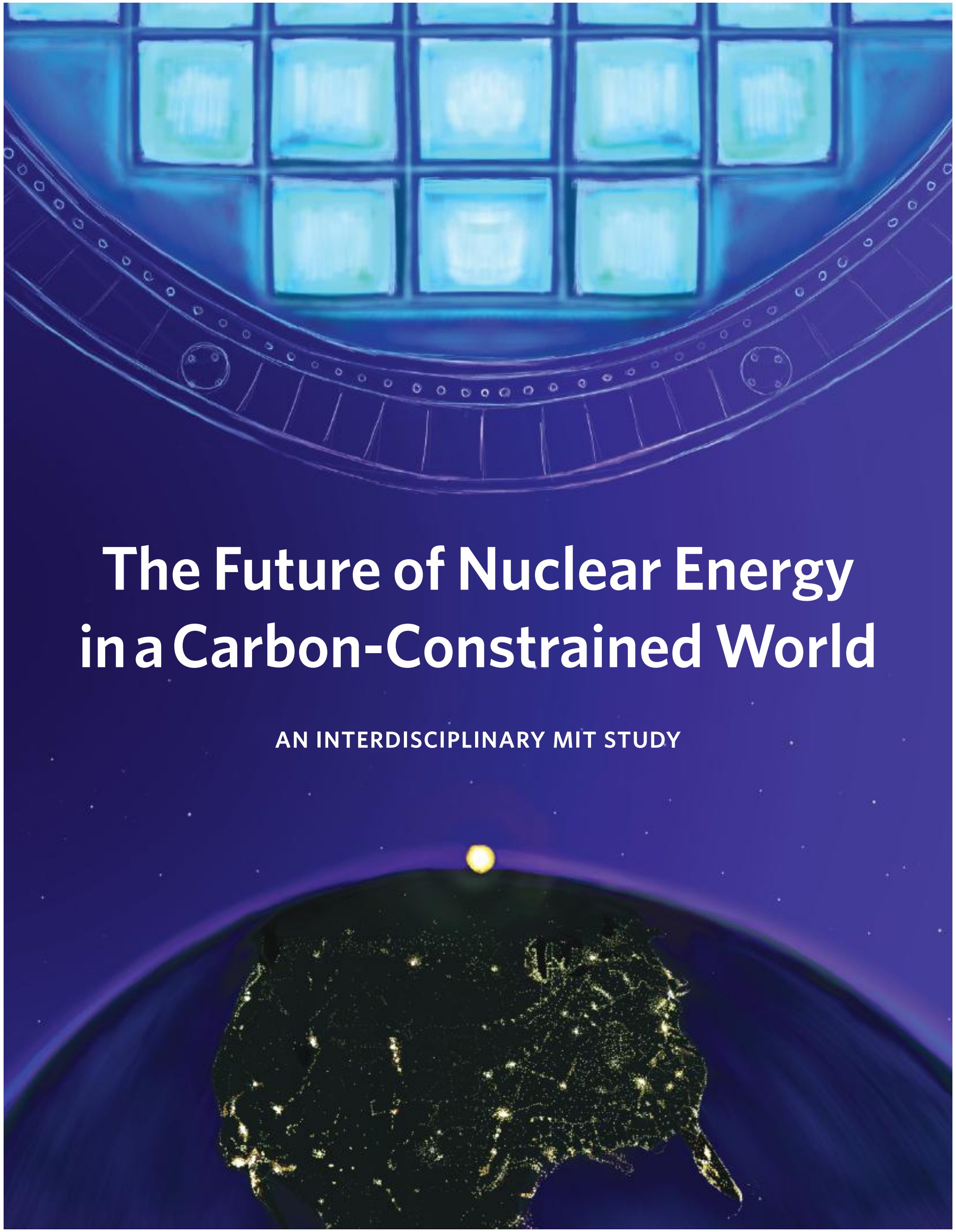


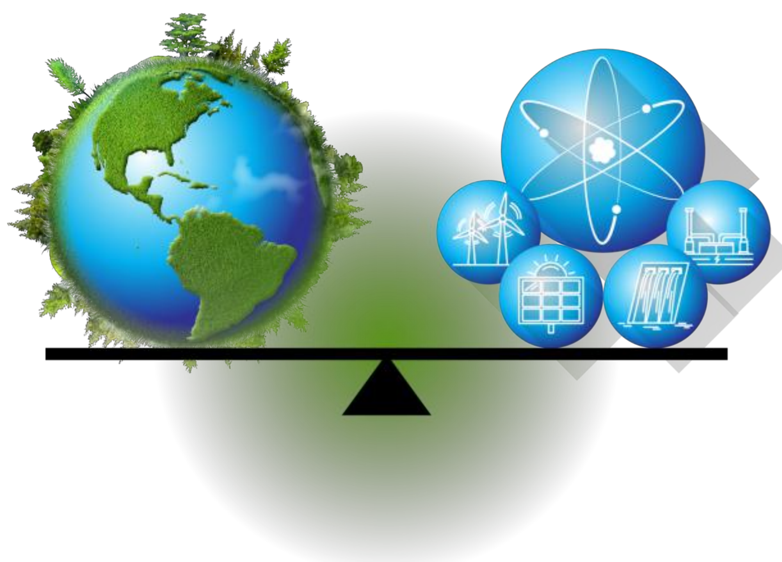
MIT Energy Initiative

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

Hard copies of the Executive Summary available in the room

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



Study Team

Executive Director
Dr. David Petti (INL)

Co-Director
Prof. Jacopo Buongiorno (MIT)

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

Co-Director
Dr. John Parsons (MIT)

Team Members: Faculty, Students and Outside Experts

Prof. Joe Lassiter (Harvard)

Prof. Richard Lester (MIT)

Prof. Jessika Trancik (MIT)

Dr. Charles Forsberg (MIT)

Prof. Dennis Whyte (MIT)

Dr. James McNerney (MIT)

Jessica Lovering (Breakthrough Institute)

Dr. Robert Varrin (Dominion Engineering)

Eric Ingersoll (Energy Options Network)

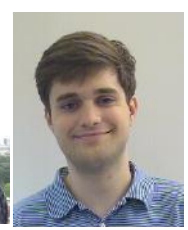
Andrew Foss (Energy Options Network)

Ka-Yen Yau (MIT student)

Amy Umaretiya (MIT student)

Rasheed Auguste (MIT student)

Lucas Rush (MIT student)



Patrick Champlin (MIT student)

Patrick White (MIT student)

Karen Dawson (MIT student)

Magdalena Klemun (MIT student)

Nestor Sepulveda (MIT student)

Advisory Board

Name	Title	Background
Philip Sharp (Chair)	President, Resources for the Future; former US Congressman; Professor Emeritus, Harvard University	Government, energy policy
Kathryn McCarthy	Vice President for Research and Development, Canadian National Laboratories	Nuclear technology
Richard Meserve	President Emeritus, Carnegie Institution for Science; Head Emeritus, NRC	Nuclear regulations, science
William Magwood	Director, Nuclear Energy Agency; Commissioner Emeritus, NRC; Director Emeritus, DOE-NE	Nuclear technology, regulations, government, international dimension
Bernard Salha	Sr. Executive VP & President of EDF R&D	Nuclear technology and R&D
Robert Budnitz	Project Scientist, Lawrence Berkeley National Laboratory	Nuclear waste and regulations
Dirk Smit	Vice President Exploration Technology, Chief Scientist Geophysics, Shell	Energy markets and fuels
Zach Pate	CEO and Chairman Emeritus, INPO and WANO; former US Navy submarine commander	NPP operations, industry oversight, Navy experience
Susan Landahl	Sr. VP, Exelon Corporation	NPP operations/industry
Jean-Pierre Benque	President Emeritus, EDF Development Inc. and EDF North America	International nuclear industry and energy markets
Edward Steinfeld	Professor of China Studies, Brown University	China energy markets
John Deutch	Institute Professor, MIT; Director Emeritus, CIA	Non-proliferation, government
Marvin Fertel	Ex-President and Chief Executive Officer, Nuclear Energy Institute	Nuclear industry, government
Michael Shellenberger	Founder and President, Environmental Progress	Environmental perspective
Akira Omoto	Professor, Tokyo Institute of Technology and Advisor to Nuclear Risk Research, ex-Director, Division of Nuclear Power, IAEA	Nuclear safety, Japan perspective
James Del Favero	Head, Cross-border M&A, Goldman Sachs	Finances

Acknowledgements

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Alfred P. Sloan Foundation 1934

EDF

the David & Lucile Packard Foundation

General Atomics

Neil Rasmussen

James Del Favero

Zach Pate

Anthropocene Institute

and in-kind contributions from

INL Idaho National Laboratory

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.

Dissemination

Report Online Release: Sep 3, 2018
Executive summary translated in French, Japanese and Chinese

Rollout Events
London (Sep 2018)
Paris (Sep 2018)
Brussels (Sep 2018)
Washington DC (Sep 2018)
Tokyo (Oct 2018)
South Korea/China (Jan 2019)

46 presentations at universities, industry organizations, government, conferences, research labs
BEIS UK June 2017 (JB), ICAPP Plenary 2018 (JB), CEA Oct 2017 (JB), RMIT Jan 2017 (JB), Yale Univ. Mar 2018 (JB), Imperial College, June 2017 (JB), Zhejiang Univ. Sep 2017 (JB), Curtin Univ. Jan 2017 (JB), TAMU, Oct 2017 (JB), U-Houston, Oct 2017 (JB), Harvard Univ. HBS, Nov 2017 (JB), Harvard Belfer Center, June 2018 (JB), National Univ Singapore (NUS) Jan 2018 (JB), EPRI (Engineering, Procurement, and Construction Workshop), Nov 2017 (JB), Royal Acad. Eng. Nov 2017 (JB), Nuclear Insider SMR Summit, Apr 2017 (JB), MITEI Advisory Board Oct 2017 (JB, Parsons), Forum of India's Nuclear Industry, Jan 2018 (JB), Canadian Nuclear Society, Nov 2018 (JB), MIT Alumni Association of New Hampshire, Jun 2018 (JB), 49th Annual Meeting on Nuclear Technology, Berlin, May 2018 (JB), U-Edinburgh Aug 2018 (JB), Duke Energy Aug 2018 (JB), NSE May 2018 (JB, Petti, Parsons), Golay Fest, Mar 2018 (JB, Petti), Nuclear Bootcamp at UCB, July 2018 (Corradini), GA visit to MIT April 2018 (all), Armstrong and Moniz August 2017 (all), ANS Orlando, Nov 2018 (Corradini), Mark Peters INL Lab Director, June 2017 (Petti), JASONs June 2017 (Petti, Parsons, Corradini), Wisconsin Energy Institute (MLC), Mar 2018 (Corradini), CNL, Oct 2017 (Petti), CSIS, Sept 2017 (Petti), DoE Dep Sec and Chief of Staff and NE-1, Jan 2018 (Petti, Parsons, Corradini), NRC, Sep 2018 (Corradini), NEI, Sep 2018 (Corradini), EPRI/NEI roadmapping meeting, Feb 2018 (Petti), INL, March 2018 (Petti), Gain Workshop, March 2018 (Petti), Golay Workshop, March 2018 (Petti), WNA, September 2018 (Petti), NENE Slovenia, September 2018 (Petti), PBNC SF, September 2018 (Petti), Zurich, December 2018 (Petti), Undersecretary of Energy – Science P. Dabbar, Aug 2018 (JB)

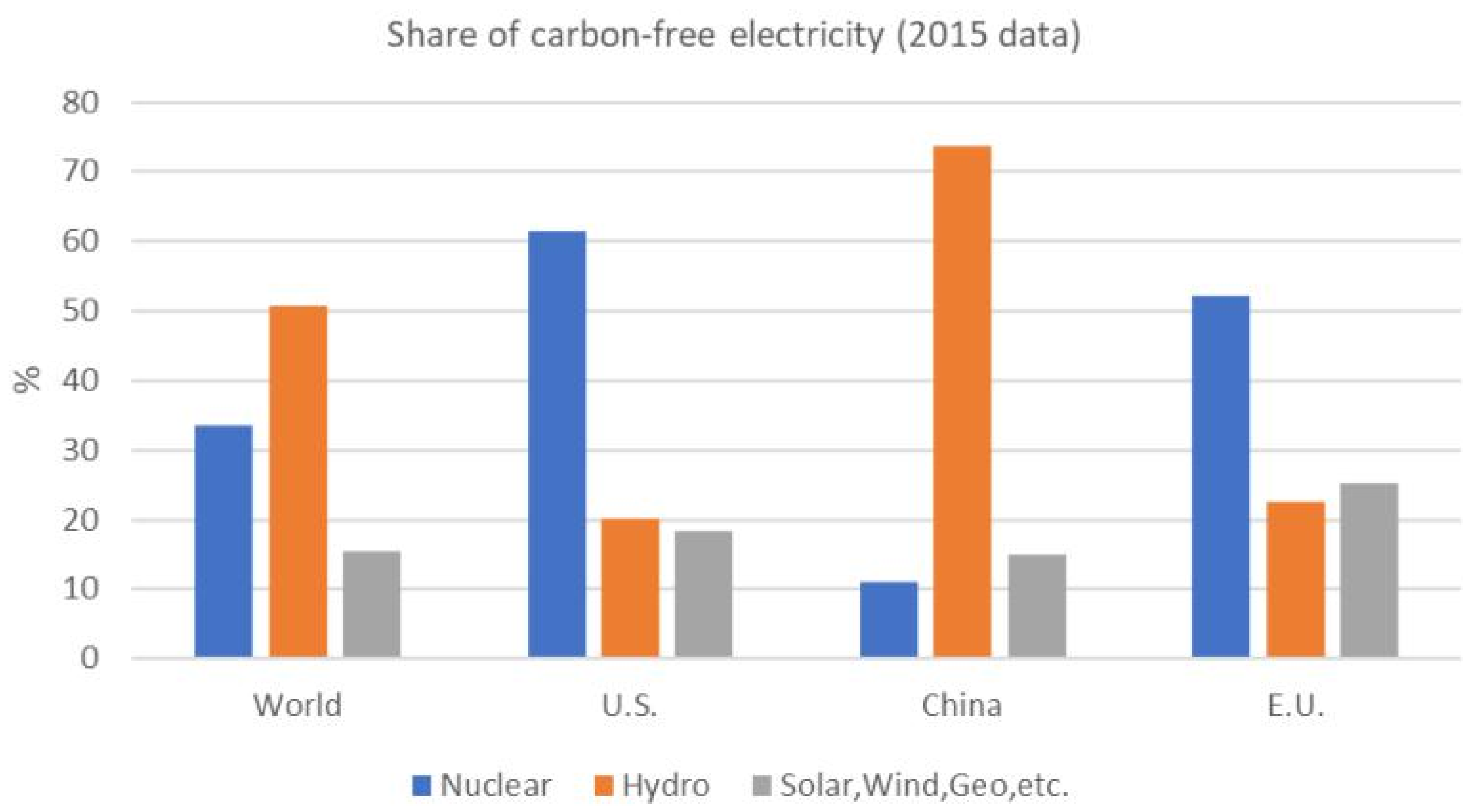
Key Questions Analyzed in the MIT Study

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?

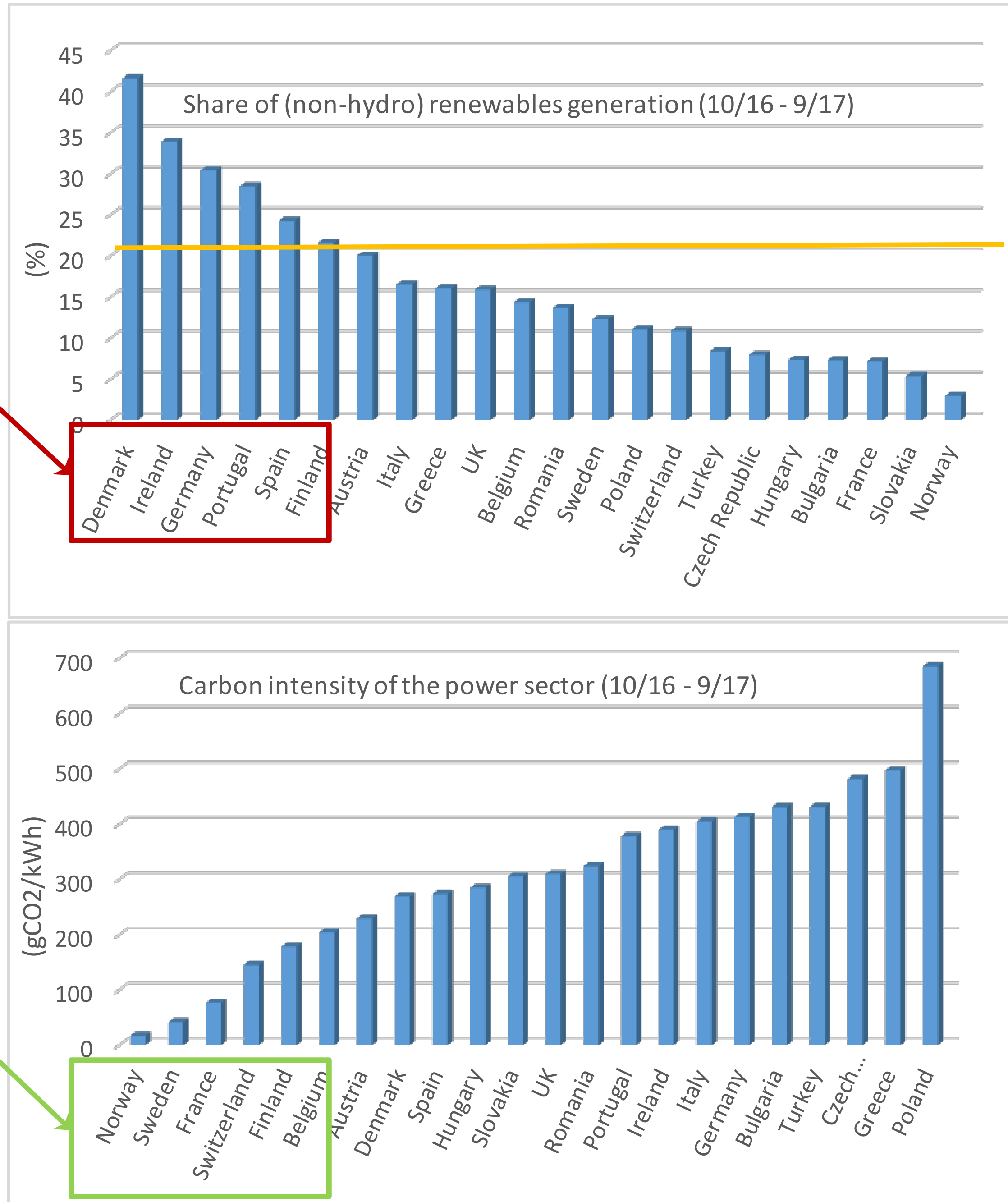
Do we need nuclear to decarbonize the power sector?

Nuclear is the largest source of emission-free electricity in the US and Europe



EU countries with high capacity of solar and wind

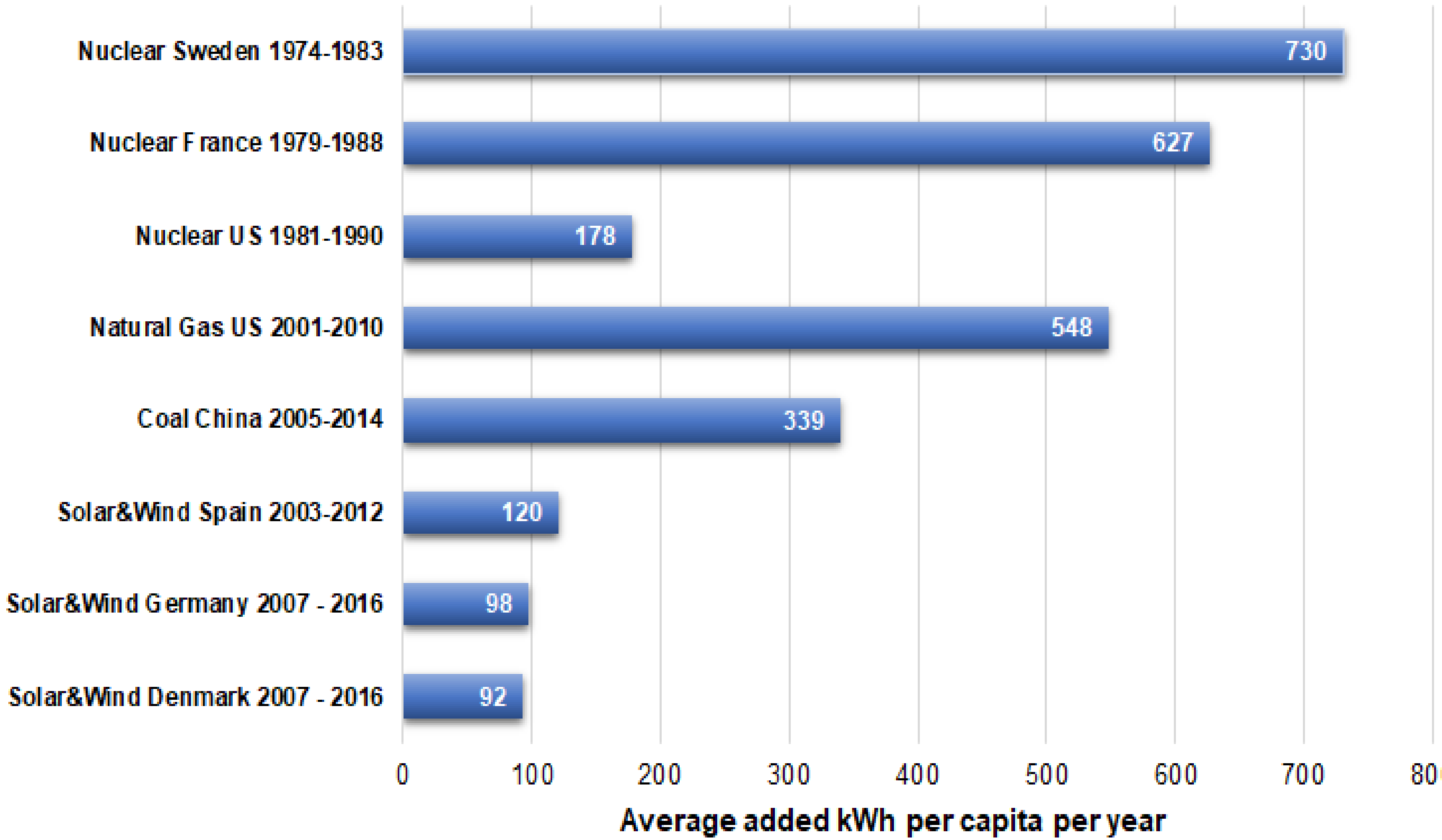
EU countries with low carbon intensity



Data source: European Climate Leadership report 2017 (Energy for Humanity, Tomorrow, the Electricity Map Database)

Low carbon intensity in the EU power sector correlates with nuclear and hydro

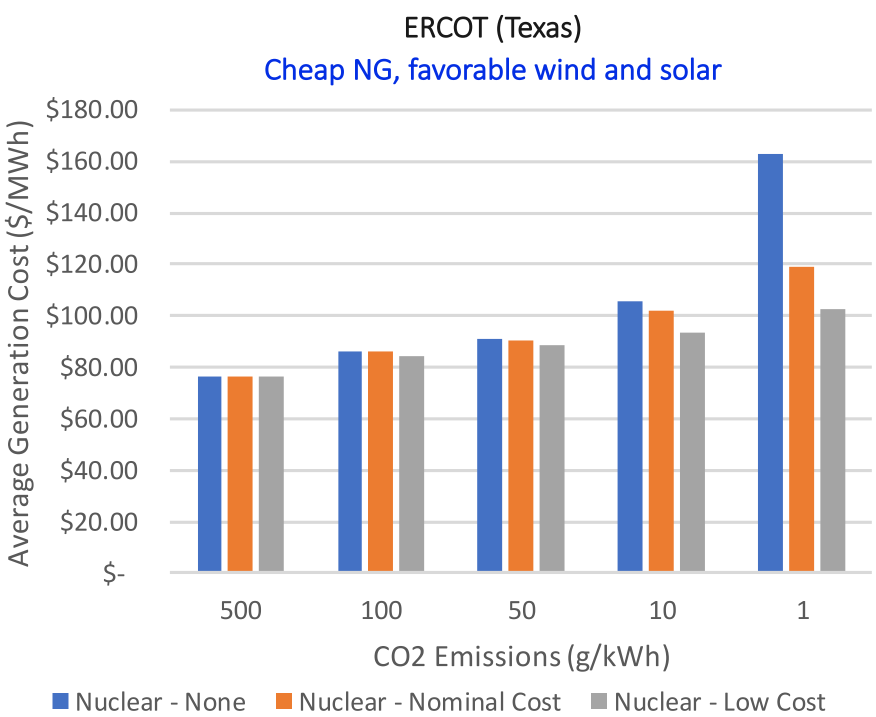
The scalability argument

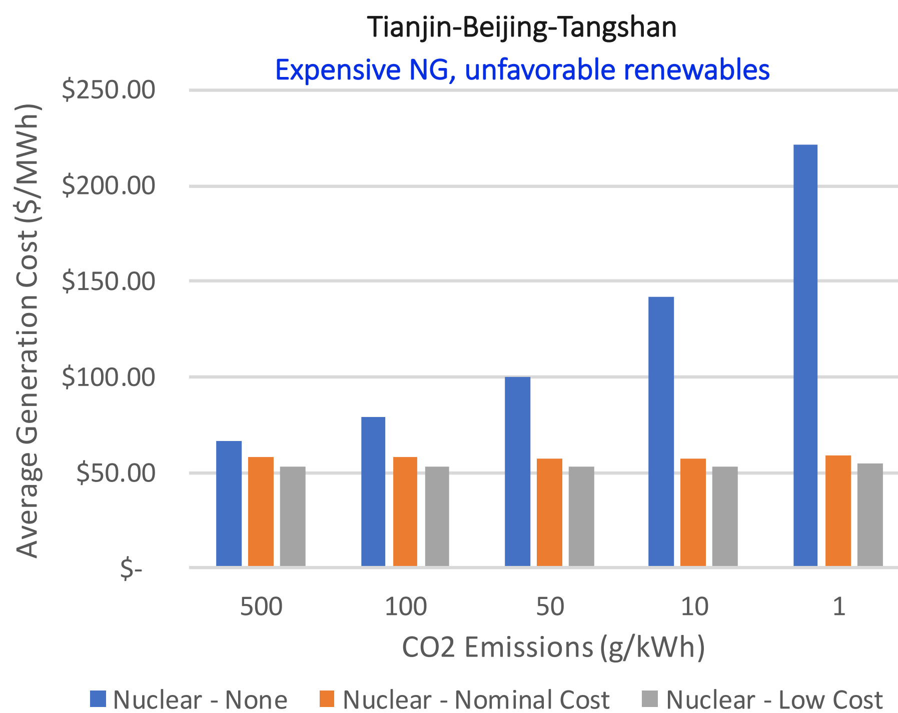


Nuclear electricity can be deployed as quickly as coal and gas at a time of need

The economic argument

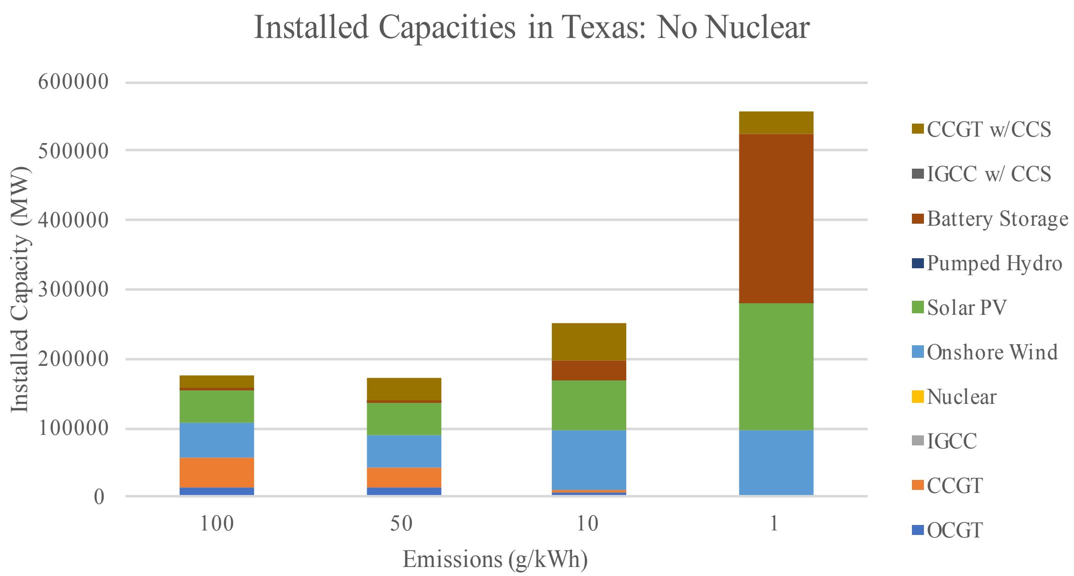
Excluding nuclear energy drives up the average cost of electricity in low-carbon scenarios





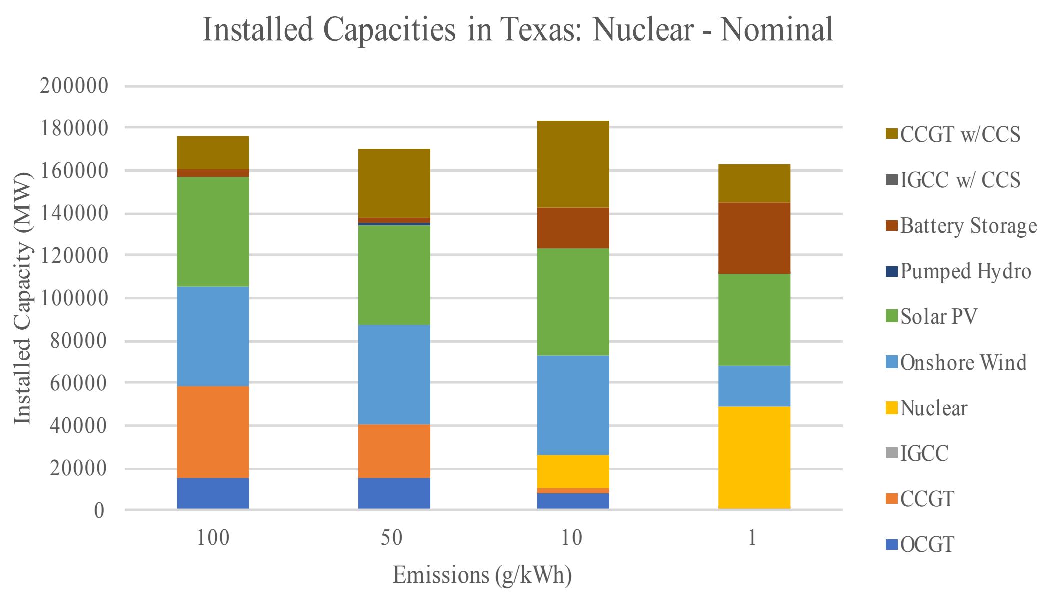
Simulation of optimal generation mix in power markets
MIT tool: hourly electricity demand + hourly weather patterns + capital, O&M and fuel costs of power plants, backup and storage + ramp up rates

Texas (ERCOT) Results

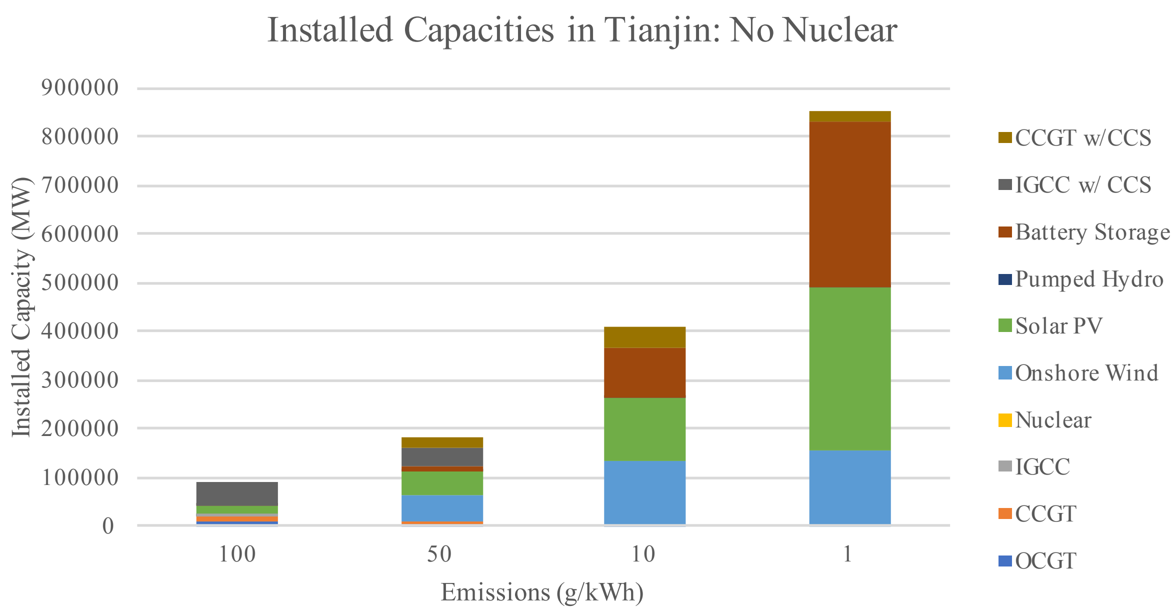


To meet constraint w/o nuclear requires major build-out of renewables

By contrast, installed capacity is relatively constant with nuclear allowed



Tianjin-Beijing-Tangshan Results



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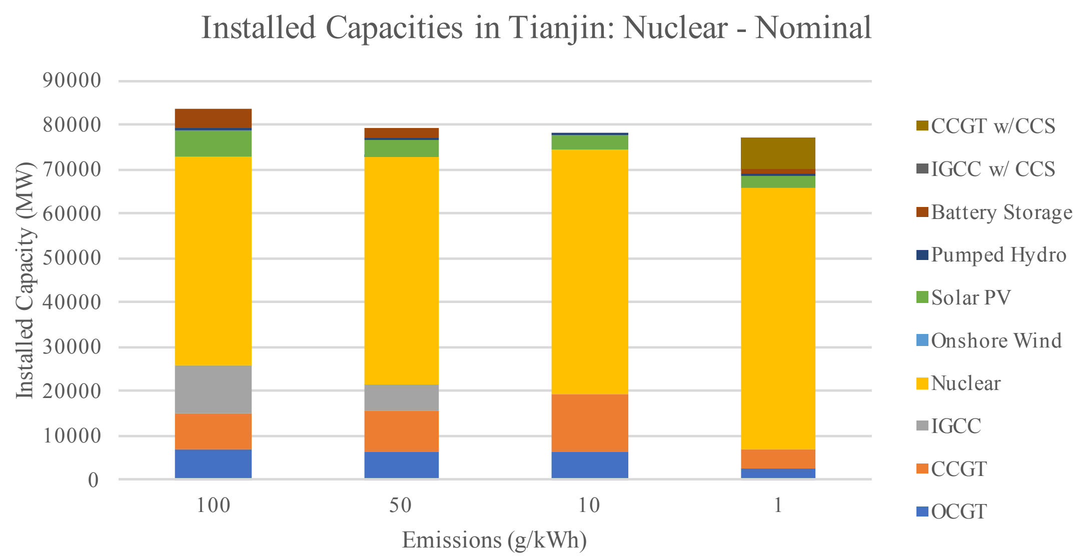
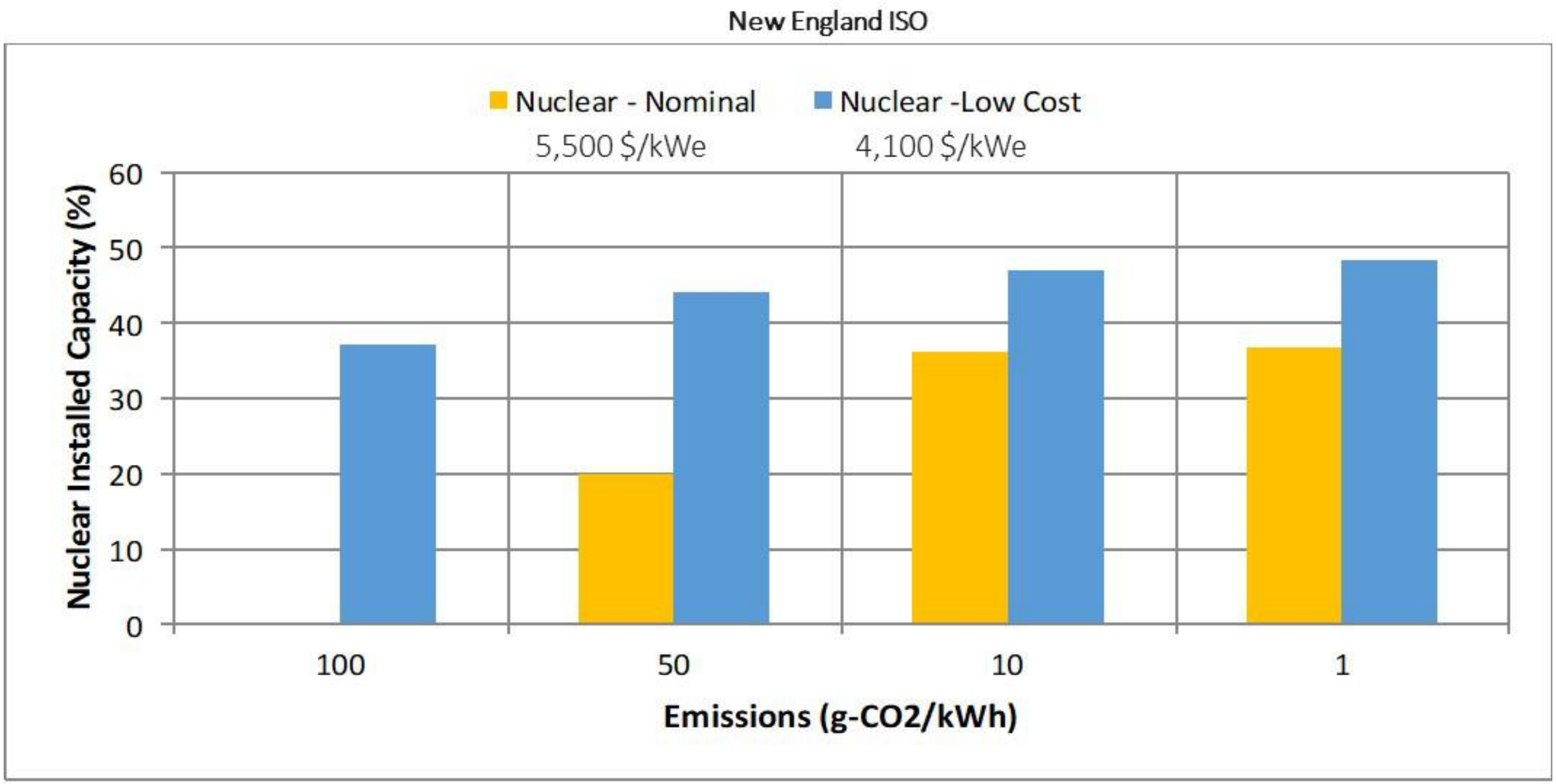


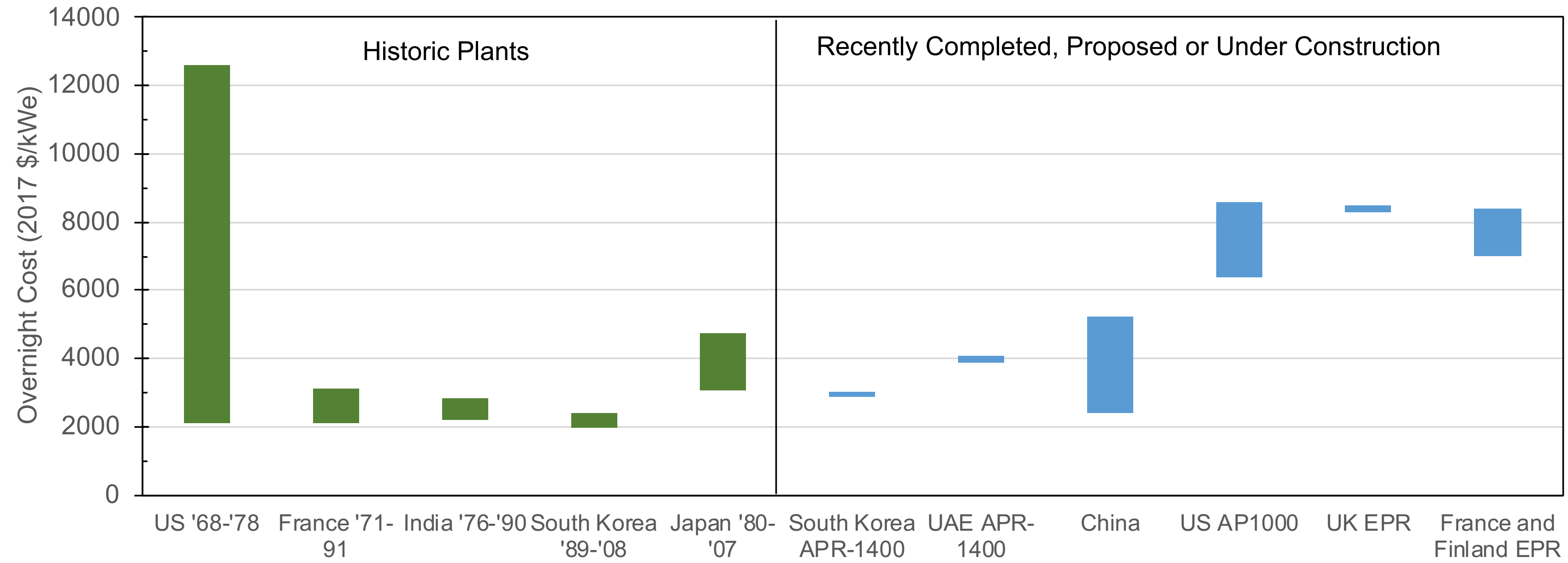
Capital cost of nuclear matters!



Markets expand dramatically for nuclear even at modest decarbonization targets, if its cost decreases

The cost issue

Nuclear Plant Cost

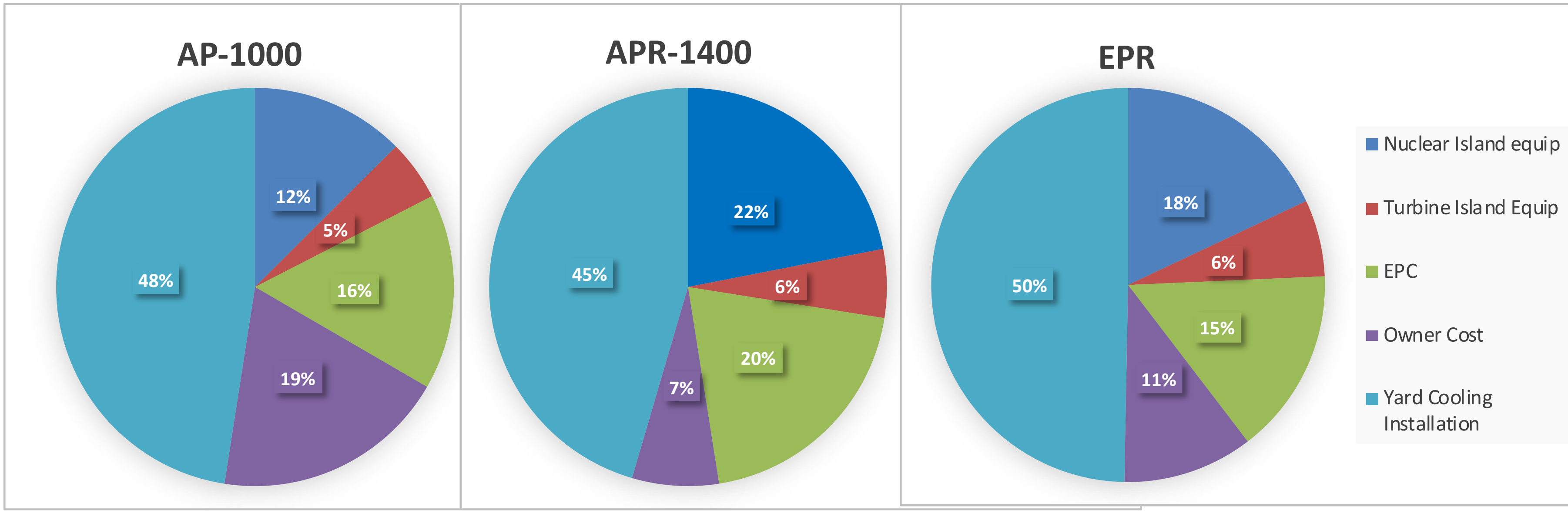


An increased focus on using proven project/construction management practices will increase the probability of success in execution and delivery of new nuclear power plants

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

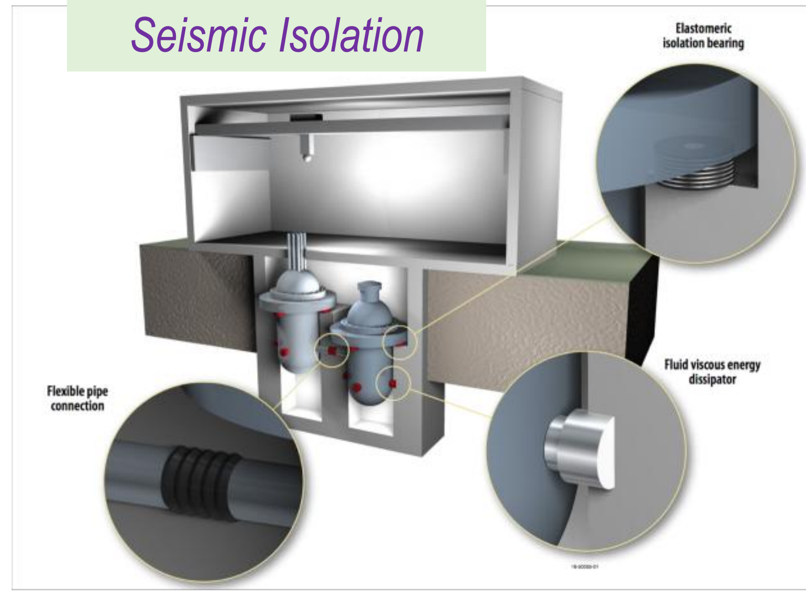
Civil works, site preparation, installation and indirect costs (engineering oversight and owner's costs) dominate

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

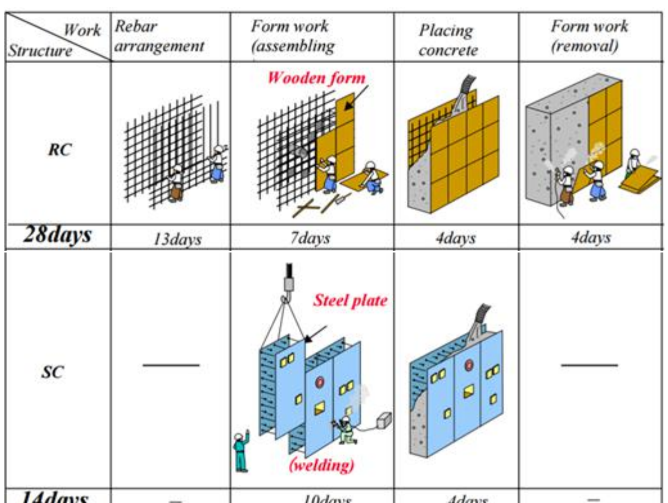
(True for all plants and all technologies. Without these, the inherent technological features will NOT produce the level of cost reduction necessary)

Standardization on multi-unit sites

Seismic Isolation



Advanced Concrete Solutions

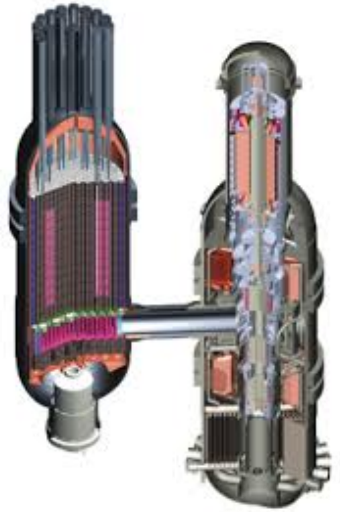


Modular Construction Techniques and Factory Fabrication

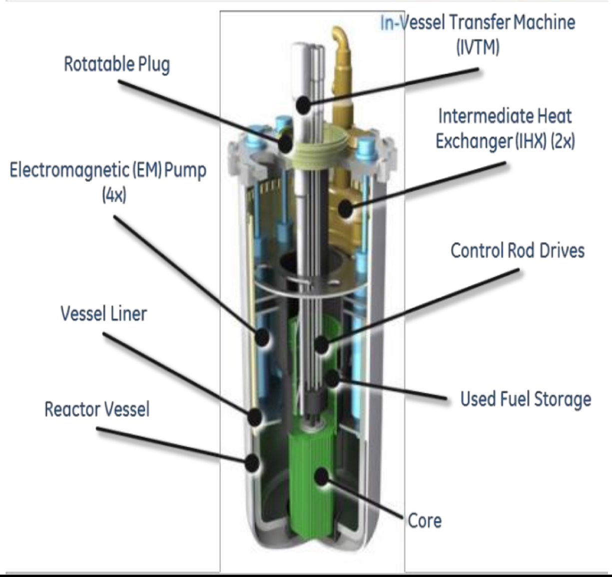
Advanced reactors

Advanced Reactors (Generation-IV)

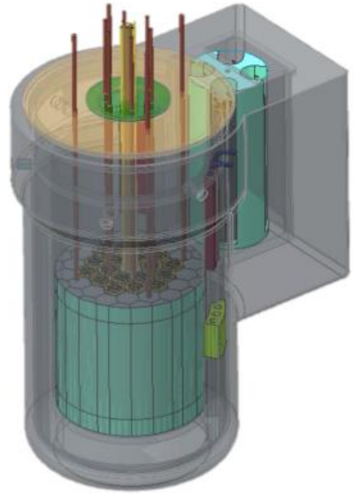
High Temperature Gas-Cooled Reactors



Sodium Fast Reactors

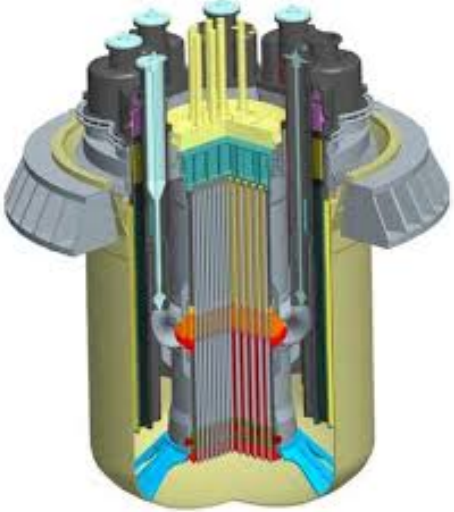


Fluoride High Temperature Reactors

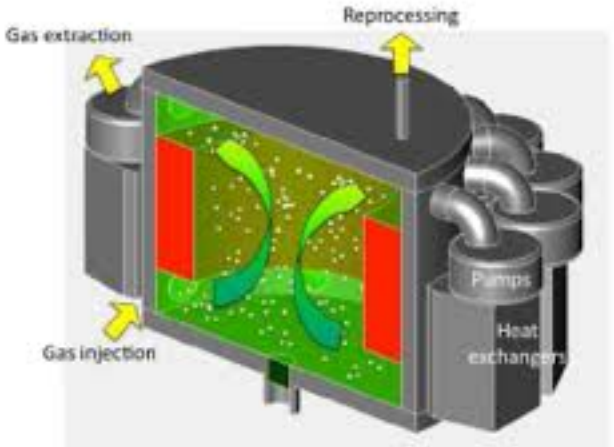


Gas-Cooled Fast Reactors

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.

What is the value proposition for advanced reactors? (2)

There exists a small (but not insignificant) potential market for nuclear heat

	300 MW_{th} Reactor		150 MW_{th} Reactor	
Industry	U.S. Capacity (MW_{th} Installed) (%)	Global Capacity (MW_{th} Installed) (%)	U.S. Capacity (MW_{th} Installed) (%)	Worldwide Capacity (MW_{th} Installed) (%)
Co-Generation Facilities	82,800 (61.7%)	340,800 (59.8%)	86,250 (57.5%)	355,050 (55.7%)
Refineries	15,600 (10.4%)	76,800 (12.1%)	17,250 (11.5%)	84,750 (13.3%)
Chemicals	7,800 (5.2%)	36,600 (5.7%)	7,050 (4.7%)	34,200 (5.4%)
Minerals	2,100 (1.4%)	8,700 (1.4%)	2,100 (1.4%)	8,700 (1.4%)
Pulp and Paper	12,600 (8.4%)	51,900 (8.1%)	21,300 (14.2%)	87,750 (13.8%)
Other	13,200 (8.8%)	55,200 (8.7%)	16,050 (10.7%)	66,450 (10.4%)
Total	**134,100 (100%)**	**570,000 (100%)**	**150,000 (100%)**	**636,900 (100%)**

Methodology:

- EPA database for US sites emitting 25,000 ton-CO_2/year or more
- Site must need at least 150 MW_{th} of heat
- Nuclear heat delivered at max 650°C (with HTGR technology)
- At least 2 reactors per site for assured reliability
- Heat from waste stream not accessible
- Costs not evaluated

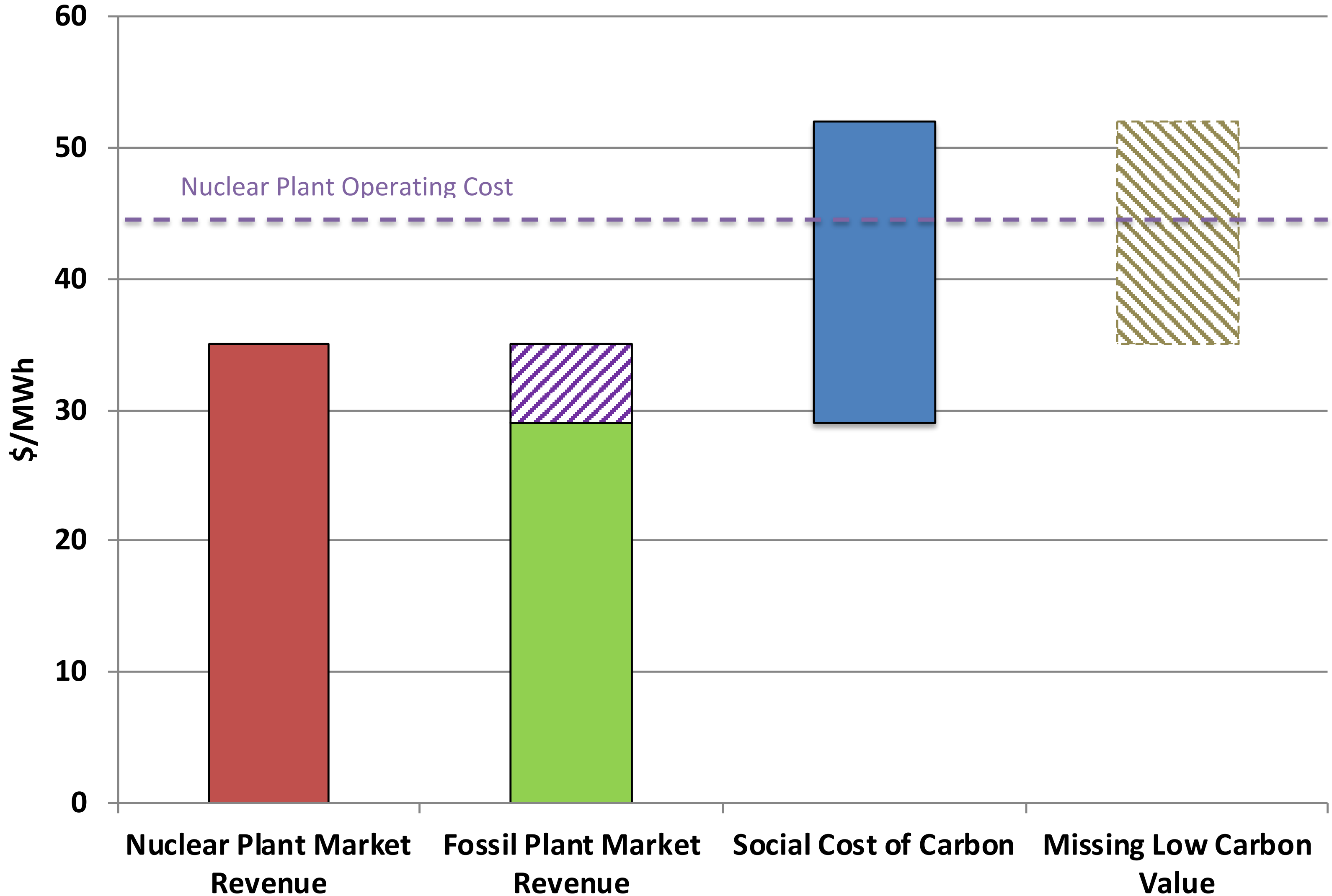
Government role

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



Global Nuclear Market

- Growth in electricity demand is primarily in the non-OECD.

- Plenty of choice of vendors.
  - Korea has been successful.
  - Russia is extremely active globally.
  - China has built a domestic foundation to become an exporter.

- US success as a nuclear innovator must be won in this new context.

New Reactor Designs

Electricity sector remains the major energy product

- Bigger than ever on a global scale, and
- with electrification of transportation and other energy services in the offing

Cost is the driver

- That means cutting the capital cost of the entire plant.
- $5,500 overnight is only competitive when carbon constraints are very tight
- $2,000 overnight is required without carbon constraints

How can the government help to deploy new nuclear technologies?

Improve the design of competitive electricity markets

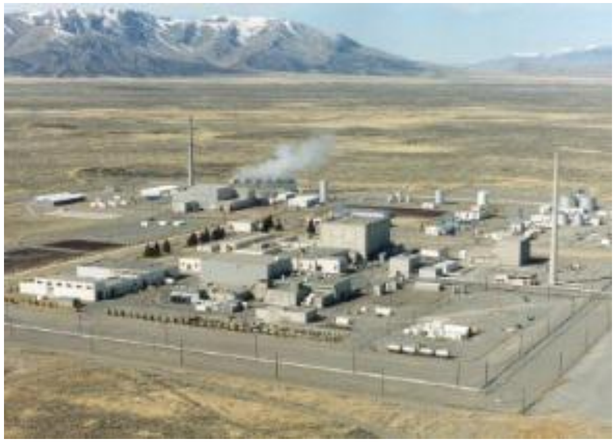
- Decarbonization policies should create a level playing field that allows all low-carbon generation technologies to compete on their merits.
- Ensure technology neutrality in capacity markets
- Enable investors to earn a profit based on full value of their product (include reducing CO_2 emissions)
- 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.

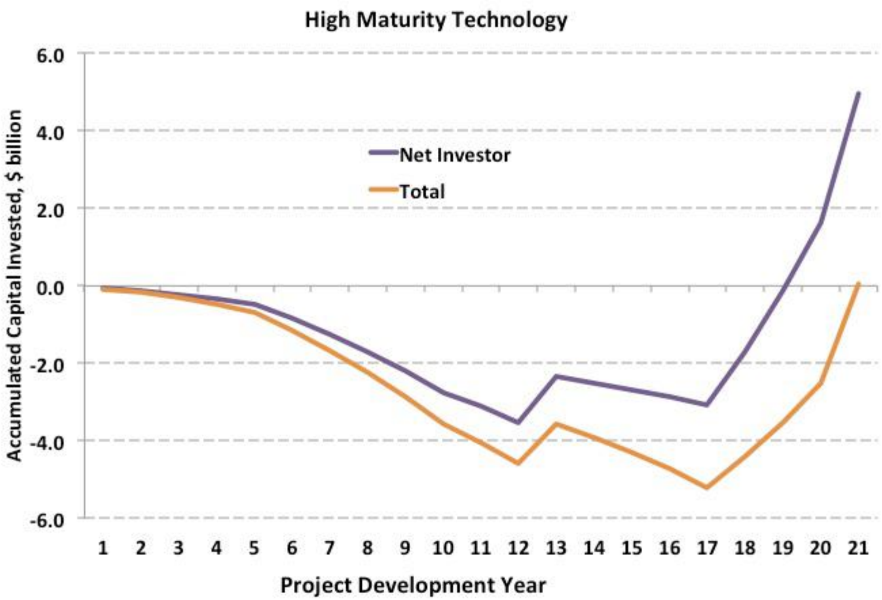
- Government provides site security, cooling, oversight, PIE facilities, etc.
- Government provides targeted objectives, e.g. production of low-cost power or industrial heat, for which it is willing to provide production payments as an incentive

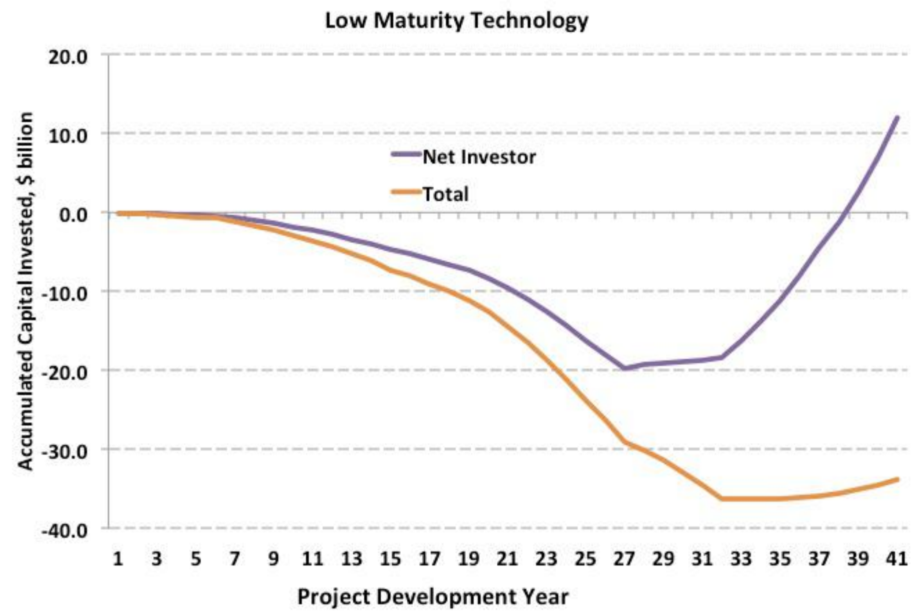


- Government takes responsibility for waste disposal
- Companies using the sites pay appropriate fees for site use and common site services
- Supply high assay LEU and other specialized fuels to enable tests of advanced reactors

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)



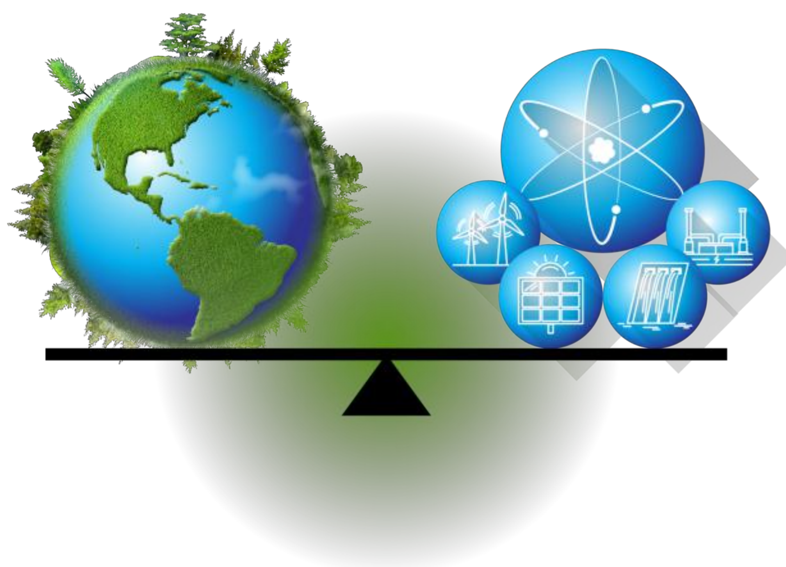


Early government support helps. Four “levers”:

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



Backup slides

Why a new study

BBC
Switzerland votes to phase out nuclear power

FINANCIAL TIMES
Cheap gas has hurt coal and nuclear plants, says US grid study

REUTERS
South Korea's president says will continue phasing out nuclear power

THE BLADE
News • Sports • A&E • Business • Opinion • Jobs
Davis-Besse nuclear power plant to shut down permanently in 2020

The State
SCANA leaves failed nuclear project to rot, upsetting some who want it finished

NEW YORK POST
More problems with closing Indian Point

The Telegraph
Hinkley Point's cost to consumers surges to £50bn

Los Angeles Times
Regulators vote to shut down Diablo Canyon

REUTERS
France will need to close nuclear reactors: minister

The Washington Post
San Onofre nuclear power plant to shut down

The New York Times
Westinghouse Files for Bankruptcy, in Blow to Nuclear Power

The nuclear industry is facing an existential crisis (especially in the U.S. and Europe)

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Competitive pressure from cheap natural gas

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Political factors

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The New York Times
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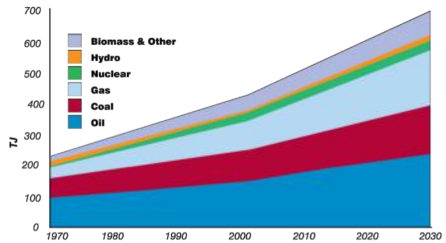
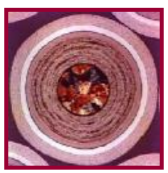
The nuclear industry is facing an existential crisis

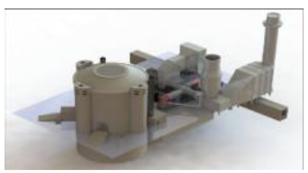
Self-inflicted wounds

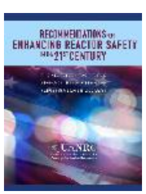
(especially in the U.S. and Europe)

Five Major Themes









1. Opportunities

2. Cost

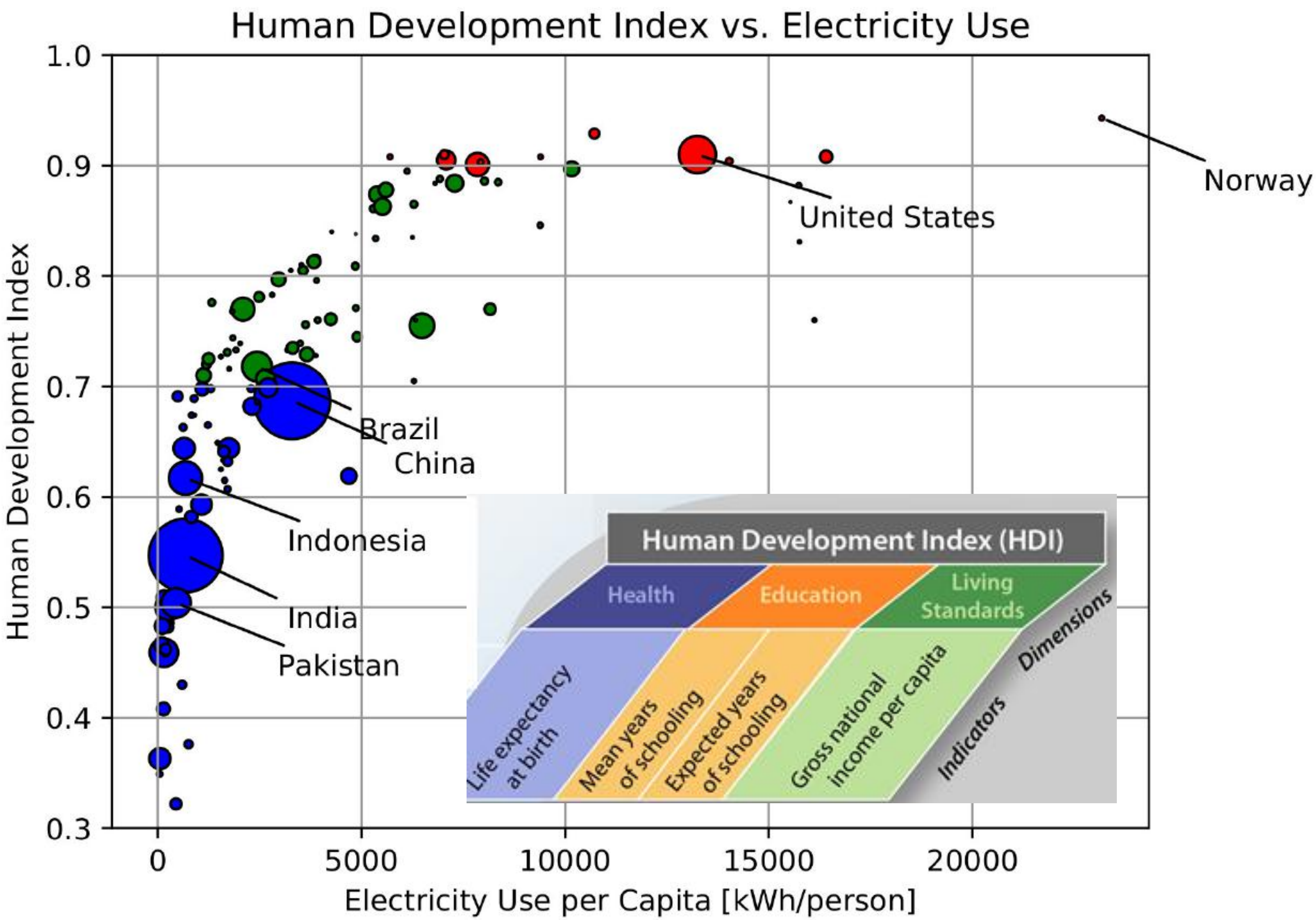
3. Advanced Reactor Evaluation

4. Policy and Business Models

5. Regulatory Assessment

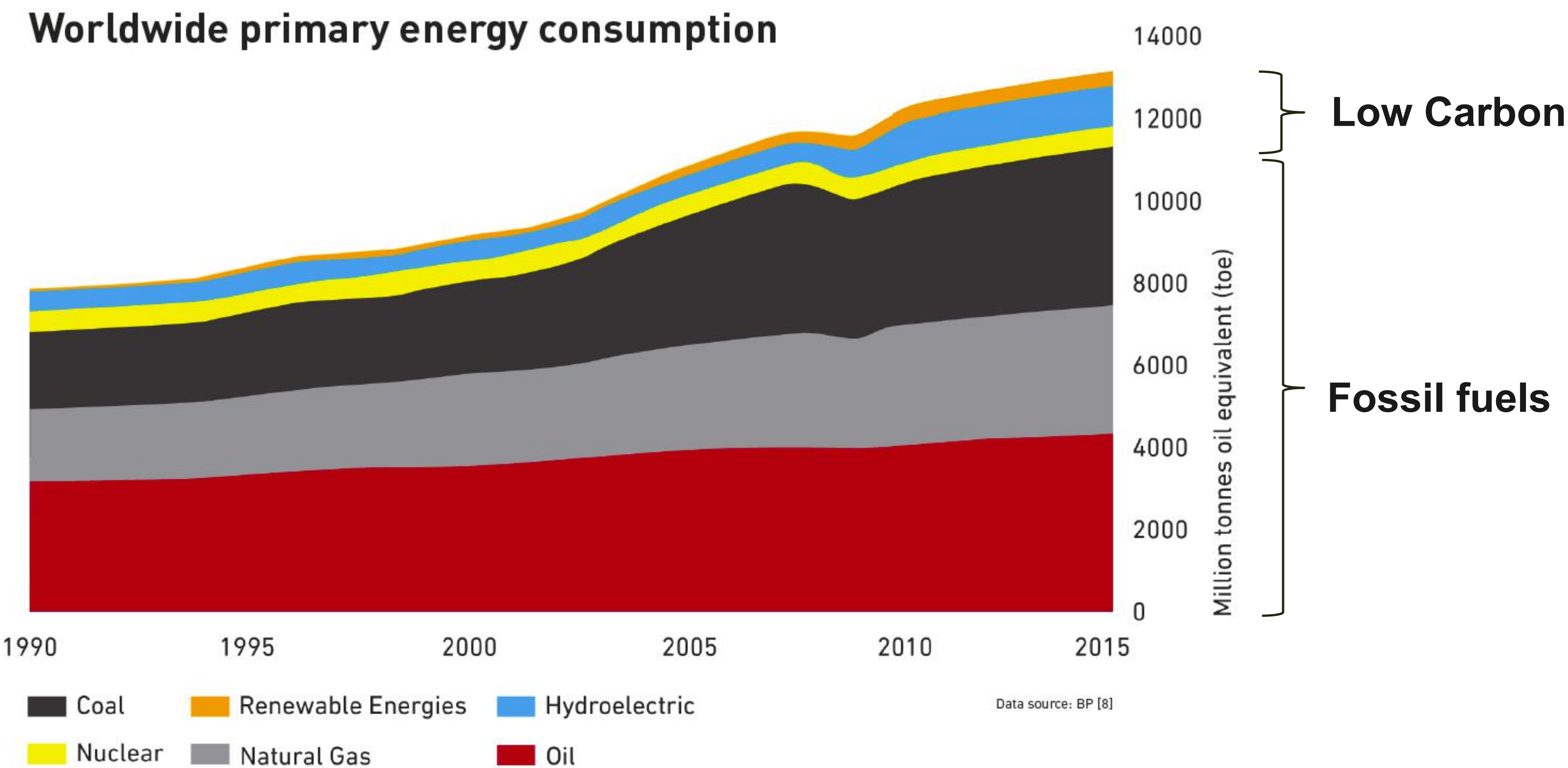
The big picture

The World needs a lot more energy



The World electricity consumption is projected to grow 45% by 2040

The key dilemma is how to increase energy generation while limiting global warming

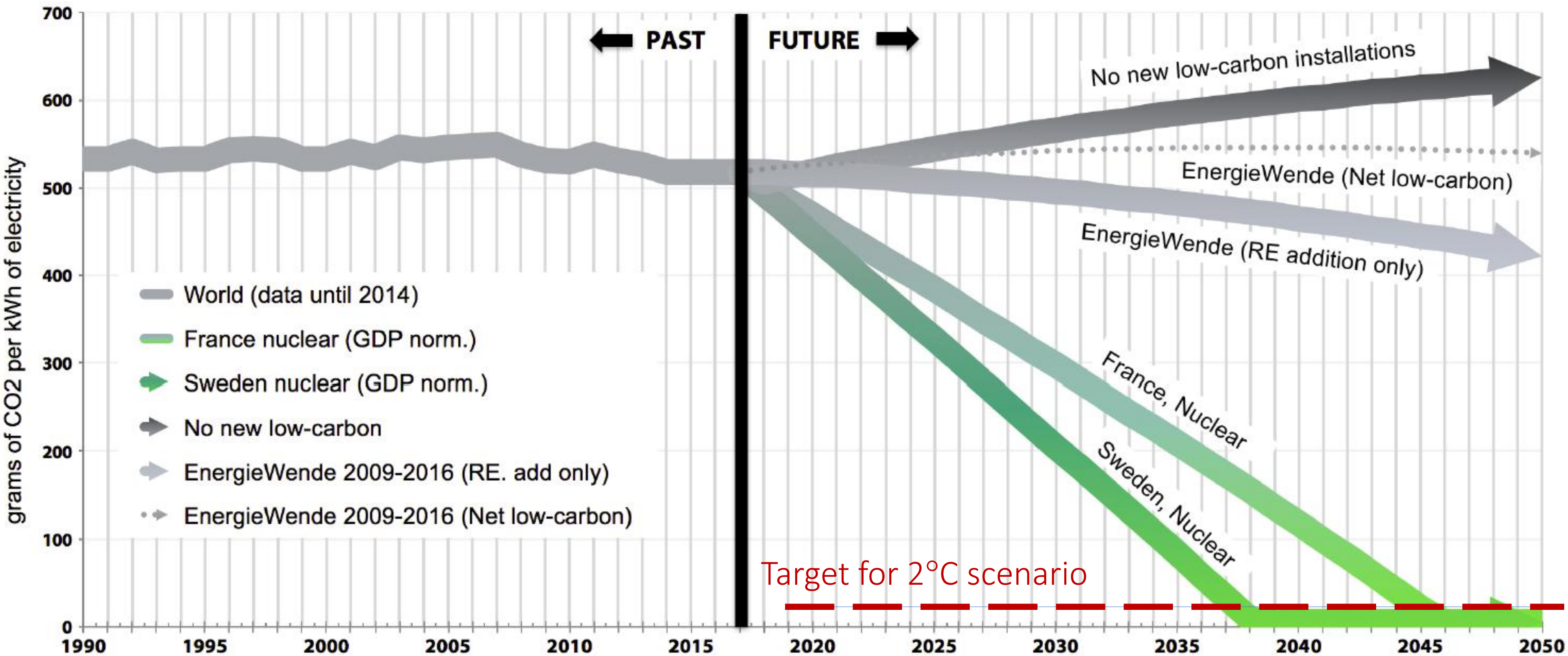


CO_2 emissions are actually rising… we are NOT winning!

Can we decarbonize using *only* wind and solar?

Opportunities for Nuclear Energy

The scalability argument



Source: Staffan Qvist, 2018

A nuclear build-up (at historically feasible rate) can completely decarbonize the World's power sector within 30 years

US Overnight Cost Assumptions

Resource	Low Cost	Nominal Cost	High Cost
OCGT [A]		\$805/kW	
CCGT [A]		\$948/kW	
Coal [A]		\$3,515/kW	
Nuclear	\$4,100[C]/kW	\$5,500[A]/kW	\$6,900/kW
Wind [A]	\$1,369/kW	\$1,553/kW	\$1,714/kW
Solar [A]	\$551/kW	\$917/kW	\$1,898/kW
Battery Storage [B]	\$429/kW (\$215/kWh)	\$715/kW (\$358/kWh)	\$1,430/kW (\$715/kWh)
Coal IGCC+CCS [A]		\$5,876/kW	
Gas CCGT+CCS [A]		\$1,720/kW	\$2,115/kW

[A] NREL-ATB report (2016)

[B] Lazard.com report (2015)

[C] OECD (2015)

GenX Results

Simulated Texas-ERCOT and NE-ISO with GenX; similar analyses for China (Tianiin, Zhejaing province) and UK and France with a range of carbon constraints (500-nominal, 100, 50, 10, 1 gm-CO2/kWh)

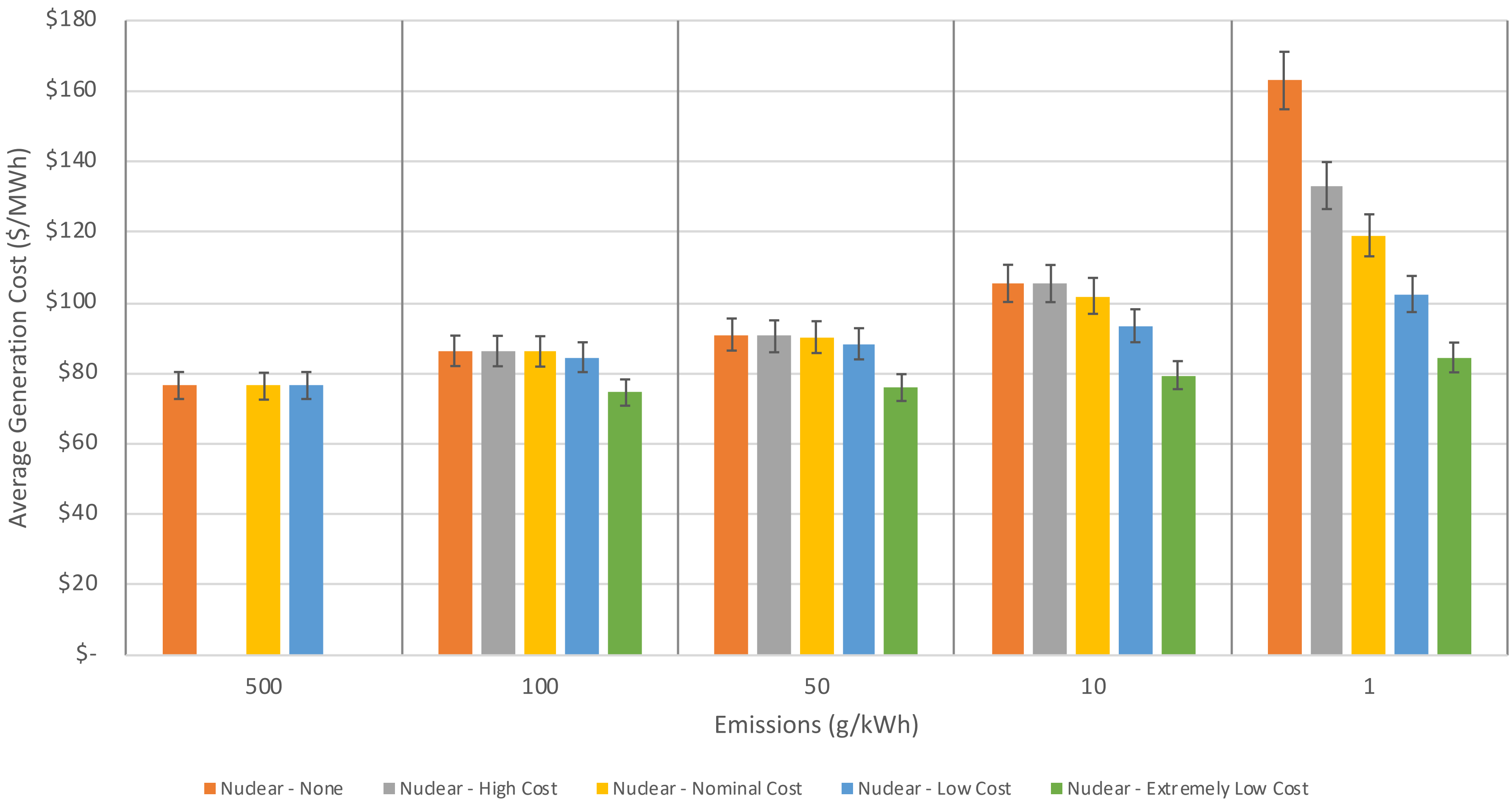
Performed a range of sensitivity studies on:

- Renewables plus battery storage cost (hi-nominal-low)
- Nuclear capital cost (nominal – low with improvements)
- Natural gas price (hi-nominal-low)
- CCS Cost and Efficiency (nominal-hi; 90% and 99%)
- Demand-Side Response (with and without)
- Extreme Weather (clouds/low-wind for a time period)

Texas – ERCOT ISO

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



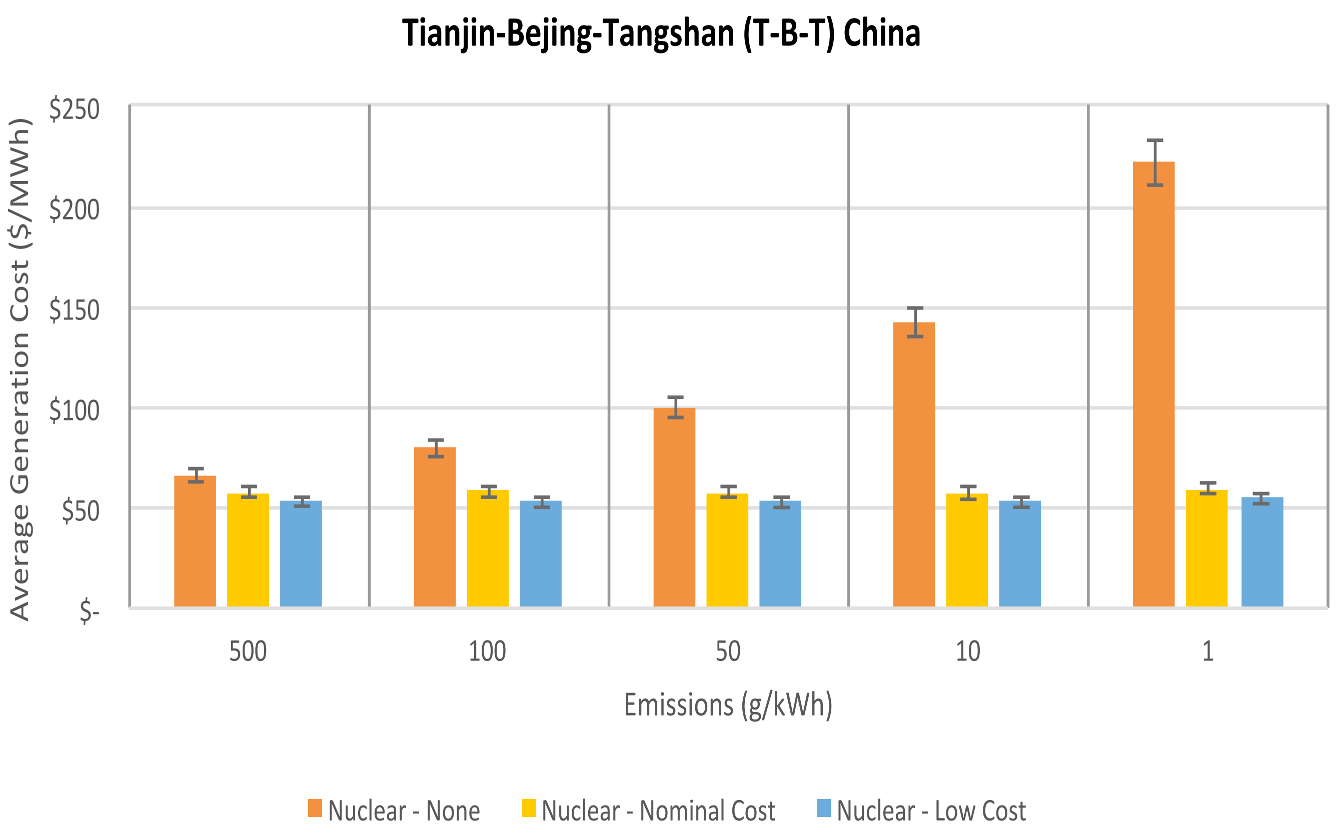
Similar results were found for Europe (U.K. and France)

China Overnight Cost Assumptions

Resource	Low Cost	Base Cost	High Cost
OCGT		$421/kW	
CCGT		$496/kW	
Coal		$1,160/kW	
Nuclear	$2,084/kW	$2,796/kW	
Wind	$1,117/kW	$1,267/kW	$1,398/kW
Solar	$404/kW	$671/kW	$1,389/kW
Battery Storage	$429/kW ($215/kWh)	$715/kW ($358/kWh)	$1,430/kW ($715/kWh)
Coal IGCC+CCS		$1,940/kW	
Gas CCGT+CCS		$900/kW	$1,159/kW

NOTE: Study used the relative costs for each technology from the 2015 OECD Report with NREL U.S. cost values used as cost basis for scaling to other countries

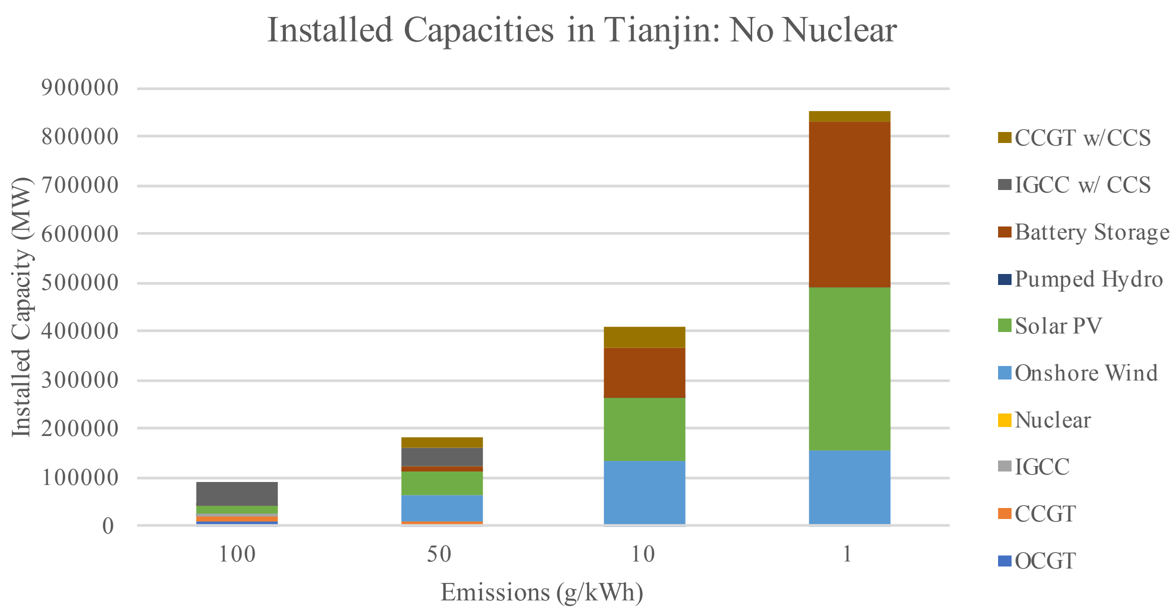
T-B-T Province Results



Due to its low relative cost, having nuclear as an option always decreases overall system cost

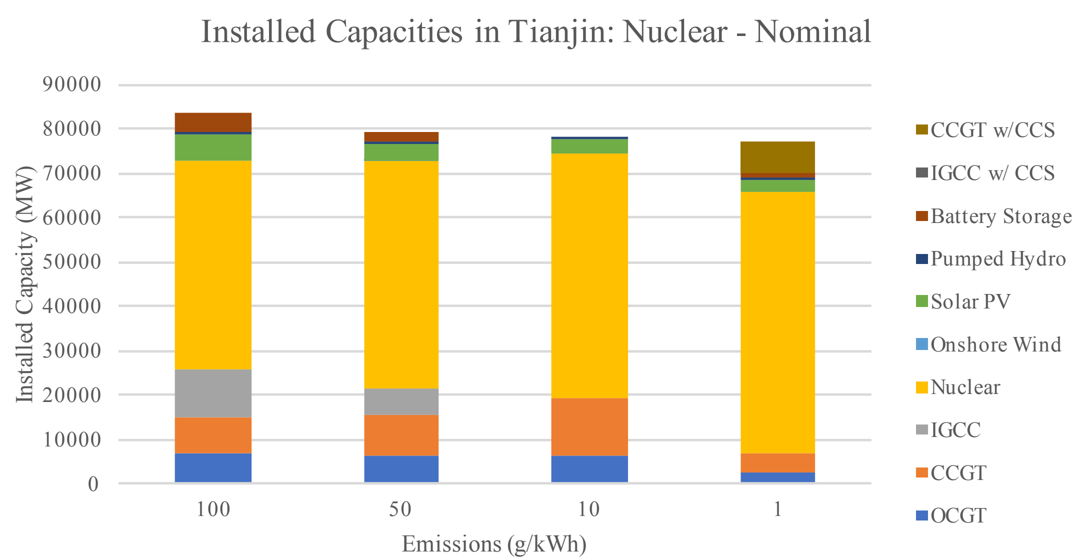
This decrease in system cost is dramatic for low carbon scenarios

T-B-T Province Results

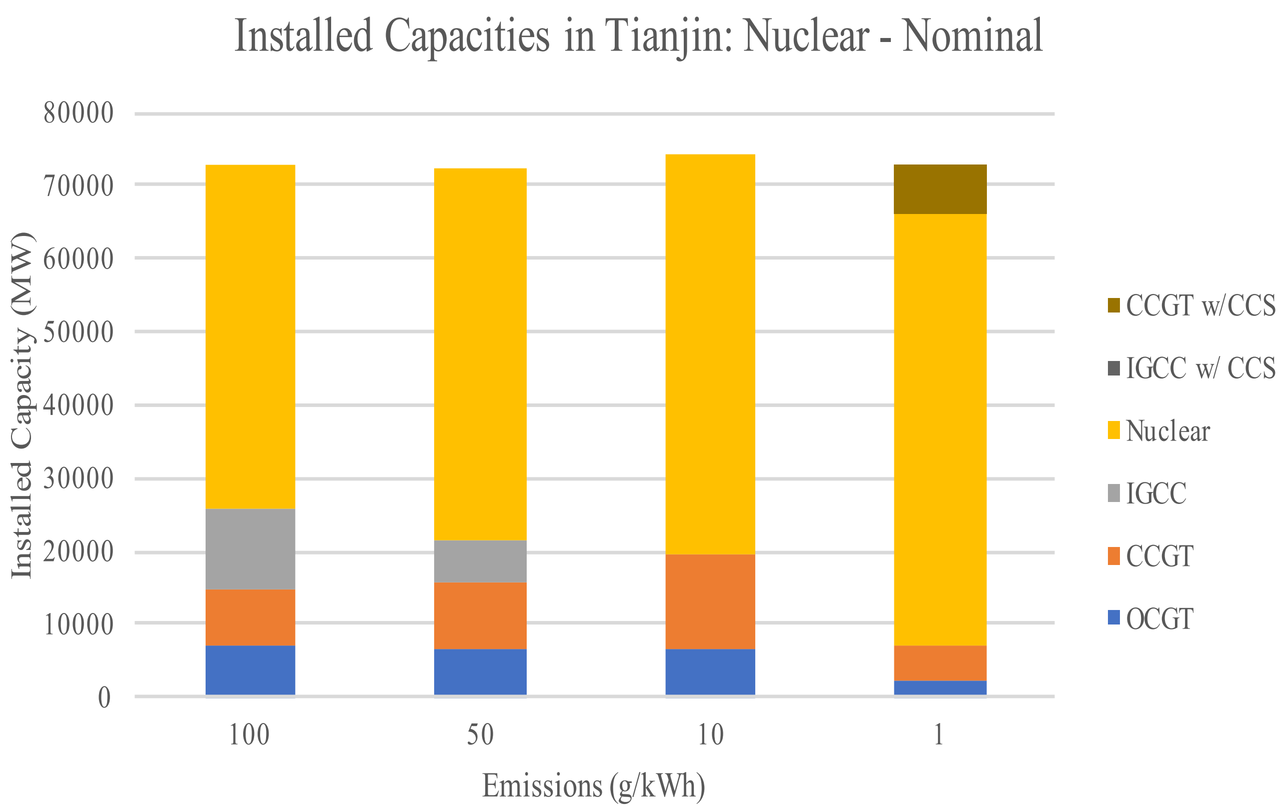


To meet constraint w/o nuclear requires significant build-out of renewables

In contrast, installed capacity is relatively constant w nuclear allowed



Tianjin-Beijing-Tangshan Dispatchable Generation Competition

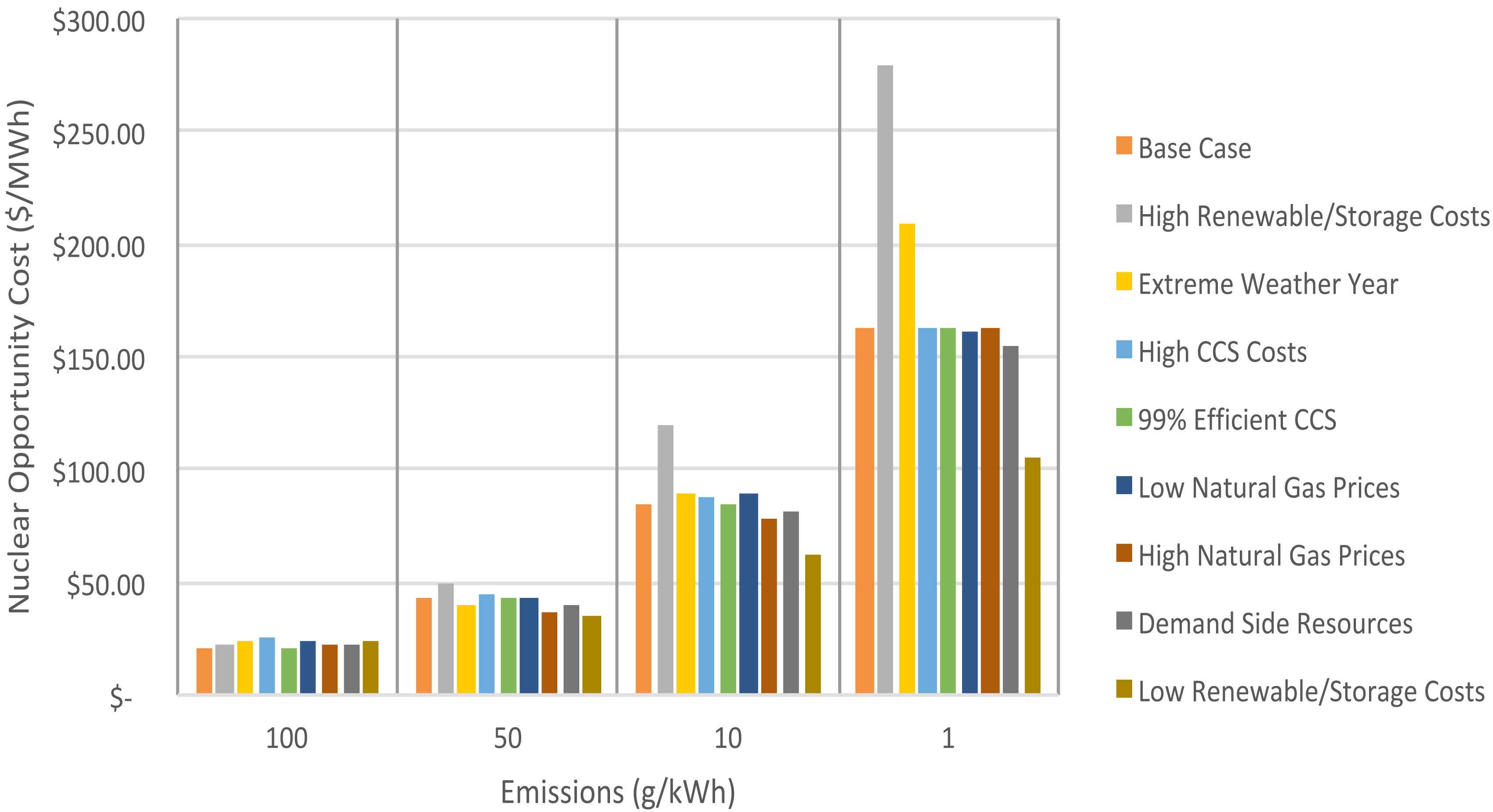


- Fossil (Coal & NG) selected for ≥10g/kWhr
- NG with CCS is only selected in Tianjin between 10 g/kWh and 1g/kWh
- Nuclear is always selected at 100 g/kWh and below

GenX Sensitivity Nomenclature

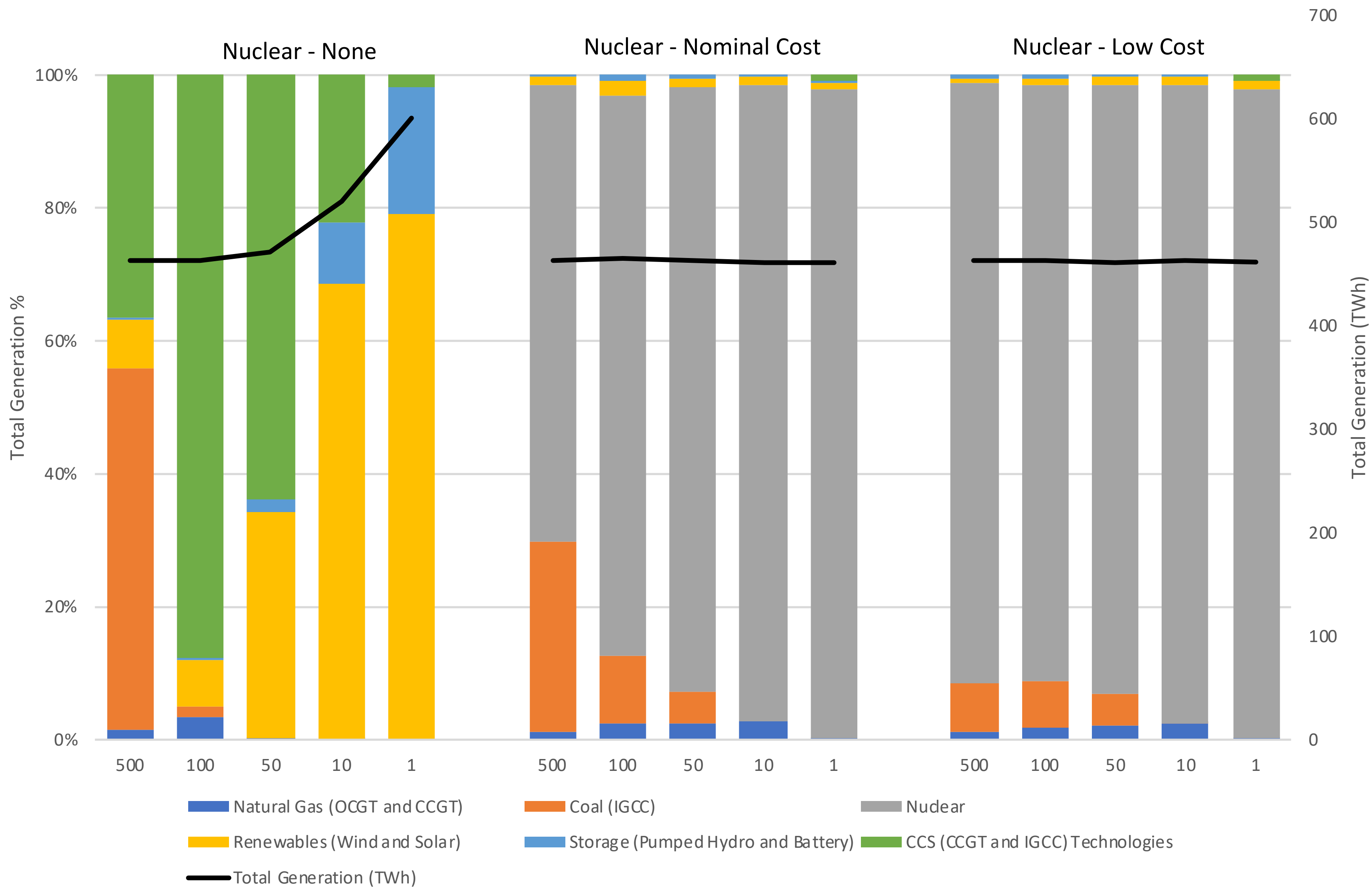
- No nuclear case: All costs at nominal conditions w/o nuclear
- Nuclear-nominal: Nuclear included w nominal conditions
- Nuclear-low cost: Lower cost w improved enabling technology
- Renewable/Battery Low cost: Nominal w low cost renewables
- Renewable/Battery High cost: Nominal w hi cost renewables
- High Nat.Gas cost: Nominal w high natural gas fuel cost
- Low Nat.Gas cost: Nominal w low natural gas fuel cost
- 99% CCS: Nominal costs with 99% Carbon-capture efficiency
- Demand-side response allowed (DSM + DR)
- Extreme weather year: Nominal w 1wk-Low-Renew Cap.Fac.

T-B-T Cost Sensitivity Results



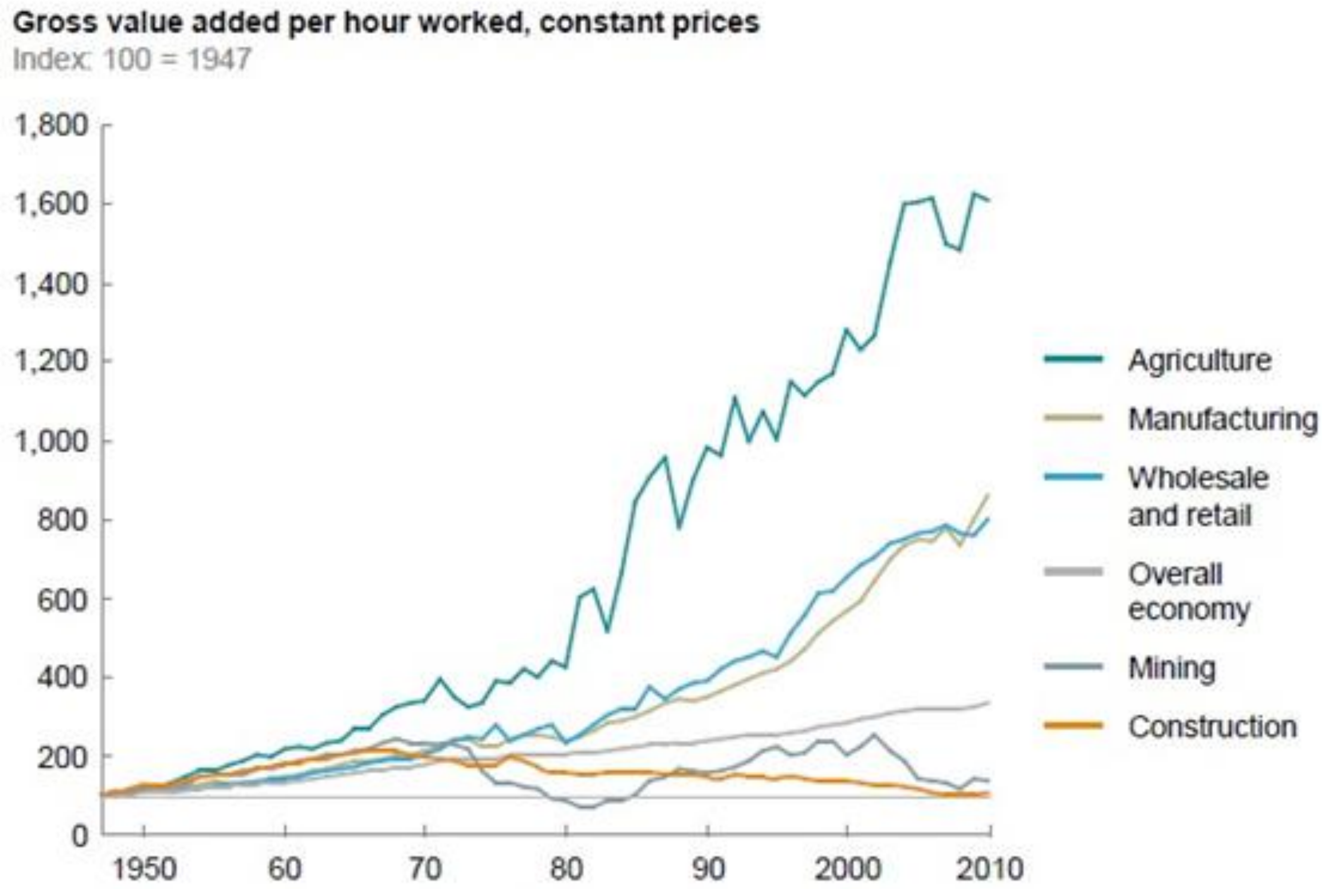
Even with low renewables/storage cost, nuclear is still chosen for all constraints

T-B-T Electrical Energy Generation



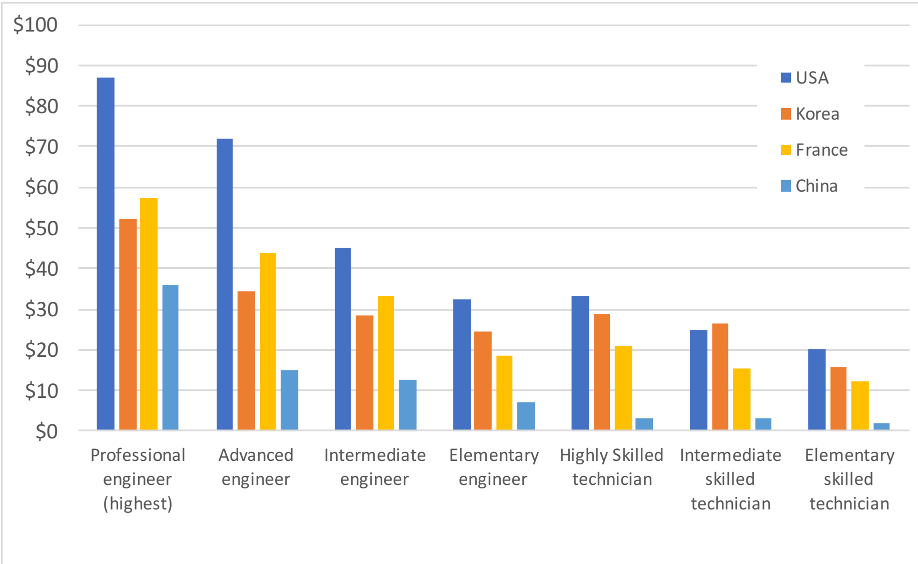
Advanced Reactors and Cost

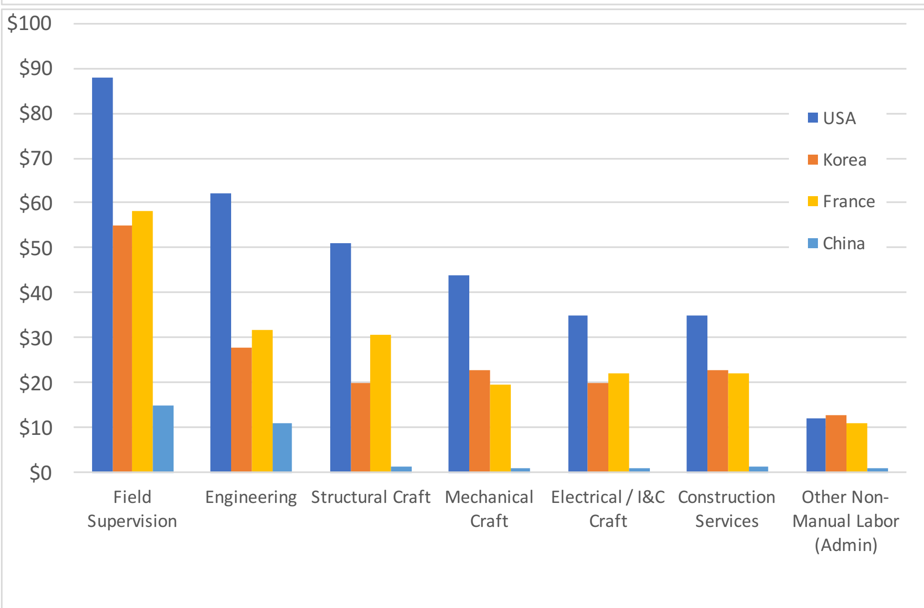
Why are nuclear construction projects in the West particularly expensive?



Construction labor productivity has decreased in the West

Why are nuclear construction projects in the West particularly expensive? (2)





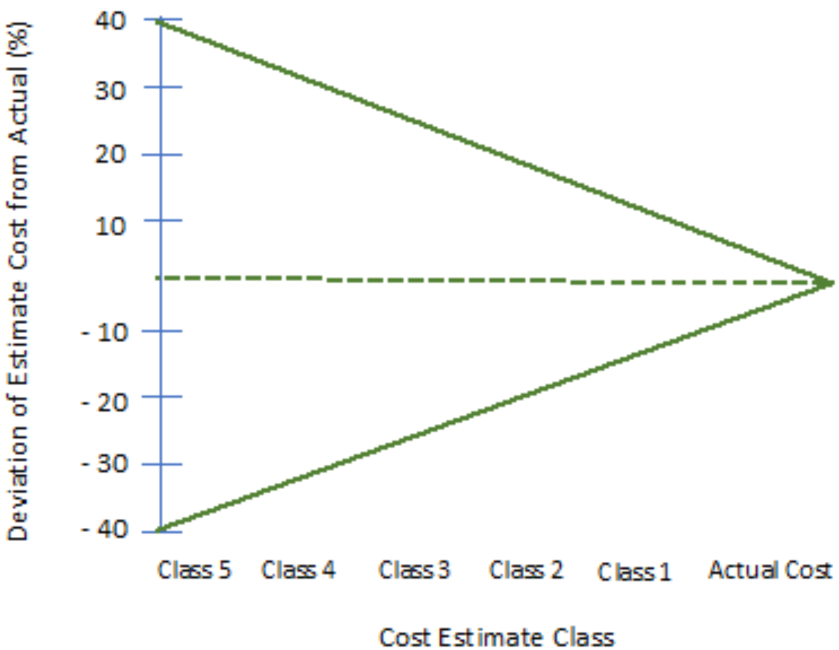
Construction and engineering wages are much higher in the US than China and Korea

Estimated effect of construction labor on OCC (wrt US):
-$900/kWe (China)
-$400/kWe (Korea)

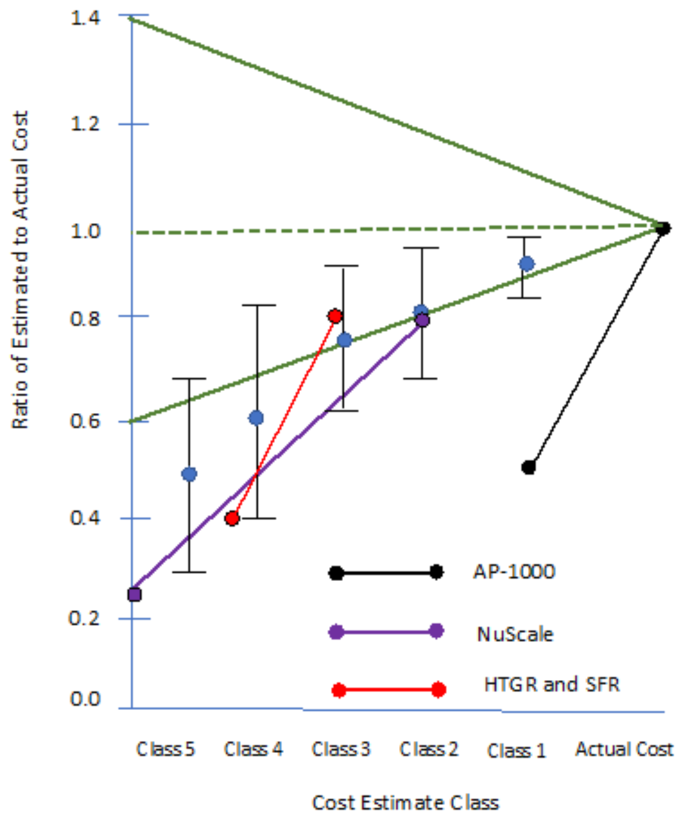
Source: Bob Varrin, Dominion Engineering Inc.

Uncertainties in cost estimates for large, complex projects

Conventional View



Reality

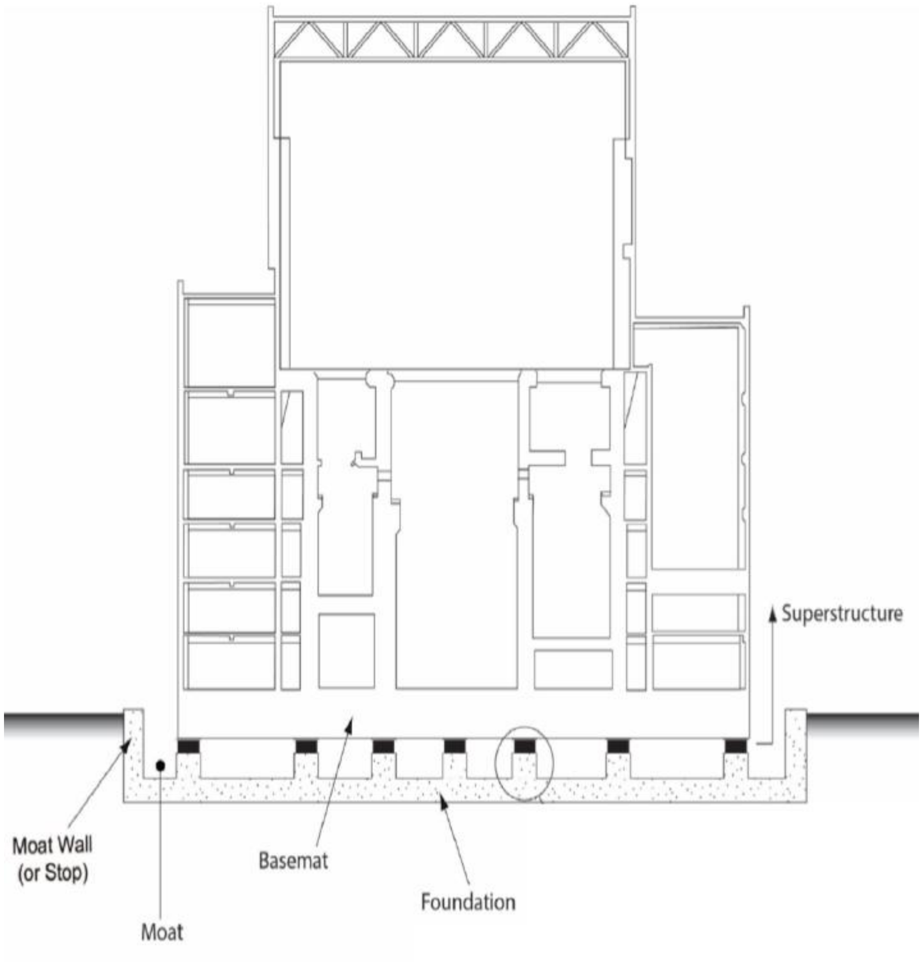


Early-stage cost estimates are unreliable predictors of the eventual cost of mega-projects. This is valid across *all* nuclear technologies and also large non-nuclear mega-projects.

Modularity - the experience

- Transformational impact (40-50%) in other industries (e.g. chemical plants)
- Major impact on nuclear submarine construction; 20% savings in cost and schedule for Virginia class subs
- Advanced construction techniques were adopted in Japanese BWR builds where over 15 years, construction schedules were reduced by nearly 20% and non-civil construction man-hours were reduced by nearly 40%
- Much less impact on cost and schedule (10-15%) for US nuclear based on talks with AP-1000 experience and NuScale
  - Extra transportation costs
  - Additional engineering time to assure modules fit together
  - Fit up and dimensional tolerance issues

Seismic isolation means less materials & site-independent designs

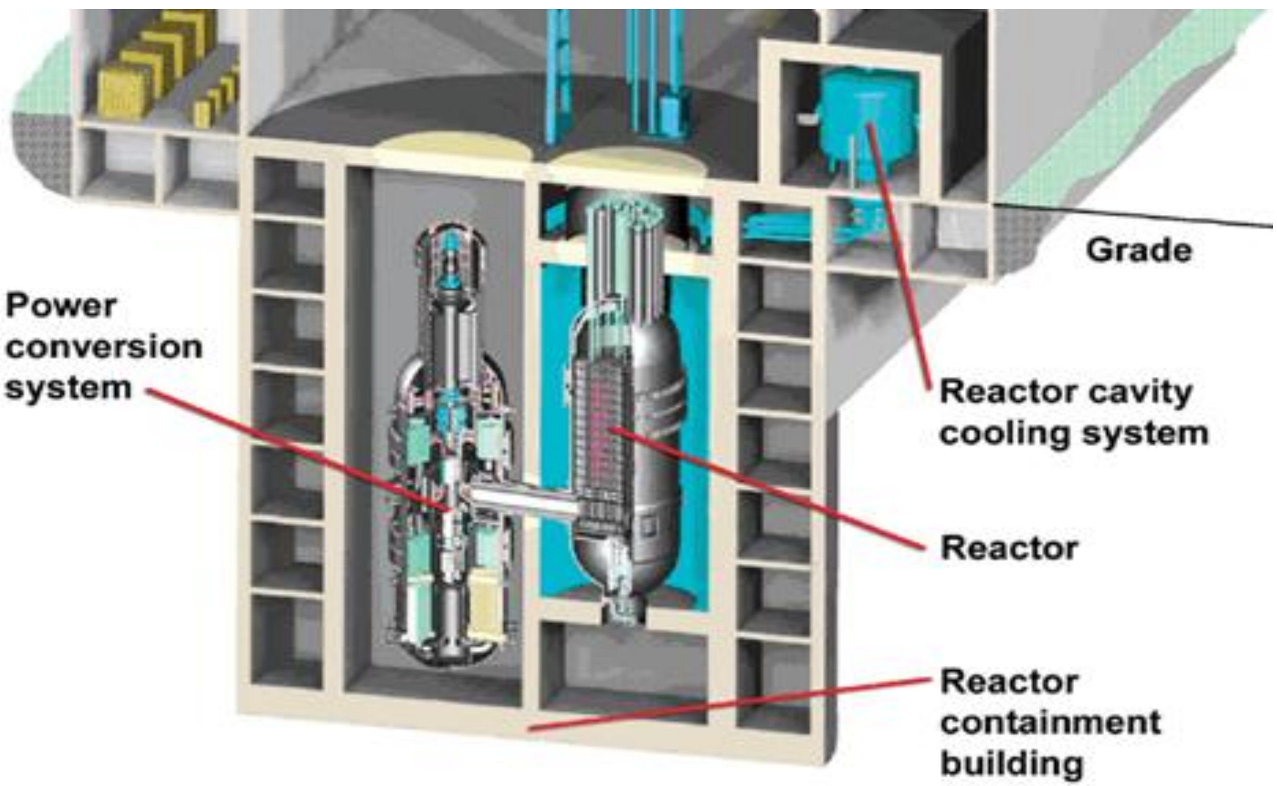


Courtesy of A. Whittaker (U-Buffalo) and J. Coleman (INL)

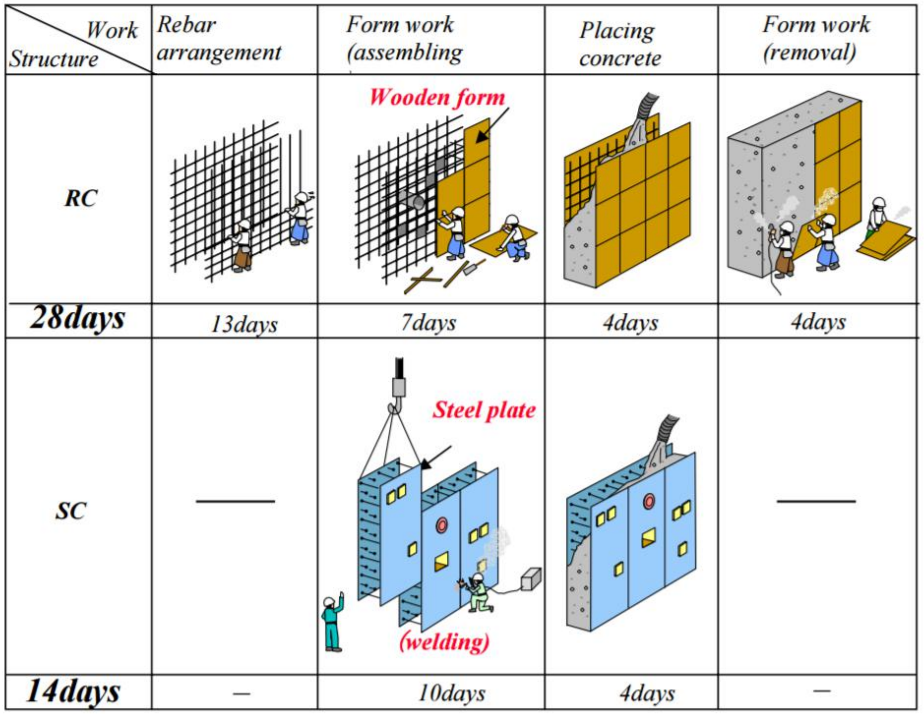
- Isolates the plant to reduce seismic risk and costs
- Isolation is cost effective above peak ground accelerations of 0.2 g – that includes every plant in the US
  - 5% reduction in overnight capital (reduced thickness and reinforcement of all structures within the building envelope, including SCC supports) for small nuclear projects
  - Expected to be larger for gigawatt-level plants and for highly-seismic sites
- External shield building cannot be thinned because of airplane crash protection
- Minimal maintenance required with Lead Rubber (LR) and Friction Pendulum (FP) sliding isolators
- Allows for site-independent NSSS design

Full embedment of NSSS eliminates need for shield building

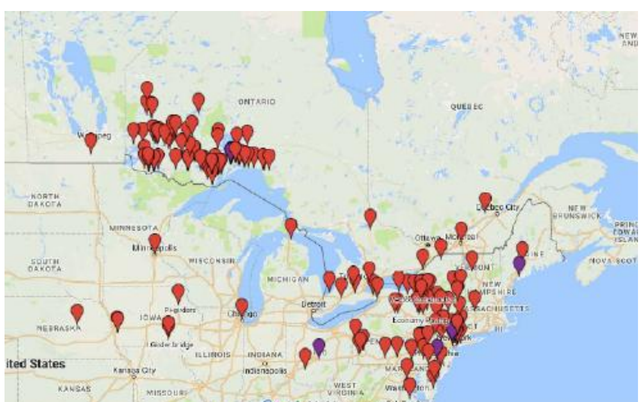
- Shield building vs conventional building cost differential is ~$250/kWe
- Embedment:
  - Reduces seismic input at RPV supports
  - Reduces exposure to aircraft crash and extreme weather
  - Maintenance costs (e.g. dewatering) unknown



Advanced concrete can replace construction-slowing rebar and form work



- Ultra-High Performance Concrete (UHPC) is very strong concrete (metallic fibers impart strength), can be self-consolidating
- Steel Plate Composites (SPCs) are steel shells that are filled with concrete onsite (alternatively can use precast UHPC shells)
- Both aim to reduce/eliminate formwork and rebar, thus reduce cost and schedule



Ductal® projects in the US, Lafarge-Holcim

What is the value proposition for advanced reactors? (2)

Cost ($/kWe)	HTGR	SFR	FHR (Large)	FHR (Small)	MSR
Machine Size	4 x 600 MWth	4 x 840 MWth	3400 MWth	12 x 242 MWth	2275 MWth
Design Stage	Conceptual approaching Preliminary	Conceptual approaching Preliminary	Early conceptual	Early conceptual	Early conceptual
Direct Cost	2400	2500	2100	2300	2500
Indirect Cost	1400	1600	1400	1300	1700
Contingency	800	800	1100	1100	1200
Total Overnight Cost	4600	4900	4600	4700	5400
Interest During Construction	600	700	600	700	700
Total Capital Invested	5200	5600	5200	5400	6100

1. E. Ingersoll, "International Nuclear Project Costs, Proprietary and Confidential
2. F. Ganda et al., "Reactor Caital Costs Breakdown and Statistical Analysis of Historical US Construction Costs," ICAPP 206
3. A. M. Gandrik, "Assessment of High Temperature Gas-Cooled Reactor (HTGR) Capital and Operating Costs," TEV-1196, Jan. 2012
4. F. Ganda, "Economcis of Promising Options," FCRD-FCO-2015-000013, Sept. 2015
5. D. E. Holcomb et al., "Advanced High Temperature Reactor Systems and Economic Analysis,' Sept. 2011
6. J. Engle et al., "Conceptual Design Characteristics of a Denatured Molten-Salt Reactor with Once-through Fuelings, ORNL/TM-7207, July 1980
7. C. Andreades, "Nuclear AirBrayton Combined Cycle Power Conversion Design, Physical Performance Estimation and Economic Assessment," UC Berkely Thesis, 2015

Independent cost estimates for advanced reactors confirm importance of civil works (buildings and structures) and indirect costs, and do not suggest significant cost reduction with respect to LWRs

What is the value proposition for advanced reactors? (3)

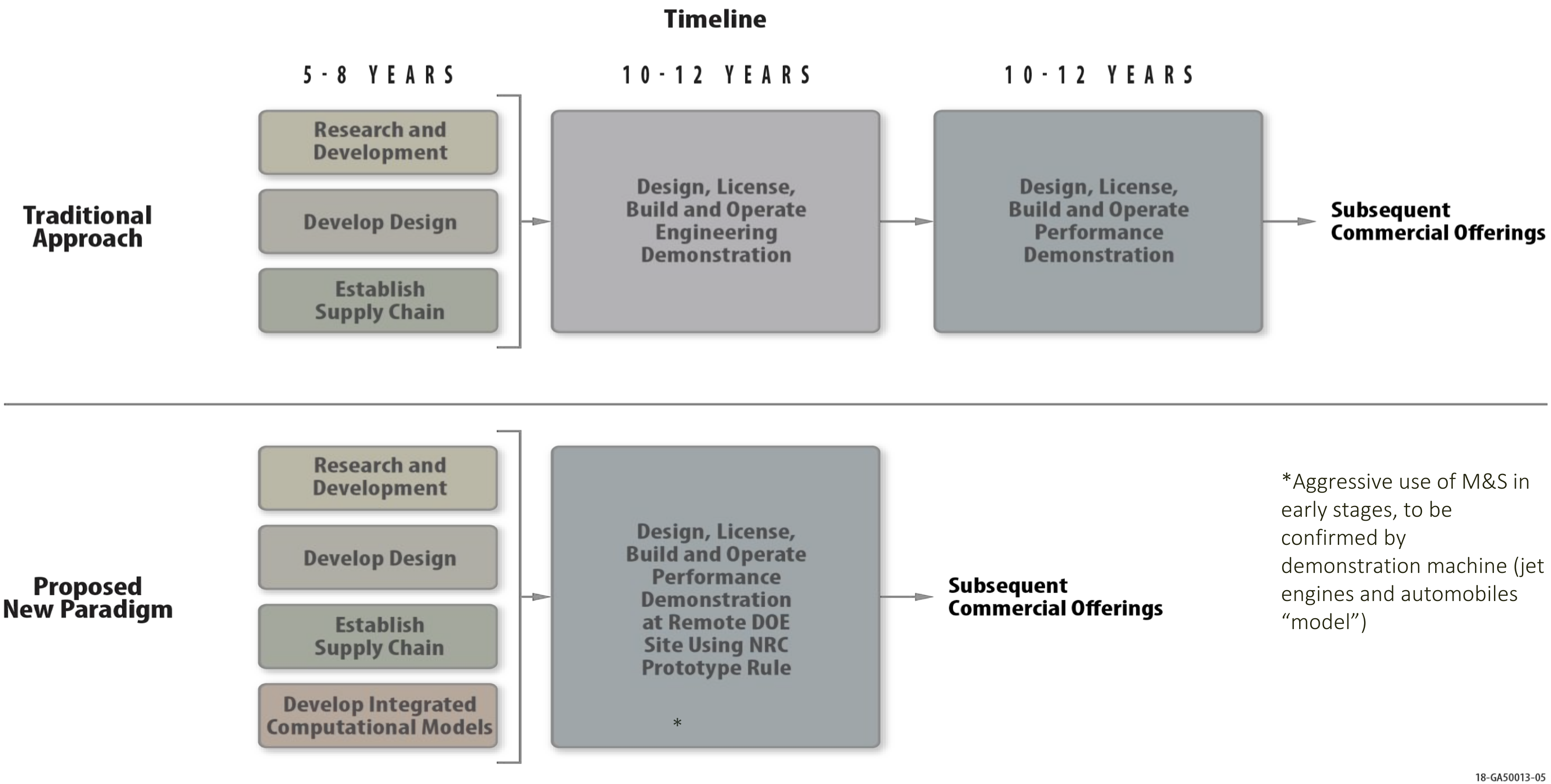
There exists a small (but not insignificant) potential market for nuclear heat

	300 MW_{th} Reactor		150 MW_{th} Reactor	
Industry	**U.S. Capacity (MW_{th} Installed) (%)**	**Global Capacity (MW_{th} Installed) (%)**	**U.S. Capacity (MW_{th} Installed) (%)**	**Worldwide Capacity (MW_{th} Installed) (%)**
Co-Generation Facilities	82,800 (61.7%)	340,800 (59.8%)	86,250 (57.5%)	355,050 (55.7%)
Refineries	15,600 (10.4%)	76,800 (12.1%)	17,250 (11.5%)	84,750 (13.3%)
Chemicals	7,800 (5.2%)	36,600 (5.7%)	7,050 (4.7%)	34,200 (5.4%)
Minerals	2,100 (1.4%)	8,700 (1.4%)	2,100 (1.4%)	8,700 (1.4%)
Pulp and Paper	12,600 (8.4%)	51,900 (8.1%)	21,300 (14.2%)	87,750 (13.8%)
Other	13,200 (8.8%)	55,200 (8.7%)	16,050 (10.7%)	66,450 (10.4%)
Total	**134,100 (100%)**	**570,000 (100%)**	$\boxed{\textbf{150,000 (100\%)}}$	**636,900 (100%)**

Methodology:

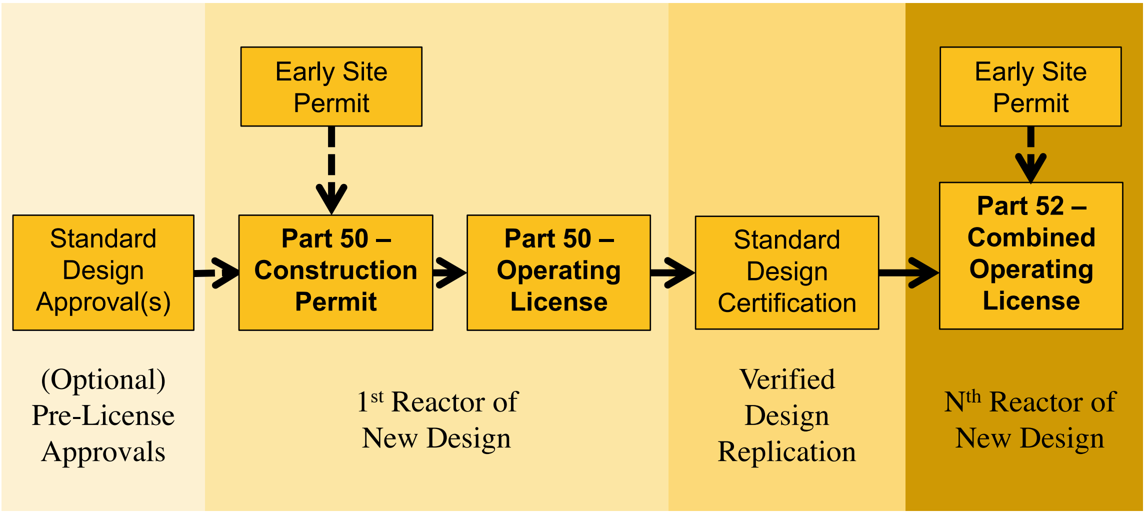
- EPA database for US sites emitting 25,000 ton-CO_2/year or more
- Site must need at least 150 MW_{th} of heat
- Nuclear heat delivered at max 650°C (with HTGR technology)
- At least 2 reactors per site for assured reliability
- Heat from waste stream not accessible
- Costs not evaluated

Can we accelerate commercialization of the less mature advanced reactors?



By combining the engineering demonstration machine (traditionally a small-scale machine) with the at-scale performance demonstration machine, and using the NRC prototype rule at a "forgiving" site (e.g. INL) it may be possible to accelerate the commercial deployment of the less mature advanced reactors (i.e. molten salt-cooled and lead-cooled designs) by over 10 years

Can we license advanced reactors?



Adapted from *Advanced Demonstration and Test Reactor Options Study*, Chapter 7, INL

Finding: Regulatory agencies in other nations have similar basic principles as described in IAEA policies and as embodied in NRC regulations, but vary widely in the detailed application of these policies and principles.

Finding: Advanced reactor concepts should consider NRC prototype option (10CFR50.43(e)) to license less mature designs to accelerate these concepts toward commercialization

Finding: The current NRC regulatory structure is flexible and can be adapted to accommodate licensing of (mature) advanced reactors (such as SFRs and HTGRs), without a new regulatory paradigm. NRC has sufficient and diverse tools at hand to provide a stepwise process with intermediate licensing decisions without unnecessary delays, given required design information.

Government role

Global Nuclear Market

- Growth in electricity demand is primarily in the non-OECD.
- Plenty of choice of vendors.
  - Korea has been successful.
  - Russia is extremely active globally.
  - China has built a domestic foundation to become an exporter.
- US success as a nuclear innovator must be won in this new context.

New Reactor Designs

Electricity sector remains the major energy product

- Bigger than ever on a global scale, and
- with electrification of transportation and other energy services in the offing

Cost is the driver

- That means cutting the capital cost of the entire plant.
- $5,500 overnight is only competitive when carbon constraints are very tight
- $2,000 overnight is required without carbon constraints