

Table 2. Storage Technologies (from DOE/EPRI 2013 Electricity Storage Handbook unless noted)

	Capacity	Round Trip Eff	Discharge Time	Capital Cost $/kW	Fixed O&M $/kW-yr	Variable O&M $/kWh
Pumped Hydro	Up to 4000 MW	81%	8-22 hr	2300	6.5	0.0003
Compressed Air Below Ground	Up to 400 MW	70%	8-26 hr	1100	4.3	0.0033
Lithium-Ion Battery	Up to 10 MW	90%	1 - 5 hr	3400	7.6	0.0028
Flywheel	20 MW	75%	15 min	2200	5.8	0.0003
Molten Salt Storage	20 MW (or more)	~93%	15 hr	$5600/kW capital cost if coupled to small-scale solar thermal system		
Hot Rock Storage [DOE 1978]	~100 MW-yr minimum storage for reasonable efficiency			$900-2400/kW capital cost; variable costs decrease with increasing ΔT		

In the context of storage technologies, several challenges must be overcome to develop the needed data set. First, many thermal storage technologies have been developed for relatively small scales, such as associated with solar thermal systems. Several of these are directly applicable to nuclear; however, the nuclear scale is one to two orders of magnitude larger. Economies of scale may result in major cost reductions for storage and will be quantified under this task. Second, during and after the oil embargo of the 1970s, there were studies on coupling thermal storage to reactors for peak power production. These studies (e.g., [Gilli 1973]) need to be updated to reflect current technology and economics. Last, three storage technologies will be considered in detail because the preferred technology depends upon the hourly, weekly and seasonal market price structure. For example pumped storage, the traditional storage technology, is based on pumping water over 6 to 8 hours in the night and using that electricity in the day over a similar time. If there is a large solar capacity, such as in California, the low-price electricity will be generated only a few hours at mid-day with a demand for peak power over a shorter time as the sun sets. The daily charging and discharging time may make a large difference in the preferred storage technology.

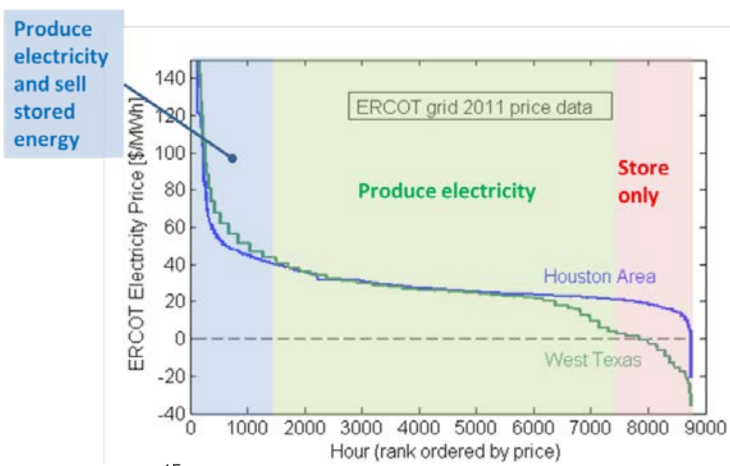
Each fully defined nuclear strategy will be comprised of a reactor technology coupled with an energy storage/conversion technology. Fully defined strategies are specified by their capital, fixed and variable operating costs, thermal-to-electric and round trip (for storage technologies) efficiencies, fuel requirements, and generation and storage capacities and charge/discharge times.

Task 4: Quantify the benefit of nuclear strategies in each scenario. In this task, the nuclear strategies from Task 3 will be put into the electricity load dispatch model developed for every energy scenario in Task 2. The figures of merit for each strategy/scenario pair will be the net revenue change for the nuclear strategy relative to a base case with no nuclear energy storage or conversion technology as well as the mean annual price of electricity.

These expected outcomes are illustrated for a generic energy storage technology with the aid of Figures 7-9. Figure 7 shows the 2011 electricity price duration curves for the ERCOT Houston (blue) and West Texas (green) settlement points. Houston was overwhelmingly supplied by gas and coal, while wind comprised 68% of nameplate capacity in West Texas (though less than 20% of electricity generation). Electricity prices in Houston were generally moderate: negative prices were not observed, and prices exceeded $50/MWh for less than 500 hours out of the year. In West Texas, on the other hand, even though the average electricity price was lower, large amounts of variable, non-dispatchable wind generation led to a more extreme price distribution. Prices were negative in nearly 1,000 hours and rose above $50/MWh for nearly 1,000 hours. These curves exemplify two energy sector scenarios.

The shaded regions in Figure 7 define a simple approach to scoping the maximum benefit that can be obtained from an energy storage technology. Here, for illustration purposes energy is assumed to be stored during the hours of lowest price and sold during the same number of highest-price hours. Figure 8 shows the increase in revenue that would be attained at each settlement point as a function of the number of hours stored and round trip storage efficiency.

The revenue increase at Houston, while substantial, is generally less than half of what could be obtained in West Texas.



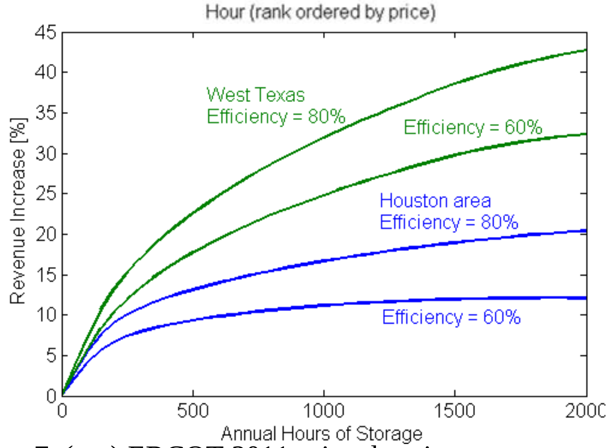


Figure 7. (top) ERCOT 2011 price duration curves illustrating energy storage strategy.
Figure 8. (bottom) Additional revenue attained from energy storage strategy.

These scoping results are included to illustrate the nature of the results. The analysis to be carried out with the electricity market simulators will account for day-ahead electricity market planning as is currently the practice on all US grids. Figure 9 shows an optimized daily strategy for a small storage unit operating in the day-ahead market. Energy storage also exerts a feedback effect on prices, which will be captured by the electricity market model: the more nuclear plants using storage that are on the grid, the smoother the day-ahead electricity price distributions will become. Therefore, the value of storage declines somewhat when a great deal of it is in use (but the presence of nuclear plants with storage can *increase* the revenue of non-dispatchables like wind and PV).

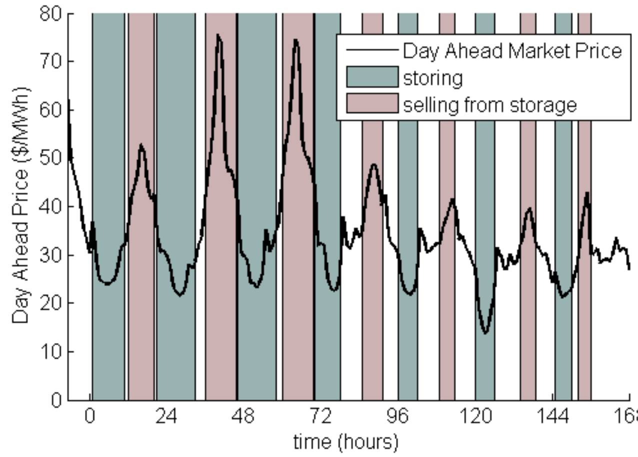


Figure 9. Example of optimal storage strategy. 13% revenue increase at 60% round trip efficiency. Houston day ahead prices for a week in Oct 2013.

For the nuclear-NG hybrid, scoping assessments suggest a potential revenue gain of 50% or more after subtracting NG costs. Figure 10 illustrates a 3-mode sales strategy with the 2012 ERCOT Houston price distribution. Here, the Brayton cycle always produces electricity, but above a critical price supplemental natural gas is also injected, increasing the generation capacity of the plant by up to 140%. Low temperature process heat (steam) from the heat recovery steam generator (Fig. 6) is sold when electricity prices are low to moderate but used to further boost electrical output when prices are high.

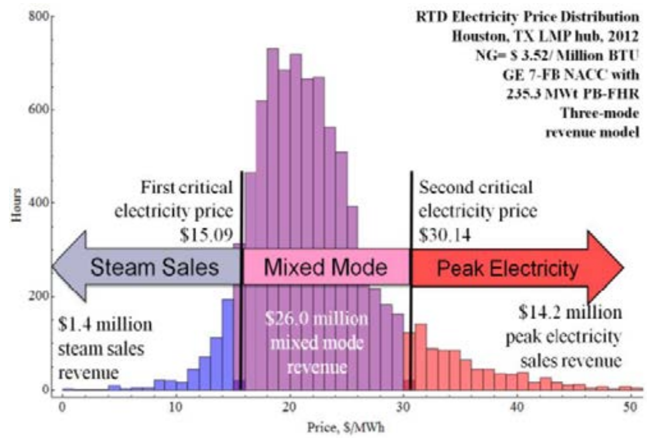


Figure 10. Operating strategy for nuclear-NG hybrid given 2012 ERCOT Houston hub prices. Source: Co-I1 publication.

All sample results presented here are illustrative and do not account for market feedbacks or technology construction and fixed operating costs. Optimization and price feedback are the key capabilities being supplied by the electricity market simulators. The hybrid, for instance, will operate its gas co-firing system in an optimized fashion when electricity and natural gas prices warrant it, and many hybrids on the grid will modify electricity prices from their nuclear-only values. The market simulators will account for energy conversion system technology costs when optimizing as well.

The main outcome of this task will be the net annual revenue of the nuclear units for each nuclear strategy and energy sector scenario. The deliverable will rank order the nuclear strategies by net revenue for each scenario. It is not expected that the ordering will be the same for every scenario: for instance, a nuclear/natural gas hybrid will outperform a storage technology on a grid with few non-dispatchable generators and under conditions of continued low gas prices. Uncertainties such as those associated with commodity prices will be handled explicitly in Task 5.

Task 5: Recommend a portfolio of nuclear strategies to hedge against the range of energy scenarios. The proposed work is intended to inform a future decision to invest in R&D in nuclear energy conversion and storage technology in order to catalyze their future deployment by utilities. But the best technology/ies to foster, or the wisdom of pursuing any technology at all, depends on the uncertain future

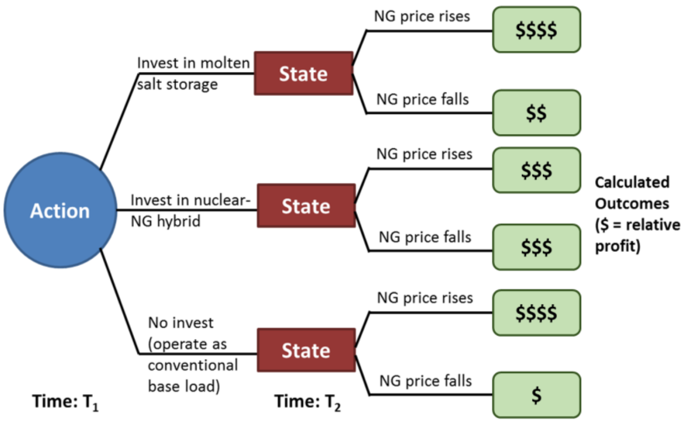


Figure 11. Illustrative decision tree structure.

state of the electricity markets. Natural gas prices, renewables cost and penetration, carbon policies, and nuclear unit costs are all subject to uncertainty. This gives rise to an example of the *no-data* decision problem in which a choice to develop or deploy a technology must be made before the uncertainty is resolved. [Gorenstin 1993] reviews several techniques for handling the no-data problem in the context of energy system planning. The proposed work will use a deterministic scenario analysis approach.

This approach builds upon decision trees that define all combinations of actions (nuclear energy strategies) and states (e.g., natural gas prices rise or fall). Figure 11 illustrates a tree that will arise in this work. The action must be taken before the uncertainty is resolved. The states (here, natural gas price levels and their likelihood of arising) will have been defied in Task 1. Each outcome represents a nuclear strategy/state combination for a given energy scenario. Its net annual revenue (qualitatively depicted by $ signs in the figure) will have been calculated in Task 4. Here, for instance, investing in a nuclear-natural gas hybrid is shown as beneficial should gas prices remain low.

The deterministic analysis then evaluates the net present value (NPV) of each nuclear strategy by weighting the net revenue associated with each outcome by the likelihood of that outcome arising. An effective hedging strategy is then one that moves forward with developing the two or three technologies that offer the highest average NPV across all outcomes. The decision trees themselves will be more complex than the illustrative example, as there are levels of uncertainty through time as well as multiple decision points. For example, a storage technology might be adopted in 2020 or delayed until 2040.

The final deliverable from this work will be the hedging portfolios described above.

Relevance and Outcomes/Impacts

Nuclear power plants are being shut down because the addition of renewables combine with cheap NG to create more hours per year with low or negative electricity prices – but also periods of higher prices from which nuclear cannot fully profit. Solutions are needed. This work improves upon traditional nuclear electricity market analysis in two key ways. A levelized cost of electricity (LCOE) analysis omits consideration of variability in the price at which electricity can be sold. It therefore misses the value added by flexibility in nuclear-fossil hybrid and storage systems. The decision analysis explicitly incorporates uncertainties in market parameters such as NG prices into the technology recommendations.

Project Schedule and Milestones/Deliverables

Task	**Duration***	**Timeline* and (M)ilestone with Deliverable**
1. Define Energy Sector Scenarios	1-9	3: select major scenario parameters (grids, time frame) 6: complete collection of energy market data for energy scenarios **9: (M) report documenting energy sector scenarios to be modeled**
2. Model hourly electricity load profiles and prices	7-18	12: complete first energy scenario model in PLEXOS and EnergyPLAN. Down select modeling platform. 12: conclude data collection task for electricity generation technologies **18: (M) full documentation of inputs and electricity price distribution results for each scenario**

3. Define and quantify nuclear strategies	10-30	12: down select three energy storage technologies 18: complete definition of first energy storage technology 21: complete definition of second energy storage technology 24: complete definition of nuclear-fossil hybrid technology 24: conclude data collection and pre-conceptual design task for nuclear technology and storage system couplings 27: complete definition of third storage technology **30: (M) documentation of characteristics for each nuclear strategy**
4. Quantify the benefit of nuclear strategies in each scenario	19-33	24: use completed model from Task 2 to complete scenario analysis for first nuclear energy storage strategy 30: complete analyses of all nuclear strategies for every energy scenario and submit draft report to IP for review & feedback **33: (M) report and publication identifying and rank ordering viable nuclear strategies for each energy scenario (key product #1).**
5. Recommend portfolio of nuclear strategies	25-36	27: define and document actions and states of nature (uncertainties) that characterize the decision trees 33: complete the real options analysis and submit draft report to IP for review & feedback **36:(M) report and publication identifying the nuclear strategy set that represents the best hedge against all future energy scenarios (key product #2).**

* months from start of project.

Type/Description of Facilities Needed to Complete Scope
N/A

Roles and Responsibilities of Partners

Task	Partner Roles
1. Define Energy Sector Scenarios	Design basic scenario structure and parameters; obtain energy market data (task 1a): **LU**. Select grids in which to focus the scenarios, reference LWR and HTR technologies (1b): **UP**. Provide data to inform reactor technology selection: **IP**.
2. Model hourly electricity load profiles and prices	Lead electricity market modeling tool evaluation and down selection; implement energy sector scenarios from task 1 in model (2a, 2b): **LU**. Provide technology expertise and data, projections for advanced renewables & biomass: **IP**.
3. Define and quantify nuclear strategies	Carry out down selection of storage strategies and lead techno-economic quantification of nuclear reactor and energy conversion/storage technologies (3a, 3b) **UP**. Work with UP to provide technical and system integration guidance and data to inform the techno-economic depiction of the reactors and storage options: **IP**. Coordinate with UP to implement the nuclear strategies into the electricity market model: **LU**.
4. Quantify the benefit of nuclear strategies in each scenario	Act as main author on nuclear strategy evaluation report and execute electricity market model for scenarios including nuclear-NG hybrid: **UP**. Run electricity market model for scenarios featuring energy storage and integrate results: **LU**. Provide industry perspective and feedback on draft strategy evaluation report: **IP**.
5. Recommend portfolio of nuclear strategies	Lead decision tree definition and scenario analysis; act as lead author on hedging portfolio deliverable: **LU**. Review draft hedging portfolio report and provide feedback: **UP, IP**.

Unique Challenges and Plans to Overcome Them

A key challenge, one not addressed to the authors' knowledge for nuclear energy storage or hybrid strategies, is to couple the technology analysis to a meaningful model of the hourly electricity market. The electricity price curve is crucial because the shape of that curve drives the economics. Neglecting market feedbacks will lead to an erroneously over-optimistic prognosis for the technologies. Historically storage and hybrid energy studies assumed a 6 to 8 hour charging time in the middle of the night for use in the middle of the day – the basis for pumped storage. Solar implies low-cost electricity in the middle of the day with two peak periods, morning and night. Wind is even more complex. Recent modeling of grids with high renewables is providing an understanding of this change in the market structure.

Another challenge will lie in quantifying the thermal storage options. There was a short time after the oil embargo of the 1970s when studies of energy storage technologies for nuclear plants were initiated. However, with the return of cheap oil, most of those studies were curtailed. Given the available resources, simple pre-conceptual designs of the storage options must be synthesized from these older information sources along with modern work focused on smaller-scale systems for solar and wind installations. The industrial partner's design experience will be leveraged to ensure that the updated or scaled designs and costs are realistic.

Quality Assurance

We will comply with the QA requirements specified by DOE. We will utilize existing university processes for this purpose as well as directives provided by the NEUP Quality Assurance documents.

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