Economics of Nuclear Power and The Role of Nuclear Energy for Decarbonization

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OUTLINE

1. Why Japan went to Nuclear and the current evaluation of economics of nuclear power in Japan
2. Cost-benefit analysis for launching a NP program or a new NPP project
3. Role of Nuclear Energy for decarbonization

Why going to Nuclear? - case of Japan -

- AEC of Japan
  - Established in 1956, after “Atoms for Peace” address (UN) in 1953
  - Set NE policy in 1956…largely unchanged until 2011
- 57 commercial NPPs in 1966-2010, because of conceived benefits in:
  - a) Energy Supply Security: Nuclear as quasi-domestic energy contributes to shield from fluctuating fossil price,
  - b) Economics: cheap electricity
  - c) Technology for the future and industrialization
  - d) Environment: air pollution→ (later to) GHG emission reduction

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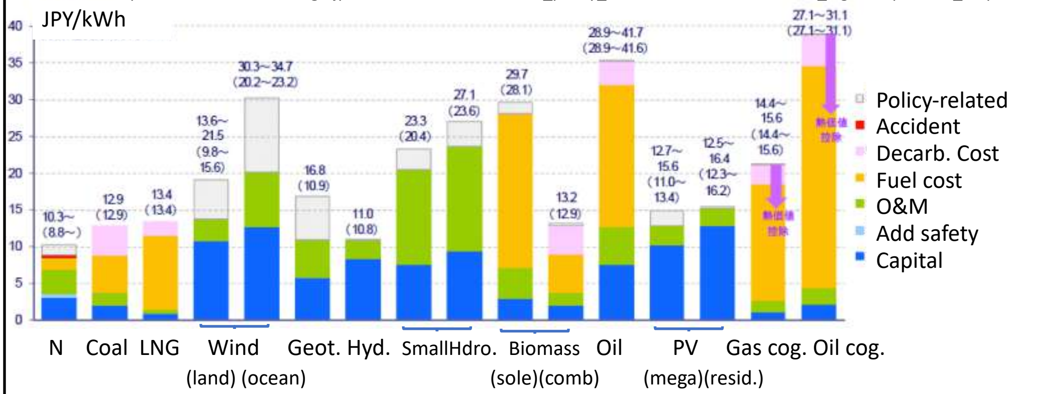
Comparison of power generation cost 2015 –Gov. of Japan-

IEEJ version of summary of cost evaluation WG by the Government committee

[source] https://www.enecho.meti.go.jp/committee/council/basic_policy_subcommittee/mitoshi/cost_wg/007/pdf/007_05.pdf



- 2030 slice comparison using LCOE
- Nuclear<Hydro<PV (w/FIT)<Coal<LNG
- Included;
  - Policy-related cost (tax such as for regulation, for local area vitalization, for Government support to R&D), Accident cost, Decarbonization cost (cap & trade CO2 emission right)
  - Sensitivity analysis

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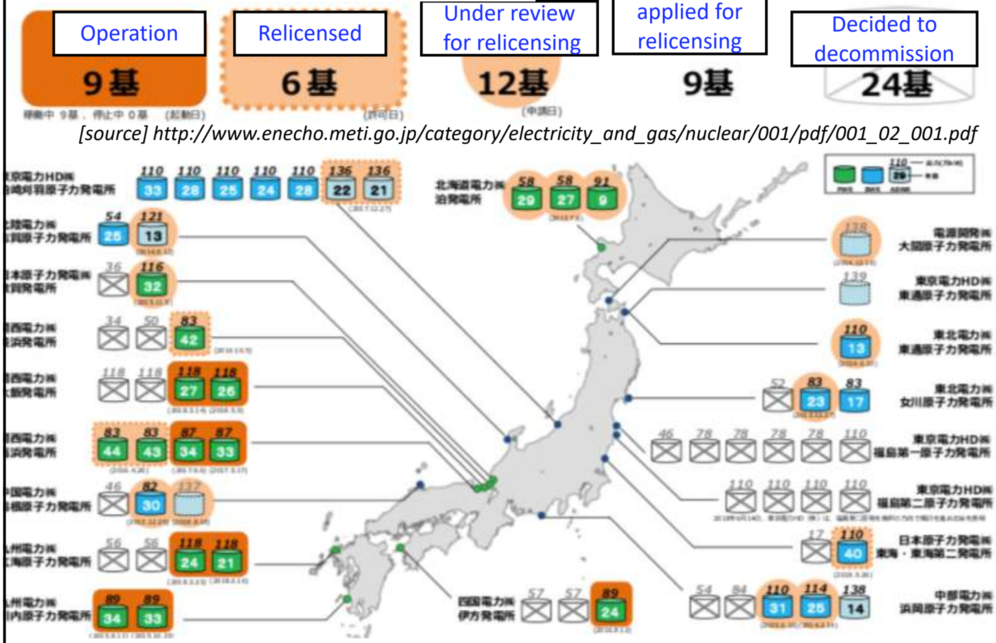
Japanese NPPs as of July2019

As of 8July2019



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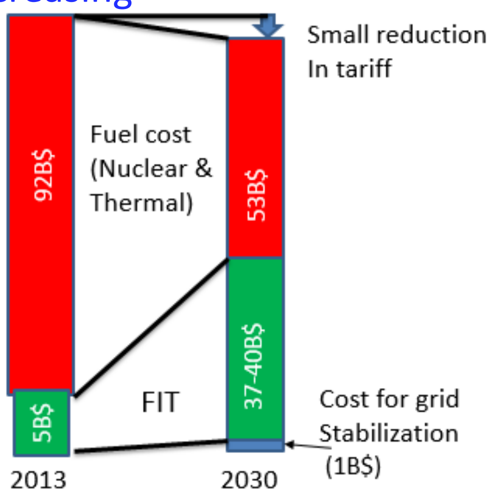
- Replacement of nuclear electricity by Import of oil/gas
  20 ~ 30 B$/year
- FIT in JPN
  20B$/year and is still increasing

[SOURCE] METI



Assuming 1US$~ 100JPY

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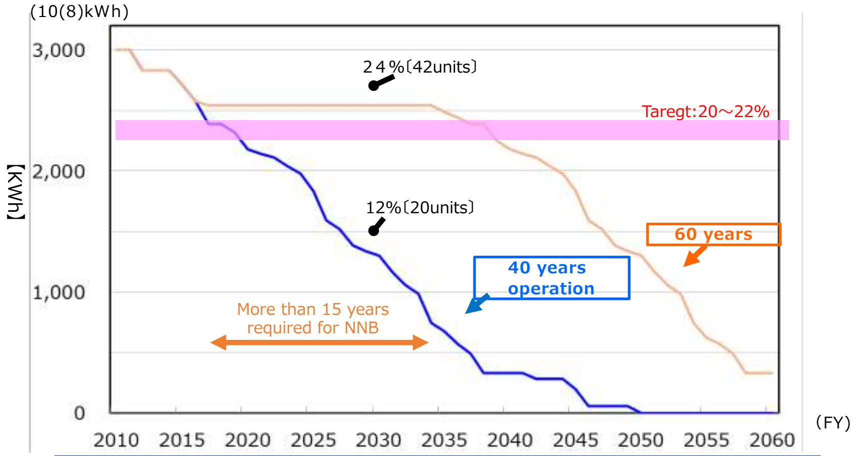
"More saving, more renewables, less nuclear" policy since 2011

Share of nuclear electricity in National Energy Strategy 2018 endorsed by Cabinet



In order to meet 20%～22% goal

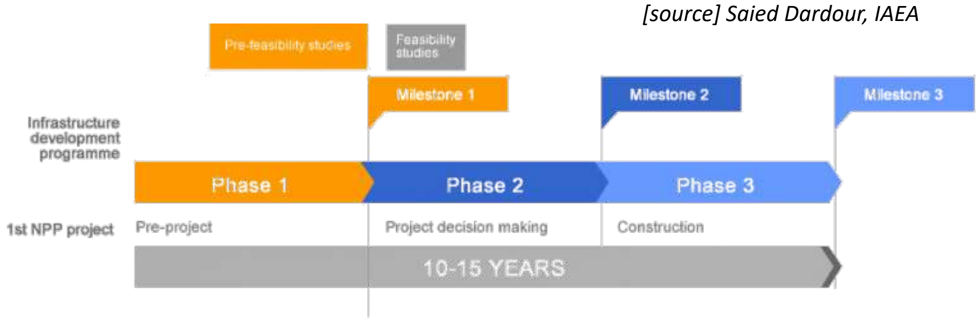
①Restart ②60 years operation ③NNB

1. Why Japan went to Nuclear and the current evaluation of economics of nuclear power in Japan
2. Cost-benefit analysis for launching a NP program or a new NPP project
   - 2.1. CBA for NE program or NNB?
   - 2.2. Context analysis
   - 2.3. Capital cost of NNB
   - 2.4. LCOE and VALCOE
   - 2.5. Accident cost
   - 2.6. Security value
   - 2.7. Large unit or SMR?
3. Role of Nuclear Energy for decarbonization

2.1. CBA for launching NE program or NNB?

- Relevance with the IAEA's milestone document (phase I, II, III)
  - ✓ Study of launching NE program as a whole before making a knowledgeable decision (phase I)
  - ✓ Study of a specific NPP project (FS in the beginning of phase II)

[source] Saied Dardour, IAEA



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Cost
- ✓ Investment (infrastructure, facility, land, research, associated fuel cycle related investment….)
- ✓ Cost for O&M, Cost for refurbishment and LTO, Fuel, public information….
- ✓ Accident cost

Benefit
- ✓ Revenue from Energy Supply (electricity, heat, energy carrier)
- ✓ Substitution for alternate more-expensive power generation
- ✓ Environmental value of clean energy supply (GHG, pollution)
- ✓ Security value (against fluctuating fossil price, supply security)
- ✓ Jobs and vitalization of local community hosting NPP
- ✓ Renewable smoothing by complementary use with renewables (enabler of reducing renewables curtailment, reducing network cost)
- ✓ Spin-off effect of Nuclear Science and technology (newcomers) to industrialization

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➢ Considerations be given in CBA to;

✓ Non-market values (Environment, Energy Supply Security)

✓ Characteristics of NE as a dispatchable clean energy that contribute to decarbonization with less system cost

✓ Risks of NPP project: political, financial, licensing, construction & supply chain readiness, public opposition (incl. against EPR), market risk (sales of nuclear electricity in a market with merit order of marginal cost marginal cost) ….

✓ Benefit from possible future expanded use of NE beyond just electricity production to heat/energy carrier and to NET

✓ Evaluation of individual PG source vs. scenario integration

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➢ Guidelines for CBA for investment project (>50M€) in EU
- Binding if seek for EIB funding
- NPP exempted
- Yet, valuable for justification of NNB

➢ Flow of analysis
- Context analysis (environment in which NPP is operated)
- Objectives
- Technical Feasibility of options
- Financial analysis
- Consideration of non-market values in Economic analysis from the viewpoint of the Society
- If green light, then go to risk management

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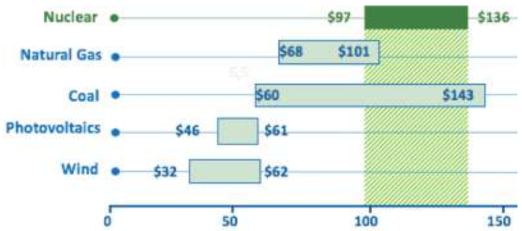
2.2. Context analysis
a. Deep penetration of intermittent renewables

- “Solar becomes the cheapest source of electricity generation in many places including China and India”
  (F. Birol, IEA OECD, 2017 World Energy Outlook)

- Comparison of unsubsidized levelized cost of electricity
  not including social/environmental externalities nor intermittency-related cost



[source] Lazard’s levelized cost of energy analysis (2016)

$/MWh

- “Why going to Nuclear at a time when renewables are cheap enough?”

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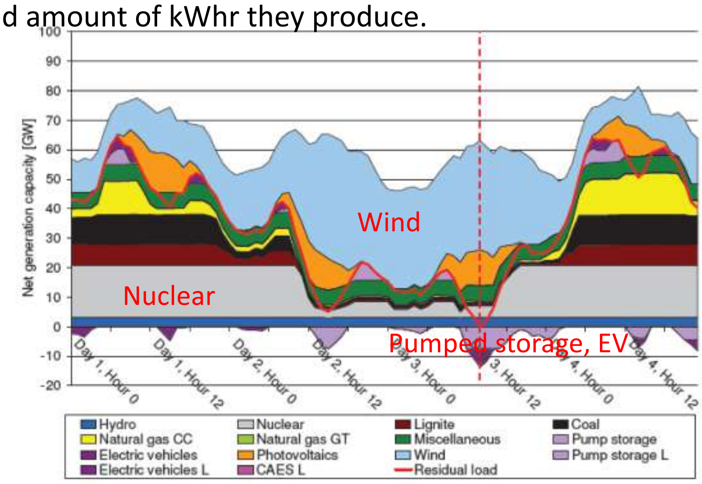
Deep penetration of intermittent renewables has rendered the concept of “baseload” obsolete

Although this Figure is hypothetical, it is still valid in a generic sense, and visualizes the economic difficulty faced by nuclear power plants due to reduced amount of kWhr they produce.

[SOURCE] Universität Stuttgart, “Compatibility of renewable energies and nuclear power in the generation portfolio”, 2009



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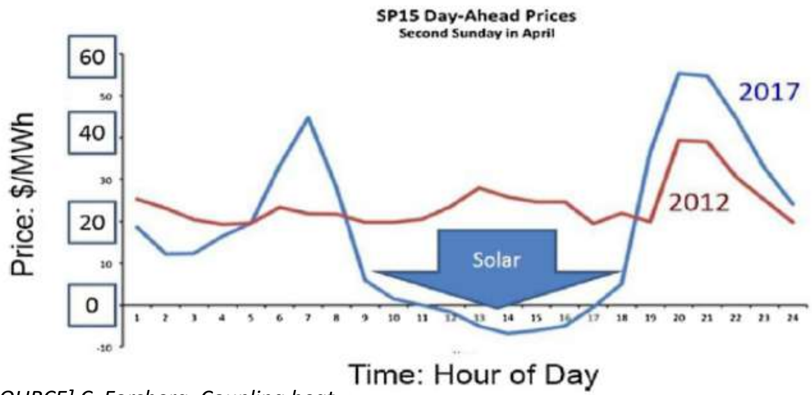
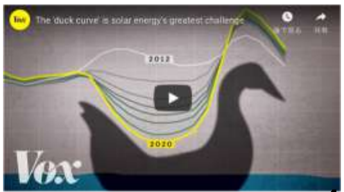
Excess Electricity Production Midday (California) Leading to "price collapse"



[SOURCE] C. Forsberg, Coupling heat storage to nuclear reactors for variable electricity output with baseload reactor operation, The Electricity Journal 31 (2018) 23–31

Duck curve



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Interaction among different power generation sources:

Deep penetration of intermittent renewables is threatening economics of nuclear power (US)

2/3 of NPPs in US are not yielding profit (MIT, March2017)

- Cheap shale gas
- PTC (Production Tax Credit) & price collapse

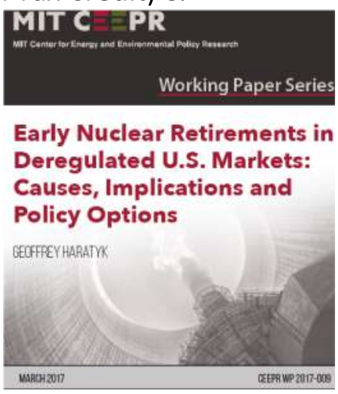

Figure 2. The profitability of the 61 U.S. nuclear plants studied ranges from -$29 to +$15 /MWh over the 2017-2019 time period.

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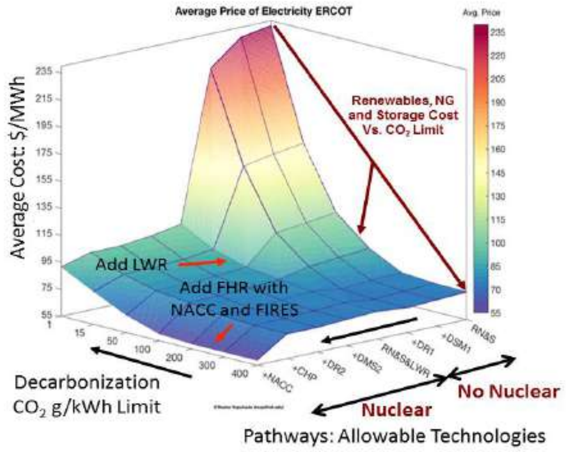
2.2. Context analysis
b. Deep decarbonization: carbon-neutral by 2050

Cost of decarbonized electricity: impact of profile cost, storage cost….



RN&S: natural gas, solar, wind, pumped hydro and battery storage
+DMS1: all of the above RN&S plus demand side management
+DR1: all of the above plus demand response (curtailment)
RN&S & LWR: RN&S plus LWR
+DMS2: all of the above RN&S & LWR plus demand side management
+DR2: all of the above plus demand response
CHP: all of the above plus heat storage and combined heat and power systems
FHR: Fluoride-salt-cooled High-Temperature Reactor
FIRES; Firebrick resistance heated energy *storage*
NACC: Nuclear Air-Brayton Combined Cycle

[source] Forsberg, Omoto et al, MIT-Japan Study "Future of Nuclear Power in a Low-Carbon World: The Need for Dispatchable Energy", MIT-ANP-TR-171, Nov. 2017

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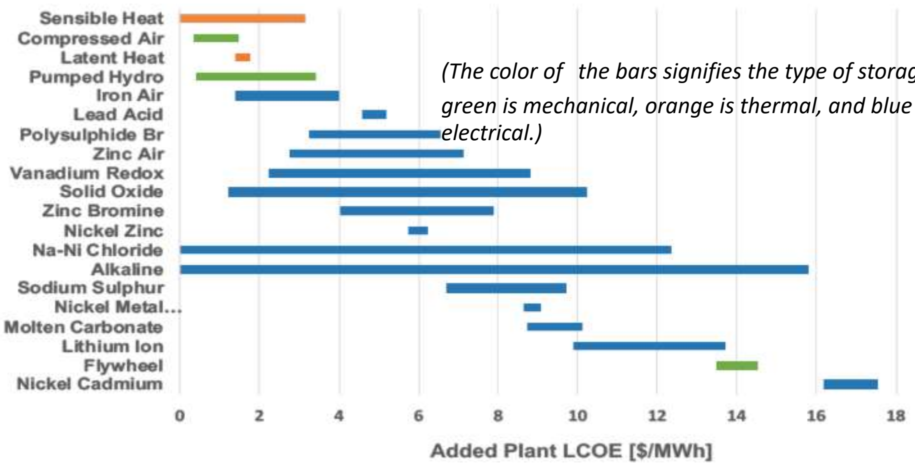
Battery price

Added nuclear power plant LCOE ($/MWh) for different energy storage options



(The color of the bars signifies the type of storage: green is mechanical, orange is thermal, and blue is electrical.)

[SOURCE] "The Future of Nuclear Energy in Carbon-Constrained World", MIT, September 2018

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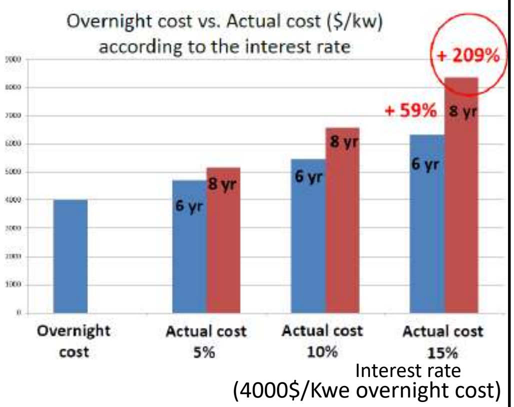
2.3. Capital cost of NNB

- ➢ Significant impact from interest rate and construction delay for capital-intensive NPP project

✓ Achieving "on-time within budget"
- Construction after detail design is complete
- Project management
- Test before use

✓ Europe & N. America:
Building FOAK plants when experiences of construction project management is lost



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2.4. LCOE and VALCOE

Classic LCOE on specific generating source

- ➢ Does not analyze overall system cost, especially related to VRE with variation & uncertainty
  - Need to consider <u>kWhr value</u> (in the market with merit order of marginal cost), <u>kW value</u> (meeting demand anytime) and flexibility to <u>adjust to δkWh</u>
  - Shadow prices (profile cost due to intermittency….)

  VALCOE (WEO2018 model)
  System cost analysis ["Cost of decarbonization", NEA, 2019]

- ➢ Interaction among power generation sources …price collapse

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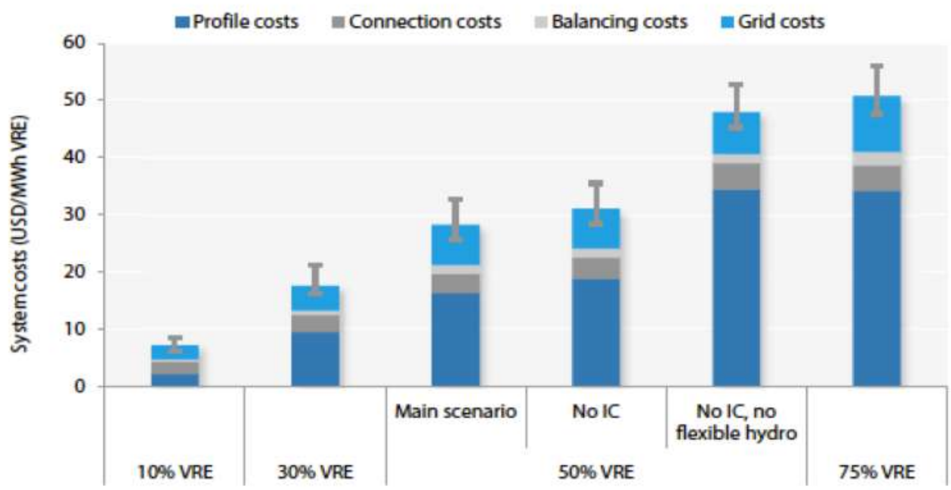
value/adequacy of electricity in power system

	Market values	Nuclear/Thermal	Intermittent Renewables
	kWh value	Yes	Yes, competitive in the market with merit order of marginal cost
Adequacy	kW value (capability to cover peak demand anytime)	Yes	Not fitted (Availability depends on weather) Need supplemented by ✓ Capacity market ✓ Storage ✓ hybrid production ✓ Curtailment ✓ Complementary use with dispatchable sources
Adequacy	δkW value (flexibility to demand changes)	Yes, by load following etc. [dispatchable]	

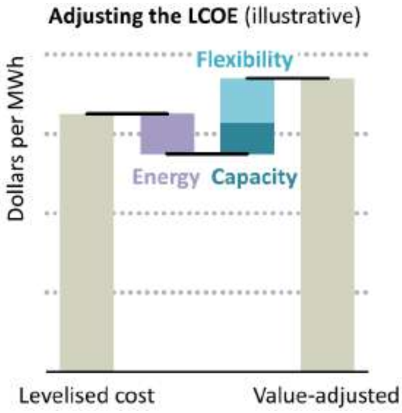
Figure ES6. System costs per MWh of VRE



[source] OECD/NEA, Cost of decarbonization, 2019

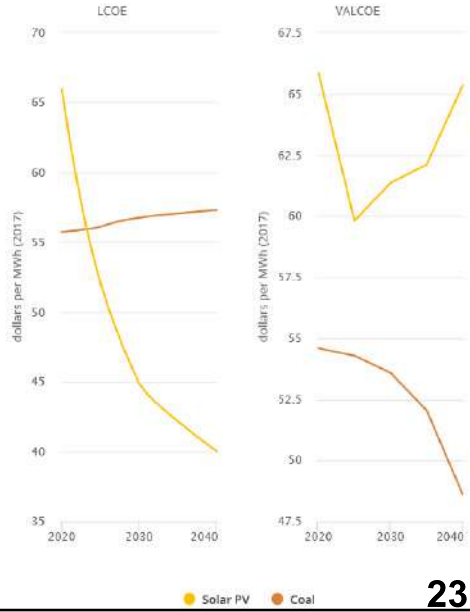
Value-adjusted LCOE (VALCOE) for solar PV and coal-fired power plants in India (value of daytime production drops and the value of flexibility increases)

[source] By Brent Wanner, 6 February 2019



World Energy Model 2018

[source] WEO2018

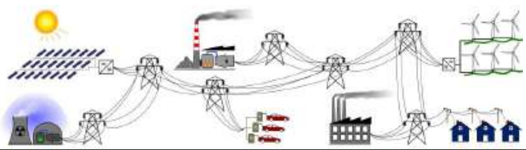


system cost

Profile costs : increase in the installed generation capacity in response to the variability of IR output

Balancing costs to ensure the system stability due to the uncertainty in the power generation such as marginal costs of reserve fossil plants and mitigating options in the system, such as storage

Grid costs and Connection Costs



2.5. Accident cost

- Significant uncertainties
- 2015 LCOE calculation by cost evaluation committee (Gov. of J)

1. Assume all the Utilities with NPPs bear accident cost during NPP's 40 years of operation [mutual aid system]
2. Accident cost after applying post-Fukushima modifications: 122B$ (liability 57, decontamination and storage 36, additional decommissioning cost 18, others 11)
3. Post-Fukushima modifications (1B$) x60% (for a model plant) would reduce probability of severe accident
   - assume 2.5x10(-4)
   - PRA of 11 re-licensed units shows CDF reduction: 1.9x10(-4) to 8.3x10(-5) by assuming one of 30 modifications be taken credit of in PRA…..later analysis by Operators: 1/55-1/300

$$R = \{(S_i, L_i, X_i)\}_c$$

- S：scenario
- L：likelihood
- X : consequence (cost)

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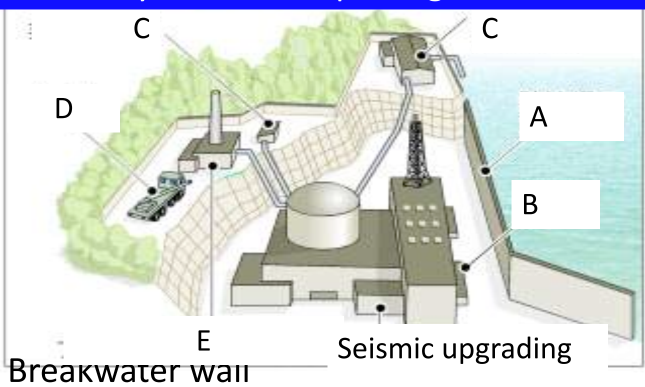
Post-Fukushima safety modifications (illustration by media interpreting NRA new requirements)



A. Breakwater wall
B. Water-tight doors
C. Independent power supply, cooling capability and mobile equipment, backup control room (terrorist attack, CV venting, cooling…as bunkered facility)
D. Water cannon
E. Filtered venting system

Others (fire, tornade, instrumentation, …)

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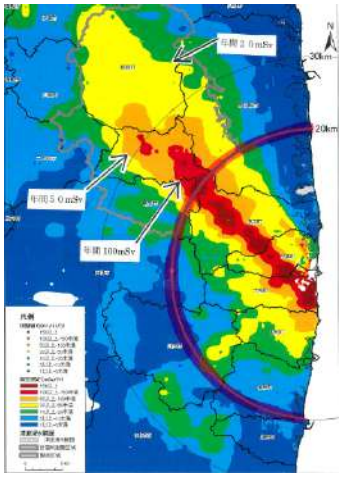
- Accident cost significant varies, depending on assumptions
- Fukushima-Daiichi Accident, March2011
  - ✓ METI data: 215B$ (2016, not including disposal cost, power replacement cost)
  - ✓ AEC study (2012)
    AEC subcommittee on "fuel cycle options and economics of NP" is based on data from TEPCO: 45B$
  - ✓ JCER estimation : 700B$, as the worst case
- IRSN report on accident cost



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2.6. Security value: an example of analysis

Estimation of Energy Security Value (ESV) of nuclear power by TEPCO-sponsored study at Baker Institute of Rice University (currently RISE Working Paper 14-023 "The Role of Nuclear Power in Enhancing Japan's Energy Security")

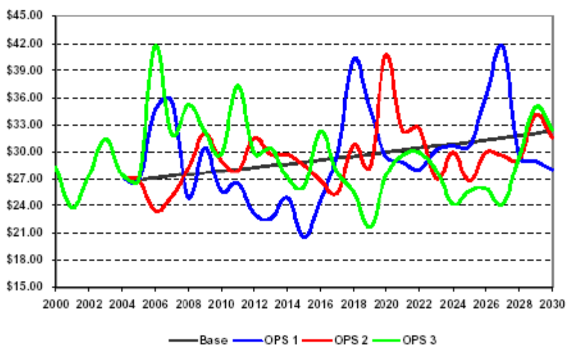
- ✓ Assuming cases of fluctuating price of fossil ("shock") for a certain period of time
- ✓ Methodology & model used: Markovitz's portfolio theory and Japan's macro economic model

$$ESV = \sum_{t=t_0}^{T} \frac{1}{(1+\beta)^{t-t_0}} (GDP_t^{withN} - GDP_t^{withoutN})$$

β (discount rate)= 7.2%,T=12 years

	w/oNuclear	w/ Nuclear
Nuclear	0%	40%
Gas	34%	18%
Oil	8.2%	4.6%
Coal	41%	22%
Hydro	8%	8%

Single 25% shock
→ ESV=16% of capital
Ops1-3 fluctuation
→ ESV=21-58% of capital



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2.7. Large unit or SMR?

- **Opportunities for SMR (Where does it fit?)**
  1. Developing countries with a small grid ("Grid-appropriate design": max 10% of grid size as a rule of thumb)
  2. Incremental investment to avoid financial risk
  3. Dual purpose supply in remote area (industry complex, military base)
  4. Weak local infrastructure : small domestic component manufacturing capability, transportable reactor without onsite refuelling
- **Distributed siting or not?**
- **Challenges**
  1. Economics of scale vs. Economics by Series
     Need significant standardization……not proven yet
  2. Licensing of non-conventional designs
  3. Multi-unit accident by CCF due to natural hazards
  4. No EPR?

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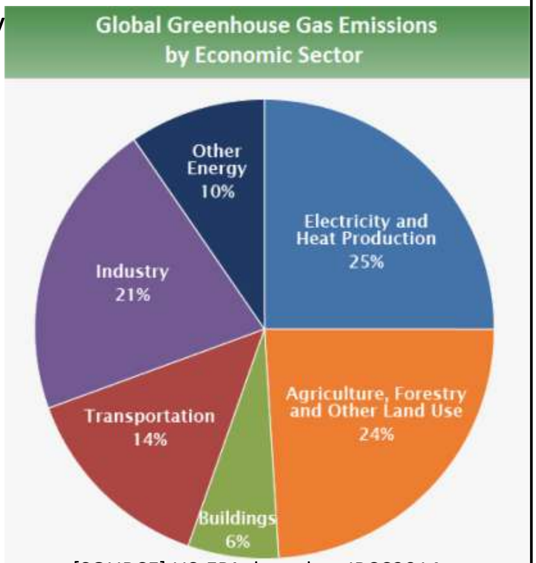
Role of nuclear energy in low carbon society

1. Supply of affordable clean energy (electricity, heat, energy carrier)
   - ✓ NE needs to go beyond just electricity production
2. Help intermittent renewables power smoothing
3. Radiation & Isotope: Monitoring & adaptation to Climate Change
4. Power supply to NETs, together with conservation and others (NET: DAC,BECCS, MCFC [molten carbonate fuel cell]...)

etc.



[SOURCE] US-EPA, based on IPCC2014

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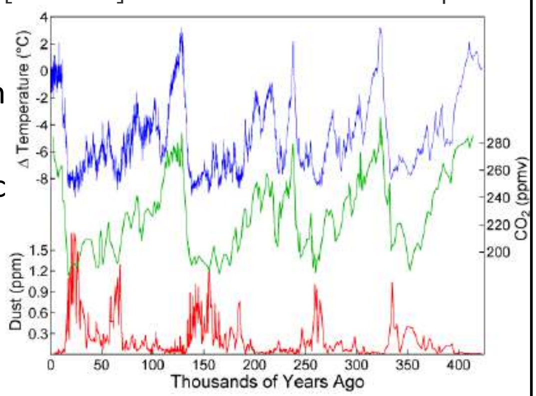
Global warming

✓Many factors involved in climate change...volcano eruption, solar activity, earth's magnetic field, changes in Earth's orbit and Earth's axis [Milankovitch cycle (10(5) yr)] etc

✓ Alternative views such as temperature change primarily by Sun's heat

[Ex.] Dr. A. Tsuchida's argument: Heat from Sun→ temp. change→ atmospheric CO2 level change by supply from ocean

[SOURCE] Vostok Ice Core Data Graph



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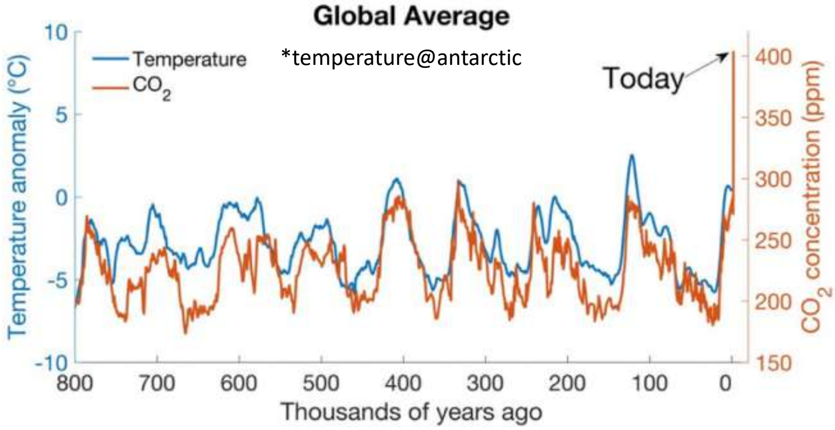
Recent rise of atmospheric CO_2 level and ocean acidification by human activities seem to have little room to doubt



[SOURCE] Kevin Loria, "The amount of carbon dioxide in the atmosphere just hit its highest level in 800,000 years", 2018June

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However, high share of VRE does not necessarily translate to low gCO_2/kWh emission nor affordability

	Sweden	France	Denmark	Germany	Japan
gCO_2/kWh	11	46	174	450	540
cent/kWh	20	22	41	40	24
Intermittent Renewables	10%	5%	51%	18%	4%
Dispatchable clean energy	88%	88%	15%	25%	12%

2015 data [source] METI, based on IEA CO2 Emission from combustion
https://www.enecho.meti.go.jp/committee/studygroup/ene_situation/pdf/report_02.pdf

- Carbon-based backup power to intermittent renewables
- Current global average= 500gCO_2/kWh
- Goals: UK CCC =50gCO_2/kWh,
  MIT report (Sept2018) 15~20gCO_2/kWh to meet 2DC scenario
  France: carbon neutral

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Nuclear Power in a Clean Energy System

- Offsetting less nuclear power with more renewables would cost more
- Strong policy support is needed to secure investment in existing and new nuclear plants
- Value dispatchability

"Without an important contribution from nuclear power, the global energy transition will be that much harder," (Dr. Fatih Birol, IEA)

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Increased share of VRE in the grid requires system flexibilities to deal with Intermittency (variability & uncertainty)

Flexibilities by;

a) **Flexible generation**:
flexible renewables, load-following operation of baseload generation source, curtailment of IR generation
* load following of NPPS is generally not economically viable for capital-intensive NPP

b) Storage and/or hybrid production

c) Smart grid management
virtual power plant, peer-to-peer transaction among prosumers etc.   and Ancillary services

\+ supporting policy tools

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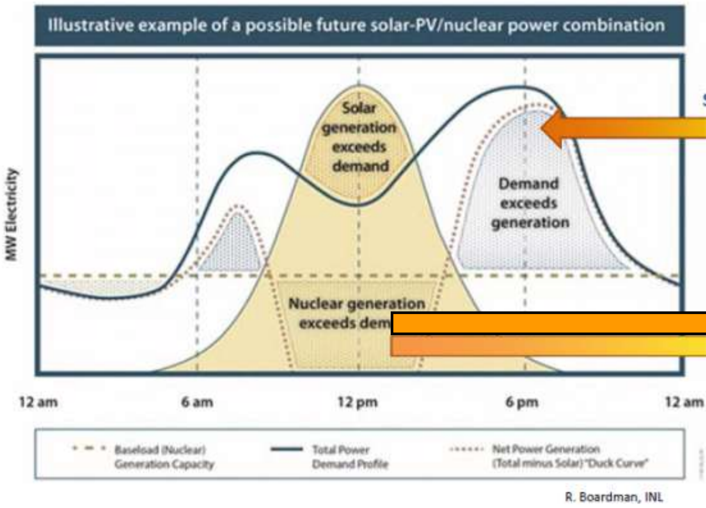
Technological innovations necessary for integration of Nuclear Power and Intermittent Renewables



Integration of PV and NE in a daily load curve

Electricity Generation

- -Steam Turbine (heat storage)
- -Fuel Cell (hydrogen)
- ……

Storage & Hybrid Production@NPP

- -Heat
- -Hydrogen
- -CAES
- …..

Other sectors

- -Industry
- -Transportation

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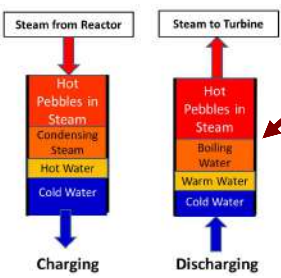
Many Heat Storage Technologies Couple to LWRs and Can Produce Peak Power

[source] Forsberg, MIT

Steam Accumulators

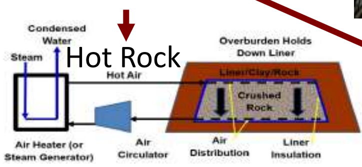
Sensible Heat



Cryogenic Air

Packed Beds

Geothermal



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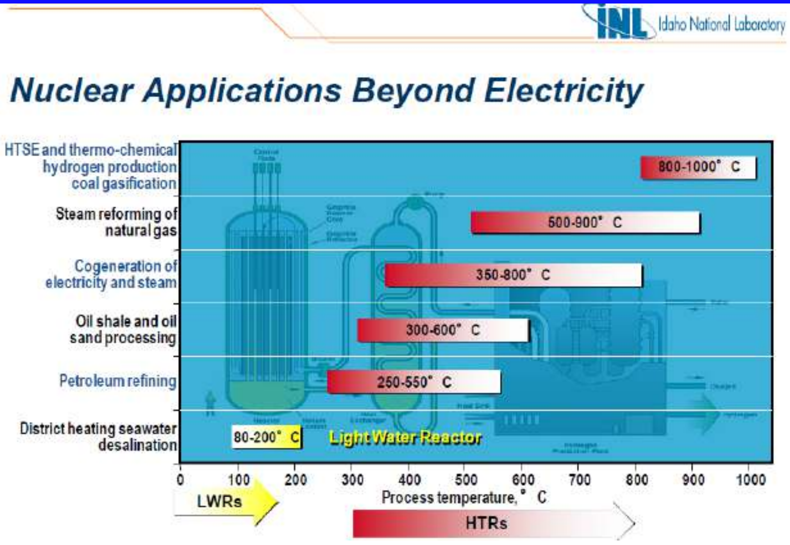
Technological innovations for use of heat requires higher temperature than LWR



[source] Shannon Bragg-Sitton, Light Water and High Temperature Reactor Opportunities, June 2016 Golden WS

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High Temperature Reactors for Gen-IV

[source] JAEA

- Coal-fired plants reaching 610 deg. C steam condition
- Gas turbine reaching 1800 deg. C by blade cooling and resistant material

System	Neutron Spectrum	Coolant	Outlet temp. (℃)	Fuel cycle	Power (MWe)
Sodium-cooled Fast Reactor (SFR)	Fast	Sodium	500-550	Closed	50-1500
Very High Temperature Reactor (VHTR)	Thermal	Helium	900-1000	Open	250-300
Gas-cooled Fast Reactor (GFR)	Fast	Helium	850	Closed	1200
Supercritical Water-cooled Reactor (SCWR)	Thermal/ Fast	Water	510-625	Open/ Closed	300-1500
Lead-cooled Fast Reactor (LFR)	Fast	Lead	480-570	Closed	20-1200
Molten Salt Reactor (MSR)	Thermal/ Fast	Fluoride/ Chloride salts	700-800	Closed	1000

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Nuclear hybrid production

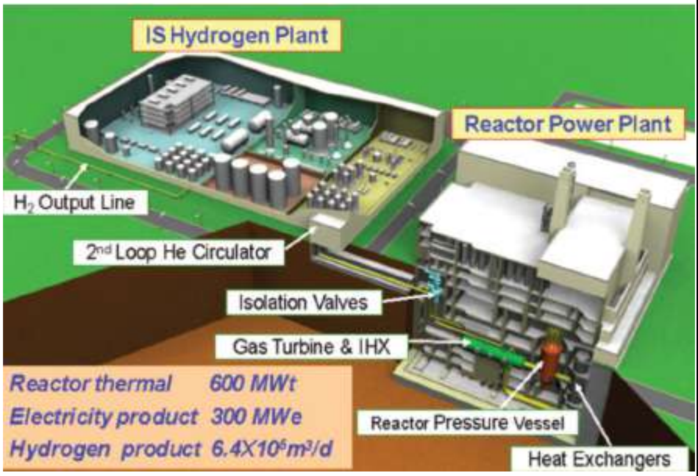
(Gas Turbine High Temperature Reactor for Cogeneration)

HTTR (JAEA, Japan)

- Operated at 950 deg C
- Hydrogen production by thermochemical water splitting on lab. Scale

Hybrid production in future HTGR

- While reactor is kept at rated power, use of control valves and bypass valves enables automatic response (in production of electricity and hydrogen) following grid demand change



[source] X. L. Yan et al, Evaluation of high temperature gas reactor for demanding cogeneration load follow, Journal of Nuclear Science and technology, Vol. 49, January 2012, pp.121-131

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Take-aways

1. Cheap electricity as one of the most important reasons for Japan to go to nuclear….and still it is (2030 model plant)

2. CBA in the context of deep penetration of intermittent renewables and deep decarbonization

3. Some key issues in CBA:
   - Quantification of externalities (Environment, Security) and various risks
   - Overall power system cost and interaction among generating sources: price collapse, profile cost…

4. Driver to nuclear energy: "How we can achieve deep decarbonization at a minimum cost to the Society?"

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