PROBABILISTIC, POSSIBILISTIC AND DETERMINISTIC SAFETY ANALYSIS

Nuclear Applications

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PREFACE

“Do not go where the path may lead; go instead where there is no path and leave a trail.”
Ralph Waldo Emerson

This work covers the field of probabilistic, possibilistic and deterministic safety analysis. The material is general and addresses the interests of engineers and physicists in different fields of science and engineering. It emphasizes the nuclear applications of the covered methodologies.

Nuclear energy is being reconsidered in addition to wind, tidal and solar energies as the clean non-carbon and green energy options for what is referred to as the post-petro economy. The threat of global climatic change came along and the world woke up to the fact that burning fossil fuels for a planet with 7 billion energy hungry souls longing to emerge from poverty just was not the only option.

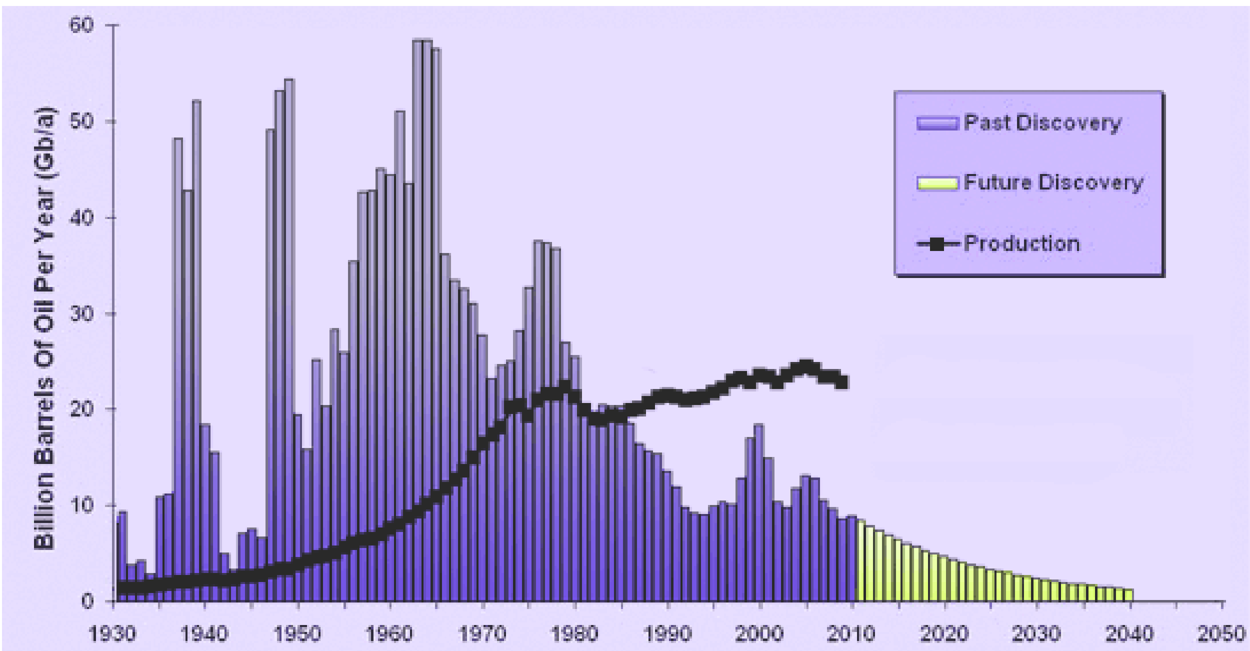

Figure 1. Growing gap between conventional petroleum production and new discoveries. Production is reaching a peak suggesting a need to switch to non-carbon nuclear and renewables sources. The shale oil and gas fracking and horizontal drilling may be a short-lived last hurrah and an exit party for the petroleum age. “Peak Oil” does not mean the end of the petroleum supply, but it means a decreased availability, hence decreased production and use and the necessity of its substitution with other energy sources.

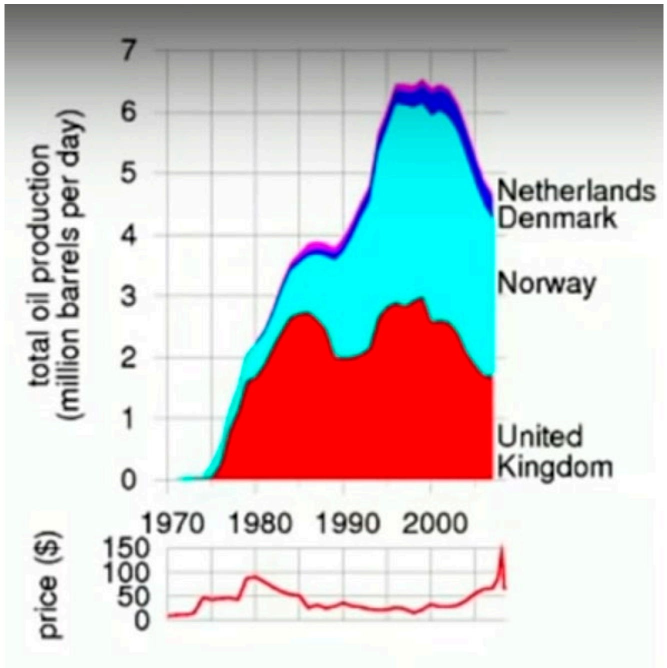

Figure 2. Peak Oil, North Sea: UK, Norway, Denmark, and Netherlands. Source: David MacKay.

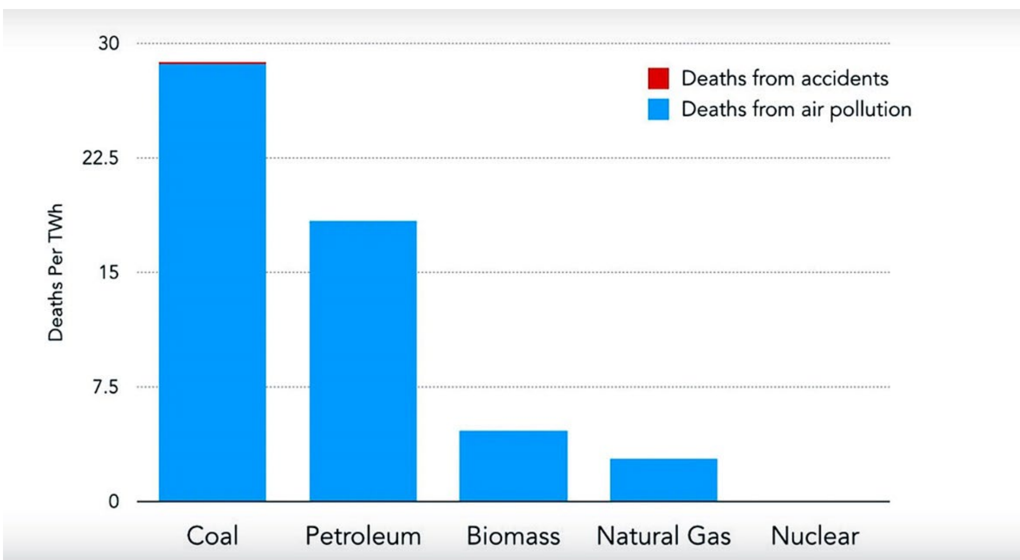

Figure 3. Risks from different energy sources. Source: Michael Shellenberger, The Lancet.

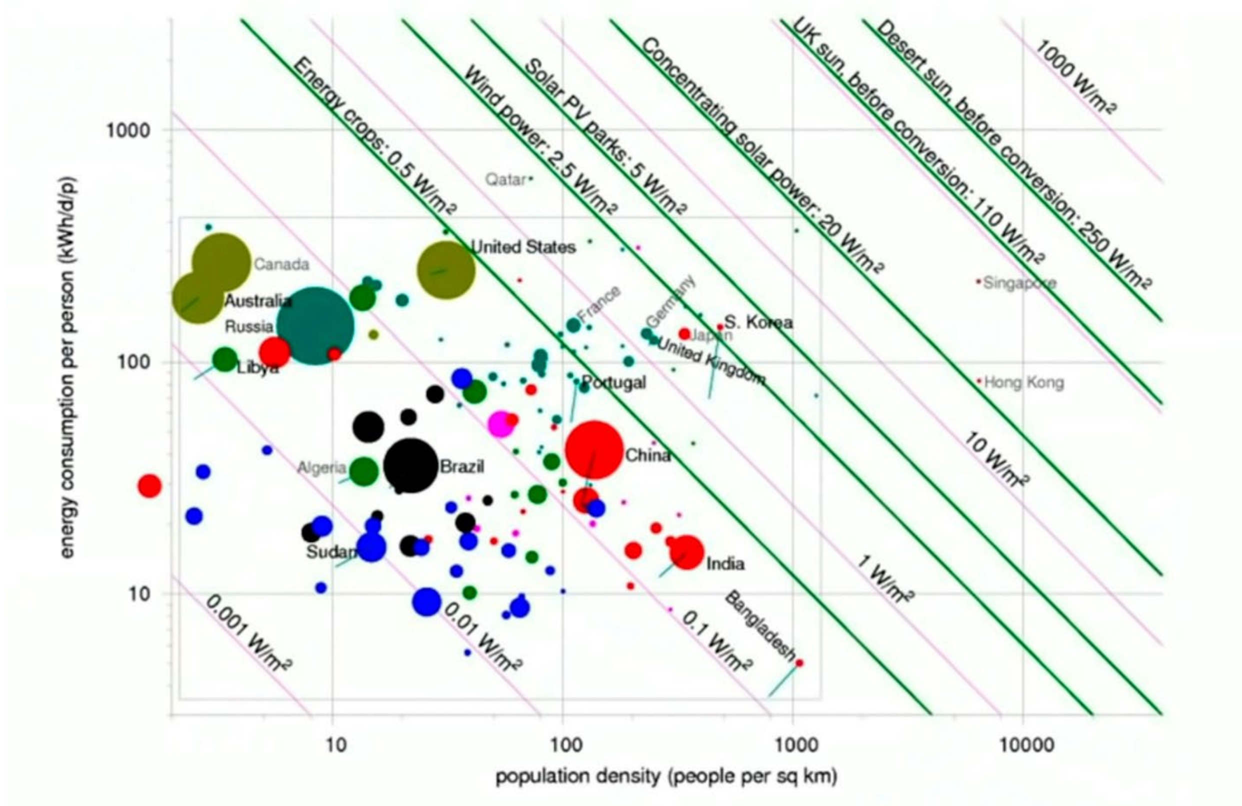

Figure 4. Only Nuclear Power at 1,000 Watts/square meter and a combination of renewables can satisfy future global energy needs from the perspective of land area availability. Logarithmic scale. Source: David MacKay.

Table 1. Power fluxes of different energy options.

Energy option	Power flux [Watts / m^2]
Rain-water, highlands	0.24
Energy crops, biomass, plants	0.5
Wind power	2.5
Tidal pools	3.0
Tidal stream	8.0
Solar Photo Voltaic panels(PV)	5.0-20.0
Concentrated thermal solar power, deserts	15.0-20.0
Solar power, before conversion (UK)	110.0
Desert areas sun, before conversion	250.0
Nuclear electricity	1,000.0

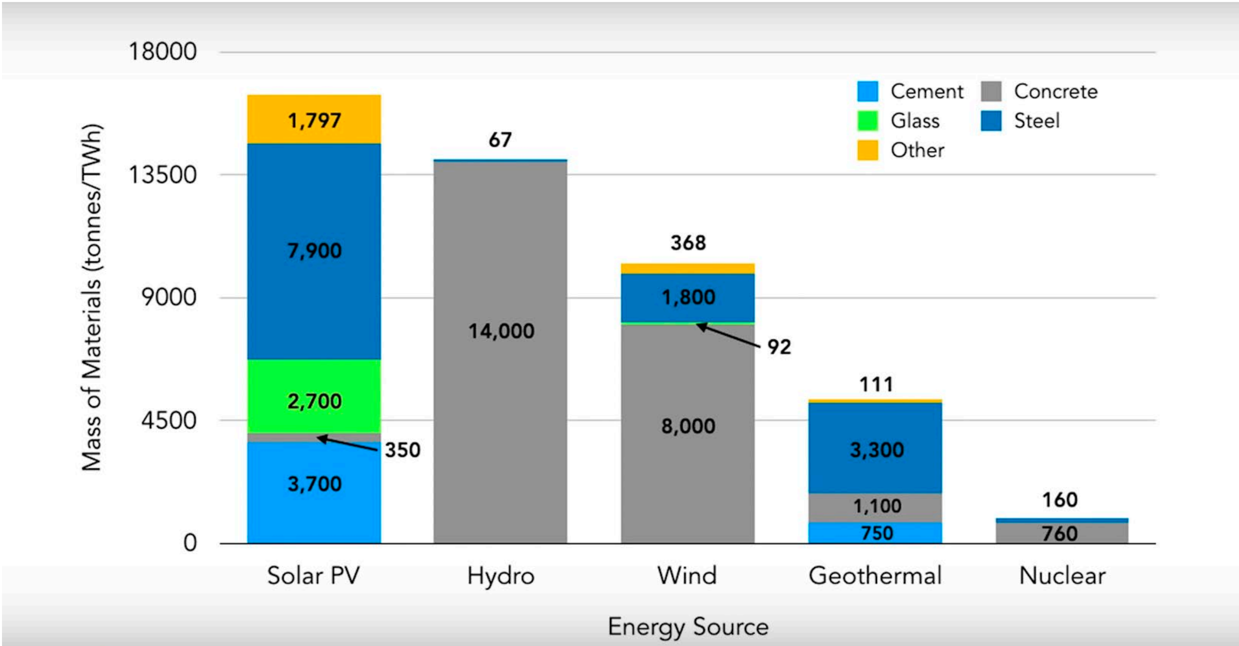

Figure 5. Materials needs of different energy sources. 1 TW = 1 Terawatt = 1 trillion Watt = 10^{12} Watt). Source: USDOE.

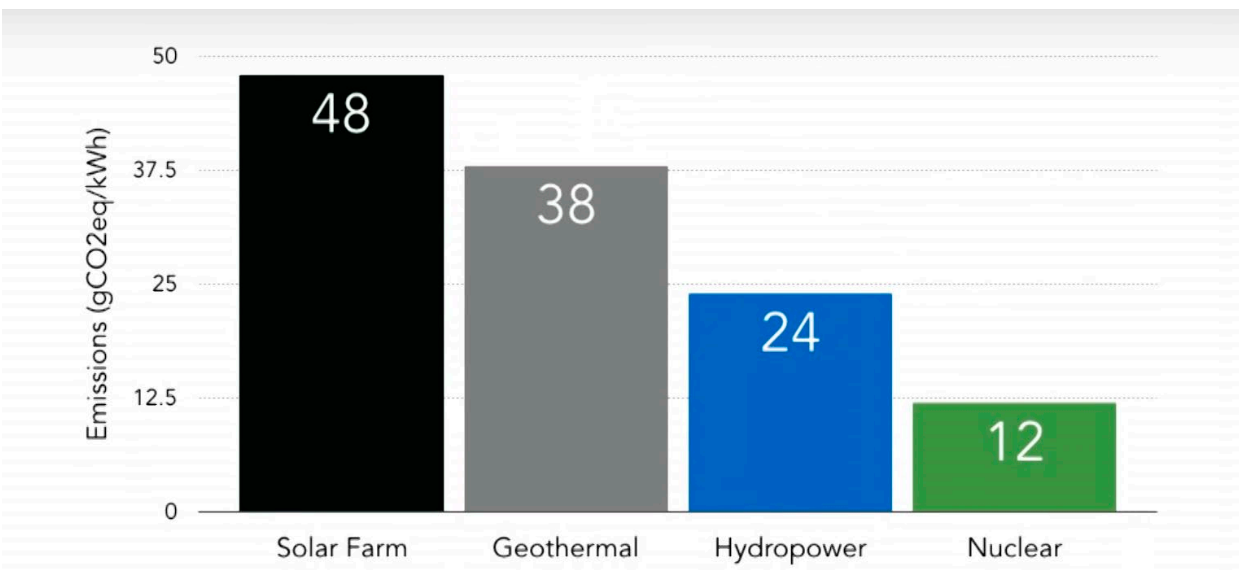

Figure 6. Carbon emissions from different sources. IPCC 2014.

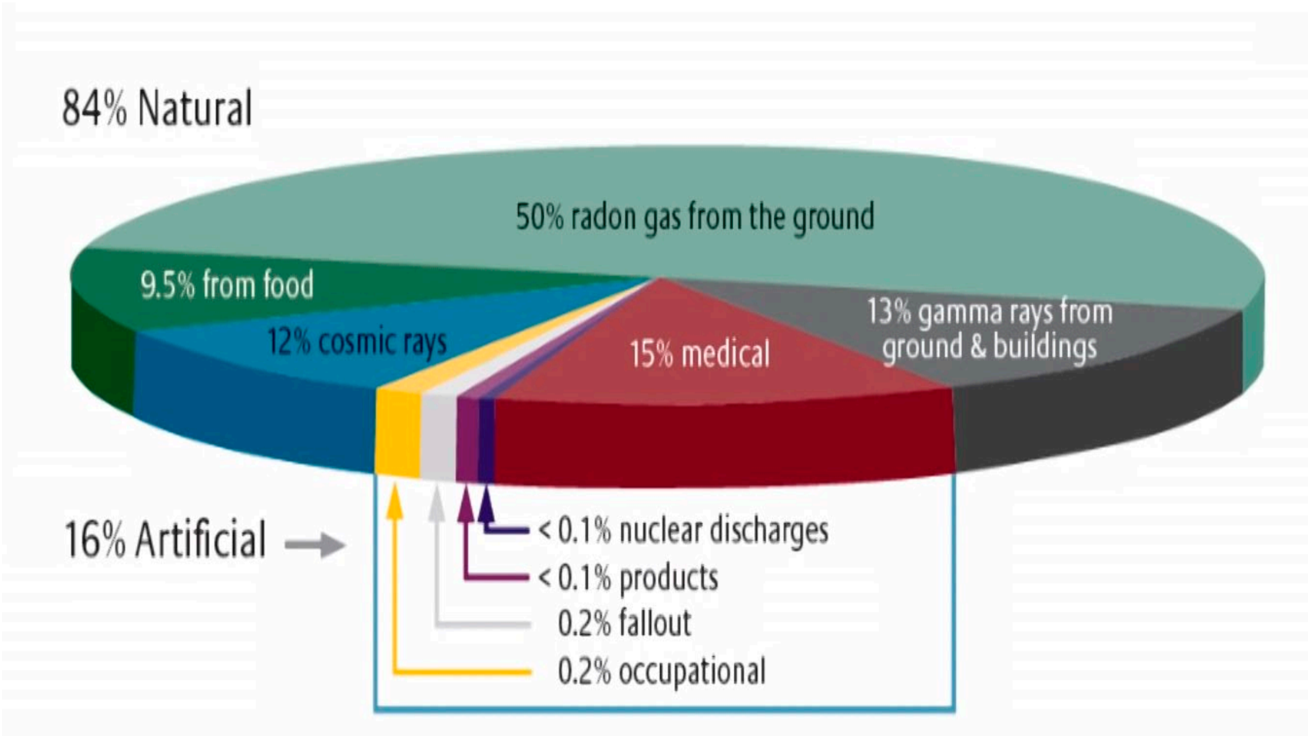

Figure 7 Ionizing radiation sources different sources. Source: Gerry Thomas, Imperial College, London.

James Lovelock, the British environmental scientist, in his book: "The Revenge of Gaia," has come to the hard conclusion that the unprecedented challenge of global warming leaves us no choice but to make a massive global investment in nuclear power, which emits no greenhouse gases. Lovelock places the risks of different energy alternatives into perspective when he considers China's Yangtze Dam, a huge source of clean hydroelectric power: "If the dam burst, … perhaps as many as a million people would be killed in the wave of water roaring down the course of the Yangtze River."

Nuclear power is economically competitive to other sources of energy. As of 2007, the electrical generation costs were 1.82 cents per kilowatt-hour versus 2.13 cents for coal fired plants and 3.69 cents for natural gas.

As far as carbon emissions, nearly 700 million additional tons of carbon dioxide would be released into the atmosphere every year without nuclear power; the equivalent of the exhaust from 100 million automobiles. In comparison, the Clean Air Council reports that coal power plants are responsible for 64 percent of sulfur dioxide SO_x emissions, 26 percent of nitrous oxides NO_x and 33 percent of mercury emissions in the USA. A coal fired plant releases 100 times more radioactive material as uranium, thorium and their daughter radioactive nuclides in the particulate ash released, than an equivalent nuclear reactor.

The recent USA Global Nuclear Energy Partnership (GNEP) has several goals. One is to reduce nuclear proliferation by providing fuel suitable for nuclear power plants; but not nuclear weapons, to nations willing to submit to international oversight and safeguards. Another goal is to reduce the volume of nuclear waste by reprocessing spent fuel so that part of it can be reused.

The GNEP would not eliminate the need for a nuclear waste disposal site like Yucca Mountain in the USA, but it could mean that whatever waste is generated will have a much shorter radioactive life.

The next generation of nuclear reactors known as Generation IV designs, are safer, more reliable and more versatile than the current ones. They are applicable to applications in the coming hydrogen economy and fresh water production from sea water. A demonstration reactor is planned by 2018 with a design that is ready for commercialization by 2025.

Regarding safety, while nothing is 100 percent risk free, paraphrasing Patrick Moore, if we banned everything that is potentially risky, humans would never have harnessed fire. When a reactor core melted down at Three Mile Island, the containment system did just what it was designed to do and prevented radiation from escaping to the environment. There were no worker injuries nor deaths, and none among the nearby residents. No one has ever died of a radiation related accident in the history of the USA civilian nuclear reactor program. In comparison, 100 coal miners die each year in the USA in coal mine accidents and another 100 die transporting it. Considering the Chernobyl accident, the RBMK-1000 reactor design had no containment vessel, was an inherently unstable design at low power, and its operators literally blew it up by sidestepping the established safety rules. The United Nations (UN) Chernobyl Forum reported that 56 deaths could be directly attributed to the accident, most of those from radiation or burns suffered while fighting the ensuing fire.

According to PBS's "Frontline," between 1931 and 1995 some 33,134 fatalities occurred in the USA coal mining industry. In the USA civilian aviation between 1938 to the present there has been more than 54,000 fatalities. There have been no deaths historically with civilian USA nuclear power.

The Not In My own Back Yard or NIMBY objections about nuclear plants are fading in favor of economic development. About Entergy's Grand Gulf Nuclear Generating Station near Port Gibson, Mississippi, Michael Herrin, pastor of Port Gibson's First Presbyterian Church commented: "In this town, the dragon is unemployment. Entergy is the hero."

A typical 1000 MWe reactor of the world's 446 nuclear power plants provides electricity to 700,000 typical homes and uses just five pounds of uranium which amounts to a 2 inch cube of pure uranium per day. A fossil fuel power plant of the same capacity burns 20 million pounds of coal using 200 million pounds of air, yielding an equal weight in polluting particulate ashes and gases that are disposed off by dilution in the Earth's atmosphere.

Globally, within 20 years, growth in electricity demand is expected to add 5,000 billion kilowatt-hours to annual electrical consumption. This would require either burning 10 billion barrels of oil annually, or three billion tons of coal per year. Alternatively this would require mining just 150,000 tons of uranium yellowcake or U_3O_8. Supplying that amount of electricity would require one million more of the largest solar arrays currently deployed.

Globally, nuclear power is an existing success and provides 78 percent of France's electricity, 58 percent of Belgium's, 50 percent of Sweden's, 40 percent of South Korea's, 37 percent of Switzerland's, 31 percent of Japan's, 27 percent of Spain's and 23 percent of the UK's. Overall, 30 percent of the entire European Union's electricity is generated by nuclear power.

There were 112 power reactors operating in 1990 in the USA. By 2019 there were 97 in operation with aging plants being retired, and plants facing economic competition from natural gas and wind power. The Energy Policy Act of 2004 is encouraging the planning for building over 30 new nuclear power plants. These would provide electricity to about 30 million typical American homes. The 1979 Three Mile Island reactor accident which caused no deaths, no injuries and resulted in an irrelevant radiation exposure that is 1/6 of a typical chest x ray to the two million residents in the area around the reactor. A World Health Organization (WHO) report showed that 56 deaths could be directly attributed to the Chernobyl accident. The amount of radiation from the accident was just slightly higher than background radiation and there is no indication of higher rates of cancers in the Chernobyl population than any other population. This can be compared with the industrial explosion in Texas City, Texas, that triggered a massive fire at an oil refinery and caused the death of 500 people, but did not stop oil exploration, drilling, and refining.

In the 2005 Energy Policy Act, the USA Congress signaled its interest in nuclear power by including $ 13 billion in incentives for the industry. New spending in the act included risk insurance and loan guarantees for the construction of new plants. It included tax credits of 1. 8 cents / kilowatt.hour of energy generated in a plant's first eight years of operation. And the law lowered from 35 percent to 20 percent the tax rate on investment gains utilities make in funds they must set aside to decommission plants.

The USA Department of Energy (DOE) projects a 45 percent growth in electricity demand by 2030, suggesting 35 to 50 new nuclear plants will be needed by then just to maintain the nuclear energy share of the electricity market around 20 percent. The 2005 energy bill passed by Congress provides subsidies for the first six plants, which the industry sees as a one-time "jump start."

Europe in particular is poised to begin a new nuclear age, reversing two decades of policies aimed at abandoning nuclear power as an energy source following the Chernobyl accident in 1986. Driving the turnaround are high oil and gas prices, possible peak oil, climate change worries; and concerns about the reliability of supplies from Russia, which provides 25 percent of Europe's natural gas and 12 percent of its oil. The UK wants to replace some of the 18 aging nuclear plants that are due to be shut down by 2023. Finland is building the first new nuclear generating plant in Western Europe since 1991. Sweden, Italy and the Netherlands have either abandoned plans to phase out old nuclear plants or opened discussions on construction of new ones. Switzerland has lifted a moratorium on new plants. Italy, which shuttered its four nuclear plants after Chernobyl, is Europe's biggest energy importer has plans to buy power from a plant under construction in France. Poland agreed to help build a plant in Lithuania. It will provide power to Latvia and Estonia, in addition to Poland and Lithuania. Belarus plans the construction of a plant that would begin generating power in 2014 and plans additional units by 2025.

France is almost entirely powered through nuclear and hydroelectric power and has some of the lowest CO_2 emissions rates in the world. Germany has invested in wind and solar energy and is reconsidering a decision to close its nuclear power plants. It is phasing out its old nuclear power plants after Fukushima. If it still thinks it can lower its carbon emissions, this places it in an impossible situation.

Even though nuclear power accounts for just 20 percent of the USA's electrical energy, it provides 80 percent of France's electricity needs; 79.9 percent of Lithuania's; 55 percent of Belgium's; and 50 percent of Sweden's. China has built 9 new reactors since 1991, with plans to accelerate its nuclear power program. India is building 8 reactors. Half of the Ukraine's energy comes from the nucleus despite the Chernobyl reactor accident. Russia has 31 reactors at 10 nuclear power plants sites, accounting for 16-17 percent of its electricity generation and plans to increase the proportion of nuclear-generated power to at least 25 percent by 2030.

As of 2019, there were 448 nuclear reactors worldwide in 31 out of 200 countries producing 370.22 GWe of electricity, of which 97 were in the USA. They provided 14 percent of the electrical energy produced globally.

Forty eight additional nuclear plants were under construction and 60 reactors are in the planning stage. Thirteen countries that already have nuclear capacity, and 10 that do not, were in the process of building new reactors. The new reactors would double the existing installed capacity.

The chapters in this work are self-contained and can be read in the order that the reader wishes. The work is still in progress and is evolving and is frequently being updated. It is continually "under construction." In fact, it is an ongoing experiment that started in 1998. The suggestions by Reier Groven are thankfully acknowledged.

The hope is that this modest effort will contribute to the scientific literacy of the readers in the safety analysis area of knowledge, and satisfy their intellectual curiosity about our universe and our world, whose better future we all dream about.

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