MIT-서울대 심포지엄
탄소제약사회에서 원자력의 미래

장소
한국 프레스 센터 19층 기자회견실

날짜 및 시간
2019년 1월 14일 (월요일), 13:00- 16:00

일정

13:00 - 13:20	**등록**
13:20 - 13:30	**개회사** 주한규 교수(서울대학교)
13:30 - 14:00	**탄소제약 세계에서 원자력의 역할은 무엇인가?** Prof. Jacopo Buongiorno (MIT)
14:00 - 14:30	**원자력의 핵심 도전 과제를 어떻게 극복할 것인가?** Dr. David Petti (INL), Dr. John Parsons (MIT)
14:30 - 15:00	**APR1400의 설계부터 건설까지** 오승종 교수(KINGS)
15:00 - 16:00	**토론 및 질의응답** 황일순 교수(서울대학교, 좌장), 최연혜 국회의원(자유한국당), 이용환 에너지산업정책관(산업통상자원부), 강연자들
16:00	**마무리**


Prof. J. Buongiorno
MIT


Dr. D. Petti
INL


Dr. J. Parsons
MIT


오승종 교수
KINGS


황일순 교수
서울대학교


최연혜 국회의원
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주한규 교수
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동시통역 제공

주최
MIT Energy Initiative
서울대학교 원자력정책센터(SNEPC)

MIT-Seoul Nat'l Univ. Symposium on the Future of Nuclear Energy in a Carbon Constrained World

Venue

Korea Press Center (19 th Floor, Press Conference Room)

Date & Time

January 14, 2019 (Mon), 13:00-16:00

Time Table

13:00 - 13:20	**Registration**
13:20 - 13:30	**Opening** Prof. Han Gyu Joo (SNU)
13:30 - 14:00	**What Role for Nuclear Energy in a Carbon-Constrained World** Prof. Jacopo Buongiorno (MIT)
14:00 - 14:30	**How to Overcome Nuclear's Key Challenges** Dr. David Petti (INL), Dr. John Parsons (MIT)
14:30 - 15:00	**APR1400 from Design to Deployment** Prof. Seung Jong Oh (KINGS)
15:00 - 16:00	**Panel Discussion, Q&A** Prof . Il Soon Hwang (SNU, Chair), Hon. Dr. Yeon Hye Choi, MP (Liberty Korea Party) DG Yong Hwan Lee (MOTIE), and Speakers
16:00	**Closing**

Simultaneous Interpretation Provided

Hosts

MIT Energy Initiative
SNU Nuclear Energy Policy Center (SNEPC)

Symposium on the Future of Nuclear Energy in a Carbon Constrained World

Jacopo Buongiorno

-Massachusetts Institute of Technology (MIT)
-Professor, Nuclear Science and Engineering
-Director, Center for Advanced Nuclear Energy Systems (CANES)
-Member, Accrediting Board, National Academy for Nuclear Training
-Fellow, American Nuclear Society

David Petti

-Idaho National Laboratory (INL)
-Chief Scientist and Fellow, Nuclear Science and Technology
-Director, Nuclear Fuels and Materials Division
-Former Co-National Technical Director, Advanced Reactor Technologies (ART) Program, DOE
-Fellow, American Nuclear Society

John Parsons

-Massachusetts Institute of Technology (MIT)
-Senior Lecturer, Finance Group, MIT Sloan School of Management
-Co-Director, Center for Advanced Nuclear Energy Systems (CANES)
-Co-Chair, Energy Oversight Committee at the Global Association of Risk Professionals Former Member, Global Markets Advisory Committee, U.S. Commodity Futures Trading Commission

Seung Jong Oh

-KEPCO International Nuclear Graduate School
-Professor Emeritus, Nuclear Engineering
-Fellow, American Nuclear Society
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-Member, National Academy of Engineering of Korea
-President, International Forum for Reactor Aging Management (IFRAM)
-Director, Nuclear Security Research Institute of the Korea Nuclear Policy Society

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-Former President, Korea National Railroad College

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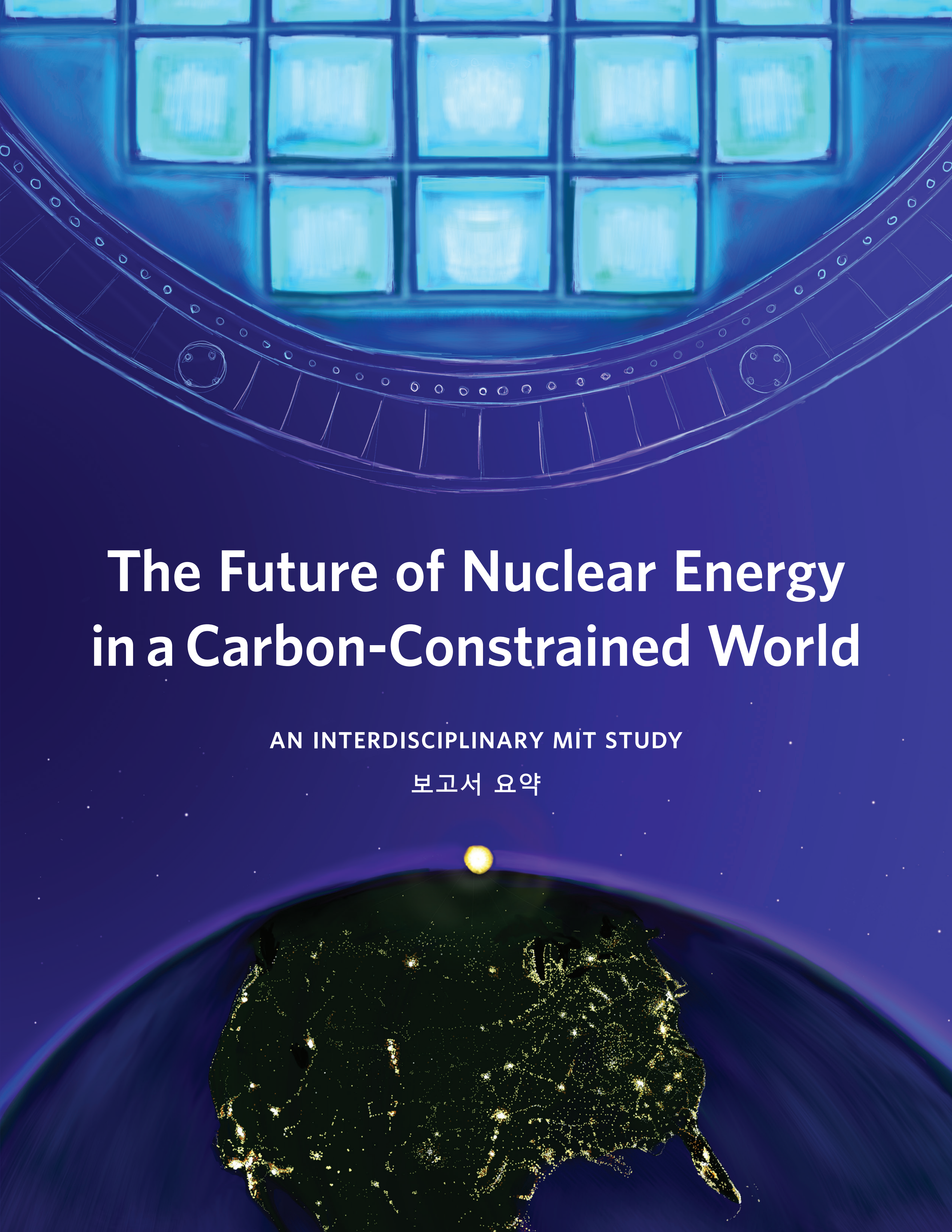


The Future of Nuclear Energy in a Carbon-Constrained World

AN INTERDISCIPLINARY MIT STUDY

보고서 요약

* https://atomic.snu.ac.kr/index.php/탄소제약_세계에서의_원자력_미래

The Future of Nuclear Energy in a Carbon-Constrained World

AN INTERDISCIPLINARY MIT STUDY

보고서 요약

Translation by MIT students Jee Hyun Seong and Haeseong Kim

보고서 요약

원자력 에너지의 평화적인 이용은 20세기 과학·기술의 가장 위대한 성취 중 하나이며 의학, 안보, 에너지 분야에 도움을 주었다. 하지만, 수십 년 동안의 빠른 성장 후, 많은 선진국에서 원자력에너지에 대한 투자를 멈추었고, 원자력에너지는 현재 세계 주요 에너지 생산의 5% 만을 구성하고있다.

21 세기에 들어, 세계는 수십억 인구에 대한 에너지 접근성 향상 및 경제적 기회의 확대와 더불어 온실가스의 방출을 대폭 줄여야 하는 새로운 과제를 맞이했다. 이 보고서에서는 심층적 탈 탄소화의 대표적인 방안으로써 전력 부문을 검토했다. 대부분의 지역에서 2050 년 예상되는 전력 부하를 해결하는 동시에 탄소 배출량을 줄이기 위해서는 기존 시스템과는 다른 발전(發電)믹스 모델이 필요하다. 이번 분석을 통하여 다양한 종류의 저탄소 혹은 무탄소 기술을 이용하는 발전믹스들 가운데, 원자력에너지가 급전 가능 저탄소 기술로서 기여할 수 있음을 보였다. 원자력에너지를 발전믹스에서 배제 할 경우, 심층적인 탈 탄소화의 비용은 현저하게 증가한다 (Figure E.1, 왼쪽 열 참조). 최저 비용의 포트폴리오는 원자력에너지 비중이 큰 경우이며 원전 건설비용이 낮아지면 발전비용은 훨씬 더 줄어든다.

이러한 가능성에도 불구하고, 세계의 많은 지역에서 원자력에너지 확대 전망은 그다지 밝지 않다. 가장 핵심적인 문제는 비용이다. 최근 수십 년 동안 다른 발전(發電) 기술은 저렴 해 진데 반해, 신규 원전 건설 비용은 여러 요인들로 인해 증가해왔다. 이는 원자력에너지의 잠재적 기여도를 감소시키며 심층적인 탈 탄소화 비용을 증가시킨다. 이번 연구에서는 이러한 추세의 원인과 해결방안에 대해 조사했다.

본 연구에서는 전 세계의 최근 경수로 건설 프로젝트를 조사하고, 다양한 선진 원자로의 개념, 설계 및 건설에 적용될 수 있는 최신 기술의 발전을 조사했다. 원자력에너지가 갖는 비용 문제의 해결을 위한 제안은 다음과 같다:

(1) 검증 된 프로젝트 및 건설 관리 사례를 통한 신규 원자력 발전소 건설의 성공 확률 증대

최근 미국과 유럽의 원전 건설 프로젝트에서는 예정 공사 기간 및 예산 범위 내에서 제품을 조달하는데 있어 반복적으로 실패한 건설 관리 사례가 발생했다. 이와 관련해 몇몇 시정 조치가 시급히 요구된다: (a) 건설에 들어가기전에 세부 설계의 상당 부분을 완료한다. (b) 입증 된 공급망 및 숙련된 노동력을 사용한다. (c) 설계 과정의 초기 단계부터 제조와 건설사를 설계 팀에 합류시켜, 제작과 시공이 효율적으로 이루어지도록 발전소 시스템, 구조 및 부품이 관련 표준에 따라 설계되도록 한다. (d) 다수의 독립적 협력업체를 관리하는 데 있어 입증 된 전문 지식을 가진 단독 계약 관리자를 임명한다. (e) 모든 계약자가 프로젝트의 성공을 통해 얻을 수 있는 확정된 권리를 가지고 있음을 보장하는 계약 구조를 수립한다. (f) 설계 및 건설 중 예기치 않은 변화를 적기에 수용 할 수 있는 유연한 규제 환경을 조성한다.

(2) 복잡하고 부지 종속적인 기존의 건설방식에서 표준화 된 발전소 제작으로의 전환

신규 원자력 발전소의 자본 비용을 대폭 줄이고 건설 일정을 단축 할 수 있는 방법은 다음과 같다. 첫째, 표준화된 원전의 다수 호기 건설 특히 단일 부지에서의 다수호기 건설은 매 호기건설로부터 상당한 경험을 얻을 수 있다. 건설 생산성이 낮은 미국과 유럽에서는 높은 생산성을 갖는 공장 생산을 확대하여 복잡한 시스템, 구조 및 부품을 제작하는 것을 권장한다. 공장 및 조선소에서의 모듈화 제작, 개량 콘크리트 기술 (예 : 강판 복합재, 고장도 철근, 초 고성능 콘크리트), 면진 기술 및 진보된 발전소 배치(예: 매립, 해양 부지 선정) 등을 포함한 최신 기술 활용은 신규 원자력 발전소 건설 비용 및 공기에 긍정적인 영향을 줄 수 있다. 기존보다 덜 복잡한 시스템, 구조 및 부품의 제조 또는 건설 현장에서의 생산성이 높은 지역(예 : 아시아)에서는 반대로 기존 방식을 고수 하는 것이 가장 비용이 적게 드는 방법일 수 있다.

모든 원자로 개념 및 설계 전반에 걸쳐 앞에서 언급된 권장 사항을 광범위하게 적용 할 수 있다. 비용 절감은 특히 3세대 개량형 경수로, 소형모듈형 원자로 (SMR) 및 4세대 원자로 와 밀접한 관련이 있다. 설계 표준화나 건설 부문의 혁신이 없는 단순한 선진 원자로 기술만으로는 다른 발전 기술보다 가격 경쟁력을 갖지 못할 것이다.

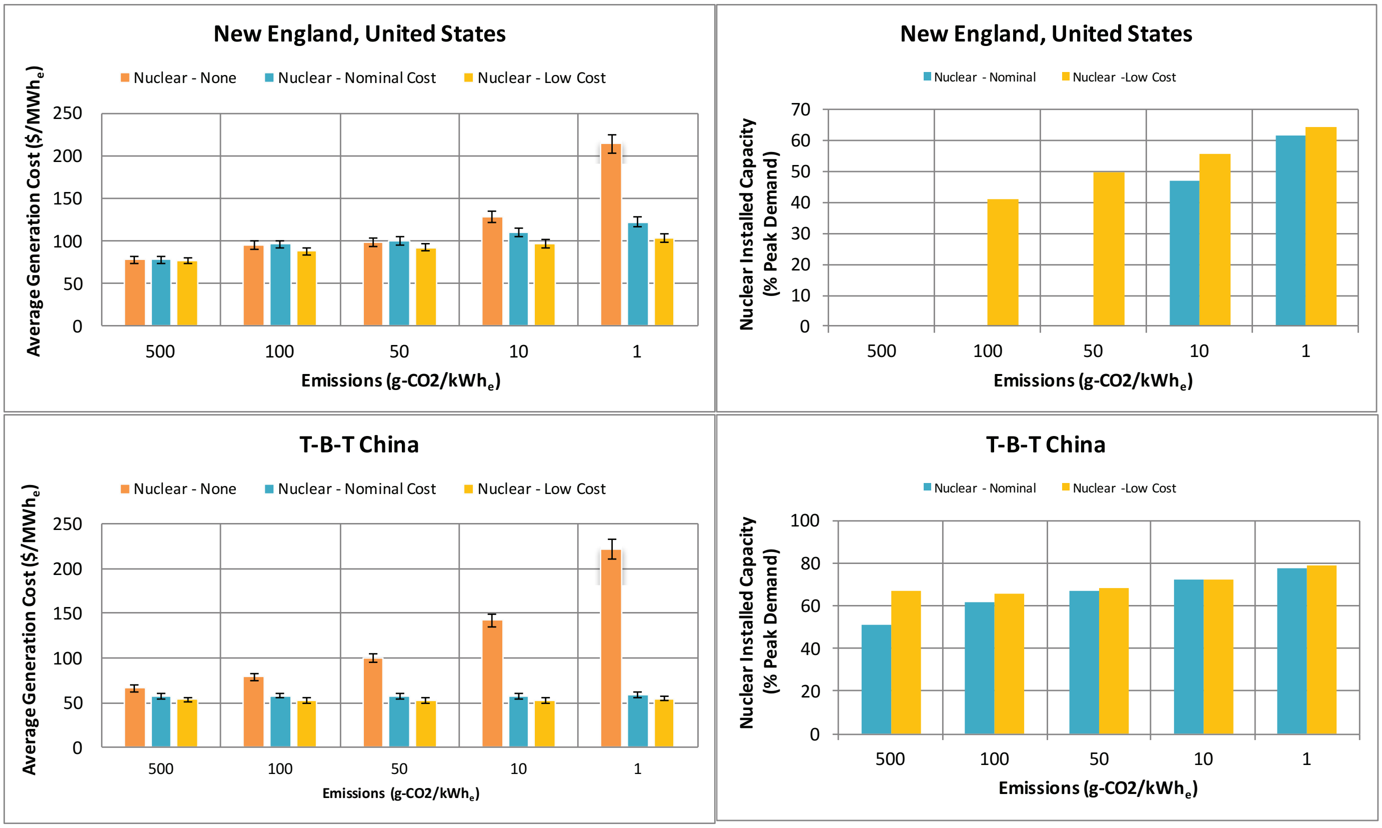
높은 비용뿐만 아니라, 기존의 2세대 원자로 중대 사고에 대한 사회적 우려는 원자력 에너지의 발전을 저해 시켰다.(예: 2011년 후쿠시마 사고) 이로 인해 몇몇 국가들이 탈원전 정책을 결정하게 되기도 하였다. 이러한 원자력 안전 문제를 해결하기 위해 다음 사항을 제안한다:

(3) 고유 및 피동 안전성을 갖는 원자로 설계로의 전환

우수한 노심 재료 (높은 화학, 물리적 안전성, 높은 열용량, 음의 궤환 효과, 핵분열 생성물 보유 특성) 와 비상 발전기 및 외부 개입이 최소화된 안전 시스템 계통은 원자로 운전을 단순화하고 인적 오류의 위험성을 감소시킨다. 이러한 개선사항은 일부 3세대 원자로 설계 시 이미 반영되었으며, 현재 중국, 러시아, 미국에서 건설중인 원자로에서도 나타난다. 피동 안전 설계는 중대 사고의 발생 확률을 낮춤과 동시에 사고 인근지역의 피해를 줄일 수 있다. 이러한 설계는 신규 원자력 발전소의 인허가를 유리하게 하며 선진국과 개발도상국에서의 배치를 가속시킨다. 소형 경수로(예: NuScale)와 같은 개량형 원자로 및 4세대 원자로 개념(예: 고온 가스로, 소듐 고속 냉각로)은 앞에서 언급된 특성을 가지고 있으며 상업적으로 이용될 준비가 되었다. 또한, 이 연구에서 수행된 미국 및 국제 규제 환경평가는 현재의 규제 시스템이 선진 원자로의 인허가에 있어 충분히 융통적임을 시사한다. 기존 규제 체계의 개선은 인허가 검토의 효율 및 효과를 더욱 향상 시킬 수 있다.

[1] 원자로 설계는 주로 네 세대로 분류된다. 1950년대 후반과 1960년대에 건설된 최초의 상업용 원자로는 1세대 시스템으로 분류된다. 2세대 시스템은 1970년에서 1990년 사이에 건설된 상업용 원자로를 포함한다. 3세대 원자로는 2세대 시스템에서 혁신적으로 발전된 설계를 포함한 상업용 원자로이다. 4세대는 오늘날 개발되고 있는 물 이외의 냉각제를 사용하는 선진 원자로 설계를 일컫는다.

Figure E.1 미국 뉴 잉글랜드 지역과 중국의 천진 - 베이징 - 당산 (T-B-T) 지역의 탄소 배출량 규제 (gCO2/kWhe)에 따른 2050 년 예상 평균 발전 비용 ($/MWhe) (좌) 및 원자력 시설 용량 (첨두 수요량 대비 %) (우). 세 가지 시나리오: (a) 원자력 비 허용 (b) 명목상 순건설 비용에서 원자력 허용 (뉴 잉글랜드에서 $5,500 per kWe, T-B-T에서 $2,800 per kWe) (c) 개선된 순건설 비용에서 원자력 허용 (뉴잉글랜드에서 $4,100 per kWe, T-B-T에서 $2,100 per kWe). 시뮬레이션은 GenX라는 MIT 시스템 최적화 도구로 수행되었다. 주어진 전력 시장에 대해 필요한 입력 값은 모든 발전소 (원자력, 풍력, 태양, 화력)에 대한 시간당 전력 수요, 시간 별 날씨 패턴, 경제적 비용 (자본, 운영 및 연료)과 모든 입력 값의 변화율이다. GenX 시뮬레이션은 각 시장에서 평균 시스템의 전력요금을 최소화하는 발전믹스를 식별하는 데 사용되었다. 강력한 탄소 제약 조건 하에 비핵화 시나리오에서 확인되는 비용의 상승은 에너지 저장장치의 증축 및 건설 비용에 기인한다. 변동성을 갖는 신재생에너지 기술에 전적으로 의존하는 경우 이러한 에너지 저장장치는 필수적이다. 오늘날 전세계 에너지원의 평균 이산화탄소 배출량은 500 g/kWhe이다. 2017년 국제에너지기구 (International Energy Agency) 에서 발표된 기후변화 안정화 시나리오에 의하면, 지구 온난화를 현재 기준 평균 2℃ 이내로 제한하기 위한 전력 부문에서의 탄소 배출 목표량은 2050년 까지 10~20 g/kWhe, 2060년 까지 2 g/kWhe이다.



마지막으로, 원자력 에너지의 이점을 살리기 위해서 정책결정자들에게 다음과 같은 사항이 요구된다:

(4) 탈탄소화 정책을 통한 저탄소 기술의 고유 경쟁력 향상

원자력 혁신 개발의 투자자들은 해당 투자를 통한, 이산화 탄소 배출절감의 효과를 비롯한 외부요인들 만큼이나, 이윤의 회수가 중요하다. 또한 원자력 에너지를 배제하는 정책은 원자력 기술에 대한 투자를 감소시킨다. 그리고 이와 같은 정책과 그로 인한 투자위축은 저탄소화의 비용을 증가시키며 기후 변화 억제에 관한 목표 달성을 현실적으로 어렵게 한다. 이에 따라 탄소배출비용을 전력요금에 포함시키는 방식으로 에너지원을 평가한다면, 여타의 저탄소 에너지 기술들과 비교하여 원자력이 공정한 기준 하에 평가 받을 수 있다. 그리고 현재 운영 중이거나 계획중인 원자력 발전은 경쟁에서 큰 이점을 가지고 있는 기술이다.

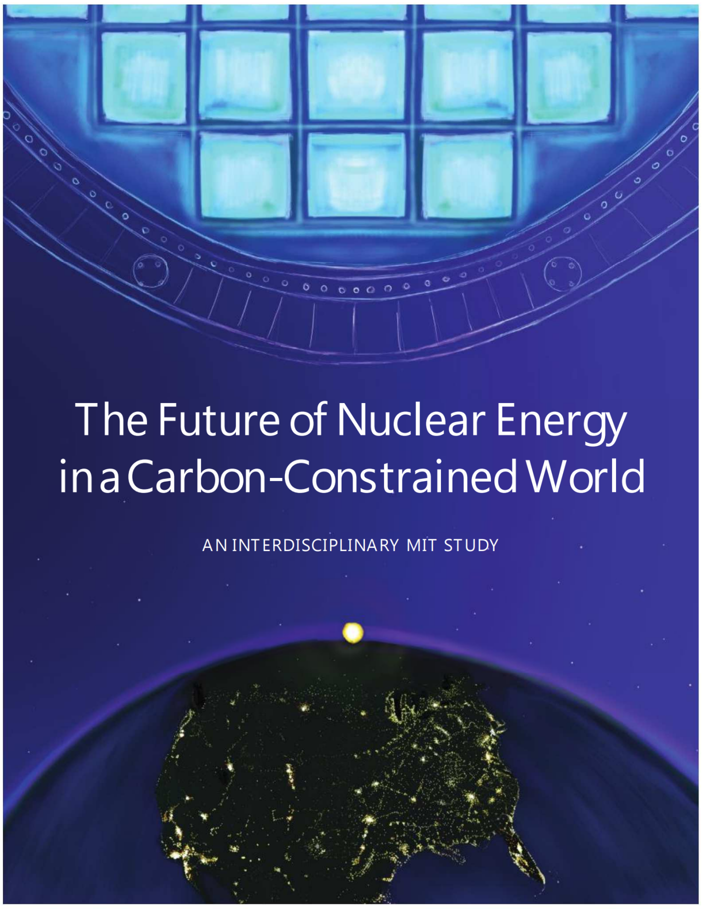
(5) 기업의 인허가용 실증로 건설 부지를 정부가 마련

실증로 부지는 기업이 선택한 다양한 원자로형을 수용 할 수 있어야 한다. 정부는 적절한 지원과 감독 (안전 규약, 설비, 환경평가 및 승인, 핵연료주기 서비스)을 제공 하며 모든 시험에 함께 직접 참여해야 한다.

(6) 선진 원자로의 실증로 시험 및 상업적 이용을 위한 재정 지원 계획의 수립: (a)규제 인허가 비용의 분담, (b) 연구 및 개발 비용의 분담, (c) 세부적 기술 목표 달성의 지원,(d) 초기 신규 실증로 및 새로운 유형의 원자로에 대한 지원

본 연구에 대한 자세한 논의는 연구 보고서의 개관 및 본문에 수록되었으며, 각 장은 원자력 에너지의 가능성, 원자력 발전소의 비용, 선진 원자로 기술의 평가, 원자력 산업의 비즈니스 모델과 정책, 원자로 안전 규제 및 인허가의 다섯 가지 주제로 구성되었다.

Massachusetts
Institute of
Technology



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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

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

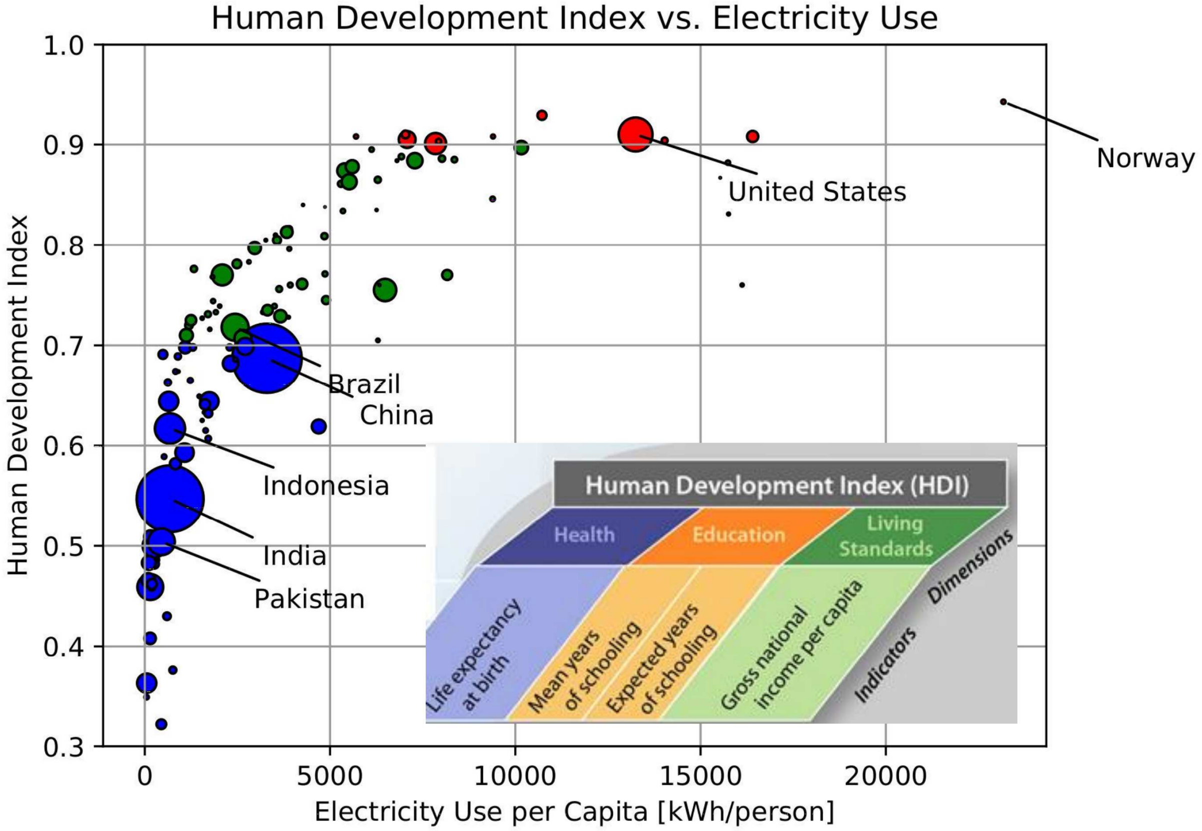
The Washington Post
San Onofre nuclear power plant to shut down

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)

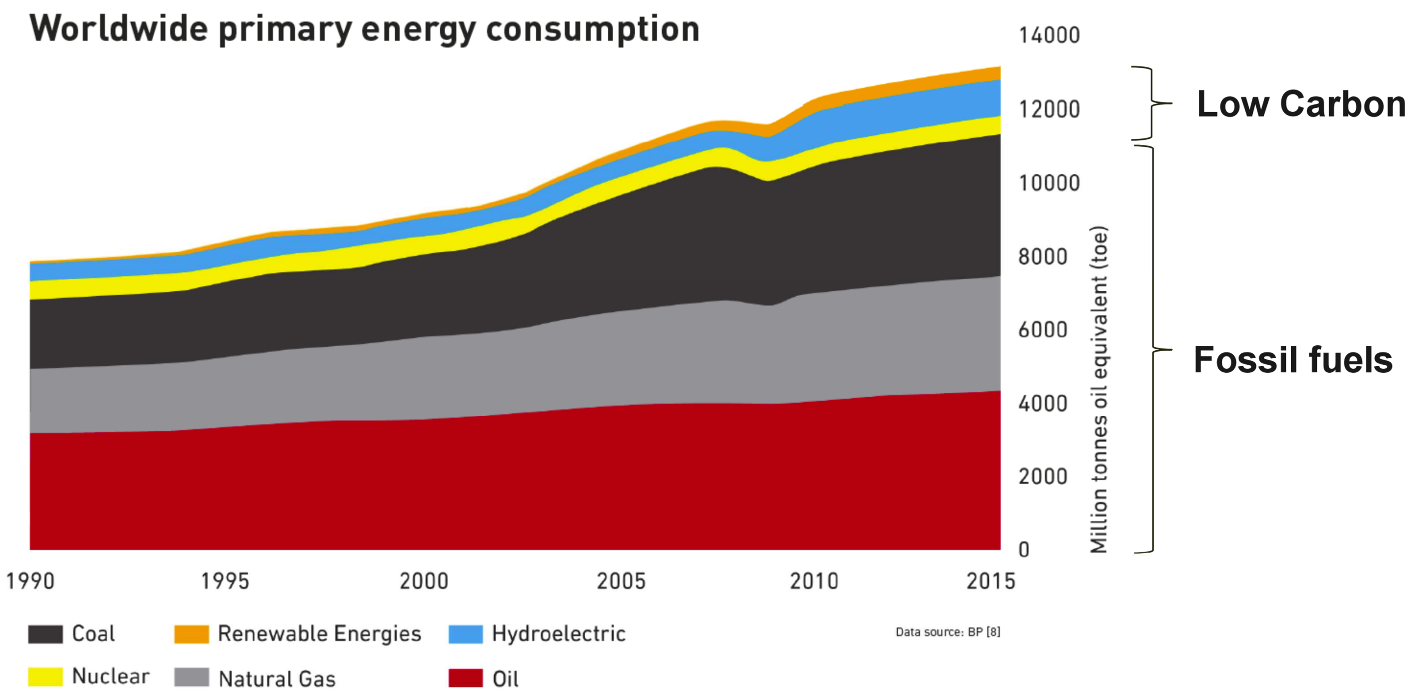
The big picture

The World needs a lot more energy



Global 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?

Some say yes

gtm:

IPCC: Renewables to Supply 70%-85% of Electricity by 2050 to Avoid Worst Impacts of Climate Change

Mark Jacobson
(Civil and Environmental Eng., Stanford)
"There is no technical or economic barrier to transitioning the entire world to 100 percent clean, renewable energy with a stable electric grid at low cost"

Barbara Hendricks
(Minister for the Environment, Germany)
"The Energiewende is the cornerstone of our climate policy. We want to encourage other countries to follow our example."

Some say no

Union of Concerned Scientists For Nukes!

Activist group finally recognizes that it can't achieve its energy and climate goals without nuclear power.

We need a low-carbon electricity standard. A well-designed LCES could prevent the early closure of nuclear power plants while supporting the growth of other low carbon technologies.

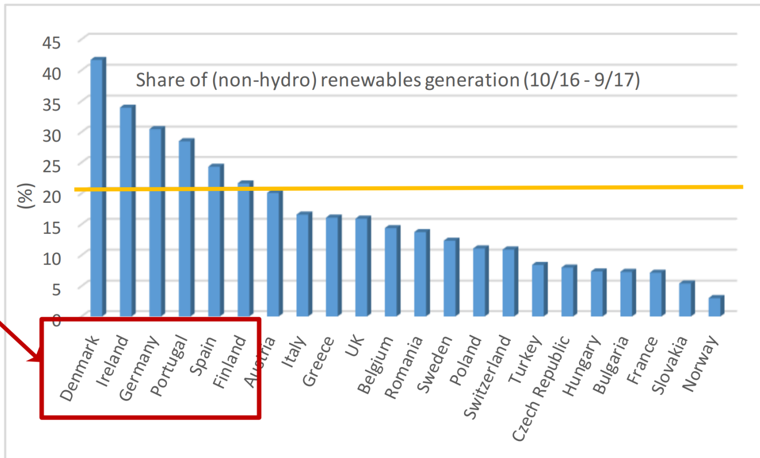
Ken Caldeira, Kerry Emanuel, James Hansen, Tom Wigley (Climatologists)
"There is no credible path to climate stabilization that does not include a substantial role for nuclear power."

Emmanuel Macron (President of France)
"My priority in France, Europe and internationally is CO_2 emissions and (global) warming… What did the Germans do when they shut all their nuclear in one go?… They developed a lot of renewables but they also massively reopened thermal and coal. They worsened their CO_2 footprint, it wasn't good for the planet. So I won't do that."

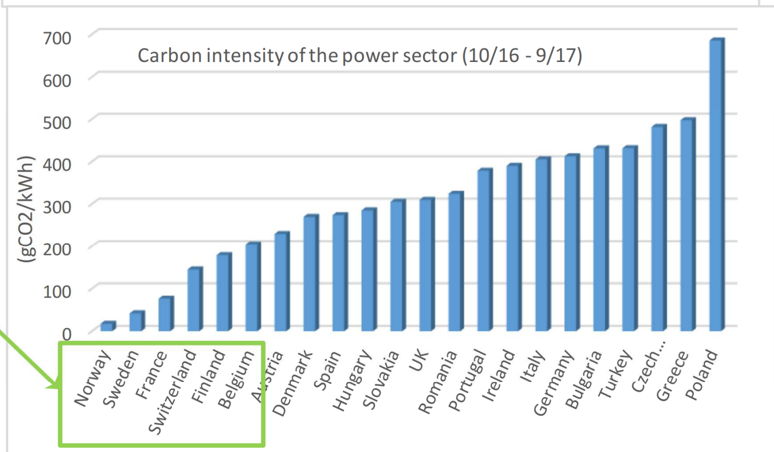
Ernie Moniz (former U.S. Energy Secretary)
"I know we can't get there [meeting carbon dioxide reduction goals] unless we substantially support and even embolden the nuclear energy sector."

Let's look at the evidence

EU countries with high capacity of solar and wind



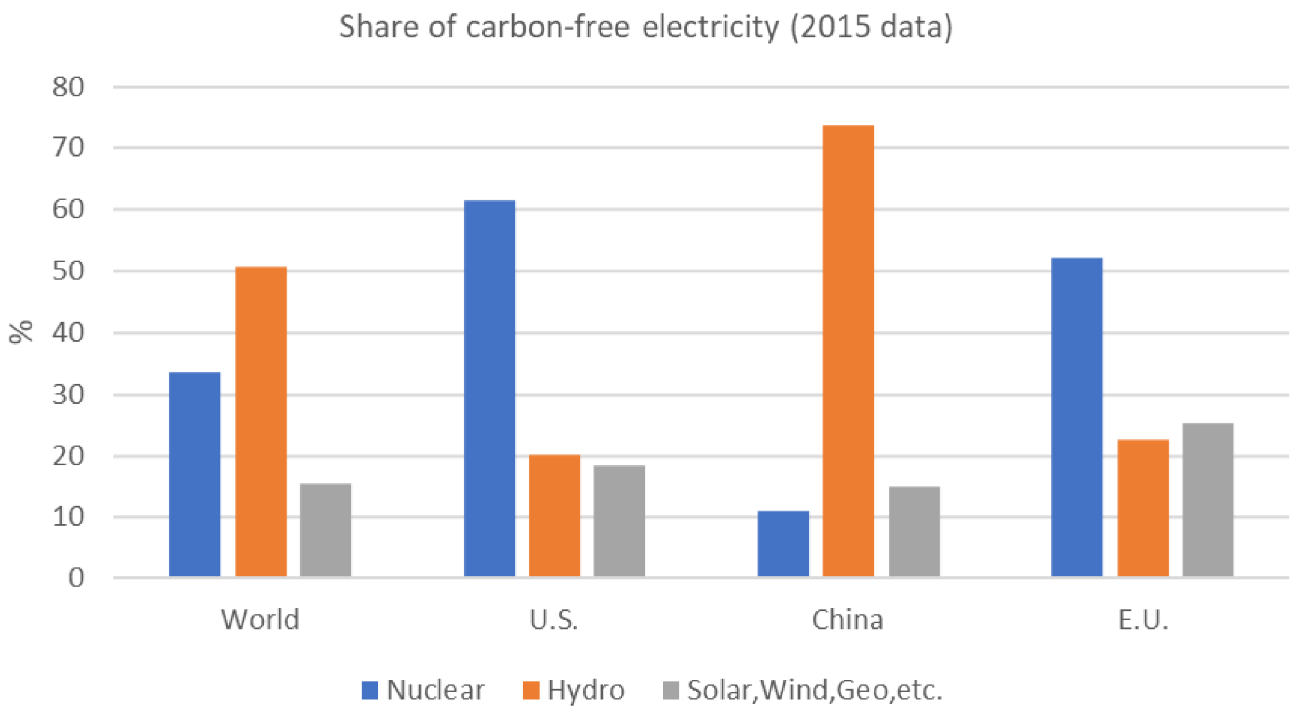
EU countries with low carbon intensity



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

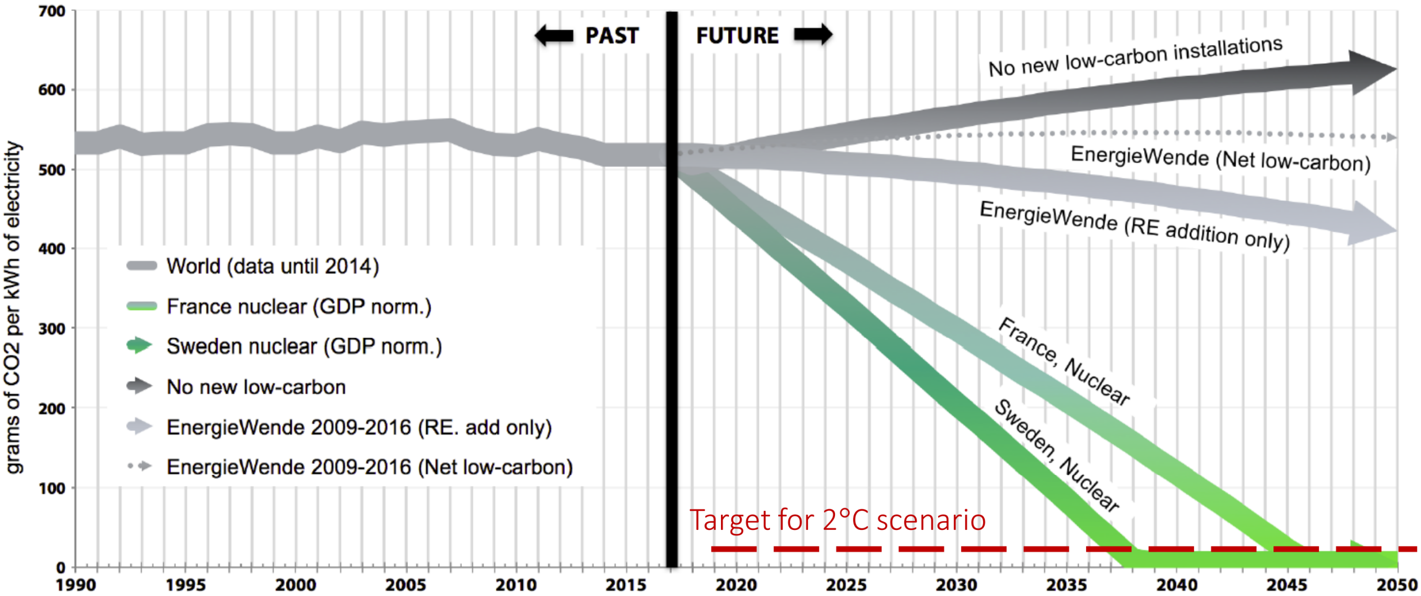
Low carbon intensity correlates with nuclear and hydro

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



Do we need nuclear to deeply decarbonize the power sector?

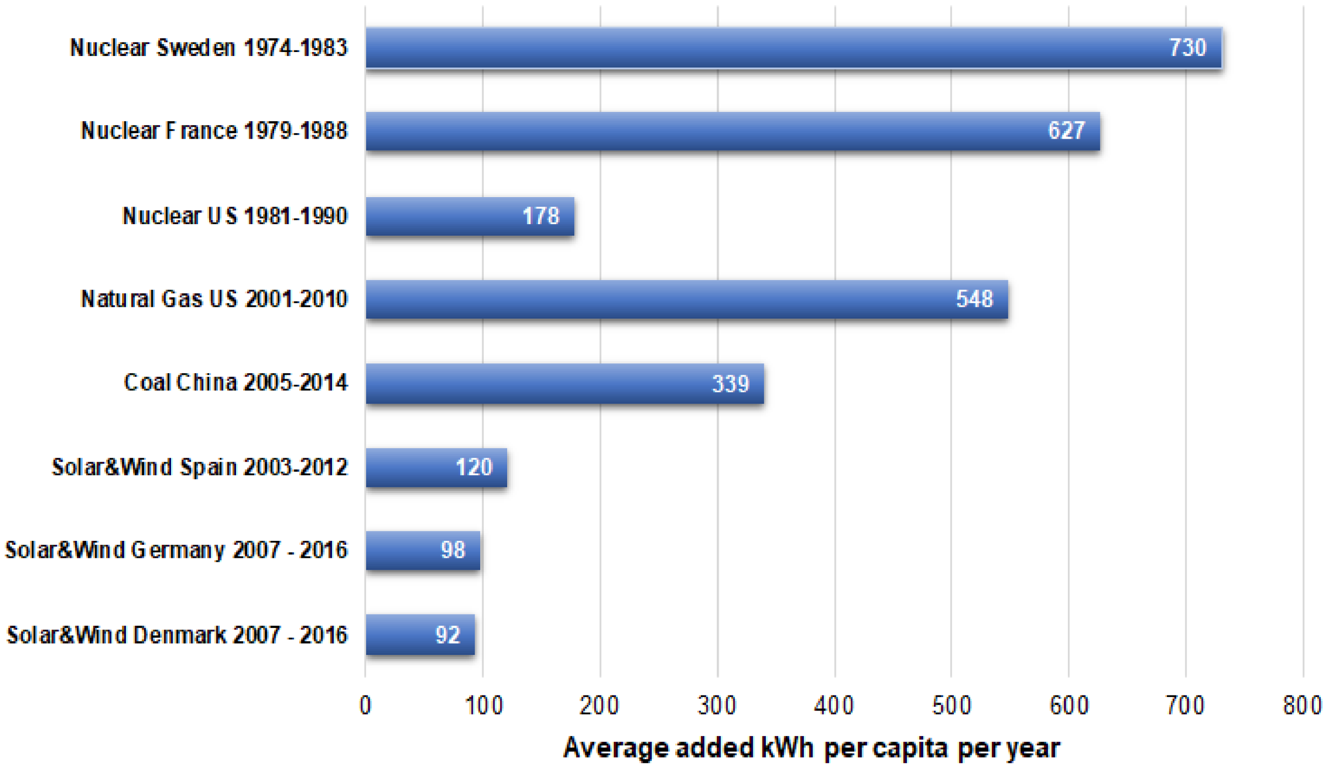
The scalability argument



Source: Staffan Qvist, 2018

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

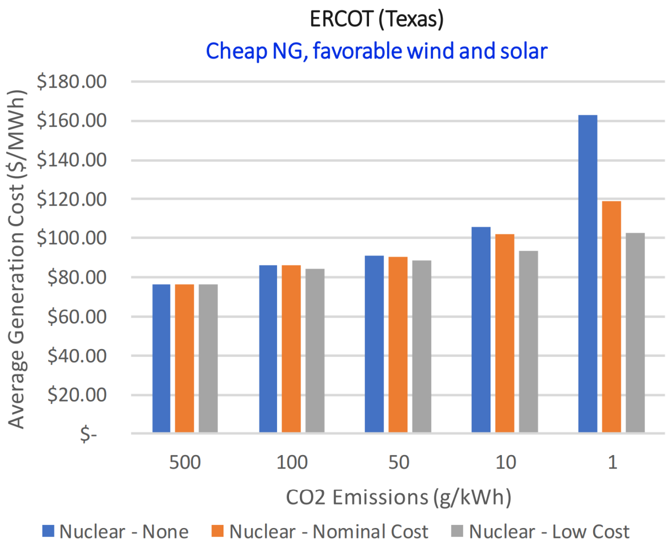
The scalability argument (2)

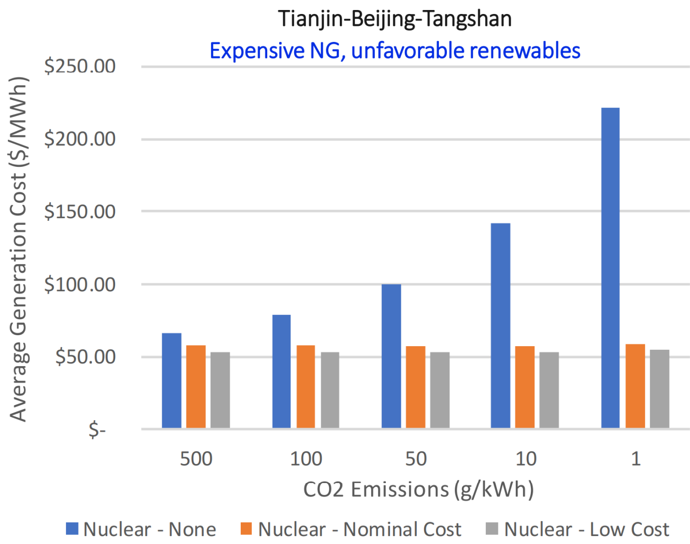


Nuclear electricity can be deployed as quickly as coal and gas at a time of need

The economic argument

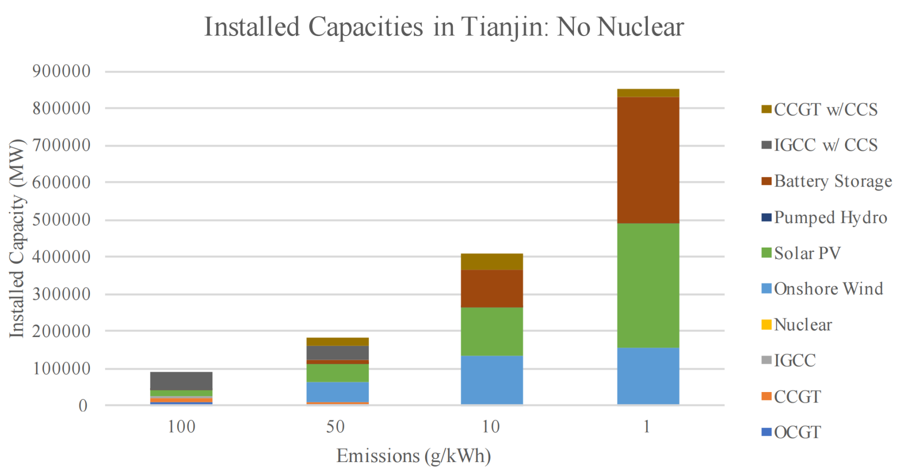
Excluding nuclear energy drives up the average cost of electricity in low-carbon scenarios





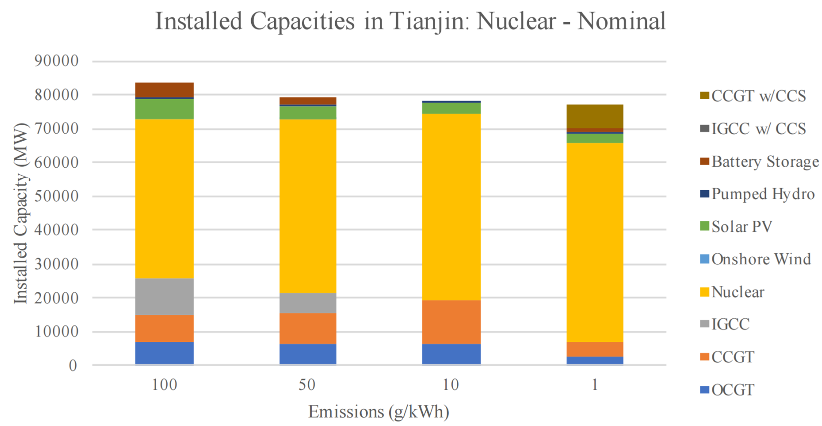
Simulation of optimal generation mix in power markets
MIT tool: hourly electricity demand + hourly weather patterns + capital, O&M and fuel costs of power plants, backup and storage + ramp up rates

Tianjin-Beijing-Tangshan Results

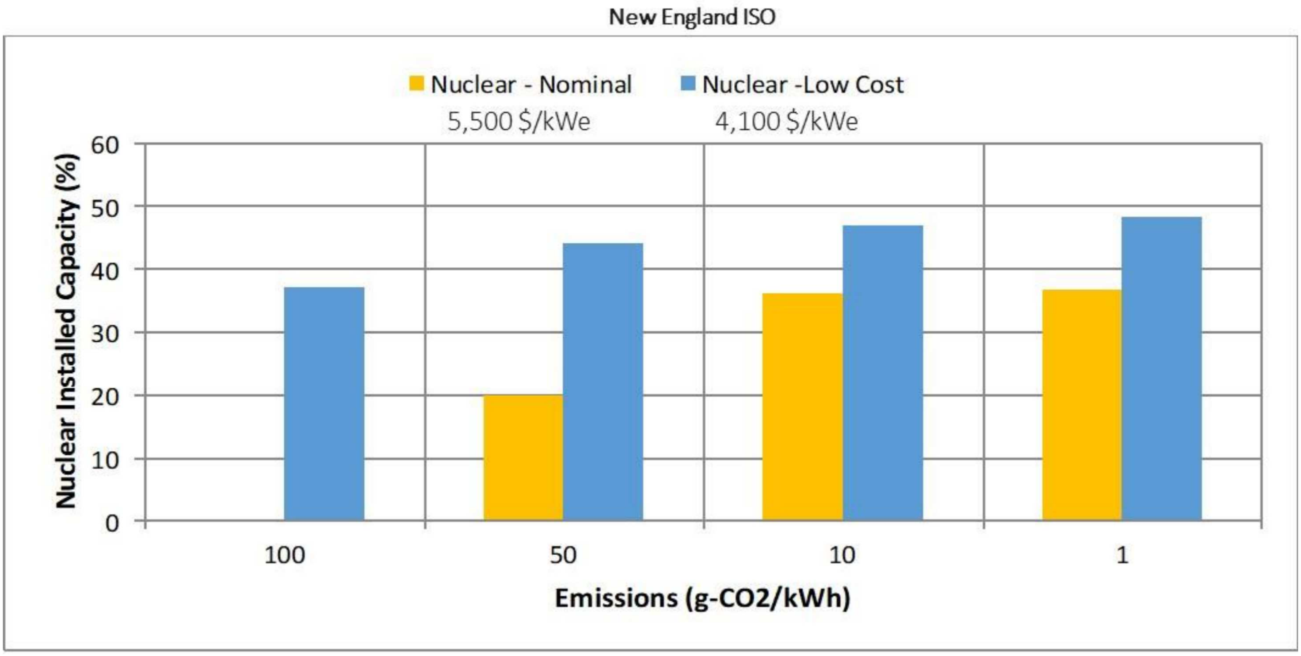


To meet constraint without nuclear requires significant overbuild of renewables and storage

By contrast, installed capacity is relatively constant with nuclear allowed

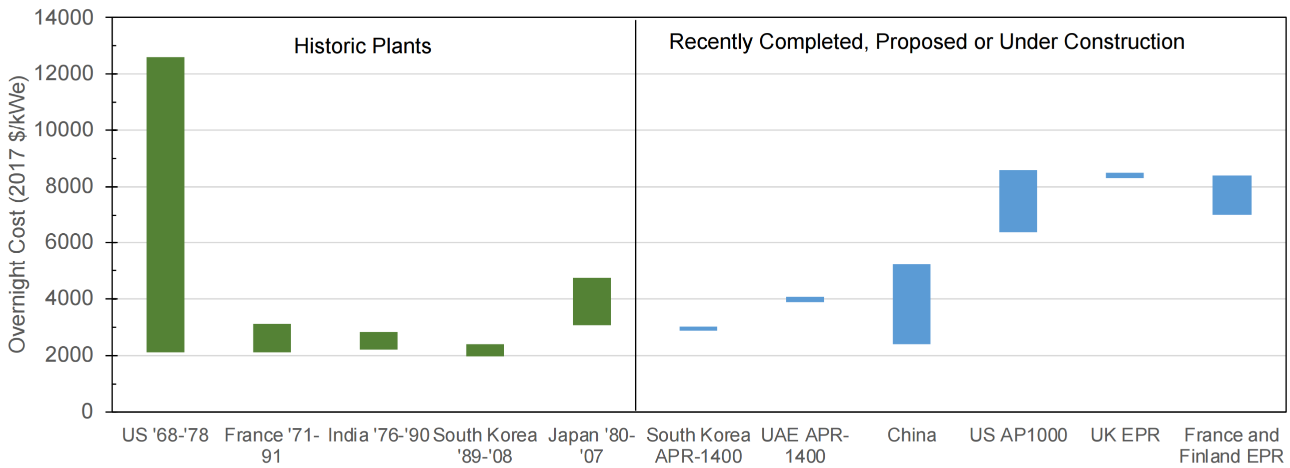


The business opportunity for nuclear expands dramatically, even at modest decarbonization targets, if its cost decreases



The cost issue

Nuclear Plant Cost

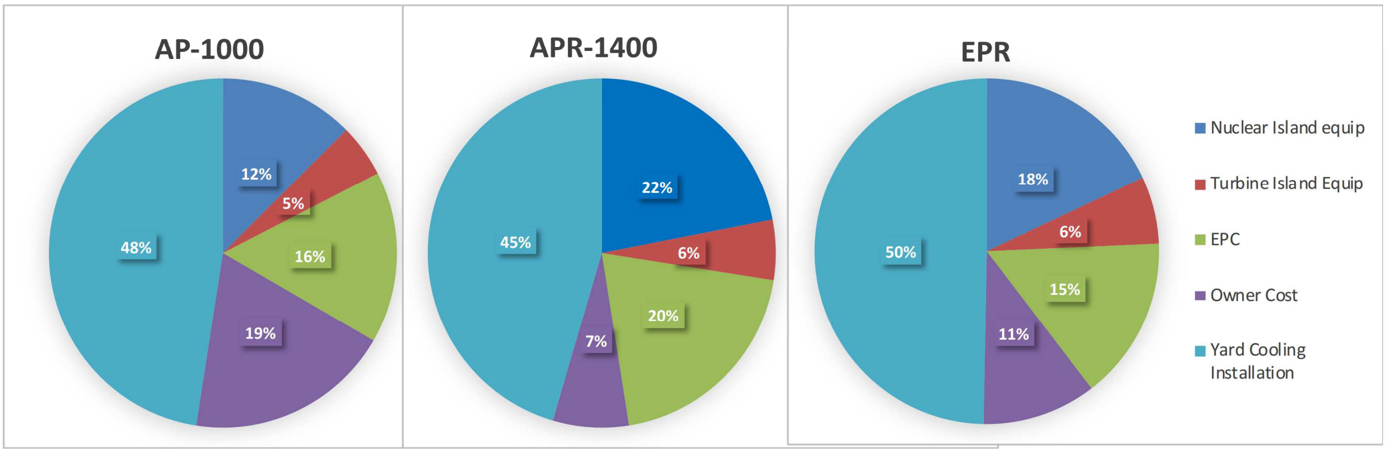


An increased focus on using proven project/construction management practices will increase the probability of success in execution and delivery of new nuclear power plants

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.

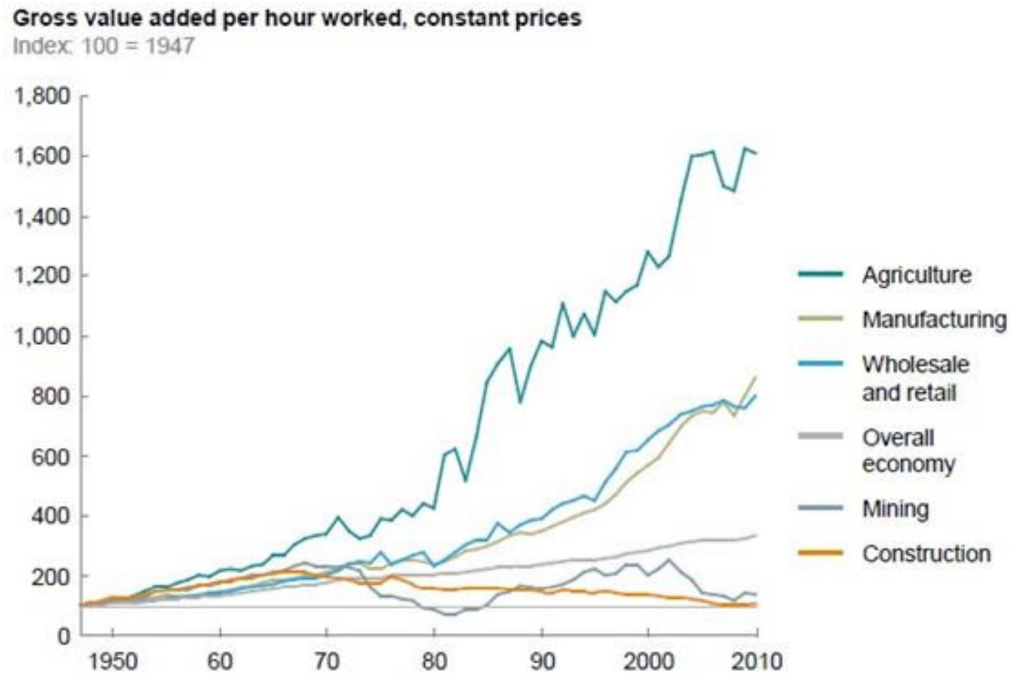
Nuclear Plant Cost (2)



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

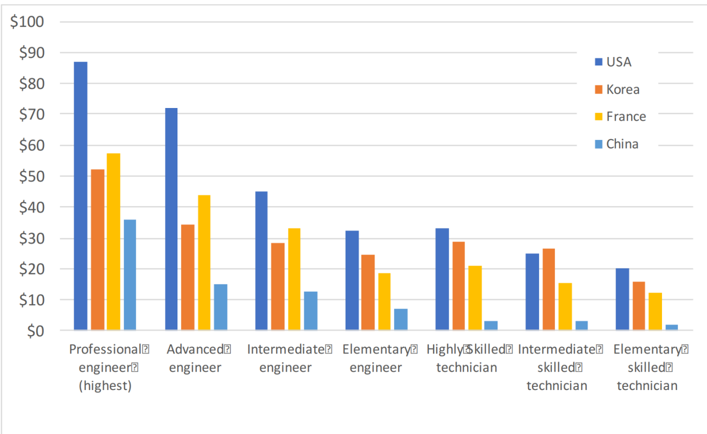
Civil works, site preparation, installation and indirect costs (engineering oversight and owner's costs) dominate

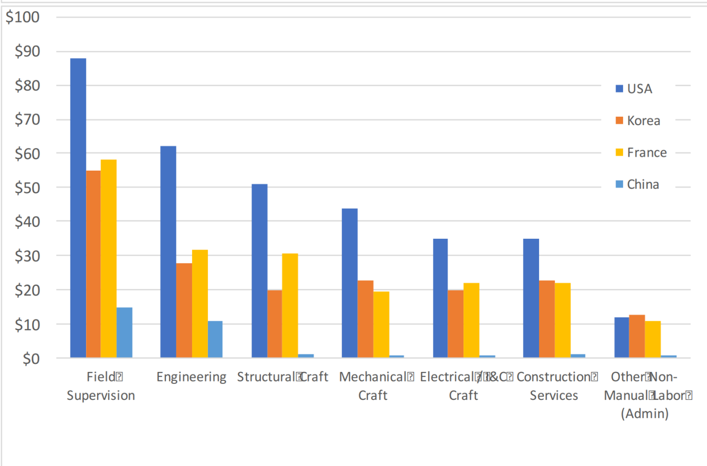
Why are nuclear construction projects in the West particularly expensive?



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)

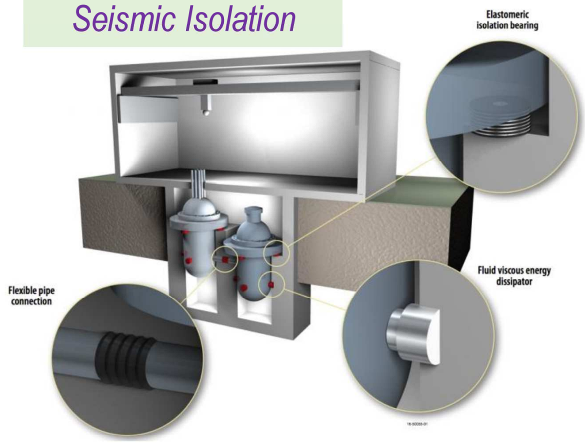
Source: Bob Varrin, Dominion Engineering Inc.

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

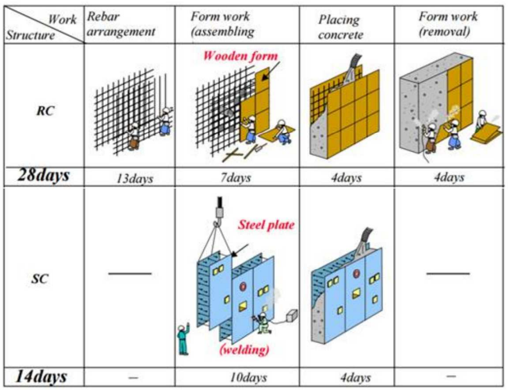
(True for all plants and all technologies. Without these, the inherent technological features will NOT produce the level of cost reduction necessary)

Standardization on multi-unit sites

Seismic Isolation



Advanced Concrete Solutions



Work / Structure	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	–

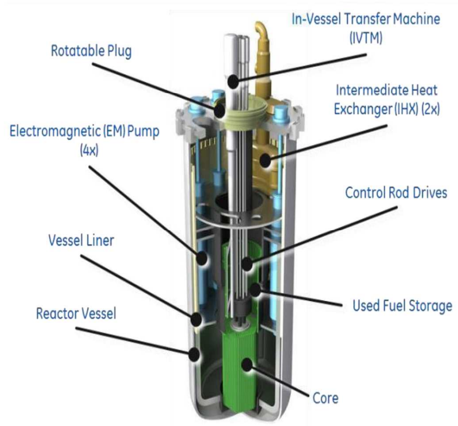
Modular Construction Techniques and Factory Fabrication

Advanced reactors

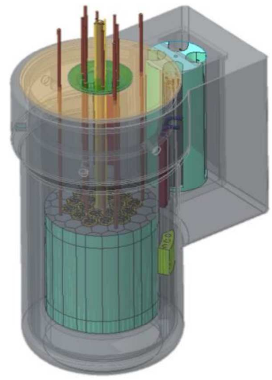
Advanced Reactors (Generation-IV)

High Temperature Gas-Cooled Reactors

Sodium Fast Reactors

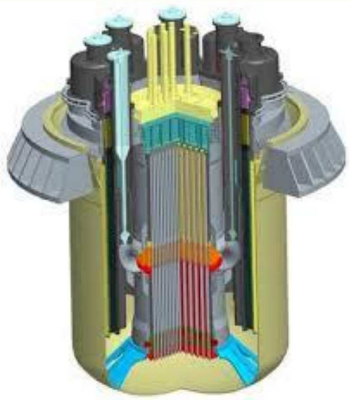


Fluoride High Temperature Reactors

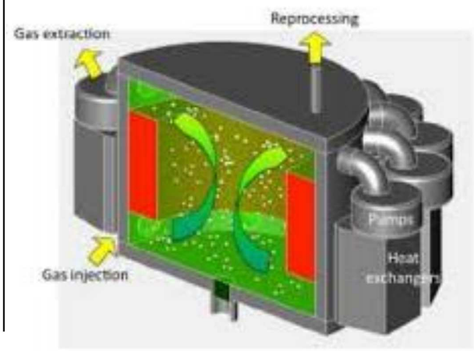


Gas-Cooled Fast Reactors

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.

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

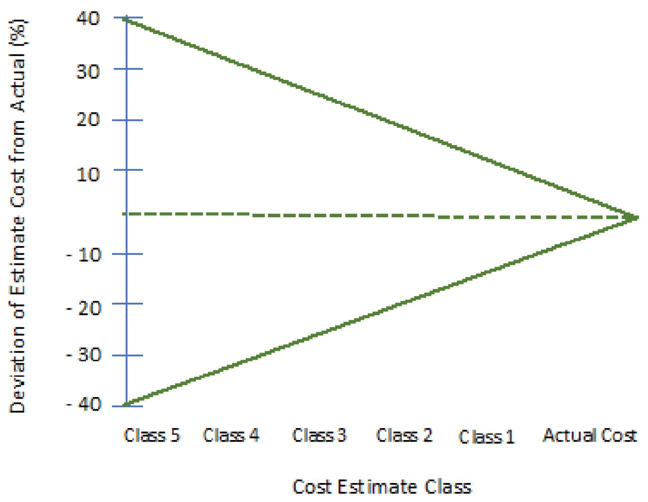
Cost ($/kWe)	HTGR	SFR	FHR (Large)	FHR (Small)	MSR
Machine Size	4 x 600 MWth	4 x 840 MWth	3400 MWth	12 x 242 MWth	2275 MWth
Design Stage	Conceptual approaching Preliminary	Conceptual approaching Preliminary	Early conceptual	Early conceptual	Early conceptual
Direct Cost	2400	2500	2100	2300	2500
Indirect 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

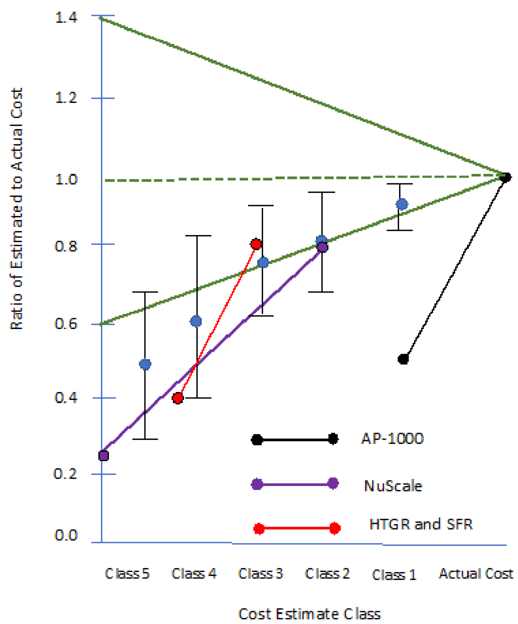
Independent cost estimates for advanced reactors confirm importance of civil works (buildings and structures) and indirect costs, and do not suggest significant cost reduction with respect to LWRs

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.

The government role

Existing Reactors

- Existing nuclear reactors are cost-efficient providers of low-carbon electricity
  - Recognized in *Zero Emission Credits* established in US states NY, IL, NJ
- Premature closures undermine efforts to reduce CO_2 and other power sector emissions
  - Increase the cost of achieving emission reduction targets
- Life-extensions of existing reactors are usually a cost-efficient investment

Existing reactors (the example of Spain)

Table 14: Relative System Costs for Incremental Low Carbon Generation from Alternative Portfolios Benchmarked to 7 Nuclear Plant Life Extension

		[A] N7	[B] S7	[C] W7	[D] SW7	[E] WS7
[1] Incremental Capacity	(MW)	7,117	109,800	30,160	49,134	32,411
[2] Incremental Generation	(GWh)	46,015	46,011	46,014	46,838	46,014
[3] Incremental Capacity Factor		74%	5%	17%	11%	16%
[4] Incremental Unit Cost	(€/MWh)	34.96	157.02	61.24	76.27	60.95
[5] Incremental System Cost, gross annual	(€ millions)	1,609	7,225	2,818	3,572	2,804
[6] Incremental System Cost, gross PV 10 years	(€ millions)	11,298	50,743	19,793	25,091	19,697
[7] Difference to Nuclear	(€ millions)		39,446	8,495	13,794	8,399
			349%	75%	122%	74%

Life-Extensions for all 7 reactors.

No nuclear scenarios.

The Climate and Economic Rationale for Investment in Life Extension of Spanish Nuclear Plants, by Anthony Fratto Oyler and John Parsons, MIT Center for Energy and Environmental Policy Research Working Paper 2018-016, November 19, 2018.
http://ssrn.com/abstract=3290828

Electricity Market Policy

- Current wholesale electricity prices do not fully compensate nuclear plants for the low-carbon attribute.
- Out-of-market subsidies target renewables exclusively, reducing market revenues to nuclear.
  - Encourages premature closure.
  - Discourages investment in life-extensions.
- Public policies to advance low-carbon generation should treat all technologies comparably.
  - Recognized in recent solicitations by US state of CT.
  - Many alternatives: cap-and-trade, carbon tax, clean energy standards.

How the government can aid deployment of new nuclear technologies (1)

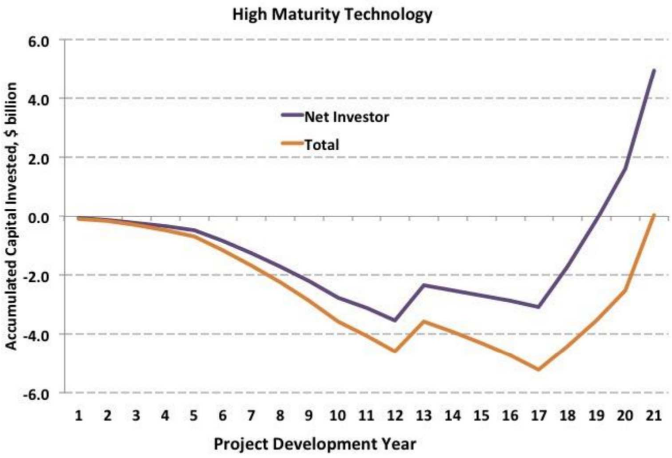
Governments should establish reactor sites where companies can deploy prototype reactors for testing and operation oriented to regulatory licensing.

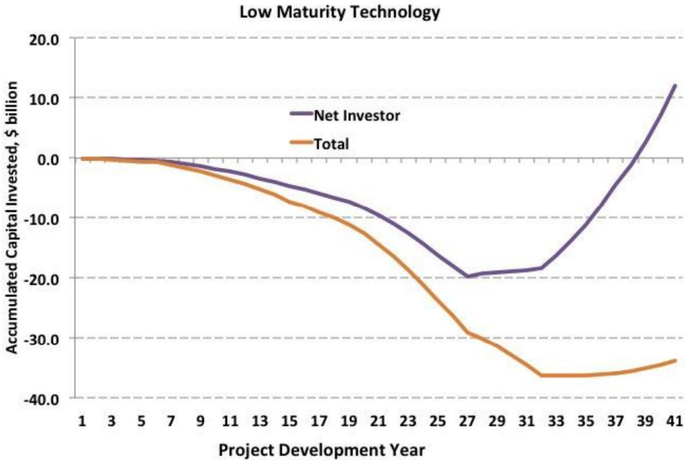
- Government provides site security, cooling, oversight, PIE facilities, etc.
- Government provides targeted objectives, e.g. production of low-cost power or industrial heat, for which it is willing to provide production payments as an incentive

- 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 the government can aid deployment of new nuclear technologies (2)

High upfront costs and long time to see return on investment





Early government support helps. 4 "levers":

- Share R&D costs
- Share licensing costs
- Milestone payments
- Production credits

Study Team

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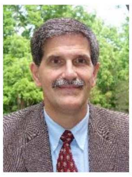
Co-Director
Prof. Jacopo Buongiorno (MIT)



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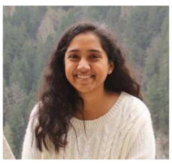

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Neil Rasmussen

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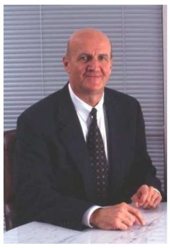

Zach Pate

and in-kind contributions from

INL Idaho National Laboratory

Dominion Engineering, Inc.

The Breakthrough

Lucid Strategy

Blumont

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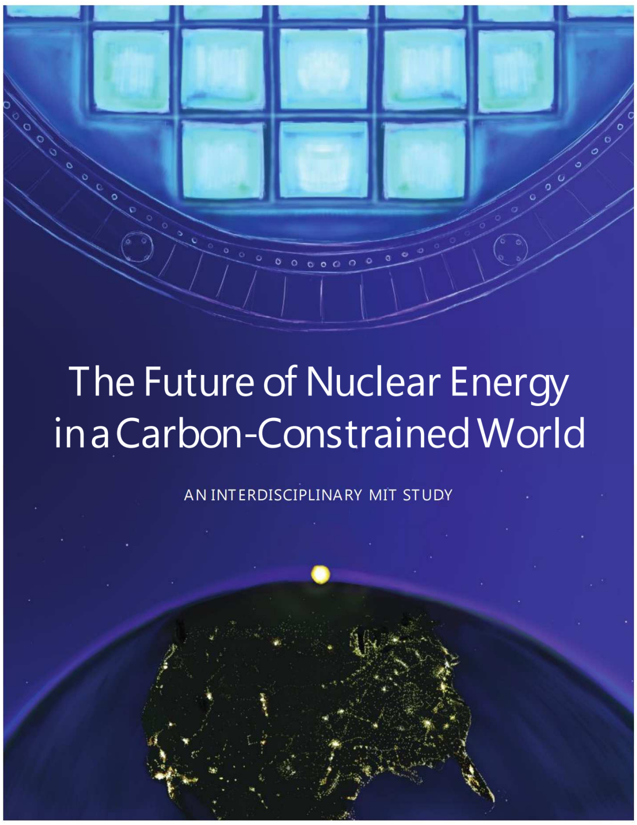
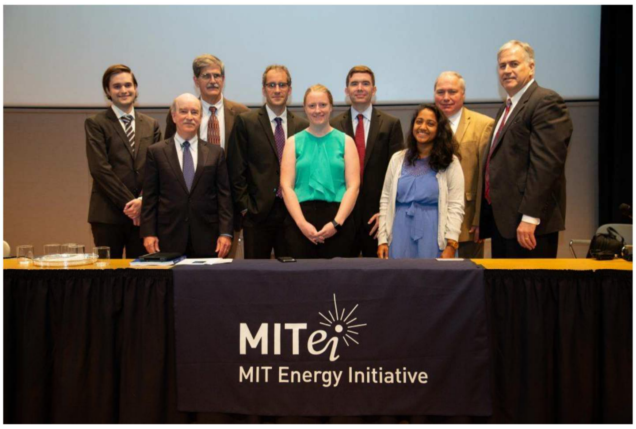


Dissemination



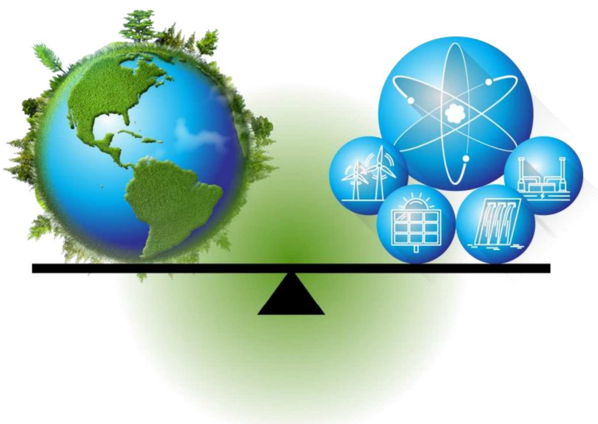
Report Online Release: Sep 3, 2018
Executive summary translated in
French, Japanese, Korean and Chinese

Rollout Events
London (Sep 2018), Paris (Sep 2018), Brussels (Sep 2018)
Washington DC (Sep 2018)
Tokyo (Oct 2018)
Seoul (Jan 2019), Beijing (Jan 2019)

51 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), INPO CEO Conf Nov 2018 (JB), Total S.A. at MIT Nov 2018 (JB), G4SR-1 Conf. Ottawa Nov 2018 (JB), Masui ILP MIT Nov 2018 (JB), Lincoln Labs MIT Nov 2018 (JB), Foratom Spain Madrid Nov 2018 (JB), Orano Paris Nov 2018 (JB), NAE Dec 2018 (Corradini)

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**



APR1400: From Development to Deployment

Seung Jong OH

KEPCO International Nuclear Graduate School

After reading MIT report,

- It demonstrates the role of nuclear in decarbonization
- High cost of new nuclear project is a key issue
- It examined various options including SMR and Advanced Reactors
- I consider US still led the way with 99 units operating, supplying 20% of electricity
- To maintain the nuclear contribution in US, ALWR has a role to play in replacing retiring NPPs
  - RDDD cycle for nuclear is lengthy
  - 20 years for APR1400 development to deployment
- Introducing ALWRs has been difficult, specially in US and Europe
  - Successful completion of Vogtle project is important
- A roadmap similar to near-term deployment by US DOE would be valuable
  - Sharing the construction experience and lessons learned would be the first step in developing successful roadmap
  - APR1400 experience would be useful in this regard: One in operation, nine under construction

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Nuclear Energy in US

- In US, there are 99 operating NPPs with 99,635MWe baseload capacity
  - 92.2% capacity factor (2017)
- It supplies 20% of electricity generation (2017)
- Most of plants received for 60 year operating licenses
- However, with cheap gas price, the pressure for premature shutdown is continuing
  - Seven units were shutdown prematurely between 2013 and 2018
  - Two units are expected to shutdown in 2019
- With state policies, 3 units were saved from premature shutdown in 2017 alone
- Plants will start to reach 60 year life from 2024
  - Half of NPPs will reach the point in 2036

APR1400: From Development to Deployment

- Transition from APR1400 Development to Deployment
  - Design optimization with detailed design
    - ✓ Customer need
  - APR1400 Constructability and Operability Review
  - Establishment of APR1400 Pre-project TF
    - ✓ Long lead items
    - ✓ Bid preparation
- Lessons Learned from the Construction of the First APR1400
  - FOAKE
  - Supply chain management
  - Regulatory stability

Development of APR1400 :Three Phases

- Conceptual Design
  - Evolutionary vs. Passive Option
  - Basic design requirement
- Detailed Design
  - Basic design of APR1400
  - SSAR
- Optimization
  - Design optimization
  - Detailed design

APR1400 Development Schedule

Development Schedule	'93	'94	'95	'96	'97	'98	'99	'00	'01
	Phase I				Phase II			Phase III	
- Phase I Dec.92~Dec.94)	· Select reactor type · Develope a concept design								
- Phase II Mar.95~Feb.99)			· Develope of a basic design · Issue a standard safety analysis report · Write design specifications for major components						
-Phase III Mar.99~Dec.2001)							· Achieve of a standard design certification · Optimize APR1400 design · Perform technology development for major issues in long-term base		

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Conceptual Design

- In U.S. System 80+, AP600 and ABWR were under development
- 'A 4000MWt class, evolutionary PWR' was chosen
  - Utilization of technology transfer as a part of YGN 3&4 project
  - Size of reactor
  - OPR1000 and System 80+ as the reference plants
- Use of EPRI ALWR Utility Requirement Document

Basic Design

- Level of details to be able to produce Standard Safety Analysis Report
- General Arrangement
  - 2 units
  - A slide along-type arrangement
  - Compound building between the unit
- Emphasis on development, including new design features

Key Design Features

- Four quadrant design
- PS concrete, double containment
- 2 loop NSSS design
- POSRV depressurization system
- In-containment refueling water storage tank
- Severe accident mitigation features; PARs, ERVC capability
- Digital I&C and compact workstation MCR
- 52"LSB Turbine design (GE)

Design Optimization

- With the basic design completed, the questions on whether it is ready for deployment was raised
- Drop of coal price and economic crisis in Korea forced the reevaluation of the economy of APR1400
- At the same time, meeting the customer needs becomes important
  - Constructability and Operability Review

Optimization topics

- Double containment
- Daily load follow operation
- MMIS
- Site envelope characteristics
- Safety injection system (DVI + FD)
- Passive secondary condensing system
  - For each item, integrated evaluation was performed (constructability, cost, safety impact, operability and maintainability)

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Independent Review

- APR1400 Constructability and Operability Review
  - Independent review by KEPCO construction staff and operation staff
  - New design features and its impact on construction and operation
    - ✓ Examination of integrated evaluation of optimization topics
  - Issues related to the increase of power rating from 1000MW to 1400MW

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Transition to the Construction

- Included in the Basic Plan for Electricity Supply and Demand (MOTIE, January 2000)
- KHNP established Construction Basic Plan (Feb. 2001)
  - Formation of Preproject TF
  - NSSS Supply Contract (March 2006)
  - Construction Contract (March 2007)
- Approval of NPP Execution Plan (Sept. 2007)
- Construction Permit (April 2008)

Transition to the Construction

- APR1400 Construction Preproject TF
  - Joint operation of construction project team (HQ) and the APR1400 development team
    - ✓ From Jan. 2003 to Dec. 2004
  - NSSS Supply Contract (Technical bid preparation and review)
    - ✓ Long lead items
    - ✓ FOAKE (MMIS, Safety Injection system, etc.)
  - Construction
    - ✓ Bid spec review
    - ✓ Construction schedule evaluation
  - Licensing support

Long Lead Item

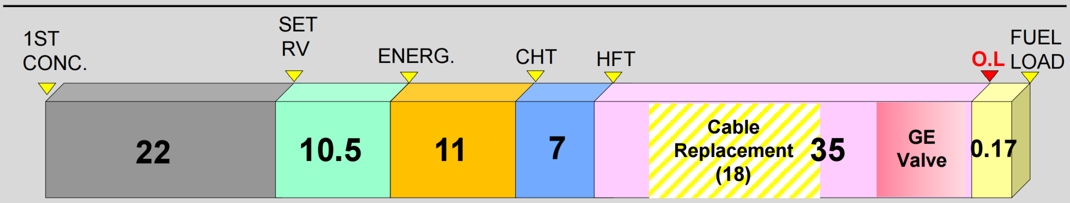
- Reactor vessel, steam generator, and turbine need long lead time to manufacture and install at site
- Design should be completed early and manufacturing should start with enough lead time
  - Management of the long lead items are very important for both owners and contractors
  - KHNP utilized ATP (Authorization to Proceed) approach

SKN 3&4 Construction Project

- Reactor Type: PWR (APR1400)
- Capacity: 1,400MW X 2 units
- Construction Period: Sep. 2007 – Sep. 2014 (from Site Grading to COD of Unit 4)
- Contractor (based on the standard contract package)
  - NSSS Supplier: Doosan Heavy Industries & Construction Co.
  - Architect Engineering (A/E): Korea Power Engineering Co. (KOPEC)
  - Construction: Hyundai/Doosan/SK Consortium

SKN 3 Project Key Milestone

Key Milestones	Planned (2009)	Current Schedule
First Concrete	0	0
Set Reactor Vessel	22.5	22
Energize Start-up Transformer	27.5	32.5
RCS Cold Hydro Test	43.5	43.5
Hot functional Test	47.5	50.5
Operation License	--------	85.5
Fuel Loading	51.5	85.67



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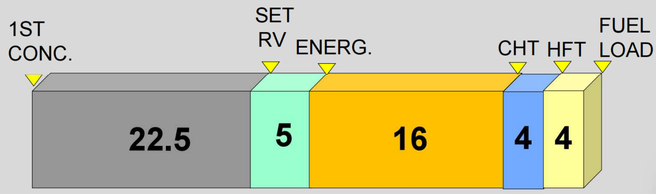
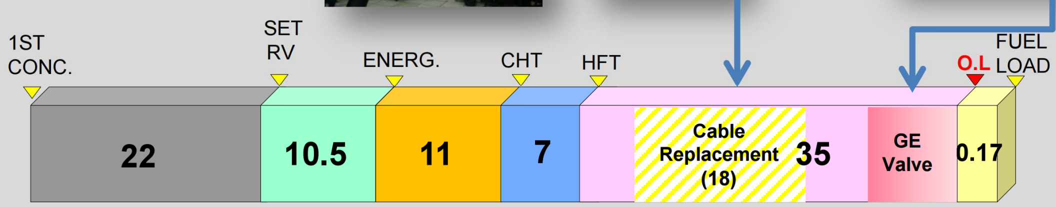
SKN 3 Project Key Milestone

- Planned (2009)



- Actual



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Schedule Impact Items

- FOAKE
  - MMIS (requires installed equipment information)
  - ESF (IRWST, POSRV)
- Weakening Supply Chain
  - Safety grade cable (CGI)
  - Valves (quality issues)
- Regulatory review
  - Two-step licensing
  - Post Fukushima action items
  - Inputs from Baraka project and NRC DC review

APR1400 Follow-on Projects

- Nine APR1400 construction projects are in progress
  - Projects progress to hot functional tests smoothly, close to the planned schedule
  - With Fukushima accidents, concern on earthquake risk delays the O/L step in Korea
- Barakah1 project started after ShinUljin 1 project (4th unit)
  - Project structure is the same as SKN project
- US NRC issued Standard Design Approval in September 2018
  - First application reviewed on schedule

Project Management Experience

- APR1400 detailed design was fixed
  - SDA received by NSSC in 2002
  - Note: MMIS requires detailed equipment information
- FOAKE is expensive (from licensing to commissioning)
- DHIC participated from the development phase of APR1400
  - Long lead items
- Feedback and buy-in of KHNP construction and operation staff were keys to successful transition to deployment
  - Constructability/operability review
  - Construction Pre-project TF
- The same contracting structures used in all projects
  - Vertical integration
  - Transfer of knowledge/experience to next projects
- Challenges are
  - Maintain supply chain with weakening NPP market
  - Difficult political environment and new regulatory requirements

Conclusion

- MIT report shows the importance of nuclear power in decarbonization scenarios
  - There is a need for the new build to replace retiring NPPs
- Current environment in new build market for NPP forces the vendors to take higher risk
- In this environment, the assurance in performance, cost and construction schedule is critical
  - Maintaining robust supply chain is more difficult but critical
  - Regulatory stability is important
  - Need for new design features should be carefully examined before adoption into the design
- Collaborative effort between US and Korea to understand shortcomings and best practices in new build would be valuable
  - The experience we gained from building SKN3&4 and other ongoing APR1400 construction projects will be a plus in this regard

Thank you.


The Global Leading Institution in Nuclear Power Plant Engineering, KINGS