

The Future of Nuclear

Is Nuclear the Future of Unlimited Clean Energy?

- From the looks of it, it's not just humans who are hungry for power. In the age of the Internet of Things (IoT), everything needs unlimited power. Whether it's a small hand-held device or something as big as a space station; the incessant need for power is forcing the sharpest minds in the world to think out of the proverbial box. But, how do we tap into unlimited clean energy?
- Mankind has already experimented with a lot of unique ways to generate power. Every iteration of experimentation ushers in new findings and opens previously unimaginable doors to harness energy from fossils, water, the sun and even nuclear fusion. However, with each attempt we discovered the shortcomings with various power generation methodologies and realized we don't just need energy; we need clean energy.

Time to Say Goodbye to Fossil Fuels

- Using the earth's fossil fuels was fine until we realized we will exhaust them at some point. Plus, during the process, we discovered some drastic side effects of this process that include global warming and many other environmental issues. So, we had to abandon our hopes with the process of generating power by burning or utilizing fossil fuels.
- We started looking up to hydro, geothermal and solar power generation, as they are cleaner and more practiced methods of power production. However, it doesn't mean that they don't present their own challenges. The Three Gorges, a Chinese hydro power dam and also the world's largest dam, is capable of producing 22.5 GW. The costs include, but are not limited to, the relocation of a record number of people (1.2 M) and the flooding of 13 cities, 140 towns and 1,350 villages. Geothermal and solar are being employed around the globe but they too present their own set of challenges.

The Sun: A Natural, Eternal Fusion Reactor

- Nuclear fusion is responsible for continuously causing gigantic explosions on the surface of the Sun. This is why the Sun is so hot and radiates energy powerful enough to travel a distance of 150 M km to reach our planet.
- Nuclear fusion is a process which combines two or more nuclei or sub-atomic particles. This combination results in the formation of new nuclei and also releases incredible amounts of energy in the process.
- Nuclear fusion requires really high temperatures around 150 M K. At these temperatures, matter changes its state to plasma.
- For the generation of power using fusion, plasma is needed to hold its current state for a long time. The amount of plasma governs the total power produced. Fusion reactors were struggling because of the amount of plasma they could hold.
- We can be optimistic about a future with a clean, infinite source of energy.

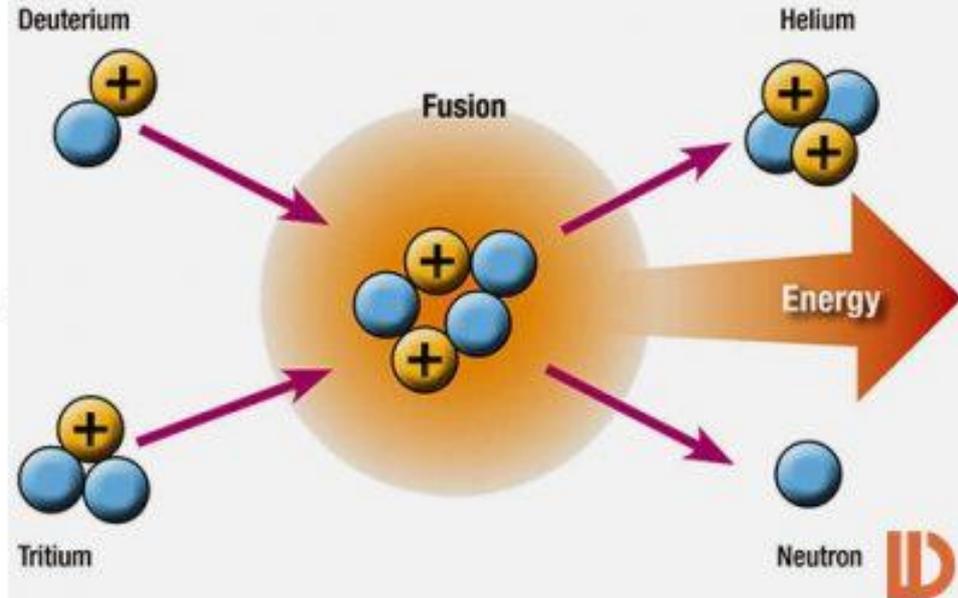
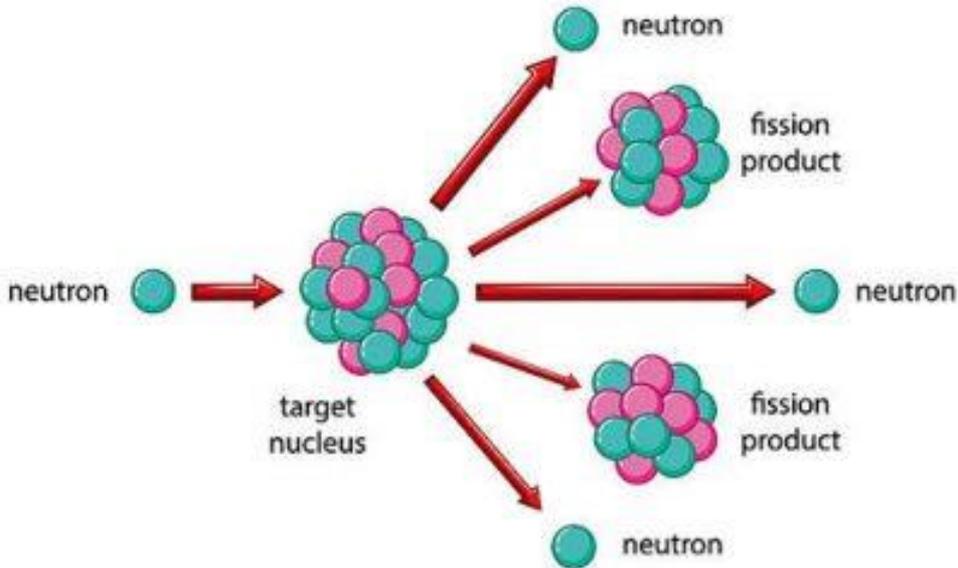
Fission v. Fusion

- Nuclear fission involves the breakdown of a nucleus into smaller nuclei. This breakdown can either be the result of an external force or can also happen naturally because of radioactive decay. Nuclear fission is fine; it produces a lot of energy but it's not as good as nuclear fusion.
- Nuclear fusion is the process that actually powers the Sun and exists at the very center of it. Keeping in mind that the center is where the temperature of the Sun is the highest, it wouldn't be wrong to assume that nuclear fusion can provide infinite amounts of clean energy.
- The path to unlimited clean energy has always been a long and difficult one. Initially, our ideas and desires were limited only what was fantasized in science fiction movies. Like how they made a little Sun in the Spiderman movie. In theory, it all sounded as a good enough idea but making it happen was a different story altogether.

NUCLEAR FISSION

VS

NUCLEAR FUSION



Fission

- In 1940 Enrico Fermi built a nuclear reactor. Nuclear fission was discovered by Lise Meitner, Otto Hahn and Fritz Strassmann. Nuclear fission takes place when high speed neutrons are bombarded on the unstable isotope. During fission process, a neutron is accelerated and hits the target nucleus, which in the majority of a nuclear power reactor is uranium. It splits the target nucleus and breaks it down into small isotopes, 2~3 high speed neutrons and a large amount of energy.
- Produced energy is used to heat water in nuclear reactors and generate electricity. High speed electrons become projectiles that initiate other fission reactions which are called chain reactions. Radioactive wastes are generated as a byproduct of fission reaction whose results take thousands of years to lose their dangerous level. Safeguards must be used with nuclear reactors for this waste and its transportation for storage.

Fusion

- Fusion occurs when two low mass isotopes (mostly hydrogen) combines under extreme temperature and pressure. Fusion reaction powers the sun. Atoms of tritium and deuterium combines under high temperature and pressure to produce a neutron and helium isotope. Besides this, an enormous amount of energy is released which is much greater than the energy of fission reaction. Researchers continue to work on controlling nuclear fission to make a fusion reactor to produce electricity.
- Scientists believe that fusion reaction produces less radioactive materials than fission reaction so has unlimited fuel supply which can be used for different opportunities. But it is tough to control reaction in a confined space, so this is a big challenge in its use. Nuclear fusion was achieved in the reaction of hydrogen bomb first time. It is also used in different experimental devices for the production of energy.

To Unite or To Split

	Nuclear Fission	Nuclear Fusion
Definition	Splitting of a large atom into two or more small atoms	Fusion of two or more small atoms into one large atom
Type of Reaction	It is a chain reaction	It is not a chain reaction
Requirements	The high temperature is not required to initiate nuclear fission	Very high temperature is required to start nuclear fusion
Process	It occurs by bombarding the heavy nucleus with neutrons	It is carried out by heating small nuclei at high temperature Bombarding of neutrons is not required
Etymology	Fission means breaking or splitting	Fusion means combination or union
Use	Nuclear fission is used in nuclear reactors because it can be controlled	Not yet utilized to produce energy because it cannot be controlled or sustained
Example	Splitting of uranium	The combining of hydrogen nuclei to form helium nuclei, the hydrogen bomb

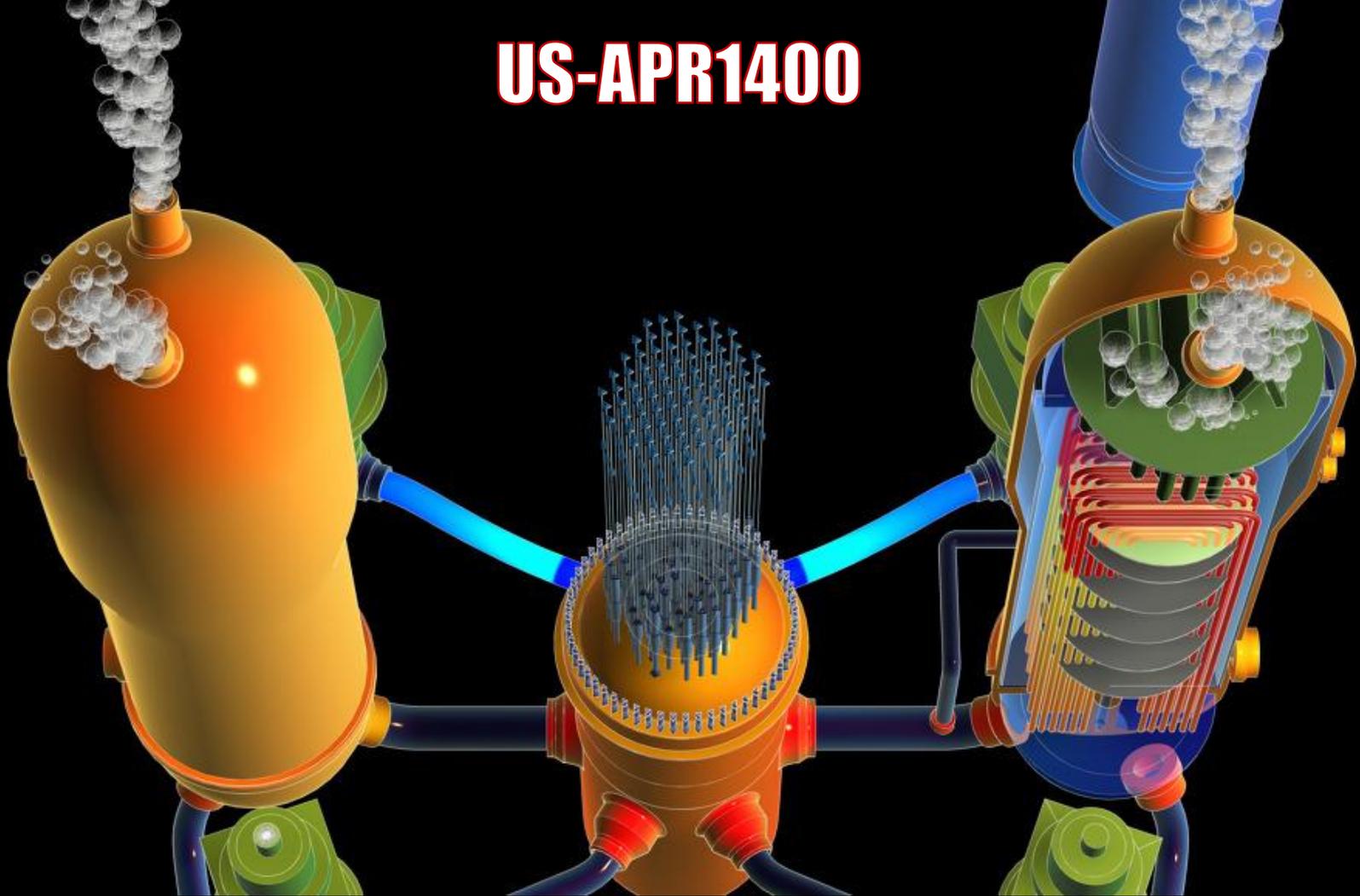
Lockheed Martin, Thereafter...

- In 2014, Lockheed Martin suggested the theory of a nuclear reactor that would be small enough to fit in the back of a truck and would weigh about 20 tons. Achieving that would have been a huge breakthrough but it was recently revealed that the new design for the same reactor is a 100 times larger and weighs 2,000 tons.
- Lockheed's promising reactor found a way to address and overcome the problem of the amount of plasma nuclear reactors can hold. They introduced a customized magnetic field generated using a compact fusion reactor. So, due to the heat generated when the plasma attempts to expand, the magnetic field will hold it back. It was a very smart solution for a complex issue; however, the designs just weren't compact enough, meaning the human race was back to square one. It cannot be denied though that they are on the right track and do hold promise.

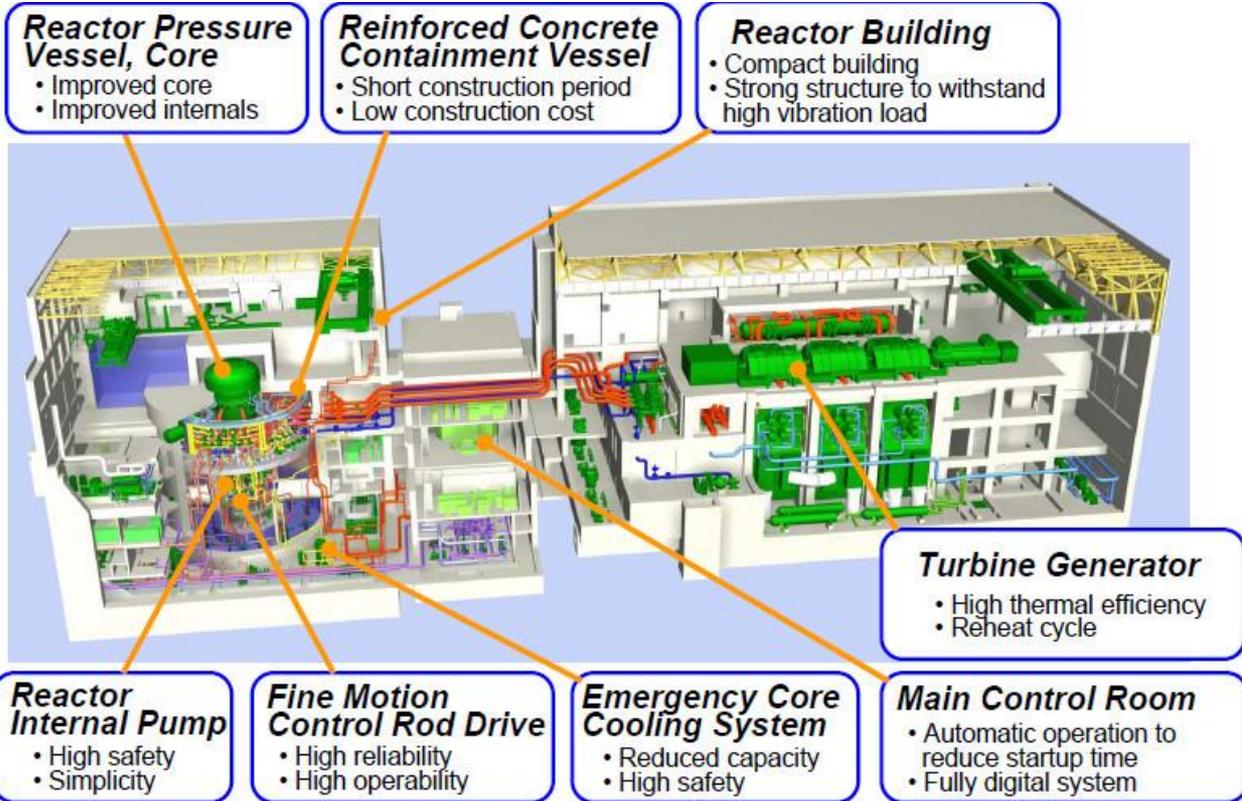
Nuclear New Build Projects

- During the early 2020s many of the UK's power stations are expected to close. If they are not replaced, there might not be enough electricity supply to meet the demands of houses and businesses.
- To provide a secure energy supply for the future, the UK needs a diverse and balanced energy mix. Nuclear power stations make an important contribution to this mix, as they reliably generate low carbon electricity. Nuclear is the most affordable large scale, low carbon energy source currently available to the UK.
- EDF owns and operates 8 of the UK's 10 existing nuclear power stations, and is building a new one at Hinkley Point C in Somerset. In addition, EDF is jointly developing other new build proposals with China General Nuclear Power Corporation, with EDF Energy leading on Sizewell C in Suffolk, and CGN leading on Bradwell B in Essex.

US-APR1400

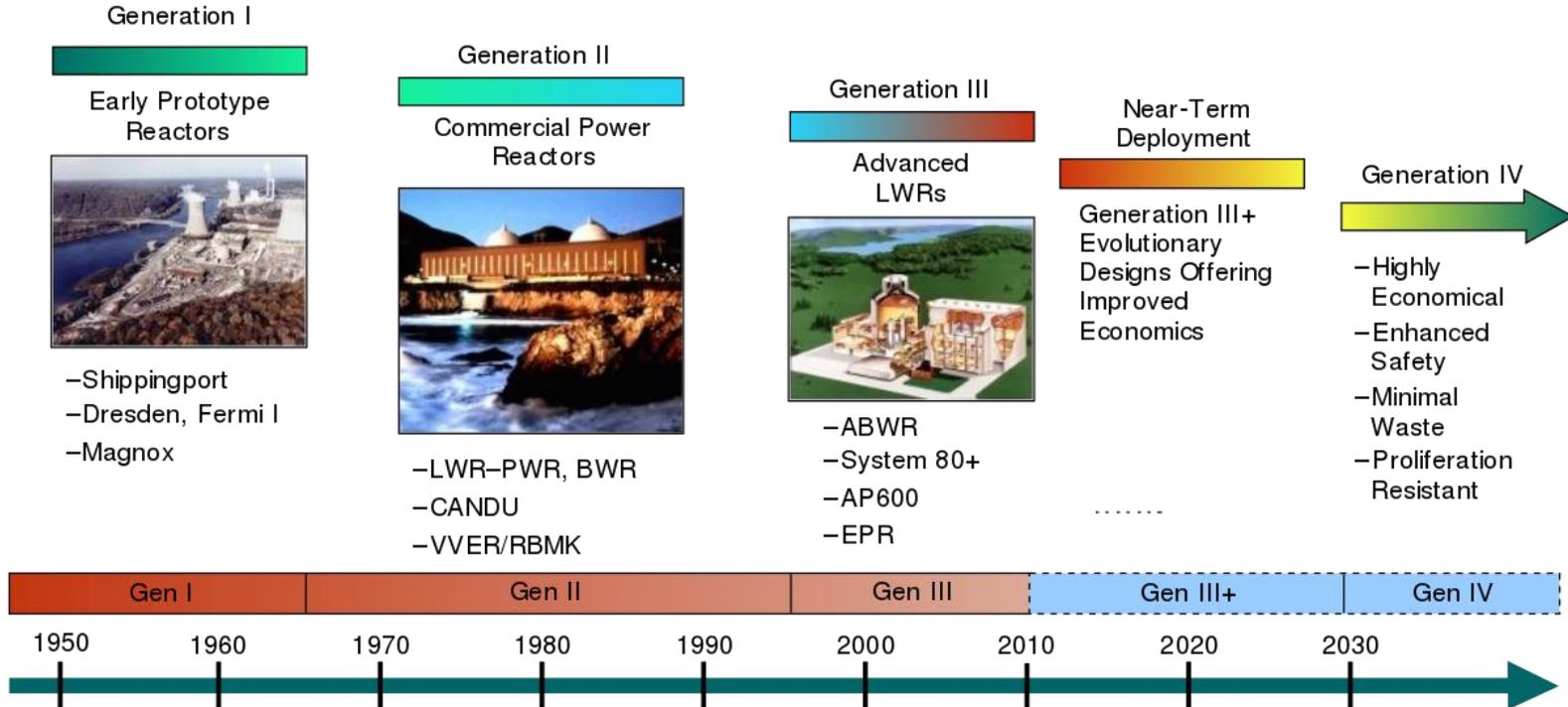


US-ABWR

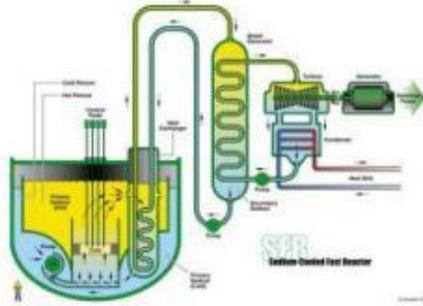


Nuclear in Generation IV

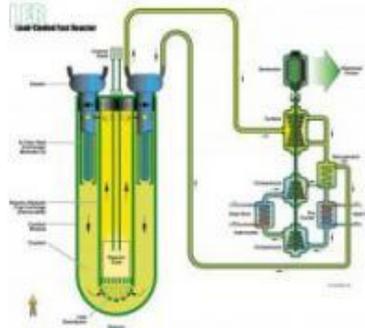
Generation IV: Nuclear Energy Systems Deployable no later than 2030 and offering significant advances in sustainability, safety and reliability, and economics



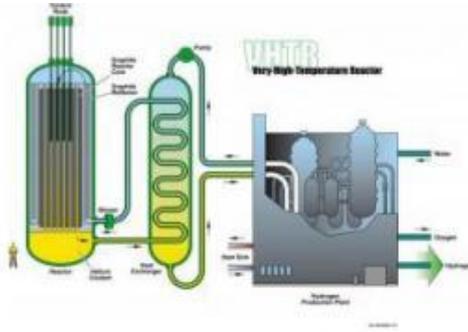
Gen IV Nuclear Energy Systems



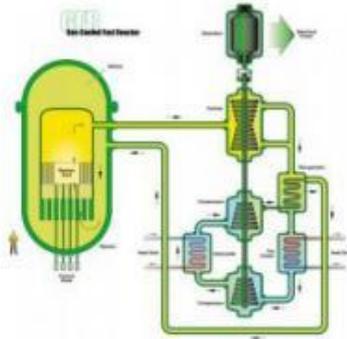
Sodium Fast Reactor



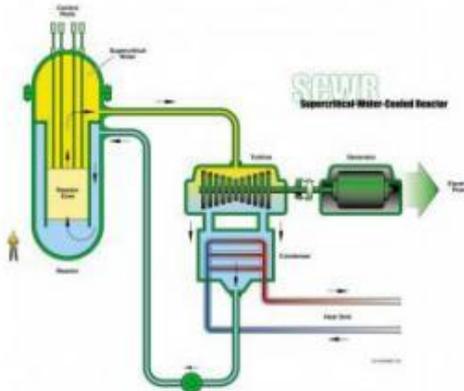
Lead Fast Reactor



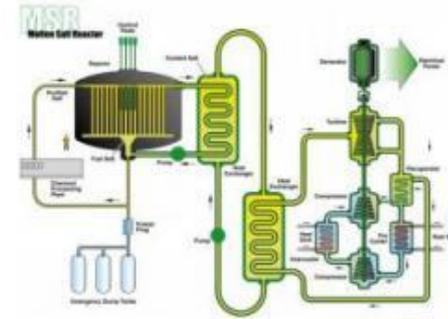
Very High Temperature Reactor



Gas Cooled Fast Reactor



Supercritical Water Cooled Reactor



Molten Salt Cooled Reactor

Generation IV International Forum

- Gen IV is a set of nuclear systems currently being researched for commercial applications by the Generation IV International Forum. They are motivated by a variety of goals including improved safety, sustainability, efficiency, and cost.
- The most developed is the sodium fast reactor which has received the greatest share of funding over the years with a number of demos operated.
- The Gen IV aspect of the design relates in largest part to the development of a sustainable closed fuel cycle for the reactor.
- Amongst the systems the molten salt reactor is considered as potentially having the greatest inherent safety of the six models.
- The thermochemical production of hydrogen to synthesize carbon-neutral fuels is deemed as strengthening the economic case for the high temperature reactor designs.

Nuclear in Perspective

- Nuclear energy today provides over a third of the world's low carbon electricity.
- For nuclear energy to continue to play its role in a sustainable global energy supply, both technical and institutional innovations are needed. This includes a new generation of reactors, such as small modular reactors, fast reactors, and the pursuit of fusion energy.
- As deep thinkers and straight talkers we need to focus on developing clean, secure and carbon neutral supplies of reliable, low cost energy. Our analysis of the world's energy realities puts a powerful lens on the stubbornly touchy issue of nuclear power, including new designs for plants that can compete economically with fossil fuels.
- We have the potential to make nuclear safer and cheaper than it's been in the past. Now we have to make the choice to pursue it.

Top 10 Nuclear Power Producers in 2017

Country	Billion kWh produced
U.S.	805.3
France	384.0
China	210.5
Russia	179.7
Korea	154.2
Canada	97.4
Ukraine	81.0
Germany	80.1
U.K.	65.1
Sweden	60.6

Nuclear: How It Works, Pros, Cons, & Its Impact

- Nuclear energy is clean, efficient, and cheap. It works by splitting uranium atoms to create heat. The resultant steam turns generators to create electricity. But there are two rate, but huge, disadvantages. If something goes wrong, it can create a nuclear meltdown. The resultant radioactivity is catastrophic. The used fuel is also radioactive, making it difficult to discard. As a result, only 4.7% of the world energy is produced by nuclear. But for many countries, nuclear power's benefits outweigh its risks.
- The U.S. is the world's largest producer of nuclear power. In 2017, it generated 805 billion kWh of electricity. That's 32% of the 2.5 trillion kWh of nuclear power produced worldwide. The U.S. leadership came from its historic role as a pioneer of nuclear power development. The first commercial pressurized water reactor, Yankee Rowe, started up in 1960 and operated until 1992.

Advantages

- Nuclear power doesn't emit any greenhouse gases, unlike coal and natural gas. As a result, it doesn't contribute to climate change. This benefit is becoming more attractive as the world seeks to reduce global warming.
- Nuclear power plants are also more resilient than other forms of energy production during natural disasters. For example, hurricanes can destroy solar and wind farms. They are less likely to damage the reinforced buildings that house nuclear plants.
- They create 0.5 jobs for every MWh of electricity produced. This is in comparison to 0.19 jobs in coal, 0.05 jobs in gas fired plants and 0.05 in wind power. The only other power source that creates more jobs is solar photovoltaic of 1.06 jobs/MWh.
- Nuclear fuel is efficient. About 28 g of uranium release as much energy as 100 metric tons of coal. As a result, transportation is less expensive.

Disadvantages

- An accident at the plant could release radioactive material into the environment as a plume or cloud-like formation of radioactive gases and particles. These particles may be inhaled or ingested by people and animals or deposited on the ground. The particles are composed of unstable atoms that give off excess energy, called radiation, until they become stable. In low doses, radiation is harmless. After a nuclear meltdown though, the large doses destroy living cells and cause mutations, illness, and death.
- Although the chances of a nuclear meltdown are rare, the potential impact can be catastrophic. The devastating incidences in Chernobyl and Fukushima are perfect illustrations of the consequences.
- The only U.S. nuclear disaster was at Three Mile Island in 1979 when the fuel partially melted. Only a small amount of radioactive gas was released.

Disadvantages

- Disposal of nuclear waste is a huge disadvantage. Low level waste comes from contact with the nuclear fuel in day-to-day operations. It is disposed of on-site or it is sent to a low level waste facility.
- High level waste consists of used fuel. It takes hundreds of thousands of years to deactivate. More than 80,000 metric tons of used fuel sit idle in 121 communities across 39 states in the U.S. Most of the waste sites are near reactors. They are located near rivers, lakes, and oceans.
- In the Nuclear Waste Policy Act of 1982, Congress told the U.S. Nuclear Regulatory Commission to design, construct, and operate a permanent geologic repository for the disposal of high level waste in Yucca Mountain, Nevada. It would cost \$100 B. It would require 300 miles of railroad tracks, and titanium shields to keep the waste intact.
- In 2018, House Republicans passed a bill to reopen the Yucca Mt. facility.

The Future of U.S. Nuclear Power

- Annual U.S. electricity demand is projected to rise 28% by 2040. With rising oil and gas prices and concern about global warming, nuclear power has started to look attractive again. In the late 1990s, nuclear power was seen as a way to reduce dependency on imported oil and gas. This policy change paved the way for significant growth in nuclear capacity.
- The Energy Policy Act of 2005 provided financial incentives for the construction of advanced nuclear power plants. Three regulatory initiatives also eased the way:
 - A streamlined design certification process.
 - The provision for early site permits.
 - The combining of the construction and operating license process.
- Since 2007, companies have applied for 24 licenses for new nuclear power plants. There are four new plants under construction.

Nuclear's Future Hinges upon Gas Prices

- On the other hand, fracking of domestic shale oil and natural gas has made gas an affordable alternative to modernizing old nuclear plants. As a result, four nuclear plants closed in the last two years. Building new gas fired plants costs less than keeping old nuclear plants running. Refurbishing old coal fired power plants to run on natural gas costs less as well.
- It seems that the future of expanding nuclear power in the U.S. depends on natural gas prices. If they rise again and stay high, expect attention to return to nuclear power generation.
- For nuclear energy to play a meaningful role in a high energy, low carbon future, we must fundamentally transform the way nuclear reactors work, how they are built, and what they cost.
- To serve rapidly escalating climate change mitigation and energy needs in the next few decades, nuclear plants must satisfy prerequisites.

Characteristics of Advanced Nuclear Energy

- Nuclear plants must be competitive on price with coal and gas; deployable as fast as coal plants or faster; and suitable for operation in developing countries that lack significant pre-existing nuclear capabilities.
 - Substantially lower capital and/or operational costs than existing plants
 - Reduced material inputs
 - Manufacturability or rapid deployment capability
 - Passive safety systems and inherent safety strategies
 - Ease of operation and maintenance
 - Reduced emergency planning zones
 - Reduced offsite impact during an accident and increased flexibility/scalability of siting
 - Increased proliferation resistant, decreased waste production and/or actinide management capacity, and more efficient use of fuel resources
 - Hybrid generation adaptability and/or load following

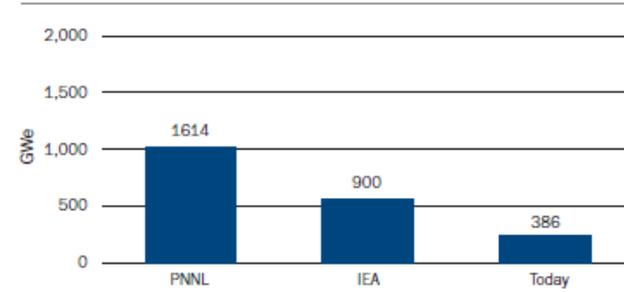
Advanced Reactors' Desired Attributes

- While new water-cooled technologies can have some of these features, non-water based technologies ultimately offer the greatest chance of achieving more of these objectives. “Advanced” does not necessarily mean “small.” Advanced reactor designs range in size from 1 MWe to 1,000 MWe or more. More often manufacturability, rather than size, lowers costs and shortens construction times.
- How do advanced reactors achieve these desired attributes?
 - Safety
 - Waste management
 - Weapons proliferation and physical protection
 - Multiple applications
 - Capital cost
 - Deployment rates

Safety

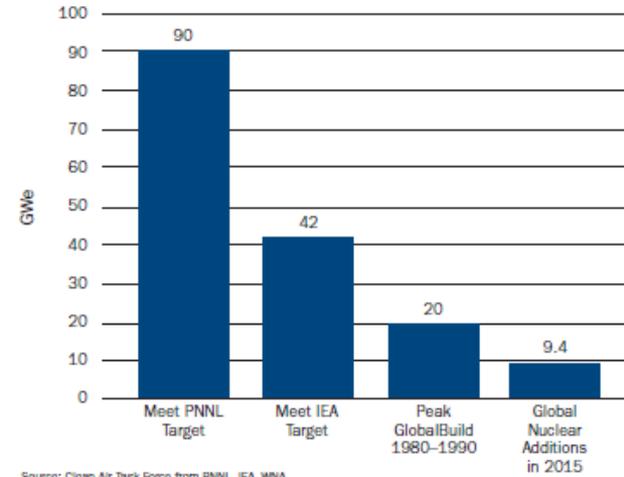
- Cooling water was a common denominator of the Three Mile Island, Chernobyl, and Fukushima accidents.
- By using non-water coolants, the likelihood of an unsafe temperature or pressure event is substantially reduced.
- Some designs, such as certain molten salt reactors, incorporate such fail-safe features as plugs that dissolve should temperatures in the fuel core rise, draining the fuel into an isolated underground chamber.

FIGURE 1
Nuclear capacity needed to meet climate targets by various estimates



Source: Clean Air Task Force from PNNL, IEA, WNA

FIGURE 2
Annual nuclear build rate required to meet various nuclear energy targets, assuming half of all current reactors will need to be replaced by 2040



Source: Clean Air Task Force from PNNL, IEA, WNA

Waste Management

- Light-water reactors use less than 5% of the energy value of their fuel, leaving 95% as waste.
- Many advanced reactors, operating on the fast neutron spectrum, can use up to 95% of the energy value of the fuel, leaving a much lower waste volume.
- Moreover, the remaining wastes are far less persistent, with toxicity half lives of hundreds, rather than tens of thousands, of years.
- These waste forms, rather than requiring geological isolation for millennia, would need only to be contained for several hundred years and could thus be housed and monitored in man-made containers.

Weapons Proliferation and Physical Protection

- As with current reactors, there is always some risk of diversion of nuclear material for illicit purposes.
- A potential benefit of advanced reactors is that many designs use fuels and produce waste streams that are less desirable for diversion.
- Many advanced fuels are not readily accessed since the fuels are contained in sealed cores that are designed so as not to be opened in the host country.
- Waste streams are often much smaller due to high burnup of fissile material during operation.
- Ongoing efforts to quantify and assess safeguardability must continue and be factored into any regulatory and licensing effort.
- Safeguards compatibility should be a priority in the design of advanced reactors.

Multiple Applications

- Today's nuclear reactors are best at producing electricity in baseload operation.
- But many advanced reactors are more versatile and can more easily cycle to match fluctuating load, which may become more important as increasing amounts of wind and solar energy are added to global grids.
- Because many advanced reactors produce much higher temperature heat, they can substitute for process heat in the chemical, refining, food processing, and steel industries whose heat use from fossil fuels accounts for more than 10% of global energy CO₂ emissions as well as displace boilers in existing coal plants.
- Higher temperature output also enables much more efficient power conversion processes such as the Brayton Cycle.

Capital Cost

- Less than 20% of the costs of a conventional nuclear plant are connected to the cost of the nuclear reactor itself and power production equipment.
- Most of the cost comes from the construction of large containment structures, cooling equipment, site infrastructure, and financing costs for lengthy construction periods that typically last four to five years or more as compared with months to two years for a gas or coal plant.
- Advanced reactor capital costs range from 33% to 80% of current large light water reactor levels in the U.S., and “nth of a kind” construction times span slightly more than two years.
- Advanced reactors address the cost issues in two ways. First, by using coolants with different characteristics and using inherent safety strategies; second, by reducing the complexity and size of the on-site structures needed.

Deployment Rates

- To power a rapidly modernizing and urbanizing planet and while managing climate change would require a minimum of 1,600 GWe of installed nuclear capacity by mid-century.
- With likely retirements of the existing fleet of 386 GWe, this goal would demand an annual reactor build rate roughly ten times the current rate or the equivalent of 100 large reactors.
- In a factory- or shipyard-build model, this goal can be achieved.
- Manufacturers such as Boeing produce 600 to 700 airplanes per year, and the world's shipbuilders annually turn out dozens of large ocean-going vessels.
- Also, because of the enhanced safety and waste characteristics, advanced reactors would likely need less site development and approval lead time.

The Policy Agenda

- Develop international safety, construction, and quality-assurance standards for advanced reactors. A core set of standards reviewed and accepted internationally would enable more rapid deployment, since each nation would not need to reassess designs based on unique national standards or try to harmonize a number of differing standards.
- Improve regulatory process and regulator experience. In addition to common standards, regulatory processes must be developed and expertise and experience built within regulatory agencies. Standards should be risk informed and nonprescriptive, allowing for phased licensing of new reactor designs rather than “all or nothing” commitments that may deter investment. Programs will be needed to eventuate depth and expertise for an expansion of advanced reactor regulatory oversight and encourage an international effort to build training pipelines.

Test & Development Infrastructure

- In many cases, advanced nuclear designs require use of new materials and fuels. Better testing facilities, especially a flexible fast neutron source, will be needed to enable efficient certification of these new materials. Additionally, once a design is well developed, a demonstration plant must be built, which requires significant effort for site development and licensing. Either a sustained national effort or a coordinated international effort would accelerate development.
- Investment in other tools such as modeling and simulation should continue to support innovation, and research in complementary technologies such as advanced manufacturing, modular construction, advanced power cycles, and 3-D printing should be scaled up and coordinated with nuclear innovation to increase the utilization of these new technologies in the nuclear field.

Export Control Procedures & Requirements

- In the U.S., some innovators have found the time, complexity, cost, and stringency of the export control process to be overly burdensome, delaying or deterring international cooperation and international business agreements.
- Efforts can and should be made to reduce the burden of the export control process without endangering the national security interests of the U.S.
- The market for advanced nuclear energy is global: it is important both to utilize international resources in development and to compete in international markets in deployment.

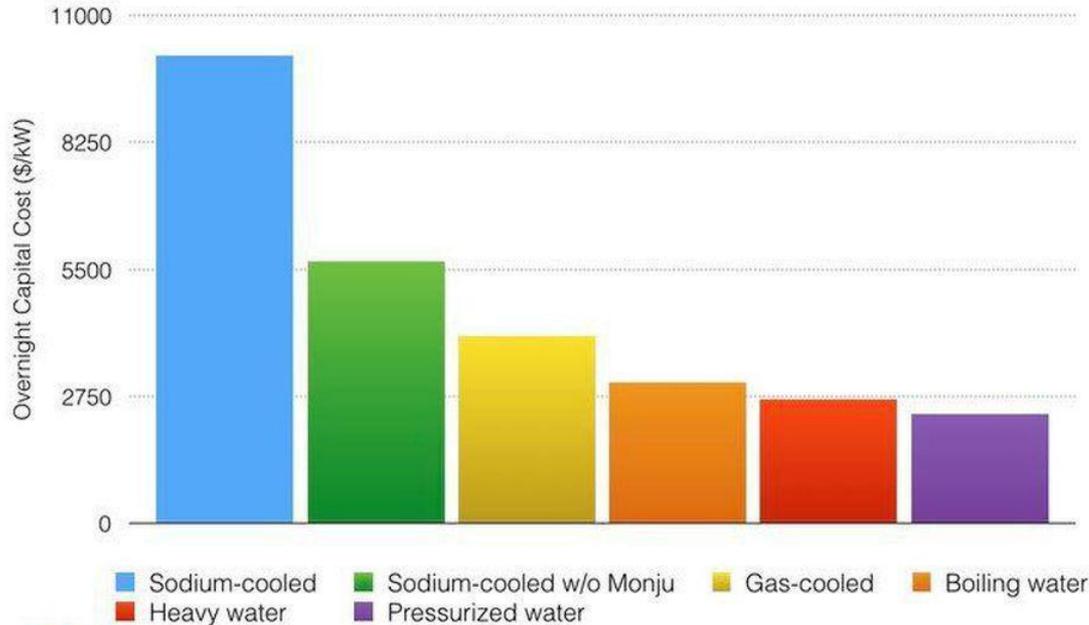
A Large Advanced Nuclear Power Plant



"Advanced Nuclear Energy: Need, Characteristics, Projected Costs, and Opportunities," Clear Air Task Force, Boston, MA 02109, USA, April 2018

Why Do We Think It Will Make Nuclear Cheap?

Construction cost of reactors by type



Father of Nuclear Power to Founder of Terrapower



Challenges for Renewed Nuclear Power

NUCLEAR SUPPLY CHAIN CHALLENGES

Components, personnel and services are no longer available in large quantities from domestic markets. The majority of procurement will be in collaboration with global suppliers, presenting a complex supply chain management challenge that is likely to include:



Global Sourcing

In the majority of cases there will be no domestic nuclear component suppliers. This leads to difficulties in developing, controlling and maintaining nuclear safety culture, technical expertise and knowledge transfer through the global supply chain.



Services

Availability of skilled workforce, services and local manufacturing facilities. This has the potential for substandard equipment and lack of available services to negatively impact the construction schedule.



Qualifying Supplier

Difficulty inspecting and certifying overseas manufacturing facilities to ensure appropriate design standards and Quality Assurance (QA) is followed. This increases the risk of substandard components and counterfeit parts entering the supply chain.



Infrastructure

Adequacy of roads, ports, port facilities and shipping lanes, heavy haulage and lifting equipment that is often project specific and one of a kind. There is only a small fleet of marine vessels that can ship large forgings resulting in shipping schedules of up to two years. All of which pose a risk to the construction schedule and potential damage to long lead time (critical path) components.



Equipment Lead Times

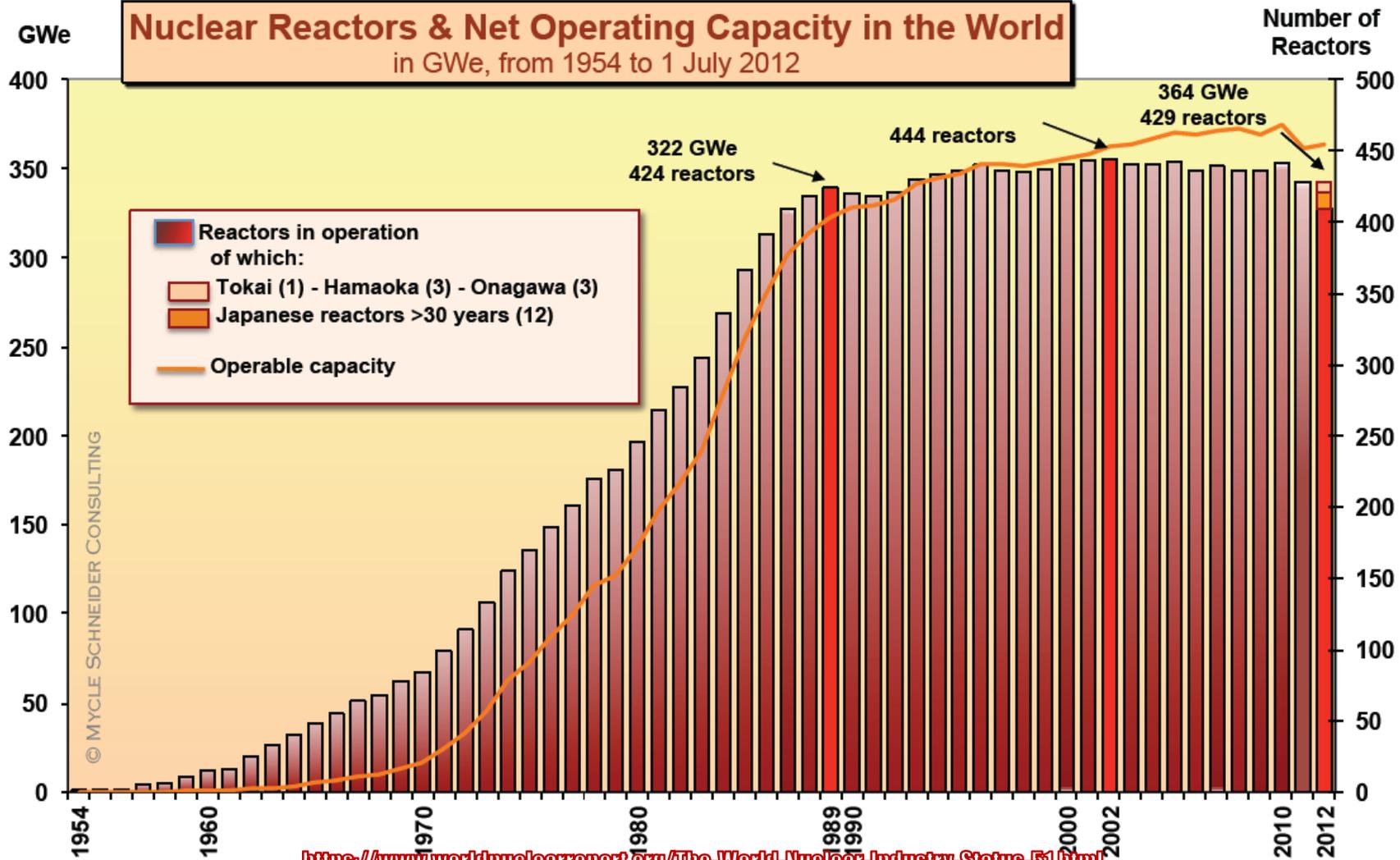
Due to the high demand for power plants, there are long lead times for critical path items, services and materials worldwide. In particular limited manufacturing facilities for nuclear grade components necessitate very long lead times of up to three years. Additional delays due to manufacturing and quality issues with other projects can have a bottleneck effect.

Willis

<https://blog.willis.com/2015/03/nuclear-power-supply-chain-challenges/>

Nuclear Reactors & Net Operating Capacity in the World

in GWe, from 1954 to 1 July 2012



RAIN: Renewable And Innovative Nuclear



Nuclear Energy and Renewables

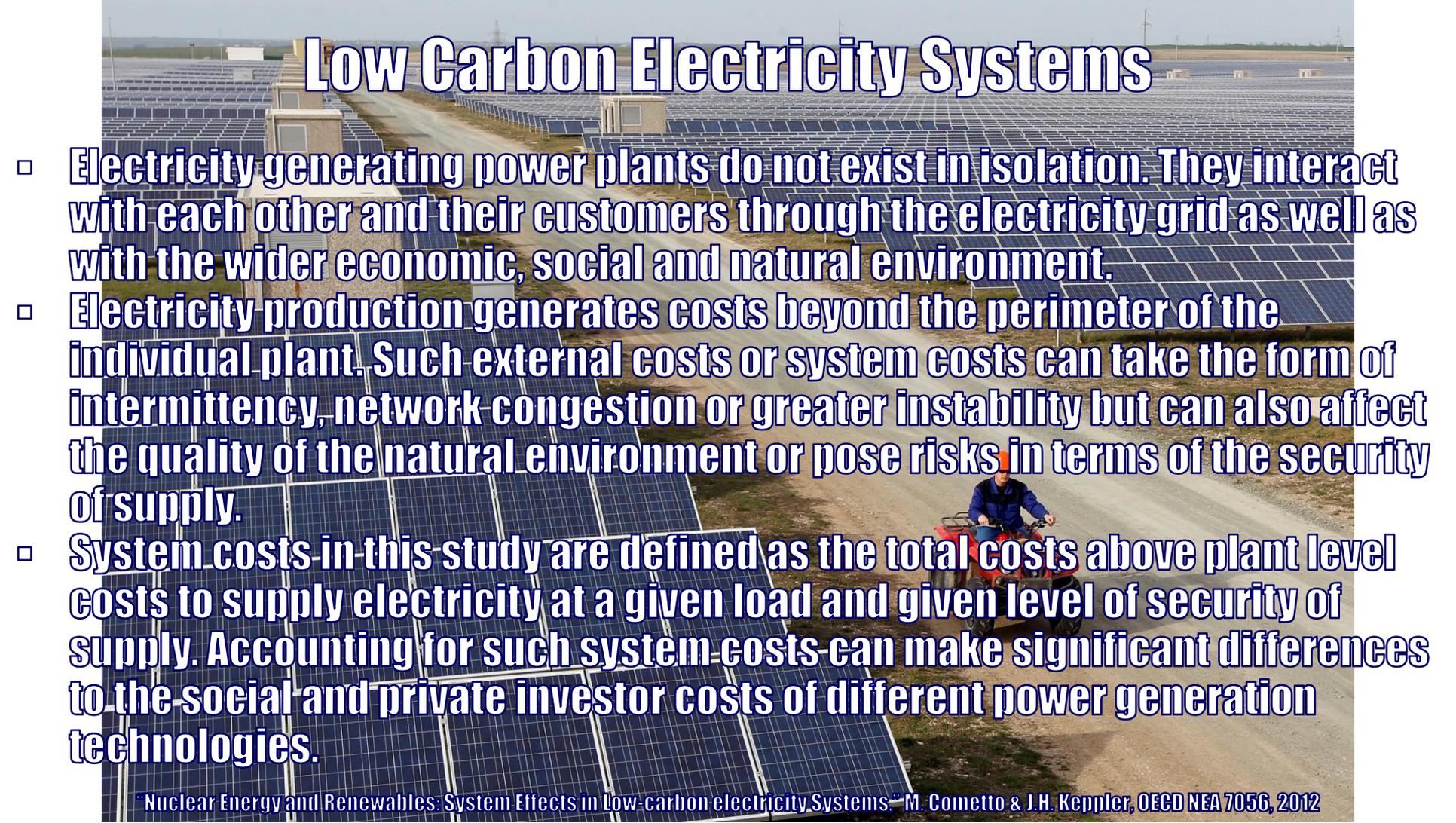
Nuclear Development
2017

Nuclear Energy and Renewables

System Effects in Low-carbon
Electricity Systems



Low Carbon Electricity Systems



- Electricity generating power plants do not exist in isolation. They interact with each other and their customers through the electricity grid as well as with the wider economic, social and natural environment.
- Electricity production generates costs beyond the perimeter of the individual plant. Such external costs or system costs can take the form of intermittency, network-congestion or greater instability but can also affect the quality of the natural environment or pose risks in terms of the security of supply.
- System costs in this study are defined as the total costs above plant level costs to supply electricity at a given load and given level of security of supply. Accounting for such system costs can make significant differences to the social and private investor costs of different power generation technologies.

Policy Implications for Governments

- The policy implications for governments are clear and unaffected by these methodological considerations.
- First, governments need to ensure the transparency of power generation costs at the system level. When making policy decisions affecting their electricity markets, countries need to consider the full system costs of different technologies.
- Second, governments should prepare the regulatory frameworks to minimize system costs and favor their internalization. This includes remunerating the capacity services of dispatchable technologies, allocating the costs for balancing, adequacy and grid connection in a fair and transparent manner and monitoring carefully the implications for carbon emissions of different strategic choices for backup provision.