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A Report on Applications of Nuclear Energy as a Potential Alternative Energy Source to Satisfy Increasing Energy Crises: Recent Developments in the Field of Nuclear Power Generation

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Abstract—As the result of increasing population, globalization and increasing demands of alternative energy sources, nuclear energy has attracted the concentration of researchers to use it as a potential alternative source of power. Though nuclear energy has a tremendous power to satisfy the needs of present energy demands still the power generation by utilizing nuclear energy is limited in most parts of the world. Present report highlights the applications of nuclear energy and projects it as a practically reliable and potential source of power generation sothat continuously depleting primary sources of energy could be saved and an immediate solution will be available in the form of nuclear power. Thus the efficiency and consistency of power related activities would not be interrupted.

1. INTRODUCTION

Nuclear power is generated using Uranium, which is a metal mined in various parts of the world. The first large-scale nuclear power station opened at Calder Hall in Cumbria, England, in 1956. Some military ships and submarines have nuclear power plants for engines. Nuclear power produces around 11% of the world's energy needs, and produces huge amounts of energy from small amounts of fuel, without the pollution [1]. The schematic flow chart of electric power generation by nuclear energy has been shown in Figure 1.

Nuclear power stations work in pretty much the same way as fossil fuel-burning stations, except that a "chain reaction" inside a nuclear reactor makes the heat instead. The reactor uses Uranium rods as fuel, and the heat is generated by **nuclear fission:** neutrons smash into the nucleus of the uranium atoms, which split roughly in half and release energy in the form of heat. Carbon dioxide gas or water is pumped through the reactor to take the heat away, this then heats water to make steam. The steam drives turbines which drive generators. Modern nuclear power stations use the same type of turbines and generators as conventional power stations. In Britain, nuclear power stations are often built on the coast, and use sea water for cooling the steam ready to be pumped round again. This means that they don't have the huge "cooling towers" seen at other power stations. The reactor is controlled with "control rods", made of boron, which absorb neutrons. When the rods are lowered into the reactor, they absorb more neutrons and the fission process slows down. To generate more power, the rods are raised and more neutrons can crash into uranium atoms.

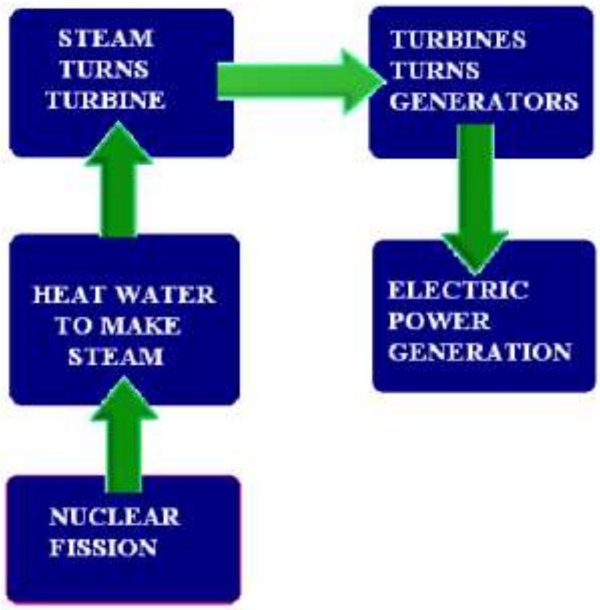

Figure 1, Scheme of electric power generation by nuclear energy

Natural uranium is only 0.7% "uranium-235", which is the type of uranium that undergoes fission in this type of reactor. The rest is U-238, which just sits there getting in the way. Modern reactors use "enriched" uranium fuel, which has a higher proportion of U-235.

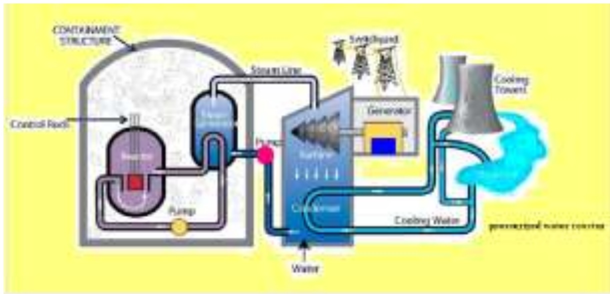

Figure 2, Nuclear Power Generation Plant, pressurized water rector

The fuel arrives encased in metal tubes, which are lowered into the reactor whilst it's running, using a special crane sealed onto the top of the reactor [2]. With an AGR or Magnox station, carbon dioxide gas is blown through the reactor to carry the heat away.

Carbon dioxide is chosen because it is a very good coolant, able to carry a great deal of heat energy. It also helps to reduce any fire risk in the reactor (it's around 600 degrees Celsius in there) and it doesn't turn into anything nasty (well, nothing long-lived and nasty) when it's bombarded with neutrons. A nuclear power generation plant has been shown in Figure 2. A nuclear fission chain reaction (Figure 3) occurs in nuclear reactors [3-5].

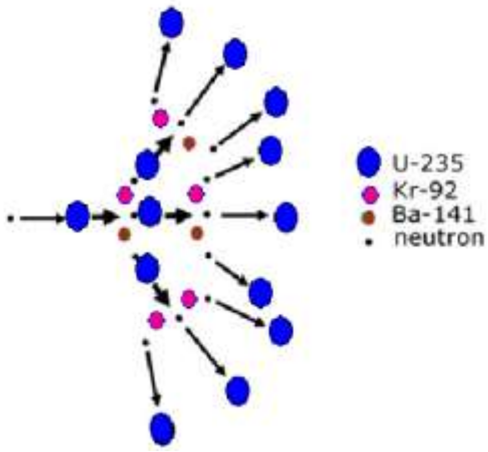

Figure 3, Nuclear Fission Chain reaction

2. ADVANTAGES OF NUCLEAR ENERGY

Nuclear energy exerts valuable impacts those have been listed below:

2.1 Environmental benefits :

Of all energy sources, nuclear energy has perhaps the lowest impact on the environment especially in relation to kilowatts produced because nuclear plants do not emit harmful gases, require a relatively small area, and effectively minimize or negate other impacts. In other words, nuclear energy is the most ***"ecologically efficient"*** of all energy sources because it produces the most electricity in relation to its minimal environmental impact. There are no significant adverse effects to water, land, habitat, species, and air resources.

2.1.1 emission-free energy source

Nuclear energy is an ***emission-free energy source*** because it does not burn anything to produce electricity. Nuclear power plants produce no gases such as nitrogen oxide or sulfur dioxide that could threaten our atmosphere by causing ground-level ozone formation, smog, and acid rain. Nor does nuclear energy produce carbon dioxide or other greenhouse gases suspected to cause global warming. Throughout the nuclear fuel cycle, the small volume of waste byproducts actually created is carefully contained, packaged and safely stored. As a result, the nuclear energy industry is the only industry established since the industrial revolution that has managed and accounted for all of its waste, preventing adverse impacts to the environment.

2.1.2 Aquatic life conservation

Nuclear power also provides water quality and ***aquatic life conservation***. Water discharged from a nuclear power plant contains no harmful pollutants and meets regulatory standards for temperature designed to protect aquatic life. This water, used for cooling, never comes in contact with radioactive materials. If the water from the plant is so warm that it may harm marine life, it is cooled before it is discharged to its source river, lake, or bay as it is either mixed with water in a cooling pond or pumped through a cooling tower [6].

Because the areas around nuclear power plants and their cooling ponds are so clean, they are often developed as wetlands that provide nesting areas for waterfowl and other birds, new habitats for fish, and the preservation of other wildlife as well as trees, flowers, and grasses. Many energy companies have created special nature parks or wildlife sanctuaries on plant sites.

2.1.3 Land and habitat preservation

Nuclear power plants provide ***land and habitat preservation***. Because nuclear power plants produce a large amount of electricity in a relatively small space, they require significantly less land for operation than all other energy sources. For instance, solar and wind farms must occupy substantially more land, and must be sited in geographically unpopulated areas far from energy demand. To build the equivalent of a 1,000-megawatt nuclear plant, a solar park would have to be larger than 35,000 acres, and a wind farm would have to be 150,000 acres or larger. By contrast, the Millstone Units 2 and 3 nuclear power plants in Connecticut have an installed capacity of over 1,900 megawatts of power on a 500-acre site designed for three nuclear plants. Also, uranium is a concentrated, low-volume fuel source requiring few incursions into the land for extraction or transport [7].

Nuclear plants are so environmentally benign that they enable endangered species to live and thrive nearby. Such endangered species as osprey, peregrine falcons, bald eagles, red-cockaded woodpecker, and even the beach tiger beetle have found a home at nuclear power plants. Programs also protect species that are not endangered, such as bluebirds, wood ducks, kestrels, sea lions, wild turkeys, and pheasant. In contrast, certain wind farms pose a hazard to endangered bird species.[8] Bald eagles and other birds of prey are apparently mesmerized by the movement of the propellers and fly directly into them. Moreover, depletion of protected birds of prey results in an increase in the pest population that was their food source. For instance, all the birds of prey in the Altamont pass of California have been killed by a wind farm, and the city of Livermore developed a rodent infestation due to their absence.

2.2 Economic Benefits of Nuclear Power:

Nuclear power plants provide ***low-cost***, predictable power at stable prices and are essential in maintaining the reliability of the U.S. electric power system. Nuclear power is a major national energy source. Nuclear energy is our nation's largest source of emission-free electricity and our second largest source of power [9-11]. The 103 U.S. nuclear units supply about 20 percent of the electricity produced in the United States. The only fuel source that produced more electricity was coal. Nuclear plants also contribute to national energy security and ensure stable nationwide electricity supply. As an integral part of the U.S. energy mix, nuclear energy is a secure energy source that the nation can depend on. Unlike some other energy sources, nuclear energy is not subject to unreliable weather or climate conditions, unpredictable cost fluctuations, or dependence on foreign suppliers. In fact, nuclear energy is a strong domestic as well as international industry, with extensive fuel supply sources. Nuclear power plants are large units that run for extended periods. They help supply the necessary level of electricity, or "baseload generation," for the electricity transmission network, or "grid," to operate. U.S. nuclear power plants are a key element in the stability of our country's electrical grid. Nuclear power plants have long periods of operation. Nuclear power plants are designed to operate continuously for long periods of time. They can run about 540 days before they are shut down for refueling. The longest continuous run by a light water reactor is Three Mile Island, Unit 1, in Pennsylvania, which completed a 688-day run.

The longest run of any type of reactor is 894 days, achieved by the Pickering 7 plant, a heavy-water reactor in Ontario, Canada (Canadian CANDU reactors can be refueled while operating). An increased capacity factor results in an increase in the production of electricity by nuclear plants [12-14]. The increase from 1998 to 1999 alone amounted to about 50 billion kilowatt-hours more electricity, for a total of 720 billion kilowatt-hours. That is roughly equivalent to adding six to seven one-thousand-megawatt nuclear reactors to the U.S. nuclear fleet. The increase in electricity produced using nuclear energy from 1990 to 1999, 143 billion kilowatt hours, is the equivalent of adding 19 one-thousand-megawatt nuclear reactors to the U.S. fleet.

The costs involved in producing electricity at a nuclear power plant, operations and maintenance plus fuel, have been declining over the past decade. In 1998 the average production cost for the U.S. nuclear fleet was 2.13 cents per kilowatt-hour, down from 3.04 cents in 1988. In addition, there are no unexpected additional costs. Power plants have future price stability. A nuclear power plant can leverage its high degree of future price stability by selling at a premium to large users an assured source of electricity supply at a known price. For instance, presently some users in California are willing to pay this premium to protect themselves against the damaging effects of price volatility in the day-ahead market. Nuclear units provide ancillary services such as voltage support, and play a key role in maintaining the reliability of the grid, a service with value in an unbundled market. Nuclear power plants have significant additional site value, such as switchyards, access to the grid, ingress and egress, and spare cooling capacity. In many cases, they were planned for more units than were built, providing room to build additional non-nuclear generation. Such diverse generation would enable a single site to execute forward sales in the bilateral contract market and participate in the day-ahead market, in particular selling highly profitable 10-minute spinning reserve capacity [15-17].

Nuclear power has great prospects in the near future as nuclear power plants are efficient and do not produce any kind of pollution, unlike other sources. All in all, if nuclear energy is implemented extensively and its potential is exploited well, it would bring down the use of other important conventional sources of energy.

3. RECENT DEVELOPMENTS IN THE FIELD OF NUCLEAR POWER GENERATION

3.1 Advanced Nuclear Power Reactors

Improved designs of nuclear power reactors are currently being developed in several countries. The first so-called 3rd generation advanced reactors have been operating in Japan since 1996. Newer advanced reactors now being built have simpler designs which reduce capital cost. They are more fuel efficient and are inherently safer.

The nuclear power industry has been developing and improving reactor technology for more than five decades and is starting to build the next generation of nuclear power reactors to fill new orders. Several generations of reactors are commonly distinguished. Generation I reactors were developed in 1950-60s, and outside the UK none are still running today. Generation II reactors are typified by the present US and French fleets and most in operation elsewhere. So-called Generation III (and 3+) are the Advanced Reactors discussed in this paper, though the distinction from Generation II is arbitrary. The first are in operation in Japan and others are under construction or ready to be ordered. Generation IV designs are still on the drawing board and will not be operational before 2020 at the earliest[18].

About 85% of the world's nuclear electricity is generated by reactors derived from designs originally developed for naval use. These and other nuclear power units now operating have been found to be safe and reliable, but they are being superseded by better designs.

Reactor suppliers in North America, Japan, Europe, Russia and elsewhere have a dozen new nuclear reactor designs at advanced stages of planning, while others are at a research and development stage. Fourth-generation reactors are at concept stage.

So-called third-generation reactors have:

- A standardized design for each type to expedite licensing, reduce capital cost and reduce construction time,
- A simpler and more rugged design, making them easier to operate and less vulnerable to operational upsets,
- Higher availability and longer operating life - typically 60 years,
- Further reduced possibility of core melt accidents,*
- Substantial grace period, so that following shutdown the plant requires no active intervention for (typically) 72 hours,
- Resistance to serious damage that would allow radiological release from an aircraft impact,
- Higher burn-up to use fuel more fully and efficiently and reduce the amount of waste,
- Greater use of burnable absorbers ("poisons") to extend fuel life [19].

3.2 Joint Initiatives

Two major international initiatives have been launched to define future reactor and fuel cycle technology, mostly looking further ahead than the main subjects of this paper: Generation IV International Forum (GIF) is a US-led grouping set up in 2001 which has identified six reactor concepts for further investigation with a view to commercial deployment by 2030. See Generation IV paper and DOE web site on "4th generation reactors".

The IAEA's International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) is focused more on developing country needs, and initially involved Russia rather than the USA, though the USA has now joined it. It is now funded through the IAEA budget [20].

At the commercial level, by the end of 2006 three major Western-Japanese alliances had formed to dominate much of the world reactor supply market:

- Areva with Mitsubishi Heavy Industries (MHI) in a major project and subsequently in fuel fabrication,
- General Electric with Hitachi as a close relationship: GE Hitachi Nuclear Energy (GEH)*
- Westinghouse had become a 77% owned subsidiary of Toshiba (with Shaw group 20%).

* GEH is the main international partnership, 60% GE. In Japan it is Hitachi GE, 80% owned by Hitachi.

Subsequently there have been a number of other international collaborative arrangements initiated among reactor vendors and designers, but it remains to be seen which will be most significant.

3.3 US Design certification

In the USA, the federal Department of Energy (DOE) and the commercial nuclear industry in the 1990s developed four advanced reactor types. Two of them fall into the category of large "evolutionary" designs which build directly on the experience of operating light water reactors in the USA, Japan and Western Europe. These reactors are in the 1300 megawatt range.

One is an advanced boiling water reactor (**ABWR**) derived from a General Electric design and now promoted both by GE-Hitachi and Toshiba as a proven design, which is in service.

The other type, **System 80+,** is an advanced pressurized water reactor (PWR), which was ready for commercialization but is not now being promoted for sale. Eight System 80 reactors in South Korea incorporate many design features of the System 80+, which is the basis of the Korean Next Generation Reactor program, specifically the APR-1400 which is expected to be in operation from 2013 and is being marketed worldwide[21].

The US Nuclear Regulatory Commission (NRC) gave final design certification for both in May 1997, noting that they exceeded NRC "safety goals by several orders of magnitude". The ABWR has also been certified as meeting European utility requirements for advanced reactors. Both GE Hitachi and Toshiba in 2010 submitted separate applications to renew the design certification for their respective versions of ABWR (Toshiba's incorporating design changes submitted to NRC already in connection with application for the South Texas Project). The Japanese version of it differs in allowing modular construction, so is not identical to that licenced in the USA.

3.4 Light Water Reactors

These are power reactors moderated and cooled by water

3.4.1 European pressurized water reactor (EPR)

Areva NP (formerly Framatome ANP) has developed a large (4590 MWt, typically 1750 MWe gross and 1630 MWe net) European pressurized water reactor (**EPR**), which was confirmed in mid 1995 as the new standard design for France and received French design approval in 2004. It is a 4-loop design derived from the German Konvoi types with features from the French N4, and is expected to provide power about 10% cheaper than the N4. It will operate flexibly to follow loads, have fuel burn-up of 65 GWd/t and a high thermal efficiency, of 37%, and net efficiency of 36%. It is capable of using a full core load of MOX. Availability is expected to be 92% over a 60-year service life. The first EPR unit is being built at Olkiluoto in Finland, the second at Flamanville in France, the third European one will be at Penly in France, and two further units are under construction at Taishan in China [22].

3.4.2 AP1000, CAP1400

The Westinghouse AP1000 is a 2-loop PWR which has evolved from the smaller AP600, one of the first new reactor designs certified by the US NRC, in 2005. Simplification was a major design objective of the AP1000, in overall safety systems, normal operating systems, the control room, construction techniques, and instrumentation and control systems provide cost savings with improved safety margins. It has a core cooling system including passive residual heat removal by convection, improved containment isolation, passive containment cooling system to the atmosphere and in-vessel retention of core damage (corium) with water cooling around it. No safety-related pumps or ventilation systems are needed. It is being built in China, and the Vogtle site is being prepared for initial units in USA. The first four units are on schedule, being assembled from modules. It is quoted as 1200 MWe gross and 1117 MWe net (3400 MWt), though 1250 MWe gross in China. Westinghouse earlier claimed a 36 month construction time to fuel loading. The first ones being built in China are on a 51-month timeline to fuel loading, or 57-month schedule to grid connection [23].

3.4.3 Advanced boiling water reactor (ABWR)

The advanced boiling water reactor is derived from a General Electric design in collaboration with Toshiba. Two examples built by Hitachi and two by Toshiba are in commercial operation in Japan (1315 MWe net), with another two under construction there and two in Taiwan. Four more are planned in Japan and another two in the USA. The ABWR is now offered in slightly different versions by GE Hitachi, Hitachi-GE and Toshiba, so that 'ABWR" is now a generic term. It is basically a 1380 MWe (gross) unit (3926 MWt in Toshiba version), though GE Hitachi quote 1350-1600 MWe net. Toshiba outlines development from its 1400 MWe class to a 1500-1600 MWe class unit (4300 MWt). Tepco was funding the design of a next generation BWR, and the ABWR-II is quoted as 1717 MWe. Toshiba is promoting its EU-ABWR of 1600 MWe with core catcher and filtered vent, developed with Westinghouse Sweden. The Hitachi UK-ABWR may have similar features but be similar size to Japanese units [24,25].

3.4.4 Other Types of Advanced Reactors

There are several advanced reactors listed as follows: Heavy Water Reactors e.g.. EC6, The Advanced Candu Reactor (ACR), Advanced Heavy Water reactor (AHWR). High-Temperature Gas-Cooled Reactors e.g. Pebble Bed Modular Reactor (PBMR), Gas Turbine - Modular Helium Reactor (GT-MHR). Fast Neutron Reactors e.g. European Lead-cooled System (ELSY), the USA, GE was involved in designing a modular liquid metal-cooled inherently-safe reactor - PRISM., KALIMER (Korea Advanced LIquid MEtal Reactor) [26,27].

4. CONCLUSION

This report analyzes what would be required to retain nuclear power as a significant option for reducing greenhouse gas emissions and meeting growing needs for electricity supply. The analysis is guided by a global growth scenario that would expand current worldwide nuclear generating capacity almost threefold, to 1000 billion watts, by the year 2050. Such a deployment would avoid 1.8 billion tons of carbon emissions annually from coal plants, about 25% of the increment in carbon emissions otherwise expected in a business-as-usual scenario. This study also recommends changes in government policy and industrial practice needed in the relatively near term to retain an option for such outcomes.

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