Innovation for Energy Security and Sustainability: Role of Nuclear Power

2019-2-27 GSDM symposium

Former Executive Director, IEA
Chairman, the Sasakawa Peace Foundation
Nobuo TANAKA

Tipping the energy world off its axis

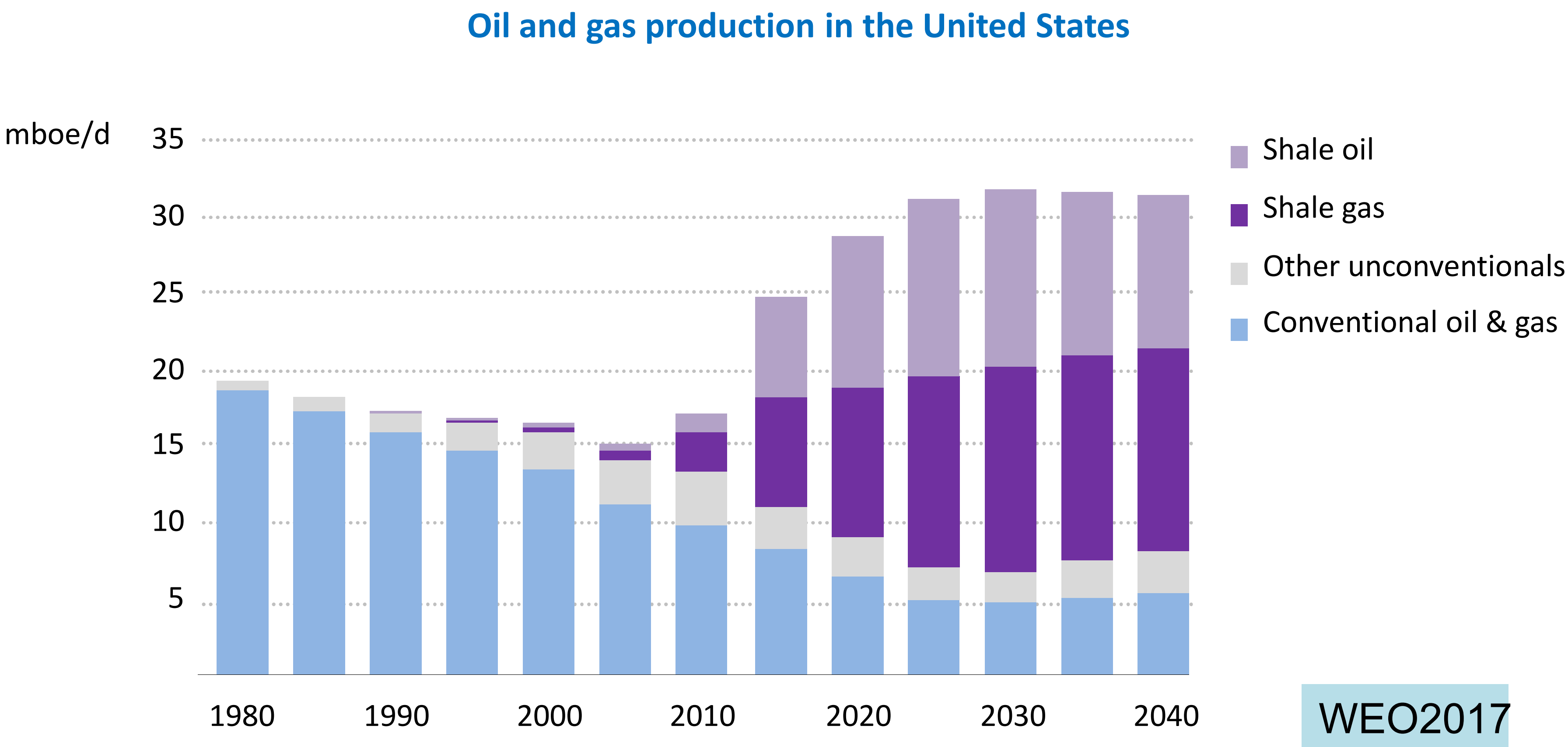
WEO2017

- Four large-scale upheavals/revolutions in global energy set the scene for the new *Outlook*:
  - The United States is turning into the undisputed global leader for oil & gas
  - Solar PV is on track to be the cheapest source of new electricity in many countries
  - China is switching to a new economic model & a cleaner energy mix
  - Electricity is broadening its horizon, spurred by cooling, electric vehicles & digitalisation

China

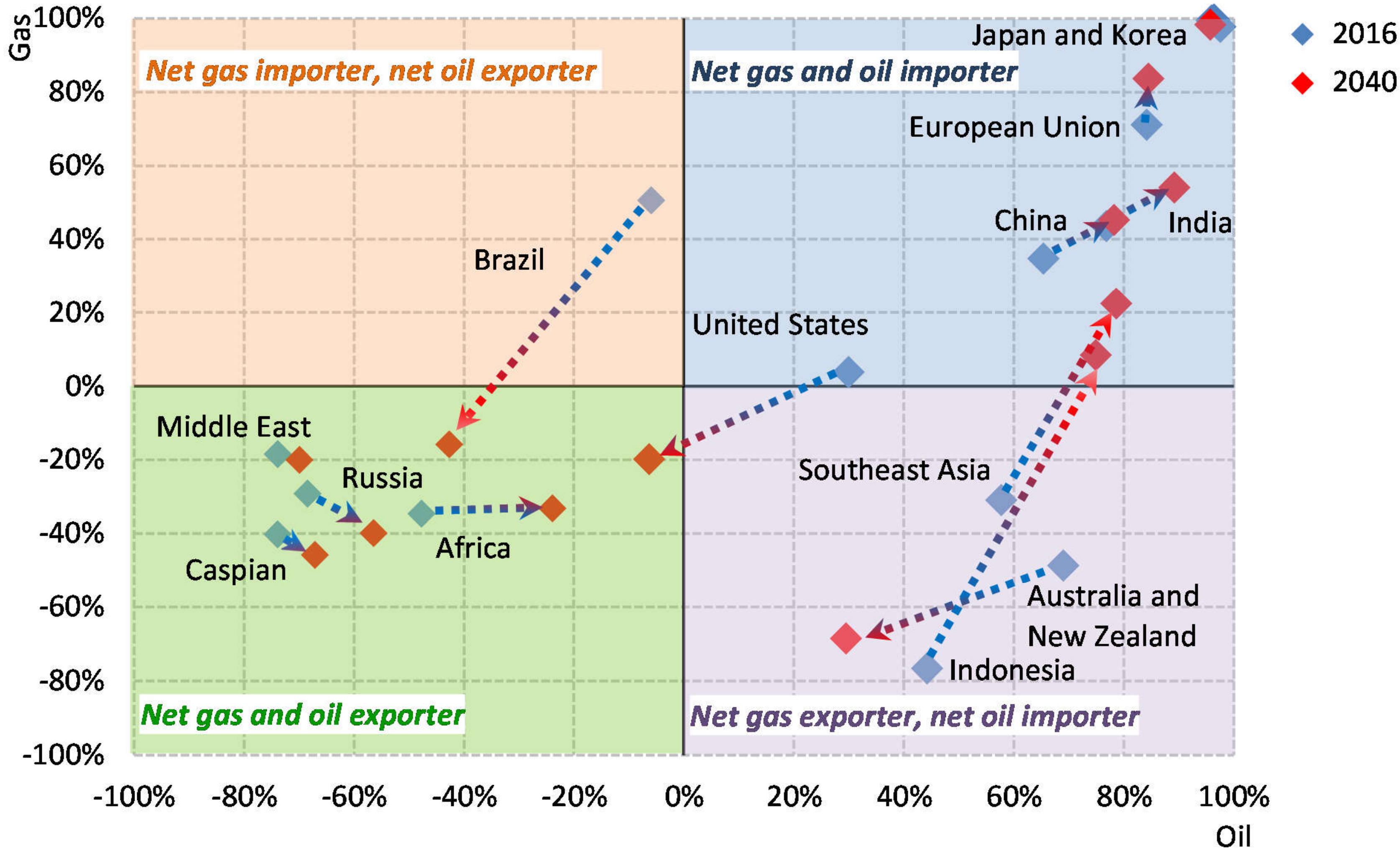
- These changes brighten the prospects for affordable, sustainable energy & require a **reappraisal of approaches to energy security.**
- There are many possible pathways ahead & many potential pitfalls if governments or industry misread the signs of change

The Shale Revolution makes US the undisputed leader for oil & gas



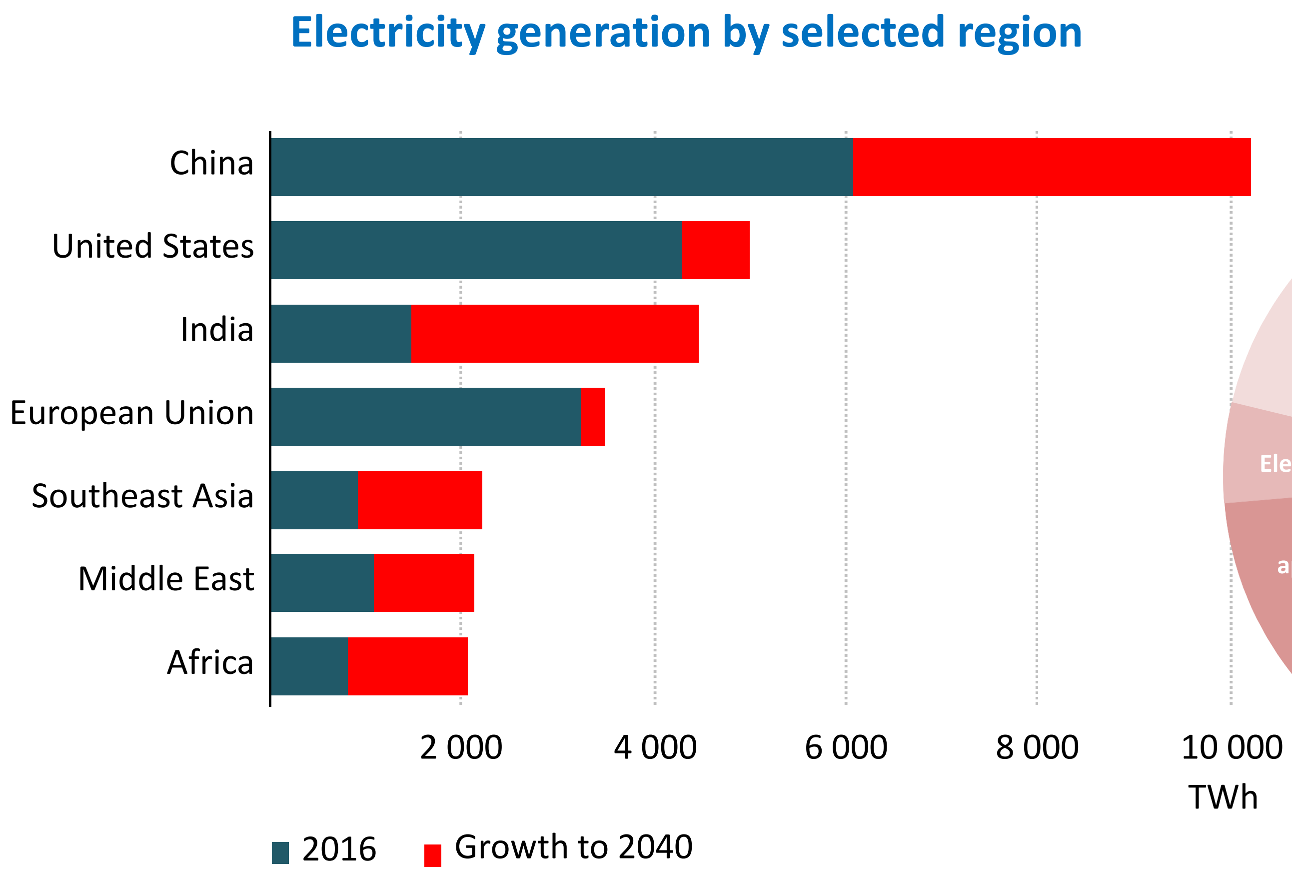
The US is already switching to become a net exporter of gas & becomes a net exporter of oil in the 2020s, helped also by the demand-side impact of fuel efficiency & fuel switching

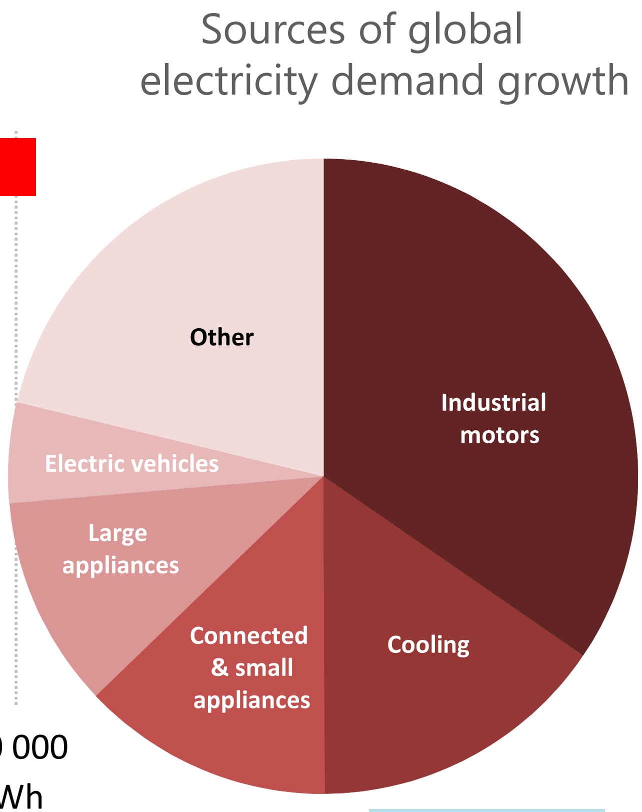
Geopolitics of the Shale Revolution: Strategic Positioning of Oil/Gas exporters and importers



IEA WEO2017 basis

The future is electrifying





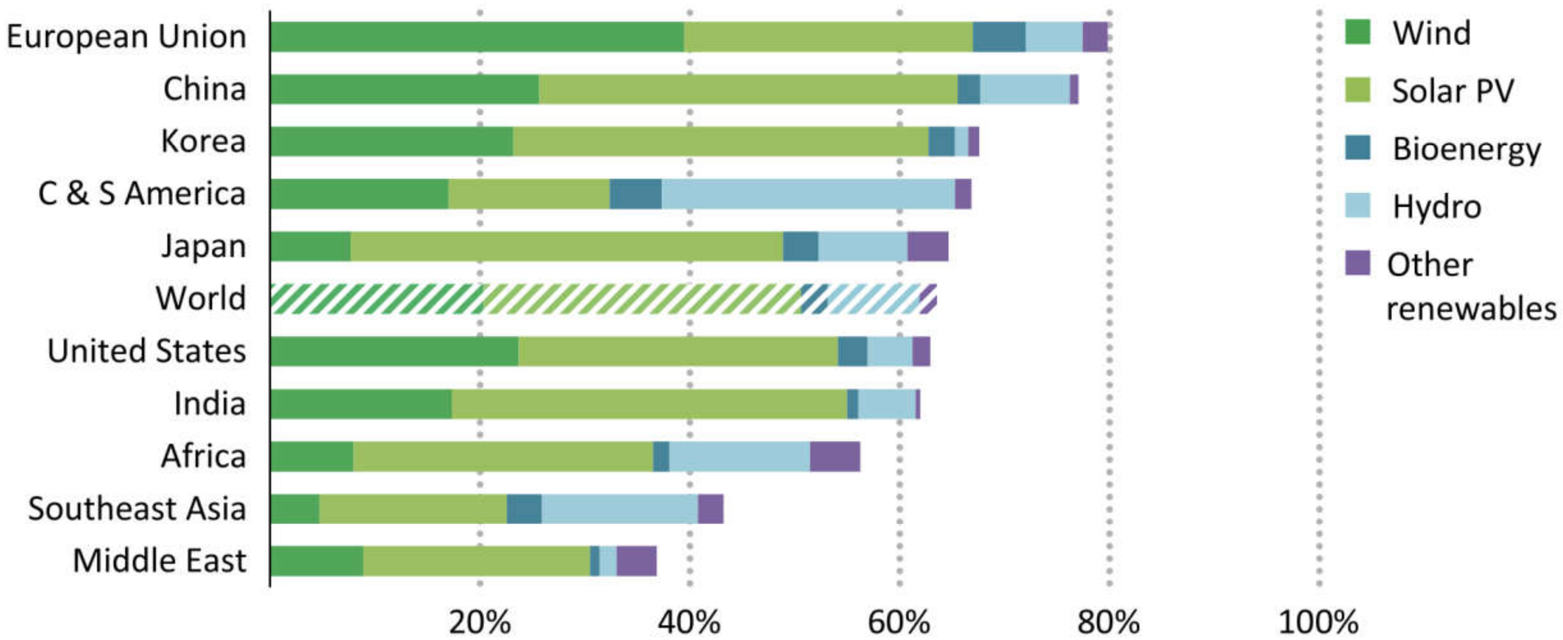
WEO2017

India adds the equivalent of today's European Union to its electricity generation by 2040, while China adds the equivalent of today's United States

80% of additional power capacity in China is Renewables

WEO2018

Figure 8.14 ▷ Share of renewables in total gross capacity additions by region in the New Policies Scenario, 2018-2040

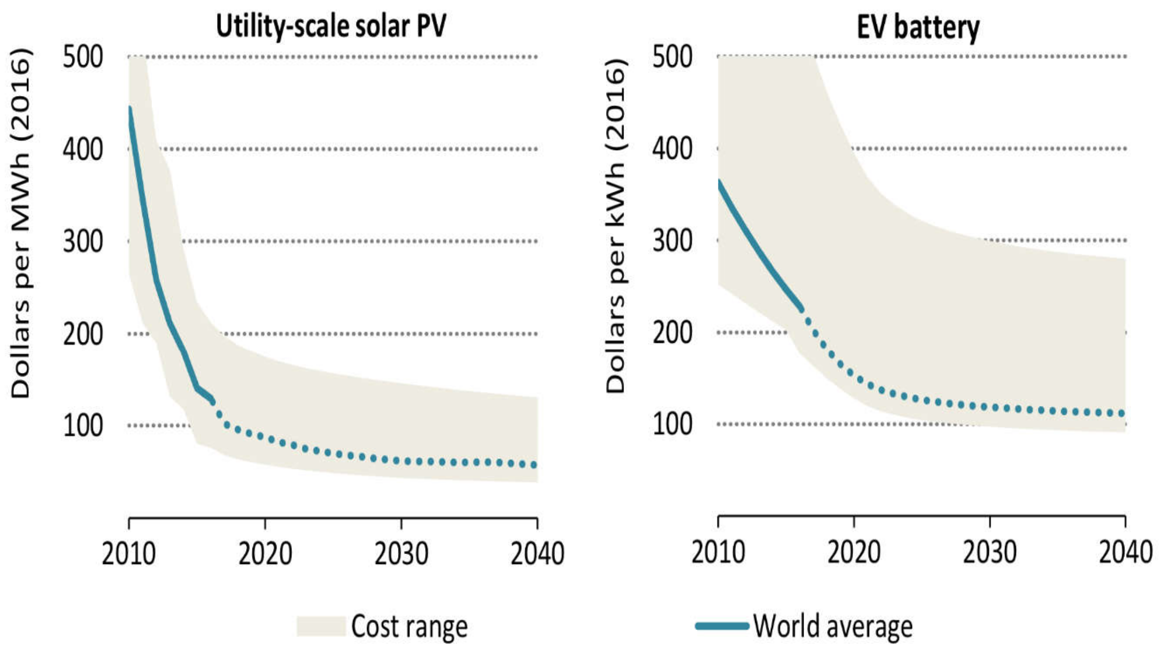


Renewables dominate capacity additions in most regions of the world, propelled by new solar PV and wind power installations

Note: C & S America = Central and South America.

Cost of Solar PV and EV battery

Figure 1.8 ▷ Evolution of global average cost for selected technologies in the New Policies Scenario



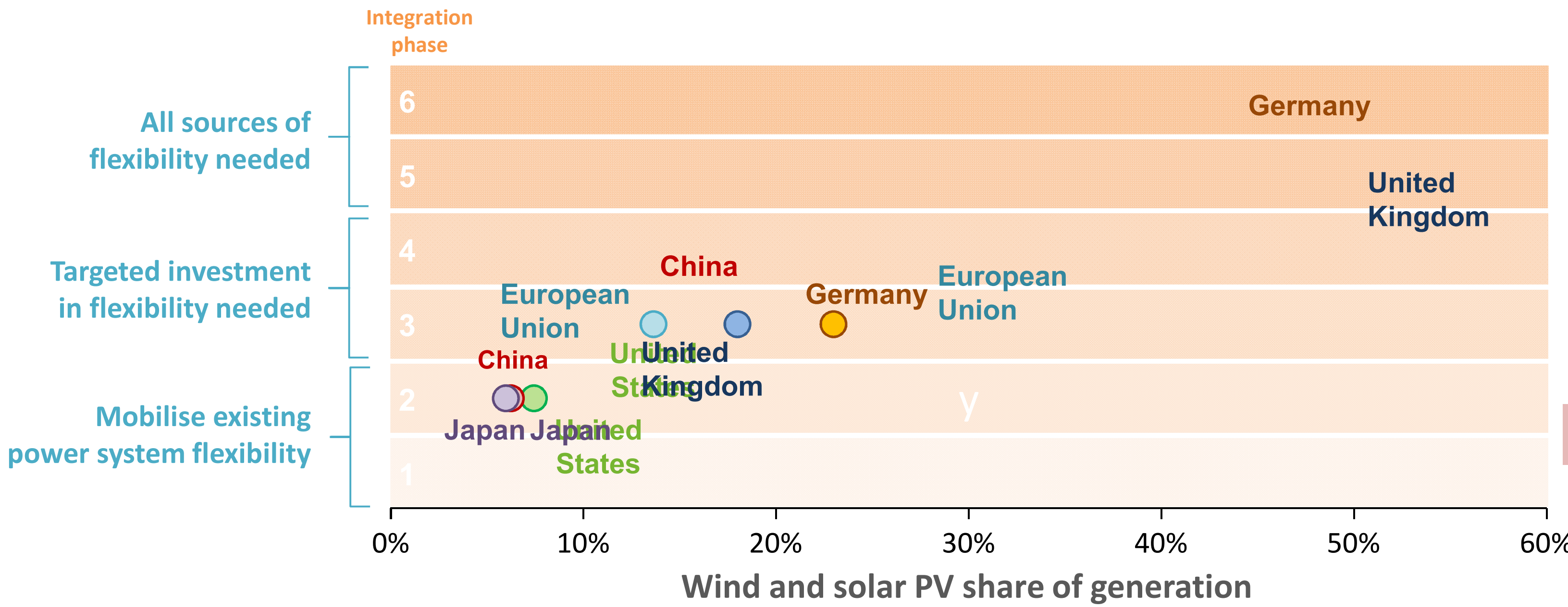
Reductions in costs of key technologies continue to give strong impetus to the energy transition

Note: PV = photovoltaic; EV = electric vehicle.

WEO2017

Flexibility: the cornerstone of tomorrow's power systems

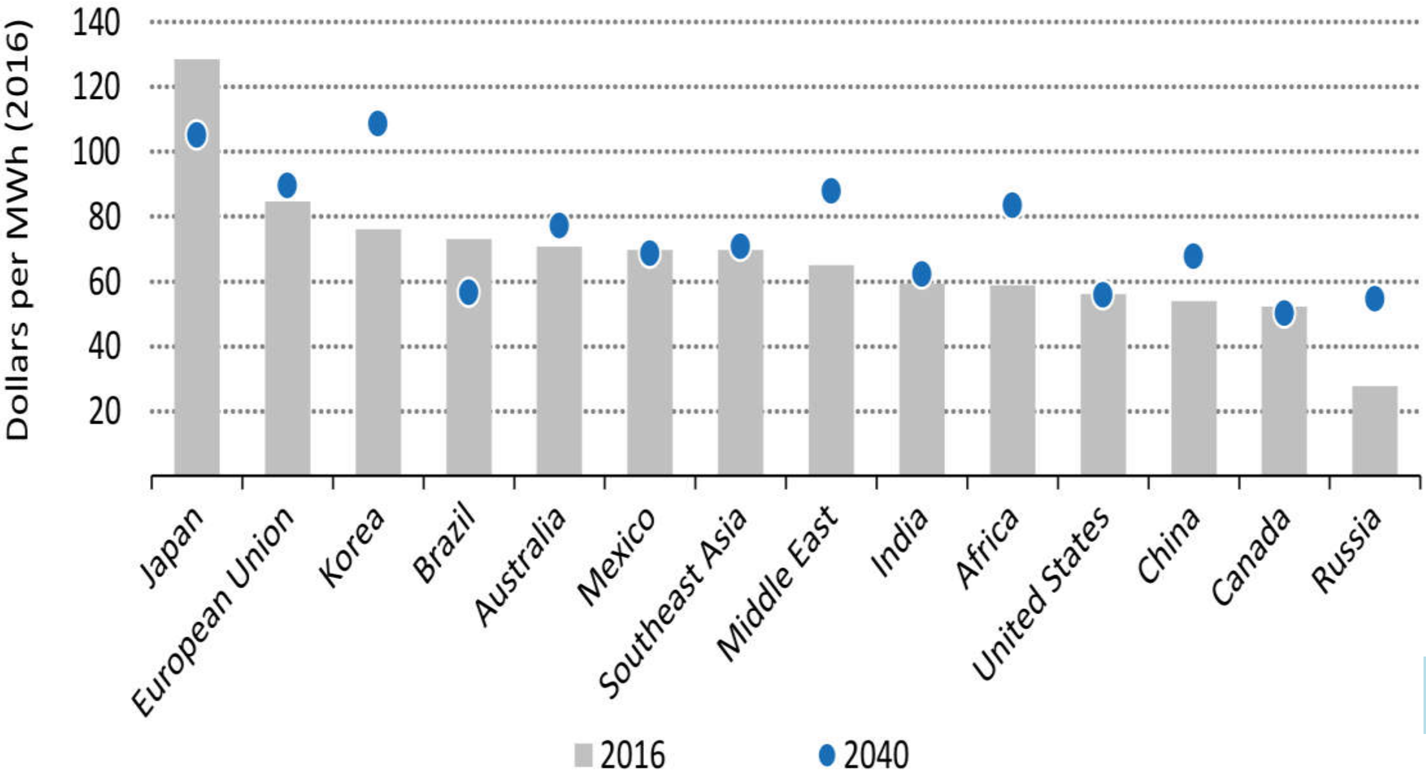
Phases of integration with variable renewables share, 2030



WEO2018

Higher shares of variable renewables raise flexibility needs and call for reforms to deliver investment in power plants, grids & energy storage, and unlock demand-side response

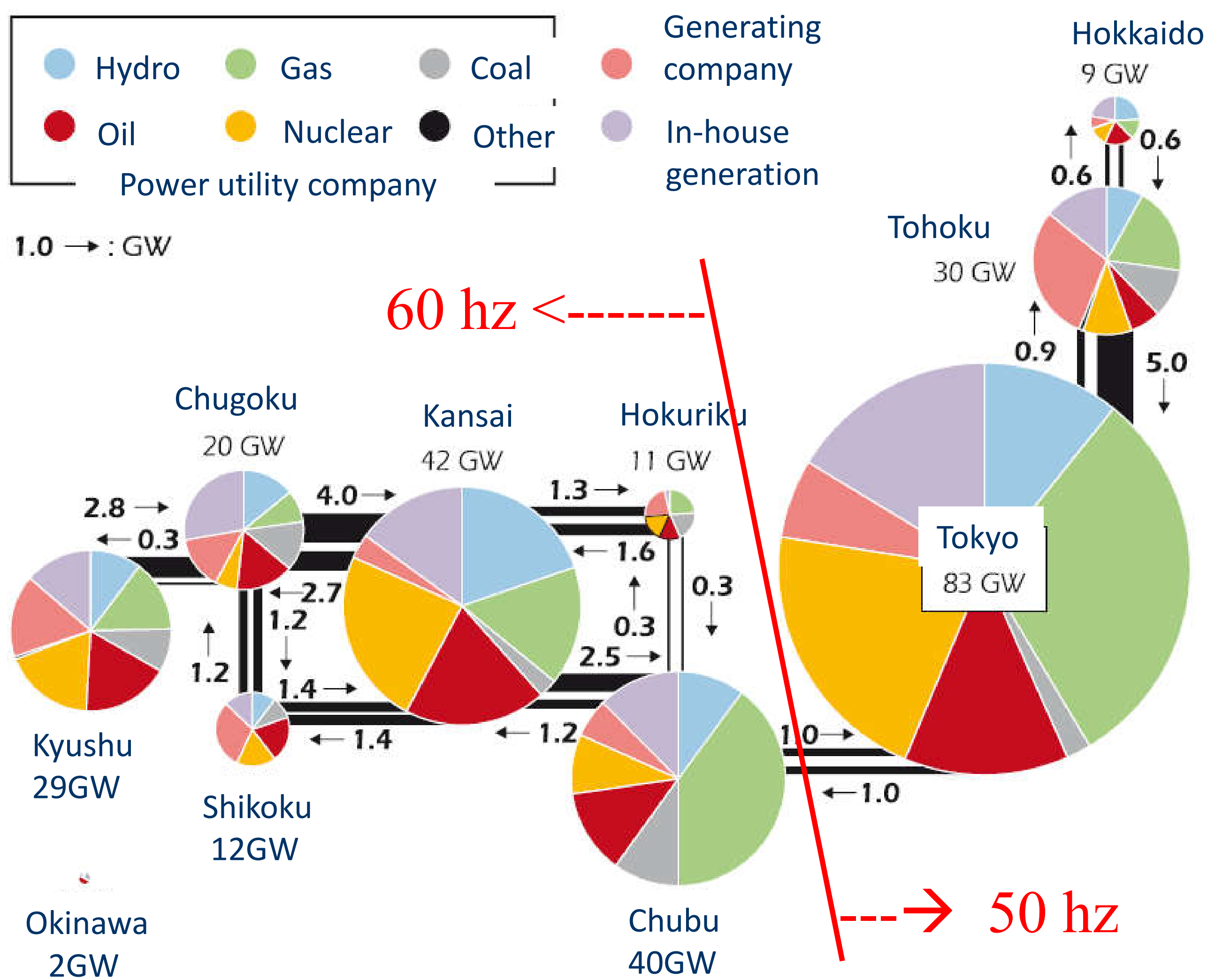
Average Costs of Power Generation



Average power generation costs are $50-80/MWh in most regions today, and most increase over time in the New Policies Scenario

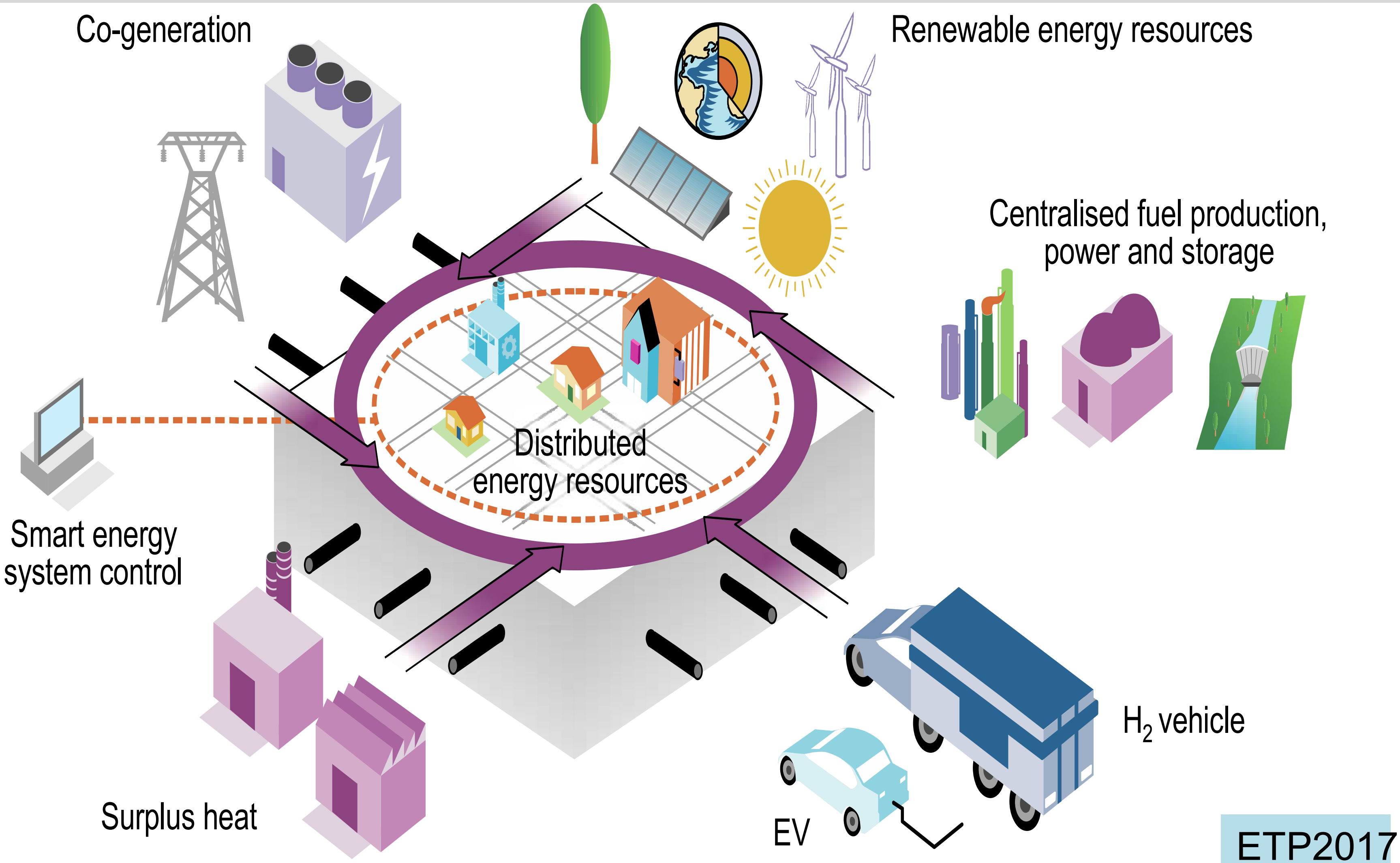
WEO2017

Lack of Grid connectivity in Japan



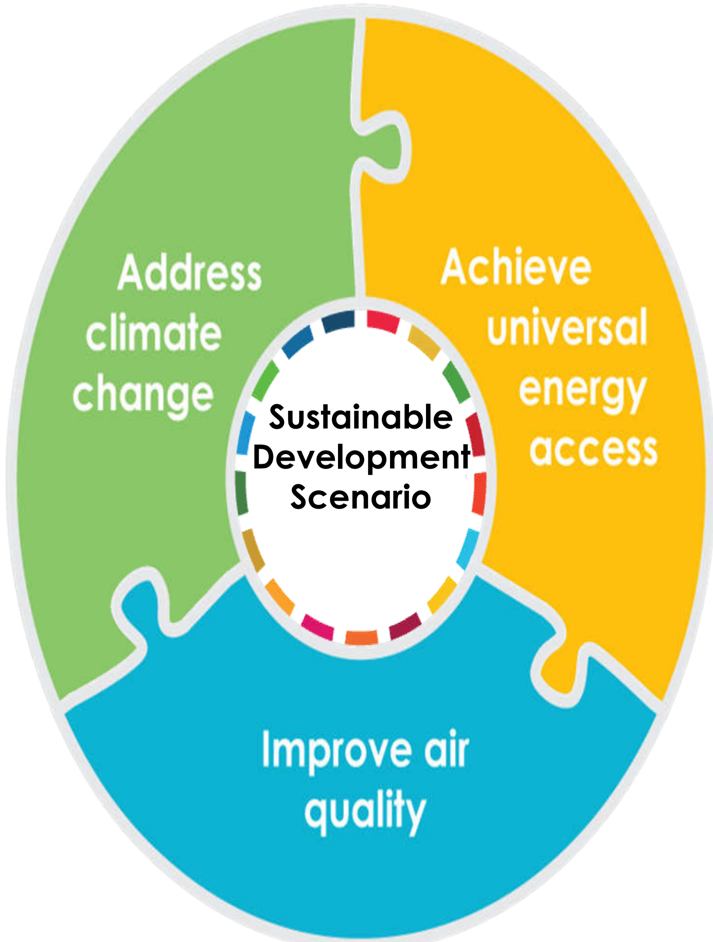
Source: Agency for Natural Resources and Energy, The Federation of Electric Power Companies of Japan, Electric Power System Council of Japan, The International Energy Agency

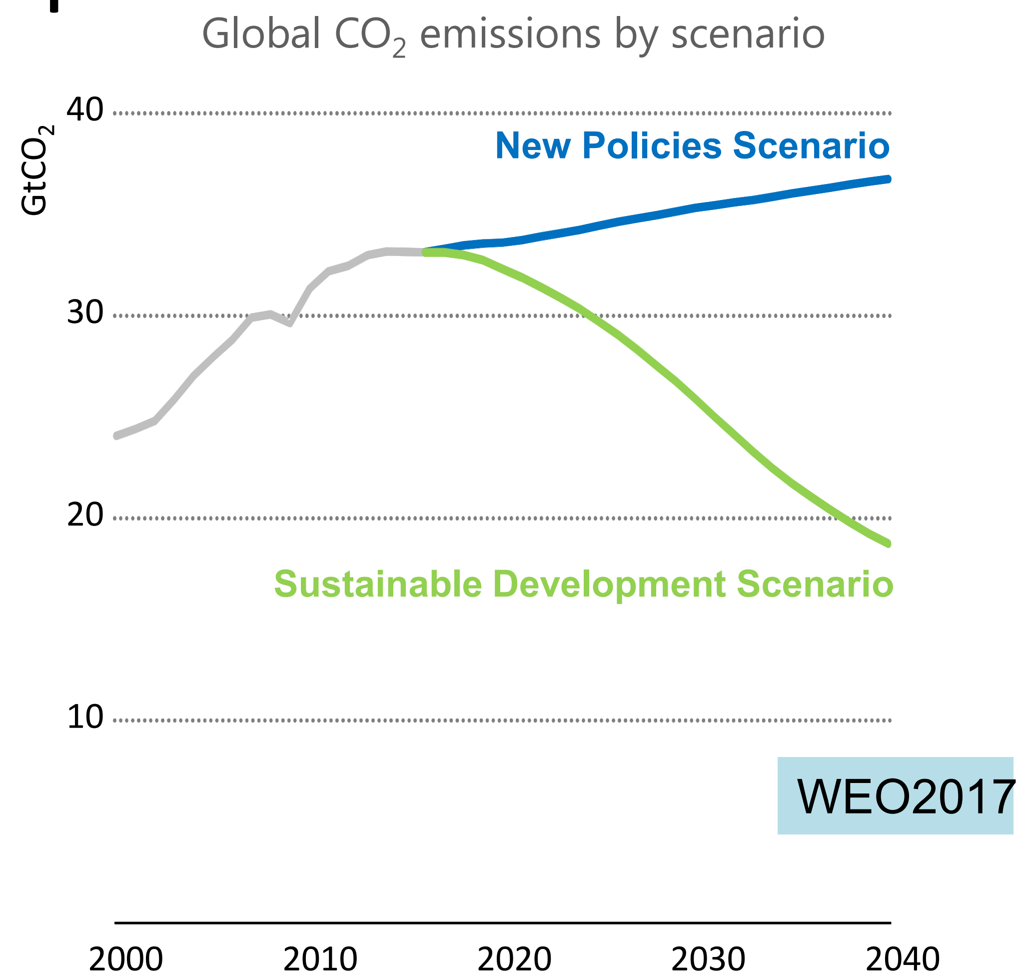
Renewable Energy needs Decentralized Smart System



We need to move away from a one-directional energy delivery philosophy to a digitally-enhanced, multidirectional and integrated system that requires long-term planning for services delivery

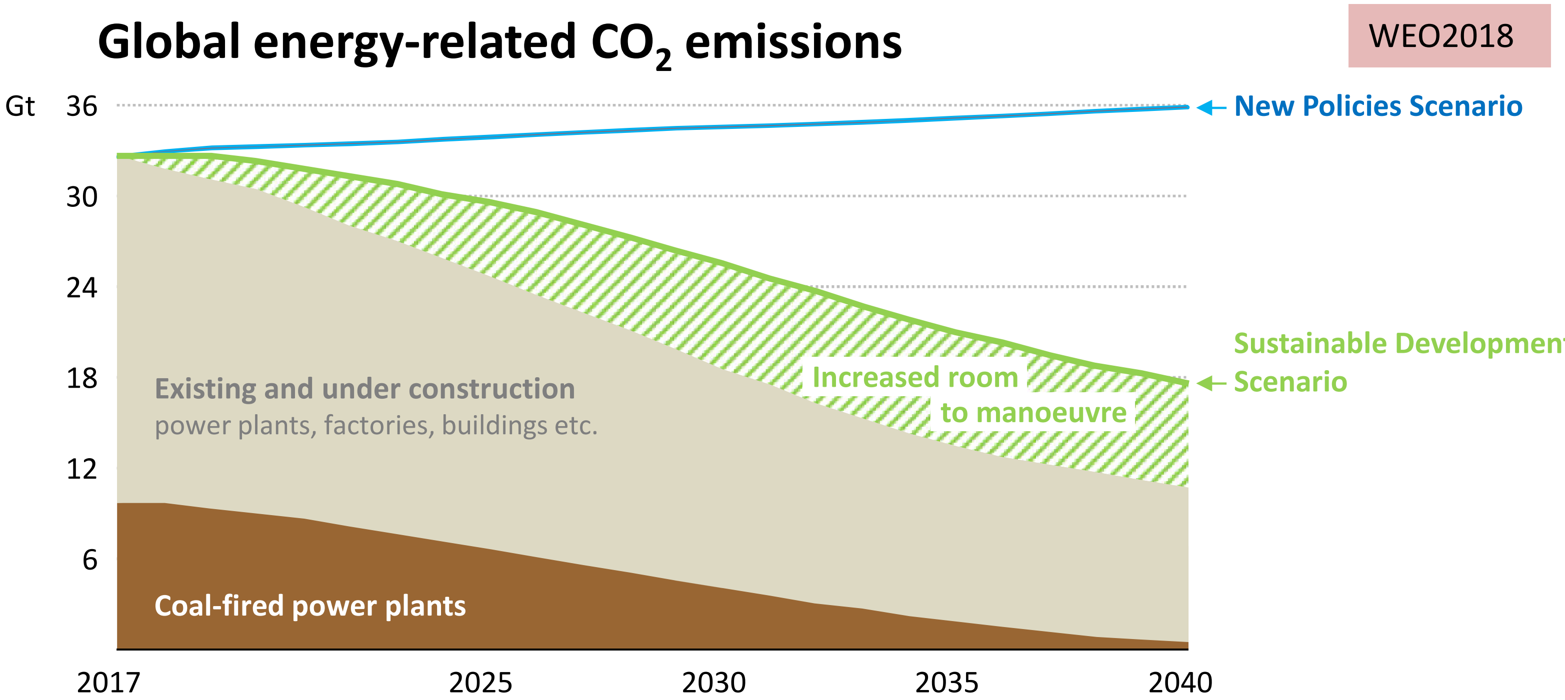
A new strategy for energy & sustainable development





The Sustainable Development Scenario reduces CO_2 emissions in line with the objectives of the Paris Agreement, while also tackling air pollution and achieving universal energy access. It needs doubling the level of energy efficiency, 900 million EVs, 3250 GW of solar PVs.

Can we unlock a different energy future?



Coal plants make up one-third of CO_2 emissions today and half are less than 15 years old; policies are needed to support CCUS, efficient operations and technology innovation

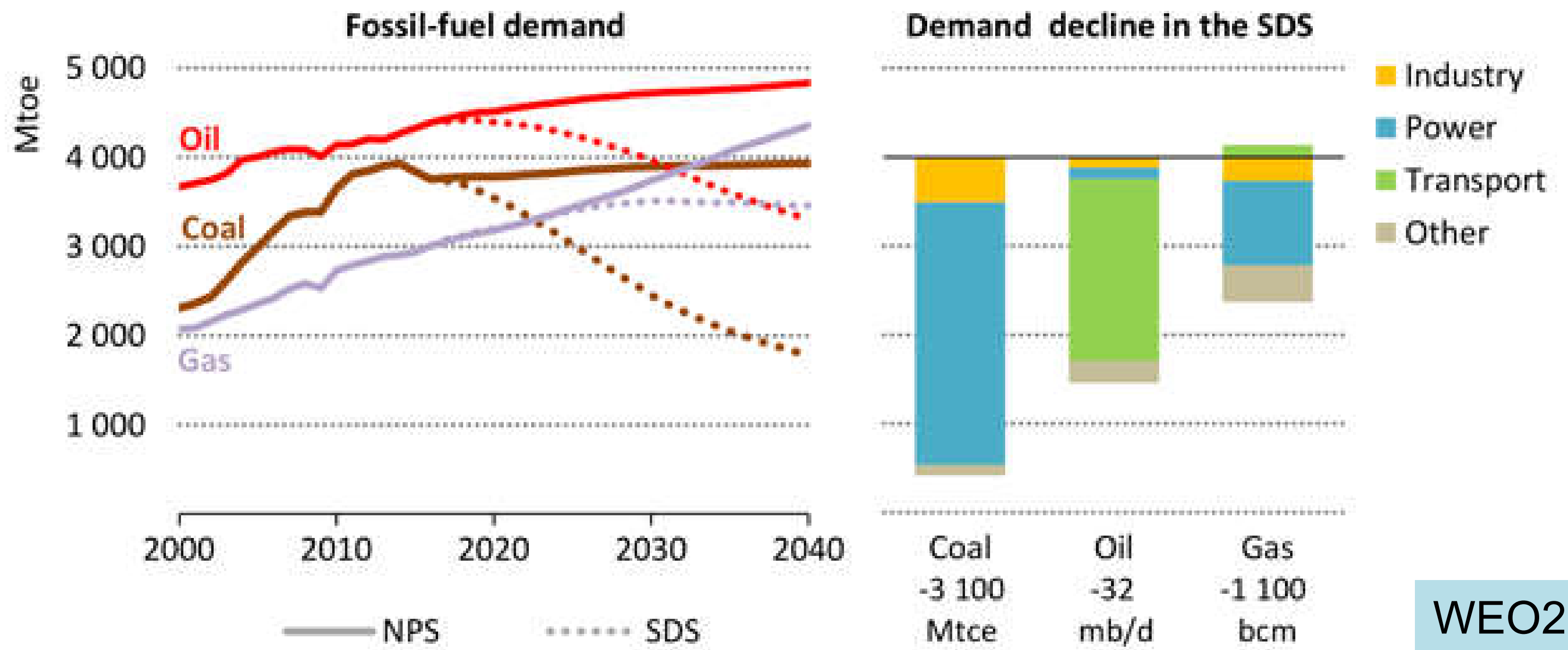
Demand Driven Energy Revolution by RE100 Corporations

156 RE100 companies have made a commitment to go '100% renewable'.

Finance(40): Swiss Re Group, alstria, Amalgamated Bank, Aviva, AXA, Bank of America, Bankia, BBVA, British Land, CaixaBank, Canary Wharf Group, Capital One, Citi, Commerzbank, Credit Agricole, Danske Bank, DBS Bank Ltd, DNB, Equinix, Fifth Third Bancorp, Fuyo General Lease Co., Ltd., Goldman Sachs, Helvetia, HSBC, ING Group, Iron Mountain Incorporated, Johnan Shinkin Bank, JPMorgan Chase & Co., Jupiter Asset Management, Land Securities, Mace, Morgan Stanley, Nordea, Prudential plc, RBS group, Schroders, TD Bank, UBS, Voya Financial, Wells Fargo
Durable Goods and Services (32): IKEA Group, AEON Co., Ltd, BMW, Burberry, Coop Sapporo, Crown Estate, Daiwa House Group, Decathlon, Dentsu Aegis Network, Etsy, FIA Formula E, General Motors, Gürmen Group, H&M, Interface, Kingspan, LEGO Group, Mahindra Holidays & Resorts India, Marks & Spencer, Marui Group, Nike, Inc., Pearson, PVH, Sekisui House, Signify, Sky, Starbucks, Tata Motors Limited, Vail Resorts, VF Corporation, Watami Co., Ltd., YOOX Group
Non-Durables and Services (24): Anheuser-Busch InBev, Califia Farms, Carlsberg Group, Clif Bar & Company, Coca-Cola Enterprises, Colruyt Group, Danone, Diageo, Estée Lauder Companies, Grupo Bimbo, Hatsun Agro Products Ltd, International Flavors and Fragrances Inc., Kellogg, L'OCCITANE Group, Mars, Incorporated, Nestle, Organic Valley, Procter & Gamble, Reckitt Benckiser (RB), TCI Co., Ltd, Tesco, TRIDL, Unilever, Walmart
Technology(21): Adobe, Apple, Autodesk, eBay, Facebook, Fujitsu, Google, Hewlett Packard Enterprise, HP, Inc., Infosys, Lyft, Microsoft, Rackspace, RICOH Company, Ltd., Salesforce, SAP, Sony Corporation , Visa, VMWare, WeWork, Workday
Other Services(17) ASKUL Corporation, Bloomberg, BROAD Group, ENVIPRO HOLDINGS Inc., Gatwick Airport Limited, Heathrow Airport, IHS Markit, La Poste, McKinsey & Company, PwC, RELX Group, SAVE S.p.A Group, Schneider Electric, SGS, Steelcase, Swiss Post, Vaisala
Material(8): AkzoNobel, Corbion, Dalmia Cement, Elion Resources Group, Elopak, Givaudan, Royal DSM, Tetra Pak
Telecom Services(6): BT Group, KPN, Proximus, Telefonica S.A., T-Mobile US, Inc., Vodafone Group
Health care(5): AstraZeneca, Biogen, Johnson & Johnson, Novo Nordisk, Royal Philips
Energy(1): Vestas

Saudi Aramco is worrying about Peak Demand of Oil by EV.

Figure 3.18 ▷ **Fossil-fuel demand by scenario and decline by sector in the Sustainable Development Scenario relative to the New Policies Scenario, 2040**

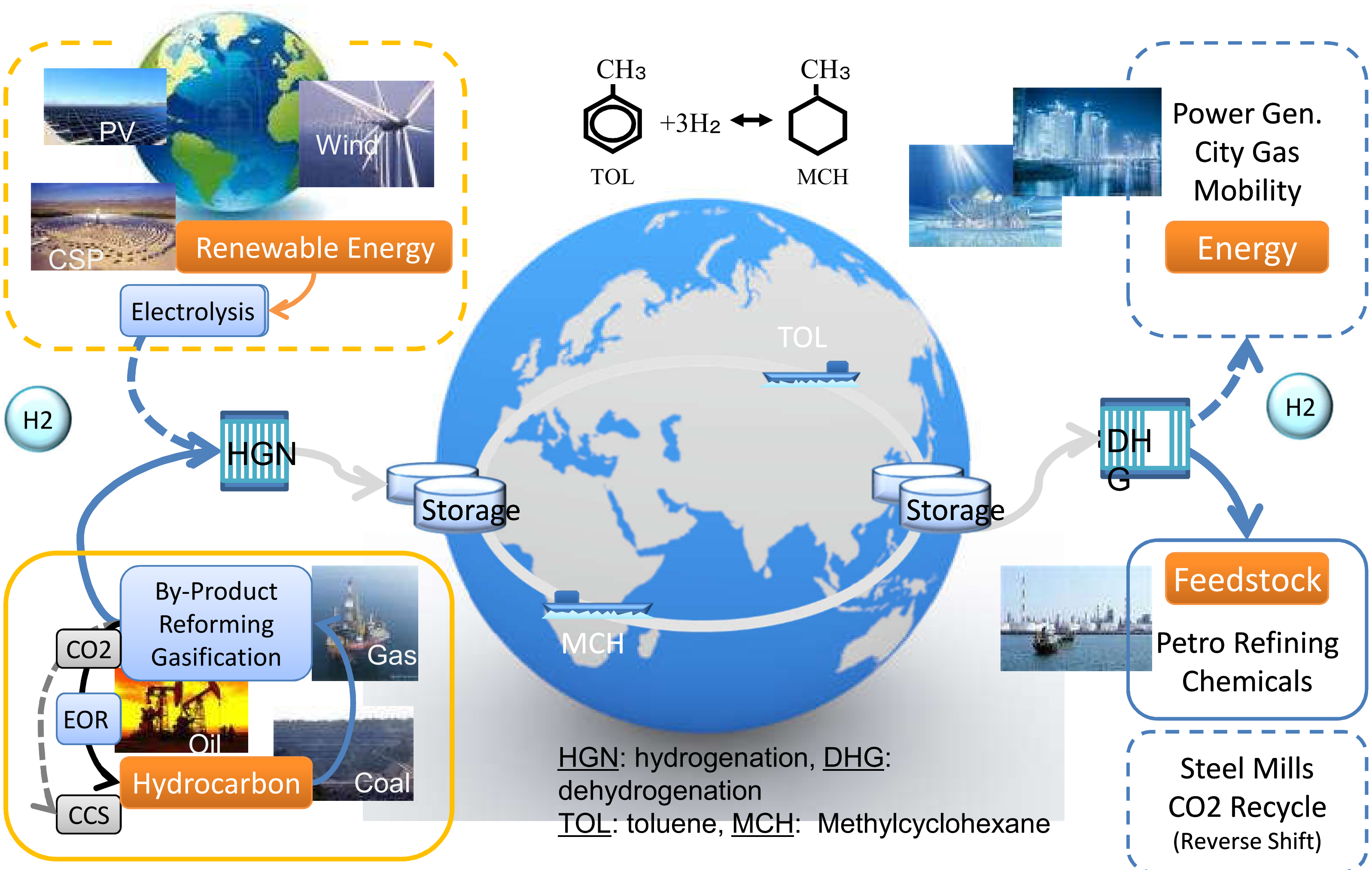


WEO2017

The Stone Age didn't end because we ran out of stones.

Hydrogen as solution: Chiyoda's Supply Chain Proposal

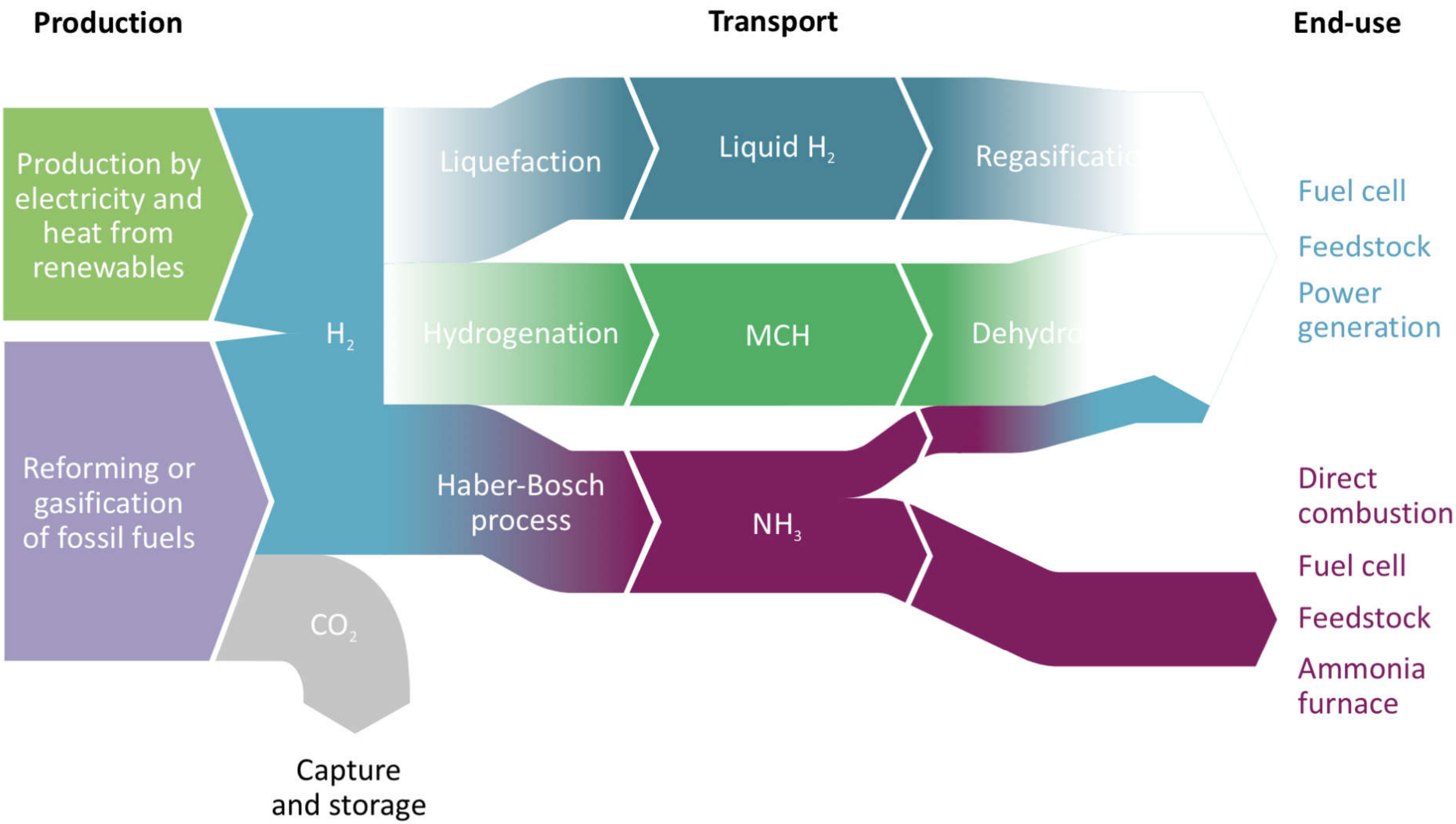
- Chiyoda established a complete system which enables economic H2 storage and transportation.
- MCH, an H2 carrier, stays in a liquid state under ambient conditions anywhere.



- H2 Supply of a 0.1-0.2mmtpa LNG equivalent scale (M.E. to Japan) could be feasible.

WEO2018

Figure 11.17 ▻ **Supply routes for low-carbon hydrogen**

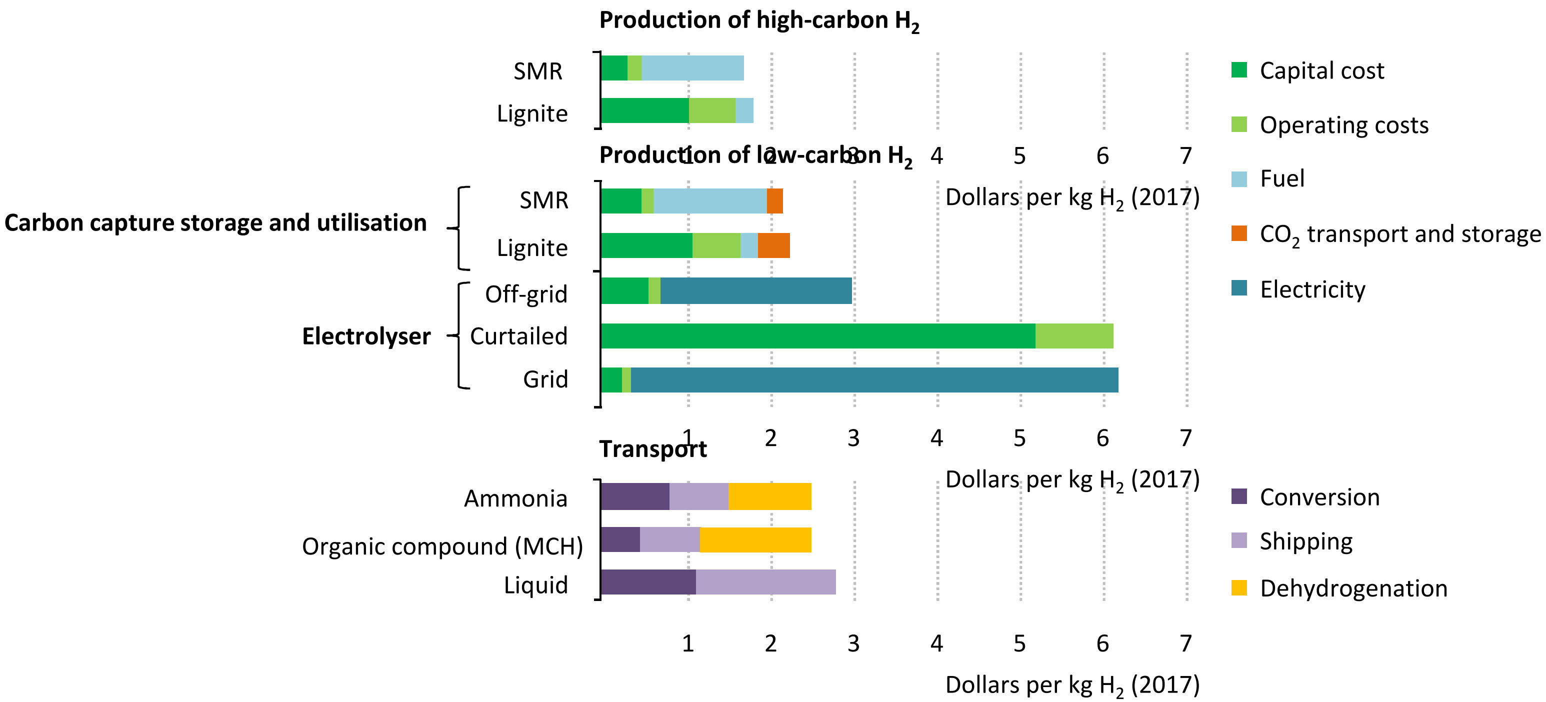


There are multiple options for the production, transportation and consumption of zero-carbon hydrogen and hydrogen-based fuels

Is hydrogen heading back to the future?

Costs for hydrogen production in Australia and transportation to Japan in 2040

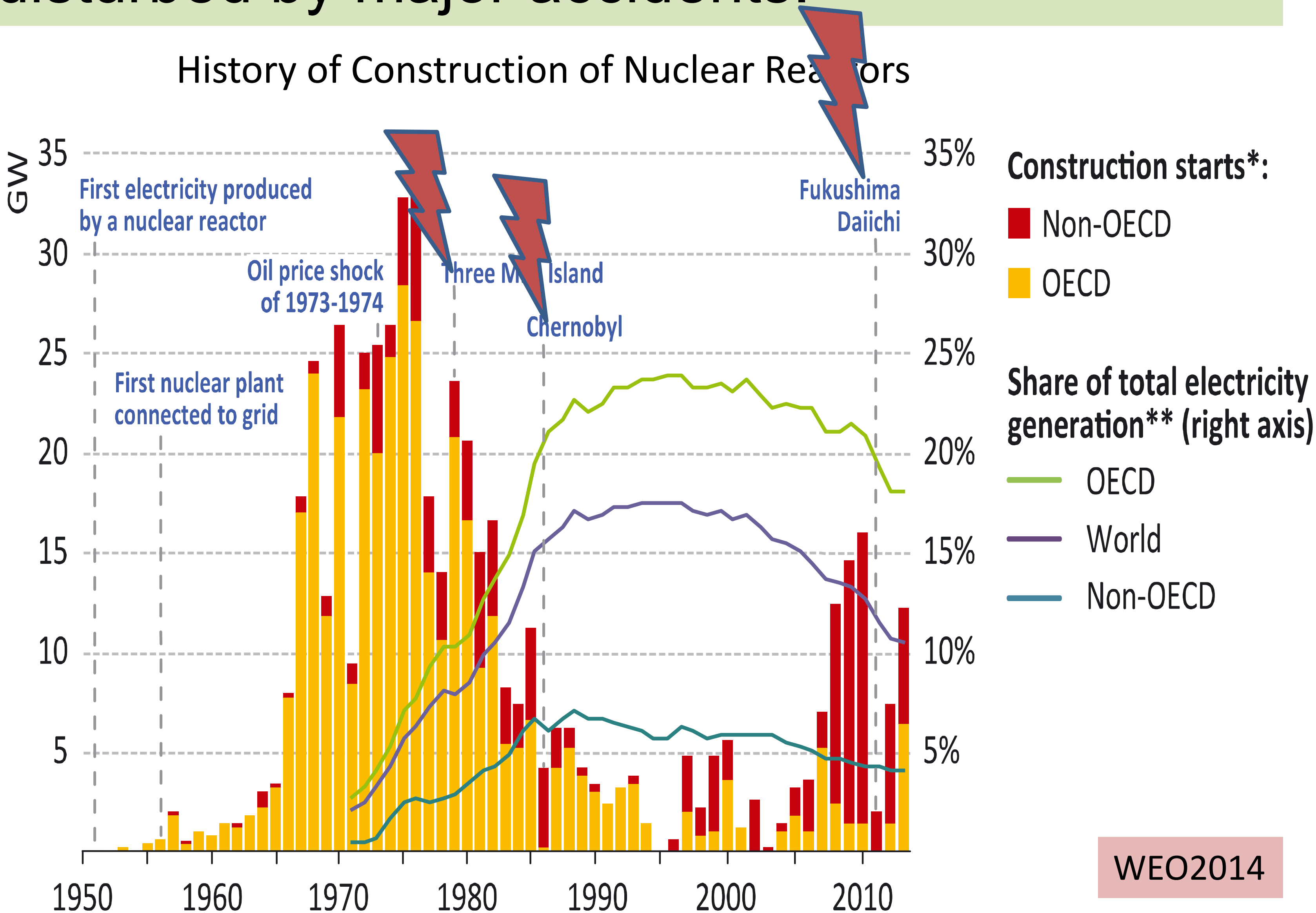
WEO2018



There are multiple options for the production, transportation and consumption of zero-carbon hydrogen and hydrogen-based fuels

SMR = Steam methane reforming, MCH = methylcyclohexane

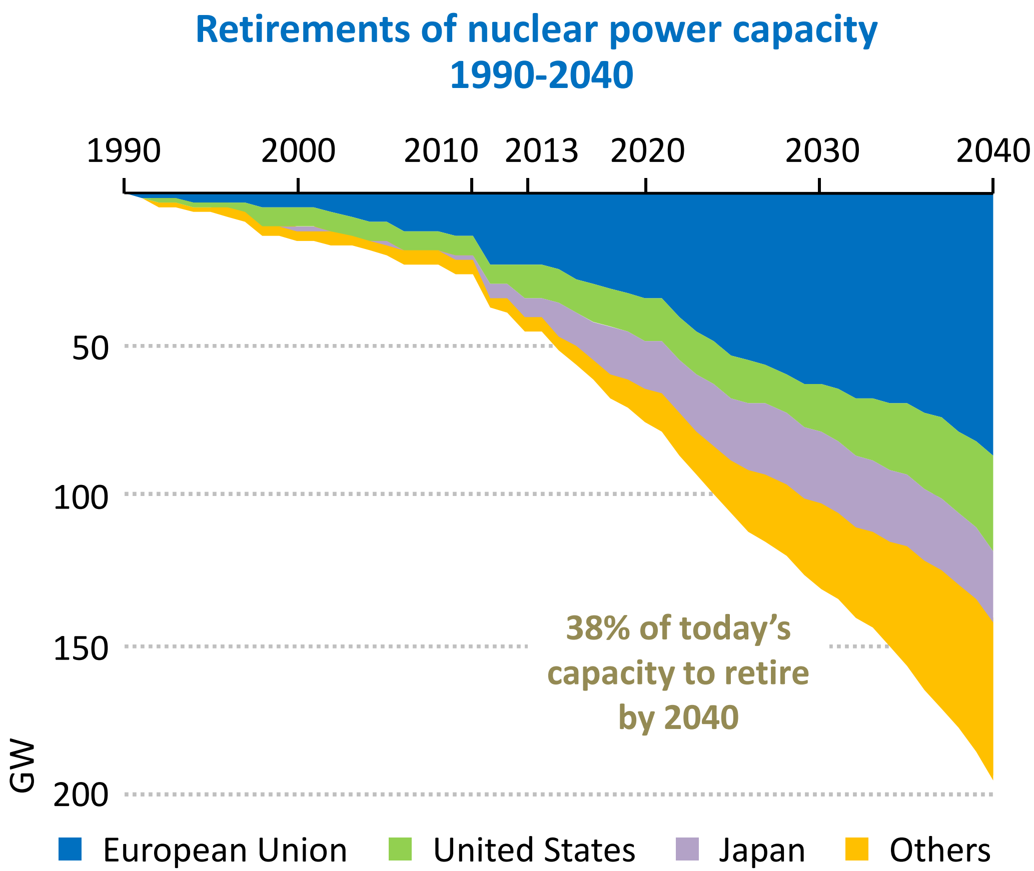
Nuclear Power development has been disturbed by major accidents.

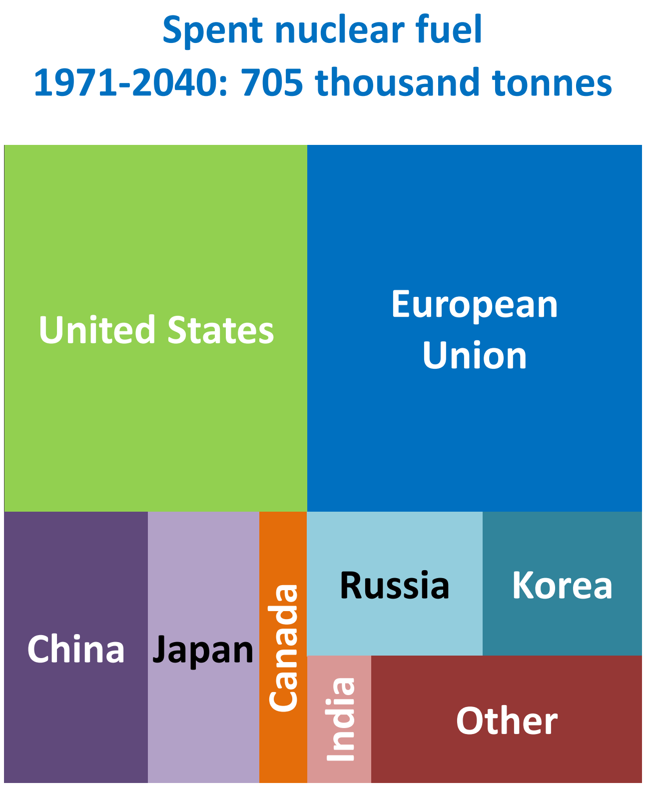


WEO2014

Nuclear power: public concerns must be heard and addressed

WEO2014

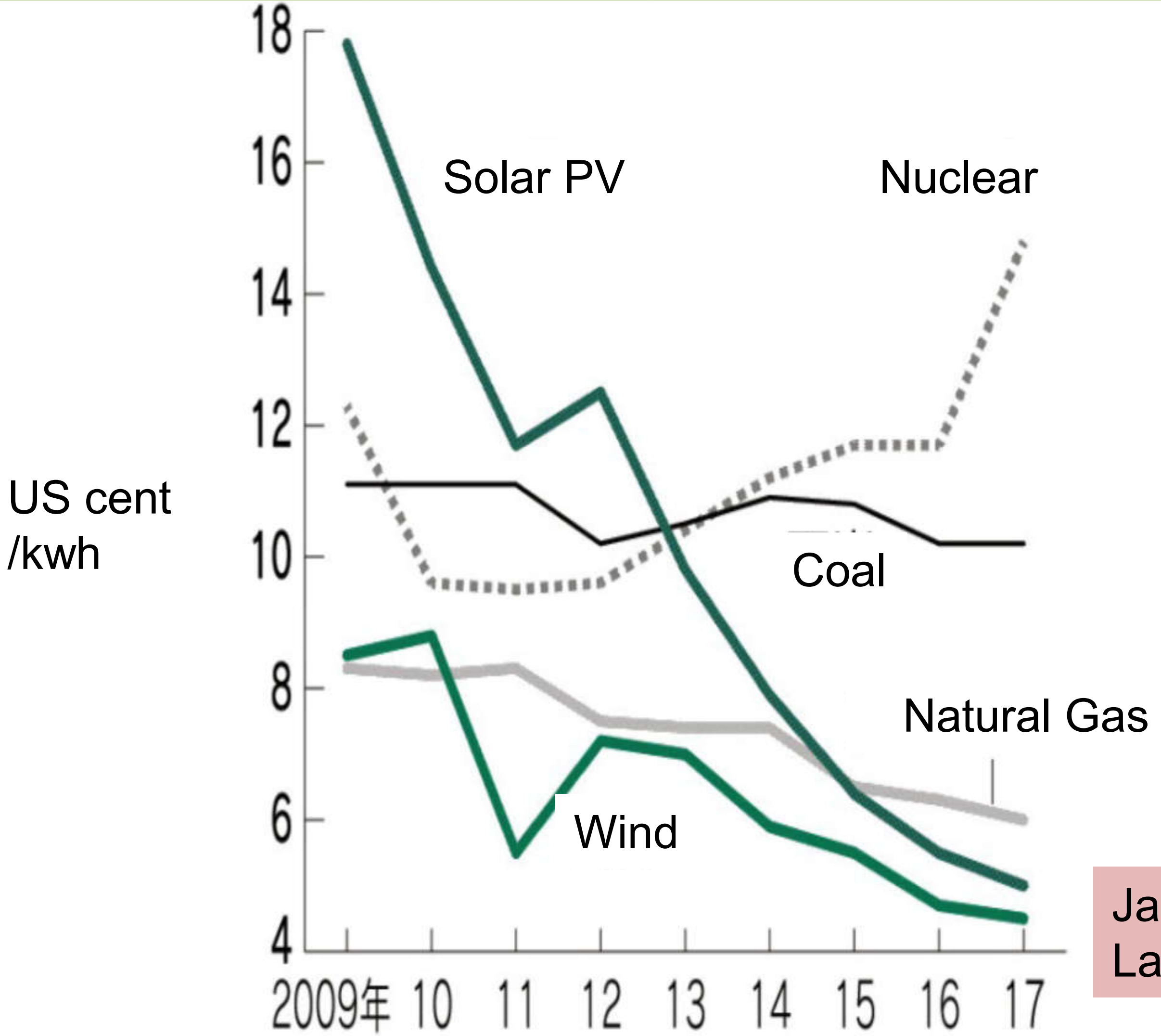




Key public concerns include safe operation, decommissioning & waste management;

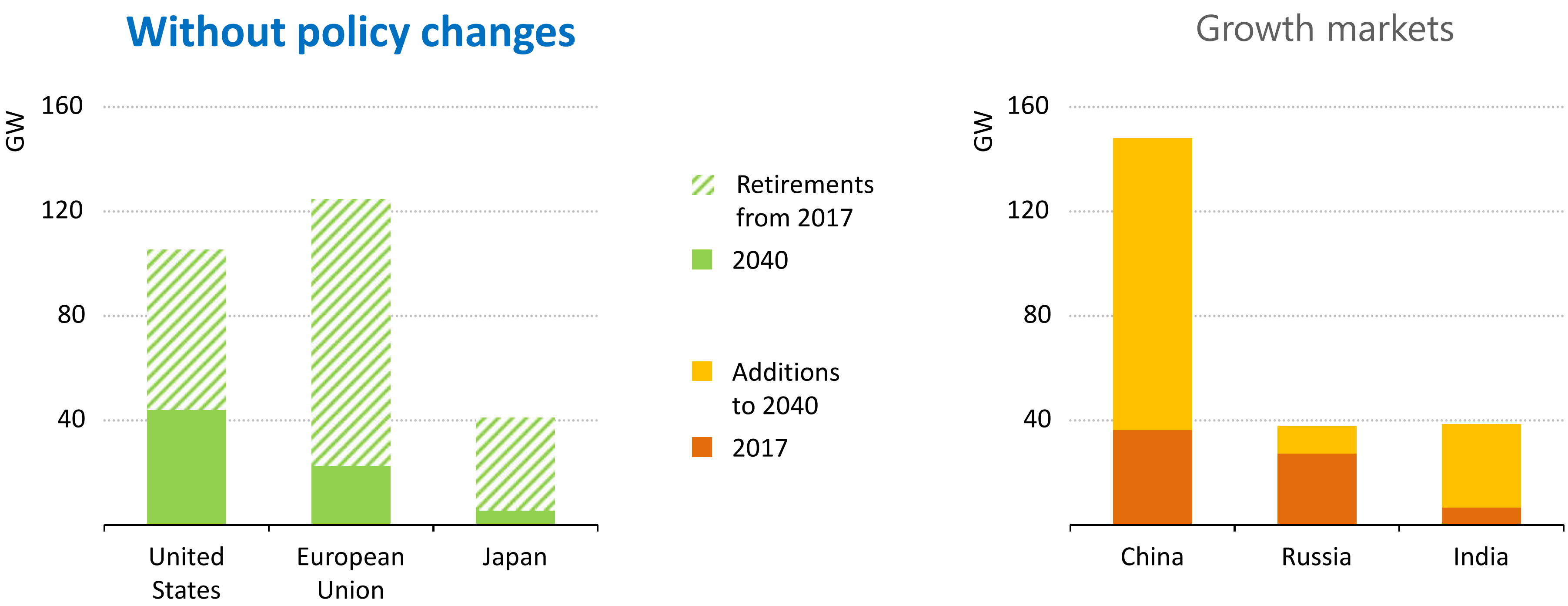
By 2040, almost 200 reactors are retired ***& the amount of spent fuel doubles***

Renewables vs other powers
Cost competitiveness structure is changing rapidly



Japan Economic Journal
Lazard Asset Management

Two directions for nuclear power



WEO2018

The contribution of nuclear power could decline substantially in leading markets, while large growth is coming, as China takes first position within a decade

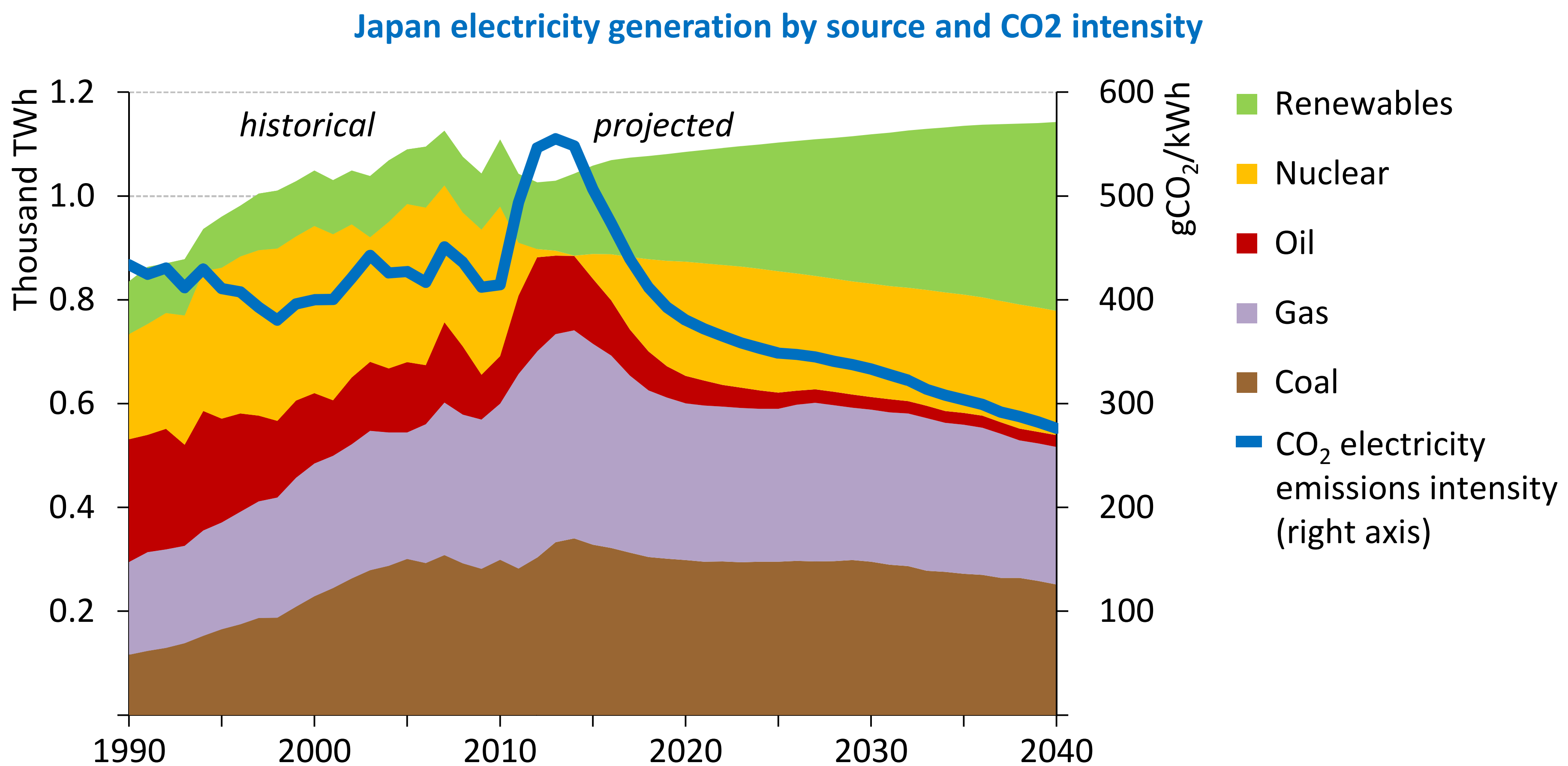
Construction cost of New power plants in China (1000yen/kw)

	2013	2014	2015	2016
Coal (USC)	53	55	61	52
hydro	154	198	219	179
nuclear	241	209	351	313
wind	123	128	147	126
solar	145	148	166	137

JEPIC/ China Federation of Power Company

Japan's power system: moving to a more diverse & sustainable mix

WEO2014



With nuclear plants expected to restart & increased use of renewables, Japan's electricity mix becomes much more diversified by 2040
(Renewables 32%, Nuclear 21%, gas 23%, coal 22%)

Generations of Nuclear Energy

Generation I
Early Prototypes

- Shippingport
- Dresden
- Magnox

Generation II
Commercial Power

- PWRs
- BWRs
- CANDU

Generation III
Advanced LWRs

- CANDU 6
- System 80+
- AP600

Generation III+
Evolutionary Designs

- ABWR
- ACR1000
- AP1000
- APWR
- EPR
- ESBWR

Generation IV
Revolutionary Designs

- Safe
- Sustainable
- Economical
- Proliferation Resistant and Physically Secure

1950 | 1960 | 1970 | 1980 | 1990 | 2000 | 2010 | 2020 | 2030

Gen I | Gen II | Gen III | Gen III+ | Gen IV

Ventures for Small Modular Reactors

State of play among nuclear fission innovators

Design

- Preconceptual: TRANSATOMIC, TERRESTRIAL ENERGY, moltex energy, ARC, LeadCold, UBATTERY
- Conceptual: AREVA, X-energy, GENERAL ATOMICS
- Preliminary: GE HITACHI
- Detailed: NUSCALE POWER

R&D

- Bench Scale testing: TERRESTRIAL ENERGY, TRANSATOMIC, UBATTERY, X-energy, ARC
- Significant Materials Testing: TerraPower, GENERAL ATOMICS, AREVA
- Fuel Scaleup and Systems: GE HITACHI
- Test or Prototype Reactor: NUSCALE POWER

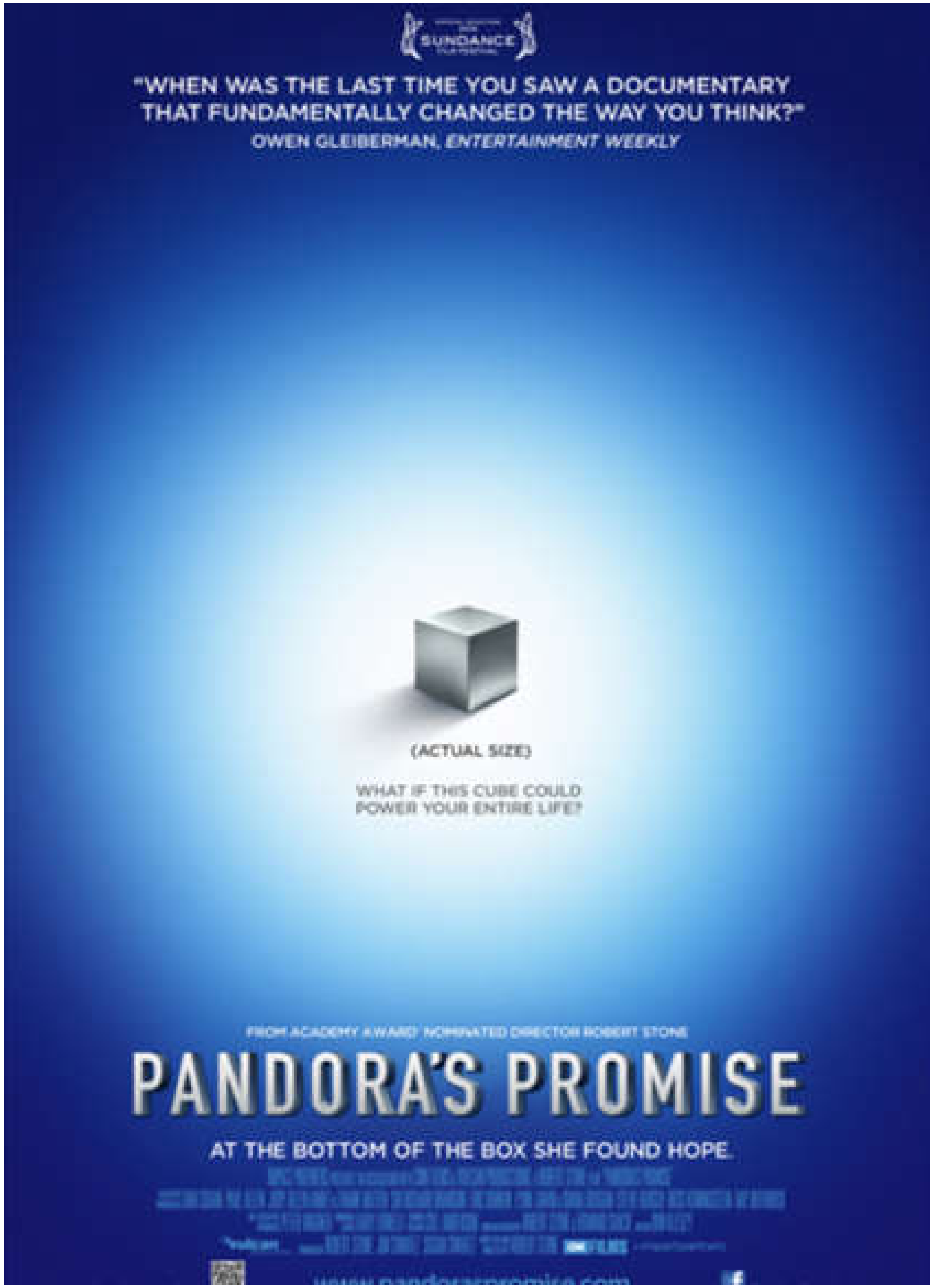
Financing

- Private Venture Capital: TRANSATOMIC, LeadCold, TERRESTRIAL ENERGY, ARC, moltex energy
- Significant Private & Public Financing: TerraPower, UBATTERY, GENERAL ATOMICS, X-energy, AREVA
- Commercial Scale Financing: NUSCALE POWER

Regulatory

- No Regulatory Work: TRANSATOMIC, AREVA, UBATTERY, X-energy, TERRESTRIAL ENERGY, GENERAL ATOMICS, moltex energy, ARC
- Prelicensing Activities: TerraPower
- Non-binding Review: GE HITACHI
- Design Certification Application: NUSCALE POWER

CLEARPATH | CLEAN ENERGY. THE CONSERVATIVE WAY.

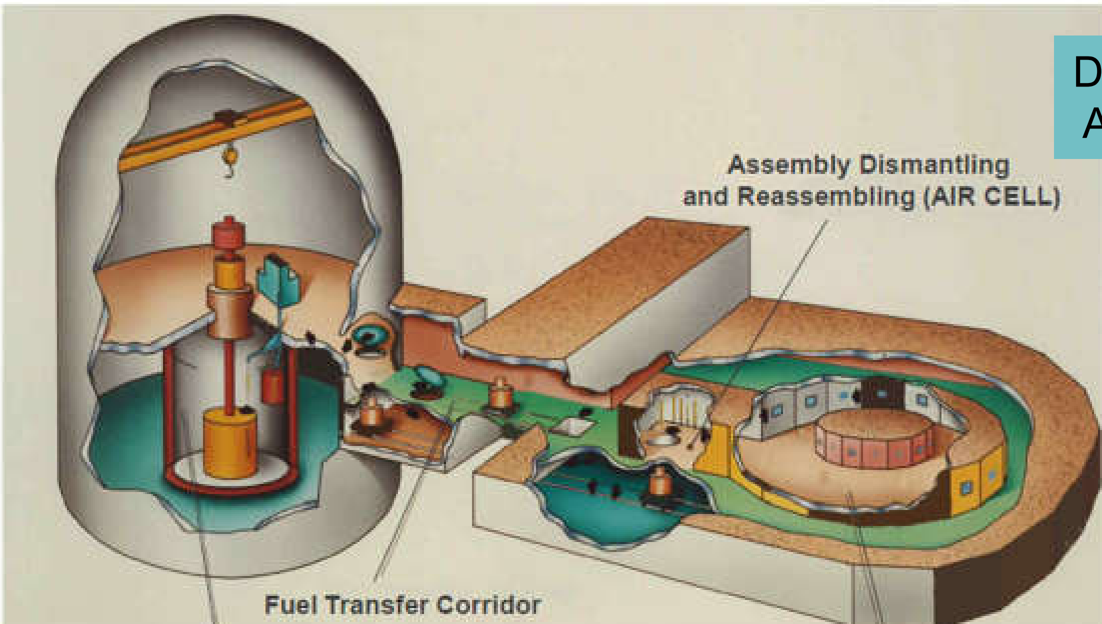


"Pandora's Promise", a movie directed by Robert Stone, is a documentary of environmentalists who changed their views about Nuclear Power.
Integral Fast Reactor (IFR) story comes up as a missed opportunity.

Time for Safer, Proliferation resistant and Easier Waste Management Paradigm:
Integral Fast Reactor and Pyroprocessing

Pyroprocessing was used to demonstrate the EBR-II fuel cycle closure during 1964-69

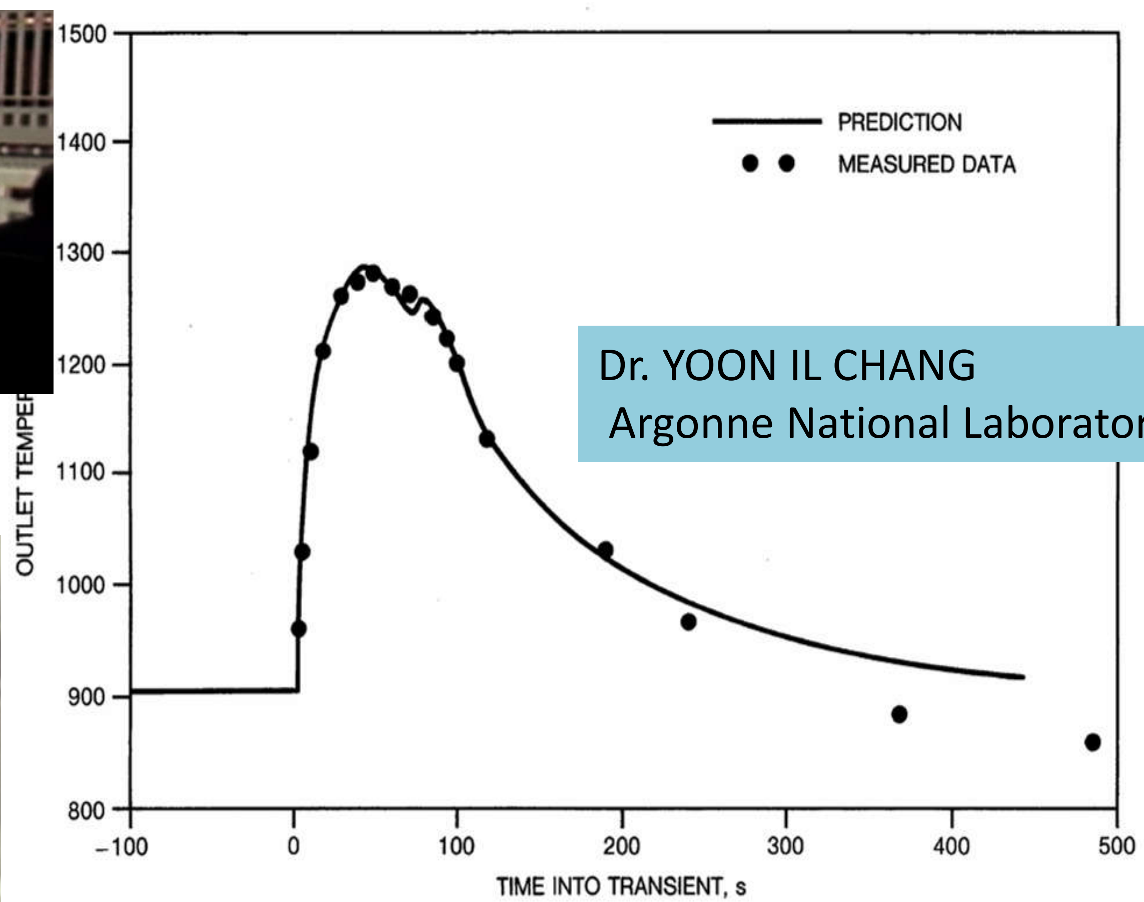
Dr. YOON IL CHANG
Argonne National Laboratory



IFR has features as Inexhaustible Energy Supply, Inherent Passive Safety, Long-term Waste Management Solution, Proliferation-Resistance, and Economic Fuel Cycle Closure.
High level waste reduces radioactivity in 300 years while LWR spent fuel takes 300,000 years.

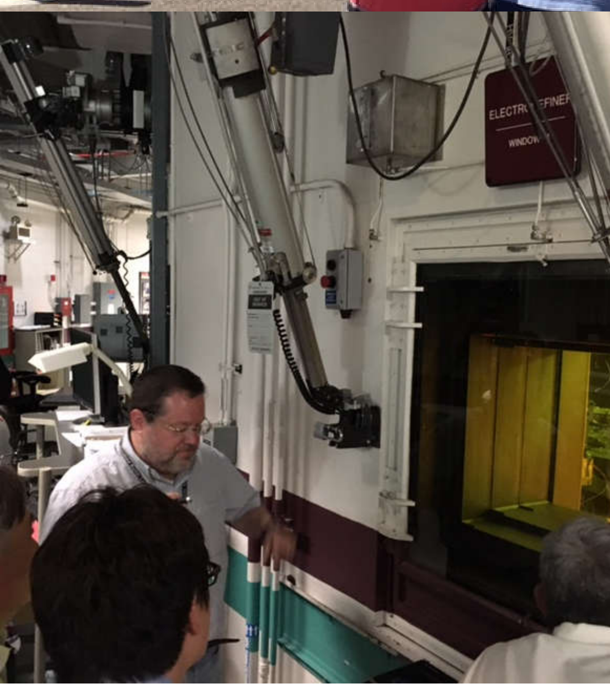
Passive Safety was proven by the 1986 Experiment very similar to the Fukushima event.

Loss-of-Flow without Scram Test in EBR-II



Dr. YOON IL CHANG
Argonne National Laboratory

Idaho National Laboratory 201



Technical Rationale for the IFR

✓ Revolutionary improvements as a next generation nuclear concept:

- Inexhaustible Energy Supply
- Inherent Passive Safety
- Long-term Waste Management Solution
- Proliferation-Resistance
- Economic Fuel Cycle Closure

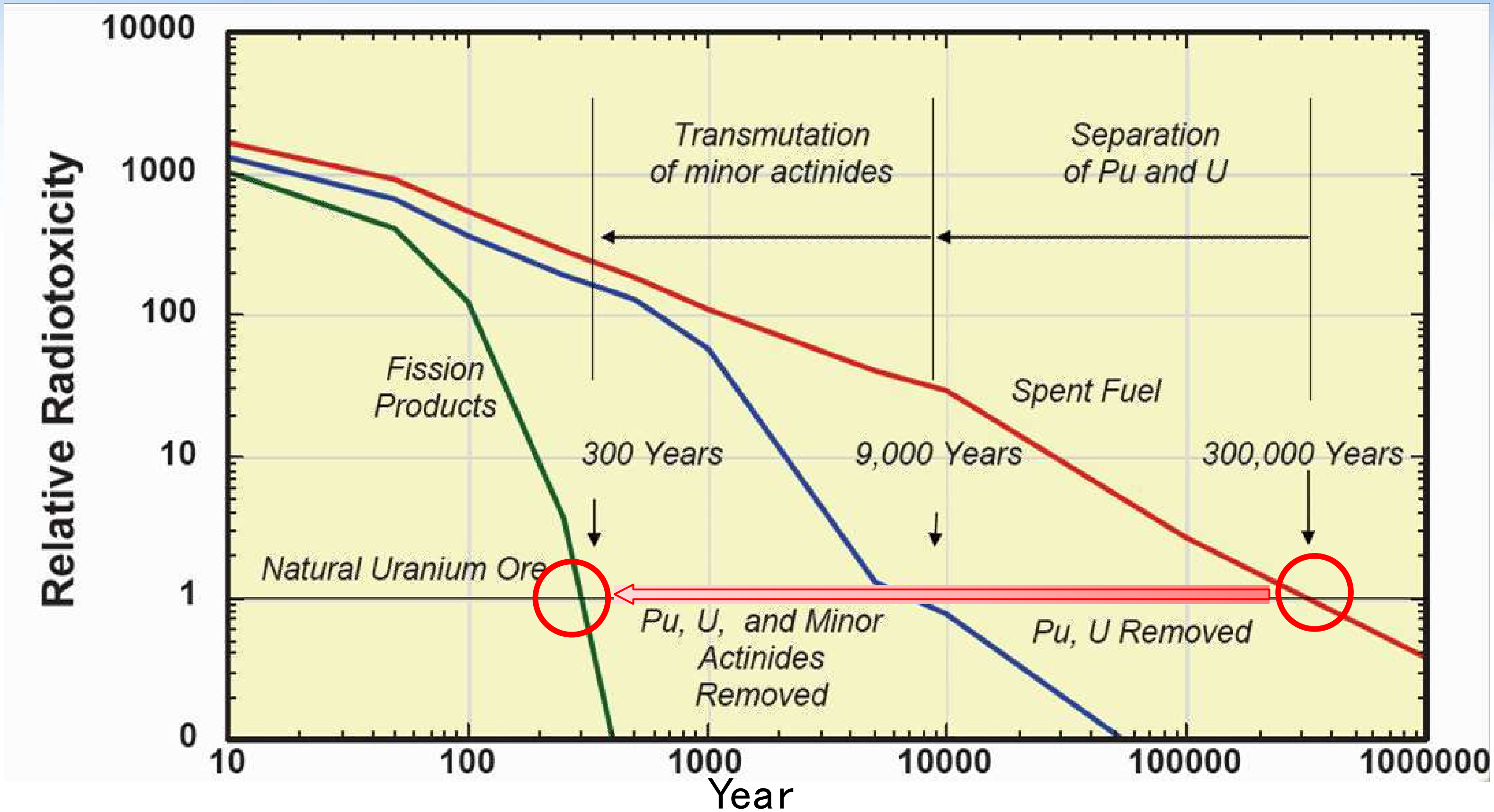
✓Metal fuel and pyroprocessing are key to achieving these revolutionary improvements.

✓Implications on LWR spent fuel management

Dr. YOON IL CHANG
Argonne National Laboratory

Transuranic disposal issues

The 1% transuranic (TRU) content of nuclear fuel is responsible for 99.9% of the disposal time requirement and policy issues



Removal of uranium, plutonium, and transuranics makes a 300,000 year problem a 300 year problem

HITACHI

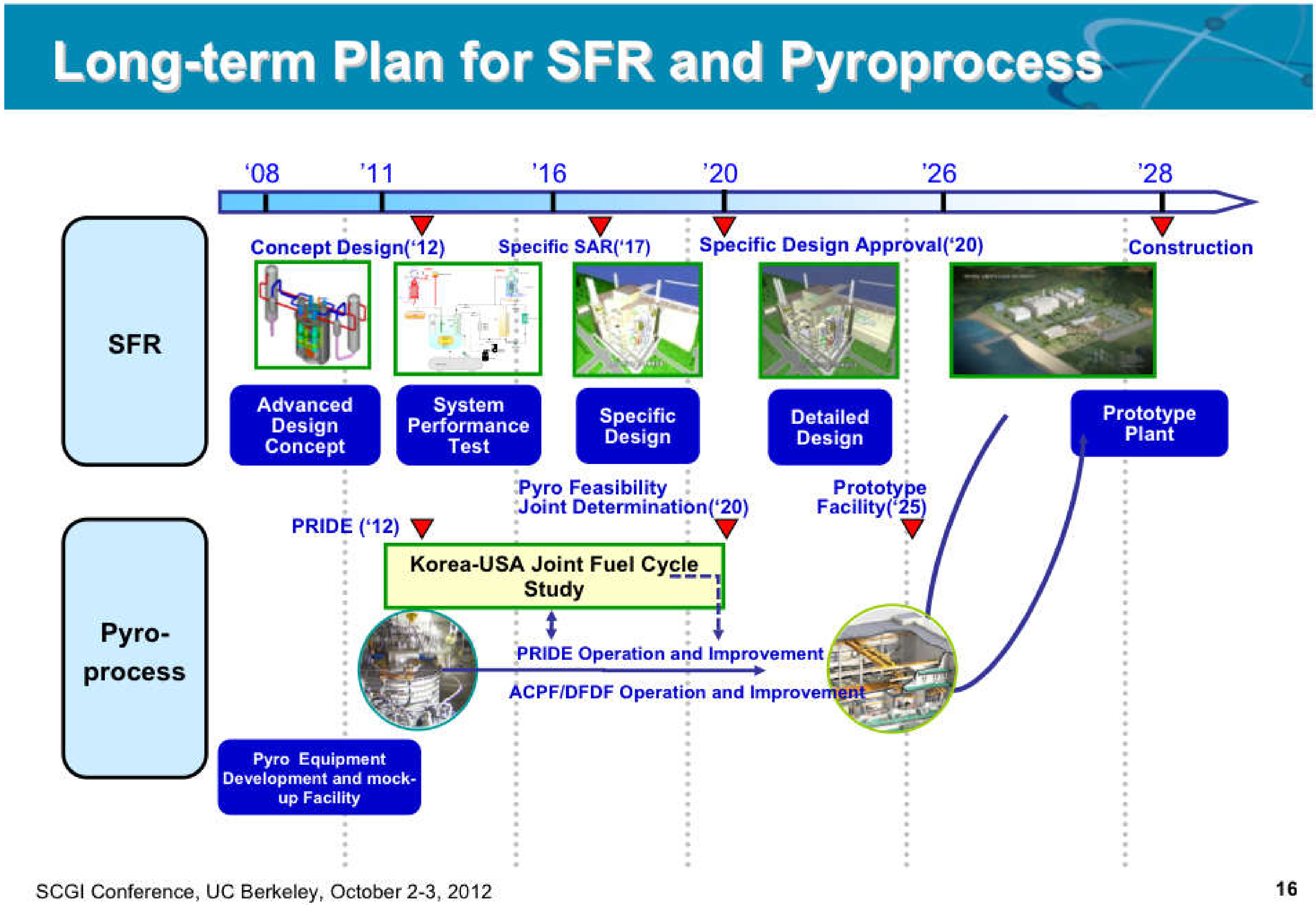
Pyroprocessing costs much less than Aqueous Reprocessing

Capital Cost Comparison ($million)
Fuel Cycle Facility for 1400 MWe Fast Reactor

	Pyroprocessing	Aqueous Reprocessing
Size and Commodities		
Building Volume, ft^3	852,500	5,314,000
Volume of Process Cells, ft^3	41,260	424,300
High Density Concrete, cy	133	3,000
Normal Density Concrete, cy	7,970	35-40,000
Capital Cost, $million		
Facility and Construction	65.2	186.0
Equipment Systems	31.0	311.0
Contingencies	24.0	124.2
Total	120.2	621.2

Dr. YOON IL CHANG
Argonne National Laboratory

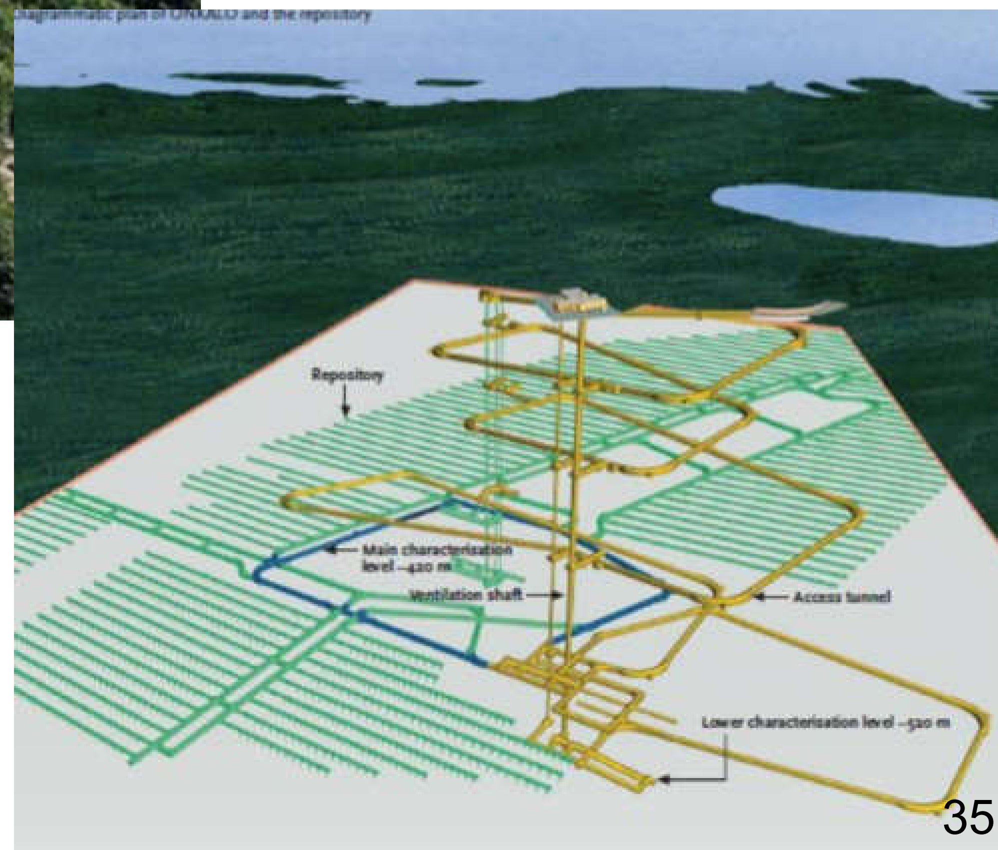
Korea is eager to build fuel cycle by IFR under the revised 1-2-3 Agreement with US



Radioactive High-level Waste Disposal or Storage

Finland Model:

Olkiluotp Nuclear Power Plant and Onkalo nuclear spent fuel repository



HQ of Teollisuuden Voima Oyj   Utility which owns Olkiluoto Nuclear Power Plant exists in the Plant site.

Proposal to Demonstrate IFR and Pyroprocessing at Fukushima

- Melt downed fuel debris and contaminated equipments will likely stay in Fukushima, though nobody admits so.
- Pyroprocessing is the most appropriate method for treating melt-downed debris.
- Pu and MA from Debris and Spent fuels be burned in IFR. Electricity is generated as by-product.
- High level waste of 300 years be easily stored or disposed geologically while decommissioning of units be cemented for tens of million years.
- Fukushima Daini (Second) Nuclear Plant of TEPCO is best located to demonstrate GE's extended S-PRISM.
- Provides ground for the extended Japan-US 1-2-3 Agreement by demonstrating complemental fuel cycle options.
- International joint project of Japan-US-Korea will provide an alternative for global non-proliferation regime (NPT).

International Conference on "Sustainability of Nuclear Power and the Possibilities of New Technology"
organized by the Sasakawa Peace Foundation (SPF) on November 18, 2016.

Technical Feasibility of an Integral Fast Reactor (IFR) as a Future Option for Fast Reactor Cycles

-Integrate a small Metal-Fueled Fast Reactor with Pyroprocessing Facilities -

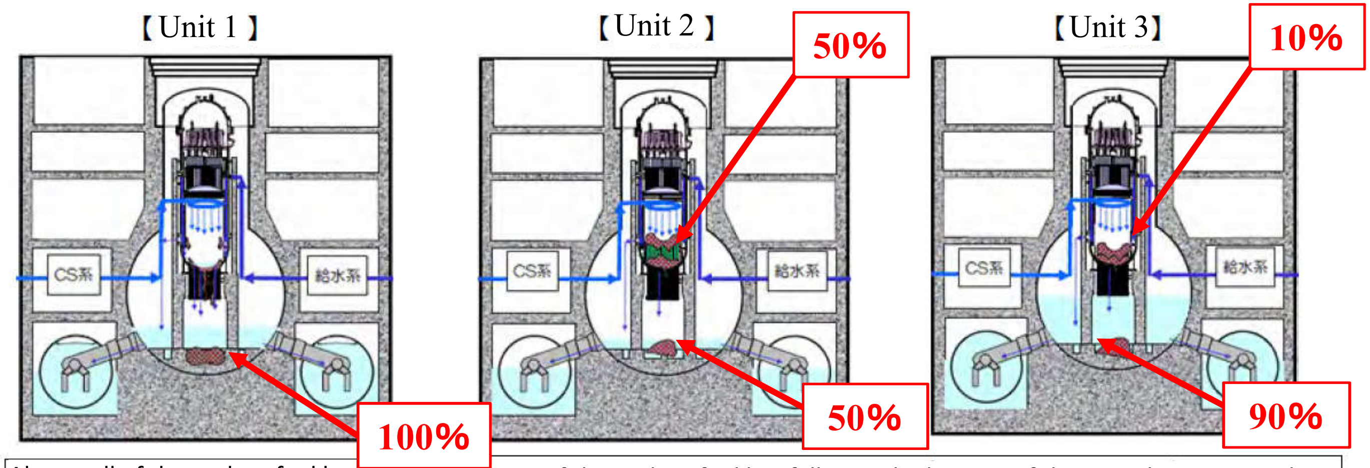
November 18, 2016

Nuclear Salon / the Sasakawa Peace Foundation

5. Research Results

Amounts of fuel debris and nuclear materials from the TEPCO Fukushima Daiichi NPS (estimated)

The distribution fraction of heavy metals (TRU+U+FP) is estimated to be as shown by the numbers to the right in red based on analyses using the SAMPSON code[*2]



Almost all of the molten fuel has fallen to the bottom of the RPV plenum and almost none of the fuel is left in the core.

-Some of the molten fuel has fallen to the bottom of the RPV plenum or to the PCV pedestal, and some fuel still remains in the core.
-It is estimated that more fuel than originally thought has fallen to the bottom of the PCV at Unit 3

Assumed states of the Unit 1~3 cores/containment vessels[*1]

The amount of debris and primary composition has been estimated as follows based upon the amount of fuel, number of control rods, and the remaining amount[*3] of structural material in each reactor.

	[Unit 1]	[Unit 2]	[Unit 3]
Amount of core region debris (Approx. 120 tons):	0	Approx. 100 tons	Approx. 20 tons
Amount of MCCI debris (740 tons):	Approx. 260 tons	Approx. 170 tons	Approx. 310 tons

- Main composition of core region debris that fused/mixed with core structure material (SUS, Zry): $(U,Zr)O_2$, SUS-Zry alloy
- Main composition of MCCI debris that fused/mixed with concrete outside the pressure vessel: $(Zr,U)SiO_4$, $CaAl_2Si_2O_8$, etc.

- As the average fuel composition for debris in Units 1~3, we used the composition at the time when void reactivity is the most severe, a maximum minor actinide ((MA) neptunium, americium, etc.) content rate and the largest number of years since the disaster within the published data.

⇒Transuranium element（TRU：Pu+MA) mass is 1.94 tons, and heavy metal (HM) mass is 251 tons

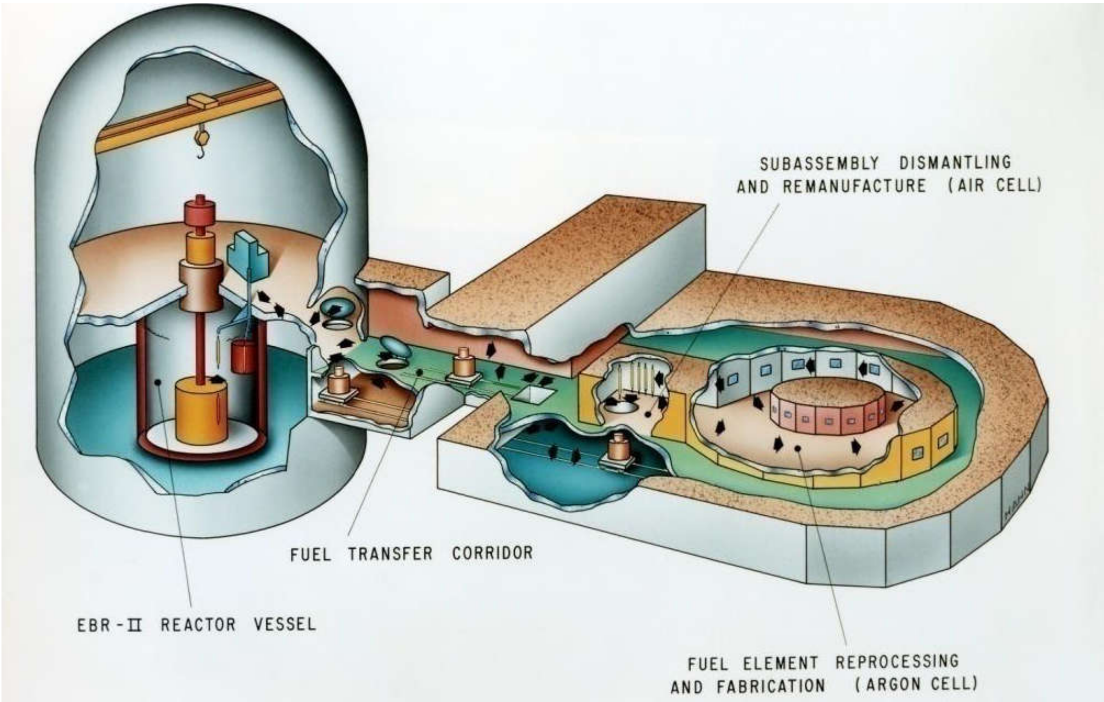
＊1：Excerpt from 1st Progress Report on the Estimate of the Status of the Fukushima Daiichi Nuclear Power Station Units 1~3 Core/Containment Vessels and the Deliberation of Unsolved Issues,"from TEPCO website.
＊2：Masanori Naito, "Analyzing Accident Event Escalation using the SAMPSON Code," Atomic Energy Society of Japan Fall Symposium, September 11, 2015.
＊3：T. Washiya et.al, Study of treatment scenarios for fuel debris removed from Fukushima Daiichi NPS, Proc. of ICONE-23, May 17-21, 2015, Chiba, Japan

Technical Feasibility of an Integral Fast Reactor (IFR)

- ✓ The concept of an integral fast reactor (IFR) consists of reprocessing the fuel debris, fabricating TRU fuel, burning it in a small MF-SFR and recycling the spent fuel by reprocessing

- ✓ Amount of heavy metals (HM), such as uranium, present in fuel debris: Approx. 250tons and **TRU elements account for approximately 1.9tons**.

- ✓ Configuration
  - A MF-SFR with inherent safety features (reactor output: 190MWt)
  - Application of a metallic fuel pyro-processing method that makes debris processing possible.

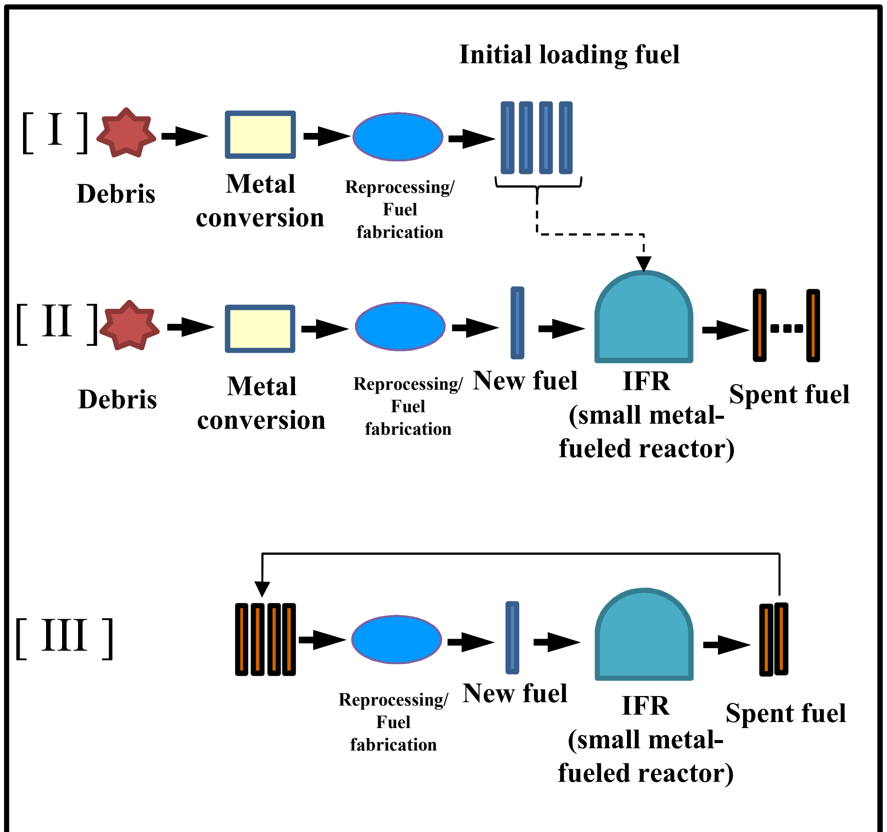


Concept diagram of an IFR that combines a fast reactor with a fuel recycling facility
(Example: Argonne National Laboratory Experimental-Breeder Reactor EBR-II and fuel cycle facility (FCF))

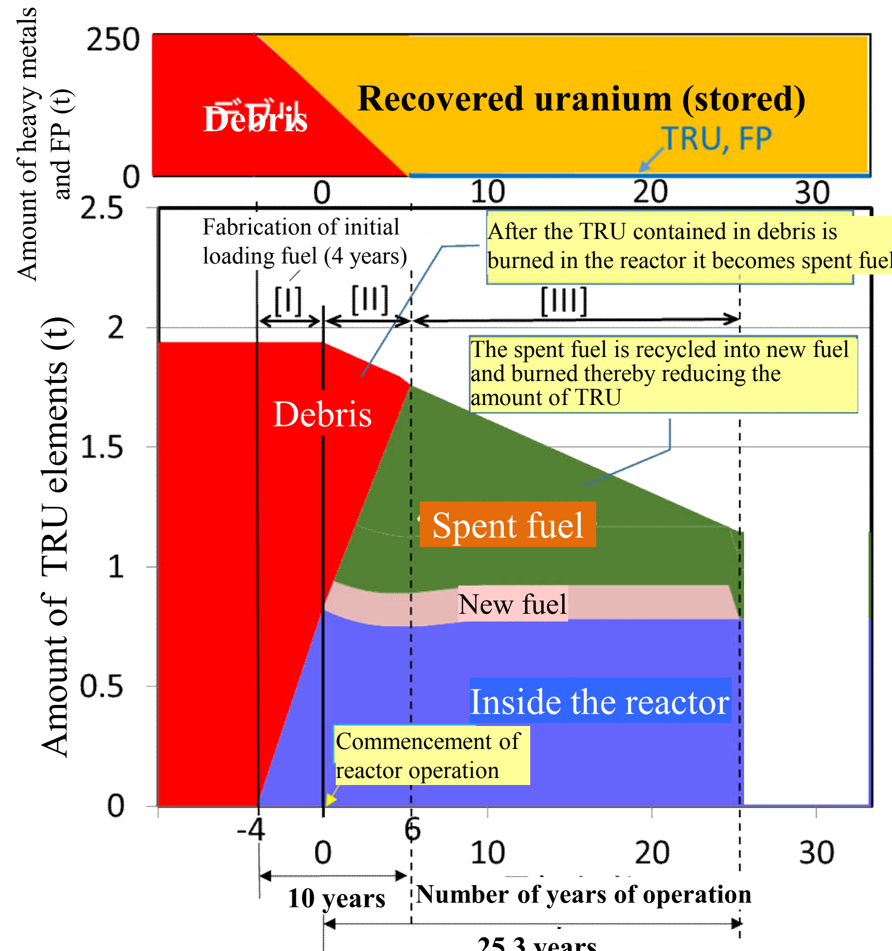
(Source: Y. I. Chang, "Integral fast reactor – a next-generation reactor concept," in Panel on future of nuclear Great Lakes symposium on smart grid and the new energy economy, Sept. 24-26, 2012.)

Debris Processing Scheme and TRU Reductions

- An assessment of TRU burn-up performances showed the originally estimated debris processing period of 15 years could be shortened to 10 years.
- The 1.9 tons of TRU present in the debris will be reduced to a total of 1.2 tons in 25 years after the launching the IFR including that remaining in the reactor and that existing in the spent fuel. Since the amount of TRU required to constantly fabricate fuel after this point will be insufficient, it will be necessary to procure TRU from external sources in order to continue continuous operation of the reactor.



Concept diagram of debris processing scheme



IFR operation and TRU reductions

Evaluation of Construction Costs for Reactor and Fuel Cycle Facilities

[Reactor]

- A small MF-SFR with the **thermal output of 190MWt** (**electrical output: 70MWe**) was estimated:
  - Decision on the major plant specifications, created general main-circuit system schematics, conceptual diagrams for reactor structures, and conceptual diagrams for the reactor building layout
  - Estimated plant commodity with referencing commodity data from past designs.
  - JAEA’s evaluation code for construction cost is adopted.
- Results: **Approx. 110 billion yen** (construction unit cost: Approx. **1.6 million yen/kWe**) (However, there is much uncertainty in these values since the system design has not yet been performed.)

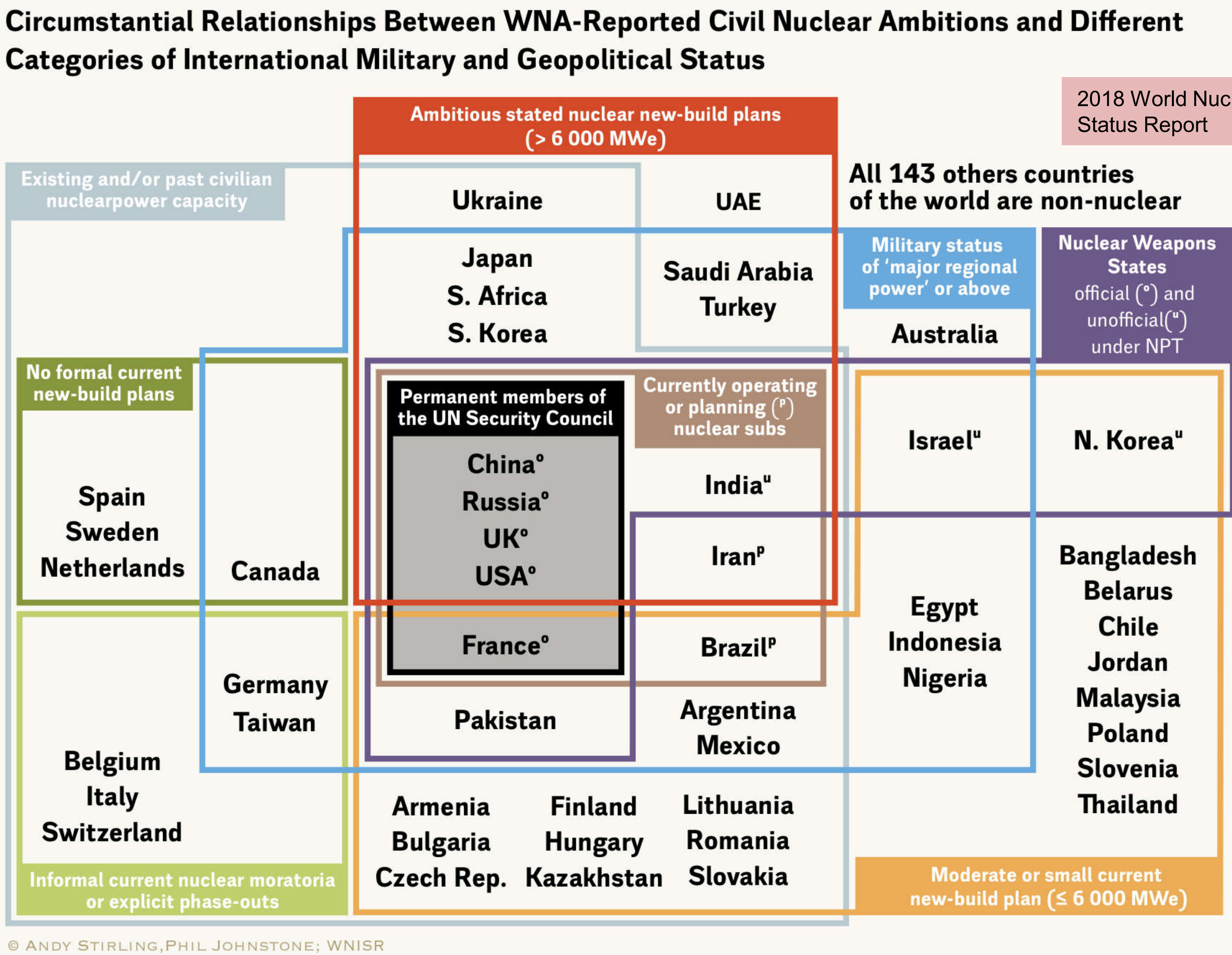
[Fuel Cycle]

- A tentative assessment of the overall construction costs of pyroprocessing facilities capable of **reprocessing 30tHM/y** and **fuel fabricating 0.72tHM/y** was done as follows:
  - The number of pieces of primary equipment were estimated based upon the processing capacity of primary equipment after determining a general process flow and material balance.
  - A general assessment was made by referencing recycle plant cell volume and building volume from past researches
- Assessment result: Whereas the construction cost of these facilities may be able to be kept at approximately **several tens of billions of yen**, there is much uncertainty in regards to reprocessing facilities and since design aspects have not been examined, it is necessary to refer to assessment values made during other design research into facilities with similar processing capabilities.

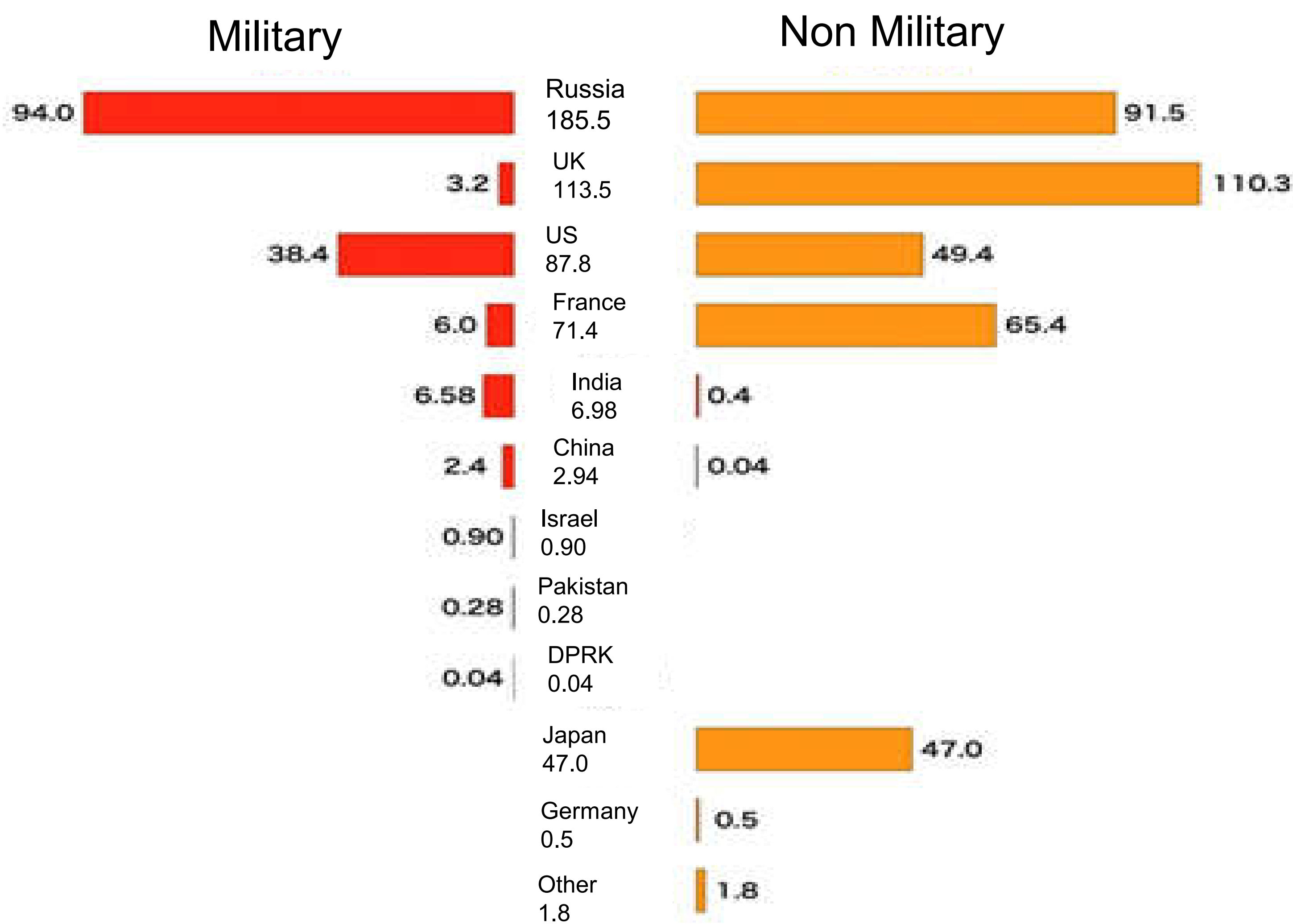
Legend of Admiral Rickover: Success of LWR for nuclear submarine has crowded out Fast Reactors

Figure 32 | Circumstantial Relationships Between Reported Civil Nuclear Ambitions and Different Categories of International Military and Geopolitical Status (civil nuclear plans are based on WNA data)[715]

2018 World Nuclear Industry Status Report



Plutonium in the World

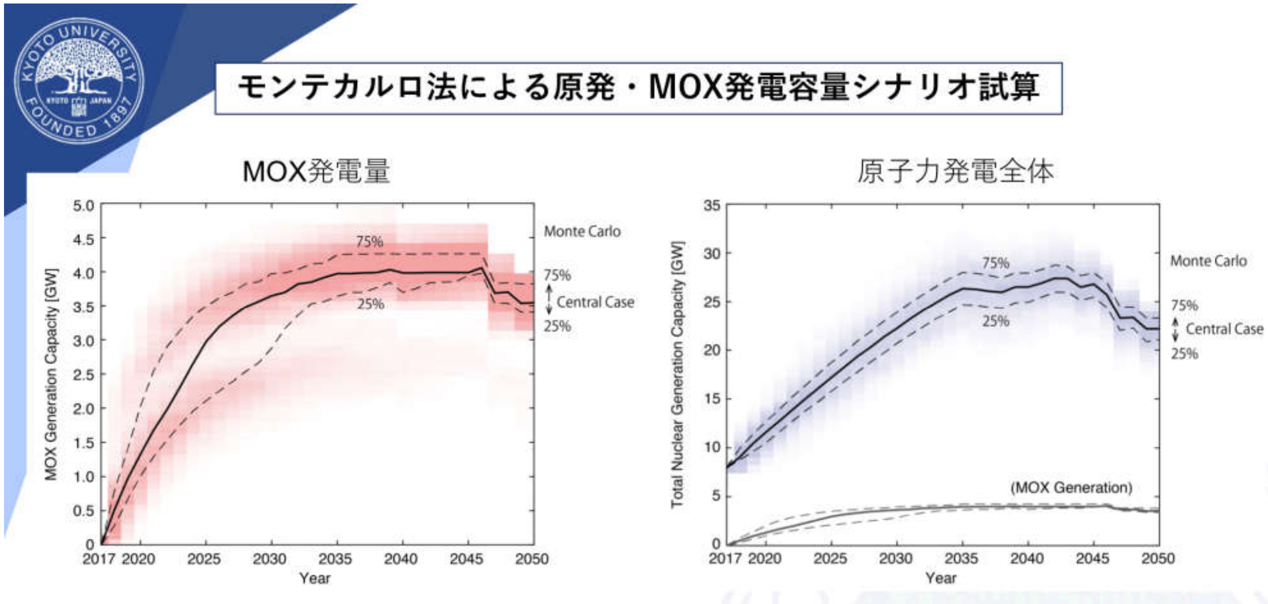


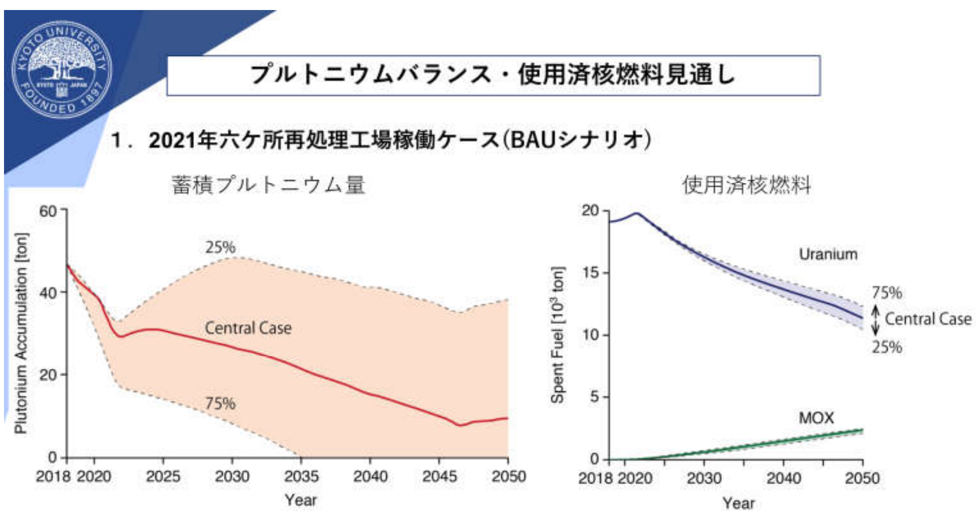
2016 Tons

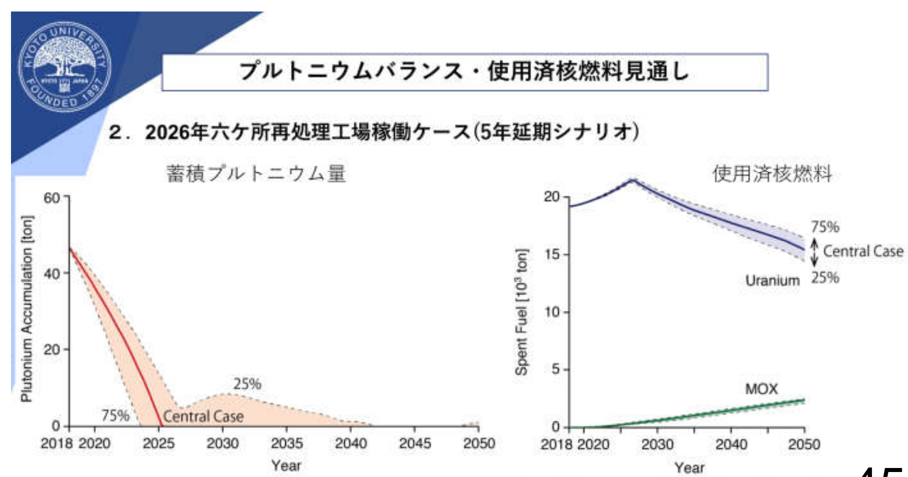
世界の分離プルトニウム保有量（長崎大学核兵器廃絶研究センターデータ）

プルトニウムバランスの試算

（武田秀太郎京都大学特任助教と笹川平和財団の共同研究）







Statement by Dr. Takashi NAGAI after Nagasaki atomic bomb. "How to turn the devil to the fortune."

Dr. Takashi Nagai, a Professor at Nagasaki University in 1945 when the atomic bomb was dropped, exemplifies the resilience, courage and believe in science of the Japanese people. Despite having a severed temporal artery as a result of the bomb, he went to help the victims even before going home. Once he got home, he found his house destroyed and his wife dead. He spent weeks in the hospital where he nearly died from his injuries. But just months after the atom bomb dropped, he said:

"Everything was finished. Our mother land was defeated. Our university had collapsed and classrooms were reduced to ashes. We, one by one, were wounded and fell. The houses we lived in were burned down, the clothes we wore were blown up, and our families were either dead or injured. What are we going to say? We only wish to never repeat this tragedy with the human race. We should utilize the principle of the atomic bomb. Go forward in the research of atomic energy contributing to the progress of civilization. Devil will then be transformed to fortune.(Wazawai tenjite Fukutonasu) The world civilization will change with the utilization of atomic energy. If a new and fortunate world can be made, the souls of so many victims will rest in peace."