ELECTRIC POWER RESEARCH INSTITUTE

EPRI / GAIN / NEI

WORKSHOP ABOUT ECONOMICS-BASED R&D FOR NUCLEAR POWER CONSTRUCTION

January 17–18, 2019 • Washington, DC

TOGETHER...SHAPING THE FUTURE OF ELECTRICITY

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AGENDA

EPRI / GAIN / NEI's
Workshop about Economics-Based R&D for Nuclear Power Construction

January 17-18, 2019
Nuclear Energy Institute / 1201 F Street NW, Suite 100 / Washington, DC 20004

OBJECTIVE: present the latest economic-related research on the costs associated with constructing nuclear power plants; and, to spur discussion and solicit input about EPRI's current project titled, *Economic Based R&D Roadmap for New Nuclear Power*

THURSDAY, JANUARY 17, 2019		
TIME	**TOPIC**	**PRESENTER**
8:00 a.m.	Registration and Breakfast	
8:30 a.m.	**1. Welcome and Introduction** Review of ANT Program; Workshop overview and purpose	David B. Scott, EPRI
9:00 a.m.	**2. Economic Perspective – US** New reactor cost reduction	Marc Nichol, NEI
9:30 a.m.	**3. MIT Study on Nuclear Power Cost** The future of nuclear energy in a carbon-constrained world	Eric Ingersoll, Lucid Catalyst
10:00 a.m.	Break	
10:30 a.m.	**4. Economic Perspective – UK** ETI Nuclear cost drivers project	Eric Ingersoll, Lucid Catalyst
11:00 a.m.	**5. Analysis of US Historical Capital Costs** The historical construction cost and cost drivers of nuclear power plants	Francesco Ganda, Argonne National Laboratory
11:30 a.m.	**6. Economic drivers, barriers, and impacts in the United States** Exploring the role of advanced nuclear in future energy markets	Andrew Sowder, EPRI
12:00 p.m.	Lunch	
1:00 p.m.	**7. Economic Based R&D Roadmap** Current findings from EPRI's R&D roadmap development	Chuck Marks, Dominion Engineering
2:00 p.m.	**8. Open Discussion – Cost Driver Category #1** Participant input on current findings from the R&D roadmap development	Led by EPRI / Dominion Engineering (attendee participation)
2:30 p.m.	**9. Open Discussion – Cost Driver Category #2** Participant input on current findings from the R&D roadmap development	Led by EPRI / Dominion Engineering (attendee participation)
3:00 p.m.	Break	
3:30 p.m.	**10. Open Discussion – Cost Driver Category #3** Participant input on current findings from the R&D roadmap development	Led by EPRI / Dominion Engineering (attendee participation)
4:00 p.m.	**11. Open Discussion – Cost Driver Category #4** Participant input on current findings from the R&D roadmap development	Led by EPRI / Dominion Engineering (attendee participation)
4:30 p.m.	Adjourn	

AGENDA

EPRI / GAIN / NEI's
Workshop about Economics-Based R&D for Nuclear Power Construction

January 17-18, 2019
Nuclear Energy Institute / 1201 F Street NW, Suite 100 / Washington, DC 20004

FRIDAY, JANUARY 18, 2019		
TIME	**TOPIC**	**PRESENTER / LEAD**
8:00 a.m.	Breakfast	
8:25 a.m.	**12. Recap**	David B. Scott, EPRI
8:30 a.m.	**13. Open Discussion – Cost Driver Category #5** Participant input on current findings from the R&D roadmap development	Led by EPRI / Dominion Engineering (attendee participation)
9:00 a.m.	**14. Open Discussion – Cost Driver Category #6** Participant input on current findings from the R&D roadmap development	Led by EPRI / Dominion Engineering (attendee participation)
9:30 a.m.	**15. Roadmap Development for R&D** Participant input on R&D multiyear plan	Led by EPRI / Dominion Engineering (attendee participation)
10:00 a.m.	Break	
10:30 a.m.	**16. Roadmap Development for R&D (continued)** Participant input on R&D multiyear plan	Led by EPRI / Dominion Engineering (attendee participation)
11:30 a.m.	**17. Advanced Reactor (AR) Construction** Application of R&D roadmap and additional AR needs	Led by EPRI / Dominion Engineering (attendee participation)
12:00 p.m.	Lunch and Adjourn	

January 19, 2019

Workshop Highlights

Advanced Nuclear Technology (ANT) Program
EPRI-GAIN-NEI Workshop About Economics-Based R&D for Nuclear Power Construction
Date: January 17-18, 2019
Location: Nuclear Energy Institute / 1201 F Street NW, Suite 1100 / Washington, DC 20004

Introduction

At the referenced date, a workshop was held at the Nuclear Energy Institute (NEI) and co-hosted by EPRI, GAIN, and NEI. The impetus for the workshop was an existing study being performed by EPRI's Advanced Nuclear Technology (ANT) group to identify cost estimating methods used by the nuclear power industry, develop a tool for analyzing construction costs, and develop a roadmap to direct future research and development towards reducing construction costs of nuclear power plants. The name of the ANT project is, *Economics-Based R&D for New Nuclear Plant Development*. It is being co-funded by ClearPath, EPRI, GAIN, NEI, and NuScale. The workshop provided the opportunity to relay the current results of the ANT study and receive industry input on the accuracy of identified cost drivers for nuclear power plant construction and potential technological solutions. More specifically and as stated in the invitation for the event, the goal was to

- *Learn about the recent international studies on cost drivers.*
- *Hear about the specific results coming from EPRI's cost study on construction.*
- *Engage in open discussion about technologies that can reduce construction costs.*

On November 19, 2018, workshop invitations were distributed to various industry stakeholders. Registration and attendance was high. The following provides a summary of the Workshop.

Workshop Structure

The first half-day of the work consisted of presentations made by representatives of various historical and current studies on nuclear power construction economics. The seven presentations at the beginning of the workshop was intended to provide the referential datum by which the open discussion portion of the workshop was to be conducted. The open discussion lasted for the balance of the workshop and included dialogue about the previously identified cost drivers for nuclear power plants and potential solutions for those cost drivers. The following consists of summaries of the presentations and open discussion.

ANT Program and Workshop Overview (David B. Scott, EPRI)

EPRI provided an overview of the ANT program and projects directed towards addressing cost reductions for constructing commercial nuclear power plants. The presentation and ensuing discussion covered:

- The mission of EPRI, Nuclear sector, and ANT
- ANT's technical focus areas and the specific research focus areas related to engineering, procurement, and construction research
- ANT research activities to address constructability and structural design, seismic isolation, reinforced concrete, advanced manufacturing, and factory fabrication

- ANT research activities to address construction economics
- Workshop objective and structure

<u>NEI Perspective (Marc Nichol, NEI)</u>
NEI provided an overall summary of their perspective on U.S. economics related to new construction of nuclear power plants. The presentation included a summary of the following.

- Nuclear generation in the United States for the operating fleet and new construction
- Policy and economic drivers for new plant construction
- Construction comparisons between natural gas CC and nuclear power plants
- NEI strategy to propel nuclear market share

<u>The Future of Nuclear Energy in a Carbon-Constrained World (Eric Ingersoll, Lucid Catalyst on behalf of the study performed by MIT-Interdisciplinary group)</u>
On behalf of the MIT-Interdisciplinary team, Eric Ingersoll gave a summary of the recently released MIT study which included the following topics.

- The role new nuclear power could play in decarbonizing the power sector and its comparative role against competitive energy resources
- Cost breakdowns of nuclear power plant designs based on historical studies and one-on-one communications
- Summary of potential technologies to reduce nuclear power construction costs
- The role of advanced reactor designs in cost reduction
- The role of polity in the future growth or attrition of nuclear power construction

<u>Nuclear Cost Drivers Project (Eric Ingersoll, Energy Lucid Catalyst on behalf of the study performed by Energy Technologies Institute)</u>
On behalf of the MIT-Interdisciplinary team, Eric Ingersoll gave a summary of the recently released MIT study which included the following topics.

- Cost breakdowns of an average nuclear power plant
- The identified cost drivers: design, materials, equipment, construction implementation, labor, governance, regulation, supply chain, and operations
- Scoring methods for aligning cost results based on benchmarks and global regions
- Global case studies that included comparison with off-shore wind

<u>Analysis of United States Historical Capital Costs (Francesco Ganda, Argonne National Laboratory)</u>
Previous studies performed by Francesco Ganda provided increased details about the historical construction costs and drivers for commercialized nuclear power plants. More specifically, the following was discussed during the presentation.

- A comparison of overnight construction costs, construction durations, and cost overruns for US nuclear power plants
- Specific cost drivers: design changes during construction, contractual frameworks, and regulatory framework
- Cost escalations per discipline / material / SSC
- A comparison of the effect of cost drivers and design changes

Economic Drivers, Barriers, and Impacts in the United States and the Role of Advanced Nuclear in Future Energy Markets (Andrew Sowder, EPRI)

EPRI provided a summary of the role that advanced reactor designs can play in the US energy markets. The topics included the following.

- Capital cost trajectories of varied energy resources and the competitiveness of nuclear
- Estimations of energy supply and demand based on the EPRI-owned economic model – REGEN- **R**egional **E**conomy, **G**HG, and **En**ergy
- The role of economic conditions and energy policy towards the potential growth of nuclear power construction - price of natural gas, production tax credits, carbon tax, increased revenue options, regional factors

Economic Based R&D Roadmap (Chuck Marks, Dominion Engineering on behalf of the ANT Group)

As the Principal Investigator of the EPRI/ANT Economic Roadmap study, Dominion Engineering provided the to-date results of the project. The slides and presentation was the dominant reference for the continued open-discussion segment of the workshop. More specifically, it included the following.

- The purpose and scope of the ANT project on economics-based R&D
- The methods of evaluating construction costs and the results of studying previous construction cost estimations
- Historical and contemporary cost drivers according to a standardized code of accounts
- Cost driver delineation into six (6) categories – directs costs, indirect costs, project preparation, project implementation and execution, technical issues, and realization of advanced technologies and practices.
- Potential technology opportunities for the cost drivers (e.g., modularization, advanced concrete, seismic isolation, advanced manufacturing, robotics)

Open Discussion (Open to all attendees and participants)

The final scope of the workshop was to provide a forum for open discussion on the topic of the specific drivers of constructing nuclear power plants. The conversation did periodically include non-technical issues such as regulatory input and contractual practices. However, the non-technical discussions did lead to potential technical solutions for these non-technical issues; and, the open discussion included an abundant amount of discussions on innovative technologies that address new construction costs for large light-water reactors, small modular reactors, and advanced (Generation IV) reactor designs. Please see the following slides title, *Workshop about Economics-Based R&D for Nuclear Power Construction /*

Open Discussion and Ideation, in this package for further details.

Attendees

The workshop was well attended with industry representatives from utilities, research institutes, national laboratories, subject matter experts, and academia. The following table indicates those who signed-in at the workshop or announced their attendance by phone.

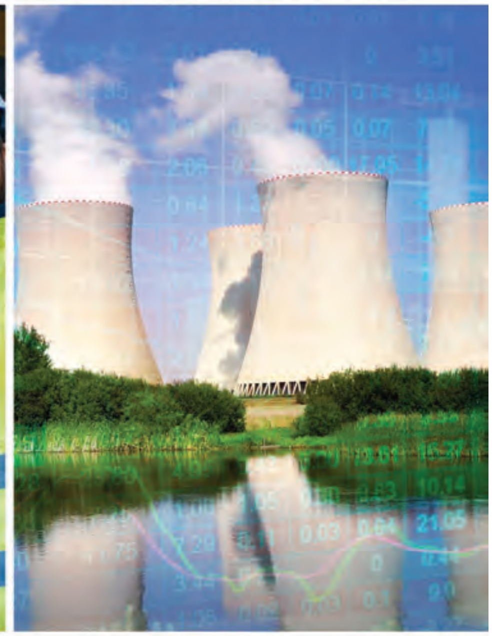
Name	Company
Irfan Ali	Advanced Reactor Concepts (ARC)
Francesco Ganda	Argonne National Laboratory
Hussein Khalil	Argonne National Laboratory
Marsha Bala	Battelle Energy Alliance, LLC
Rita Baranwal	Battelle Energy Alliance, LLC
Lori Braase	Battelle Energy Alliance, LLC
Mark Dehart	Battelle Energy Alliance, LLC
Efe Kurt	Battelle Energy Alliance, LLC
Muhammad Fahmy	Bechtel Power Corporation
Ahmet Tokpinar	Bechtel Power Corporation
Arantxa Cuadra	Brookhaven National Laboratory
Terry Garrett	Burns & McDonnell Engineering Co.
Joe Chaisson	Clean Air Task Force
Armond Cohen	Clean Air Task Force
Brett Rampal	Clean Air Task Force
Spencer Nelson	ClearPath Foundation, Inc.
Calvin McCall	Concrete Engineering Consultants, Inc.
Chuck Marks	Dominion Engineering, Inc.
Jeff Reinders	Dominion Engineering, Inc.
Bob Varrin	Dominion Engineering, Inc.
David Julius	Duke Energy Corp.
Neil Kern	Duke Energy Corp.
David Scott	Electric Power Research Institute (EPRI)
Andrew Sowder	Electric Power Research Institute (EPRI)
Vincent Maupu	Electricite de France S.A.
Amaury Coullet	Embassy of France
Greg Gibson	Excel Services
Farshid Shahrokhi	Framatome, U.S. Operations
David Hinds	GE Hitachi Nuclear Energy Americas, LLC
Michael Ford	Harvard University
Tatsu Sakamoto	Hitachi-GE Nuclear Energy, Ltd.
Yuriko Suzuki	Hitachi-GE Nuclear Energy, Ltd.
Sonny Kim	Joint Global Change Research Institute
Eric Ingersoll	LucidCatalyst
Koroush Shirvan	Massachusetts Institute of Technology

Doug Chapin	MPR Associates, Inc.
Kati Austgen	Nuclear Energy Institute
Harsh S. Desai	Nuclear Energy Institute
Marcus Nichol	Nuclear Energy Institute
Everett Redmond	Nuclear Energy Institute
Ashley Finan	Nuclear Innovation Alliance (NIA)
Mike Brasel	NuScale Power, LLC
Andrew Worrall	Oak Ridge National Laboratory
Christopher Deir	Ontario Power Generation, Inc.
Lubna Ladak	Ontario Power Generation, Inc.
Lauren Lathem	Southern Company Services, Inc.
Jason Redd	Southern Nuclear Operating Co.
Art Wharton	Studsvik
TJ Butcher	Teledyne Brown Engineering, Inc.
Spencer Klein	Tennessee Valley Authority (TVA)
Tara Neider	TerraPower
Canon Bryan	Terrestrial Energy, Inc.
Bret Kugelmass	Titans of Nuclear / Energy Impact Center
Alice Caponiti	U.S. Dept. of Energy
Andrew Whittaker	University at Buffalo
Gil Brown	University of Massachusetts Lowell
Lou Qualls	UT Battelle, LLC
Gavin Ridley	Yellowstone Energy
Sam Shaner	Yellowstone Energy

Workshop About Economics-Based R&D for Nuclear Power Construction

January 17 and 18, 2019
Nuclear Energy Institute
Washington, DC

Please join us to gather stakeholder input about technologies to reduce construction costs of commercial nuclear power plants.



GAIN Gateway for Accelerated Innovation in Nuclear | NEI NUCLEAR ENERGY INSTITUTE | EPRI ELECTRIC POWER RESEARCH INSTITUTE

Registration and information: www.epri.com

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Workshop about Economics-Based R&D for Nuclear Power Construction

Welcome and Introduction

David B. Scott
Sr. Technical Leader, ANT

January 17-18, 2019

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www.epri.com

Revision Date: 2018-01-04

Content

- Overview – EPRI/Nuclear/ Advanced Nuclear Technology (ANT)
- Select ANT Projects Related to NPP Construction Cost
- Workshop Objectives and Design

EPRI's Mission

Advancing ***safe***, ***reliable***, ***affordable,*** and ***environmentally responsible*** electricity for society through global collaboration, thought leadership and science & technology innovation

EPRI Nuclear R&D: Global Collaboration and Reach

GLOBAL PARTICIPANTS

GLOBAL BREADTH & DEPTH

>320 reactors worldwide

>75% of the world's commercial nuclear units

Participants Encompass Most Nuclear Reactor Designs

ANT Program Mission

The EPRI Advanced Nuclear Technology (ANT) Program leads Research and Development (R&D) through EPRI's collaborative model to proactively evaluate and address issues regarding the near-term deployment of advanced nuclear plant designs.

MISSION

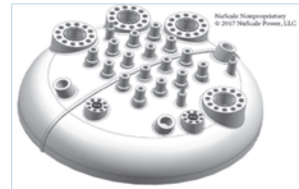
Basic Research and Development → Collaborative Technology Development, Integration and Application → Technology Commercialization

Basic Research and Development	Collaborative Technology Development, Integration and Application	Technology Commercialization
National Laboratories, Universities	EPRI	Suppliers, Vendors

The ANT Program is a scientific research program for those around the world and at various stages of new nuclear plant development and deployment, concentrating on the economic, technical, and regulatory issues that could affect the ability to license, construct, start-up, and operate new nuclear reactors.

ANT Technical Focus Areas

- **Engineering, Procurement, and Construction**
  - Siting, design, construction materials, and construction activities of the plant, including modular construction
- **Materials and Components**
  - Class 1, 2, and 3 piping systems and related components such as valves, heat exchangers, and pumps
  - Optimize methods for fabrication, installation, joining, inspection, and operations, including chemistry
  - New applications of materials and components
- **Modern Technology Application**
  - Maximize the use of existing, new, and (possibly) non-nuclear-specific technology in new nuclear plants
  - Gaps for the use of digital systems in new nuclear applications
- **Advance Reactor TI Program**
  - Strategic analysis and economics, technology assessment and tool development (ex. PHA-PRA), materials, owner-operator requirements



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Engineering, Procurement, and Construction – Construction

- **Constructability**
  - Provide guidance to designers and structural engineers on designing to ease construction, focusing on labor, schedule, and possible re-work reductions, in lieu of material efficiency
  - Identification of potential systems and structures of where this approach may be most applicable
- **Projects**
  - Guide to Designing Structures for Constructability (sch. 2019)
  - Performance-Based Design for Civil and Structural Applications (sch. 2020-2021)

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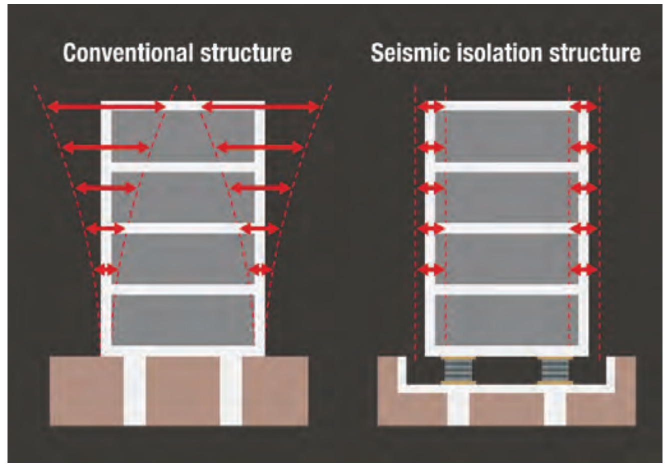
Engineering, Procurement, and Construction – Seismic

- **Seismic Isolation**
  - Structural member sizes and equipment anchorage are affected by seismic demand
  - System, structure, and component robustness, qualification, and cost are affected by seismic demand
  - Seismic isolation cost-benefit is unknown at sites
  - Parametric study showing if there is financial benefit of seismic isolation
- **Projects**
  - Seismic Isolation of Nuclear Power Plants (2013)
  - Cost Basis for Utilizing Seismic Isolation for Design (sch. 2019)



Engineering, Procurement, and Construction – Reinforcement

- **Reinforcing Steel**
  - Temporally expensive
  - Higher Yield Strength → 100-120 ksi (690-830 MPa)
  - Reduce volume, construction time, material cost, congestion (voids)
  - Generating data needed to modify ACI 349 and 359 to allow credit for high-strength reinforcing (100 and 120 ksi [690 and 830 MPa]) in safety-related structures
- **Projects**
  - High-Strength Reinforcing Steel (2015, 2016, 2017)
  - Investigating Mechanical Splicing of Reinforcing Steel (2017)
  - Field Guide for Inspections of Reinforced Concrete Construction (sch. 2019)
  - Automated QA Inspection for Reinforcing Steel (sch. 2020-2021)
  - Alternative Concrete Reinforcement Materials (sch. 2020-2021)
  - Automated Rebar Tying for Nuclear New Builds (sch. 2021-2022)

Engineering, Procurement, and Construction – Concrete

- **Concrete-Related Research**
  – Temporally expensive
  – Structurally relevant to meet the demands of pressure, dead weight, seismic requirements, and impact
  – Concrete mixtures can be difficult to manage and sensitive to process variation; and defects sometimes develop
- **Projects**
  – Conducting Quality Inspections and Tests of Concrete Placement at Nuclear Facilities (2013)
  – Demonstration and Evaluation of Self-Consolidating Concrete (SCC) Mixtures (2016)
  – Mass Concrete Modeling and Temperature Control (2018)
  – Optimization of Concrete Placements (2018)
  – Demonstration of SCC Flow Simulation Software (sch. 2019)
  – Best Practices for SCC as Mass Concrete (sch. 2019-2021)

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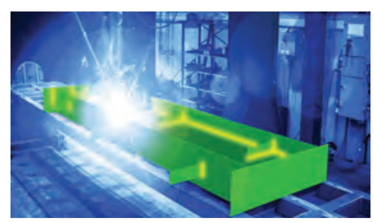
Engineering, Procurement, and Construction – Structural Steel

- **Advanced Structural Welding**
  – Fabrication of steel modules for S-C construction is laborious and slow
  – The use of advanced welding techniques (electron beam welding, friction-stir, etc.) has been shown to dramatically increase welding speed in laboratory environments
  – Field deployable technique would be useful for civil/structural applications
  – Identify techniques and their potential benefits that are most applicable for civil-related applications
  – Develop for field use
  – Demonstrate application on construction modules and / or other structural steel
  – Adapt field-version for structural steel welds
- **Project**
  – Advanced Welding for Infrastructure and Construction (sch. 2019-2021)



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Materials & Components – Advanced Manufacturing

- **Advanced Manufacturing and Fabrication**
  - Industry needs optimizing the fabrication process of components
- **Projects**
  - Powder Metallurgy–Hot Isostatic Pressing (2017, 2018)
  - Thick Section Welding (2017)
  - Demonstration of Powder Metallurgy - Hot Isostatic Pressing
  - SMR Vessel Advanced Manufacturing Program (sch. 2020)

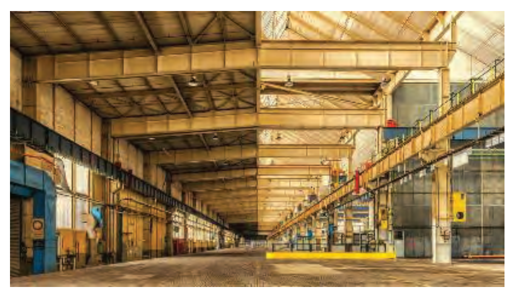
65mm (thick) x 3m length
Welding time: <10 minutes
Photograph provided courtesy: TWI (UK)

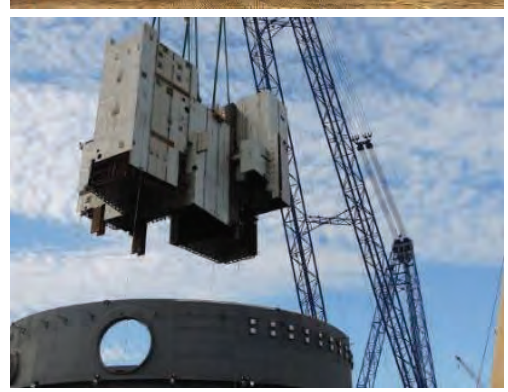
40%-scale, upper head using Powder Metallurgy-Hot Isostatic Pressing (PM-HIP)

Representative Model of NuScale Power Reactor Vessel

Materials & Components – Factory Fabrication of Models and Components

- **Factory Fabrication of Models and Components**
  - A significant portion of construction and fabrication expense (schedule and labor) is from work conducted onsite
  - Manufacturing in a factory environment could lead to lower costs and better construction schedules
  - Scope
    - Gather lessons learned from constructors, fabricators, and utilities involved in the recent construction of commercial nuclear power plants and organizations involved in other modular construction projects
    - Conduct a gap analysis to understand and document the technologies and processes needed to enable more factory fabrication
    - Develop a roadmap to guide future research in closing the gaps of factory fabrication
- **Project**
  - A Pathway to Factory Fabrication for Modules and Components (sch. 2019)

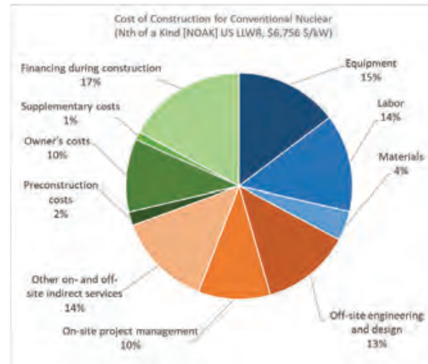




Source: World Nuclear News

Engineering, Procurement, and Construction – Cost Drivers

- **Construction Costs for New Nuclear**
  - Construction cost data has been broad and specifics are unclear
  - Support is needed to develop economics-based cost-benefit methods and evaluation models to help focus EPRI-, government-, and industry-related R&D initiatives toward reducing new plant costs
  - There is need to assess cost-drivers for existing ALWRs, SMRs, and advanced reactors in order to give quantitative evaluation of the cost-benefit of new technologies or processes
  - R&D roadmap development and prioritization can be generated as a result of comparing cost-benefit methods and drivers against the current best available data
- **Project**
  - Economic-Based R&D Roadmap for New Nuclear Plant Development (sch. 2019)



Economic Based R&D for New Nuclear Plant Development

Sponsors

CLEARPATH

NEI
NUCLEAR ENERGY INSTITUTE

NUSCALE™
Power for all humankind

GAIN
Gateway for Accelerated Innovation in Nuclear

Objectives

present the latest economic-related research on the costs associated with constructing nuclear power plants; and, to spur discussion and solicit input about EPRI's current project titled, *Economic Based R&D Roadmap for New Nuclear Power*

Agenda (Morning / Afternoon)

Workshop about Economics-Based R&D for Nuclear Power Construction

Morning Session, January 17, 2019

Time	Topic	Lead
8:00 am	Registration and Breakfast	
8:30 am	1. Welcome and Introduction Review of ANT Program; Workshop overview and purpose	D. Scott, EPRI
9:00 am	2. Economic Perspective – US New reactor cost reduction	M. Nichol, NEI
9:30 am	3. MIT Study on Nuclear Power Cost The future of nuclear energy in a carbon-constrained world	E. Ingersoll, Lucid Catalyst
10:00 am	Break	
10:30 am	4. Economic Perspective – UK ETI Nuclear cost drivers project	E. Ingersoll, Lucid Catalyst
11:00 am	5. Analysis of US Historical Capital Costs The historical construction cost and cost drivers of nuclear power plants	F. Ganda, Argonne National Laboratories
11:30 am	6. Economic drivers, barriers, and impacts in the US Exploring role of advanced nuclear in future energy markets	A. Sowder, EPRI
12:00 pm	Lunch	

Workshop about Economics-Based R&D for Nuclear Power Construction

Afternoon Session, January 17, 2019

Time	Topic	Lead
1:00 pm	7. Economic Based R&D Roadmap Current findings from EPRI's R&D roadmap development	C. Marks, DEI
2:00 pm	8. Open Discussion – Cost Driver Category #1 Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
2:30 pm	9. Open Discussion – Cost Driver Category #2 Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
3:00 pm	Break	
3:30 pm	10. Open Discussion – Cost Driver Category #3 Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
4:00 pm	11. Open Discussion – Cost Driver Category #4 Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
4:30 pm	Adjourn	

Agenda (Morning)

Workshop about Economics-Based R&D for Nuclear Power Construction

Morning Session, January 18, 2019		
Time	**Topic**	**Lead**
8:00 am	Breakfast	
8:25 am	12. Recap	D. Scott, EPRI
8:30 am	13. Open Discussion – Cost Driver Category #5 Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
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10:00 am	Break	
10:30 am	16. Roadmap Development for R&D (continued) Participant input on R&D multiyear plan	Led by EPRI / DEI (attendee participation)
11:30 am	17. Advanced Reactor (AR) Construction Application of R&D roadmap and additional AR needs	Led by EPRI / DEI (attendee participation)
12:00 am	Lunch and Adjourn	

Together…Shaping the Future of Electricity

U.S. Economic Perspective

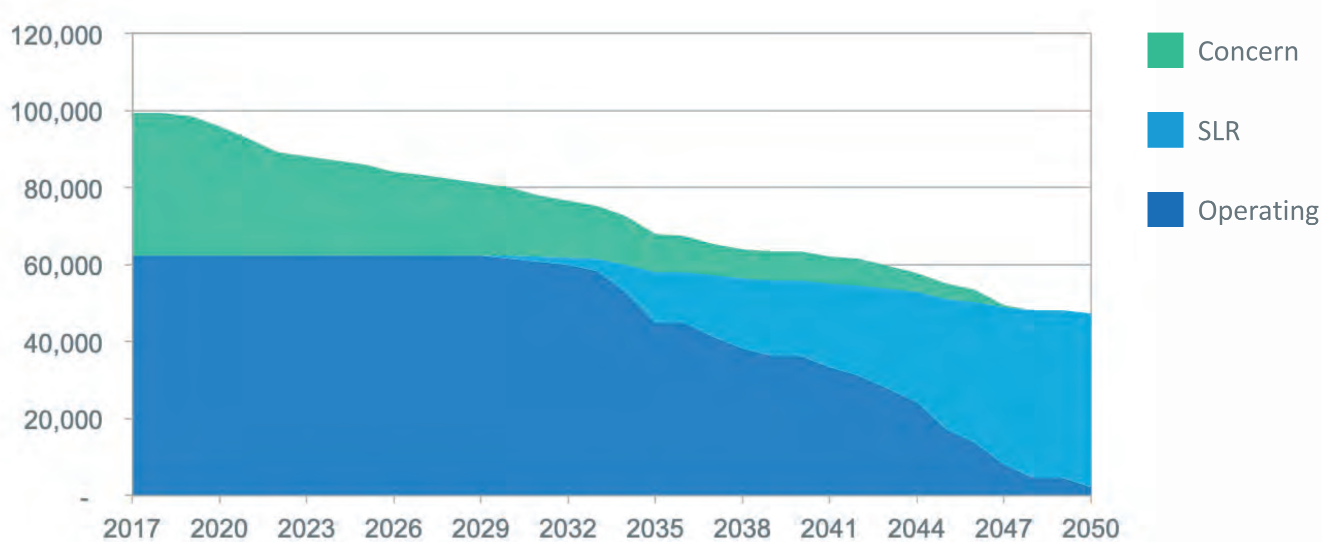
NEI/EPRI/GAIN Economics-Based R&D Workshop

January 17, 2019

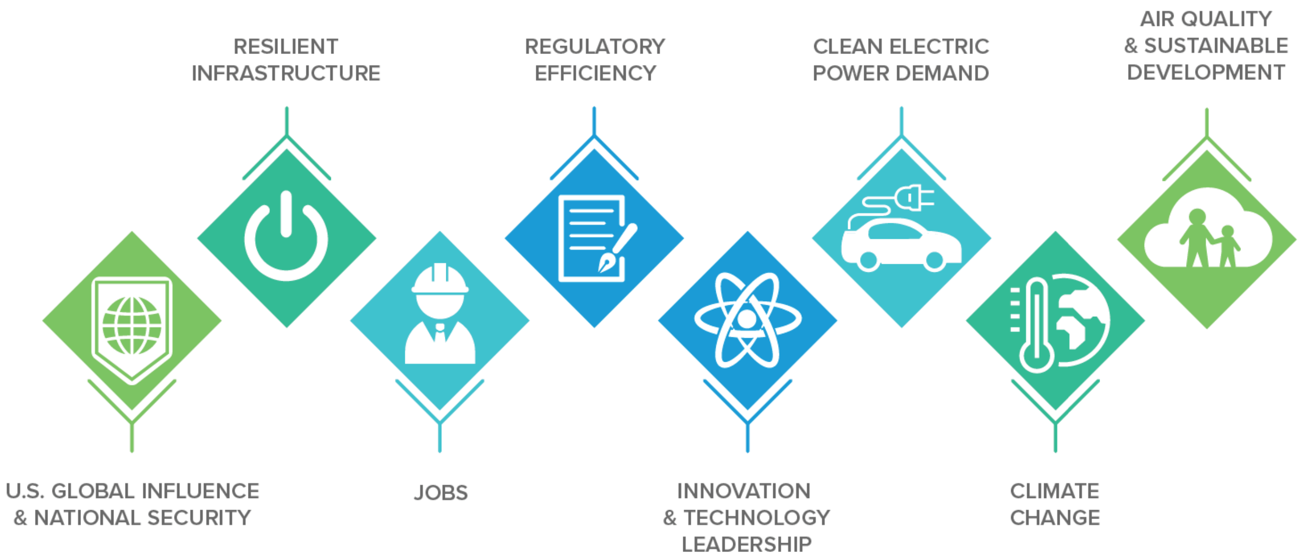
NUCLEAR ENERGY INSTITUTE

The Challenge

The U.S. could lose half of its nuclear generation by 2050

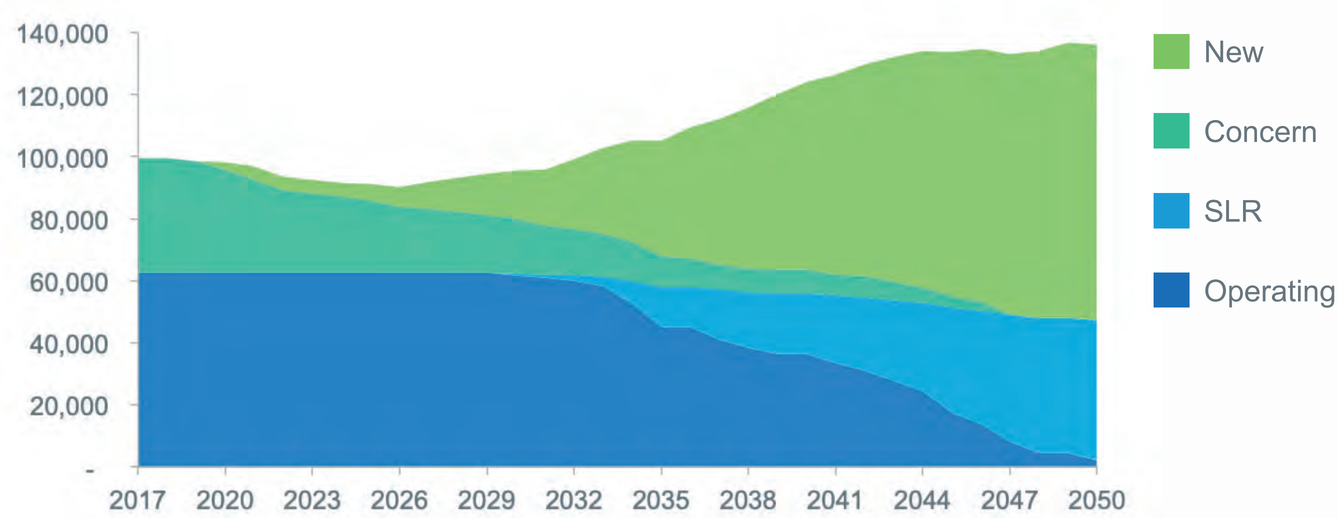


Imperatives



Scale of New Build Needed to 2050

Even with subsequent license renewal, retaining 20% market share in 2050 requires adding ~60-90 GW



National Nuclear Energy Strategy

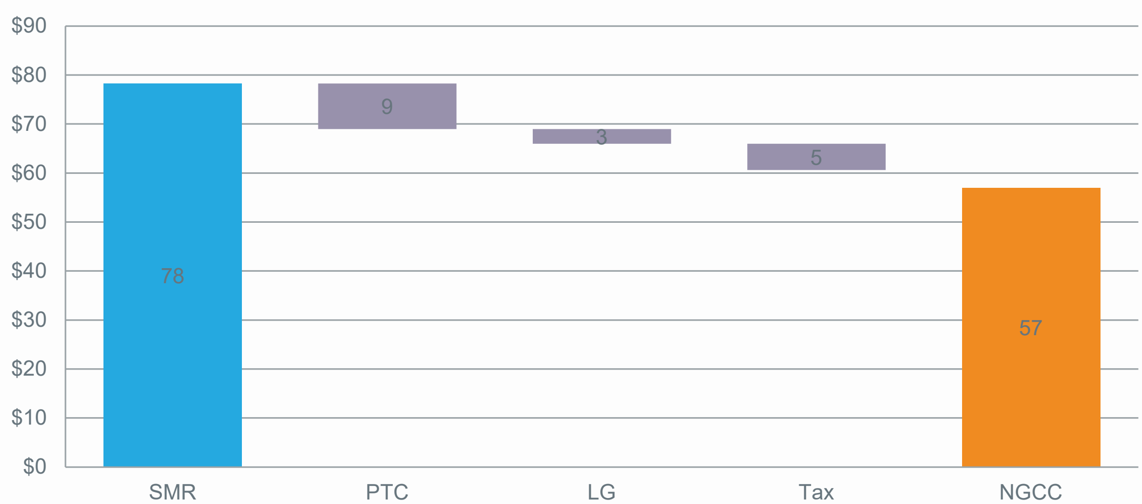
NEI

PRESERVE	SUSTAIN	INNOVATE	THRIVE
Appropriately value nuclear generation	Create sustainability via improved regulatory framework and reduced burden	Innovate, commercialize, and deploy new nuclear	Compete globally

First-of-a-Kind Cost Competitiveness

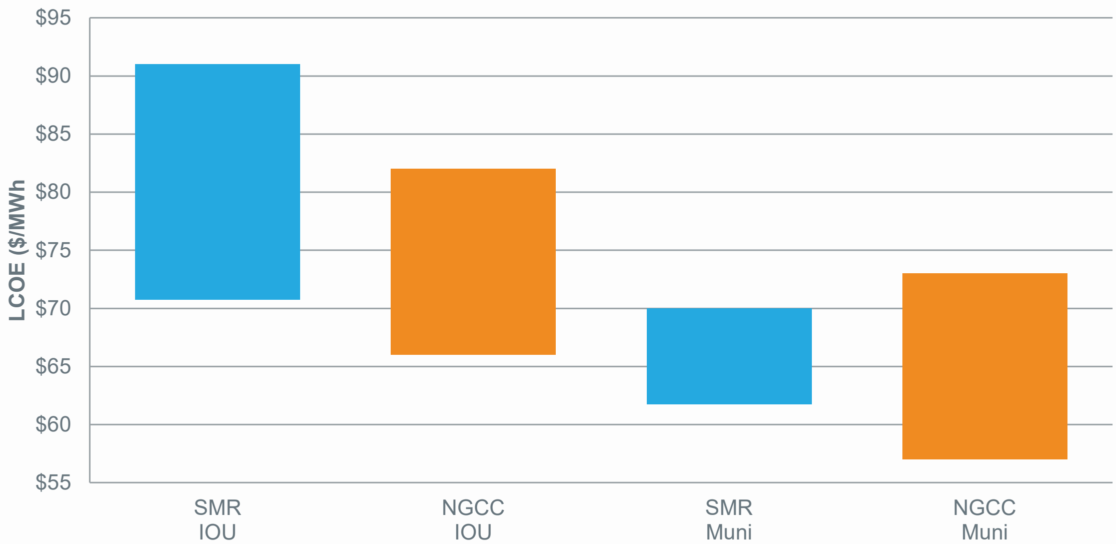
NEI

Comparison of Costs of First SMR and Natural Gas Combined Cycle
Example 2 - Municipal Utility



Source SMR Start Economic Analysis

N[th]-of-a-Kind Cost Competitiveness



Source SMR Start Economic Analysis

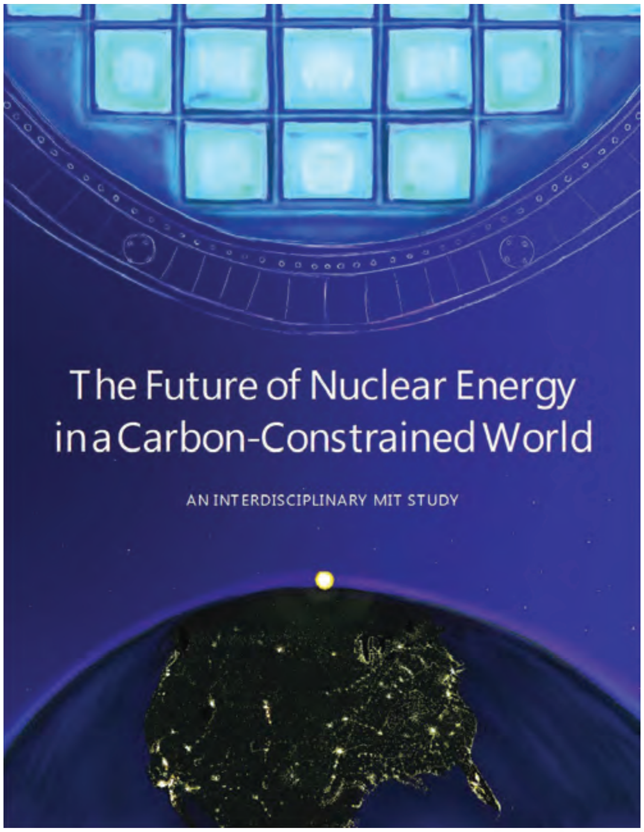
Path to Cost Competitiveness

On-the-grid reactors

- LCOE below $50/kWh, in some markets below $30/kWh
- Construction costs dominate for most reactors
- Target: About half the cost and half the schedule of today's new reactor construction

Other applications

- Off-grid electric: ~$300/kWh
- Non-electric uses (e.g., heat, hydrogen)



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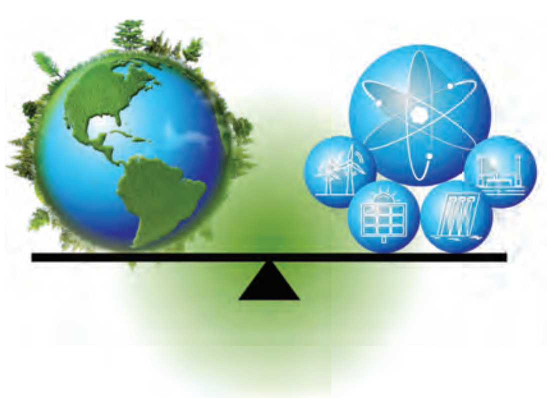
MIT

MITei
MIT Energy Initiative

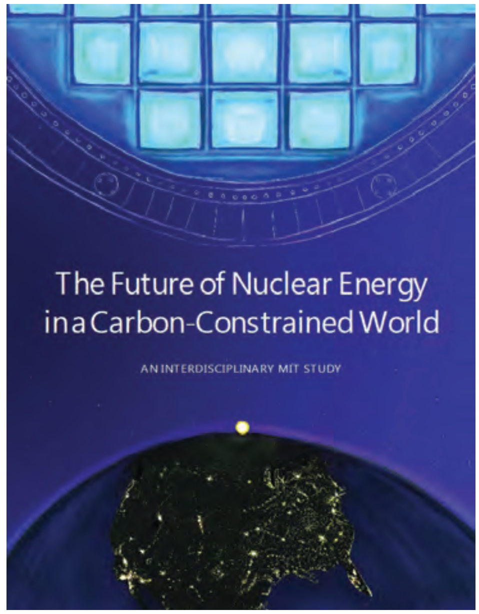
NSE
Nuclear Science and Engineering
science : systems : society

Take-away messages

- The opportunity is carbon
- The problem is cost
- There are ways to reduce it
- Government's help is needed to make it happen

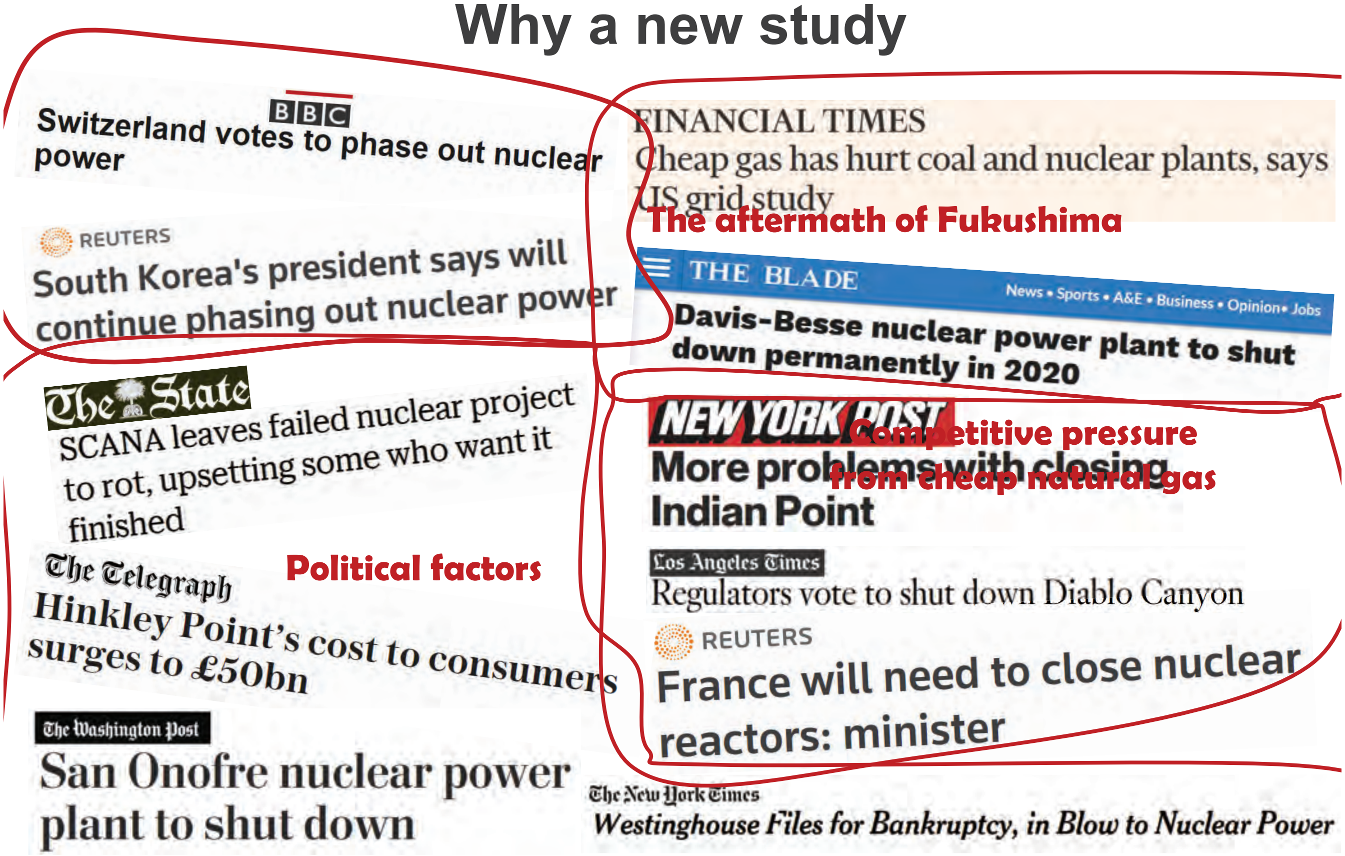


Download the report at
http://energy.mit.edu/



Hard copies of the Executive Summary available in the room

Why a new study



The nuclear industry's Self-inflicted wounds facing an existential crisis (especially in the U.S. and Europe)

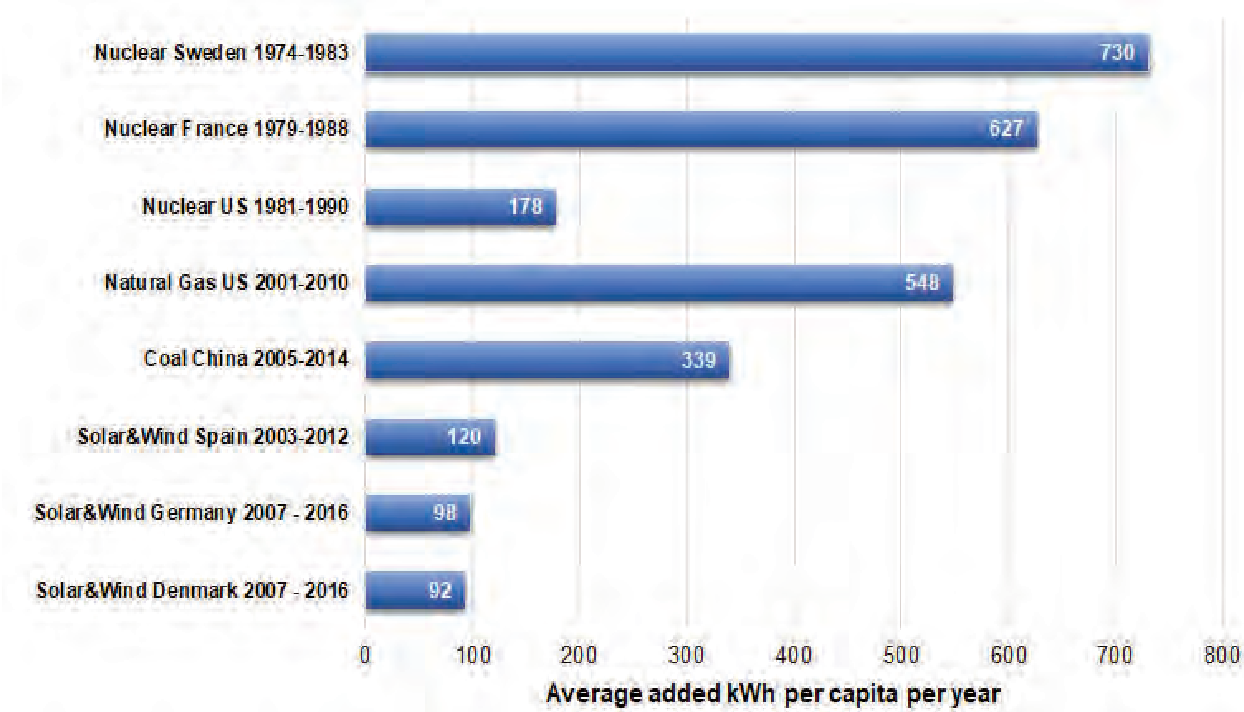
Key Questions Analyzed in the MIT Study

For the period present-2050:

- Do we need nuclear to de-carbonize the power sector?
- What is the cost of new nuclear and how to reduce it?
- What is the value proposition of advanced nuclear technologies?
- What is the appropriate role for the government in the development and demonstration of new nuclear technologies?

What role for nuclear in decarbonizing the power sector?

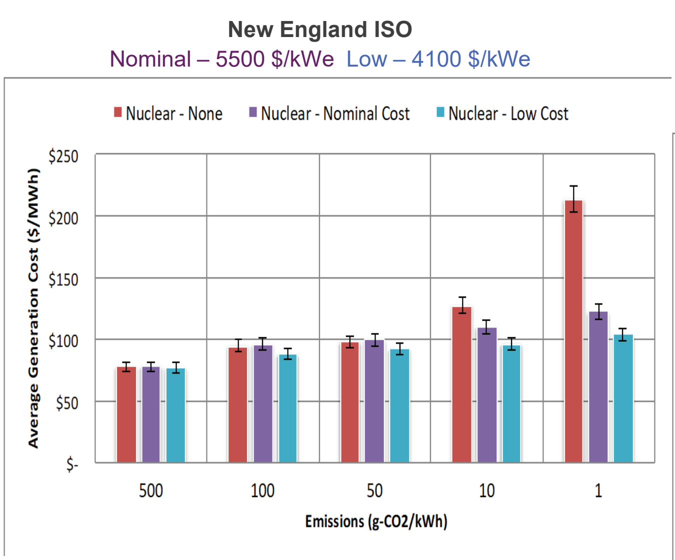
The scalability argument

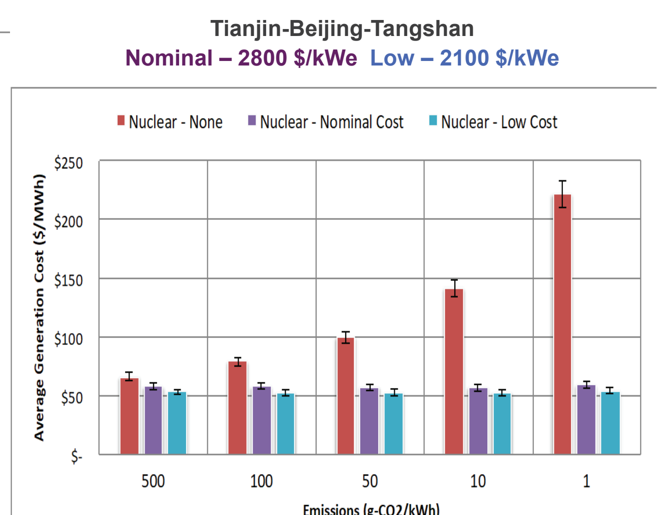


Nuclear electricity can be deployed as quickly as coal and gas at a time of need

The economic argument

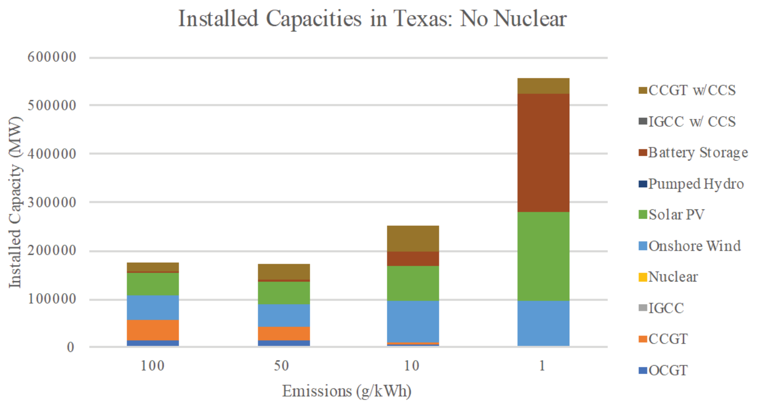
Excluding nuclear energy drives up the cost of electricity in low-carbon scenarios (U.S., Europe and China)





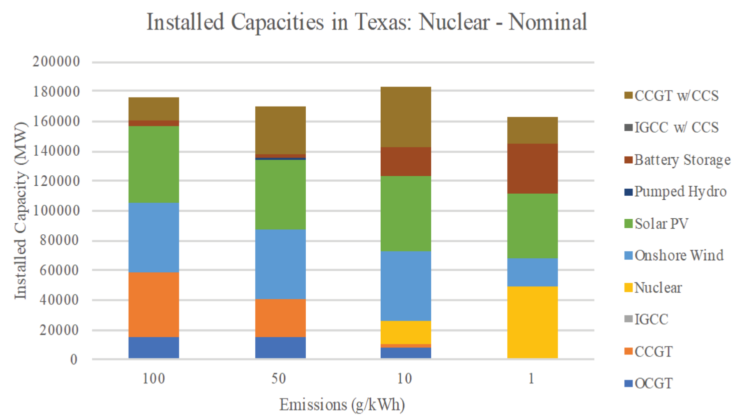
Simulation of optimal generation mix in power markets
MIT tool: hourly electricity demand + hourly weather patterns + capital, O&M and fuel costs of power plants, backup and storage + ramp up rates

Texas (ERCOT) Results

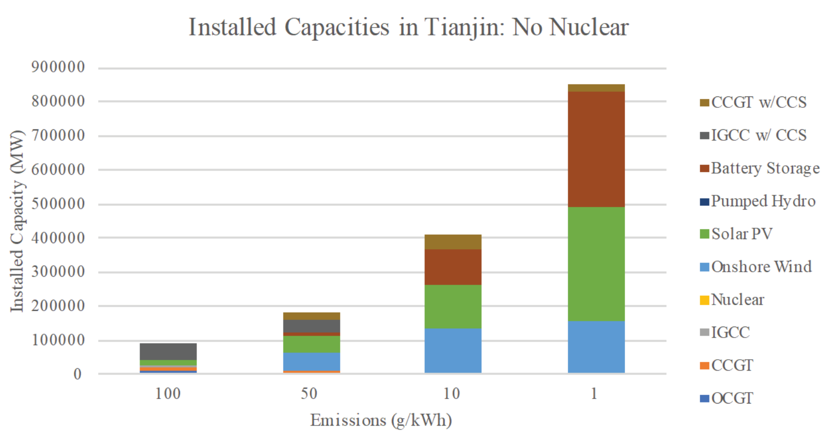


To meet constraint w/o nuclear requires major build-out of renewables

By contrast, installed capacity is relatively constant with nuclear allowed

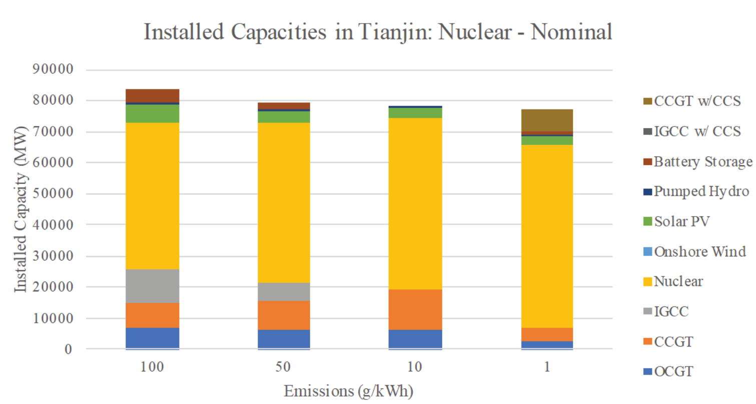


Tianjin-Beijing-Tangshan Results



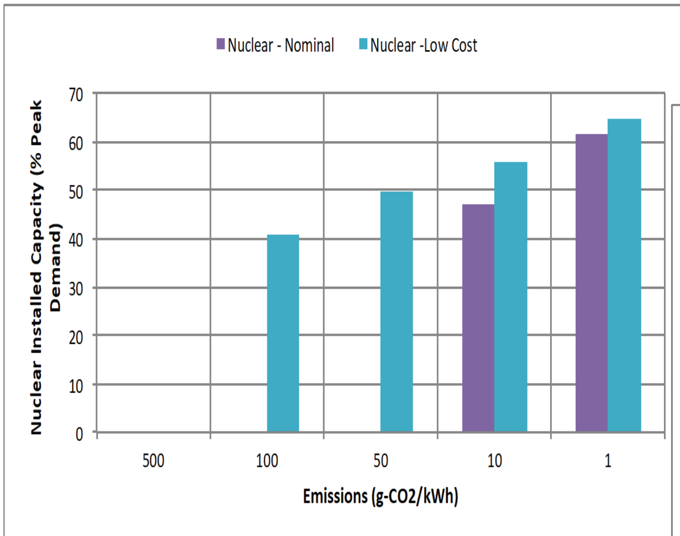
To meet constraint w/o nuclear requires significant build-out of renewables

By contrast, installed capacity is relatively constant with nuclear allowed

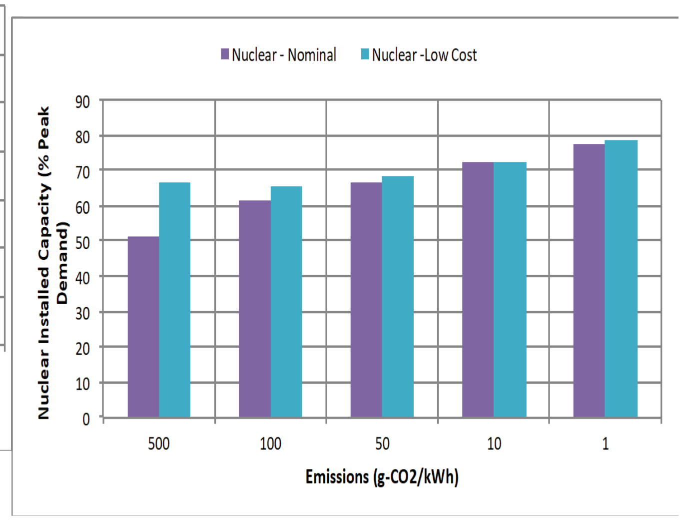


Capital cost matters!

New England ISO
Nominal – 5500 $/kWe Low – 4100 $/kWe



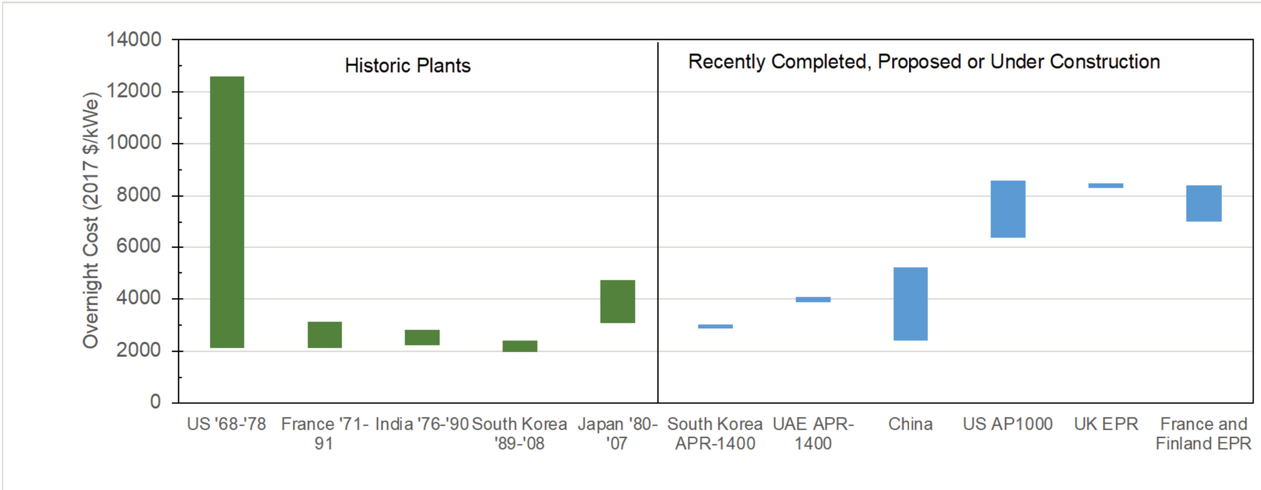
Tianjin-Beijing-Tangshan
Nominal – 2800 $/kWe Low – 2100 $/kWe



Markets can expand for nuclear even at modest decarbonization

The cost issue

Nuclear Plant Cost

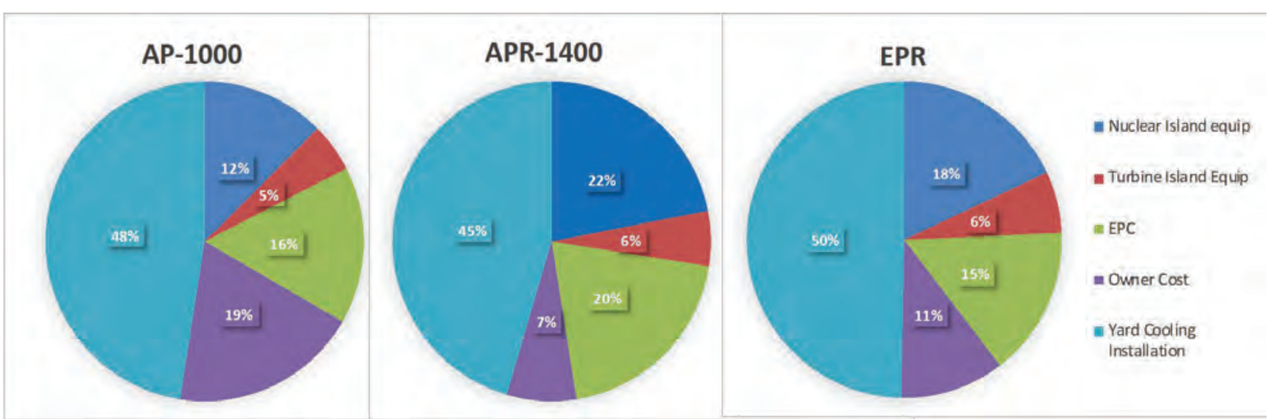


An increased focus on using proven project/construction management practices will increase the probability of success in execution and delivery of new nuclear power plants

For example:

- Complete design before starting construction,
- Develop proven NSSS supply chain and skilled labor workforce,
- Include fabricators and constructors in the design team,
- Appoint a single primary contract manager,
- Establish a successful contracting structure,
- Adopt a flexible contract administrative processes to adjust to unanticipated changes,
- Operate in a flexible regulatory environment that can accommodate changes in design and construction in a timely fashion.

Nuclear Plant Cost (2)



Sources:
AP1000: Black & Veatch for the National Renewable Energy Laboratory, *Cost and Performance Data for Power Generation Technologies*, Feb. 2012, p. 11
APR1400: Dr. Moo Hwan Kim, POSTECH, personal communication, 2017
EPR: Mr. Jacques De Toni, Adjoint Director, EPRNM Project, EDF, personal communication, 2017

Civil works, site preparation, installation and indirect costs (engineering oversight and owner's costs) dominate

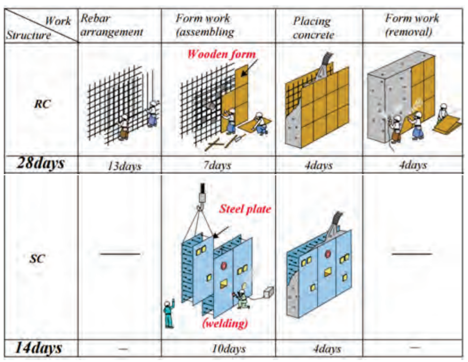
A shift away from primarily field construction of cumbersome, highly site-dependent plants to more serial manufacturing of standardized plants

(True for all plants and all technologies. Without these, the inherent technological features will NOT produce the level of cost reduction necessary)

Standardization on multi-unit sites

Seismic Isolation

Advanced Concrete Solutions



Structure \ Work	Rebar arrangement	Form work (assembling)	Placing concrete	Form work (removal)
RC		Wooden form		
28days	13days	7days	4days	4days
SC	—	Steel plate (welding)		—
14days	–	10days	4days	–

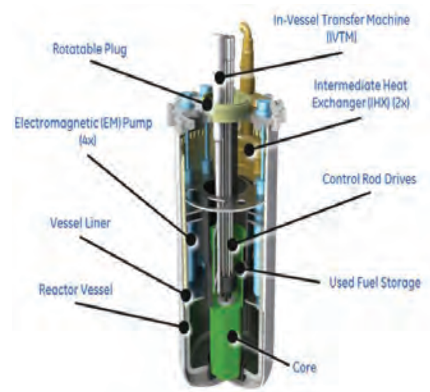
Modular Construction Techniques and Factory Fabrication

Advanced reactors

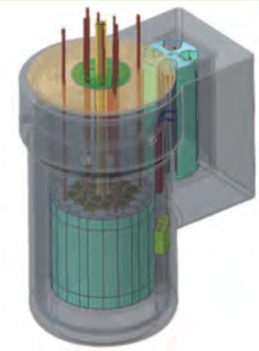
Advanced Reactors (Generation-IV)

High Temperature Gas-Cooled Reactors

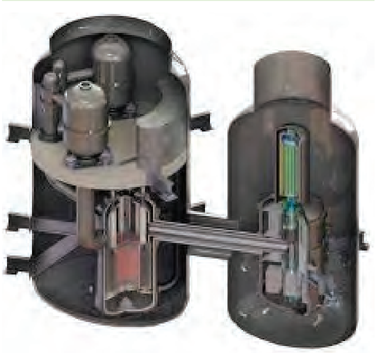
Sodium Fast Reactors



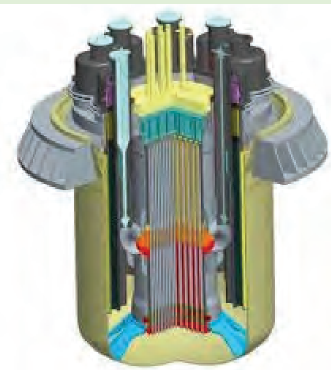
Fluoride High Temperature Reactors



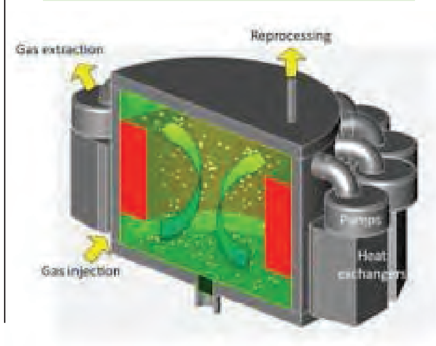
Gas-Cooled Fast Reactors



Lead-Cooled Fast Reactors



Molten Salt Reactors



Potential Advanced Reactor Missions

- Cheap grid-connected electricity
- Process heat and high temperature applications
- Flexible operation
- Microreactors for off-grid electricity and heat
- Desalination
- Improved fuel cycle (fuel recycling/waste burning)

What is the value proposition for advanced reactors?

Demonstrated inherent safety attributes:

- No coolant boiling
- High thermal capacity
- Strong negative temperature/power coefficients
- Strong fission product retention in fuel, coolant and moderator
- Low chemical reactivity

\+

Engineered passive safety systems:

– Heat removal
– Shutdown

=

- ✓ No need for emergency AC power
- ✓ Long coping times
- ✓ Simplified design and operations
- ✓ Emergency planning zone limited to site boundary

Leading Gen-IV systems exploit inherent and passive safety features to reduce the probability of accidents and their offsite consequences. Their economic attractiveness is still highly uncertain.

We judge that advanced LWR-based SMRs (e.g. NuScale), and mature Generation-IV concepts (e.g., high-temperature gas-cooled reactors and sodium-cooled fast reactors are now ready for commercial deployment.

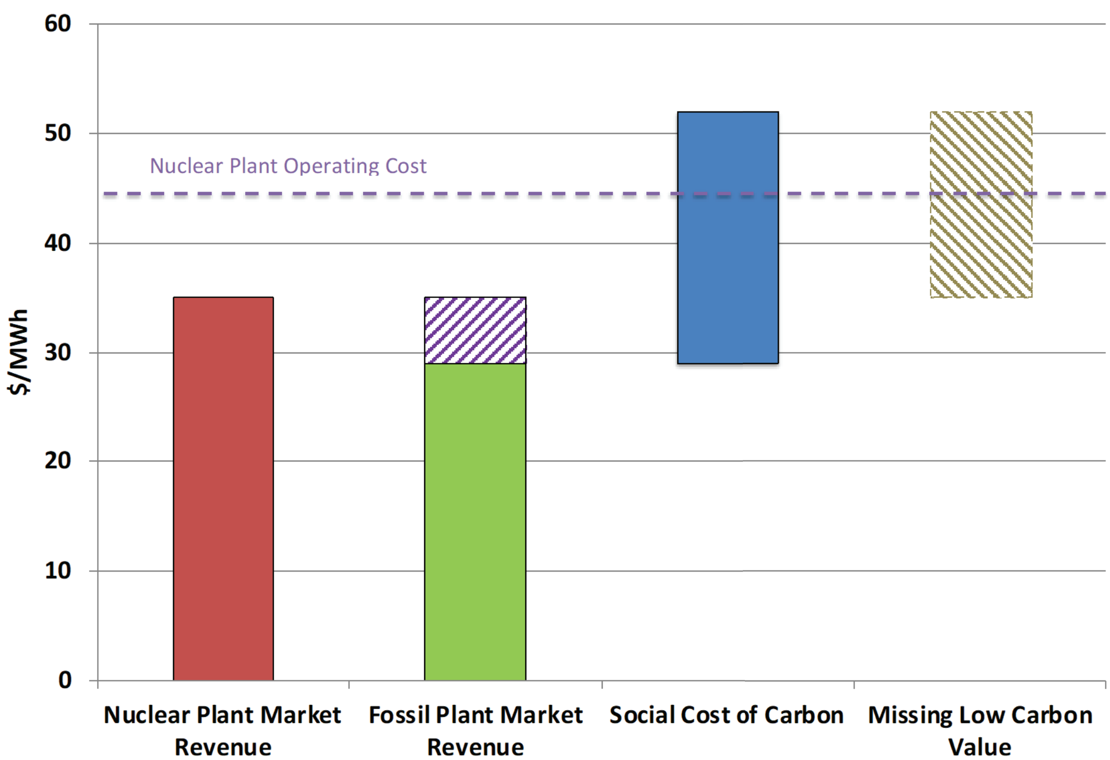
Government role

Preserve the existing fleet

An essential bridge to the future to:

- **Avoid emission increases:**
  - Keeping current NPPs is the lowest cost form of constraining carbon emissions
  - A $12-17/MWh credit would be enough to keep US nuclear power plants open
  - *Zero Emission Credits* are doing the job in NY, IL and NJ
- **Retain key technical expertise** needed to operate the nuclear systems of the future

US Electricity Markets



How can the government help to deploy new nuclear technologies?

Improve the design of competitive electricity markets

- Decarbonization policies should create a level playing field that allows all low-carbon generation technologies to compete on their merits.
- Ensure technology neutrality in capacity markets
- Enable investors to earn a profit based on full value of their product (include reducing CO2 emissions)
- Would enable current plants to compete in the market

- Develop a durable political solution for spent fuel disposal to spur private investment
- Focus government research spending on innovations that lower capital cost of NPPs vs. fuel cycle innovations, reductions in waste streams and recycling

How can the government help to deploy new nuclear technologies? (2)

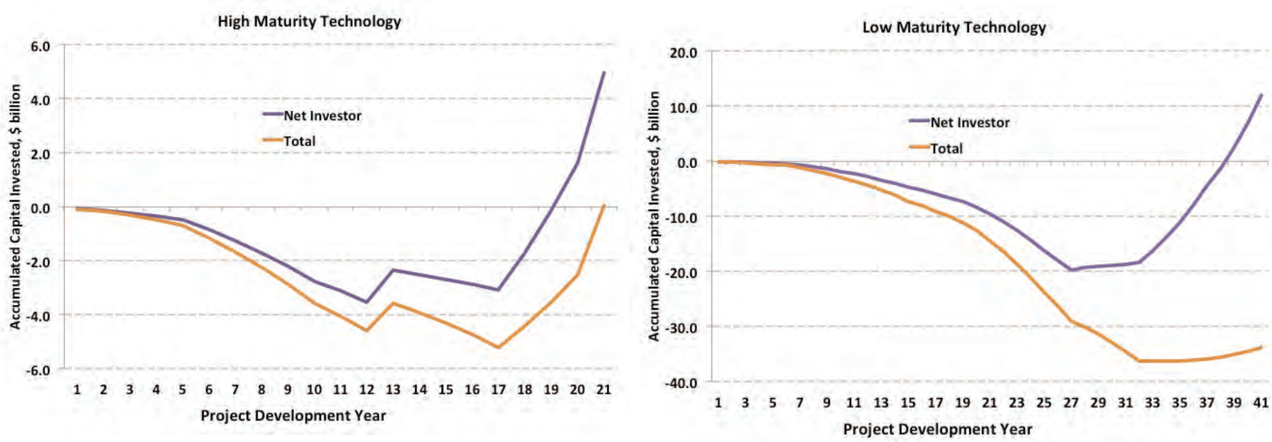
Governments should establish reactor sites where companies can deploy prototype reactors for testing and operation oriented to regulatory licensing.

- Government provides site security, cooling, oversight, PIE facilities, etc.
- Government provides targeted objectives, e.g. production of low-cost power or industrial heat, for which it is willing to provide production payments as an incentive

- Government takes responsibility for waste disposal
- Companies using the sites pay appropriate fees for site use and common site services
- Supply high assay LEU and other specialized fuels to enable tests of advanced reactors

How can the government help to deploy new nuclear technologies? (3)

High upfront costs and long time to see return on investment (more so for less mature technologies, e.g. FHR, MSR, LFR, GFR, than more mature technologies, i.e. HTGR, SFR)

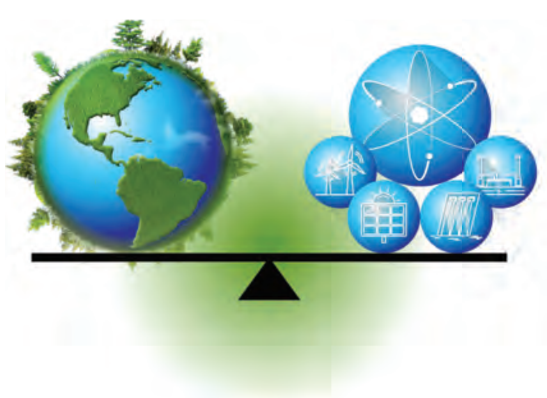


Early government support helps. Four “levers”:

- Share R&D costs
- Share licensing costs
- Payments for construction milestones
- Production credits

Take-away messages

- The opportunity is carbon
- The problem is cost
- There are ways to reduce it
- Government’s help is needed to make it happen



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Co-Director
Prof. Michael Corradini (U-Wisconsin)


Co-Director
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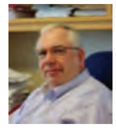
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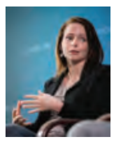
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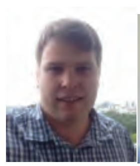
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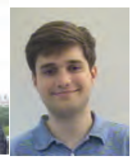
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Nestor Sepulveda (MIT student)

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Dominion Engineering, Inc.

THE BREAKTHROUGH

Lucid Strategy

BLUMONT

DISCLAIMER: MIT is committed to conducting research work that is unbiased and independent of any relationships with corporations, lobbying entities or special interest groups, as well as business arrangements, such as contracts with sponsors.

Nuclear Cost Drivers Project

Presentation to the EPRI / GAIN / NEI
Workshop on Economics-Based R&D for
Nuclear Power Construction

January 17-18, 2019

CLEANTECH CATALYST
Imaginative problem solving

Lucid Strategy

Contents

- Project Overview
- Methodology
- Findings
- Conclusions
- Recommendations

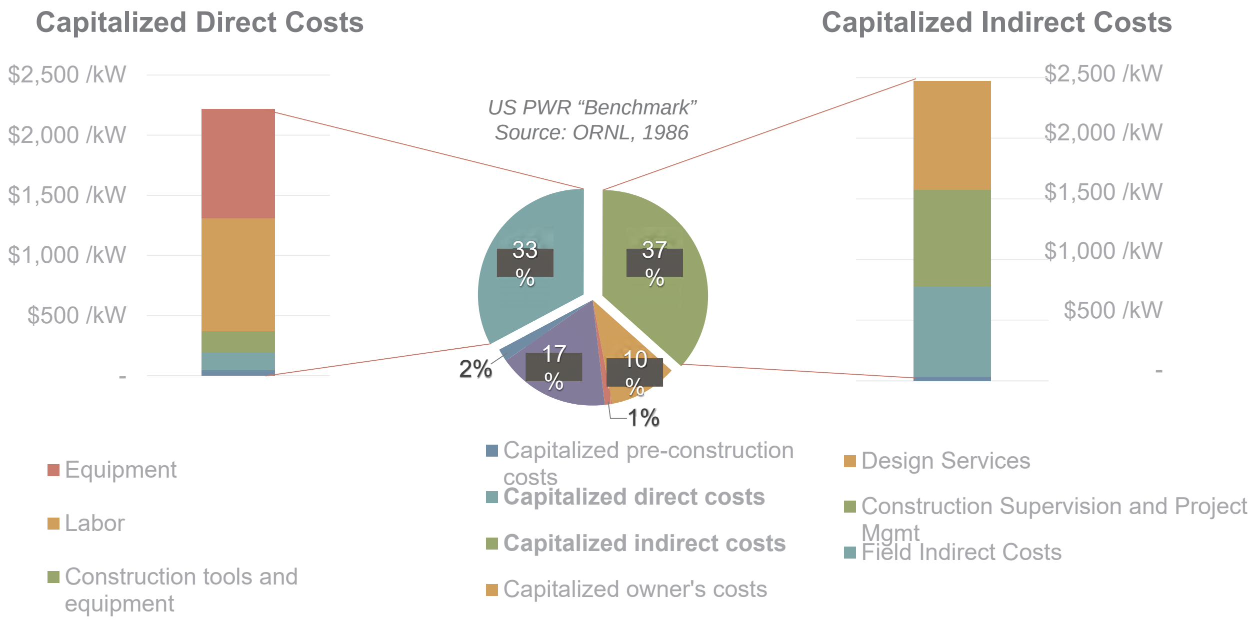
Project Objectives

- Perform and report an analysis of the principal cost drivers for contemporary designs, SMRs and advanced reactor technologies
- Assemble a credible cost database and associated cost model for the purposes of the Project and ultimately use by the ETI, the ETI Members, and (at the ETI's discretion) other third parties
- Identify areas of nuclear power plant design, construction and operation with potential to deliver cost reduction relevant to contemporary designs, advanced reactor technologies and SMRs

Contents

Cost breakdown of typical plant

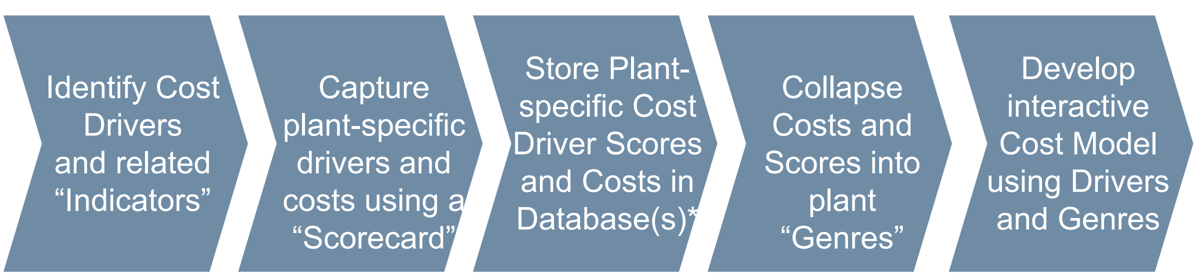
- cost breakdown of typical well documented plant to demonstrate that capital cost and cost of capital dominate



Methodology

- Methodology designed around existing and expected constraints
  - Lack of publicly-available data
  - Confidential/Proprietary nature of cost information
  - Concern with obtaining cost rationale not only costs
  - Limited time and budget but with a global scope

- Project is not intended to predict project costs but to identify trends



*Performed regression analysis on cost drivers to estimate relative influence on total project cost. Regression coefficients were used in the interactive cost model.

Identifying Cost Drivers to Analyse

- Project team held several internal collaborative workshops and extensive consultations with the ETI, the independent reviewer, and other cost experts

- Arrived at 8 cost drivers:

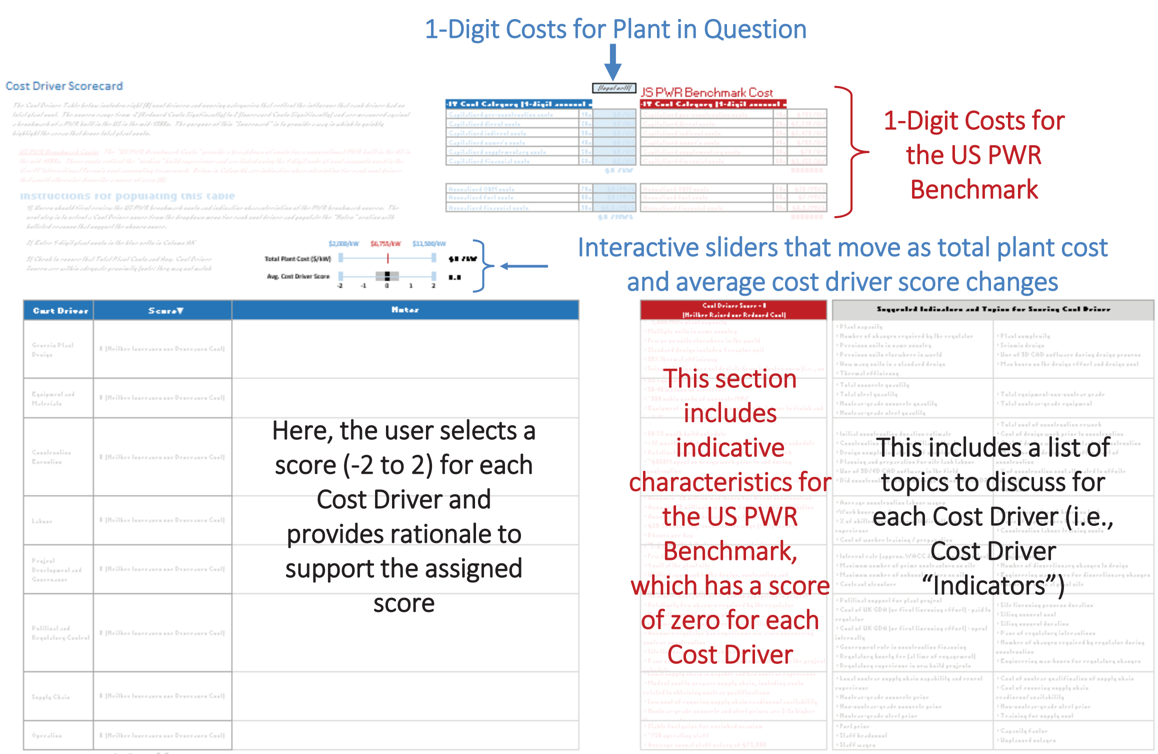
Cost Drivers
1. Vendor Plant Design
2. Equipment and Materials
3. Construction Execution
4. Labour
5. Project Development and Governance
6. Political and Regulatory Context
7. Supply Chain
8. Operations

Each driver has detailed quantitative and qualitative components

Cost Driver Indicators (Example)

Vendor Plant Design
Responsible Party: Reactor Vendor
Plant capacity
Previous units in same country
Previous units elsewhere in world
Thermal efficiency
Plant complexity
Safety systems
Seismic design
System and equipment redundancy
System and equipment complexity
Design tools - 3D CAD? 4D CAD?
Design for reusability

Cost driver Scorecard



ETI Cost Model

Cost Model Dashboard

Select genre --> Conventional in Europe / North Am

Scenario name --> Example scenario name

Save Scenario to Archive

Cost Estimates Based on Cost Driver Settings (Below) and Regression Coefficients

			Reference US PWR	Conventional in Europe / North Am: Representative Cost	Change from Represent. Cost	Updated Cost With Change
Capital	10s	Preconstruction Costs	$133 /kW	$179 /kW	-	$179 /kW
	20s E	Direct Construction Costs: Equipment	$1,006 /kW	$1,354 /kW	-	$1,354 /kW
	20s M	Direct Construction Costs: Materials	$292 /kW	$393 /kW	-	$393 /kW
	20s L	Direct Construction Costs: Labour	$957 /kW	$1,287 /kW	-	$1,287 /kW
	30s	Indirect Services Costs	$2,512 /kW	$3,379 /kW	-	$3,379 /kW
	40s	Owner's Costs	$715 /kW	$962 /kW	-	$962 /kW
	50s	Supplementary Costs	$79 /kW	$106 /kW	-	$106 /kW
	60s	Financing During Construction	$1,175 /kW	$2,794 /kW	-	$2,794 /kW
		Total Construction Costs	$6,870 /kW	**$10,454 /kW**	-	$10,454 /kW
		Levelised Construction Costs	$59 /MWh	**$89 /MWh**	-	$89 /MWh
Operating	70s	O&M Costs	$21 /MWh	$14 /MWh	-	$14 /MWh
	80s	Fuel Costs	$7 /MWh	$10 /MWh	-	$10 /MWh
	90s	Financing During Operation	$0 /MWh	$0 /MWh	-	$0 /MWh
		Total Operating Costs	$28 /MWh	**$25 /MWh**	-	$25 /MWh
		Levelised Cost of Electricity	$87 /MWh	**$114 /MWh**	-	$114 /MWh

Cost Driver Settings

	Reference US PWR	Conventional in Europe / North Am: Representative Value	Cost Driver Sliders	User's Updated Value
Generic Plant Design - Vendor	0.0	+2.0		+2.0
Equipment and Materials - EPC/Vendor	0.0	+1.8		+1.8
Construction Execution - EPC	0.0	+1.4		+1.4
Labour - EPC	0.0	+1.4		+1.4
Project Development and Governance - Owner	0.0	+1.2		+1.2
Political and Regulatory Context - Government	0.0	+1.0		+1.0
Supply Chain - Vendors	0.0	+1.8		+1.8
Operation - Owner	0.0	+0.4		+0.4
Average	0.0	**+1.4**		+1.4

Cost driver settings can range from -2 (significant cost reduction) to +2 (significant cost increase); 0 corresponds to PWR Reference

Click on scroll bar arrows to adjust cost driver settings

Breadth and extent of expert interviews

- Most nuclear cost studies attempt to get data on costs, which is difficult and cost data is not particularly reliable. We wanted to get around this by getting detailed story for each unit in our database using our scorecard and cost driver analysis.
- Team triangulated with multiple sources (where possible) for each scorecard. Interviewed 30 organisations (many of whom we met multiple times)
- >150 hours of interviews
- Experts included:
  - Construction Managers
  - Chief Project Officers
  - Board-level Directors
  - Regulators
  - Infrastructure project mgrs
  - Global nuclear new build mgrs
  - Project Directors
  - Quality Assurance experts
  - Contract lawyers
  - Senior Policy Directors
  - Government policymakers
  - Senior Management at vendor companies
- Interviewees from: Japan, Korea, France, US, UK, Sweden, Russia, Finland, India

Methodological assumptions

- Key supporting assumptions include:
  - Plants are compared on an apples-to-apples basis by adding IDC (interest during construction)
  - Common interest rate of 7%
  - Standardised fuel cost
  - Depreciation period of 60 years (consistent with BEIS LCOE methodology for new power plants)
  - Same interest rate during operations phase as per construction phase
  - Capacity factor of 95%

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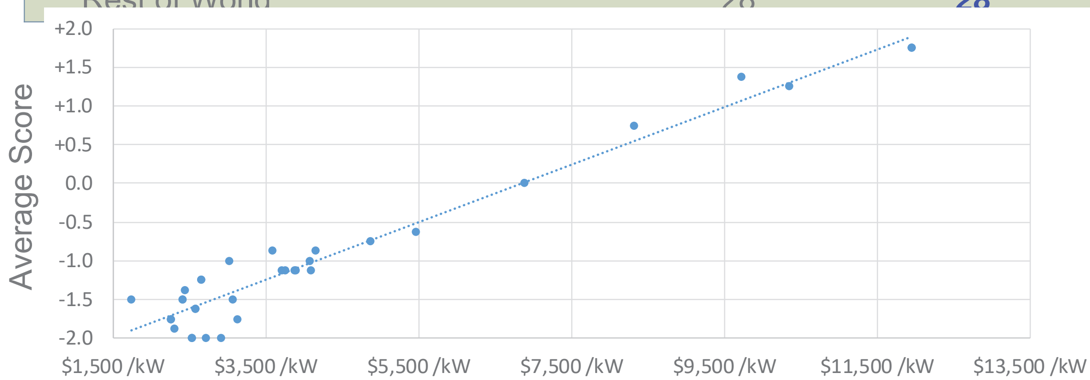
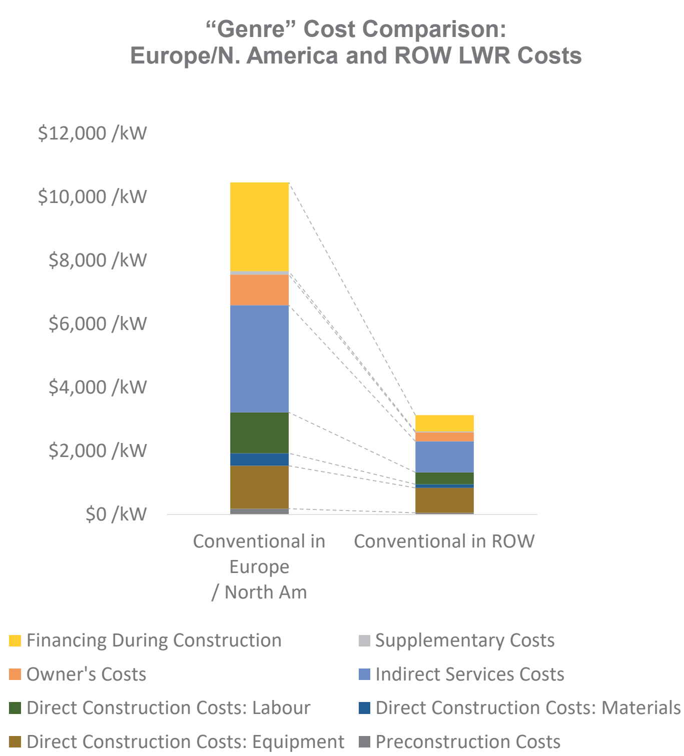
Broad range of cost and scores

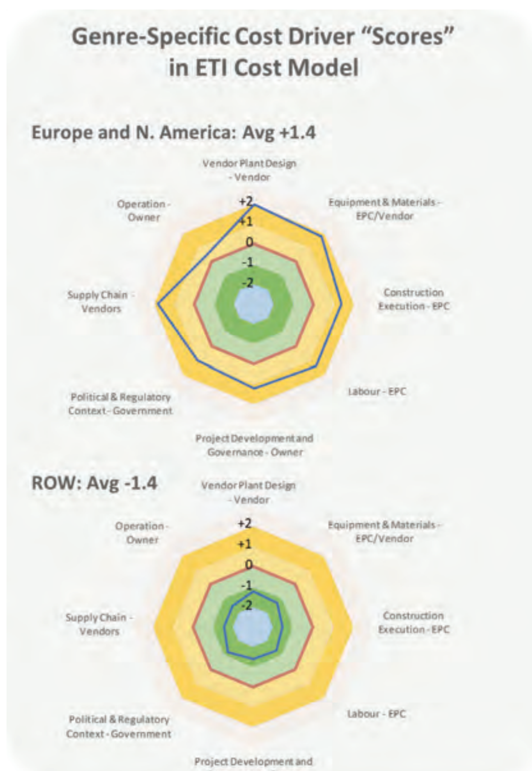
Data used in Analysis

Genre	# of Units in CTC-Lucid	# of Units in ETI Database
US PWR Benchmark	1	***1***
North America & Europe	5	***5***
Rest of World	28	***28***



LWR “genre” costs: EU/N. America vs. ROW





Common characteristics

Common characteristics of low-cost and high-cost projects

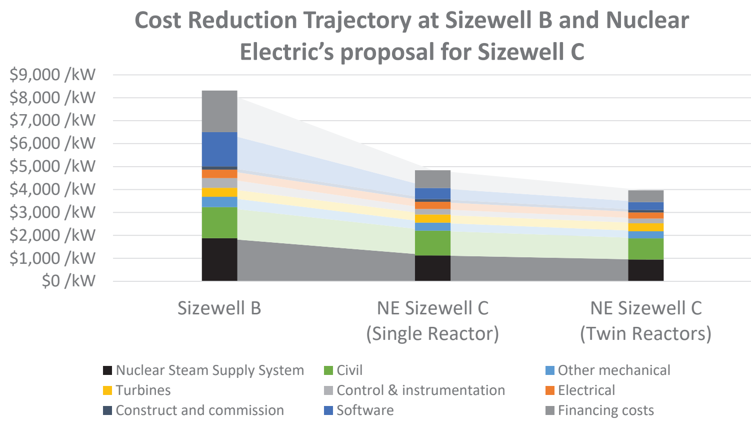
Low Cost Plants	High Cost Plants
• Design at or near complete prior to construction • High degree of design reuse • Experienced construction management • Low cost and highly productive labour • Experienced EPC consortium • Experienced supply chain • Detailed construction planning prior to starting construction • Intentional new build programme focused on cost reduction and performance improvement • Multiple units at a single site • NOAK design	• Lack of completed design before construction started • Major regulatory interventions during construction • FOAK design • Litigation between project participants • Significant delays and rework required due to supply chain • Long construction schedule • Relatively higher labour rates and low productivity • Insufficient oversight by owner

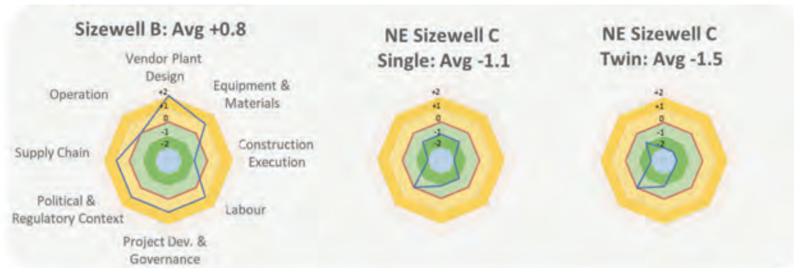
Case studies

- Sizewell B and Nuclear Electric’s proposal for Sizewell C
- Barakah 1-4
- Vogtle 3 & 4
- Rolls Royce SMR
- Japan Atomic Energy Agency’s High Temperature Engineering Test Reactor
- Molten Salt Reactor (generic)
- Offshore Wind

Learnings from Sizewell B

30% reduction in overnight costs from Sizewell B to Nuclear Electric's proposal for Sizewell C (single reactor)





Capital Costs	Cost Reductions from Sizewell B: Sizewell C Single	Cost Reductions from Sizewell B: Sizewell C Twin
Nuclear Steam Supply System	$752 /kW	$935 /kW
Civil	$271 /kW	$419 /kW
Other mechanical	$103 /kW	$147 /kW
Turbines	$38 /kW	$44 /kW
Control & instrumentation	$185 /kW	$224 /kW
Electrical	$53 /kW	$100 /kW
Construct and commission	$23 /kW	$35 /kW
Software	$1,008 /kW	$1,146 /kW
Financing costs	$1,041 /kW	$1,302 /kW
Total Cost Reductions	**$3,475 /kW**	**$4,352 /kW**

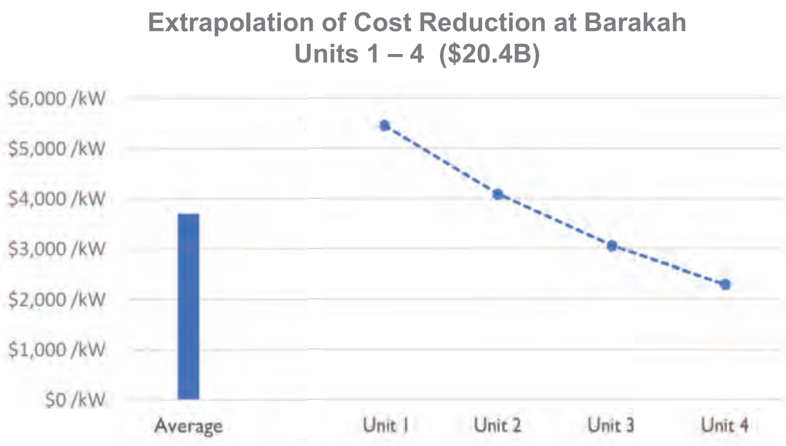
- Savings based on contractually-bound estimates for Nuclear Electric's proposal for Sizewell C

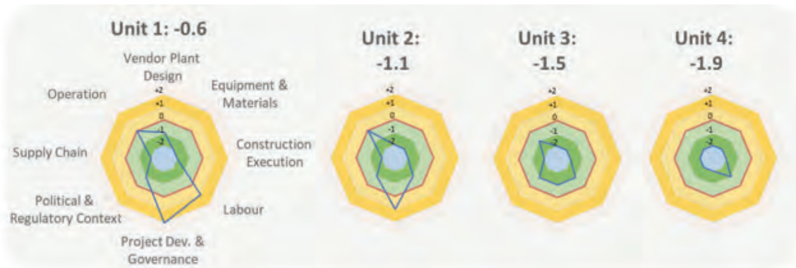
*Nuclear Electric plc paid expenditures for Sizewell B with income from other nuclear plants without incurring significant debt. We estimated financing costs for Sizewell B (as well as the Sizewell C configurations) for consistency with financing calculations for other plants in the database.

Cost reduction through learning

- Use of same contractors, vendors, and labour
- Regulators experienced with the design and delivery team (fewer expected changes)
- 30% reduction in schedule duration
- 40% overall cost reduction (with assumed financing)
- Twin units reflect sequenced delivery to optimise labour and construction schedule

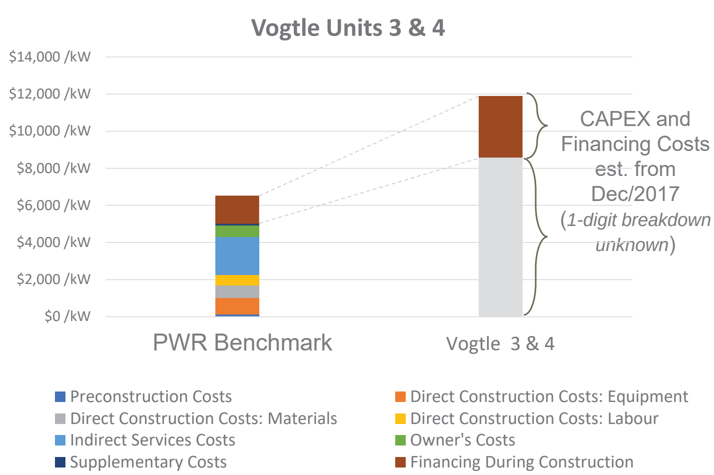
Barakah: benefits of a multi-unit programme





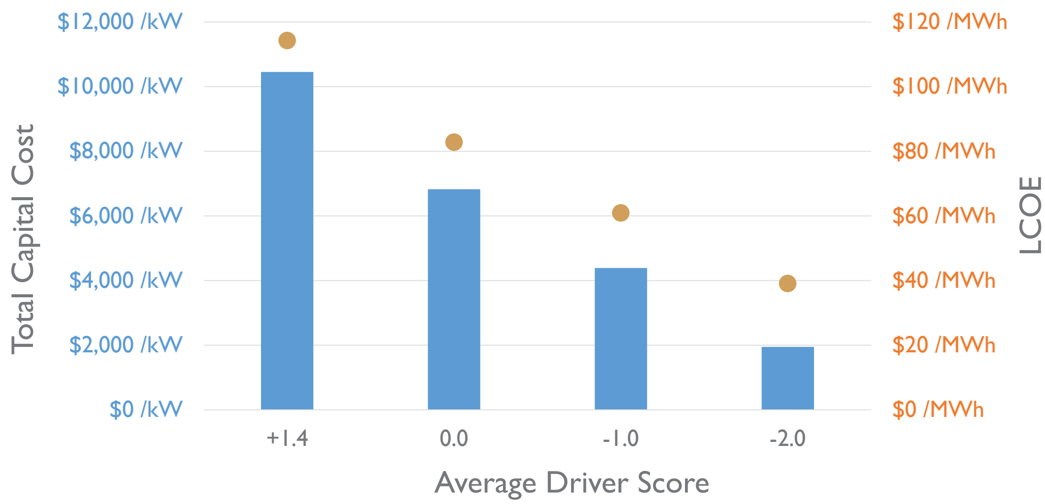
- Programme incorporates best practices in all cost driver categories
- Commitment to 4-unit purchase
  - Building on successful multi-unit builds in Korea
  - Same contractors and suppliers
  - Economies of scale in equipment procurement
- Exceptional project governance
  - Purchased plants in a way that allowed vendor to optimise process/ sequence, build continuously, maintain skills and experience
  - Fixed price project with significant success fee tied to on-time delivery
  - KEPCO was free to modify schedule but not delivery date
- RfP and bidding process preceded by comprehensive "lessons learned" study

Vogtle Units 3 & 4



- Started construction well before design was complete (precluded meaningful/ detailed construction planning)
- FOAK design
- Extreme lack of experience in supply chain and labour force
- Poor QC of modules manufactured offsite
- Project is now 68 months beyond initial COD target, escalating financing costs.
- Numerous construction setbacks
- Complicated contracting and poor liability assignment (reactor vendor eventually bought prime contractor to end lawsuits between both parties)

Cost Reduction Scenarios for EU/US Genre

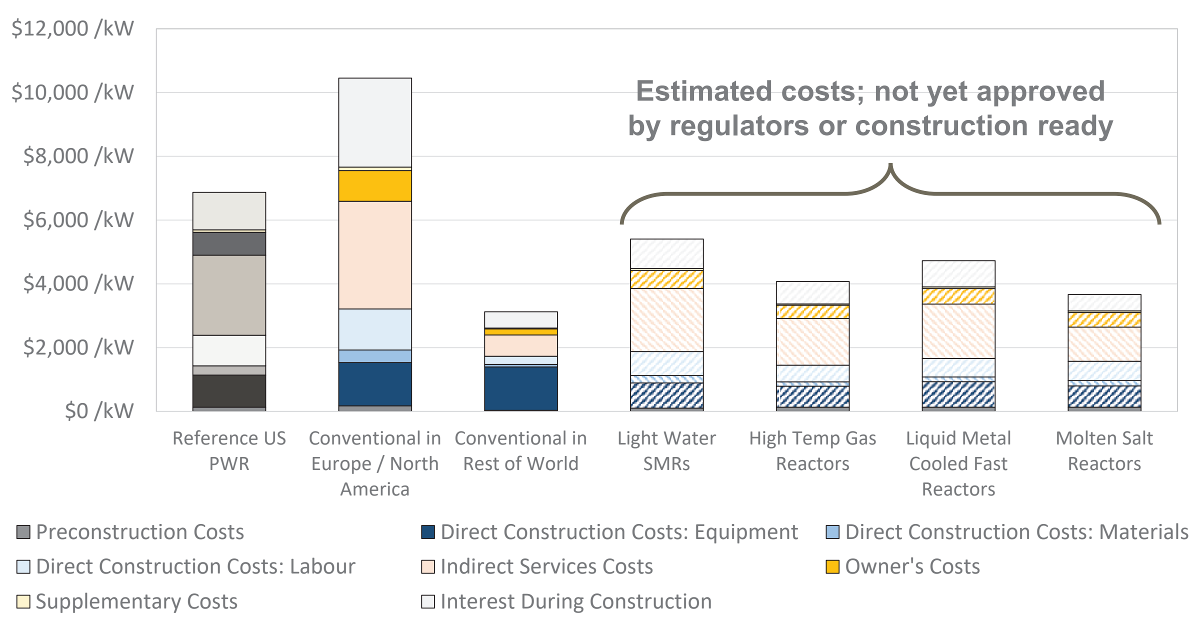


Alternative Cost Scenarios with Other Rate Assumptions

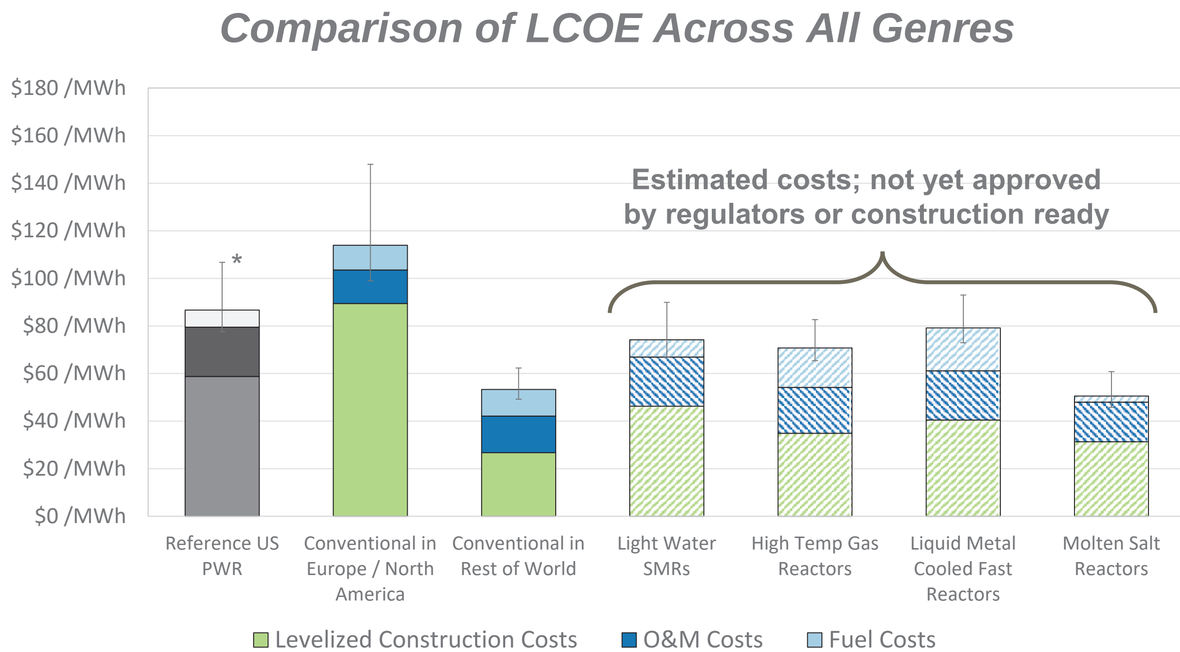
Avg.			7%		6%		9%	
Score	Capex/kW	Opex	Capex/MWh	LCOE	Capex/MWh	LCOE	Capex/MWh	LCOE
+1.4	$10,454 /kW	$25 /MWh	$89 /MWh	$114 /MWh	$75 /MWh	$99 /MWh	$123 /MWh	$148 /MWh
0.0	$6,826 /kW	$24 /MWh	$58 /MWh	$83 /MWh	$48 /MWh	$72 /MWh	$84 /MWh	$108 /MWh
-1.0	$4,386 /kW	$23 /MWh	$38 /MWh	$61 /MWh	$29 /MWh	$53 /MWh	$57 /MWh	$81 /MWh
-2.0	$1,946 /kW	$22 /MWh	$17 /MWh	$39 /MWh	$11 /MWh	$34 /MWh	$31 /MWh	$53 /MWh

Genre summary results (CAPEX)

Comparison of Capitalized Costs Across All Genres

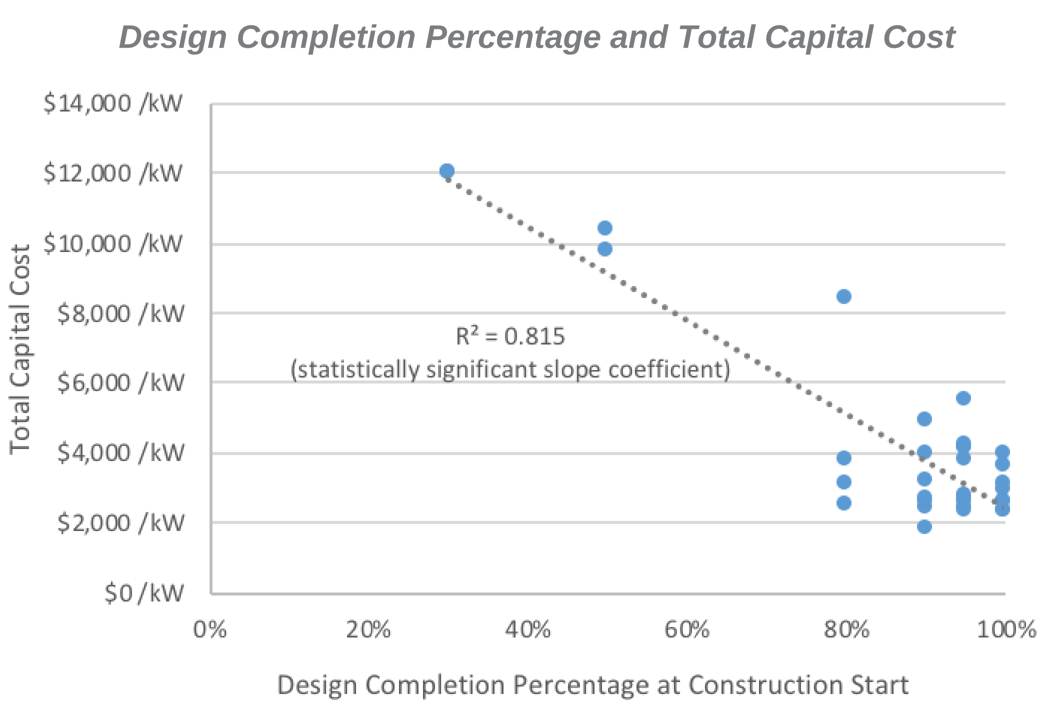


Genre summary results (LCOE)



* Boxplot whiskers represent LCOE at 6% and 9% Interest During Construction

Correlations: Incomplete design = high costs



Contents

Conclusions (1 of 3)

- A relatively small number of understandable factors drives the cost of nuclear plants. Whilst building nuclear plants takes place through large, complex projects, the findings of this study are straightforward and there was a high degree of consensus among the experts consulted
- Strong evidence of applicable cost reduction in the UK
- Fleet deployment by itself does not necessarily guarantee cost reduction
- Relatively significant cost reduction is possible outside reducing the cost of capital during construction
- Larger Gen III/III+ reactors and light-water SMRs are more market-ready than advanced reactors

Conclusions (2 of 3)

- Cost reduction and more predictable delivery can reduce perceived risk and potentially lower the cost of interest during construction (reducing CapEx even further)
- The cost reductions in “Rest of World” LWRs are a consequence of national nuclear programmes and the consistent, rational implementation of best practices
- Project delivery organizations in China, Korea, and Japan allocate adequate resources toward maintaining constant efficiency improvements in plant delivery
- Recent challenges in North America and Europe new build projects are partially attributable to local “context.”

Conclusions (3 of 3)

- Within the 35 cost reduction opportunities identified in this study, the Project Team identified a smaller group of actions that present the best opportunities for reducing project cost and risk in the UK. This group of actions is strongly supported by the evidence base, interviews, and regression analysis

Finding	Cost Driver Category
o Complete plant design prior to starting construction	(Vendor Plant Design)
o Follow contracting best practices	(Project Dev. & Governance)
o Project owner should develop multiple units at a single site	(Project Dev. & Governance)
o Innovate new methods for developing alignment with labour around nuclear projects	(Labour)
o Government support should be contingent on systematic application of cost reduction measures	(Political and Regulatory Context)
o Design a UK programme to maximize and incentivize learning, potentially led by a newly-created entity	(Political and Regulatory Context)
o Government must play a role in supporting financing process	(Political and Regulatory Context)
o Transform regulatory interaction to focus on cost-effective safety	(Political and Regulatory Context)

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The historical construction cost and cost drivers of nuclear power plants

Dr. Francesco Ganda (ANL)

EPRI NEI GAIN workshop on Construction Economics

January 17-18 at NEI, Washington DC

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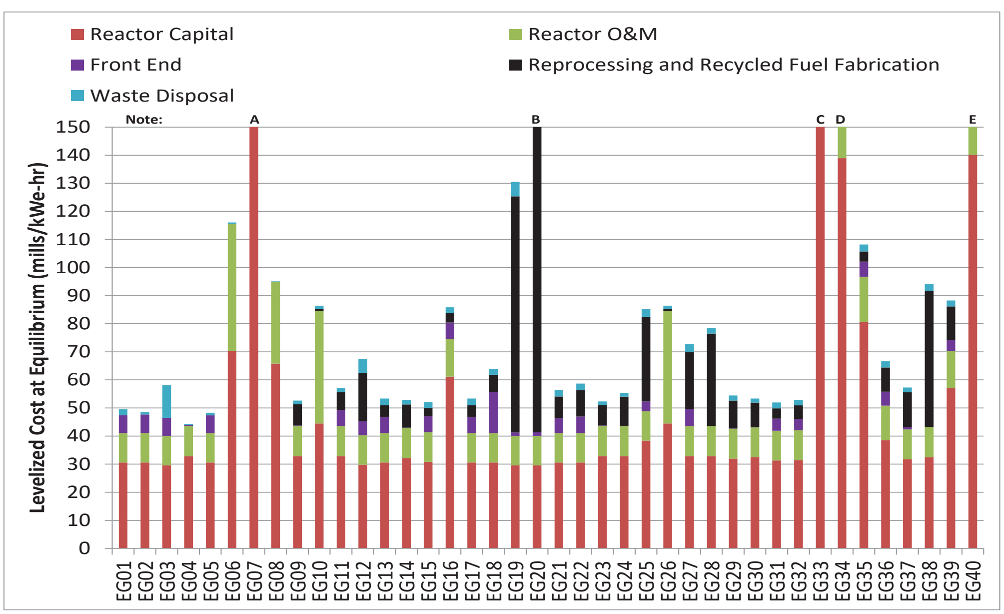
The biggest LCOE driver

– The Reactor Capital Cost and the Reactor Operation & Maintenance (O&M) costs dominate the overall LCOE.



Historical construction costs for LWR in the US

– Early reactors had low overnight costs, short construction times and limited cost overruns

Name of reactor	MW		State	Start constr	End constr	**Years for construction**	Lifetime	th. Efficiency	**Overnight capital cost (2018 $)**	TOT capital cost (2018 $)
Palisades	697	PWR	MI	3/15/1967	12/31/1971	**4.8**	40	32.90%	**889.76**	**998.3**
Vermont Yankee	507	BWR	VT	12/12/1967	11/30/1972	**5**	40	33.70%	**1857.24**	**2091.74**
Maine Yankee	879	PWR	ME	10/22/1968	6/29/1973	**4.7**	23.4	32.50%	**1425.76**	**1591.92**
Pilgrim	672	BWR	MA	8/27/1968	12/2/1972	**4.3**	40	33.50%	**1823.74**	**2011.34**
Surry 1	790	PWR	VA	6/26/1968	12/22/1972	**4.5**	40	33.90%	**1180.54**	**1310.52**
Turkey Point 3	672	PWR	FL	4/28/1967	12/14/1972	**5.6**	40	31.00%	**765.14**	**879.04**
Surry 2	793	PWR	VA	6/26/1968	5/1/1973	**4.8**	40	33.90%	**1180.54**	**1325.26**
Oconee 1	851	PWR	SC	11/7/1967	7/15/1973	**5.7**	40	32.80%	**818.74**	**943.36**
Turkey Point 4	673	PWR	FL	4/28/1967	9/2/1973	**6.4**	40	31.00%	**765.14**	**899.14**
Prairie Island 1	511	PWR	MN	6/26/1968	12/16/1973	**5.5**	40	31.80%	**1811.68**	**2071.64**
Zion 1	1069	PWR	IL	12/27/1968	10/19/1973	**4.8**	23.3	32.50%	**1222.08**	**1370.82**
Fort Calhoun	478	PWR	NE	6/8/1968	9/26/1973	**5.3**	40	32.10%	**1922.9**	**2186.88**
Kewaunee	521	PWR	WI	8/7/1968	6/16/1974	**5.9**	40	31.00%	**1687.06**	**1952.38**
Cooper	764	BWR	NE	6/6/1968	7/2/1974	**6.1**	40	31.80%	**1606.66**	**1871.98**
Peach Bottom 2	1078	BWR	PA	2/1/1968	7/2/1974	**6.4**	40	32.40%	**1618.72**	**1905.48**
Browns Ferry 1	1026	BWR	AL	5/11/1967	7/31/1974	**7.2**	11.4	32.70%	**1072**	**1294.44**
Oconee 2	851	PWR	SC	11/7/1967	9/9/1974	**6.8**	40	33.10%	**818.74**	**976.86**
Three Mile Island 1	790	PWR	PA	5/19/1968	9/2/1974	**6.3**	40	30.60%	**2115.86**	**2481.68**
Zion 2	1001	PWR	IL	12/27/1968	11/14/1973	**4.9**	22.8	32.50%	**1222.08**	**1373.5**
Arkansas 1	836	PWR	AR	12/7/1968	12/19/1974	**6**	40	30.80%	**1192.6**	**1388.24**
...	...	...	...	...	...	**...**	...	...	**...**	**...**

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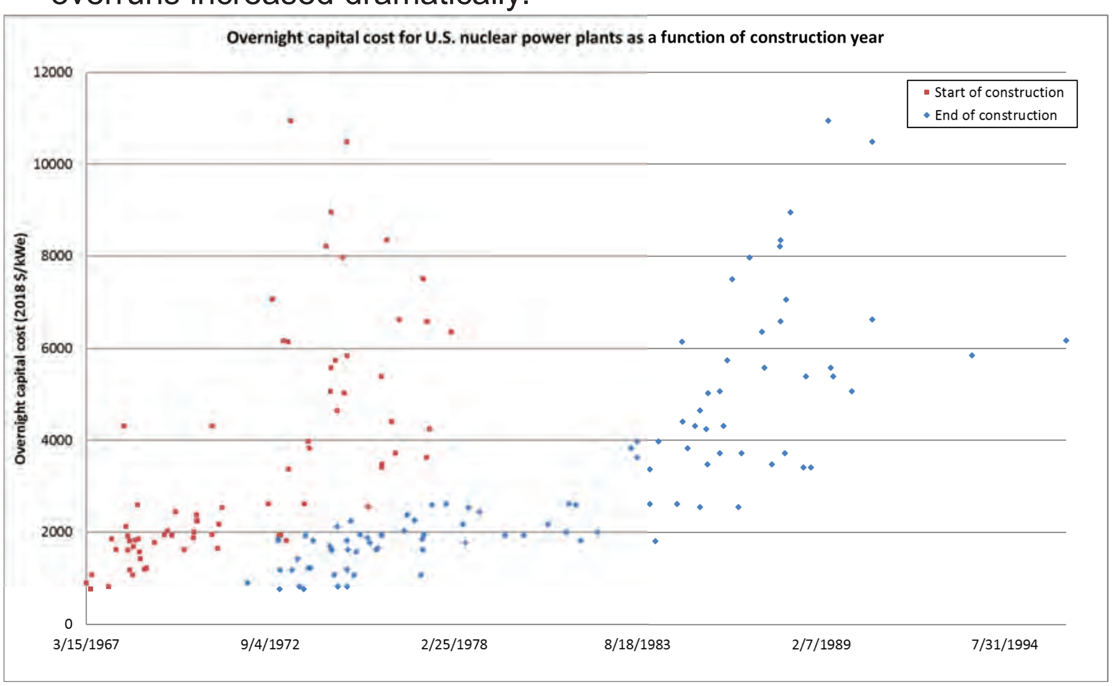
Historical construction costs for LWR in the US

– During the ‘70s and ‘80s construction costs, construction time and cost overruns increased dramatically.



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Understanding reactor capital costs

- A key objective:
  - *Establish a framework for understanding the reasons for the observed historical capital costs*
- Identify:
  - *The fundamental drivers of cost,*
  - *The reasons of the biggest cost overruns observed historically.*
- Distinction between:
  - *Cost of "best experience" in reactor construction;*
  - *Cost overruns.*
- Most of the literature on the subject mostly take, at best, an observational approach, with mathematical attempts to interpolate, and sometimes extrapolate, from historical data.
- Single construction cost drivers are not easy to identify, contrary to the case of coal plants, for example: in the '70s, the addition of scrubbers, and particulate abatement equipment, measurably increased the cost of construction.

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The main cause for the over budget constructions

- A key driver of cost overruns during construction is the degree of design changes requested during the construction phase:
  - *Incomplete engineering at the start of construction;*
  - *Regulatory turbulence.*
- If design is fully completed before the construction starts and no changes are requested during the construction phase, complex construction projects can be kept reasonably within budget:
  - *Fixed price contracts, negotiated with competitive bidding: minimize the construction costs and keep the project within budget.*
- If design changes significantly during the construction phase, the original fixed price contracts become un-tenable and re-bidding is usually impractical:
  - *Fixed price contracts have to be switched to "cost plus" contracts and efficiencies are lost.*

F. Ganda, T. K. Kim, T. A. Taiwo and R. Wigeland, "Analysis of reactor capital costs and correlated sampling of economic input variables", Proceedings of ICAPP 2015, May 03-06, 2015, Nice (France), Paper 15342.

F. Ganda, J. Hansen, T. K. Kim, T. A. Taiwo, R. Wigeland, "Reactor Capital Costs Breakdown And Statistical Analysis Of Historical U.S. Construction Costs", Proceedings of ICAPP 2016, April 19th, 2016, San Francisco, CA, Paper 16829.

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Changes during construction

– Changes during construction affect cost overruns:

- *Completed work has to be removed/altered, often with "ripple effects" on nearby systems;*
- *Construction sequences has to be altered, and equipment delivery schedules has to be altered, potentially idling groups of workers → lower labor productivity;*
- *Increased construction duration can create a positive feed-back loop by exposing the project to increased risk of regulatory turbulence; increasing interest costs and disrupting construction logistics.*

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A case study: the Davis Besse power station

– Construction approved by the board of Toledo Edison in December 1967, for \$136 million (\$1 billion in 2018 \$), for 800 MW_e on the shores of Lake Erie → 1300 $\$_{2013}/kW_e$.

– Completion expected for 1974. When completed in 1977, the final cost was \$650 million (\$2.7 billion in 2018 \$) for 906 MW_e → 3000 $\$_{2018}/kW_e$.

– Originally expected to reduce utility bills in Ohio, at completion it added 19% to the average utility bill because of costs overruns.

– Christopher Bassett, then with the Ohio Public Utilities Commission, published a paper quantifying the details of the cost escalation:
C. Bassett, "The high cost of Nuclear Power Plants", Public Utilities Fortnightly, April 1978.

– Addition of a cooling tower, at the request of the Ohio Water Pollution Control Board, and an increase in power output from 800 to 906 MW_e were commonly associated with the cost escalation. Not significant after close examination.

– Some contracts were tied to escalation (while others were lump sum bidding): during a period of high inflation this was believed to be a main source of cost escalation. Not dominant after quantification.

A case study: the Davis Besse power station

– Summary table of construction cost increases for Davis Besse:

TABLE 1
DAVIS-BESSE UNIT NO. 1
ANALYSIS OF CONSTRUCTION
COST INCREASES

		Thousands of Dollars	
Original Appropriation — 12/26/67		$136,000	21%
Unit Size Increase 800 Mw to 906 Mw		18,000	3%
Inflation in Labor and Materials		86,000	13%
Cooling Tower Addition		11,000	2%
Higher Land Cost for Restoration of Marshlands		1,000	0%
NRC Modifications and Their Chain Effects			
design modifications	$195,000		
lost of productivity due to retrofitting the above changes	72,000		
increase in AFDC charges due to construction delays and cost increments for above changes	110,000		
greater cost for training and acceptance	21,000		
		398,000	61%
Ultimate Total Project		$650,000	100%

Because effects are very intertwined, the table is approximate:
For example: AFDC charges were increased by an increase in allowable FPC (FERC) AFDC rates from 6.5% to 8% during the project life, but this was a small effect compared to the effects of delays caused by the changes in regulatory requirements.

From: Bassett C. (1978), "The high cost of nuclear power plants", April 27, 1978, Public Utilities Fortnightly.

A case study: the Davis Besse power station

– Large escalation was observed for "Piping and Mechanical", "Civil and Structural", "Architect-Engineer" and "Electric", all intensively labor oriented where retrofitting had a large impact.

– In contrast, contracts which involved relatively fixed pieces of hardware (e.g. "steam supply system", "turbine generators", "cooling towers", and "containment vessel") did not experience substantial escalation: retrofits had limited impact on those procurement costs. (About 50% of original cost, before escalation).

TABLE 2
DAVIS-BESSE UNIT NO. 1
TEN OF THE LARGEST CONSTRUCTION CONTRACTS

Contract	*Low Bid*	*Hight Bid*	*Ultimate Amount Paid Out*
	($ in Thousands)		
Piping and Mechanical	$14,822	$18,470	$ 79,940
Civil and Structural	10,672	11,485	67,235
Architect-engineer	7,821	7,821	46,310
Electrical	4,900	8,711	43,890
Steam Supply	28,745	33,981	39,960
Turbine-Generator	22,259	22,259	24,073
Instrumentation	4,016	4,449	14,507
Cooling Tower	8,380	9,964	7,571
Containment Vessel	5,980	5,980	6,583
Concrete	1,639	2,559	3,550
Total			$330,619

From: Bassett C. (1978), "The high cost of nuclear power plants", April 27, 1978, Public Utilities Fortnightly.

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A case study: the French construction program

– The French construction program benefited from:

- *Rigorous cost control and planning by EDF (which acted as Architect Engineer).*
- *Engineering stability*
  – “*Whenever an engineer had an interesting or even genius [improvement] idea either in-house [EDF] or at Framatome, we said: OK, put it on file, this will be for the next series, but right now, we change nothing.*” Boiteux, CEO of EDF, 2009 [b].
- *Regulatory stability*
  – *There are no documented regulatory incidences from 1970 to 1999 [a];*
  – *The “Authorité de Sureté Nucléaire” (ASN, the independent regulatory agency) was created in 2006, 4 years after the last reactor was completed in 2002 [a];*
  – *EDF, despite the stability of safety rules, integrated progressively more stringent safety features in new reactors [a].*

[a] *L. Rangel, F. Leveque, “Revisiting the Cost Escalation Course of Nuclear Power. New Lessons from the French Experience”, Ecoles de Mines, Paris, Dec. 2012.*

[b] *A. Grubler, “The Cost of the French Nuclear Scale-up: A Case of Negative Learning by Doing”, Energy Policy 38 (2010).*

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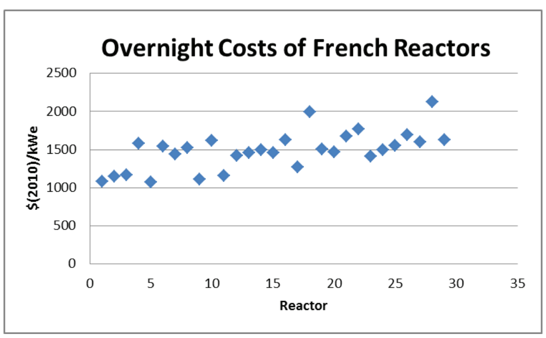
A case study: the French construction costs



Source of data: Cour des Comptes, 2012

	Plant	MW	Criticality	Type	Cost (E_{2010}/kW)	Cost ($/kW)
palier 900 MW	Fessenheim1.2	1780	1978	CP0	836	1087
	Bugey2.3	1840	1979	CP0	886	1152
	Bugey4.5	1800	1979	CP0	899	1169
	Dampierre1.2	1800	1980	CP1	1,217	1582
	Gravelines1.2	1840	1980	CP1	822	1069
	Tricastin1.2	1840	1980	CP1	1,188	1544
	Blayais1.2	1830	1982	CP1	1,110	1443
	Dampierre3.4	1800	1981	CP1	1,172	1524
	Gravelines3.4	1840	1981	CP1	856	1113
	Tricastin3.4	1840	1981	CP1	1,247	1621
	Blayais3.4	1820	1983	CP1	890	1157
	Gravelines5.6	1820	1985	CP1	1,093	1421
	SaintLaurent 1,2	1760	1983	CP2	1,120	1456
	Chinon 1,2	1740	1984	CP2	1,148	1492
	Cruas1.2	1760	1984	CP2	1,119	1455
	Cruas3.4	1760	1984	CP2	1,253	1629
	Chinon3.4	1760	1987	CP2	978	1271
palier 1300 MW	Paluel1.2	2580	1985	P4	1,531	1990
	Paluel3.4	2580	1986	P4	1,157	1504
	St Alban1.2	2600	1986	P4	1,129	1468
	Flamanville1.2	2580	1987	P4	1,287	1673
	Cattenom1.2	2565	1987	P'4	1,358	1765
	Belleville1.2	2620	1988	P'4	1,083	1408
	Cattenom3.4	2600	1991	P'4	1,149	1494
	Nogent1.2	2620	1988	P'4	1,194	1552
	Glofech1.2	2620	1992	P'4	1,305	1697
	Penly1.2	2660	1991	P'4	1,227	1595
palier 1450 MW	Chooz1.2	2910	2000	N4	1,635	2126
	Civaux1.2	2945	2002	N4	1,251	1626

Regulatory stringency

– Expansion of the nuclear sector appears to be the best predictor of increased construction costs, as driven by increasing regulatory stringency:
  - *Example: AEC staff on the need for additional regulation for "Anticipated Transient Without Scram", in 1973:*
    "The present likelihood of a severe ATWS is acceptably small, in view of the limited number of plants now in operation. [...] As more plants are built, however, the overall chance of ATWS will increase, and the staff believe that design improvements are appropriate [...]".

– Common in every regulated sector: e.g. the current rapid increase in regulatory stringency for the oil-by-rail sector.

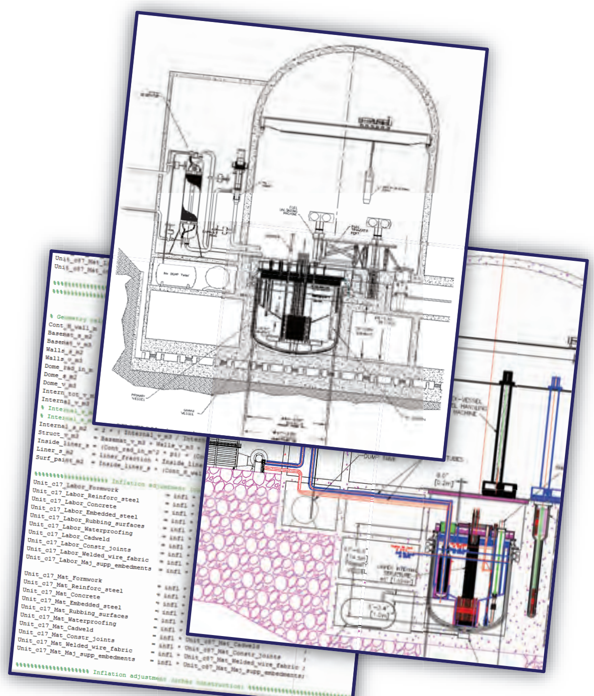
– In 1970 the publication of regulatory guidelines started (4 in 1970, 21 in 1971 and 33 in 1972, 143 in 1978 and 234 today for "division" 1, Power Reactors). 53 have since been withdrawn, and 10 have not been issued. Net of 171 today.

– For a given amount of power level, all the new requirements imposed during the '70s, approximately (Atomic Industrial Forum (now NEI), 1978):
  - *Doubled the amount of materials, equipment and labor;*
  - *Increased by two-thirds the amount of engineering effort.*

The Algorithm for the Capital Cost Estimation of Reactor Technologies (ACCERT)

– Functionality:
  - *Estimate the capital cost of advanced nuclear reactor designs.*

– Relevance:
  - *Facilitate independent assessments of claims about capital costs for advanced concepts.*
  - *Standardize approach for capital cost estimation.*
  - *Fills an identified gap in the tools available to DOE.*
  - *Perform preliminary cost assessments during the initial planning phase for new constructions.*
  - *Detailed cost models offer insight about the cost drivers for advanced designs.*
  - *This can be used to inform R&D decision making about cost reduction for advanced concepts.*



Report available at: https://publications.anl.gov/anlpubs/2018/07/144923.pdf

Exploring the Role of Advanced Nuclear in Future Energy Markets

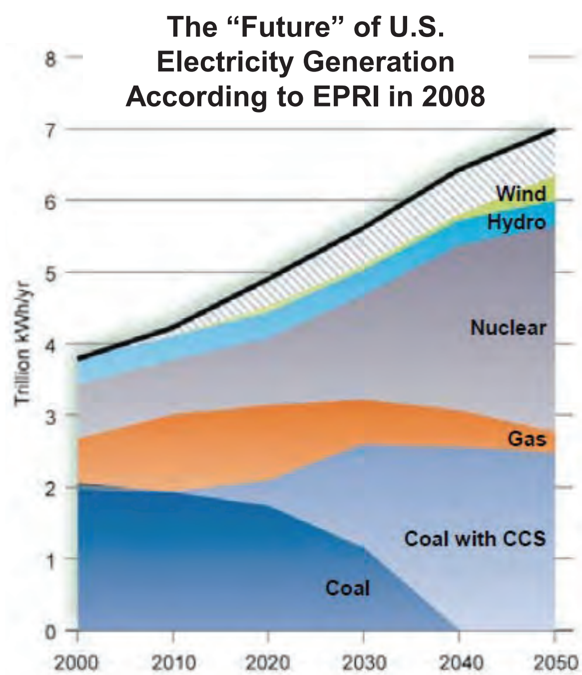
Economic Drivers, Barriers, and Impacts in the United States

Andrew Sowder
Technical Executive

GAIN-EPRI-NEI Workshop on Economics-Based R&D for Nuclear Power Construction
January 17, 2019

Global Context for Future of Nuclear: Uncertainty

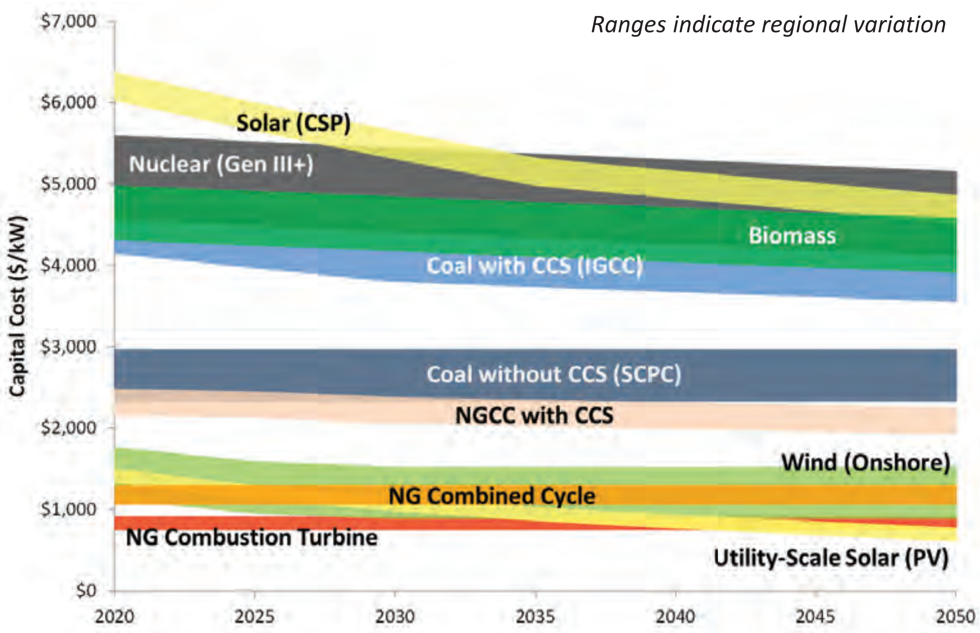
- What will the price of natural gas be?
- What will the price of carbon be?
- What will the technology competition be?
  - Natural gas with CCS?
  - Renewables with grid-scale energy storage?
- "Unknown unknowns" … *i.e., the next shale gas revolution*



EPRI 2008. The Power to Reduce CO2 Emissions: The Full Portfolio.

U.S. Cost Trajectories for Nuclear are NOT Compelling

EPRI REGEN Reference Case



Source: 2016 Integrated Generation Options Report (3002011806)

How can nuclear energy compete in future markets?

Analysis Approach and Scenario Matrix

← Cost Scenarios →

Market and Policy Sensitivities			Technology Sensitivities: Nuclear Capital Cost Scenarios ($/kW in 2030)			
			$5,000	$4,000	$3,000	$2,000
Reference Natural Gas Prices						
	Electric Sector CO_2 Policy	$15/t-$CO_2$ Tax @ 5%				
		95% Cap				
	Additional Revenue Streams	$5/MWh				
		$15/MWh				
	RPS with New Nuclear	50% by 2050, No Trading				
		50% by 2050, Trading				
High Natural Gas Prices						
Low Natural Gas Prices						

↑ Value Scenarios ↓

- Advanced nuclear capital cost sensitivities vary after 2030 ($/kW)
- Natural gas price trajectories based on EIA's *Annual Energy Outlook*
- Additional revenue streams → Proxy for PTC, sales of primary heat, or other products
- Expanded RPS: New nuclear considered an eligible resource; requirements expanded to all regions and stringency increased over time (30% by 2030 through 50% by 2050); sensitivity to national REC trading

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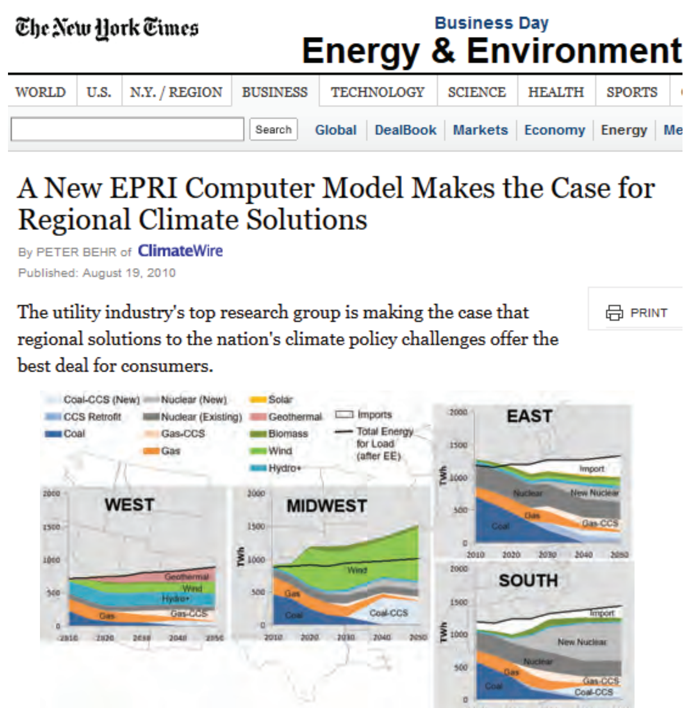
US-REGEN: EPRI's In-House Electric Sector and Economy Model

- State-of-the-art computable general equilibrium (CGE) model of the U.S. economy with enhanced regional detail
- Includes detailed focus on the energy sector and electricity system
- Regional breakdown captures variability in generation mix, resources, and demand
- Tool to support scenario planning, IRPs
- Incorporates EPRI's proprietary datasets related to expected costs and performance of electric generation technologies and environmental controls
- Developed and maintained by EPRI staff


The New York Times
Business Day
Energy & Environment
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A New EPRI Computer Model Makes the Case for Regional Climate Solutions

By PETER BEHR of ClimateWire
Published: August 19, 2010

PRINT

The utility industry's top research group is making the case that regional solutions to the nation's climate policy challenges offer the best deal for consumers.

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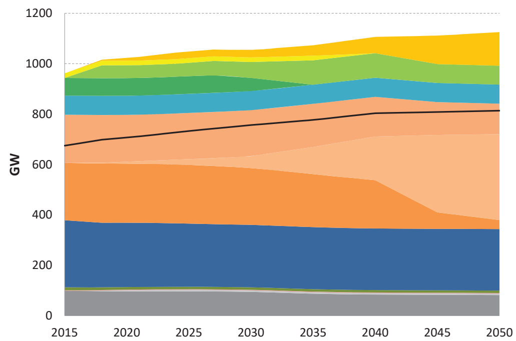
US-REGEN: EPRI's In-House Electric Sector and Economy Model

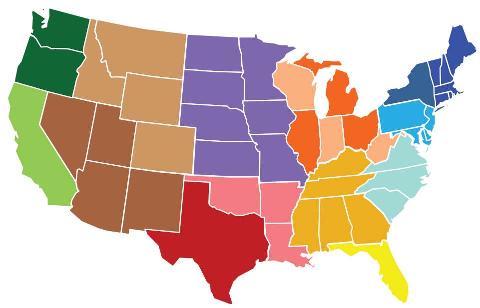
U.S. Regional Economy, GHG, and Energy

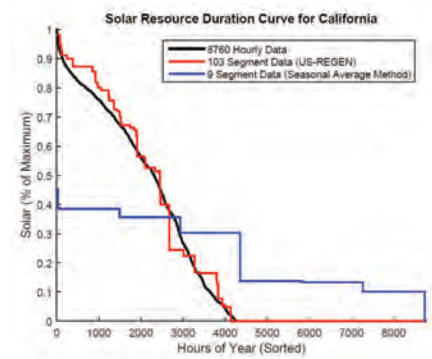
Capacity Expansion Economic Model, Long Horizon to 2050

Customizable State/Regional Resolution for Policy and Regulatory Analysis

Innovative Algorithm to Capture Wind, Solar, and Load Correlations in a Long-Horizon Model



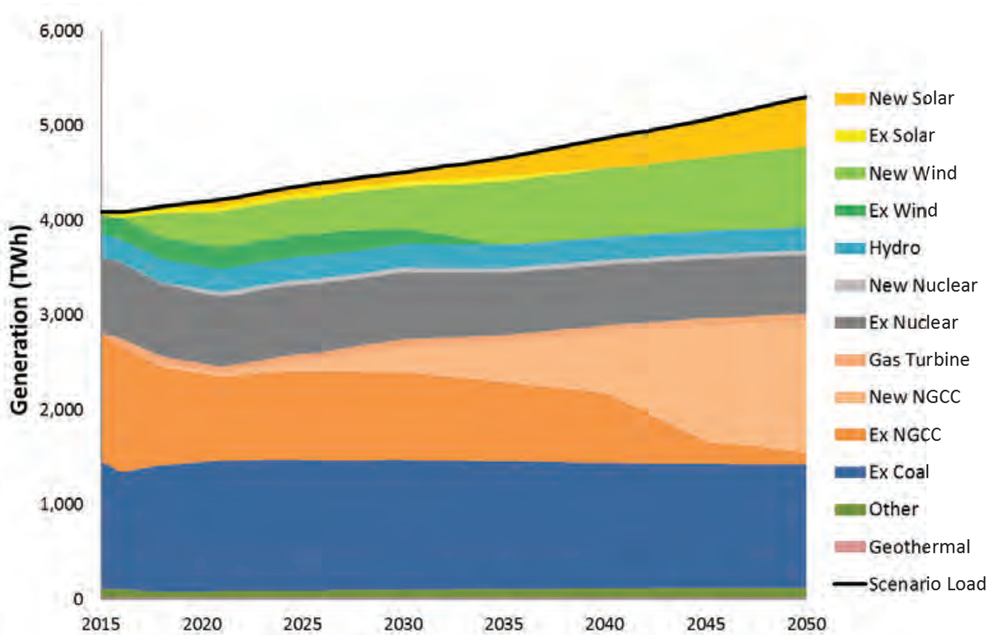




For more information, see website at http://eea.epri.com

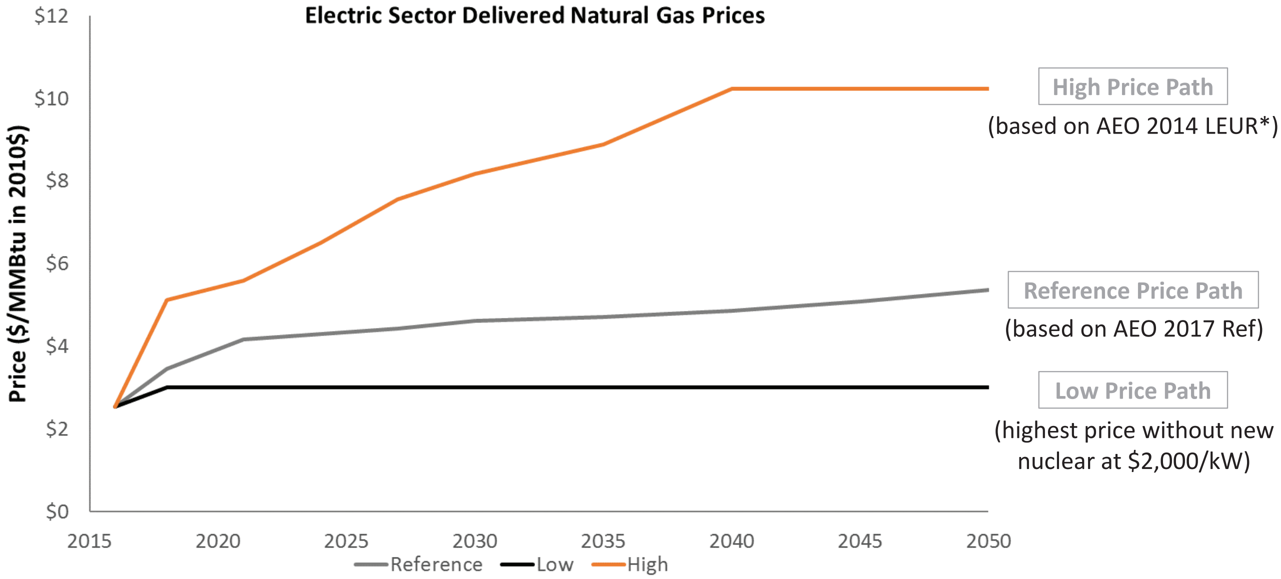
"The future ain't what it used to be." Yogi Bera

Absent Further CO_2 Policy with Reference Policies, Reference Gas Prices, and $5,000/kW Nuclear



- Absent additional policies, new builds are mostly gas, wind, and solar
- Existing nuclear and coal capacity remains unless gas prices are lower (80% of nuclear to 80 years)
- **New nuclear build limited to current projects**

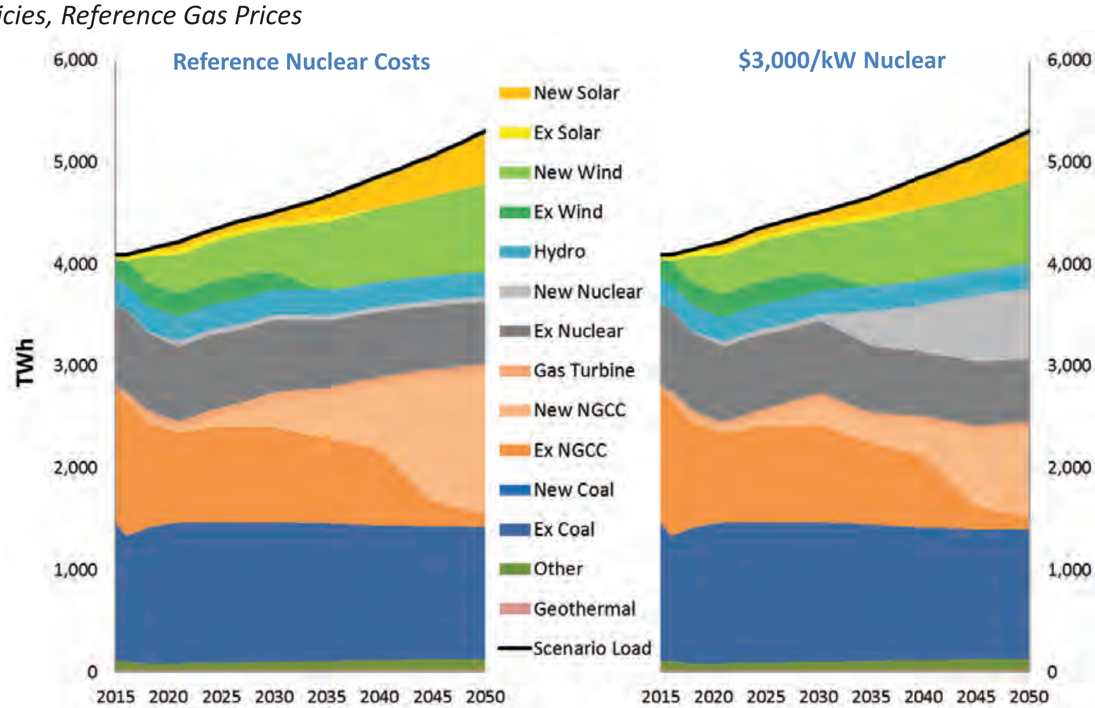
Natural Gas Price Uncertainty: Key Driver



*AEO = Energy Information Administration's Annual Energy Outlook; **LEUR** = low estimated ultimate recovery (i.e., high prices)

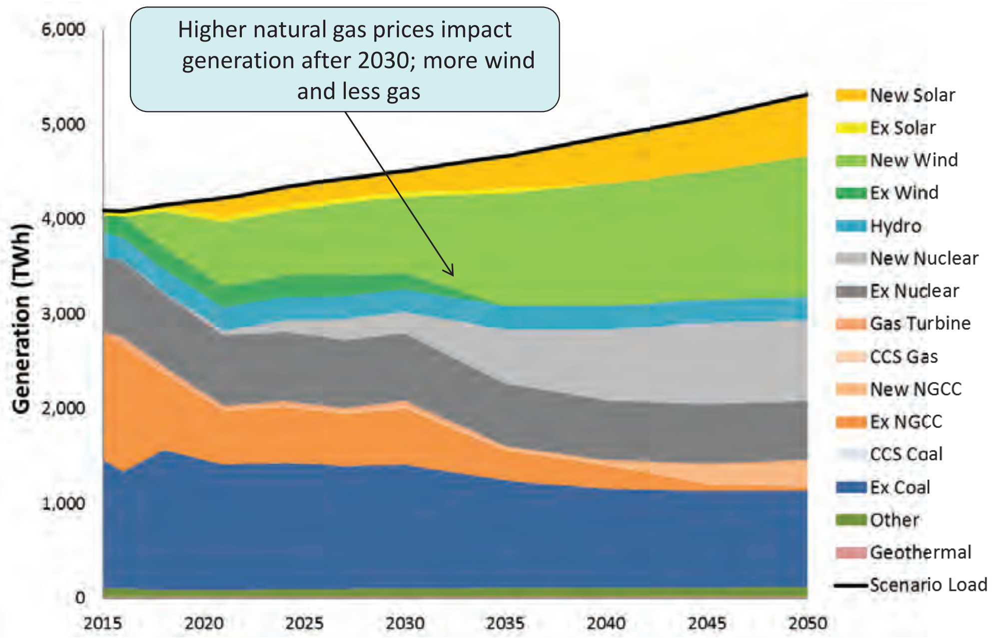
Lower Capital Costs Drive Expansion of Nuclear

Reference Policies, Reference Gas Prices



Higher Gas Prices Impact Investments and Dispatch

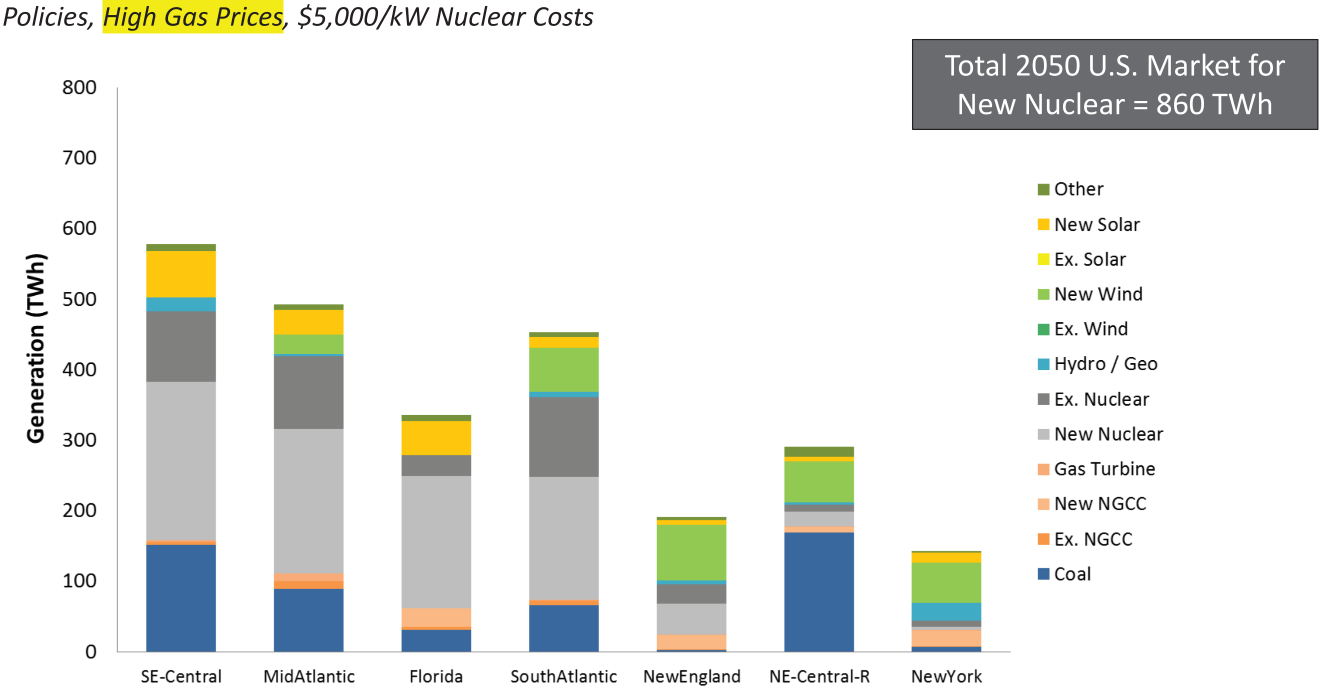
Reference Policies, High Gas Prices, $5,000/kW



- New wind and solar are more competitive with high gas prices (even more than with lower renewables costs)
- **New nuclear is economic in some regions even without new policy**

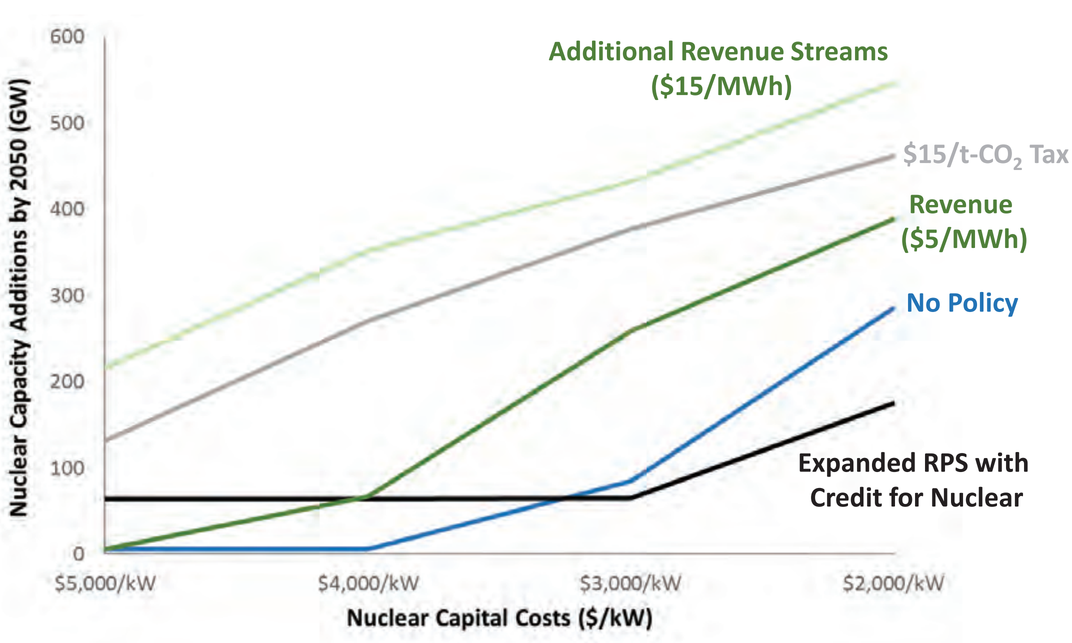
Regional Effects: 2050 Generation with High Gas Prices

Reference Policies, High Gas Prices, $5,000/kW Nuclear Costs



Big Picture: Advanced Nuclear Deployment vs. Cost

Reference Gas Prices



- Cost competitiveness of nuclear impacted by costs of other technologies and markets
- Without policy and with **reference gas prices**, levels below $4,000/kW are required for nuclear deployment
- With strong policy support, additions depend jointly on technology value and costs

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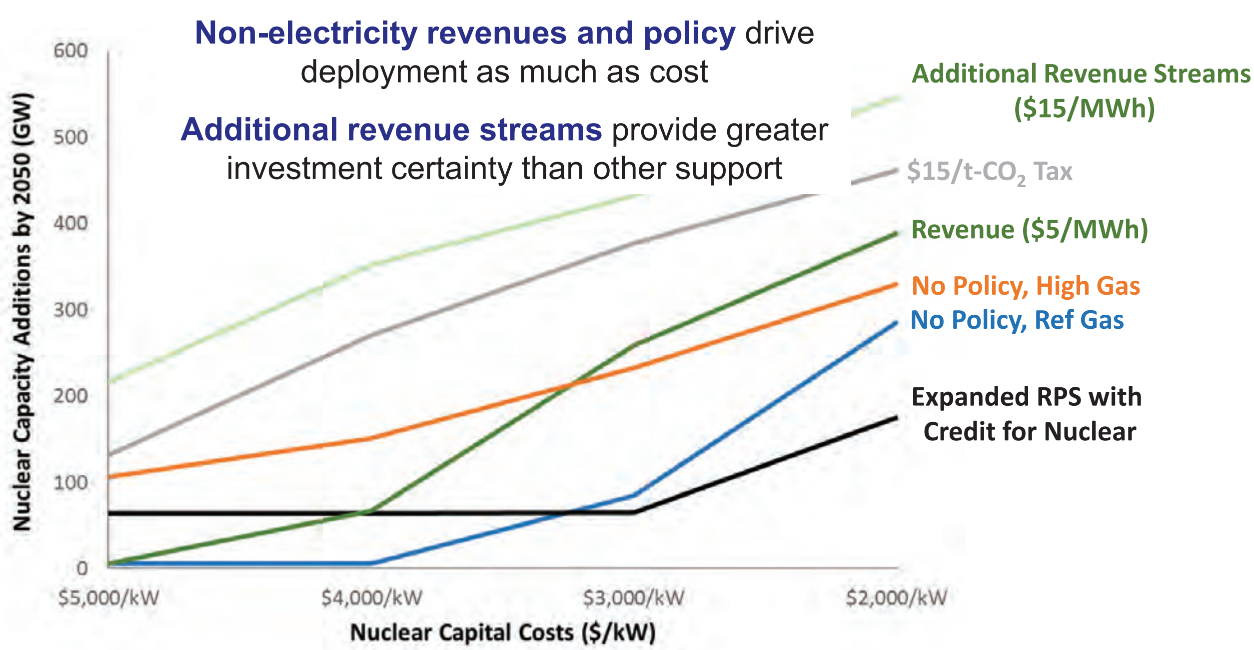
Big Picture with Addition of High Gas Price Scenario



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Key Drivers for Advanced Nuclear Role in Future Markets

- Competition (including arrival of disruptive technology)
- Capital costs
- Additional revenue
- Energy and environmental policies
- Regional factors and differences

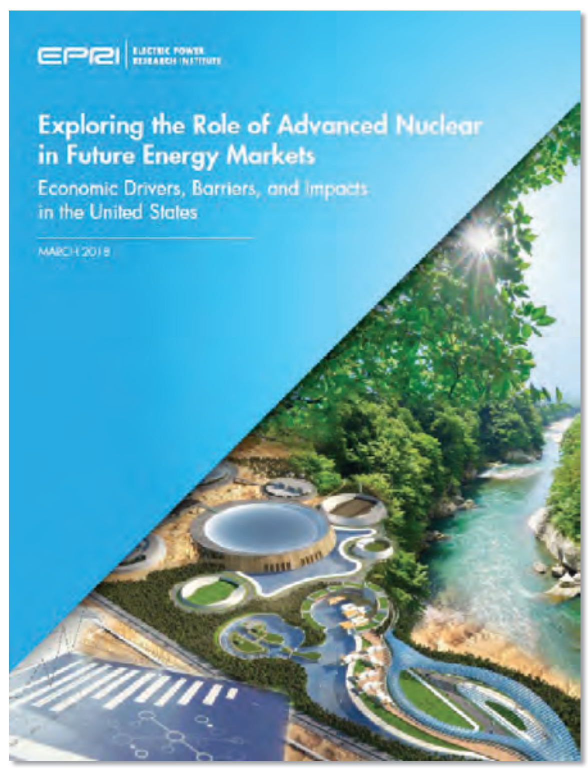
Future nuclear deployment is driven by multiple factors…not just cost.

Exploring the Role of Advanced Nuclear in Future Energy Markets:
Economic Drivers, Barriers, and Impacts in the United States

EPRI Report No. 3002011803

Published March 2018

https://www.epri.com/#/pages/product/3002011803/



Another recent study of potential relevance and interest:
Government and Industry Roles in the Research, Development, Demonstration, and Deployment of Commercial Nuclear Reactors: Historical Review and Analysis. December 2017. Report # 3002010478.
https://www.epri.com/#/pages/product/3002010478/

Additional References

- Bistline and Blanford (2016), More Than One Arrow in the Quiver: Why "100% Renewables" Misses the Mark, *PNAS*, 113(28):E3988.
- Blanford, Merrick, Bistline, Young (2018), Simulating Annual Variation in Load, Wind, and Solar by Representative Hour Selection, *The Energy Journal*
- EPRI (2016), Understanding Clean Power Plan Choices in Michigan: Options and Uncertainties, Report 3002009036
- EPRI (2015), US-REGEN Unit Commitment Model Documentation, Report 3002004748
- EPRI (2014), US-REGEN Model Documentation, Report 3002004693

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Together…Shaping the Future of Electricity

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Economic-Based R&D Roadmap

Current Findings from EPRI's R&D Roadmap Development

David B. Scott, ANT, EPRI
Senior Technical Leader

Chuck Marks, Dominion Engineering
Bob Varrin, Dominion Engineering

EPRI/GAIN/NEI Workshop
January 17-18, 2019
Washington, DC, USA

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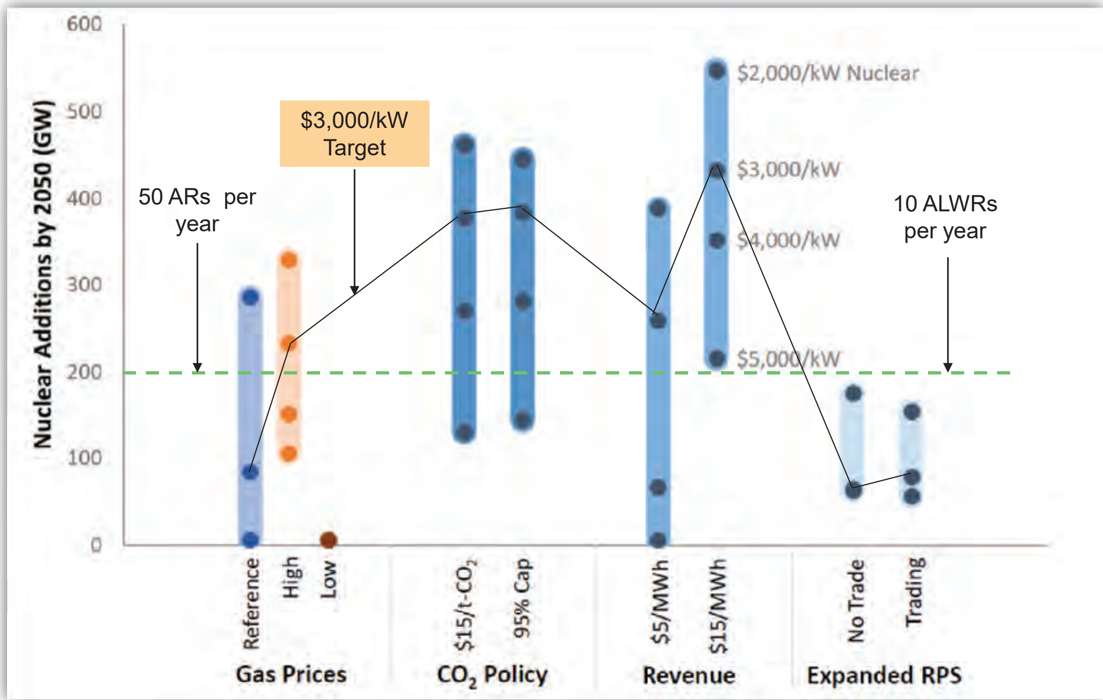
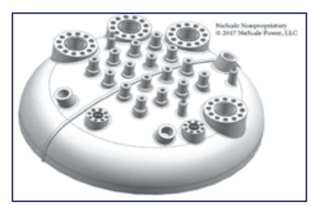
Discussion Topics

- EPRI Perspective
- ANT Focus Areas
- Project Objective and Scope
- Goals for this Presentation/Workshop
  - Project summary and "expert elicitation"
- Evaluation Methodology
- Examples of Cost Drivers
- Opportunities
  - Direct and Indirect Cost Drivers
  - Project Planning
  - Project Execution
- Selected Examples
- Discussion

New Reactor Economics Study (3002011803)



ANT Technical Focus Areas



- **Engineering, Procurement, and Construction**
  - Siting, design, construction materials, and construction activities of the physical plant, including modular construction
- **Materials and Components**
  - Class 1, 2 & 3 piping systems and related components such as valves, heat exchangers, and pumps
  - Optimize methods for fabrication, installation, joining, inspection, and operations, including chemistry; and apply new applications of M&C
- **Modern Technology Application**
  - Maximize the use of existing, new, and possibly non-nuclear specific, technology in new nuclear plants
  - Gaps for the use of digital systems in new nuclear applications
- **Advance Reactor TI Program**
  - Strategic analysis and economics, technology assessment & tool development (ex. PHA-PRA), materials, owner-operator requirements

ANT Program Challenge Goal

- Prioritize EPRI (or other) R&D initiatives to help achieve
  - 30-50% reduction in cost of construction (>$2,500/kWe savings based on ~$5,500/kWe assumed baseline in this study to achieve $3,000/kWe construction cost)
  - Examples discussed herein are focused on 1GWe ALWR (for reasons discussed later)
  - Advanced reactor discussion tomorrow
- Supplement heuristics with economic modeling to establish such a prioritization
  - Use both historical and recent construction cost data and experience to assess opportunities
  - Quantify degree to which R&D successes could contribute to cost reductions
  - Consider both ALWRs and advanced reactors in such evaluations
- Timeframe
  - Realization in 5 to 10 years

Current Project Objective and Scope

- Objective
  - Predict the potential effect of new technologies, construction practices, or other research outcomes on nuclear power plant construction costs
  - Quantify effect in terms of overnight construction cost (OCC) reductions
  - Quantify effect of OCC reductions on cost of electricity
- Scope
  - Briefly summarize historical costs trends
    - 1970s to 1990's
    - Recent new builds in US and Europe
    - More recent overseas experience
  - Summarize methods used to estimate construction costs and cost of electricity
  - Pick an economic modeling approach
  - Use such a model to assess effects of specific initiative/practices
- Key project goal
  - Consider ALWRs and advanced designs

Task Overview

Task 1 → **Overview of Economics**
- Overview of Economics
- Overview of LCOE Bases
- Typical Schedules
- Typical OCC Estimates

→ **Cost Drivers**

Task 2 → **Methodologies**
- Identify open-source models
- Compare methods
- Identify needs for accommodating advanced reactors

→ **Model Summaries**

Task 3 → **Gap Analysis**
- Identify gaps
- Peer review findings by project participants
- Risk/uncertainty analysis

→ **Report**

Task 4 → **Apply Tools**
- Develop model
- Identify candidate technology innovations
- Run cases
- Sensitivities

→ **Recommendations**

Important Perspective and Context

- Over the course of the next day's discussions, keep in mind….
  - There is a significant difference in experience in mature markets and new-build environments in terms of construction costs
    - <$3,000/kWe mature markets
    - >$5,500/kWe in new-build environments (or more)
- In discussing an R&D initiative or cost-driver, must distinguish between
  - What has been done in country X but not in country Y (but perhaps could…or could not apply to country Y)
  - What R&D initiatives have <u>not</u> been applied in X or Y but possibly could benefit both

These discussion should be open to talking about both types of "cost drivers" - country specific and non-country specific

Figures of Merit for the Evaluations

- **Overnight Construction Cost (OCC)** ⬅ Main topic for this presentation
  - Direct costs + indirect costs = OCC
- Total Capital Investment Cost (TCIC)
  - OCC + escalation + interest during construction (IDC) + Owner's Costs
- Levelized Cost of Electricity (LCOE) (EIA Advanced Nuclear ~$90/MWh)
  - OCC ~40% (60% direct, 40% indirects) **$5,500** ⬅ Notional baseline
  - Owner's cost and contingency ~20% multiplier $1,110
  - IDC ~15-20% (or more) $1,000
  - Fuel~15%
  - O&M~15%
- Also, in this study, the level of detail in economic modeling…
  - Comparable to Class 4 or 5 Estimates using AACE terminology (study or feasibility phase)

Other Metrics (not specifically included in this study)

- O&M costs
- Fuel costs or benefits of accident tolerant fuel (ATF)
- Plant reliability (capacity factor)
- "Nuclear Promise"
- Non-base load operations (flexible operations)
- Siting (e.g., seismic isolation – part of separate EPRI project)
- Interaction with regulator or licensing approach (Part 50/52)

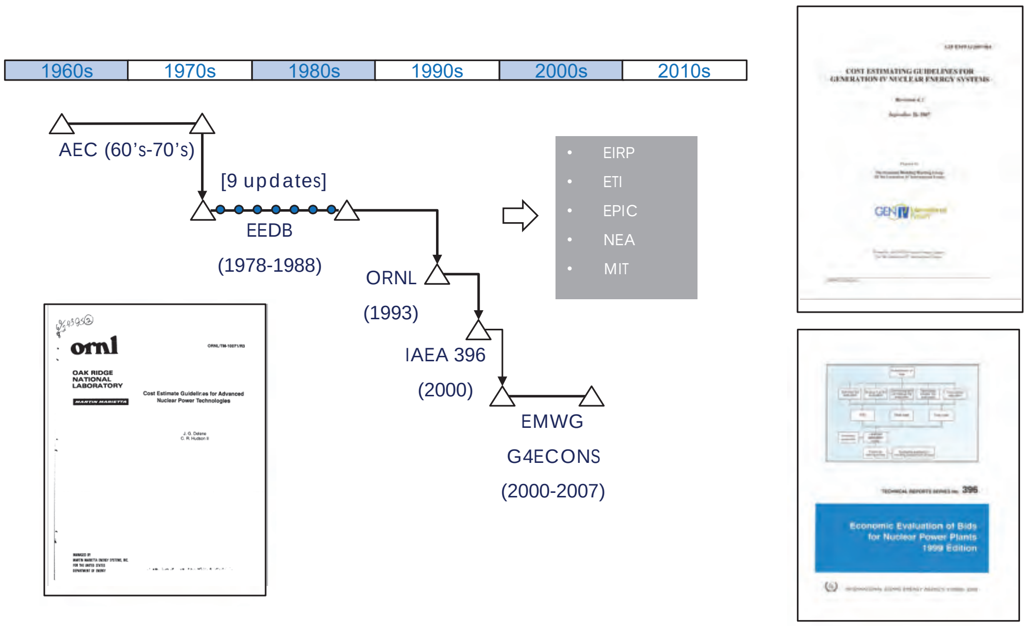
Why Use "Older" Construction Costs Estimate Methods?

- Construction cost and project scheduling models have been utilized in the power industry since the 1960's – not just for nuclear
- Audience/users:
  - Utilities, governments, regulators, research institutions, public sector, investors
- Results were/are used to support decision making:
  - (1) to build or not to build (nuclear or fossil, and now renewables and energy storage)
  - (2) timing
  - (3) plant type and size
  - (4) number of units, etc.
- Highlights/capabilities
  - 100's of man-years of effort invested in the design, validation, and population of these databases
  - Common framework used today in US and overseas

Cost Modeling Review

- Approximately 20 models and ~100 associated references were reviewed
  - Models represent cost estimating methodologies from seven (7) countries
  - Range from detailed bottom-up estimates to top-down extrapolation of historical cost data
- 11 models downselected for comparison
  - Assumptions
  - Scope (Gen III, advanced reactors, etc.)
  - Approach
  - Source of data
- First expert elicitation workshop was held in June 2018
- Second elicitation (today and tomorrow)

Notable Models Facilitating Assessment of Cost Drivers



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Historical Cost Drivers (1978-1987)

- Regulatory stringency and compliance
- Design changes
  - Equipment design changes
  - Material quantities and costs (37% above inflation)
- Commodity costs, equipment cost, required man-hrs
- Indirect costs (increased at rate 53% above inflation)
- Labor costs (increased at rates 44-220% above inflation depending on site)

TMI Under Construction circa 1970

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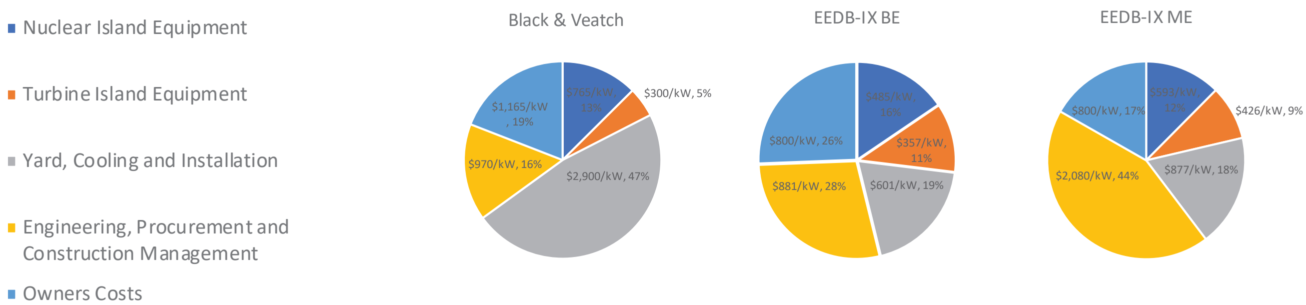
Comparison of “Pie Charts”



EEDB Codes	Scope	B&V (2012)		EEDB IX-BE (2009 adjusted)		EEDB IX-ME (2009 adjusted)	
		Cost	Percent	Cost	Percent	Cost	Percent
22	Nuclear Island Equipment	$765/kW	13%	$485/kW	16%	$593/kW	12%
23	Turbine Island Equipment	$300/kW	5%	$357/kW	11%	$426/kW	9%
21, 24, 25, 26	Yard, Cooling and Installation	$2,900/kW	48%	$601/kW	19%	$877/kW	18%
91, 92, 93	Engineering, Procurement and Construction Management	$970/kW	16%	$881/kW	28%	$2,080/kW	44%
	Owners Costs	$1,165/kW	19%	$800/kW	26%	$800/kW	17%
	Total	$6,100/kW	100%	$3,124/kW	100%	$4,775/kW	100%

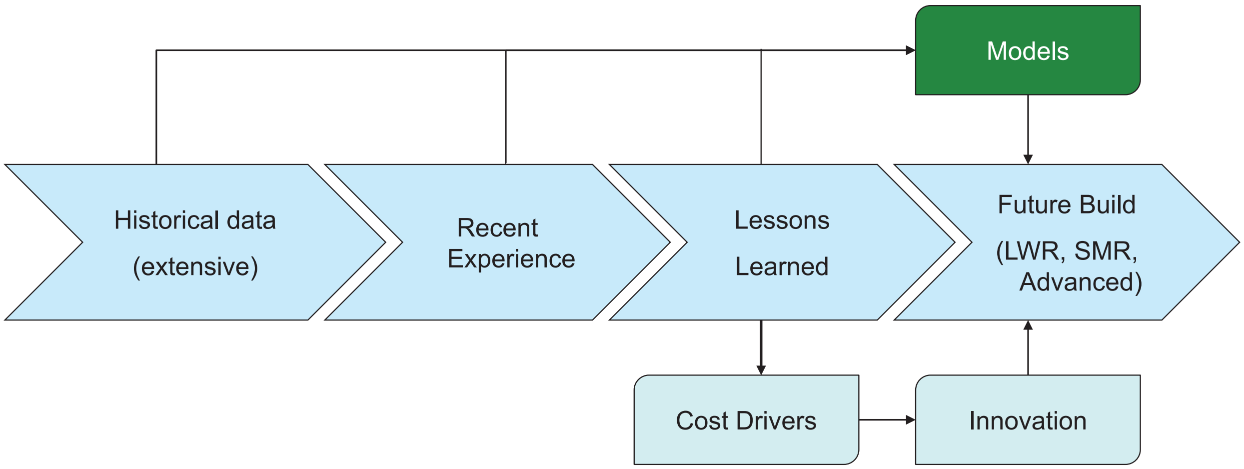
Note: Owners costs included

EEDB (one open source model)

- Multi-year program to inform DOE
  - Began under AEC sponsorship in 1960s (NUS, 1969)
  - Total of 23 years of analysis
  - Nine phases or updates from 1978 to 1988
- 33 power plant configurations in total over 10 years
  - ~8 nuclear configurations
- Code-of Accounts System (up to 9-digit)
  - Assumed that all electric stations have same basic features at two to three digit level
- Direct Cost Accounts (linked to SDDs)
  - Commodities (concrete, rebar, piping, wiring)
  - Components
  - Equipment
  - Installation man-hours

Approach for Technology Evaluation

- Assessment of the potential effect of R&D and associated innovative technologies on plant costs



Example Assessment of an Advanced Technology

- Self Compacting Concrete (Champlin, 2018)
  - Flows more readily requiring less vibration after pouring
  - 20% increase in concrete materials cost, 34% decrease in concrete labor
- EEDB (DOE,1986) provides the total quantity materials used on site
  - Site materials are ~28% concrete, ~1% formwork, and ~69% rebar
- Chaplin provides an approximate cost breakdown for labor
  - Site labor cost is ~20% concrete, ~4% formwork, ~76% steel labor
- EEDB shows the breakdown of cost of structures in site labor, site materials, and factory equipment.
  - Site surface buildings (COA 21)
  - The turbine generator pedestal (COA 231)
  - Structures (COA 261)
- If self compacting concrete could provide the suggested savings to some or all concrete structures the resulting savings would be **~20-28 $/kWe or 1% of the target**

High Level Roll up of COAs

Code	Category	Cost Input Mechanisms
10s	Preconstruction Costs	Line-item adjustment multipliers
20s	Direct Construction Costs	Line-item adjustment multipliers
30s	Indirect Services Costs	Design standardization reduction factor and line-item adjustment multipliers
40s	Owner's Costs	Line-item adjustment multipliers
50s	Supplementary Costs	Line-item adjustment multipliers
60s	Financing During Construction	Construction duration for calculating interest
70s	O&M Costs	Line-item adjustment multipliers
80s	Fuel Costs	User-defined values (or defaults)
90s	Financing During Operation	Line-item adjustment multipliers

EIRP

Direct Cost Accounts

EEDB (EMWG)	Category
21	Structures and Improvements
22	Reactor Plant Equipment
23	Turbine Plant Equipment
24	Electric Plant Equipment
25 (26)	Main Condenser/Heat Rejection System
26 (25)	Miscellaneous Plant Equipment
27	Special Materials
28	Simulators

Indirect Cost Accounts

EEDB (EMWG)	Category
91 (36)	Construction Services
92 (34)	Engineering Home Office Services
93 (37)	Field Supervision and Field Office Services

EPRI Model for this Project

More Versatile for Identifying Cost Reduction Opportunities

	Conventional Code of Accounts (Gen IV Intl Forum/EEDB)	New Model
Includes detailed code of accounts for cost categories?	Yes	Yes
Includes build schedule and other time aspects?	No	Yes: Enables evaluation of innovations that compress schedule and reduce schedule overrun risk
Includes construction activities in sequence?	No	Yes: Aligns better with project planning process and simulates knock-on effects of delays early in project
Includes physical metrics underlying cost estimates?		
- Labor headcount	No	Yes: Shows labor needs for each activity and enables modeling of productivity improvements or labor innovations
- Labor wage rates	No: In DOE EEDB reports but not by COA	Yes: With flexible country data
- Labor man-hours	Yes: DOE EEDB has man-hours by COA	Yes: Labor headcounts x time for each activity
- Materials amounts and prices	No: In DOE EEDB reports but not by COA	Yes: Enables evaluation of innovations related to concrete and steel amounts and grades (nuclear vs. non-nuclear)
Includes modularization parameters and effects?	No	Yes: With default cost reduction estimates from GIF report
Includes risk?	No	Yes: Enables evaluation of innovations that mitigate cost or schedule risks

Detailed Direct and Indirect Cost Worksheet

- Derived from EMWG COA with EEDB Data (PWR12)
- Screenshot below is 20 of ~400 inputs

Summary of Code of Accounts PWR12•BE EEDB Phase IX

Base Year	1987
Current Year	2018
ENR Cost Multiplier	2.50
Gross Mwe	1144

	Two-Digit Code of Accounts (COA)						Three-Digit Code of Accounts		Unit Cost per kWe				
Direct Costs	EEDB	IAEA	EMWG	Scope	Purpose	Examples	EMWG	Scope COA	Factory Equipment	Site Labor Hours (man-hrs)	Site Labor Cost	Site Materials	Total Cost
	20		10	Preconstruction Activities	Secure rights and permission to construct the plant	• Land and land rights	10	Total Cost	$/kW	MH/kW	$5/kW	$/kW	$6/kW
						• Site permits			$/kW	MH/kW	$5/kW	$/kW	$6/kW
						• Plant licensing			$/kW	MH/kW	$/kW	$/kW	$/kW
						• Plant permits			$/kW	MH/kW	$/kW	$/kW	$/kW
						• Plant studies			$/kW	MH/kW	$/kW	$/kW	$/kW
						• Plant reports			$/kW	MH/kW	$/kW	$/kW	$/kW
							TOTAL		$/kW	MH/kW	$5/kW	$/kW	$6/kW
	21	21	21	Structures and Improvements	House and support equipment, components, piping, ducting, wiring, fire protection, MEP, personnel, access, habitability structures	• On-Site Surface Buildings	21	Total Cost	$49/kW	5 MH/kW	$248/kW	$141/kW	$438/kW
						• Subsurface Foundations	211	Yardwork	$1/kW	1 MH/kW	$32/kW	$22/kW	$55/kW
						• Tunnels	212	Reactor Containment	$31/kW	1 MH/kW	$78/kW	$33/kW	$141/kW
						• Site Improvements	213	Turbine Bldg and Heater Bay	$1/kW	MH/kW	$24/kW	$25/kW	$51/kW
						Clearing	214	Security Bldgs	$/kW	MH/kW	$2/kW	$1/kW	$3/kW
						Excavation	215	Prim Aux Bldg and Tunnels	$7/kW	MH/kW	$23/kW	$10/kW	$40/kW
						Grading	216	Waste Processing Building	$1/kW	MH/kW	$20/kW	$10/kW	$31/kW
						Roadways	217	Fuel Storage Building	$2/kW	MH/kW	$10/kW	$10/kW	$22/kW
						Rail Spurs	218A	Control Room/DG Bldg	$3/kW	MH/kW	$24/kW	$12/kW	$39/kW
						• Buildout/detailing	218B	Admin and Service Bldg	$2/kW	MH/kW	$7/kW	$5/kW	$15/kW
						• Does not include	218D	Fire Pump House	$/kW	MH/kW	$1/kW	$/kW	$1/kW
						Equipment Pedestals	218E	Emergency Feed Pump Bldg	$/kW	MH/kW	$4/kW	$2/kW	$5/kW
						Heat Reject Bldg	218F	Manway Tunnels (RCA)	$/kW	MH/kW	$1/kW	$/kW	$2/kW
							218G	Electrical Tunnels	$/kW	MH/kW	$/kW	$/kW	$/kW
							218H	Non-Essential Switchgear	$/kW	MH/kW	$1/kW	$/kW	$1/kW
							218J	Main Steam and FE Chases	$/kW	MH/kW	$12/kW	$6/kW	$17/kW
							218K	Pipe Tunnels	$/kW	MH/kW	$/kW	$/kW	$1/kW
							218L	Tech Support Center	$/kW	MH/kW	$1/kW	$1/kW	$2/kW
							218P	Equipment Hatch Missile Shield	$/kW	MH/kW	$/kW	$/kW	$/kW
							218S	Wastewater Treatment	$/kW	MH/kW	$1/kW	$1/kW	$2/kW
							218T	UHS Structure	$/kW	MH/kW	$7/kW	$3/kW	$10/kW
							218V	MCR Air Intake Structure	$/kW	MH/kW	$/kW	$/kW	$/kW

Cost Drivers Discussions

Direct Costs

- Materials and commodity costs
- Capital equipment costs
- Labor rates
- Workforce siting costs (per diems, etc.)
- Productivity

Indirect Costs

- Home office engineering costs
- Construction management and staff cost/size
- Indirect labor rates
- Workforce siting costs (per diems, etc.)

Project Preparation

- Design completion and Standardization
- Pre-construction rigorous integrated schedule
- Design for constructability
- Avoiding overdesign
- Use of project planning software tools

Project Implementation & Execution

- Managing change (engineering)
- Supply chain
- Non-domestic supply chain management
- Implementation of best construction practices
- Regulatory learning curves
- Change management
- Non-optimal construction practices

Technical Issues

- Design tolerances
- Backfill requirements
- Rebar placement
- Optimum use of modularization
- Transportation associated with modularization

Realization of Advanced Tech and Practices

- Modularization
- Construction practices

Example Opportunities

Opportunities

- Best construction practices
- Modularization
- Steel plate construction
- Advanced concrete
- Excavation/embedment technology
- Seismic isolation
- High performance materials
- Additive manufacturing
- Innovative external event shielding
- HYS rebar (or alternative rebar)

- Advanced concrete construction
- Effective implementation of digital I&C
- Advanced controls
- Data management and analytics
- Mobile and wearable devices
- Robotics
- Improved NDE for construction
- Safety class/safety boundary reclassification

- Commercial grade dedication streamlining
- Worker productivity tools
- Methods for improving/assuring NOAK benefits
- Advanced sensors for operations (reducing LCOE)

Context of Today's Cost-Driver Discussions

- NOAK ALWR plant assumed (discussion of NOAK/FOAK, learning curves later)
- Wide range of baselines from which to choose….
  - Mature standardized design market with established supply chain and order book
    - $2,500/kWe
  - Black & Veatch Study
    - $6,100/kWe
  - EEDB PWR12-BE adjusted to 2017
    - $5,500/kWe
  - EEDB PWR12-ME adjusted to 2017
    - >$10,000/kWe
  - ….others
- For this review, baseline OCC is $5500/kWe with target reduction to $3000/kWe
- Therefore, we are "looking for" $2500/kWe in this scenario (45% reduction)
  - Reduce "the bill" by this amount

Another Qualifier….

- Since we are looking at OCC and not LCOE in this presentation, schedule affects outcome here only to the extent it affects directs and indirects
  - Example: increased productivity which results in shorter schedule and therefore reduces direct labor costs and indirect costs
- Schedule will of course have major effect on final costs (LCOE, TCIC) due to interest during construction, financing models, regulatory environment, accounting rules, etc.
- Interest cost reductions could be comparable to the target reductions in OCC

Six Opportunity Categories

- 1. Direct Costs
- 2. Indirect Costs
- 3. Project Preparation
- 4. Project Implementation/Execution
- 5. Technical Issues
- 6. Realization of Advanced Technologies and Practices

1. Direct Cost Opportunity

- Opportunity (COAs 21-26) : $3500/kWe "bill"
  - 64% of OCC
  - Other studies site from 36 to 71% of OCC
- Why is this an opportunity?
  - Commodities and equipment costs increased 37% above inflation in period from 1979 to 1989 (DOE, 1988)
  - More recently, equipment costs increases averaged 11% per annum (Rothwell, 2016)
  - Commodities up by $500/kWe from 2007 to 2011 (Univ Chicago - EPIC, 2011)
  - Labor cost portion of directs (about 30-40% of OCC) represent up to $1,500/kWe opportunity
    - Consisting of wage rates, OH, G&A, profit, productivity, and work schedules
  - In Japan, in absence of inflation, labor cost effect on OCC rose 50% over period from 1996 to 2016
- How can we realize?
  - Reduce factory equipment costs (currently baselined at about $1000/kWe)
  - Standardization
  - Mature NQA and commercial parts supply chains
  - Redefine the safety/non safety boundary (although out of scope for today's discussion)
  - Increased productivity installation/construction
  - Realization of advanced construction practices
  - Modularization (for ALWRs, SMRS, and Advanced Designs)

2. Indirect Cost Opportunity

- Opportunity (COAs 91-93) : $2000/kWe "bill"
  - 36% of OCC (in this analysis)
  - Other studies site from 10 to >60% of OCC
  - Indirect Costs
    - Construction Services
    - Engineering and Home Office
    - Field Supervision and Field Office Support
- Why is this an opportunity?
  - Early nuclear deployment expectation was indirect costs would be only 10-30% of OCC
    - Particularly in a utility led build at non FOAK sites
  - Later EEDB evaluations estimated in excess of 50% of OCC at some plants (DOE, 1988)
  - Latest estimates (Ganda, 2018) up to 60% multiplier on directs or ~40% of OCC
  - In EPC contract approach, could be higher?
- How can we realize?
  - Design and build model (EPC, utility lead, AE with utility lead?)
  - Finalization of design (see next slide)

3. Project Preparation Opportunity

- Opportunity (effect on COAs 20s and 90s): $1000/kWe "bill" due to inadequate project preparation
  - Estimated effect of *design not being final*
    - 25% due to engineering and other labor (2 million man-hrs)
    - 25% due to material and equipment changes (estimate 25% bump in equipment cost)
    - 50% due to 2 year schedule increase (not IDC, but carrying indirects) (GIF, 2007)
  - 60% of difference between EEDB PWR12-ME and PWR12-BE
- Why is this an opportunity?
  - Plants have been built using essentially complete designs
  - Schedule improvements have been achieved at N-pack sites
    - Shin Kori 1: 72 months (OPR-1000)
    - Shin Kori 2: 64 months (OPR-1000)
    - Shin Kori 3: 54 months (APR-1400)
    - Shin Kori 4: 54 months (APR-1400)
- How can we realize this opportunity?
  - Multiple project needs ("85%" design finalization, experienced project management, supply chain, etc.)
  - Standardization? – perhaps with SMRs and Advanced Reactors leading this opportunity
  - Modularization

4. Project Implementation/Execution Opportunities

- Opportunity (affects direct and indirect labor costs): ~$1200/kWe "bill" (total labor)
  - Two example opportunities in implementation/execution
    - Schedule (and scheduling)
    - Productivity
  - Baseline schedule of 72 months (median from 1970 to 1995 was 80 months; 1996 to 2014 median 83 months)
    - Decreasing to 60 months decreases indirects about $230/kWe
    - This is in addition to saving in IDC
  - Productivity (based on ~12 Million MH/unit)
    - US baseline (reference) $0/kWe (baseline)
    - "Best experience" overseas $475/kWe lower cost
    - 20% improvement in best experience $600/kWe lower cost (50% savings theoretically)
- Why is this an opportunity?
  - Has been done in multiple regions and markets
- How can we realize this opportunity?
  - Training and tools (integrated schedules)
  - Realization of NOAK, N-pack and learning curve benefits
  - Reverse the "unlearning" trends of US builds in 1980's

Construction Practices

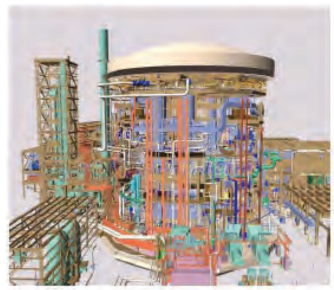
Kashiwazaki Kariwa-7 Supermodule

SP Reinforced Concrete

Automatic/HYS Welds

Open Top

Heavy Lift



Design

5. Technical Issues – Some Examples

- Opportunity (affects direct and indirect costs): Site specific
  - Perhaps $0/kWe to $200/kWe for a cumulative two year delay due to technical issues
  - In addition to IDC cost increase which would likely be much higher
- Why is this an opportunity?
  - It may be from an R&D perspective if generic technical issues identified
    - Siting could be one
  - May be most valuable as an opportunity for non-LWR advanced designs
    - Materials
    - Corrosion
    - NDE
    - Codes and standards support
    - Licensing support
- How can we realize this opportunity?
  - Identify gaps in non-LWR technologies that may be resolved with R&D

6. Realization of Advanced Technologies and Practices

- Opportunity (affects direct and indirect costs): $850/kWe
  - 15% of costs (NEA, 2000)
  - Significant (IAEA, 2011)
  - Numerous other citations
- Why is this an opportunity?
  - Benefits of implementation of advanced technologies and construction practices have been realized but probably above those assumed in PWR12-BE (the $5,500 baseline)
  - Example
    - Modularization benefit in ALWR may be only 1-4% (NEA, 2000) – but that could be significant in reduction of overall projects risk, enhanced quality, etc. (see Kang, IAEA, 2014)
    - Other studies for SMRs suggest >40% reduction (Moronati, 2018; Champlin 2018)
- How can we realize this opportunity?
  - Country specific
  - Design specific

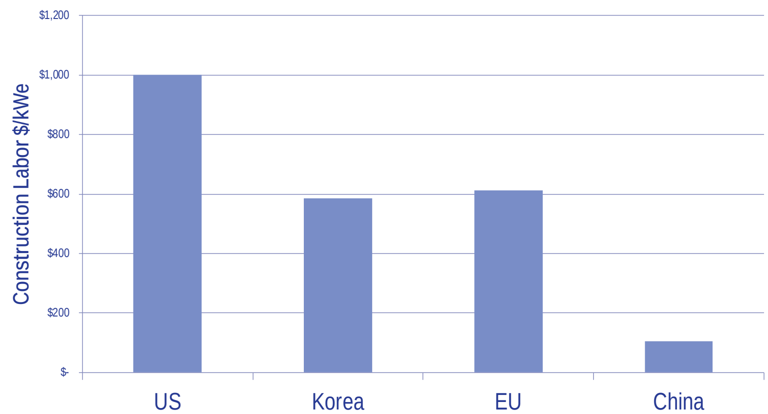
Example Savings for Five Cost Driver Opportunities

OCC	$5,500/kW
Schedule	72 months
Target Reduction	$2,500/kW

Number	Candidate Cost Driver	Total Cost/Impact (and therefore potential)	Target Reduction	Net Reduction in OCC (example)	Percent Goal	Cumulative Reduction
		OCC Baseline				
1	Direct Costs	$3,500/kW	15% reduction factory equipment $ 5% reduction in installation costs (example: modularization)	$220/kW	9%	9%
2	Indirect Costs	$2,000/kW	Reduce to 30% of OCC plus shortened schedule (60 months) (From 36%)	$530/kW	21%	30%
		Opportunity				
3	Project Preparation (Design Maturity)	$1,000/kW	50% reduction in impact of incomplete design	$500/kW	20%	50%
4	Project Execution (Project Labor)	$1,200/kW	Reduce schedule to 60 mos. Increase productivity 30%	$430/kW	17%	67%
5	Advanced Technologies	TBD	Reduce OCC by 5%	$275/kW	11%	78%

More Caveats....

- Remember the $5,500/kWe baseline already assumes utilization/benefits of advanced construction practices such as modularization
  - Extrapolated from EEDB PWR12-BE (about 4% above inflation from 1988 to 2017)
  - So 5% benefit of advanced technologies in previous slide is above and beyond this baseline
- Direct and Indirect costs are 15-35 % labor so this is very country specific



Wrap-Up

- EPRI Project is attempting to define benefits of R&D initiatives
- Target "goal" is 45% reduction in OCC
  - But incremental and cumulative progress should not be ignored
- So far, it is challenging in Western markets to predict achieving more than about 40% of goal with targeted reductions in direct and indirect costs for a given design/schedule
- Better opportunities may exist in project planning (e.g., design completion) and execution
- Another difficult question – can what is being achieved in country "X" be achieved in country "Y" in the next 5-10 years?
  - Supporting progress toward targets for new deployment by 2050

Together…Shaping the Future of Electricity

ELECTRIC POWER RESEARCH INSTITUTE

Workshop about Economics-Based R&D for Nuclear Power Construction

Open Discussion and Ideation

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Dominion Engineering

January 17-18, 2019

www.epri.com

Revision Date: 2018-01-04

Agenda (Morning / Afternoon)

Workshop about Economics-Based R&D for Nuclear Power Construction

Morning Session, January 17, 2019

Time	Topic	Lead
8:00 am	Registration and Breakfast	
8:30 am	1. Welcome and Introduction Review of ANT Program; Workshop overview and purpose	D. Scott, EPRI
9:00 am	2. Economic Perspective – US New reactor cost reduction	M. Nichol, NEI
9:30 am	3. MIT Study on Nuclear Power Cost The future of nuclear energy in a carbon-constrained world	E. Ingersoll, Lucid Catalyst
10:00 am	Break	
10:30 am	4. Economic Perspective – UK ETI Nuclear cost drivers project	E. Ingersoll, Lucid Catalyst
11:00 am	5. Analysis of US Historical Capital Costs The historical construction cost and cost drivers of nuclear power plants	F. Ganda, Argonne National Laboratories
11:30 am	6. Economic drivers, barriers, and impacts in the US Exploring role of advanced nuclear in future energy markets	A. Sowder, EPRI
12:00 pm	Lunch	

Workshop about Economics-Based R&D for Nuclear Power Construction

Afternoon Session, January 17, 2019

Time	Topic	Lead
1:00 pm	7. Economic Based R&D Roadmap Current findings from EPRI's R&D roadmap development	C. Marks, DEI
2:00 pm	8. Open Discussion – Cost Driver Category #1 Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
2:30 pm	9. Open Discussion – Cost Driver Category #2 Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
3:00 pm	Break	
3:30 pm	10. Open Discussion – Cost Driver Category #3 Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
4:00 pm	11. Open Discussion – Cost Driver Category #4 Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
4:30 pm	Adjourn	

Agenda (Morning)

Workshop about Economics-Based R&D for Nuclear Power Construction

Morning Session, January 18, 2019		
Time	Topic	Lead
8:00 am	Breakfast	
8:25 am	12. Recap	D. Scott, EPRI
8:30 am	13. Open Discussion – Cost Driver Category #5 Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
9:00 am	14. Open Discussion – Cost Driver Category #6 Participant input on current findings from the R&D roadmap development	Led by EPRI / DEI (attendee participation)
9:30 am	15. Roadmap Development for R&D Participant input on R&D multiyear plan	Led by EPRI / DEI (attendee participation)
10:00 am	Break	
10:30 am	16. Roadmap Development for R&D (continued) Participant input on R&D multiyear plan	Led by EPRI / DEI (attendee participation)
11:30 am	17. Advanced Reactor (AR) Construction Application of R&D roadmap and additional AR needs	Led by EPRI / DEI (attendee participation)
12:00 am	Lunch and Adjourn	

Cost Drivers (Ideas for solutions are in green)

- Design Optimization / Designing for Constructability (Need to be inexpensive and swift)
  - Design for cost minimization, constructability, maintainability, operability, inspection-ability (create a functional design)
  - Design change without affecting licensing basis
  - Increase the use of BIM to support design optimization
  - Increase the use of AI for bottom's up design
  - Design away accidents to eliminate components and decrease volume of materials
- Regulatory Requirements / Conservatisms Stack-ups / Design Requirements
  - Separate non-nuclear from license (e.g., turbine island)
  - Remove unnecessary conservatism by NRC (e.g., digital I&C, source term/LNT, seismic conservatism stack-up)
  - Rapid NRC decision/issue resolution
- Designing Around Civil / Structural
  - Determine the best use of modules (study accelerated bridge construction)
  - Increase appropriate use of factory fabrication
  - Increase appropriate use of steel-plate composites
  - Increase appropriate use of ultra high performing concrete and metals (including high strength reinforcement)
  - Increase appropriate use of seismic isolation

Cost Drivers (Ideas for solutions are in green) (continued)

- Inspection (QA/QC) Delays
  - Automate the inspection and qualification of concrete
  - Develop continual or near-real-time inspections of material and member placement (deployment can be through laser, drone, scanner, etc.)
  - Automate the development of as-built drawings / conditions
  - Increase appropriate use of sensors (including for concrete placement)
  - Increase appropriate use of automated monitoring/control
  - Increase appropriate use of advanced NDE (e.g., GPR, UT, other)
  - Develop rationale for fewer inspections
- Variations in Materials
  - High performance materials
  - Increase appropriate use of advanced manufacturing and welding
  - Develop smart formwork for concrete
  - Develop smart batch plant for concrete
  - Develop method to testing concrete prior to loading in truck

Cost Drivers (Ideas for solutions are in green) (continued)

- Incentivizing Stakeholders
  - If appropriate, increase small demos for vendor and supply chain
- Worker Productivity
  - Increase appropriate use of artificial intelligence (AI) and machine learning
  - Increase appropriate use of augmented reality
  - Incentivize personalized productivity
  - Address “swarm”
  - Improve training/qualification
  - Develop ways to automate construction
  - Link the use of a smart batch plant with in-situ work activities
- Paperwork Slowness / Alternatives
  - Digitize work packages
- Workforce Training (qualifications) – may be overlap with worker productivity
  - Inspector training (increased expertise)

Cost Drivers (Ideas for solutions are in green) (continued)

- Excessive Margin (risk-informed, performance based); (see Conservatisms Stack-up on slide 4)
  - RTNSS and move to 3 classes of safety (internationally accepted)
- Unknown Risks
  - Increase appropriate use of rapid prototyping (see military examples of use)
  - Increase appropriate use of BIM / modeling
  - Develop process / design change orders without impacting schedule
  - Address safeguards and security
  - Develop process for go/no-go components
  - Demos
- Supply chain / Specialized / Unique components / Difficulty with CGD process (Construction and Manufacturing groups are unable to buy off-the-shelf)
  - Utilize pre-existing supply chain
  - Reduce the amount of Q components, expand use of commercial grade dedication
  - Reduce barriers-of-entry for suppliers
- Non-severability of Design Features

Cost Drivers (Ideas for solutions are in green) (continued)

- Code Committee Slowness
  - Risk-informed guidance on use of code in-lieu of rulemaking
  - Incentivize resources (volunteer) to develop standards
  - Increase collaboration among multiple code committees
  - Improve pathway for NRC (or other regulator) acceptance without waiting for code case

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