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Planning of Nuclear Power Systems

To Save the Planet

Ekoenergo Oy

August, 2011

The nuclear power could generate 27 % of electricity by 2050 and 34 % by 2075. Nuclear electricity generation can make the biggest change in reducing greenhouse gas emissions and it would be possible to limit the global temperature increase to 2 degrees Celsius by the year 2100.

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Cover page: the Planet and Atoms. Created by my son Architect Teo-Tuomas Vuorinen

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PREFACE

Nuclear power was proven to be an economical source of electricity in my previous book, "Planning of optimal Power Systems". However, the planned use of nuclear power was limited to 25% of electricity generation in 2050 because the uranium resources estimated to be limited. For this book the uranium resources have been re-evaluated and use of nuclear power could peak in 2075 by generating 34% of electricity of the world. Thereafter the nuclear share would drop to 25% by 2100, by which the renewable sources would generate majority of electricity.

Nuclear power is needed as an intermediate source of energy to solve the greenhouse gas problem. According to energy models done by the author of this book, the temperature rise can be limited to about 2 °C by 2100. To achieve this target all possible CO₂-free energy technologies should be exploited: both nuclear and renewable energy sources.

There are many industrial countries that can generate most of electricity by using nuclear power. One of them is Finland, which is becoming one of the largest producers of nuclear power per capita. Finland has four reactors in operation, one reactor under construction and another two reactors have received a license from the parliament in 2010. Thus in about 2020 there will be seven operating reactors in a country with five million people.

It has been a pleasure of being one of the engineers, who were designing the first Finnish nuclear plants with many fine colleagues in the Atomic Power Project Group between the years 1970-80. Since then we have made designs of Loviisa-3 plant, which concept of which was actually constructed in Tianwan in China. The Tianwan concept was the first design to use the core catcher in reality, because it was a requirement of the Finnish safety standards. The second core catcher will be built in the Olkiluoto-3 nuclear plant in Finland.

The Finnish experience of building several nuclear plants according to the latest safety standards could be used also in other countries. I will try to present my vision of a nuclear future from the point of view of an old chief design engineer. In my opinion there is still much to be changed in order for the new plants to be more economical and safe. Current light water technology can still be used, but the manufacturing of the plants should be done using more prefabricated modules in their construction.

August 2011

Asko Vuorinen

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I also wish to thank the former director general of STUK Dr. Antti Vuorinen, who has also read the manuscript and commented on radiation and safety aspects of nuclear power. He was the man who was actually behind the western safety standards, which Finland has adopted when building its nuclear plants in the 70's.

In addition I wish to thank my former colleague, Prof. Björn Wahlström from Technical Research Centre VTT and Ilkka Mikkola from TVO for their comments. Additionally my new colleagues Harry Lindroos, Jussi Heikkinen and Lars-Gustaf Martin from Wärtsilä have helped me in many ways in writing this book. Lars-Gustaf is the director of nuclear business at Wärtsilä and he has read the manuscript and given many valuable comments.

I would celebrate all of the old pioneers in nuclear power engineering. It will soon be 60 years since the first nuclear power, the Experimental Breeder Reactor (EBR-I) in the United States started electricity generation for the first time. Electricity production at the EBR-I started on December 20th, 1951, when project engineer Harold Lichtenberger turned a switch, which lit a 200 W lamp. The EBR-I was a breeder reactor, which has the potential to generate more fissionable materials than the reactor consumes.

The second great moment for all the Finnish engineers was the moment, when the first nuclear power plant in Finland was connected to the network. This happened on February 8th 1977, when the Loviisa-1 unit was connected into network. Now we are waiting, that the Olkiluoto-3 will make Finland the number one in nuclear electricity generation per capita.

Finally, I would thank all of my colleagues for the fact that Finland will be the first country to start the final disposal of spent fuel in 2020. This will happen in Olkiluoto site for the first time in any country in the world. By the year 2120 all of the spent fuel from the five existing reactors will be disposed into ground rock repository, 400-700 meters below sea water level.

Thus the energy which has come from the ground will be buried back into the ground, and practically no environmental effects on the nature will be left. I will hope that the future generations will be happy that our generation has taken care of the waste that has come from the nuclear power plants. All things considered I believe that we have done the best that could be done.

1 INTRODUCTION

1.1 The smallest particles

In 420 BC the Greek philosopher **Leucippus** and his student **Democritus** (460-370 BC) explained that matter can be divided into smallest parts, **atoms**. An atom is a particle so small that it cannot be seen. The word "atom" comes from the Greek word "atomos", which means "**indivisible**".

This theory has lasted for two thousand years until an English chemist and physicist **John Dalton** (1766-1844) developed his atomic theory. He found that there are different atoms that have a different atomic weight. In September 1803 he listed twenty atomic weights, in relation to the weight of hydrogen:

Hydrogen	1	Lime	23	Copper	56
Azote	5	Soda	28	Lead	95
Carbonate	5	Potash	42	Silver	100
Oxygen	7	Strontites	46	Platina	100
Phosphorus	9	Barytes	68	Gold	140
Sulphur	13	Iron	38	Mercury	167
Magnesia	20	Zinc	56		

In his Law of Multiple Proportions Dalton said that 1) there are as many types of atoms as there are different materials. 2) atoms cannot be divided into smaller particles, and 3) molecules can be formed by combining atoms. He defined water by combining hydrogen and oxygen as OH (the correct formula is H_2O).

The Russian scientist **Dmitri Mendelejev** (1834–1907) classified atoms in ascending according to their atomic number Z, from one to 90, at the University of Saint Petersburg in 1869. Later on this number was found to correspond to the number of protons in each atom. Thus hydrogen has one proton and its atomic number is Z = 1 etc. He found that the chemical properties of atoms are repeating after 18 and thus made his periodic tables which had eighteen columns. The noble gases 2 helium, 18 argon, 36 krypton, 54 xenon and 86 radon formed the eighteenth column.

Mendeliev's theories helped chemists to calculate masses in several reactions between different atoms. The burning of coal means combining carbon (C) with oxygen (O_2) . The result is heat and CO_2 . Thus the chemical energy received by burning coal could be explained in theory.

In 1896 **Henry Becquerel** (1852–1908) found that there was something else involved. He was a professor of physics at the **university of Paris** and was interested in the phosphoresce of different materials. He found that uranium salt was constantly emitting green light when exposed to a photographic plate. He called this phenomenon the **natural radiation** of uranium. He thought that the radiation was the same type as what **Wilhelm Röntgen** (1845–1923) had created by X-rays.

Becquerel found that natural radiation could be deflected in electric and magnetic fields, and X-rays could not. Later on the unit of natural radiation was named after him. One Becquerel corresponds to the radiation of one change per second (s⁻¹).

Polish born **Marie Sclodowska-Curie** (1867–1934) and her future French husband **Pierre Curie** (1859–1906) were students of Becquerel. Marie wanted to study the natural radiation discovered by Becquerel, and make her doctoral thesis on him. Marie started studying uranium ore, from which liquid uranium salt and waste could be separated. She then found that the uranium itself was not active, but the waste from the liquid was. The waste contained copper, arsenic, nickel, iron and several other metals, but they should not be active. But some unknown material remained that was highly active. When measuring this radiation, Marie Curie started to call this radiation phenomenon **radioactivity**.

Eventually she could separate the new material that was the actual source of radiation. She called this new material **radium**. She found that actually the radiation of radium was 10 000 times higher than the radiation of pure uranium. For his inventions Becquerel, together with Marie and Pierre Curie, shared the Nobel Prize in Physics in 1903.

No one could understand the radiation at that time. Henry Becquerel used to hold some milligrams of radium in his pocket, and got his skin burned by the radiation. Later on radiation was found useful in the medical treatment of cancer patients, and the demand of radium skyrocketed.

Additionally, Pierre Curie found that the one gram of **radium also emitted 136 calories of heat energy** in one hour (1192 kcal/year). A remarkable discovery was that radium was not losing any of its weight. Thus a new source of energy was found. This was much more than burning one gram of coal, which releases 6 kcal of heat altogether.

The next big discovery in the research of atoms was made by a nuclear physicist **Ernest Rutherford** (1871 New Zealand-1937), professor at the **McGilly University** in Canada and his assistant **Fredrik Soddy** (1877-1956).

Rutherford was studying radiation in magnetic fields and out found that part of the radiation deflected. He gave the positive particles the name **alpha particles**. The negative particles deflected in the opposite direction, and he called them **beta particles**. Finally, he found that some part of the radiation did not deflect at all, and he called this **gamma radiation**.

Rutherford found that the alpha particles were actually positively charged helium-atoms that had a charge two. The alpha particles could be stopped by a piece of paper or clothing, whereas the beta particles could go through an aluminum plate that was several millimeters thick. Gamma radiation was the strongest; it could go through any material and several ten centimeter thick lead plated were needed to stop the radiation.

The next big thing which was found by Rutherford was alpha-radiation, where the alpha-ions were changing to helium atoms. He found that half of the ions were changing in three days and 19 minutes. Then again half of the remaining ions changed in the same time. The question remained what was the explanation for this. This was the first time in history that someone has found in practice that an original substance was changing into another. The dream of the alchemists was nearing reality.

Rutherford's assistant **Hans Geiger** (1882-1945) at the **University of Manchester** was given a task to calculate how many alpha-particles went through in a given period of time. Geiger hat the idea to put a metal plate in an isolated bottle and to place a metal wire above it. If he gave them a voltage difference, then the particles would cause a current between the plate and the wire. So he could count the number of particles going through. He created a registering device that emitted a visible sound each time the particle passed this counter. Thus for the first time in history one could hear the voice coming from a single atom. So he had created the **Geiger counter**, or the Geiger-Müller counter (with improvements made by **Walther Müller** (1905- 1979) in 1928).

In 1909 by bombing a cold plate by positive alpha-particles Rutherford and his team members Hans Geiger and **Ernest Marsden** (1889-1970) found that not all of the ions did go through the gold plate, but deflected from it. Thus they concluded that **atoms have a positively charged nucleus** that could reflect the positively charged alpha-ions. Rutherford could then calculate that the probability of refraction was about 1/100 000 and that the radius of the nucleus was about 1/100 000 of the radius of the atom. He concluded that the rest was empty space.

The theories of Rutherford were further developed by his Danish-born pupil **Nils Bohr** (1885-1962), who concluded that the nucleus is surrounded by negatively charged electrons that are rotating in circles on the outer surface of the atoms like planets. The electrons are additionally rotating around themselves like the earth rotates once each day. This planetary model of atoms has been named the **Rutherford-Bohr atomic model**.

Additionally it was found that the nucleus consists of positively charged **protons** and neutrally charged **neutrons**. The atomic weight was determined as the total number of protons and neutrons in the atom. Thus for example hydrogen atoms have one proton and one electron and the atomic weight of 1. Helium atoms have two protons, two neutrons and two electrons and the atomic weight of 4.

The neutron was actually discovered in 1932 by **Irene Curie** (1897-1956) and her husband **Frederic Joliot** (1900-1958). They were bombing beryllium and boron atoms with alphaparticles and found that this caused unknown radiation that was not electrically charged. At first they thought that it was gamma radiation, but then they found out that it could do something that gamma-radiation did not do; release protons from paraffin. Thus the neutral particle, neutron was discovered.

During the same year an English born doctor **James Chadwick** (1891-1974) could show that the mass of the neutron was the same as the mass of the proton. Some sources say that it was James Chadwick who actually discovered neutrons. Later on in 1950 it could be evaluated that neutrons can be divided to beta-particles and protons. The understanding of atoms was complete enough to start nuclear energy studies.

1.2 Theories of nuclear energy

Albert Einstein (1897 Germany-1955) discovered that energy and mass can be described by his equation E= mc². He was a 26-year old official working in a patent office in 1905, when he published an article called the **theory of relativity**; which included his most famous formula. Nobody could understand his formula at that time. He could have read the papers of Marie and Pierre Curie, who got the Nobel price from their inventions of radioactivity two years earlier in 1903. From his theories Einstein achieved the Nobel-prize in Physics in 1921.

On June 28th of 1934 Hungarian born scientist **Leo Szilard** (1898-1964) applied for a patent in neutron chain reaction. He was a student of Albert Einstein in Berlin, where he became a Doctor of Physics in 1922. Leo Szilard made several inventions during his years in Berlin, where in 1928 he applied for a patent for a linear accelerator and in 1929 for a patent for a cyclotron. He escaped in 1933 to London, where he discovered the chain reaction of neutrons when walking in the street. He travelled from London to Columbia University in Manhattan in 1938 and was later one of the key persons in the Manhattan project.

The question of how to release the energy from the atoms actually started to get light only after 1938. Austrian born nuclear physicist, **Lise Meitner** (1878-1868) became the assistant of **Max Planck** (1858 Germany-1947) at the **Kaiser Wilhelm Institute** in Berlin in 1912. In 1917 she became the director of the **Independent laboratory of physics** in the Institute. There she came into contact with Albert Einstein who visited her laboratory quite often. The leader of the chemistry institute was **Otto Hahn** (1879 Germany-1968).

In Berlin Meitner and Hahn did experiments in bombing uranium atoms with alpha-particles. They thought that they would find heavier atoms than uranium, but something else was found. Because Meitner's family was of Jewish origin, she escaped to Holland in 1937 and from there to Sweden in August 1938, because all Jewish scientists were discriminated by that time in Germany.

However, Lise Meitner could advise Otto Hahn and **Fritz Strassman** (1902-1980) at the Kaiser Wilhelm Institute to do research according to her instructions. In this way the first splitting of uranium atoms was done in Berlin, but they could not give an explanation of the experiment. In December 1938 they sent a manuscript to *Naturwissenschaften*, in which they described how the bombing of uranium by neurons produced barium.

On December 19th, 1938 Otto Hahn wrote to Lise Meitner asking whether she could find some explanation for the experiment, where by bombing uranium atoms with neurons barium isotopes were produced as a result. Hahn was a radiochemist and not a nuclear physicist, and could not explain his discovery. Lise Meitner could not explain it either and wrote to Hahn that anything is possible in physics.

Lise Meitner was in Sweden when her brother's son **Robert Frisch** (1904 Austria-1979) visited her. Robert was studying physics at Nils Bohr's laboratory in Copenhagen. The two physicists together were able to find explanation to what happened in the experiment that Hahn had described in his letter to Meitner.

Both Meitner and Frisch understood the theories of Albert Einstein and Niels Bohr, recarding the structure of atoms and the magnitude of energy releasing. Bohr had described that the nucleus of atoms is just like a water drop, which is not stable. Thus Lise Meitner and Robert Frisch concluded that by bombing the nucleus by neutrons it could split the atoms into two pieces. They concluded that Hahn had actually split the atoms in two pieces. For these studies Otto Hahn got the Nobel Prize, taking all the credit of discovering the fission, even though he could not explain what had happened.

Lise Meitner was forgotten and lived out her last years in Britain. However, on February 11, 1939 the British journal, Nature published a letter of Robert Frisch and Lise Meitner, which explained their theories about the fission of atoms. Frisch had started to use the word **fission** for the first time. Thus part of the credit of the discovery of fission should also be given to Robert Frisch and Lise Meitner.

The theories of fission and chain reaction were developed further by **Fredrik Joliot** in France. His theories on chain reaction explained that the fission of uranium atoms released two or three neutrons, which could then make other fissions of uranium atoms in a pile. He applied for several patents for **uranium piles** and explained his theories to Lise Meitner.

Robert Frisch explained this experiment to Niels Bohr, who travelled to USA in January 1939 to give a lecture on the spitting of atoms at the **Princeton University** in Washington DC. He explained how neutrons can cause the fission of uranium atoms and how the fission can release energy and still free neutrons. This could then cause a chain reaction and a massive release of energy. He explained that to cause a chain reaction the neutrons should be moderated to slow neutrons, which can then cause the fission of U-235 atoms.

Bohr also concluded that it would be very difficult to get U-235 from natural uranium as it contains only 0.7% of U-235 atoms and 99.3% of U-238 atoms. Bohr also explained that when uranium-238 will absorb one neutron, it will change to a new material that has 93 protons and 146 neurons. He called this new material **plutonium-239** according to the Greek God of underworld metals and wealth. For the Romans Pluto was a god of the underworld, or Hades.

His speech caused an explosion among the scientists. Everybody wanted to tell this news to their colleagues. Thus the idea of nuclear fission was immediately spread to the **University of California** in Berkley, to **Chicago**, to **Harvard** in Cambridge, to **Yale** in New Haven and to the **Columbia University** in New York.

After the visit of Nils Bohr to the USA the first experiment on nuclear fission was then done on **January 25th, 1939** at the Columbia University by **Enrico Fermi** (1901 Rome-1954). Since 1927 Fermi had been the professor of theoretical physics at the **University of Rome**, where he was making experiments on slow neutrons and beta-fissions. For these studies Fermi won the Nobel Prize in 1938 and thus he knew how the bombing with the neutrons can be experimented on. His wife was of Jewish origin and thus the family escaped to the USA in fear of possible discrimination.

In his experiments independently from Bohr, Fermi discovered that fast neutrons caused the fission of U-238 atoms, and that slow neutrons caused the fission of U-235 atoms. The slow neutrons were obtained by letting the fast neutrons collide with atoms that have nearly the same mass as the neutrons. The best materials were hydrogen or materials such as paraffin, which contains hydrogen. Carbon and heavy water were also found to be suitable moderating materials for the neutrons.

In **April 1939 Niels Bohr** explained in Copenhagen in a newspaper that "by bombing uranium-235 atoms with slow neutrons a chain reaction or an explosion can be achieved. The explosion can be so big that the laboratory and neighboring building could be destroyed". After this the press fell silent and nobody could write about atomic weapons. The idea of the atomic bomb had been revealed for the first time to the general public.

In **August 1939 Albert Einstein** sent the letter to **Franklin D. Roosevelt**, the President of United States, about the possibility of making atomic bombs. Fermi and Szilard had actually written the letter, which was then signed by Einstein. Einstein explained that:

"the recent work of E. Fermi and L. Szilard lead me to expect that the element of uranium may be turned into a new and important source of energy in the immediate future. This new phenomenon would also lead to the construction of bombs and it is conceivable – though much less certain – that an extremely powerful bomb of a new type may thus be constructed. A single bomb of this type, carried by a boat and exploded in a port, might well destroy the whole port

together with some of the surrounding territory. However, such bombs might very well prove to be too heavy for transportation by air".

In addition Einstein made the following recommendations:

- a) Particular attention should be given to the problem of security of supply of uranium ore for the United States. I understand that Germany has actually stopped the sale of uranium from the Czechoslovakia mines that she has taken over.
- b) To speed up the experimental work, which is at present being carried on within the limits of the budgets in University laboratories, funds should be provided and the co-operation of industrial laboratories which have the necessary equipment, should be obtained

.

1.3 Development during the Second World War

The first "iron curtain" in Europe was formed by Germany and the Soviet Union in August 1939, by the foreign ministers Molotov and Ribbentrop. They divided Europe into the Soviet bloc, which included Finland and the Baltic Countries and into the German block, which included most of Poland.

On the first of September 1939 Germany invaded Poland with two million men, 2300 aircrafts and 2750 tanks. Poland was occupied in three weeks and divided in two between Germany and the Soviet Union. The casualties included 86 000 dead or lost, 164 000 wounded altogether 250 000 soldiers. **The Second World War** had started.

On November 30th 1939 the Soviet Union attacked Finland with 800 000 soldiers, 3800 aircrafts and 3000 tanks. The Finnish army had totally 350 000 soldiers and 200 aircrafts. My father was one of the soldiers, as were the majority of all Finnish men between 18 and 35 years of age. Finland was almost alone to defend western democracy at that time. Sweden gave us Boforsguns and volunteers, which would fight with our soldiers. The USA or Germany did nothing to help us at first. France, Italy and Great Britain promised to send some soldiers, but they were not asked by the Finns. The US sent us some financial aid and sympathy, but the US Brewster fighter airplanes arrived to Sweden after the war was over.

The Finnish **Winter War** lasted 105 days. The casualties of Soviet Red army were 127 000 men in dead or lost and 265 000 men were wounded, totaling 392 000 men (40 % of their forces). The casualties of the Finnish army were 26 000 men dead or lost and 44 000 wounded, altogether 70 000 men (20 % of the army forces). Finland survived and made peace with the Soviet Union in March of 1940, having to give up a part of Karelia, which was a south-eastern part of Finland.

The Second World War accelerated the development of nuclear weapons. Based on the letters of Albert Einstein and advise from other scientists the US established **Advisory Committee on Uranium** in October of 1939. The first report by the committee was given in November 1939. The report reviewed the work done at the Columbia University by Fermi and Szilard on the construction of a uranium pile and on the fission of atoms. In April 1940 the Committee held a meeting in Washington, and 40 000 dollars were granted by the committee for making pure uranium and pure graphite.

This budgetary decision was also noted by the German side. Germany started studies on the possibility of nuclear energy. Professor **Werner Heisenberg** (1901 Germany-1976) was one of the scientists, who wanted to help the German military after the occupation of Poland. He had won the Nobel Prize in Physics in 1932 for his theories on quantum mechanics. However, most of the scientists, including Otto Hahn, were reluctant to develop atomic weapons. In February 1940 Heisenberg made a report where he concluded that a reactor that would use natural uranium and be moderated by heavy water, might generate energy.

Heisenberg was nominated to lead the reactor designs in Berlin and Leipzig. The needed uranium was received from Czechoslovakia, which had been occupied by the Germans one year earlier. Uranium was brought to Berlin for the first reactor. The heavy water was planned to be used as a moderator, but it was very difficult to obtain in the beginning of 1940. Thus the first experiments did not start a chain reaction.

In the British side the **Military Application of Uranium (MAUD)** committee held its first meeting in April 1940. They discussed the possibilities of separating U-235 and U-238 isotopes and the fission of atoms by using fast neutrons. In June 1940 **Franz Simon** (1893 Germany-1956) started the development of separation of isotopes by using the gaseous diffusion-method. The gaseous diffusion method was proven to work in December 1940 by Simon.

After this the committee started to send their reports to the US. The theory on atomic energy was described in **July 15th, 1941 in the MAUD-reports**. One of the reports was "The use of Uranium for a Bomb", in which was said that about 12 kg of uranium-235 world be needed for an atomic bomb. The other report "Use of Uranium as a Source of Power", explained how heavy water or graphite could be used as a moderator to establish a chain reaction.

In July 1940 the US formed a **National Defense Committee** (**NDC**), which was aimed to support atomic studies. The chairman of the committee was **Vannevar Bush** (1890-1974). One of the tasks of the committee was the separation of U-235 from U-238. It was given to Professor **Harold Clayton Urey** (1893-1981), who was working at Columbia University in New York. He had discovered deuterium by distilling of liquid hydrogen. Deuterium in the form of heavy water became one of the moderators for neutrons in later reactors and in the future it will be the fuel of the fusion reactors. He won the Nobel Prize in Chemistry in 1932.

Princeton University in New Jersey was developing atomic pile, which was needed to establish a chain reaction in uranium atoms. In practice graphite would be used as a moderator for neutrons, which would then cause the fission of the uranium-235 atoms. In the beginning, Fermi's team constructed a small pile called the exponential pile. The size of the cubic formed graphite pile was $2.5 \times 2.5 \times 2.5$ meters. The uranium was in the form of uranium oxide. The reactivity factor reached with the pile was only K = 0.86. There was a long way to go to reach the 1.01 needed for a chain reaction.

University of California in Berkley was developing plutonium in a team led by **Ernest Orlando Lawrence** (1901-1958), who won the Nobel Prize in Physics in 1939 for his invention of the cyclotron in 1929. The cyclotron was used to accelerate particles in nuclear experiments, where new materials were formed. However, Leo Szilard had made his patent application of cyclotron independently that same year.

During the war years Lawrence was one of the members of the team that developed the atomic bomb. Lawrence was also developing the methods to separate uranium-235 and -238 atoms using electromagnetic fields. The theory of nuclear explosion was also discovered by Lawrence. Later on the separation of uranium for the Hiroshima atomic bomb was done by using this method.

Plutonium-239 was discovered in University of California in Berkeley for the first time on March 1941 by the team of **Glenn T. Seaborg** (1912-1999) and **Edwin McMillan** (1907-1991), who were bombing uranium-238 atoms with slow neurons. By this time the discovered element was called element 94²³⁹, and the name plutonium was proposed by McMillan. Both men received the Nobel Prize in Chemistry in 1951 for their discoveries of several new isotopes.

Plutonium could be separated by chemical means, which was impossible in the case of uranium isotopes U-235 and U-238. Plutonium-239 was behaving in the same way as U-235 and fast neutrons could cause the immediate fission of the plutonium atoms.

Plutonium-239 was also noted by the German scientists in **Dahlem** to be the key to nuclear energy. In August 1940 Germany occupied Norway and overtook the **Norsk Hydro** facilities in **Vermok** which were producing hydrogen by using the electrolytic process. Norsk Hydro was also making heavy water and the Germans now had the facility that could make the moderator for a nuclear reactor. Then the reactor could make plutonium, which could be separated chemically from other fission products.

In June 1941 Germany started operation **Barbarossa**, the aim of which was the occupation of the Soviet Union. The Finnish army wanted to get back the lost Karelia and followed the German attack via the northern front two weeks later. Finland occupied the lost areas in two months and advanced to the Russian part of old Karelia, which had been populated by the Finnish tribe, the Karelians. Britain declared war against Finland for this advancement, but did not start military

operations against Finland. The US army gave more than 10 000 aircrafts to the Soviet Red army, which was using them also for dropping bombs on Finnish cities.

In the autumn of 1941 Heisenberg had enough uranium and heavy water to start the experiment again. In the beginning of 1942 the first chain reaction of uranium had been achieved in Leipzig. However, the reactor was not large enough for massive plutonium production. Also there was not enough heavy water to make new larger reactors.

The US the national defense committee held a meeting in December, 1941 on the development of nuclear science. During the meeting the delegates received the news that Japan had attacked Pearl Harbor and the US was at the war. Japan had already occupied several countries in Indo China and was now attacking the Pacific islands. This Japanese attack put the US war machines into action.

1.4 The Manhattan project

Within one day from the attack on Pearl Harbor the members of the Uranium Committee established an organization which was openly discussing the atomic bomb. The task was to make a nuclear reactor that could be used to make some kilograms of plutonium. The plutonium could then be used to make an atomic bomb. The planning organization was headed by US Vice president **Henry Wallace** (1888-1965), war minister **Henry L. Stimson** (1879-1950) and Vannevar Bush, who coordinated the scientific research.

As the theories about the possibility to make an atomic bomb were spreading the race to make the actual bomb was started. In 1942 was established the **Manhattan Engineering District**, which was a code name for the **Manhattan project**. The leader of the whole project was given to General **Leslie R. Groves**, who had his office in Washington.

One group of scientists was conducting studies on chain reaction at the Metallurgical Laboratory of University of Chicago. The team was led by **Arthur H. Compton**. The first critical pile was constructed in an old tennis hall, which had been abandoned by the tennis players. Several scientists from the Columbia University were called to Chicago to construct the pile. Among the scientists were Enrico Fermi and Leo Szilard as well as doctors **Walter Zinn** (1906-2000), **Eugene Wigner** (1902-1995) and **John Wheeler** (1911-2008).

This pile, with the code name **CP-1** (Chicago Pile), was the seventh pile the team had been constructing. Now this pile was bigger than the others. The bottom and the walls were constructed by using 60 cm thick graphite tiles. This blanket was aimed to reflect all the escaping neutrons back into the pile. Then the inside of the pile was loaded with graphite tiles and uranium. Every other layer was the same type without uranium. Other layers had two holes that could be loaded with uranium tiles, which weighed 2.5 kg each. The control rods on the top of

the pile were made of cadmium, which was known for its ability to absorb neutrons. The size of the pile was $9 \times 6.3 \times 9.6$ m and the weight was 1400 tons.

In November of 1942 the team had received about 52 tons of uranium and the assembling of the uranium could be started. On December 2nd 1942 the 50 layers of uranium tiles had been assembled and the control rods were drawn out of the pile the chain reaction started for the first time in history. The thermal output of the reactor was only about 50 milliwatts and later on 200 Watts of thermal energy was achieved. This was a small step in energy production, but a giant step in the history of atomic energy.

In the late 1942 a team, code name Y, consisting of top atomic scientists in **Los Alamos** New Mexico, was given a mission to design and construct the actual atomic bomb. The site was selected so that the test explosion could be carried out near Los Alamos in the desert. The leader of the scientific project was **Robert Oppenheimer** (1904-1967), who was a professor at University of California in Berkeley. The members of the team included Niels Bohr, Enrico Fermi, Leo Szilard and James Chadwick. They made the basic design of the bomb, which was to be made by using both uranium-235 and plutonium-239.

The principle of the bomb was that it had to reach the critical mass of fissile material within a very short time. This could be achieved by combining two uncritical pieces of uranium or plutonium in a cylinder, where half of the material is in one end and another half in the opposite end. Then the pieces could be put together by using a conventional bomb. The fissile material had to consist of 90% pure uranium-235 or plutonium-240. The main difficulty was then, how to produce the fissile material.

A team, code named **X**, was working in **Oak Ridge** in Tennessee to separate U-235 and U-238 atoms. Massive power plants to supply the energy for this process would be needed. Theories on the separation of uranium isotopes were developed by **Professors Harold Urey** (1893-1981) and **John N. Dunning** (1907-1975) in Columbia University. They were experimenting on three methods: gaseous diffusion, centrifuges and electromagnetic separation.

Pure uranium-235 was planned to be produced by the electromagnetic separation developed by Lawrence in Berkeley. Thus the huge magnets of Berkeley were transported to Oak Ridge, where the separation plant, code name **Y-12**, was constructed in 1943. The uranium-235 for the Hiroshima bomb was made at this huge plant, which had a total of 45 000 workers. Additionally a huge gaseous diffusion plant, with code name **K-25**, was constructed during 1943-44 in Oak Ridge.

A team, code name **W**, was collected in **Hanford**, **Washington**, which was selected as the main site to make the graphite piles to make plutonium. The selection criteria for the first nuclear reactor were following: *No village should be closer than 10 miles from the plant upwind. No town with more than 1000 inhabitants should be closer than 20 miles from the reactor.*

The design for a large pile, code name **X-10**, was done in 1943. The construction of the plant in Hanford was started in April 1943, and in September the first pile started to operate. By the end of the year the first grams of plutonium had been produced. A separation that which used the methods developed by Glenn T. Seaborg was constructed by the **DuPont** engineers.

Additionally **Wendover in Utah** was selected as a training site for the air force which would actually drop the bomb. The huge **B-29 "Superfortress**" -bomber was the only plane suitable for a long range bombing flight. It had been modified to be able to carry weapons. The task was given to **Colonel Paul W. Tibbets** (1915-2007), who already had experience on dropping the first bombs on Germany. Thus his team was trained by dropped huge normal bombs in Utah, and Tibbets was the only man who knew there that they were training to drop the atomic bomb.

All the projects were top secret and only a handful of people knew the purpose of the massive facilities that were being built in several locations. Also radiation sicknesses were experienced with the atomic piles. At Oak Ridge **Doctor Bruns** and his colleague were lying in hospital beds suffering from radiation overdose. The first victim of the atomic bomb was this young man, who had been too eager in testing, and who then had to meet his destiny.

The scientists in **Dahlem** Germany were also studying the possibilities of making nuclear materials. The Norsk Hydro heavy water facilities in Norway were destroyed by the English. Thus the work with the atomic pile was started with limited resources in Dahlem. In February the allied destroyed the facilities and the construction of the pile was transferred to **Hechingen**. There was a rock cellar that gave shelter to the facilities. However, there were not enough uranium and moderator materials to reach the critical mass.

The heavy water factory in **Vermok** in Norway had been repaired by the engineers of **I. G. Farben** and was now in full operation again. In February 1944 the heavy water was ready to be transported to Germany. A Norwegian resistance soldier named **Knut Haukelid** (1911-1994) knew how the transportation to Germany would be done. He installed a bomb on board the ship, and the explosion sunk with the heavy water aimed for the German reactors.

In 1944 the allied forces prepared to make the combined attack on Germany. The United States and Great Britain would attack from the Western front on Normandy and the Soviet Union on the Eastern front. On June 6th about 175 000 allied soldiers landed on Utah, Omaha, Juno and Sword beaches in Normandy under heavy fire of the German machineguns. Additionally about 24 000 airborn troops landed behind the German lines.

The casualties of the allied forces included about 10 000; killed, wounded, missing or captured. The memorial site and the graves of 9387 US soldiers killed in the invasion are still today near the Omaha Beach. There you can see US war veterans, who still journey there to relive their memories.

On June 10th 1944 about 605 000 soldiers of the Red army attacked to Finland. This came as a big surprise to the Finnish army Generals, who thought the main target at that time would be Germany.

Finland survived but about 70 000 men were killed or went missing in one month. The Red Army lost about 100 000 men, dead or missing and 300 000 were wounded; totaling more than half of its attacking forces in one month. The invasion was stopped in July 1944 and the rest of the soldiers were returned to the German front.

In February 1945 US intelligence started its operations in Germany. One of the main tasks was to detect possible nuclear research and the development of an atomic bomb. In the spring of 1945 the US intelligence detected that Werner Heisenberg was living in **Hechingen**. Thus they thought that the German atomic development was done there.

On March 1945 the US troops entered Heidelberg and found **Walther Bothe**, **Richard Kuhn**, **Wolfgang Gertner** and **Beckner**. They told that Verner Heisenberg and **Max von Laue** were at Hechingen, and that the experimental uranium pile in Dahlem had been moved to **Haiderloch**, which was a small town near Hechingen.

The American army had captured the site of the German pile and the scientists were asked about the development of an atomic bomb. It was found that the experimental pile was not critical, but Heisenberg group had made plans for a bigger pile, which could be.

Another discovery was that centrifuge separation method of uranium isotopes 235 and 238 had been developed quite far, and that in theory the Germans had the possibility to make uranium-235. The centrifuge research had been started at the **University of Hamburg** by **Dr. Harteck,** and was continued at Celle. A small centrifuge was found in Hechingen and it was said "operating satisfactorily".

On May 8th 1945 president **Harry S. Truman** (1884-1972) in the US, **Winston Churchill** in London and **Joseph Stalin** in Moscow announced in their radio speeches that the war in Europe was over. This was a day of victory for many in the allied forces. It was also actually the starting point of the Soviet occupation of the Baltic and many Central-European countries, which should be also remembered.

President Truman had been in office for 24 days by the time of his speech and he was still thinking about the war in the Pacific, which was still in full force. In the summer of 1945 the preparations for the atomic bomb were at full speed. The uranium bomb with a gun-type design was believed to operate without a test and there was not much uranium-235 available for the tests. The implosion type plutonium bomb was considered more difficult, and thus the scientists considered that a test would be needed.

The **Alamogordon airport** had been selected as the test site. The site was in New Mexico about 320 km south of Los Alamos. In the morning of July 13th, 1945 the atomic bomb was installed in the tower. All connections and relays were tested and everyone was waiting for an explosion. But then suddenly the sky turned black and all the preparations had to be stopped. The bomb was lifted back from the tower and everything had to be started again.

Finally on July 16th everything was installed and tested again. But a thunderstorm approached the site again. Lightning were striking here and there and everyone was thinking about the possibility that lightning might hit the tower and destroy the instruments. However, the explosion was to be made at 4:00. The bomb was made of plutonium-239 atoms and its force was calculated to correspond to 20 thousand tons of dynamite, if all of the nucleus would split. However, it was thought that hardly a tenth of it would explode.

At 3:30 the loudspeakers at the site announced that time zero will be at 5:30. The work on the final reparations started. It had been calculated that half an hour before zero time everyone should leave the site. At time zero people should turn their faces away from the explosion. At 45 seconds before time zero the automatic procedure was started and nobody could stop it.

Robert Oppenheimer was standing in the commanding bunker ten miles away. Everyone was told to lie face down on the ground, close their eyes and cover their heads with their hands before the countdown to zero. After the flash they could stand up and watch the explosion through smoked glass.

What would happen? Would the bomb explode? Could it be possible that the whole world would be destroyed, as some scientists had predicted? Then suddenly a bright light flashed, as though thousands of suns were burning. The light ball was getting bigger and bigger and turning red and purple. 50 second later the pressure wave hit the men in the shelter, and the sound of thunder was heard at the same time. A dark cloud was rising from the bomb site and soon it covered the sky. Was this the end of the world?

At the same time on the island of **Tinian** in the Pacific Ocean the preparations on the airport were almost ready. Six runways had been constructed and the huge **B-29 Superfortress** bombers had arrived. The number of them reached several hundreds. The island was also the new location for Tibbet's 509th Composite Group, aimed for a special mission. The site also included several scientists from Los Alamos. Large containers were arriving to the site on ships with extra guards from the military police.

The B-29 bombers delivered their cargo to Japan in large squadrons. They returned within twelve hours. The last months of the war had begun. Colonel Paul Tibbets and his men were waiting for the final command to drop the bomb. The generals were calculating the losses that would lie ahead if the war would go on island after island. How many soldiers could be saved if the bomb would be dropped and how many civilians will be killed by dropping the bomb.

Finally, Tibbet had made his plan how the mission would be competed. He had noted that the heaviest artillery fire was targeted at the bombers that came in large formations, when single aircrafts were left to fly in peace. Thus, his plan was to drop the bomb by one of two planes that would approach the target.

On August 2nd 1945 the B-29 bombers arrived from Wendover to Tinian with special boxes and dangerous materials. No one knew what was inside the boxes. On August 5th 1945 **General Farrel** arrived and Tibbet had assembled his groups at the airport. Tibbet called the men one by one by name. Finally 27 names had been called and then everyone knew that this was enough for just three bombers.

The named men formed a half circle and the rest were dismissed. Then General Farrel said: Tomorrow, you will fly the atomic bomb under the command of Colonel Tibbets who will fly with you.

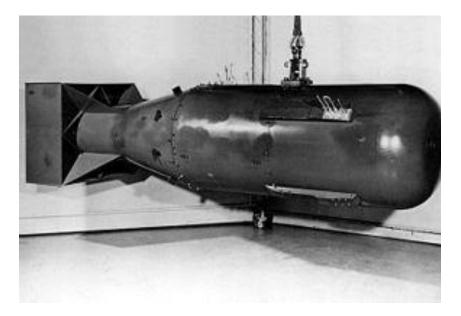


Figure 1.4.1 Little Boy was the first uranium bomb. It was dropped on Hiroshima

On the next morning a B-29 bomber with the nick name **Enola Gay** started its engines. It was named after Colonel Tibbets mother. A special package with the atomic bomb was lifted into the plane. The bomb was nick named the **Little Boy. Captain Parson** assembled the explosives onto the bomb. The bomb itself contained 35 kg of uranium-235, which had been separated at the gaseous diffusion plant in Oak Ridge. The bomb was 3.0 m long and 0.71 m in diameter. It weighted four tons.

Colonel Tibbets explained to his staff what would happen next. He said that one hour before take off three spy planes would start the journey to the targets. If everything would be clear, they would give the target where the bomb will be dropped. It would be the place where the sky

would be the clearest. The explosion caused by the bomb was explained to them for the first time. The bomb would explode at 600 meters above the ground by automatic ignition.

On August 6th, at 2:45 the engines were started. Two escort planes left the ground first. After them Enola Gay followed. The planes met at **Iwojima** before their final target. The escort planes sent a message that they were above Iwojima and that the final weather forecast was heart. All three targets were having thin clouds. After a while one of the escort planes gave a message to Enola Gay: *The weather is the clearest above Hiroshima*.

The planes were flying in an attack formation that had been trained hundreds of times. Then the radio technician shouted that he caught a Japanese message: *Danger over*. **Captain Lewis** started looking at the ground from the plane at 31 700 feet (9500 m) above Hiroshima.

Finally, the target was found and the bomb was dropped. The planes turned 150° and started to return back. The automatic ignition mechanism of the bomb was started at 7000 feet (2135 m) from the ground. At 1900 feet (579 m) the last radio signal from the bomb was captured and the electronic ignition happened. This caused the conventional explosion in which a smaller piece of uranium-235 was shot into a canon pipe about 120 cm forward to the other end of the canon pipe, which in turn contained the rest of the uranium-235 and an immediate explosion followed.



Figure 1.4.2

Boeing B-29 Superfortress plane was used to drop the atomic bombs on both Hiroshima and Nagasaki

The aircraft was returning to the base and was about fifteen miles from the site the pressure wave shook them within one minute of the explosion. On the ground about 80 000 people were killed instantly and 70 000 were injured. The force of the bomb was estimated to correspond to 13 thousand tons of TNT.

On August 9th, 1945 another B-29 Superfortress, nicknamed as **Bockcar**, started its trip to **Nagasaki**. This time the bomb was loaded with plutonium-239 and nick named the **Fat Man**. It was 3.3 meter long and 1.52 meters in diameter. It weighed 4.6 tons, including 6.4 kg of

plutonium-239. The plutonium was installed on the surface of a sphere to prevent the spontaneous fission of the plutonium-239 atoms.

The plutonium bomb was constructed according to the calculations of **Hans Bethe** (1906 Germany-2005), who was the leader of the Theoretical Physics division at Los Alamos. He was one of the physics who could design the inward movement, implosion and the critical mass of the plutonium. The plutonium-239 had been produced in the Hanford reactors by bombing uranium-238 atoms with neutrons.

The devastation in Nagasaki was enormous. About 40 000-80 000 people lost their lives and more than this were injured by the radiation or the heat. On August 12th, Japan surrendered and the war was over.

1.5 Other nuclear programs

After Hiroshima the atomic bomb was known everywhere. The atomic race had started. **Igor Kurchatov** (1903-1960) was the leader of the Soviet program. He had established the first Soviet nuclear team in 1932 and built the first cyclotron in 1939.

The program to develop uranium studies was initiated by a secret government order; № 2352ss, in which the organization of uranium-related activities was described. The order was signed on August 28th, 1942. An ad hoc committee was set up to take overall charge of uranium mining and development of the atomic bomb. On February of 1943, a new order was given to move the laboratory to Moscow, and to appoint Professor Igor Kurchatov as the scientific leader of all uranium research. On April 12th, 1943, the Instrumentation Laboratory No. 2 or the **Russian Research Center Kurchatov Institute** was established within the Academy of Sciences.

The Soviet Union had received the **Maud** report in 1943 and were aware of the British ideas on nuclear weapons. The report "Atomic Energy for Military Purposes" or the so called **Smyth-report** was published in August, 1945 just after Hiroshima and Nagasaki. The report described the development of the atomic bomb between years 1940 to 1945. Thus the basic data of atomic energy was available to everyone.

Josef Stalin ordered Igor Kurchatov to build an atomic bomb in 1948. The plutonium was produced in a 100 MWt **reactor** (**A**) at **Chelyabinsk**, which was a secret city for a long time. The plutonium bomb was the same type as the Fat Man in Nagasaki (Figure 1.5.1). The first Soviet atomic bomb (RSD-1) exploded on August 9th, 1949 in **Semipalatinsk** in Kazakhstan, four years after Hiroshima.

The radioactive fallout was detected on September 3rd by an American B-29 aircraft that was flying near the Kamchatka peninsula, and the Americans could then calculate the time of explosion and the type of the Soviet atomic bomb. The time of the **Cold War** and nuclear threat had started.



Figure 1.5.1 The first Soviet nuclear bomb used plutonium. It had similar measures than the "Fat Man", which was dropped on Nagasaki. The document in the front is the order on the "Atomic Project in the Soviet Union"

The information regarding the atomic bomb was said to have spread through German born Doctor **Klaus Fuchs** (1911 Germany-1988), who was working at Los Alamos and gave the information to the Soviet scientists. Fuchs was sentenced to 14 years in prison in 1950. However, the Soviet scientists did actually know the same basic facts as the Americans, and they were able to build the bomb also without the data from Fuchs. However, the Soviet design of the plutonium bomb was similar to Fat Man and even the external shape of the bomb was identical.

The father of the British atomic bomb was **William Penney** (1909-1991), who attended the US weapons program at Los Alamos. He was asked to be the technical leader of the British team in May 1948. In October the first reactor went critical and started to produce plutonium. The British joined the atomic club on October 3rd, 1952 by exploding their first plutonium bomb.

By this time the cold war between the West and East had started and the atomic weapons were thought to give atomic shield to Europe, when the Soviet Union had excessive capacity in tanks and conventional weapons. Korean War started in June, 1950. Both the Soviet Union and the US had atomic weapons available and some generals even thought to use them. However, they were never used again in war.

1.6 Energy of the sun

Cecilia Payne (1900 UK-1979) pointed out in her doctoral thesis in 1925 that the sun consists mainly of hydrogen and helium. She also found that the stars are mainly consisted of hydrogen. Until then all the astronomers believed that the sun consists of iron, and the new fact was not accepted. One reason was that Payne was an English born woman in America, and at the time she was discriminated by the scientific community.

1.6.1 The American hydrogen bomb

The fusion bomb was discussed in 1942 at Berkeley summer school, where **Robert Oppenheimer** met **Enrico Fermi** and **Edward Teller** (1908-2003). Fermi presented the idea of the fusion bomb, which would give more energy than the fission bomb. Edward Teller was fascinated about this idea and was developing it further, but it was abandoned at that time.

Robert Oppenheimer had left Los Alamos and in 1947 he took the position of Professor of Advanced Studies in Princeton, New Jersey. He also became an adviser for the US Atomic Energy Commission, which led the development of atomic science since 1946. He was opposing the development of the hydrogen bomb and proposed that the US should have instead more fission bombs.

After the Soviet atomic bomb in 1949 US President Harry Truman demanded further actions to be taken by scientists about development of **the super-bomb** in January of 1950. Edward Teller was invited to return to Los Alamos that same year. He had also seen what had happened to his home country Hungary after the war under Soviet dictatorship.

Another man behind the idea of the hydrogen bomb was **Stanislaw Ulam** (1909-1984), a Jewish-Polish mathematician. Ulam proposed that the bomb could be built so that it had a fission bomb in one end and thermonuclear material in the other. Thus the fission bomb could cause the compression of the thermonuclear material, which would then reach the pressure and temperature needed for the fusion.

The first hydrogen bomb was developed using this principle, named the **Teller-Ulam design**. The idea was to use fast X-rays instead of neutrons in triggering the fusion of the deuterium (hydrogen-2) and tritium (hydrogen-3) atoms. The fission bomb was placed in a cylinder and detonated. Then the X-rays caused the secondary fission of plutonium-239 by implosion, which was boosted by fast neutrons coming from the fusion. Therefore actually much of the energy will came from the plutonium fission.

Both Teller and Ulam applied for the patent of the hydrogen bomb. The first hydrogen bomb of this type was then exploded on November 1st, 1952 on **Bikini Island**. The bomb had the power of 10.4 megatons of TNT and it made a crater 50 meters deep. It also caused radiation on the island and a lot of radiation damage among the native people.

1.6.2 The Soviet hydrogen bomb

In the Soviet Union, **Andrei Sakharov** (1921-1989) invented the same type of hydrogen bomb in Igor Kurchatov's team. The design of the bomb was based on Sakharov's *Third Idea*, nearly the same design as the Teller-Ulam bomb. The bomb was exploded on November 22nd, 1955 at the Semipalatinsk test site in Kazakhstan, only three years after the US hydrogen bomb.

Then on October 30th, 1961 the Soviet Union exploded the biggest hydrogen bomb in Novaya Zemlya. It had the power of 50 Megatons of TNT and so the Soviet Union had taken the lead in hydrogen bombs. The bomb was about 5000 times more powerful than the first bomb in Hiroshima. The fallout of radiation was also noticed in the Nordic countries, as the test site was quite near.

1.7 Opposition voices

In 1950 Albert Einstein sent his letter to the US President, in which he warned that nuclear testing might destroy the environment. In 1954, four months before his death Einstein said:

"I have made one great mistake in my life when signing the letter to President Roosevelt recommending that atom bombs should be made".

Also Oppenheimer wanted to put limits to the development of nuclear weapon programs in their home countries. Oppenheimer was then accused for his connections to the communist party, which has contacts with the Soviet Union. His wife had been a member of the communist party.

Also his war time colleague in Los Alamos, Edward Teller, testified against him. Oppenheimer lost his classification status in 1953, and **President Dwight D. Eisenhower** asked him to resign. Ten years later in 1963 **President John F. Kennedy** awarded Oppenheimer with the **Enrico Fermi Award** and his status was rehabilitated.

Sakharov was also politically active. He spoke against nuclear testing and ballistic missiles. He became a leader in the Soviet liberalization movement after the Soviet invasion in Prague in 1968. He was awarded the **Nobel Prize of Peace in 1975**, but was arrested because of his liberal ideas. Sakharov was released when President **Mikhail Gorbachev** started his perestroika policies in 1986.

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2. NUCLEAR REACTORS

2.1 The first power reactors

The United Nations was established on October 24th, 1945. The UN countries thought that the organization would be needed to prevent future wars and also to control the spreading of weapons. One of the main aims was also to help the development of nuclear energy for peaceful uses.

Ten years later in August, 1955 the UN organized the first **Geneva Conference**, aim of which was to discuss "*The Peaceful uses of Atomic Energy*". Some 1000 papers were presented during four days. Many of the papers gave thoughts about the building of atomic power plants, which were thought to be able to generate electricity "*free of charge*".

The International Atomic Energy Agency (IAEA) was then established in October, 1956 in New York. The headquarters of the IAEA were established in 1958 in Vienna, Austria. The safeguard systems came to full effect in 1963, after five year discussions between the participating countries.

The race to build nuclear power plants had started. The first nuclear reactors for power generation were built in the United States (EBR-1 1951 Arco), the Soviet Union (Obnisk 1954), the UK (Calder Hall 1956) and then again in the US (Shippingport 1957).

2.2 Fast breeder reactors

2.2.1 USA

The fast breeder reactors actually started the construction of power reactors. The basic idea behind the fast reactors is their possibility to use fast neutrons, which can then breed the uranium-238 atoms into plutonium-239. The primary fissionable material is plutonium-239, which produces 25% more neutrons than uranium-235 and thus the extra neurons can be used to convert uranium-238 in the blanket into plutonium-239. The cooling media in fast reactors is normally liquid metal, which does not slow down the neurons as water does.

Several metals can be used, depending on the melting and boiling points: mercury (-38.8 and 356.7 $^{\circ}$ C), sodium-potassium NaK (-11 and 785 $^{\circ}$ C), sodium (97.7 and 883 $^{\circ}$ C), lead-bismuth (123.5 and 1670 $^{\circ}$ C) and lead (327.5 and 1749 $^{\circ}$ C). Because the atoms of the metals are heavier they do not slow down the neutrons. But the metals are not liquid at normal ambient temperatures and thus they must be heated.

The first reactor actually built was the **Experimental Breeder Reactor** (**EBR-1**). It used sodium-potassium (NaK), which has excellent cooling properties. It was a prototype of breeder reactors developed by **Walter Zinn** (1906-2000).

Walter Zinn was said to be the man who caused the fist critical nuclear reaction by removing the control rods in the Chicago pile on December 2nd, 1944. After the Manhattan project Zinn was the first director of the Argonne National Laboratory (1946-1956), which had been established 40 kilometers southwest of Chicago. The Argonne National Laboratory was a direct descendant of the Metallurgical laboratory of the University of Chicago, where the first reactor (CP-1) was constructed.

EBR-I was built in Arco, Idaho in 1951 for experimental purposes to demonstrate the breeder reactor concept. The breeder reactor generated more fissile materials (plutonium-239) than it consumed. The uranium-235 elements were surrounded by a uranium-238 blanket, where they were converted into plutonium-239 in neutron radiation.

The output of the EBR-I was 1.4 MWt and it produced 200 kWe of electricity. It generated the first electricity by using nuclear energy on December 20th, 1951 in a steam turbine; *enough for lighting four light bulbs*. The main goal of the experiment was to demonstrate breeding concept so that larger reactor, the EBR-II, could be built.



Figure 2.2.1 EBR-1 generated electricity on December 20th, 1951 (Source: Rick Michal, Nuclear News November 2001)

The EBR-II reached criticality in July of 1964. In its final phase of operation the reactor output reached 62.5 MWt. The EBR-III had also been planned, but it was never realized.

The first commercial fast reactor in the US was the **Enrico Fermi-1** built near Detroit, Michigan. It had an electrical output of 61 MWe and started operation in 1963. After three years of operation the reactor experienced a partial meltdown, when the sodium cooling

circuit was blocked by loose parts of zirconium. The reactor was repaired and started again in 1969 until a sodium fire stopped its operation in 1970. Finally its operation license was not renewed and the reactor was decommissioned in 1973.

The US was starting to construct the first commercial scale breeder, **the Clinch River**, in 1973. The reactor was designed to produce 350 MWe of electricity from 1000 MWt of thermal energy. It was a loop type reactor, cooled by liquid sodium. By this time the US uranium resources were estimated to support 1000 GWe of electrical capacity using light water reactors. Thus additional capacity had to be constructed by using the breeder reactors.

The development of breeders in the US was terminated, when the construction of the Clinch River plant was stopped in 1983 by a voting of the Congress. The costs of the breeder reactor power plant were estimated to be double the costs of a light water reactor and the price of uranium should be more than \$165 per ounce to make to this type of reactor competitive. However, the actual prices have remained below \$100 per ounce most of the time, because the nuclear expansion never happened.

2.2.2 The United Kingdom

The British also started the fast reactor design based on sodium-potassium (NaK) coolant. The first experimental fast reactor, **Dounreay Fast Reactor** (**DFR**), started operation in 1962 in Scotland. The power plant had an electrical output of 14 MWe. Plutonium-239 was used as the primary fuel of the reactor. It was a loop type reactor that had 24 sodium-potassium coolant loops. The plant was decommissioned in 1977.

The second plant in Dounreay, **Prototype Fast Reactor** (**PFR**), had an electrical output of 250 MWe and was taken into operation in 1970. It was a pool type reactor, which was cooled by liquid sodium and the primary fuel was a mixture of uranium oxide and plutonium oxide (MOX). The plant was decommissioned in 1994 when its financing was stopped.

2.2.3 France

France had also built sodium cooled fast reactors. The 130 MWe **Phénix** reactor was connected to the grid in 1973 in Marcoule. The Phénix reactor continued its operation until 2009 when it was stopped and remained waiting for decommissioning.

The 1200 MWe commercial **Superphénix** was then commissioned in 1986 at the same site. The Superphénix reactor was stopped for maintenance in 1996 and was not started again.

France is planning to build the next liquid sodium cooled breeder reactor by 2020. However, no decision has been made yet. The main reason behind building of new reactors is the rising price of uranium, which would make the breeders competitive.

2.2.4 The Soviet Union

The development of breeder reactors has continued in the Soviet Union and it is the only country in Europe that still has operating fast reactors. The Soviet Union put much of its research into breeder reactors because its uranium resources were quite limited.

Several conceptual breeders were developed. The first experimental fast reactor **BR-1** (**Bistra Reaktor**) went critical in 1955 and had a thermal output of only 100 W. The sodium cooled **BR-5** went critical in 1959 and it had 5 MW of thermal output.

The next research fast reactor was **BOR-60**. The reactor was commissioned in 1969 and it is still in operation. The reactor has 60 MWt of thermal output and 10 MWe of electrical output. It uses a mixed oxide fuel in which uranium-235 content varies from 45% to 90%. The next reactor was **BN-350**, which was built in Kazakhstan in 1972. The reactor had 350 MWt of thermal output and 150 MWe of electrical output. The plant was operating until 1999.

Beloyarsk-3 was the site of the **BN-600** breeder reactor. It was connected to the grid in 1980 and is still in operation. The reactor is a pool type and cooled by liquid sodium. It has 560 MWe of electrical output. Until today the operating history of BN-600 has been excellent. Its load factor has been more than 70% for twenty years in row. The specific construction costs of BN-600 were estimated to be 50% more than the costs of a VVER-1000 reactor.

Also plans for a larger fast reactor **BN-800**, **Beloyark-4**, have been made and the construction of unit started in 2006. The specific costs have been estimated to be 40% higher than in a VVER-1000 plant.

BN-600 Reactor Design

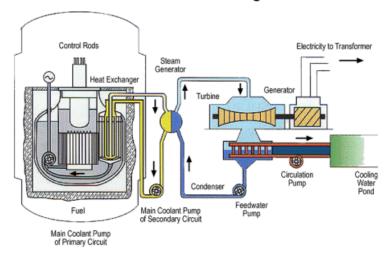


Figure 2.3.1 BN-600 is a pool type fast reactor

There are also plans to build lead-bismuth cooled 300 MW **Brest** reactors in Russia. The Brest reactor has natural circulation in the primary circuit and it has been used in submarine reactors in Russia for 40 years. The reactor does not need new enriched uranium, but only reprocessed plutonium-239, uranium-235 and depleted uranium-238.

The Brest reactor could breed in the blanket the depleted uranium-238, which is the waste from the enrichment plants. If enriched uranium-235 reactors can support a 1000 GW program for 100 years, the breeders cold support a 10 000 GW program for 1000 years. They can also burn the long living isotopes of plutonium and reduce the amount of waste.

2.3 Graphite reactors

2.3.1 The Soviet Union

The first Soviet nuclear plant to generate power was **Obninsk.** It was connected to the grid in June 1954. It was a prototype for the **RBMK-reactors**, which are cooled by water and moderated by graphite. The output of the reactor was 30 MWt and the power plant could generate 5 MWe of electricity.

The reactor vessel was assembled by using graphite modules, which had a cylinder shape, 1.5 m diameter and 1.7 m height. The 128 vertical rods can be assembled into vertical holes in the graphite fuel elements. The elements include two tubes where the cooling water is pumped in through the inner tube and out through the outer tube. The uranium was assembled between the two tubes. The primary cooling water was then led to a steam generator which generated 12 bar steam for a 5 MW steam turbine.

The reactor used enriched uranium-235 and it could be used to produce plutonium, because fuel could be loaded continuously. Thus the uranium-238 atoms could be converted to plutonium-239 atoms in the neutron flux of the reactor. The fuel was unloaded before the plutonium-239 atoms were converted into plutonium-240 atoms.

The reactor could be used for making plutonium bombs and thus the design of the reactor was not optimized regarding safety aspects. The reactor could become promptly critical by accident. The same type of reactor had the worst nuclear accident to date in 1986 in Chernobyl, which then stopped nuclear power projects all over the world.

2.3.2 Magnox in the UK

The **Calder Hall** reactor was a prototype of the **Magnox-reactors**, which were constructed in the UK. The name of the reactor comes from the cladding material of the fuel, which has been made by using **mag**nesium **n**on-**ox**idizing material. The power plant was connected to the grid on 27th of August, 1956.

The reactor was cooled by carbon dioxide gas, which was then used to generate steam in a steam generator. The steam was used in steam turbine to rotate a 50 MWe generator. The gas cooling system was designed so that during accidents the cooling could be done by using natural cooling by air. This was thought to be safer, as a steam explosion was impossible. In Chernobyl, the steam explosion was caused by the combination of burning graphite and water.

The moderator of the Calder Hall reactor was graphite, as in the Chernobyl. The graphite was packed in a steel reactor vessel. In later designs the reactor vessel has been made by using reinforced concrete. The Magnox-material was found to deteriorate, if the spent fuel was stored in water. Thus all the fuel had to be reprocessed, which increased the costs and lead to AGR-reactors, where the cladding was made from steel.

In the first years the Magnox-reactors were also used for the production of weapons grade plutonium-239. This same design has also been used in North Korean reactors for weapons grade plutonium production.

2.3.3 The AGR in the UK

The second generation UK reactors were called the **Advanced Gas Cooled Reactors (AGR)**. They used graphite as the moderator and carbon dioxide as the coolant. The AGR reactors use stainless steel fuel cladding, which allows for a higher exit temperature (648 °C) of the coolant and thus enables higher efficiency (41 %) of the power plant.

The first AGR plant was the **Dungeness B**, which was connected to the grid in 1983 and is still in operation. The plant has two 1500 MWt reactors in the same reactor building and two 550 MW steam turbines. A total of seven AGR plants were constructed by 1989.

The following UK plant was the **Sizewell B**, which used pressurized water reactor technology. One of the reasons for abandoning the AGR's were the higher investment costs of the gas cooled reactors and low energy availability factors of the plants. The lifetime energy availability of UK nuclear plants has been 71% while the world average availability factor has been 77%.

2.3.4 UNGG in France

The first French reactors followed UK gas cooled reactor development. The reactor type UNGG (Uranium Naturel Graphite Gaz) that was developed in France was also a graphite moderated and carbon dioxide cooled reactor. The cladding material in the fuel rods was magnesium-zirconium, instead of the magnesium-aluminium that was used in the Magnox-reactors.

The first reactors **G1, G2 and G3** were built in **Marcoule** in 1956, 1959 and 1960 respectively. The first reactor (G1) had a 2 MWe electrical output and it was in operation until 1968. The next two reactors (G2 and G3) had a 38 MWe output and they were in operation more than 20 years until they were decommissioned.

The development continued with reactors **A1**, **A2** and **A3**; with output of 70 MWe, 180 MWe and 360 MWe. Finally 500 MWe reactors were built in **Saint Laurent** and **Bugey** sites in France and in **Vandellos** in Spain. After them the construction of gas cooled reactors was stopped and the new reactors were pressurized water reactors.

2.3.5 The HTGR in the US

The first gas cooled reactor in the US was designed in Oak Ridge. The idea of the high temperature reactor was to use graphite as the moderator and helium as the coolant. The first HTGR reactor was built in **Peach Bottom**, Pennsylvania in 1967. The output of the plant was 40 MWe and it was shut down in 1974.

The second HTGR plant to be built in the US was **Fort Saint Vrain** in Colorado. The output of the plants was 330 MWe and it was connected to the grid in 1976 and shut down in 1979.

The plant used a pre-stressed concrete pressure vessel. The main problems occurred with the helium circulators and availability factor of the plant was very low.

2.3.6 The Pebble Bed Reactor in Germany

The German HTGR reactor design was started by building a 15 MWe demonstration **AVR** (**Arbeitsgemeinschaft Versuchreaktor**) plant in 1967. The fuel was collected graphite spheres 6 cm in diameter, which were then cooled by helium. This **pebble bed** concept still offers very promising modular design. The first AVR plant was permanently shut down in 1988.

The next design of the pebble bed concept was the **THTR** (**Thorium Hoch Temperatur Reaktor**) **300**, which was built in 1971 and permanently shut down in 1988. The electrical output was 300 MWe and it used a steam turbine cycle. It used uranium-235 and thorium-232 fuel, which was packed into graphite spheres, 6 cm diameter.

China has licensed the AVR technology from Germany and built the first 10 MWt reactor in 2000. The next graphite moderated plant will be a 200 MWe plant in **Shidaowan**. The plant includes two 200 MWt modular reactors and one 200 MWe steam turbine. The construction of the plant is expected to start in 2011 and the plants will be ready by 2015. China is planning to build 18 units with a 200 MWe unit size each.

The high temperature gas cooled reactors are considered to be one of the major IV generation technologies that are under development. The 400 MWt helium cooled pebble bed reactor is under licensing process in the US. The technology seems to be inherently safe and possible to be sited near populated areas. It can also be used for high temperature steam generation and hydrogen production. South Africa has also announced to use the same technology, but the construction has not started.

2.4 Pressurized water reactors

The **pressurized water reactor** (**PWR**) was originally developed to power nuclear submarines. This project was started by **Admiral Hyman Rickover** (1900-1986) in 1949. The first PWR submarine, **Nautilus**, was then launched in January, 1954. Its reactor was using uranium fuel with zirconium cladding. The submarine engines were produced by **Westinghouse** and **General Electric**. During the project the companies acquired the necessary knowledge to build the nuclear power plants. In 1958 Nautilus made its first trip under the polar ice cap.

The reactor's primary circuit was surrounded by a containment building, which could hold all the leakages in the building. No radioactive materials would be released into the environment. The containment building is a large pressure vessel, which can be made with steel, pre-stressed concrete or with reinforced concrete with a steel liner.

2.4.1 Westinghouse

The first modern type power reactor was built by **Westinghouse in Shippingport**, Pennsylvania, USA. The reactor was a prototype of the pressurized water reactor, which later became one of the most built reactors in the world. The plant had a pressurized primary circuit that was cooled the reactor and was radioactive. The non-radioactive secondary circuit then produced steam for the steam turbine, which in turn rotated the generator.

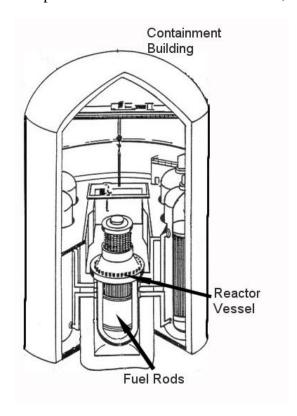


Figure 2.4.1 A typical layout of the containment building of a PWR plant (NRC)

The electrical output of the Shippingport plant was 60 MWe. The reactor plant was installed inside a reinforced steel containment, which has been a standard in the most pressurized water reactors since then (Figure 2.4.1). The possible reactor cooling accidents were taken into account for the first time. The reactor became critical on December 2nd, 1957, just 15 years after Enrico Fermi's first reactor became critical in Chicago.

After this Westinghouse became the number one supplier of pressurized water reactors in the world markets. The reactors were using two, three or four vertical steam generators in each reactor depending on the output.

The reactor pressure vessel (RPV) is made of steel and it contains fuel elements. The vessel head can be opened for refueling. The control rods are above the pressure vessel and they can be moved up and down by using the reactor power control system. The control rods will be automatically dropped into the reactor, if the reactor safety system detects that two out of three signals have exceeded the safety limits.

The pressure is maintained by a pressurizer, which is a large pressure vessel in which the pressure can be increased by heating the electric resistors and decreased by purging steam to a water release vessel. The pressure should be always so high that the water in the primary circuit does not start boiling.

If a water leakage occurs in the primary circuit, the additional make-up water is injected into the system first by pressure accumulators, then by high pressure safety injection water pumps and finally by low pressure safety injection pumps, which all have diesel engine back-up.

The latest Westinghouse reactor, **AP1000**, has passive emergency cooling systems, which can provide make up water to the reactor primary circuit without emergency pumps. Thus emergency diesels are not needed for water injection and several components have been eliminated. The reactor output is 3400 MWt. The electrical output depends on the cooling water temperature, ranging between 1150 - 1200 MWe.

Two AP1000 reactors are under construction in China. Additionally several AP1000 plants are in planning stage in the US. AP1000 plant is also one of the alternatives for the new reactors to be built in the UK. However, AP1000 has not been selected as a candidate by the Finnish utilities, which are planning to build two new reactors before 2020.

2.4.2 Combustion Engineering

Combustion Engineering (CE) was another supplier of reactors in the US. The company supplied the first Nuclear Steam Supply System (NSSS) for the **Palisades** nuclear plant in 1971. The plant has two steam generators, four cold legs, four circulating pumps and two hot legs.

The largest nuclear plant in the US is the **Palo Verde**, which has three units with a total capacity of 3800 MWe. All three NSSS plants have been supplied by CE and they use the two steam generator concepts. In addition CE has also supplied NSSS for some Korean nuclear plants.

The Swedish-Swiss engineering company **Asea-Brown Boweri** (**ABB**) acquired Combustion Engineering in 1990. After this acquisition CE was bankrupted because of asbestos liabilities. Thus no new CE type PWR plants have been built by ABB, but **the Korean Electric Power Company** (**Kepco**) has developed their plants using CE technology.

2.4.3 Babcock Wilcox

Babcock Wilcox was one of the old boiler manufacturing companies established in 1867. It was also involved in the Manhattan project and supplied equipment for the first US nuclear submarine, **Nautilus**. B&W supplied the Nuclear Steam Supply System for the first nuclear ship **Savannah** in 1961.

The first NSSS for a nuclear power plant was supplied by B&W for a 275 MWe **Indian Point** nuclear plant in New York about 60 km north from New York City. The plant was connected to grid in September 1962 and it used thorium in its first core.

The thorium did not meet expectations and it was changed to uranium oxide fuel. After some safety problems the operation license was not renewed in 1974 and the reactor was shut down permanently.

B&W has supplied several other NSSS for US plants. One of them was the famous **Three Mile Island (TMI)** plant in Harrisburg. The first reactor **TMI-1** had a 786 MWe output and it was connected to the grid in 1974.

The second unit **TMI-2** had a 880 MWe output and it was connected to the grid in 1978. The plant had similar features as the Westinghouse and Combustion Engineering plants. The main difference was the once through steam generator and that the primary system had smaller water volume than the others. Thus the TMI-plant was more vulnerable to transients and left the operators less reaction time.

On March 28th, 1979 the TMI-2 reactor experienced the worst accident ever to happen to any pressurized reactor in history. The pilot operated relief valve (PORV) of the pressurizer had stuck open. The operators were not able to note the failure because no warning signal from this was given. The primary circuit was leaking water into the purge tank and the reactor core was left without cooling water. This caused the partial meltdown of the reactor core.

The radioactive release was about 43 000 Curies (1.59 PBq), mainly Krypton. Also a small amount of iodine was released and the people in the area were evacuated. At the time it was said that that the maximum dose of radiation for anyone within the power plant boundary would be the same as if the person had been in a normal X-ray inspection.

However, this accident practically stopped the construction of new nuclear plants in the US. The public opinion also turned against nuclear plants. By this time the movie "*China Syndrome*" (Jane Fonda, Jack Lemmon and Michael Douglas) was spreading the story of TMI-2. It was a big surprise to us all that the movie had predicted the TMI-2 accident so well before it actually happened.

Today B&W is trying to make a comeback with its modular reactor design. The new reactor plant will be built by using 125 MWe reactor modules, which have been designed for railway transportation. The reactor has a five year refueling cycle and passive safety systems. It will remain to be seen what is the future of this new design.

2.4.4 VVER (Rosatom, Atomstroiexport)

The first PWR reactor in the Soviet Union was the **Novovoronesh-1 VVER-200** reactor. The name VVER comes from the Russian "Voda Vodyanoi Energetichesky Reaktor", which means that the reactor is moderated and cooled by water. The next VVER units in Novovoronesh were **VVER-380**, **VVER-440** and **VVER-1000**, which is the latest model.

The difference between the Soviet VVER and the Westinghouse units is the horizontal steam generators of VVER reactors. The VVER-440 has six horizontal steam generators and the

VVER-1000 has four. Another feature is the VVER reactor pressure vessel, which has smaller diameter to allow railway transportation.

The VVER-440 was the first Soviet nuclear plant to be exported. Finland was the first country to buy the two VVER-440 reactors for the Loviisa plant. The plant was provided with western type safety systems. They include containment building, emergency cooling systems and diesel generators, which could eliminate the radioactive releases during a postulated loss of coolant accident. Additionally, the instrumentation and computer system was built using very modern technology.

The latest **VVER-91** design of the VVER-1000 plant also includes a core catcher, which can cool the molten reactor core during core meltdown accidents. The first core catcher was built in the VVER-91 reactor **Tianwan-1**, which was connected into the grid in 2006 in China.

The architect engineering of the Tianwan reactors was done by the Finnish Utility Company **Imatran Voima Oy (IVO)**, which was planning to build **Loviisa-3** plant using this VVER-91 design. By this time I was also in the Loviisa-3 project and responsible for conceptual studies. Unfortunately the Chernobyl reactor accident happened in 1986 and the construction of Loviisa-3 plant was suspended.

The next VVER power plants will be built in Russia. They will be using the new **VVER-1200** (**AES-2006**) design and the first four units will be the **Novovoronesh 2-1** and **2-2** and **Leningrad 2-1 and 2-2**. The Leningrad plant will be very similar to the VVER-91 design, but it will include passive systems for containment cooling. The VVER-1200 design has a 1150 MW net output, four steam generators and one 3000 r/min steam turbine.

VVER plants will also be built in India and Bulgaria. The capacity of the **Ishora** factory in St Petersburg is four VVER-1200 reactor pressure vessels annually. Two on these are available for export markets. Additionally the **JSC Machine Building** plant near Moscow might start building pressure vessels and the total capacity could increase to 8–10 vessels annually.

2.4.5 European PWR reactors

France and Germany have built several PWR plants which were originally built under license from Westinghouse. Most of the plants were four loop plants with four vertical steam generators. The difference of German plants to others was the sphere shape steel containment vessel as the Westinghouse and French plants had cylinder type layout.

The German PWR plants had four loops and four diesel engines. They used Siemens (or KWU) steam turbines. The first French plants were built under Westinghouse license. They had also four loops but only two diesel engines. They used Alsthom steam turbines.

The latest type PWR is **European Pressurized Reactor** (**EPR**) plant, which prototype is now under construction in Finland at Olkiluoto site. The **Olkiluoto-3** plant will be the largest nuclear unit in the world in 2013 with 1700 MW electrical output using just one steam turbine. It has a French reactor and the Siemens steam turbine.

The Olkiluoto-3 plant also includes a core catcher, as the Tianwan reactors in China. The core catcher was required to be built in Finnish power plants to prevent radioactive releases during possible core meltdown accidents. Now, also the next EPR in **Flamanville** in France will have a core catcher.

The design of the EPR plant also includes a double containment, where the outer concrete containment is planned to protect the plant against a possible crash by a jumbo airplane. These features have increased the investment costs of both the EPR plants. The actual investment costs will be about €3500/kWe without interests during construction and construction time will be about eight years.

The supplier of the EPR reactors, AREVA, is now planning to make smaller reactor **Atmea** with more conventional safety features to save costs. This program has been accelerated after Areva lost the United Arab Emirates (UAE) contracts to the Koreans.

2.4.6 The Korean PWR reactors

The building of nuclear power plants in Korea was started by using Westinghouse PWR technology in the first nine power plants. Later the Korean's own design was started based on the Combustion Engineering plant in Palo Verde, USA.

The first plants were called **OPR1000**, and they had two large vertical steam generators. The plant concept includes two reactor units, which will generate energy in about 52 months from first concrete. All together six of these power plants with two units have been built by now.

The latest design has been named **APR1400**, and it has been designed based on the OPR1000. The output has been increased to 1400 MWe, but the reactor plant has only two vertical steam generators. There are four cold legs and two hot legs in the primary circuit. The cold legs have four cooling water pumps. The reactor pressure vessel is located inside a concrete vessel, which has been filled with water to cool the core during a possible core meltdown accident.

The standard design includes two units at one site, with 2800 MWe total output. There are two plants in construction with four units all together. Additionally, the **Korean Nuclear Electric Power Corporation (Kepco)** received an order of a four unit **APR**+ plant in the United Arab Emirates. The APR+ is an updated version of the APR1400, with a higher output.

Thus the APR1400 is now one of the most successful concepts available. There are four APR1400 units under construction and four units APR+ units in the planning stage. Within six years the total capacity of APR-reactors will be more than 12 000 MW.

2.4.7 The Chinese PWR

China has built a 300 MWe PWR plant based on Chinese design in **Qinshan-1** in 1991. The next four units in **Qinshan-2** had 610 MWe net output each. Three Qinshan units were connected to network in 2002, 2004 and 2010 and one unit is still under construction.

The first two 900 MW PWR plants in China were constructed using French PWR technology in **Daya Bay** Guandong in 1993 and 1994. This technology was adapted for the first time with type name **CNP-1000** in **Lingao-3 and -4** plants, which were connected to grid in 2010 and 2011, respectively.

There are now twenty CNP-1000 units under construction. The CNP-1000 design is "an *improved Framatom*" plant, and it has three steam generators. The first pressure vessel for the Lingao-3 plant was manufactured in China in 2009. The design is similar to the French II generation design, without the provisions for core meltdown.

2.5 Boiling water reactors

The other light water reactor technology that became a success story is the boiling water reactor (BWR). The main difference to the pressurized water reactor is that in BWR plants there are no steam generators. Thus the water is converted into steam in the reactor itself.

2.5.1 General Electric BWR

BWR technology was invented by **Samuel Untermyer**, who is the owner of the U.S. Patent for steam generation in the reactor. He worked at the **Argonne National Laboratory** and built the first experimental boiling water reactor, **BOREX** (boiling water reactor experiment).

General Electric (GE) hired Untermyer in 1954 and the company developed the BWR plants. The first BWR plant actually built was the 24 MWe **Vallecitos** plant in San Jose, California in 1957. After this project GE started to offer this technology to the market in a large scale. The first commercial plant was **Dresden**, which had a 197 MWe electrical output. It was connected to the grid in 1960.

After that several BWR plants were built in the US and in other countries. The destroyed Fukushima Dai-ichi reactors in Japan were built by GE or under GE licenses. The old designs had a toroid type (Mark-I) pressure suppression pool type containment (wet well), into which the steam from the reactor pressure vessel would be released and condensed. This design was also used in the units 1-5 in Fukushima Dai-ichi nuclear plants.

The development of the BWR plants went to large output and more simplified design. The primary circuits were simplified, the external circulating pumps were replaced with internal circulating pumps and the new BWR type was then called as the Advanced BWR (ABWR). The new design (Mark III) had a dome type reinforced steel containment, which was similar to the PWR plants, but it was smaller because of the pressure suppression pool.

2.5.2 ABWR (GE Toshiba)

Several BWR plants were also built in Japan by using GE design. The **Kashiwazaki-Kariwa** plant in Japan is the largest nuclear plant in the world with a 8100 MWe output. It has seven BWR units in operation. The first five units had a conventional design with 1100 MWe

output. They were built between 1985 and 1993. Units 6 and 7 are of Advanced BWR-type with a 1315 MWe output. They were connected to network in 1996.

The Kashiwazaki-Kariwa plant was also designed to withstand a smaller earthquake. In 2007 a severe earthquake actually happened near the plant, and it stopped the plant for inspections. The other plants that were planned for Japan were postponed. One of the reasons was the new design, ESBWR, which was coming on the market place.

The first ABWR plants in the US will be the two **South-Texas** units near Houston. They will have a 1400 MWe output each. However, the construction of the plant has not started yet.

The Toshiba ABWR plant is of the options of plants that will be built in Finland by 2020. The output will be 1600 MWe in Finnish cooling water conditions.

2.5.3 ESBWR (GE Hitachi)

The Economic Simplified Boiling Water Reactor (ESBWR) was the next design that General Electric and Hitachi introduced to the market. The design includes passive emergency cooling systems. The design was docketed by USNRC in 2005 and the combined construction and operation license (COL) was applied in 2007.

The new concept has been designed to keep the core cooled by natural circulation for 72 hours without using outside electricity. Thus the emergency cooling water tanks have been placed above the reactors outside of containment building.

The ESBWR exists today only on paper and no reactors are under construction. Thus it is uncertain if such a reactor could get a construction license and what would the construction costs be. However, it has been taken to be one of the options of the new plants to be built in Finland.

2.5.4 BWR (Asea Atom)

Asea-Atom Ab from Sweden was also one of the designers of boiling water reactors. Asea-Atom has built eight plants in Sweden and two in Finland. It has had advanced design features and the first internal recirculation pumps of any BWR plant were built in **Olkiluoto-1 and -2** plants in Finland by Asea-Atom in 1980 an 1981.

The plant was quite advanced at that time, but it could not tolerate an electrical blackout for more than one hour, before the core cooling started to have problems. This is one of the reasons why in Fukushima Dai-ichi the core was without water very soon after the tsunami hit the plants.

Unfortunately Asea-Atom stopped its activities as Sweden denied further nuclear construction in Sweden by referendum in 1982. Asea-Atom was joined with Brown Boveri and became as ABB. Later ABB reactor operations were sold to British Nuclear Fuels and they became a part of Westinghouse. Westinghouse was taken over by Japanese Toshiba and has the AP1000 pressurized water reactor as their flag ship.

2.5.5 BWR (Areva)

Boiling water reactors were also designed and constructed in Germany by AEG under GE license. The first plant, **Kahl**, was constructed in 1961. The plant had a 16 MWe output and it was in operation until 1985. Several plants were constructed with the technology being originally licensed from GE. However, the new passive concept was developed by AEG, which was later taken over by Kraftwerk Union (KWU). The concept was not built at that time, because it was much more expensive than the II-generation reactors.

While the nuclear activities of KWU were transferred to Areva, the passive BWR plant is still available for utilities. It is one of the candidate plants to be built in Finland. The plant will be sold using a name "*Kerena*" and its output will be about 1250 MWe. The plant is planned to withstand plane crash and core meltdown. In addition, the plant has good load following capabilities with 5%/min ramp rate from 40 % to 100 % output.

2.6 Heavy water reactor

2.6.1 Candu

The pressurized heavy water reactor (Candu) in Canada was one of the early reactors, which was aimed for electricity generation. The first prototype Candu-reactor was the Nuclear Power Demonstration (NPD) reactor that was connected into grid in June 1962. It had a 22 MWe electrical power output and the reactor was moderated and cooled by pressurized heavy water. It was operated with natural uranium and no fuel enrichment facilities were needed.

After NPD a larger 200 MWe reactor was constructed at **Douglas Point**. It started operation in 1968. After it also India has built several PHWR power plants using this Canadian design.

The benefit of the Candu reactors was the possibility to use low enriched uranium and even the spent fuel of light water reactors could be used as fuel. The reactor could be reloaded online, which could help to achieve better availability. Typical light water reactors have a refueling outage that lasts from two to eight weeks, depending on the inspections.

However, the higher investment costs compensate this benefit. The online loading also gives the operator the possibility to produce plutonium-239 for atomic weapons. Thus the reactor technology could only be given for the countries that can be counted on.

Several Candu plants have been built in Canada. Also many plants in India are designed based on Candu concept. In addition, four units in South Korea, two in China and one unit in Pakistan and Romania have been built. There are four Candu reactors under construction, of which three will be in India and one in Argentina.

2.6.2 ACR-1000

The Advanced Candu Reactor (ACR-1000) is the new design of Candu reactors designed by the Atomic Energy of Canada Limited (AECL). The electrical output of the ACR-1000 plant will be about 1200 MWe, depending on site conditions. It will improve safety through passive safety features. The reactor vault will be filled with light water to prevent the core meltdown. There are four vertical steam generators that produce steam for the secondary circuit using light water.

2.7 Thorium breeder reactors

Thorium was discovered in 1828 by the Swedish chemist **Jöns Jacob Berzelius** (1779-1848). He named the mineral after the ancient Nordic Thor, God of Thunder.

Thorium-232 (Th-232) is not a fissionable material, but in a neutron radiation it can be converted into uranium-233, which is fissionable. In neutron radiation thorium-232 becomes thorium-233. Then after beta decay thorium-233 becomes protactinium (Pa-233), which again in beta decay becomes uranium (U-233).

$$n + {}^{232}Th \longrightarrow {}^{233}Th \stackrel{\beta}{\longrightarrow} {}^{233}Pa \stackrel{\beta}{\longrightarrow} {}^{233}U$$

2.7.1 Molten salt reactor

The first thorium reactor was the **Molten Salt Reactor Experiment (MSRE)** in Oak Ridge in the 1960's. The MSRE plant had a 7.4 MWth test reactor that used molten salt uranium and plutonium fuels. The reactor used ²³³UF₄ fluid fuel at temperature of 650 °C. At this temperature the heat could be also used in a gas turbine cycle.

2.7.2 VHTR

The MSRE plant had several benefits including abundant fuel (thorium), negative temperature coefficient (safety), fast response times and the small amount of long lifetime nuclear waste. It was not developed further at the time and the present development is concentrated on the **Very High Temperature Reactor (VHTR)**, which is part of the Generation IV program.

Thorium High Temperature Reactor (**THTR-300**) was built in **Hamn-Uentrop** in years 1970-83 by German Hochtemperatur Kernkraftwerk Gmbh. The reactor fuel was made of thorium-232 and uranium-235, which was packed in 670 000 spheres with 6 cm diameter.

The THTR reactor was decommissioned in 1988 because of the failures in the hot gas ducts. During the same time also Chernobyl accident caused opposition of nuclear power in Germany and the next phase of larger **THTR-500** plant was never built. One of the drawbacks THTR plants was the graphite moderator, which can get fire as happened in Chernobyl. Today, Pebble Bed reactors are one of the alternatives in Generation IV program.

2.7.3 Candu

Canadian type Candu Reactors have also been designed for thorium utilization. China has signed a co-operation agreement with AECL to develop thorium utilization in **Qinsan Candu** 6 reactors in China. Candu reactors are suitable for studies while the online reloading. Thus some fuel bundles can use thorium.

2.7.4 AHWR-300

India has an extensive experience from Candu reactors. Now India has developed also own **Advances Heavy Water Reactor (AHWR-300),** which will use thorium fuel cycle. According to the data given by Atomic Energy Commission of India the reactor will have pressure tubes, in which light water is boiling. Uranium enrichment level will be 19.75 % and which gives in average of 4.2 % enrichment in the thorium uranium bundles.

2.7.5 Thorium fired light water reactors

Thorium can also be used in a thermal reactor blanket as thorium dioxide that has a melting point of 3200 °C. It was used for the first time in the Shippingport reactor core blanket as fertile material in 1977.

India has also started cooperation with Russians to develop thorium fuel cycles for Indian VVER-1000 reactors in **Kudankulam.** The thorium cycle could be open cycle, which generates less waste than ordinary uranium fuel cycle used in VVER reactors.

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3. NUCLEAR PROGRAMS

3.1 Big plans in the United States

During the 1970s everyone thought that nuclear power would be a major source of the future energy. The US Atomic Energy Commission (AEC) forecasted that the US would need nuclear capacity of 2300 GWe by the year 2009 (Figure 3.1.1). Thus in average about 77 GWe of new capacity should be built annually.

During the best years of 1984 and 85 more than 30 GWe of new nuclear capacity was commissioned globally annually (Figure 3.1.2). A total of more than 400 GWe of nuclear capacity has been built. The US nuclear capacity is now only 100 GWe.

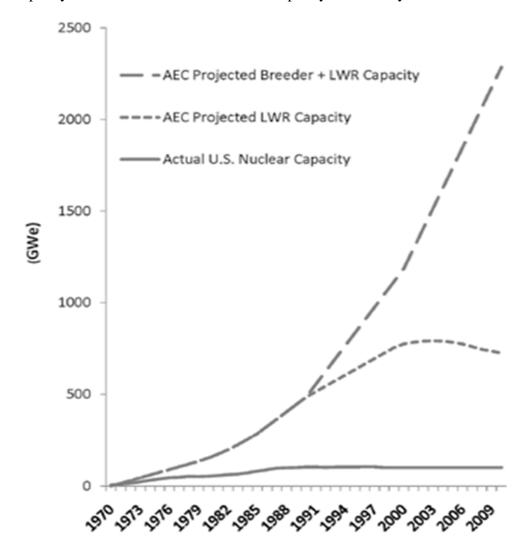


Figure 3.1.1 In 1973 the US nuclear capacity was estimated to be 2300 GWe in 2010, but it was actually only 100 GWe

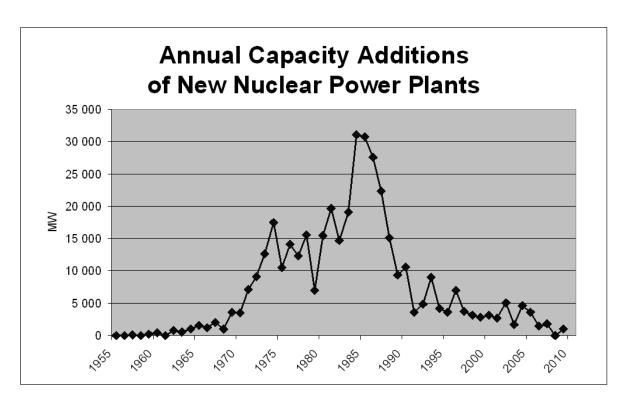


Figure 3.1.2 The nuclear capacity additions was the highest (30 000 MW) in 1984 and 1985

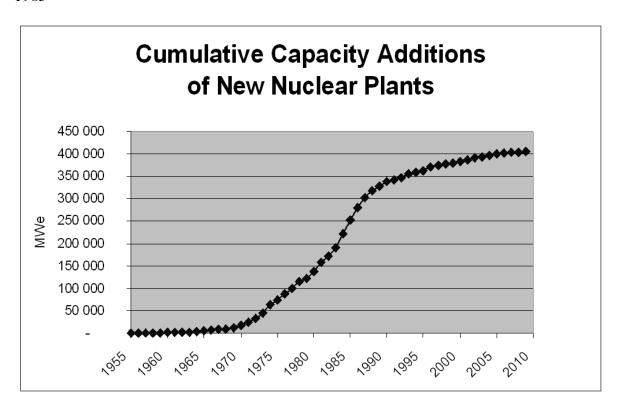


Figure 3.1.3 More than 400 000 MW of nuclear power capacity has been built, but the capacity of the operating plants is actually only 368 000 MW (May 2011)

The Tree Mile Island accident in 1979 stopped the US nuclear program completely. Several nuclear reactors were cancelled and no new reactors were ordered by the US since then. The public appetence was lost also in Sweden, which had a referendum in 1980 to stop building nuclear plants after 12 units will be in operation. These 12 units with eight million people corresponds 1.5 reactors per each million people. This was more than in any other country.

Totally 411 GWe of nuclear capacity has been constructed, but the operating capacity is only 368 GWe in 2011 (Figure 3.1.3) because 43 GWe of the old capacity has been shut down.

3.2 Finnish nuclear program

Nuclear power appeared in the text book of the Helsinki University of Technology (now called the Aalto University according to the famous Finnish architect Alvar Aalto) very soon after the atomic bombs in Japan. In "*Physics for Universities*", by Professor **Lennart Simons**, the theory behind the atomic bomb was explained in the Finnish language already in 1946.

The first pioneers in nuclear plant promotion were the Nobel Prize laureate **Artturi Virtanen** and academician **Erkki Laurila**, who was the first professor of nuclear physics in Helsinki University of Technology. They established an Energy committee to make plans for electricity generation and nuclear power during the 50's.

Very soon after the Geneva conference many countries started to look after nuclear technology. Finland established its **Radiation Protection Agency** in 1958. The first experimental **Triga-reactor** was then built in 1962. Until today, about 62 Triga-reactors have been built by General Atomics for experimental purposes.

The design of the Triga-reactor is based on uranium zirconium hydride fuel, which is installed in a pool type water pressure vessel. The reactor has a negative temperature coefficient, which means that the output decreases if the temperature increases. Thus it is safe to install the reactor at the Otaniemi campus area of the Helsinki University of Technology.

Nuclear energy started fascinating me personally after reading the **Robert Junkg's** "*Brighter than a thousand suns*", which was translated from German language to Finnish in 1957. The book explained the history of atomic science behind the atomic bombs. For me this was probably the most important experience behind deciding to enter into power engineering.

Then in 1965 professor **Eino Tunkelo** taught Albert Einstein's theory of relativity of at the Helsinki University of Technology. After this course I was approved to study electrical engineering at the University, which had been my dream since childhood. Thus my first step to becoming a nuclear engineer had been taken.

The training jobs for me were mostly at the **Neste Oil** refinery, which was built between 1965-69 under license from the engineering company **Lummus.** It was a fascinating project as Finland wanted to become independent of the big oil companies ("sisters") that dictated oil prices at the time.

At the same time Finland wanted to build nuclear power plants, as the most of the hydro resources were taken for electricity generation. The first steps were taken by the state utility company **Imatran Voima Oy (IVO)**, which hired young professionals to study nuclear engineering. Among those engineers was MSci. (Eng.) **Kalevi Numminen** who became the project manager of the **Atomic Power Project**. The project was established to build the first Finnish nuclear plant at Loviisa site.

The Loviisa Atomic Power Project was begun by signing the preliminary contract between IVO and the Russian **Teknopromexport** (**TPE**) in 1969. This covered the delivery and installation of a VVER-440 nuclear plant reactor and turbine process systems.

The containment was ordered from **Wärtsilä** under **Westinghouse** license. Wärtsilä was known for building cruise ships and icebreakers at the Helsinki and Turku shipyards and later for being the market leader in medium speed diesel engines for the ships and power plants.

The process computers and the plant simulator were ordered from **Oy Nokia Ab**, which by the time had established a department of special electronics. The computer system designed was the most advanced of its time with eight cathode ray tube displays. The displays show the process mimic diagrams and measured and calculated values for the plant operators. Nokia became well known for being the market leader in mobile phones twenty years later.

The civil works were done by Finnish construction companies and the architect engineering by IVO. Additionally, **Siemens** delivered instrumentation and **Valmet** (today's **Metso**) that loading machine. Several hundred of other manufacturers were also involved.

I joined the Atomic Power Project Group in July of 1970 in order to design a steam turbine simulator program for the Loviisa nuclear plant by using a hybrid computer at the **State Research Center (VTT)** in Espoo. Then in July 1971 the simulator program and the thesis were ready and I moved to the Ruoholahti office, where the engineering of the Loviisa plant was actually done. Among other things my responsibility was to design the conventional software algorithms for the process computer.

My boss was Licentiate (Tech.) **Heikki Väyrynen**, who had been working with the Trigareactor for some time and was responsible for nuclear engineering and the process computers. Another important person to me was Licentiate (Tech.) **Bjarne Regnell**, who was said to be the first Finnish nuclear power engineer and was responsible for safety evaluations. He had been studying nuclear engineering in the US.



Figure 3.2.1 Starting up the Loviisa-1 nuclear plant President **Urho Kekkonen** and Prime Minister **Aleksei Kosygin** in 1977. One of the seven CRT-screens of the process computer system can be seen in the left front corner

In the summer of 1971 the most important task was the preliminary safety report (PSAR), which had to be done and approved before the concrete works could be started. The first versions of the PSAR were mostly copied from the **Donald C. Cook's** PSAR that had the same type of Westinghouse ice-condenser containment as the Loviisa plant.

The PSAR of the Loviisa plant was actually done by using white paper on which the English text from the reference report was glued on and then a pencil was used to add some relevant notes. My chapters in the report included the engineering safety features including all the emergency safety systems. These chapters described how the plant would behave during disturbances.

At the age of 25 I was one of the youngest engineers in the atomic project group. However, at the time the computers were best known by young people much like today. The computers had arrived to the Helsinki University of Technology in the 60's during my student years and they included one **IBM-1710** machine and two **Donner analog computers** in the electrical engineering department.

Electronic Associates Inc. (EAI) hybrid computer was acquired at the Technical Research Centre (VTT) in 1970. The hybrid computer included a digital computer and an analog

computer that was much faster than any digital computer in the simulation of nuclear plants. My senior colleagues had hardly seen the computers during their student years.

The engineers from the Russian side were generally older men, who had been working in building the first Soviet reactors after the war and they knew computers even less than the old Finnish engineers. Computers were used mostly in the business administration, but not in the process simulation or control.

The cold war full on at the time. US computers or any computers that had US-made electronics could not be exported to the Soviet Union. IBM was ready to supply the process computers for the Loviisa plant and the US companies have supplied radars for the Finnish Army. Thus Finland was considered to be on the west side of the iron curtain.

General Atomics had supplied the Triga reactor to Finland earlier. Westinghouse was also ready to sell nuclear power plants to Finland and their PWR reactor was preferred by the managers in IVO. However, the politicians decided that the first plant would come from the Soviet Union, which had built the VVER-type reactors in Novovoronesh. The second plant Olkiluoto could be bought from the west to keep the balance in nuclear relations between the east and the west.

At the time Finland had plans to build one 500 MWe nuclear reactor every year, but actually only four reactors were built during 1977-1981. The two VVER-440 units were ordered from the Soviet Union and two BWR units from **Asea-Atom** from Sweden. The nuclear capacity in Finland in 1981 was 2210 MWe or 400 W/capita and the nuclear electricity generation was 3000 kWh/capita. By this time Finland had became one of the leading countries if counted in the nuclear power per capita (Figure 3.8.2).

3.3 The slow-down after Chernobyl

Operating nuclear power capacity in the world is now 368 000 MW (Table 3.3.1). The PWR and BWR plants now have 68% and 21% of nuclear capacity respectively. The heavy water reactors (PHWR) are located mainly in Canada and graphite moderated reactors in Russia and the United Kingdom.

In 2009 the electricity generation by nuclear power was 2690 TWh, or 13.4% of all electricity (20 090 TWh). If this had been generated by using coal power plants the emissions would have been about 2190 million tons of CO₂, even with the best available coal plants. The avoided emissions by using nuclear power are about 7% of the total CO₂-emissions of energy industries. As a matter of fact nuclear power has the highest potential of any energy source to solve the global warming problem.

Hydro power plants generated about 3272 TWh or 16% of the total electricity in 2009. Thus hydro and nuclear power generated about 30% of all electricity. Thus they cannot be omitted when the future is planned.

Table 3.3.1 Operating nuclear power plants according to countries and types (May 2011 PRIS)

N:o	Country	PWR	BWR	PHWR	Graphite	Others	Total
1	United States	67 205	34 035	-	-	-	101 240
2	France	63 130	-	-	-	-	63 130
3	Japan	19 284	24 058	-	-	-	43 342
4	Russian Federation	11 914	-	-	10 219	560	22 693
5	Germany	14 804	5 686	-	-	-	20 490
6	Korea	15 976	-	2 722	-	-	18 698
7	Ukraine	13 107	-	-	-	-	13 107
8	Canada	-	-	12 569	-	-	12 569
9	China	9 758	-	1 300	-	-	11 058
10	United Kingdom	1 188	-	-	8 949	-	10 137
11	Sweden	2 795	6 503	-	-	-	9 298
12	Spain	6 004	1 510	-	-	-	7 514
13	Belgium	5 927	-	-	-	-	5 927
14	India	-	300	4 091	-	-	4 391
15	Czech Republic	3 678	-	-	-	-	3 678
16	Switcherland	1 700	1 563	-	-	-	3 263
17	Finland	976	1 740	-	-	-	2 716
18	Bulgaria	1 906	-	-	-	-	1 906
19	Hungary	1 889	-	-	-	-	1 889
20	Brasil	1 884	-	-	-	-	1 884
21	Slovakia	1 816	-	-	-	-	1 816
22	South-Africa	1 800	-	-	-	-	1 800
23	Mexico	-	1 300	-	-	-	1 300
24	Romania	-	-	1 300	-	-	1 300
25	Argentina	-	-	935	-	-	935
26	Pakistan	600	-	125	-	-	725
27	Slovenia	688	-	-	-	-	688
28	Netherlands	482	-	-	-	-	482
29	Armenia	375	-	-	-	-	375
	Total	248 886	76 695	23 042	19 168	560	368 351
	Distribution	67,6 %	20,8 %	6,3 %	5,2 %	0,2 %	100,0 %

Nuclear power capacity has increased only by 15 GWe during the last ten years. There has been practically no growth in the European Union and the North Americas. Most of the growth has happened in Asian counties: China, India, Japan and the Korean Republic.

However, the nuclear plant construction boom has started again. The capacity will increase by about 60 GWe by 2015 if the new plants under construction will be operational by then. The biggest increase will be in China and the Russian Federation with 27 000 MWe and 9100 MWe additions (Table 3.3.2). Korea and India are adding 5500 MWe and 3500 MWe of new capacity.

Table 3.3.2 Nuclear plants under construction according to countries in MWe (Source: IAEA, PRIS)

N:o	Country	PWR	BWR	PHWR	Graphite	FBR	Total
1	China	27 230	=	-	-	-	27 230
2	Russian Federation	7 434	-	-	915	804	9 153
3	Korea	5 560	-	-	-	-	5 560
4	India	1 834	-	1 260	-	470	3 564
5	Japan	-	2 650	-	-	-	2 650
6	Bulgaria	1 906	-	-	-	-	1 906
7	Ukaraine	1 900	-	-	-	-	1 900
8	Finland	1 600	-	-	-	-	1 600
9	France	1 600	-	-	-	-	1 600
10	Brasil	1 245	-	-	-	-	1 245
11	United States	1 165	=	-	-	-	1 165
12	Iran	915	-	-	-	-	915
13	Slovakia	782	-	-	-	-	782
14	Argentina	-	-	692	-	-	692
	Total	53 171	2 650	1 952	915	1 274	59 962
	Distribution	88,7 %	4,4 %	3,3 %	1,5 %	2,1%	100,0 %

Pressurized water reactors constitute 89% of the new capacity. The share of boiling water reactors is 4% and the share of pressurized heavy water reactors is 3% of the new capacity. Thus pressurized water reactors will be the market leader in the near future.

Table 3.3.3 Market shares of pressurized water reactor plants under construction in MWe

N:o	Country	CNP-1000	VVER-1000	EPR	APR-1400	AP-1000	Others	Total
1	China	20 000		3 400		2 000	1 830	27 230
2	Russian Federation		7 434					7 434
3	Korea				5 560			5 560
4	India		1 834					1 834
5	Bulgaria		1 906					1 906
6	Ukaraine		1 900					1 900
7	Finland			1 600				1 600
8	France			1 600				1 600
9	Brasil						1 245	1 245
10	United States						1 165	1 165
11	Iran						915	915
12	Slovakia						782	782
	Total	20 000	13 074	6 600	5 560	2 000	5 937	53 171
	Distribution	37,6 %	24,6 %	12,4 %	10,5 %	3,8 %	11,2 %	100,0 %
	Export market		5 640	5 000		2 000	2 942	15 582
	Distribution		36,2 %	32,1 %		12,8 %	18,9 %	100,0 %

The Chinese CNP has the largest market share (38%) of the PWR plants that are under construction (Table 3.3.3). The Russian VVER-1000 has a 25% market share, EPR 25% and the Korean APR-1400 a 10% share.

In the exports market VVER-1000 plants are the leaders with a 36% market share of the plants under construction. The French EPR is the second with a 32% share. The Toshiba Westinghouse AP1000 is the third with a 13% share. Additionally, Korean vendors have sold the four APR1400 unit plant to the United Arab Emirates, but the plant is not in construction phase.

3.4 The Chinese program

Electricity consumption in China has been increasing very fast after the year 2000 (Figure 3.4.1). The consumption is now growing by 270 TWh annually. This has been almost 50% of the growth of the world electricity consumption. Thus about 500 GWe of new electrical capacity additions has been needed in China during the last ten years, i.e. 50 GWe annually.

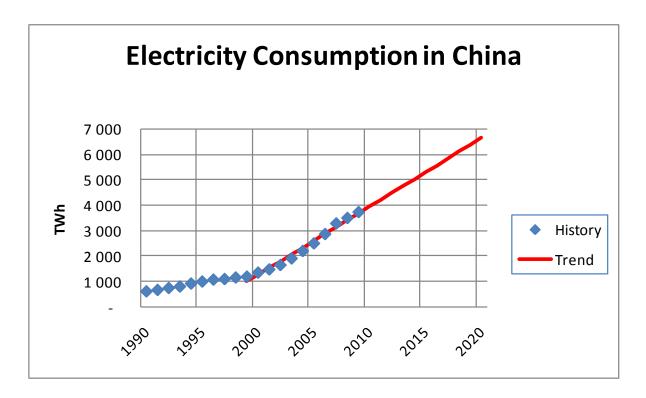


Figure 3.4.1 The growth of electricity consumption in China has been 270 TWh annually

The nuclear capacity in China has been growing by only 1500 MW during the same time. Most of the new capacity additions during the last ten years have been coal fired plants. This has mainly created the increase in global CO₂-emissions.

Although China has boomed quite late in its nuclear development, they now have the most ambitious nuclear program, if counted by the number of reactors under construction. There are now 27 nuclear power units under construction in China with a total capacity of 27.2 GWe (Table 3.4.1). The total capacity of the new CNP-1000 plants is 20 000 MW, the EPR plants 3400 MW, the AP1000 plants 2000 MW and the CNP-600 plants 1830 MW. This totals about 40% of all new nuclear power plants under construction in the world.

Table 3.4.1 New nuclear plants under construction in Megawatts in China (Source IAEA. PRIS)

Name of the plant	CNP-600	CNP-1000	AP-1000	EPR	Total
CHANGJIANG 1	610				610
CHANGJIANG 2	610				610
FANGCHENGGANG 1		1 000			1 000
FANGCHENGGANG 2		1 000			1 000
FANGJIASHAN 1		1 000			1 000
FANGJIASHAN 2		1 000			1 000
FUQING 1		1 000			1 000
FUQING 2		1 000			1 000
FUQING 3		1 000			1 000
HAIYANG 1		1 000			1 000
HAIYANG 2		1 000			1 000
HONGYANHE 1		1 000			1 000
HONGYANHE 2		1 000			1 000
HONGYANHE 3		1 000			1 000
HONGYANHE 4		1 000			1 000
NINGDE 1		1 000			1 000
NINGDE 2		1 000			1 000
NINGDE 3		1 000			1 000
NINGDE 4		1 000			1 000
QINSHAN 2-4	610				610
SANMEN 1			1 000		1 000
SANMEN 2			1 000		1 000
TAISHAN 1				1 700	1 700
TAISHAN 2				1 700	1 700
YANGJIANG 1		1 000	·		1 000
YANGJIANG 2		1 000			1 000
YANGJIANG 3		1 000			1 000
Total 27	1 830	20 000	2 000	3 400	27 230

China has now only 11 GWe of nuclear capacity in operation and the plants generate about 80 TWh of nuclear electricity. In 2015, after the new plants will be in operation, the capacity will be 38 GWe and the nuclear power plants will generate about 300 TWh of electricity. This is, however, less than 10% of the electricity generation in China.

China has been the first country building a core catcher in **Tianwan**-1 and -2. China will be leading the way in the construction of the first passive plant AP1000, which uses Westinghouse PWR technology in **Sanmen**-1 and -2 units. There are also new gas cooled reactors under development and the future will show if these will be built.

Despite the fast development of the nuclear business China is building more coal fired plants than any other country. Thus the new coal plants will increase the CO₂-emissions much more than the EU countries are reducing them. Thus it is of utmost importance that China would change its energy policy from coal to renewable sources and nuclear power as fast as possible.

3.5 The Russian program

After the year 1990 the electricity consumption in Russia has been decreasing. In 1999 it has started to rise again and in the winter of 2009/10 new records peak loads in Russian Federation and also in Russian North West power systems were achieved. The electricity consumption has been growing continuously especially in large cities such as Moscow and Saint Petersburg.

The electricity consumption is growing now at the rate of 18 TWh annually (Figure 3.5.1). Thus about 4000 MW of new capacity will be needed each year. Russia has also a large program to build gas fired CHP plants in their biggest cities. Because the most cities have a district heating network they could be independent of the outside power, as the city of Helsinki already is today.

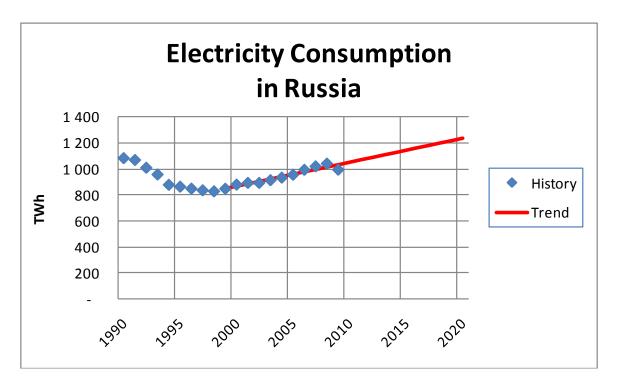


Figure 3.5.1 Electricity consumption Russia is increasing by 18 TWh annually

Today, Russia has the second largest nuclear program after China. It has eleven nuclear plants and 7370 MWe of capacity under construction (Table 3.5.1).

Table 3.5.1 Nuclear plant under construction in Russia (Source IAEA, PRIS)

Name of the plant	VVER-1000	RBMK	FBR	Other	Total
AKADEMIK LOMONOSOV 1				32	32
AKADEMIK LOMONOSOV 2				32	32
BELOYARSKY-4 (BN-800)			804		804
KALININ-4	950				950
KURSK-5		915			915
LENINGRAD 2-1	1 085				1 085
LENINGRAD 2-2	1 085				1 085
NOVOVORONEZH 2-1	1 114				1 114
NOVOVORONEZH 2-2	1 114				1 114
ROSTOV-3	1 011				1 011
ROSTOV-4	1 011				1 011
Total 11	7 370	915	804	64	9 153

Most of the Russian plants (7370 MW) are of VVER-1000 type, four loop pressurized water reactors. A similar plant was constructed in **Tianwan** in China. It used the basic design that was originally planned for the Loviisa-3 site by IVO Engineering.

Because of the lack of large uranium resources Russia is also developing fast breeder reactors. The **Beloyarsky-4** plant is the one of the very few fast reactors under construction in the world. It will have a pool type liquid metal fast breeder reactor (LMFBR) that uses sodium as the cooling media.

There are also two floating nuclear plants named the **Academic Lomonosov** under construction. The name of the plant comes from the Russian scientist and **Academic Mikhail Lomonosov** (1711-1765). The first plant was launched in St Petersburg in the summer of 2010.

3.6 The Korean nuclear program

Electricity consumption in South Korea is increasing constantly as the country is becoming industrialized. The growth rate has been 19 TWh annually (Figure 3.6.1) and the country needs about 4000 MW of new capacity each year.

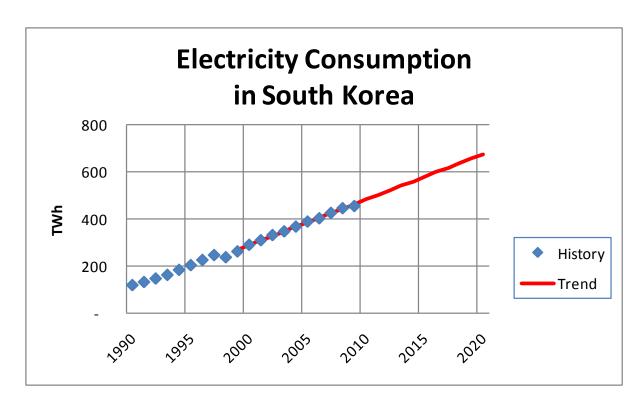


Figure 3.6.1 Electricity consumption is growing by 19 TWh annually in South Korea

The new nuclear capacity under the construction is 5500 MW, which corresponds to about 1100 MW capacity additions annually. Thus the nuclear plants could not cover the growth and other power plants will also be needed.

During the last four years the construction of five new nuclear units has been initiated:

2007 Shin Kori-2, Shin Wolsong-1 (960 MW PWR)

2008 Shin Kori-3 (1340 MW APR1400), Shin Wolsung-2 (960 MW PWR)

2009 Shin Kori-4 (1340 MW APR1400)

Shin Kori-3 and -4 units represent the new Korean design, which has also been offered abroad. They are offering the design also to Finland and have made the four unit contract with the United Arab Emirates.

3.7 The Indian nuclear program

Indian electricity consumption has been growing by 36 TWh each year (Figure 3.7.1). Thus about 7000 MWe of new power capacity will be needed annually. By 2020 about 70 GWe of new capacity is needed to cover the growth, but additional capacity is needed to cover the present deficit in capacity.

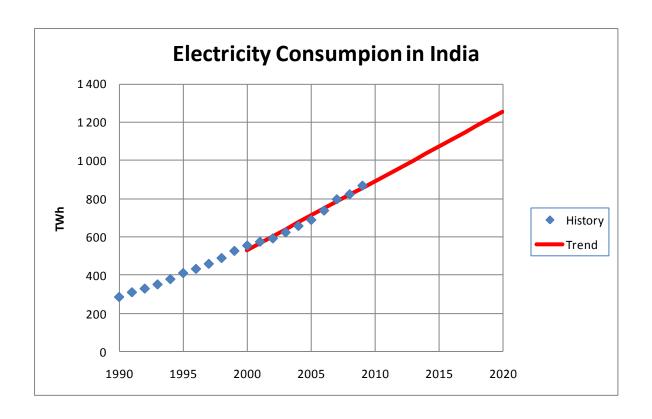


Figure 3.7.1 Electricity consumption in India

India has a very ambitious nuclear program and 3500 MW of new nuclear power capacity is under construction (Table 3.7.1). This includes two VVER-1000 plants, two heavy water reactor plants (PHWR) and one breeder reactor. All of the plants are planned to use India's huge thorium resources.

Table 3.7.1 Indian nuclear plants under construction in MWe

Plant	VVER-1000	PHWR	FBR	Total
KAKRAPAR-3		630		630
KAKRAPAR-4		630		630
KUDANKULAM-1	917			917
KUDANKULAM-2	917			917
PFBR			470	470
Total	1 834	1 260	470	3 564

3.8 The Finnish nuclear program after Chernobyl

Finland and Sweden have the highest specific electricity consumption in the EU (16 MWh/capita). Electricity consumption is still growing in Finland but is not following the earlier trend (Figure 3.8.1). The present forecast for the year 2020 is 98 TWh and the specific consumption will be 18 MWh/capita.

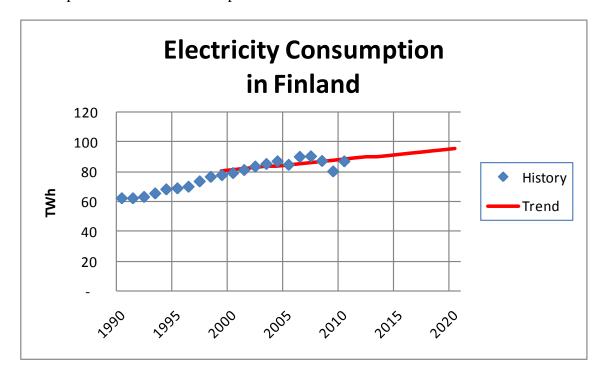


Figure 3.8.1 Forecast of electricity consumption in Finland will be 98 TWh in 2020

The main reason for the slow down of the consumption is the Finnish industry, which has been building its new factories in China and South Korea. At the same time several paper mills have been decommissioned in Finland.

Most nuclear programs in the West were ceased after Chernobyl in 1986. However, the first new nuclear plant in the EU after Chernobyl will be commissioned in Finland. The decision to build a new nuclear plant in Finland was made in 2003 by the Finnish Parliament. The construction of a new 1600 MW EPR nuclear plant in Olkiluoto was started in 2006 and the plant should be connected into the grid in 2013.

The decision in principle was made in the parliament in 2010 to build additional two new plants by 2020. The owners of the plants TVO and Fennovoima should apply for construction permit before 2015. Now the utilities are trying to select the reactor suppliers.

In specific nuclear generation per capita Finland was in the second place after Sweden, which generated 4500 kWh/capita using nuclear power in 1981 (Figure 3.8.2). The highest nuclear generation per capita will be in France, Finland and Sweden in 2015. They will all generate about 6000 kWh nuclear power per capita.

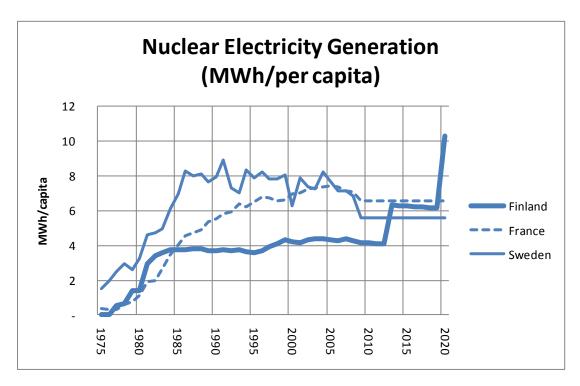


Figure 3.8.2 Nuclear generation per capita in the three leading countries. Finland will have the highest nuclear generation per capita (10 000 kWh/capita) after the two planned units will be in operation in 2020

Finland now has two nuclear plants in the planning stage. One will be the **Olkiluoto-4** (TVO), but the site of the other plant (Fennovoima) has not been determined. In 2020 the Finnish nuclear capacity will be about 7000 MW. The electricity generation by nuclear plants will be about 55 TWh or 10 000 kWh/capita after the planned two reactors Fin-6 and -7 will be in operation in 2020. Thus the Finnish nuclear power generation per capita would be larger than in any other country.

The design of the new European plants will follow the Finnish specifications, which have been designed for core meltdown and the possible crash of a jumbo airplane. The core catcher was first proposed by STUK in 1984 at NEA meeting. The meeting was attended by the former general director of STUK, **Antti Vuorinen** and the present general director, **Jukka Laaksonen**, who was the key person in responsible for reactor safety matters.

In the beginning of Olkiluoto-3 project in 2003 also aircraft crash had to be taken into account because of the September 11, 2001 terrorist attack in the US. Two large airplanes hijacked by the terrorist hit the two World Trade Center buildings in New York.

Now, the European safety authorities have a common organization, which is led by the present general director of STUK, Jukka Laaksonen. It is now becoming clear that every nuclear plant in Europe will use the same general requirements, which take into account among other things the meltdown of the reactor core.

The first LWR nuclear plant that had the core catcher was built in the Tianwan plant in China. Actually the Tianwan-type plant in China was planned in Finland for the Loviisa-3 site by IVO Engineering, in which MSci (Eng.) **Tapani Kukkola** and myself were the chief design engineers during the years 1976-86 before Chernobyl. Then the Chinese utilities ordered two same type VVER-91 units. They were designed by Kukkola's team and connected into grid in 2006 and 2007.

Finland was the first country in the world that has decided where to put the high level waste from the nuclear power plants. Today the nuclear waste geologic repository plant in Olkiluoto is under construction and it will be ready to take the first shipments of waste fuel in about 2020. The waste fuel will be encapsuled and buried into the rock about 400 meters below the sea level.

The two main reasons to build these new nuclear units are: 1) to become independent of outside electricity and 2) to cut CO_2 -emissions by 20-30% from the 1990 level by 2020. The CO_2 -emissions in Finland in 1990 were 70 million tons. Thus the maximum emissions should be 50-56 million tons by 2020.

The power generation forecast for Finland in 2020 is given in Table 3.8.1. The electricity consumption in 2020 will be about 98 TWh and the CO₂-emissions from electricity generation will be 5 Mt. Thus the specific emissions will be then about 50 gCO₂/kWh. It will be feasible to replace oil with electricity in the heating and transport sectors as oil has a higher CO₂ content (250 gCO₂/kWh) than electricity.

The fossil and biomass fuels have been left for combined heat and power (CHP) plants only. Other generation will be made by using CO₂-free technologies. CHP-generation will be 23.4 TWh in 2020. The Finnish CO₂-emissions will then mainly come from the six largest cities, which have fossil or peat fired CHP-plants.

It is possible to increase the nuclear share even to higher than 60%, but then the nuclear plant should be designed as a CHP-plant. Actually, the owner of the Loviisa nuclear plant, Fortum, has proposed to build the next nuclear unit at the Loviisa site as a CHP-plant and to build a 80 km district heating pipeline to the Helsinki area. The pipeline could transfer 1000-1200 MW of heat to Helsinki and replace the old coal fired plants in the city.

The discussions between the city of Helsinki and Fortum have been in progress for 30 years, but no agreement has been reached. The CO₂-emissions of the Helsinki area power plants are about 6 million tons of CO₂ and they are the biggest emission source in Finland.

Table 3.8.1 Electricity generation in Finland in 2020

Source	Electr	icity genera	tion	C	O2-emissio	ns
	1990	2009	2020	1990	2009	2020
	TWh	TWh	TWh	Mt	Mt	Mt
CO2-free sources						
Nuclear	18,1	27,9	55,0			
Hydro	10,8	15,6	13,6			
Wind	0,0	0,3	6,0			
Biomass	5,0	8,9	9,0			
Total	33,9	52,7	83,6	0,0	0,0	0,0
Fossil sources						
Coal	9,0	10,8	0,0	6,1	7,4	0,0
Peat	2,8	4,2	4,0	1,5	2,3	2,2
Gas	4,4	9,4	10,2	1,1	2,4	2,6
Oil	1,6	0,5	0,2	1,3	0,4	0,2
Total	17,8	24,9	14,4	10,0	12,4	4,9
Total generation	51,7	77,5	98,0	10,0	12,4	4,9
Imports	10,7	10,7	0,0	0,0	0,0	0,0
Total	62,4	88,2	98,0	10,0	12,4	4,9
Change from 1990		41 %	57 %		23 %	-51 %
CO2-content (g/kWh)				194	160	50

However, Fortum did not get the permission to build the Loviisa-3 plant, while the two other applicants got the permission from the Finnish Parliament in 2010. It is now quite obvious that the Loviisa-3 plant will be constructed before 2030, when the Loviisa-1 and -2 will be decommissioned.

If the Loviisa-3 plant will be built before 2030 with the district heating pipeline, then it will replace the coal and gas plants in the Helsinki area. The CO_2 -emissions will be reduced by an additional four million tons. Thus the reduction in CO_2 -emissions would be more than 50% from the levels in 1990. The two biggest sources of CO_2 -emissions will then be peat and natural gas. The CO_2 -emissions would be about five million tons and the specific emissions about 40-50 g CO_2 /kWh of electricity.

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4 CLIMATE CHANGE

4.1 Temperature history

The temperature of the atmosphere has been changing very much during the life on earth. The main cause of the past changes was solar radiation, which is changing constantly according to the movement of the earth. The changes in solar radiation are called as the **Milankovitch** cycles, after Serbian mathematician **Milutin Milankovic** (1879-1958), who could calculate solar radiation changes caused by the changes in the earth orbit and rotation.

He found that solar radiation changes come from precession (19 000 years), obliquity (41 000 year) and eccentricity (95 000 years) of earth orbits. Sun is a nuclear fusion reactor which is emitting radiation and amount of radiation depends on three factors: How far the earth is from the sun, the angle of the earth and intensity the radiation.

These changes have caused the ice ages. The net effect of earth orbital changes has been estimated by **M.F.Loutre** and **A. Berger** in Figure 4.1.1 for the last 200 000 years and forecasted for the next 130 000 years. According to the figure solar insolation has had a last peak about 10 000 years ago is now increasing until the next drop will come about 60 000 years after present (AP).

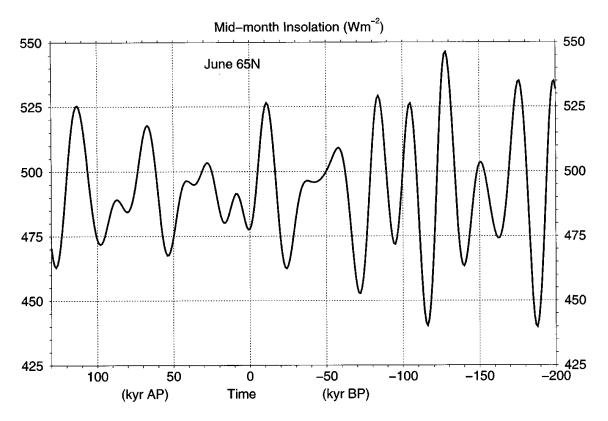


Figure 4.1.1 Changes in solar mid month insolation at 65N in June (Source: Future Climate Changes. Kluvert Academic Publications 2000)

Holocene Temperature Variations End of Last Glacial Period Climatic Optimum? 1.5 Climatic Optimum? 1.5 Climatic Optimum? 1.5 Climatic Optimum? 1.5 Climatic Optimum?

Thousands of Years BP

Figure 4.1.2 Temperature history during Holocene period or during the last 12 000 years (Source IPCC)

The present warm period started about 11 500 years ago and the ice above the Nordic countries smelted. It has been called as Holocene period (Figure 4.1.2). Thus the living in Finland became possible and our first ancestors moved to Finland at about 10 000 BP. The global warming by this time was a start of life in these higher latitudes from 60 °N to 70 °N.

The warmest period was about 8000-5000 years ago (BP) in the middle of Holocene period. The temperature in Finland was about 2.5 °C higher than today. Some southern trees (hazel) were growing in south part of Finland by this time and also northern mountain tops had trees. Today the trees and hazels have disappeared because of colder climate. If the climate will become 2.5 °C warmer in the future, the trees could come here again.

Then temperature cooled again and during 1690-95 about 30 % of Finnish population starved because of three consecutive summers with frost. During those years so called "little ice age" was covering the whole Europe. In the winter 1695 the army troops of Swedish king Karl X occupied Denmark and Copenhagen by riding with his Swedish-Finnish troops on the ice to Denmark.

The second cold period was in 1865-8 when about 10 % of the Finnish population died for the same reason. The cold period caused people to leave their farms to search for the food in

the cities. Thus difficult decease called as tyfus spread and killed several. Thus here in northern latitudes the climate change has had also positive side.

The explanation of these cold periods in 1690 BC and 1860 BC can be found in changes is solar radiation (Figure 4.1.3), which has had typically 11, 22, 88 and 208 year periods. The changes sunspots are caused by the changes in magnetic fields in sun.

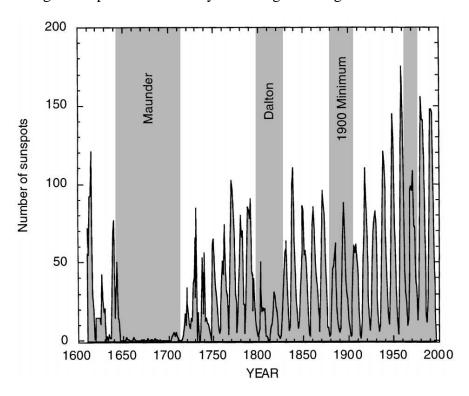


Figure 4.1.3 Variation of solar spots during last 400 years (j. Beer et al. 1999)

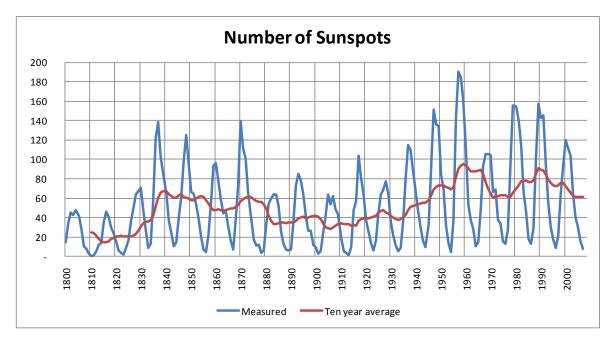


Figure 4.1.4 Number of sunspots after year 1800 (Source: Wm Robert Jonston, 2008)

The sunspots can explain also more recent cold periods. The average number of sunspots was 20 during the famine years 1866-68 in Finland (Figure 4.1.4). The ten year average number of sunspots started to increase after 1900. This may also explain the global warming in one hundred year time scale.

The warmer period after 1900 has been noticed by annual average temperature measurements by The Finnish Meteorological Institute in Sodankylä (Figure 4.1.5 and 4.1.6)).

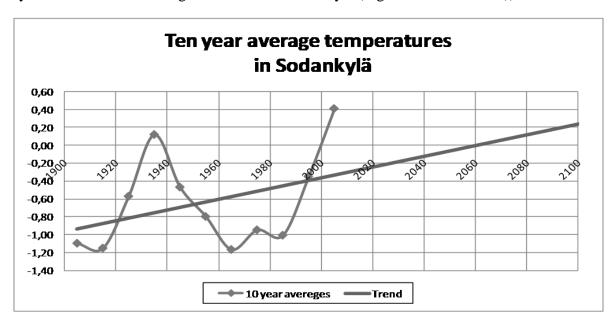


Figure 4.1.5 The 109 year trend of ten year average temperature measurements in Sodankylä indicates a 0.6 °C increase in 100 years

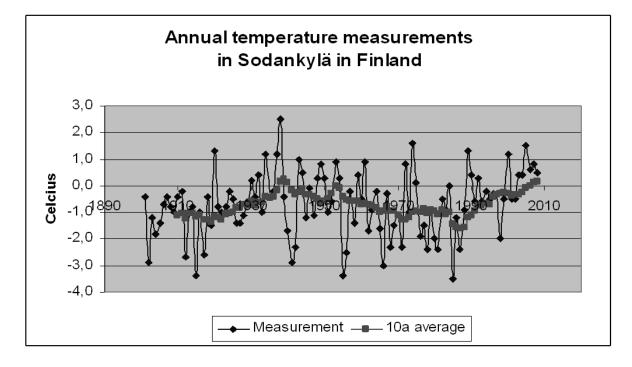


Figure 4.1.6 Temperature measurements in Sodankylä (67° N), Finland

Long term trend from the measurements shows that the average annual temperature has been increasing by 0.6 °C in 100 years. The temperature is increasing at the rate of 0.06 °C/decade. If the same trend continues the temperature will be 0.6 °C higher in 2100 than in the year 2000.

The measurement in Sodankylä is one of the only measurements made in Finland which has no effect of the population density or so called "city effect". The site is in the middle of Lapland far from the coast line. There are also many city measurements recorded, but these are not reliable because of the ambient temperature level is affected by aerosols generated by the traffic and heating of the houses.

The measurements in the middle city of Helsinki (Kaisaniemi 60°N) show 1.4 °C increase in temperature in hundred years (Figure 4.1.7). Measurements in Helsinki have large influence of the city effect, which has been found in several cities of the world. The temperature in the cities has been risen more than in other places. Additionally, the Helsinki is near the sea, which causes more clouds and rain than places far from the sea.

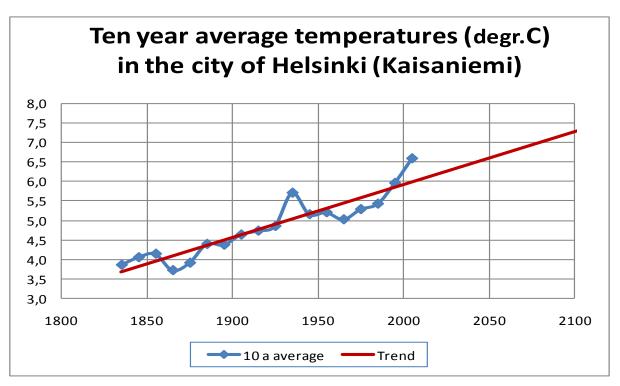


Figure 4.1.7 The 180 year trend of ten year average temperature measurements in the middle of Helsinki (Kaisaniemi) indicate trend of 1.4 °C increase of temperature in 100 years

The 30 year average temperatures from the years 1901-1930 to the years 1971-2000 from four sites; Sodankylä, Oulu, Joensuu and Helsinki, have been measured by the Finnish Meteorological Institute. They show that the annual average temperature has increased by 0.14 °C in Joensuu, by 0.46 °C in Sodankylä, by 0.57 °C in Oulu and by 1.04 °C in Helsinki (Figure 4.1.8).

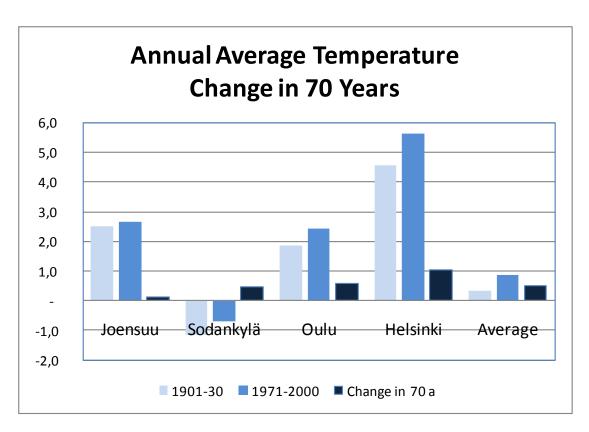


Figure 4.1.8 Changes in the 30 year average temperatures in four sites in Finland (°C)

If the cities with the highest (Helsinki) and lowest (Joensuu) changes are omitted, then the 70 year average temperature increase of the two remaining sites is 0.52 °C, which corresponds to an increase of 0.74 °C during 100 years.

In Sodankylä the highest annual average temperature (+2.5 $^{\circ}$ C) so far was measured in the year 1938, when also the ten year average was the highest (+0.2 $^{\circ}$ C) (Figure 4.1.6). The ten year average temperature curve has had an N-shape during the last 100 years. The temperature in Sodankylä increased for 28 years from -1.0 to 0.2 $^{\circ}$ C up to the year 1938. Then it started to decrease reaching -1.6 $^{\circ}$ C in 1987. Thereafter the ten year average temperature has again risen to 0.4 $^{\circ}$ C in 2010.

The measurements made in the US also indicate N-shape over the last hundred years. The temperature rose in the US by 0.7 °C from 1910 to 1940 and cooled down by 0.6 °C from 1940 to 1975, back to 11 °C. From 1975 to 2003 the temperature has again risen by 0.6 °C (source: http://www.ncdc.noaa.gov).

The measurement from Sodankylä shows the same shape as the studies made by **Beer et al.** "Role of Sun in Climate Forcing" in 2000. They evaluated that the temperature has risen in the Northern Hemisphere from -0.3 °C in 1850 to +0.4 °C in 1980 (Figure 4.1.9). The increase corresponds to 0.7 °C/130 years or to 0.53 °C over a hundred years. According to their studies more than half of the increase of the temperature has been caused by changes in solar radiation. However, anthropogenic (man-made) reasons have been increasing constantly, which might refer to greenhouse gases.

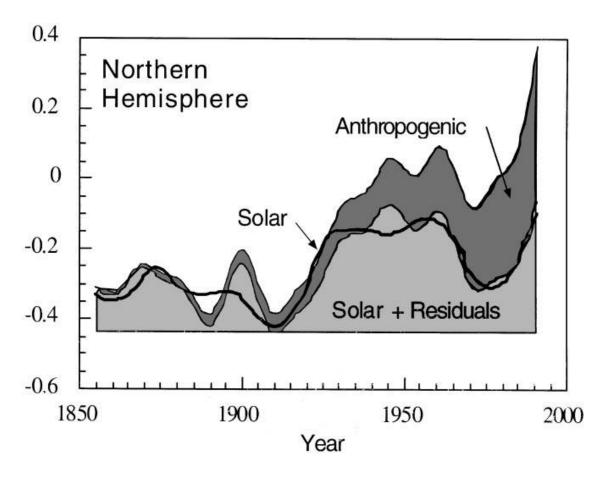


Figure 4.1.9 Temperature increase in the Northern Hemisphere (Beer et. al)

4.2 Aerosols

There are factors in the atmosphere that cause cooling. Aerosols are small particles of solid or liquid matter, emitted by industries, power plants and cars. Aerosols can influence the formation of clouds as water in the air will concentrate on the surface of aerosols and cause the formation of small water droplets.

The earth has had cold periods several times in the past. One example of cooling was found from 65 million years ago, when the dinosaurs disappeared. The scientists have discovered that a gigantic asteroid slammed into earth in Mexico's Yucatan peninsula. This caused huge clouds of dust into the air, which caused a temperature decrease of some 5-10 °C. The cooling caused the earth's surface becoming filled with snow and ice. Dinosaurs could not find enough food to survive.

The aerosol emissions started to grow after World War II (Figure 4.2.1), when the automobile industry really started to produce new cars and utilities started to build new coal fired power plants.

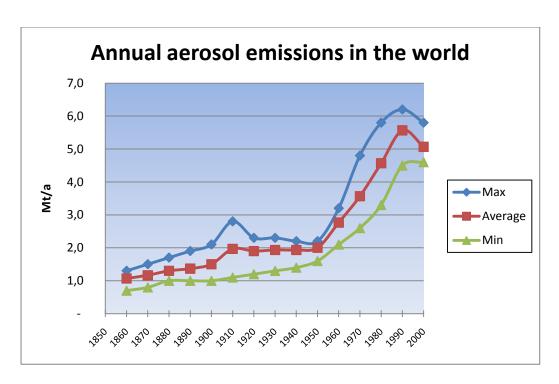


Figure 4.2.1 Aerosol emissions (Mt/a) according to three separate studies

After 1990 environmental standards required mandatory particle and sulfur filters placed into coal fired plants and catalysts into new cars. The emissions of aerosols have been reducing since 1990.

The cooling effect of aerosols has also been noticed by nuclear war studies. It was feared during the cold war period that a nuclear war will cause "a nuclear winter", which would last for several years. As a matter of fact some studies find that a nuclear winter would have larger consequences for human life than the radiation caused by the explosions.

According to recent studies (**Alan Robock** et al 2007) a nuclear war could cause 150 Mt of smoke emitted into the atmosphere, which could reduce solar radiation with 100 W/m² during the first year and 20 W/m² after ten years. This can be compared to the Pinatubo volcanic eruption in 1991, which caused a 3.5 W/m² reduction of radiation during the first year.

We the Finns live near Saint Petersburg, which was one of the targets of ballistic missiles during the cold war. Thus we have built nuclear shelters for the whole population, but there is no protection against a possible nuclear winter, which could cause disturbance in food production and famine as during the cold years of 1695-6 and 1865-7, or 65 million years ago, when dinosaurs disappeared.

However, the IPCC has not evaluated what is the real net effect of aerosols on cooling. Aerosols may explain the N-shape of the temperature curve. If aerosol emissions will be reducing, this would mean that the heating effect of carbon dioxide will become even larger in the future.

During the 70's some scientists were forecasting that the Golf stream could cause another ice age. The change in the Golf stream occurred in about 9000 BP, and the smelting of ice stopped for about 250 years and caused large sand mountains in Finland. For us, the Finns, a new ice age would be the end of all life in our country. The ice age has been forecasted to come here within sixty thousand years from now, because the earth is changing its angle so that the winter will be longer in the north (Figure 4.1.1).

Now scientists are warning that the ice in Greenland will disappear and the sea level could rise by six meters. The sea level raise could end the life in many of the islands which are located near the sea level. The land is rising in Finland at the rate of 2-7 mm/year thus this will compensate the sea level rise, which has been 1-3 mm/year. However, in other parts of the world the seawater rise is a real treat.

The biggest problem of global warming could be caused by land drying near the equator and thus causing famine in many countries. Thus global temperature changes will in any case cause problems in food supply in the north and south.

There is an optimum temperature for the earth, which would minimize hazards to nature and mankind. For the Northern countries this would be higher than today. For the countries near the equator it would be lower than today.

However, because of the CO₂-emissions the IPCC estimates that global temperature will be 2 - 5 °C higher in the year 2200 than in prehistorial times. This could be the same level that the Nordic countries experienced in 8000 years ago. The last discussions of the UN Climate Change talks in **Cancún** in 2010 concluded that we should limit the average temperature rise of the world to 2 °C.

4.3 The influence of CO₂

The theory behind man made warming of the atmosphere was explained by a Swedish chemist, **Svante Arrhenius** (1859-1927). In 1896 he made the article "On the influence of Carbon Acid in the Air upon the temperature in the Ground" in the Philosophical Magazine, where he described that the temperature on the ground is dependent of the CO₂-concentration in the atmosphere. He estimated that the temperature will rise by 5-6 °C if the CO₂-concentration would double.

An American astronomer, **Samuel Langley** (1834-1906), published infrared tables in 1890, which he had constructed by measuring the infrared radiation of the moon during the sunrise in Colorado, USA. He also measured how much energy the sun was emitting. In 1878 he developed a new instrument, the bolometer, which was able to measure the energy of electromagnetic radiation. He became famous for building the first steam engine powered unmanned airplane in 1891, which flew about one kilometer before running out of fuel.

Based on Langley's infrared radiation tables Arrhenius concluded that infrared radiation is dependent on the CO₂-content of the atmosphere. He deducted that the infrared radiation

from the earth should behave the same way. If the CO₂-concentration in the atmosphere will rise then radiation cannot escape from the earth and the temperature will rise.

The CO₂-concentration of the atmosphere was measured in 1958 by an American scientist **Charles Darwin Keeling** (1928-2005), who did his first measurements of 314 ppm (parts per million) in Hawaij at Mauna Loa. The concentration is now 390 ppm, i.e. 76 ppm higher than fifty years ago (Figure 4.3.1).

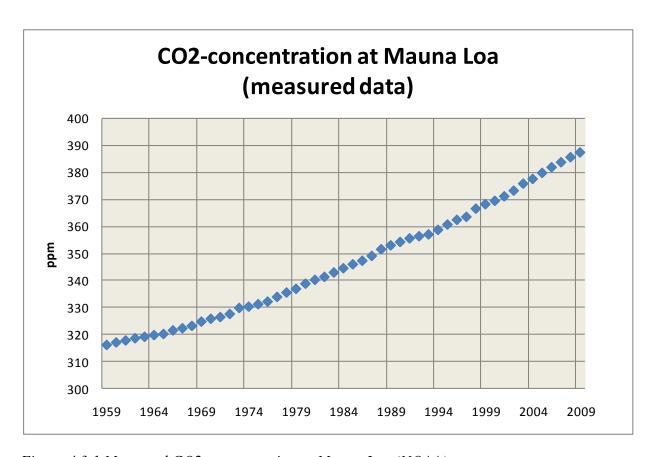


Figure 4.3.1 Measured CO2-concentration at Mauna Loa (NOAA)

The concentration is now increasing at the rate of 2 ppm/during the last ten years. If the same trend continues the concentration will reach 470 ppm by 2050 and 570 ppm by 2100 (Figure 4.3.2).

The CO₂-concentration has risen from 280 ppm during the preindustrial times to 383.7 ppm in 2007. The cumulative global CO₂-emissions from fossil fuels have been about 1237 Gt by 2007 (*cdiac-ornl.gov/trend/emis/tre_glob.html*). About 750 Gt (61%) of the emissions have remained into the atmosphere.

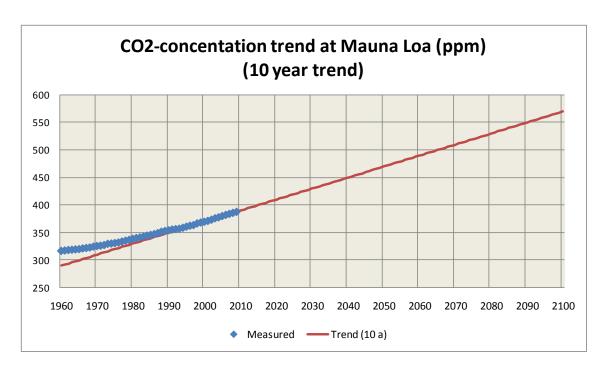


Figure 4.3.2 The CO_2 -concentration will increase to 570 ppm in 2100 according to the 10 year trend line

4.4 CO₂-emissions

The CO₂-emissions are now very well known from the energy sector, which includes power and heat generation and transportation (*bp.com*). The CO₂-emissions were 22 Gt (Gigatons or billion tons) in 1990 and 31 Gt in 2009 (Figure 4.4.1). The CO₂-emissions were rising with the rate of 3.8 %/a until the second energy crises in 1979. Thereafter the emissions have been increasing with 1.5 % annually.

One of reasons for the change in the CO₂-emission trend in the 80's have been nuclear power investments, which have reduced the need for fossil fuels in power generation. However, the growth in nuclear investments has declined after 1986, when Chernobyl stopped many new nuclear projects.

The cumulative emissions from 1990 are now 500 Gt (Figure 4.4.2). The increase of CO₂-concentration in Mauna Loa since 1990 (Figure 4.4.3) follows the trend of the cumulative CO₂-emissions. If the increase in the concentration is presented as a function of cumulative emissions, the match is quite perfect (Figure 4.4.4).

After 1990 the cumulative emissions have increased by 500 Gt and the concentration of CO_2 in the atmosphere with 34 ppm during the same time period. If this correlation is valid, then 6 x 500 Gt (3000 Gt) of cumulative emissions will cause 6 x 34 ppm (200 ppm) increase in the concentration (Figure 4.4.5). Thus the concentration will then be 354 ppm+200 ppm or 554 ppm. This is about two times the preindustrial level of 280 ppm.

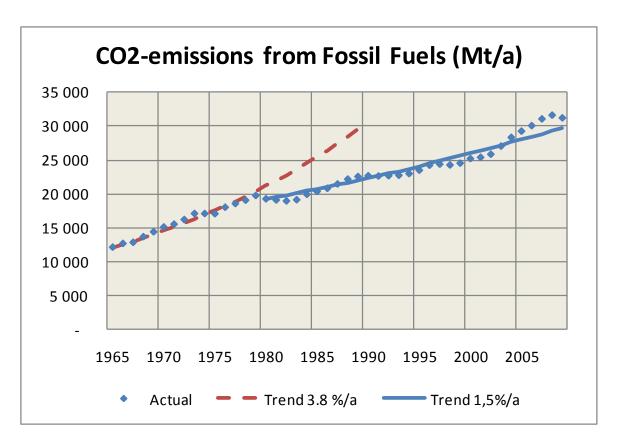


Figure 4.4.1 The CO₂-emissions of the energy sector (Source BP 2010)

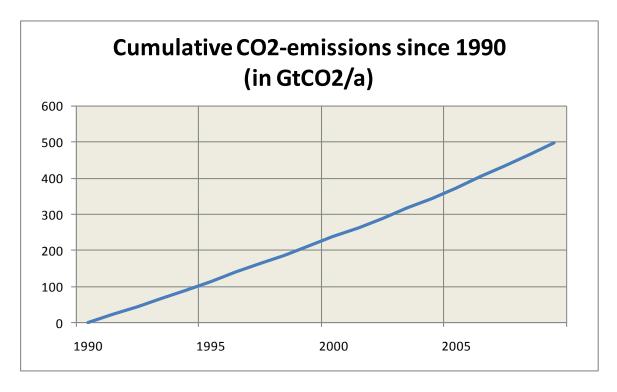


Figure 4.4.2 The cumulative CO₂-emissions after 1990

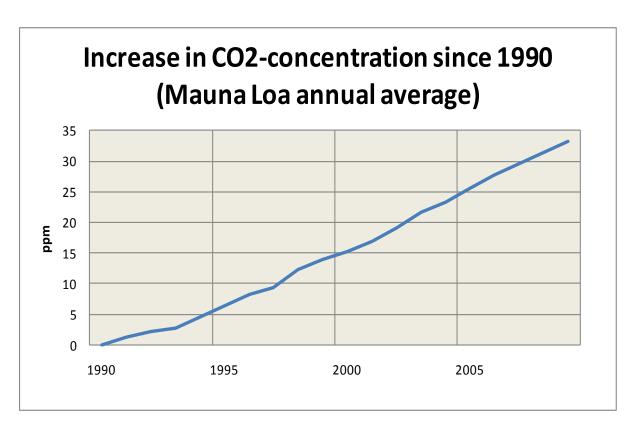


Figure 4.4.3 Increase in the concentration since 1990

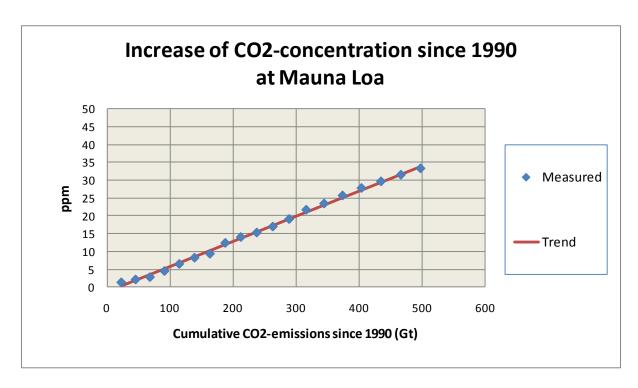


Figure 4.4.4 The increase of the concentration at Mauna Loa and cumulative emissions since 1990

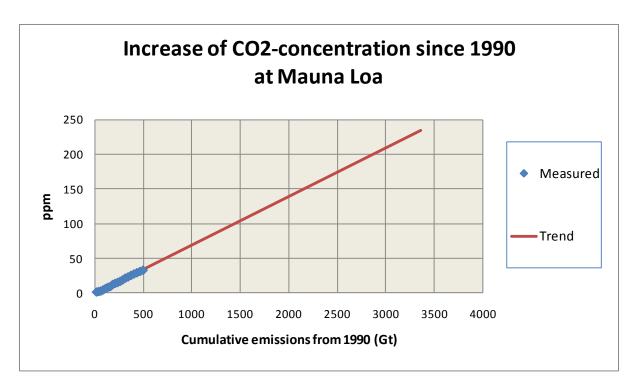


Figure 4.4.5 The forecasted CO_2 -concentration will increase by 200 ppm if the cumulative emissions will reach 3000 Gt

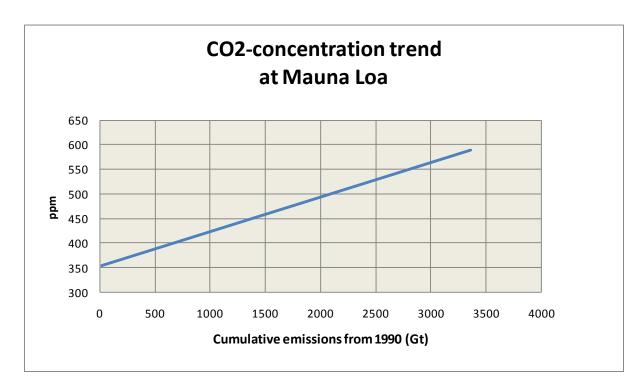


Figure 4.4.6 The critical 560 ppm level will be exceeded if the cumulative emissions will reach 3000 Gt. The target level of 450 ppm will be exceeded at 1500 Gt

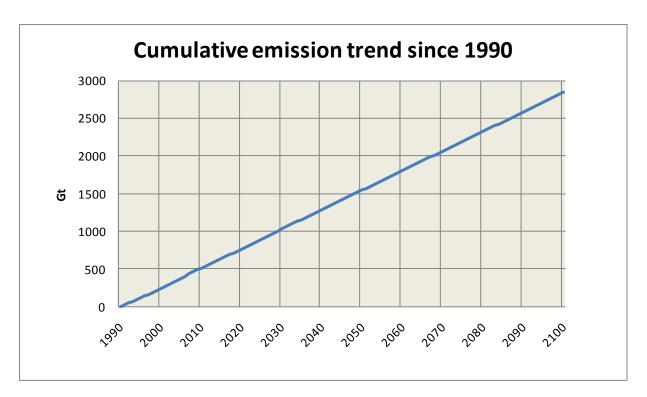


Figure 4.4.7 The cumulative emissions will grow to 2800 Gt in the year 2100 according to the current trend

The CO_2 -concentration in Mauna Loa was 354 ppm in 1990 and 388 ppm in 2009. The increase in the concentration after 1990 has been 34 ppm with 500 Gt CO_2 -emissions. The critical level of concentration has been said to be two times the preindustrial level of 280 ppm. This level of 560 ppm will be achieved if the cumulative emissions exceed 3000 Gt (Figure 4.4.6). Trend in the cumulative emissions shows that the emissions will reach 2800 Mt by 2100 (Figure 4.4.7).

4.5 The emission targets for fossil fuels

4.5.1 Cumulative emission targets

According to historic data (*Carbon dioxide Information Center. ornl.gov*) the global emissions of the energy industry have been 10.3 Gt of carbon by the year 1900 and 173.5 Gt by 1970. Global emissions have been about 180 Gt of carbon (661 Gt of CO₂) during the years 1901-1985.

The thirty year average temperatures in Finland from 1901-30 to 1970-2000 show a temperature increase of 0.52 °C during seventy years time (Chapter 4.1). If we assume the other things have stayed the same, then the 661 Gt emissions have caused a 0.52 °C change in the temperature (0.79 °C/1000 GtCO₂).

The UN climate negotiations in Cancún have given a common target to limit the temperature change to 2 °C from preindustrial times. Then this 2 °C change will be reached, when the cumulative emissions will be 2/0.79 x 1000 Gt, or 2530 Gt.

In the article of Nature /4.3/ Myles R. Allen et. al estimated that 1 trillion tons of carbon (3670 GtCO₂) emissions can cause a global temperature increase of 2 °C. The sensitivity of emissions to the global temperature would be 2 °C/3670 Gt, or 0.54 °C/1000 Gt. This sensitivity estimate is lower than the 0.79 °C/1000 Gt evaluated by the author.

Because 1357 GtCO₂ emissions have released by mankind until 2010, then the maximum emissions after 2010 are 2530-1357 Gt or 1173 GtCO₂ according my estimates. If this is divided evenly for years from 2011 to 2100 annual emissions can be 13 GtCO₂ per year in average. Myles R. Allen estimates the maximum emissions after 2010 would be 3670-1357 Gt, or 2313 Gt. This would be 26 GtCO₂ per year.

In theory the 1173 Gt emissions can be achieved by reducing the emissions from 30 Gt in 2009 linearly by 0.42 Gt each year. Then the annual emissions would be zero in the year 2083. Because of the long investment cycles of power generation this cannot be realized in practice. Actually, the emissions are still growing because of the ongoing investments to fossil fired power plants. Thus several targets will be needed.

4.5.2 Targets for energy industries

Mankind cannot change its behavior in one year, thus I am proposing targets for years 2050 and 2100. By 2050 the maximum CO₂-emissions should not exceed the 1990 level (20 GtCO₂). If the population forecast is 9.15 billion (Table 4.5.1), the maximum CO₂-emissions should be 2.2 tons per capita. The reduction in 40 years from 30 Gt to 20 Gt would mean 1 % reduction each year.

The emissions by 2100 should be 80% lower than in 1990, or 4 Gt. The reduction would be then from 20 Gt to 4 Gt or 3% per year. With 9 billion people the emission level in the individual countries should not exceed 0.45 tons per capita in 2100. Thus the reduction needed in North America and Japan should be 97%, in Europe 95% and China 93% from the 2009 level.

In my opinion the emission targets of the individual countries should be developed on a per capita basis. The forecast indicate that the population level will be stabilized at the 9 billion level by 2100 (Table 4.5.1). There will be two targets for the years 2050 and 2100:

EMISSION TARGETS FOR ENERGY INDUSTRY

- 1) 2050 less than 2.2 tCO₂/capita,
- 2) 2100 less than $0.45 \text{ tCO}_2/\text{capita}$

The reductions needed by the countries depend on the present levels (Table 4.5.2). The highest reductions are needed in North America (85%), Japan (82%) and European Union (73%). The reductions needed in China should be 58%. Africa and India can increase their emissions without reaching the limit of 2.2 tons per capita.

Table 4.5.1 Population forecast to 2100

Population in millions				
	1990	2009	2050	2100
North America	284	349	448	500
European Union	470	501	500	425
Other Europe	383	383	385	300
Japan	124	127	102	70
Latin America	442	582	729	726
Middle East	211	211	354	520
Africa	622	982	1 931	2 238
China	1 156	1 346	1 417	1 189
India	849	1 198	1 614	1 458
Rest of Asia Pacific	739	1 120	1 670	1 574
Total	5 280	6 799	9 150	9 000

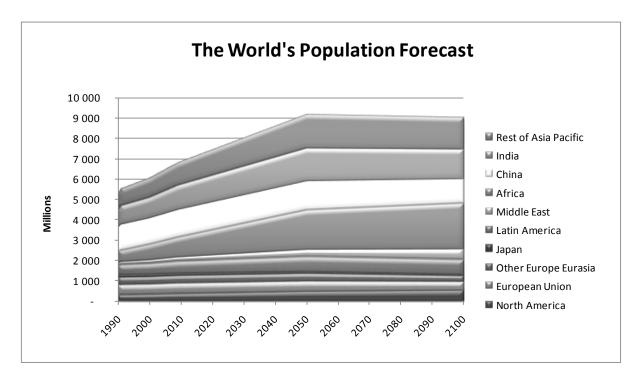


Figure 4.5.1 The world's population forecast

Table 4.5.2 CO_2 -emission targets for the energy industry (2.2 tCO_2 /capita in 2050 and 0.45 tCO_2 /capita in 2100)

CO2-emissions	Emission h	istory	Emissio	on target	Reduction from 2009		
of energy industry	1990	2009	2050	2050 2100		2100	
	Mt	Mt	Mt	Mt	%	%	
North America	5 968	6 545	996	226	-85 %	-97 %	
European Union	4 479	4 066	1 111	192	-73 %	-95 %	
Other Europe	4 171	2 784	856	136	-69 %	-95 %	
Japan	1 163	1 222	226	32	-82 %	-97 %	
Latin America	984	1 596	1 621	328	2 %	-79 %	
Middle East	734	1 799	787	235	-56 %	-87 %	
Africa	690	1 066	4 291	1 011	302 %	-5 %	
China	2 477	7 518	3 149	537	-58 %	-93 %	
India	581	1 539	3 587	659	133 %	-57 %	
Rest of Asia Pacific	1 427	2 994	3 712	711	24 %	-76 %	
Total	20 336	31 130	20 336	4 068	-35 %	-87 %	

4.6 The emission targets for electricity generation in 2050

Power generation caused 10.6 Gt of the CO_2 -emissions in 2009. This was 34 % of all emissions caused by the energy industry. The world's electricity generation was 20 090 TWh and the specific emissions were 526 gCO_2/kWh (Table 4.6.1).

Table 4.6.1 The specific emissions of electricity generation in gCO₂/kWh

Specific emissions	Emission h	istory	
of electricity	1990 2009		
generation	g/kWh	g/kWh	
North America	575	514	
European Union	501	387	
Other Europe	422	320	
Japan	457	479	
Latin America	168	196	
Middle East	675	641	
Africa	735	679	
China	750	736	
India	731	753	
Rest of Asia Pacific	603	605	
Total	528	526	

The emission targets have been calculated for 2050 (Table 4.6.2) by assuming the same reductions in power generation as for the other energy sectors. The target emissions in 2050 should be 6.3 Gt per year, or 690 kgCO₂/capita and 1.25 Gt per year or 140 kgCO₂/capita in 2100.

EMISSION TARGETS FOR ELECTRICITY GENERATION

- 1) 2050 less than 690 kg CO₂/capita,
- 2) 2100 less than 140 kgCO₂/capita

*Table 4.6.2 CO*₂-emission targets for power generation

CO2-emissions of	ssions of Emission history Emission target		mission history Emission target		Reduction from 2009		
electricity industry	1990	2009	2050 2100		2050	2100	
	Mt	Mt	Mt	Mt	%	%	
North America	2 179	2 591	307	70	-88 %	-97 %	
European Union	1 288	1 231	342	59	-72 %	-95 %	
Other Europe	843	605	263	42	-56 %	-93 %	
Japan	384	534	70	10	-87 %	-98 %	
Latin America	85	213	499	101	135 %	-52 %	
Middle East	162	485	242	72	-50 %	-85 %	
Africa	233	429	1 321	311	208 %	-27 %	
China	466	2 742	969	165	-65 %	-94 %	
India	208	655	1 104	203	69 %	-69 %	
Rest of Asia Pacific	412	1 090	1 143	219	5 %	-80 %	
Total	6 259	10 574	6 259	1 252	-41 %	-88 %	

Some could claim that it will be difficult to reach 90% reductions in some industrialized countries. This is true but the industrialized countries are the ones that have the most powerful means to generate emission free electricity: nuclear power. Then the reduction of CO₂-emission could be shared by nuclear power and renewable energy.

4.6.1 North America

The reduction of the emissions caused by electricity generation in North America should be reduced with 88% by 2050 and 97% by 2100. If consumption remains at the same level, this can be achieved by reducing the specific emissions from 514 gCO₂/kWh to 62 gCO₂/kWh by 2050.

This means that practically 90% of electricity should be generated by using CO₂-free sources in 2050. Then in 2100 in practice all of electricity generation should be CO₂-free.

4.6.2 The European Union

The reduction of emissions caused by electricity generation in the EU should be reduced with 72% by 2050 and 95% by 2100. If the specific electricity consumption remains at the same level, then the specific emissions should be reduced from 387 gCO₂/kWh to 108g/kWh by 2050. In 2100 the specific emissions should be 19 g/kWh and practically all electricity should be generated by using CO₂-free sources.

4.6.3 Finland

The countries with the highest specific electricity consumption should have the lowest specific emissions. The forecasted electricity consumption in 2050 for Finland is 117 TWh and the specific electricity consumption for 5.4 million Finns would be 22 000 kWh.

Assuming that the target for emissions caused by electricity generation will be 690 gCO₂/capita by 2050 the specific emissions of electricity generation should be less than 31 gCO₂/kWh in 2050. Because of the recent decisions of building two new nuclear plants and more renewable electricity, the emissions will be less than 50 g/kWh already in 2020 (Table 3.8.1). It would not be difficult to reach the 30 g/kWh level by 2050.

4.6.4 China

The reduction needed in China is 65% from the 2009 level. The specific emissions in China caused by electricity generation were 736 g/kWh in 2009. The emissions should be less than 258 g/kWh in 2050, if the specific consumption will not grow. Thus non-fossil electricity generation should be at least 66% of all electricity generated in 2050.

But actually the specific consumption of electricity will grow and the specific emissions should be much lower. The forecasted electricity consumption in China is 8000 kWh/capita. Thus the 690 gCO₂/capita target means that the specific emissions should be less than 86 gCO₂/kWh. This means that 90% of electricity should be generated by using non-fossil electricity sources.

4.6.5 India and Africa

The target for India would allow an increase of emissions until 2050, but by 2100 the emissions should be reduced to 1990 level. This means a 69% reduction of emissions from the present level. Thus it would be best not to increase the emissions at present. They could sell the emission rights to other countries until 2050.

Africa should as well reduce its emissions in the long run by 29% from the present level by 2100. They can sell the emission rights to other countries until 2050.

4.7 Emission reduction targets for individuals

The 2.2 ton per capita emission target for 2050 might be very challenging for individuals. However, the target for individual households should be even harder, because most of the energy use will be formed by public and industrial consumption. I have kept the one ton per

capita as the target for households in my book "The Energy user's handbook" (Ekoenergo Oy 2009). We established Ekoenergo Ltd with my family for energy saving consultations during the second energy crisis in 1979.

4.7.5 Household energy consumption targets

I and my wife Sinikka now have a city home of 83.5 m² with one sauna, a 100 m² summer home with two saunas and two cars. The analysis given in the book indicates that our family was using 50 000 kWh of energy in 2008. The energy consumption of our two homes was 30 000 kWh and our transportation energy consumption was 20 000 kWh in 2008. The CO₂-emission of our energy consumption was 8000 kgCO₂ for two homes and 5200 kgCO₂ for transportation. Thus the total emissions in 2008 were 13 300 kgCO₂ or 6 600 kg per person.

In 2010 the home energy consumption was still 30 000 kWh for our two homes, but we have bought all electricity (14 500 kWh) from renewable sources and reduced the CO_2 -emissions with 2170 kg CO_2 (Table 4.7.1).

Another reduction has been made by our district heating company Fortum, which has built a new gas fired CHP plant in our home town Espoo in 2009 and reduced the specific emissions of district heat from 350 g/kWh to 250 g/kWh. Thus the CO₂-emissions of our two homes have dropped from 8000 kg to 3100 kg, i.e. 60%. The CO₂-content in district heating will be reduced to about 200 gCO₂/kWh by 2020 and thus the per capita emission would drop to 1200 kg/person.

The next target would be to drop the household emissions below 500 kgCO₂ per person. This will mean buying electricity and heat from CO₂-free sources. This could happen by 2030, if the cities of Helsinki and Espoo would start buying heat from the nearby Loviisa nuclear power station, which is now heating only the sea with about 2000 MW of thermal power.

Another possibility would be to move to a house that has an electric or heat pump heating system. It is worthwhile to note that our summer house is now already CO₂-neutral. It is causing emissions only indirectly because of the necessity to go there by private car.

4.7.6 Transportation energy use

In 2010 the energy consumption of our two cars has dropped from 15 000 kWh to 13 000 kWh, when we sold our gasoline SUV (8.0 liter/100 km) and bought a diesel engine car (6.5 liter/100 km). This dropped the CO_2 -emissions with 300 kg CO_2 (Table 4.7.2).

Our second car will also reduce emissions, because all gasoline sold in Finland has 5-10% ethanol, starting from January 2011.

Another big saving (3000 kWh) was achieved when I practically stopped flying. I used to make one intercontinental flight annually. This was during my employment years as general manager of energy engineering. My last flight was in 2009 to New Delhi to describe optimization of power systems to the Indian Electricity Office.

Table 4.7.1 The emission target for our two homes

Home emissions	5		His	story	Targe	ets	
			2008	2010	2015	2020	2030
Home 1 (83 m2)	Consumption	kWh	2 500	2 500	2 500	2 500	2 500
Electricity	Emission/kWh	gCO2/kWh	250	-	-	-	-
	Emissions	kgCO2	625	-	-	-	-
Heat	Consumption	kWh	12 500	12 500	12 500	12 500	12 500
	Emission/kWh	gCO2/kWh	350	250	250	200	50
	Emissions	kgCO2	4 375	3 125	3 125	2 500	625
Home 2 (100 m2)) Consumption	kWh	12 000	12 000	12 000	12 000	12 000
Electricity	Emission/kWh	gCO2/kWh	250	-	-	-	-
	Emissions	kgCO2	3 000	-	-	-	-
Heat	Consumtion	kWh	3 000	3 000	3 000	3 000	3 000
	Emission/kWh	gCO2/kWh	-	-	-	-	-
	Emissions	kgCO2	-	-	-	-	-
Total	Energy	kWh	30 000	30 000	30 000	30 000	30 000
	Emissions	kgCO2/a	8 000	3 125	3 125	2 500	625
	kgCO	2/person	4 000	1 563	1 563	1 250	313

Table 4.7.2 CO_2 -emission targets for transportation

Transportation	emissions		His	tory	Targe	ets	
-			2008	2010	2015	2020	2020
Car 1	Emission/km	gCO2/km	190	170	30	30	30
	Driving	km/a	15 000	15 000	15 000	15 000	15 000
	Emissions	kgCO2	2 850	2 550	450	450	450
Car 2	Emission/km	gCO2/km	220	220	200	30	30
	Driving	km/a	5 000	5 000	5 000	5 000	5 000
	Emissions	kgCO2	1 100	1 100	1 000	150	150
Flying	Emission/km	gCO2/km	120	120	120	120	120
	Flying	km/a	7 000	700	700	700	700
	Emissions	kgCO2	840	84	84	84	84
Bus	Emission/km	gCO2/km	110	110	100	130	130
	Bus travel	km/a	4 000	500	500	500	500
	Emissions	kgCO2	440	55	50	65	65
Transportation	emissions	kgCO2/a	5 230	3 789	1 584	749	749
	kgCO	2/person	2 615	1 895	792	375	375
Home emission	ıs	kgCO2/a	8 000	3 125	3 125	2 500	625
kgCO2/person		4 000	1 563	1 563	1 250	313	
Total emissions	5	kgCO2/a	13 230	6 914	4 709	3 249	1 374
	kgCC	2/person	6 615	3 457	2 355	1 625	687
Index			100 %	52 %	36 %	25 %	10 %

Our CO₂-emissions from transportation are now 1500 kgCO₂ lower than in 2008 or 3790 kgCO₂/a. Our total emissions are still 6900 kgCO₂ annually or 3500 kgCO₂/capita. However, we have achieved a 48% saving in emissions in just two years.

Our next step could be a plug in hybrid car, which should be coming on the market within two years time. Then the emissions from transportation could be reduced to about 1300 kgCO₂ and the total emissions to 4700 kgCO₂ by 2015. This would be 64% lower than the emissions in 2008.

In that case about 70% of the emissions would be coming from district heating. District heating could become practically CO₂-free by 2030 if Helsinki will start to buy heat from the Loviisa nuclear power plant.

I am wondering what Nobel Prize winner Al Gore will do? He has made great speeches on climate change, but according to public data he consumes 220 000 kWh of electricity annually and probably also the same amount of fuels. Thus his energy consumption in one month was about the same as ours in one year.

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5 PREFERABLE ELECTRICITY SOURCES

5.1 Forecasting future electricity consumption

According to UN estimates the world population will grow to 9.15 billion by 2050. The population will then start to diminish after 2050, and will be 9 billion in 2100 (Table 4.5.1).

The world's electricity consumption was 20 090 TWh in 2009 (Table 5.1.1) and the specific consumption was 2900 kWh/capita (Table 5.1.2). The highest specific consumption was in North America (14 500 kWh/capita) and the lowest in Africa (640 kWh/capita).

Table 5 1 1	Flectricity	consumption	forecast mane	by the author
1able 5.1.1	Electricity	Consumblion	torecasi mane	ov me aumor

Electricity	Histo	ory	Fore	cast
consumption	1990	2009	2050	2100
	TWh	TWh	TWh	TWh
North America	3 786	5 042	6 913	7 865
European Union	2 570	3 182	3 876	3 637
Other Europe	2 000	1 888	3 237	3 131
Japan	841	1 115	1 245	899
Latin America	507	1 082	2 484	3 329
Middle East	239	756	2 770	5 404
Africa	316	631	2 225	3 904
China	621	3 725	11 951	13 344
India	284	870	2 299	2 875
Rest of Asia Pacific	682	1 802	4 895	6 155
Total	11 847	20 094	41 895	50 541

The forecasted electricity consumption will grow to 42 000 TWh by 2050 and will be 50 500 TWh in 2100. The biggest growth will happen in China, which will be the biggest consumer of electricity by 2050 with consumption of about 12 000 TWh. The population in China will be about 1.4 billion by 2050, thus the specific consumption will be about 8 400 kWh/capita. This will correspond with the specific consumption in the EU.

The consumption of electricity in North America will grow from 5040 TWh in 2009 to 7870 TWh in 2100 or with 50%. In 2100 the specific electricity consumption has been forecasted to be 16 000 kWh/capita (Table 5.1.2).

The consumption in the European Union will increase from 3360 TWh to 3640 TWh by 2100 or with 8%. The specific consumption EU27-area will rise to about 8 500 kWh/capita by 2100. In 2008 the highest specific consumption in the EU27-area was in Finland or 16 000 kWh/capita.

Table 5.1.2 Specific consumption of electricity

Specific electricity	Hist	ory	Fore	cast
consumption	1990	2008	2050	2100
	kWh/capita	kWh/capita	kWh/capita	kWh/capita
North America	13 355	14 467	15 420	15 730
European Union	5 463	6 351	7 754	8 557
Other Europe	5 228	4 927	8 406	10 435
Japan	6 810	8 766	12 240	12 841
Latin America	1 149	1 858	3 406	4 586
Middle East	1 657	3 586	7 824	10 392
Africa	509	643	1 153	1 744
China	538	2 768	8 434	11 223
India	335	726	1 425	1 972
Rest of Asia Pacific	846	1 567	2 930	3 910
Total	2 244	2 942	4 579	5 616

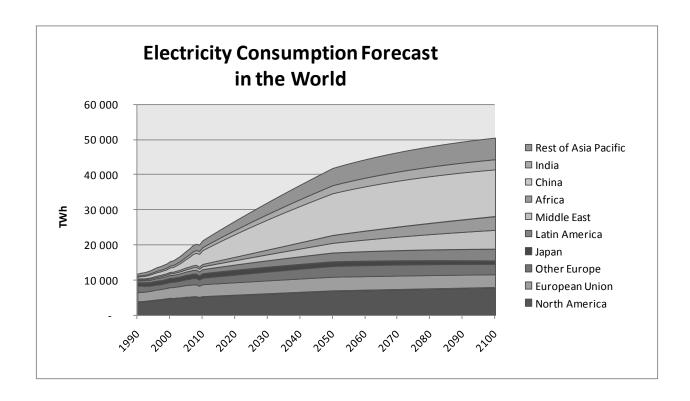


Figure 5.1.1 The forecasted electricity consumption of the world by continents

5.2 Priorities in electricity generation

5.2.1 Renewable energy programs in some countries

Because of CO₂-emissions most of countries have preferable electricity sources. These include renewable sources and combined heat and power (CHP) plants. Some of them are favored by subsidies or feed in tariffs, which make them profitable.

The EU has prioritized renewable energy sources so that they should cover 20% of the final energy use by 2020. The share of renewable electricity should be raised to 33% by 2020.

Finland should raise its share of renewable energy from 28% to 38% by 2020. This will mainly be done using wood in the heating boilers and CHP plants and wind power for electricity generation. Also feed-in tariffs have been introduced for wind power generation and wind could take about share of 5% of all electricity by 2020.

The UK has a long term program to increase its renewable energy share to 15% by 2020. The share of renewable electricity should increase from 5% to 29% in 2020 in the UK. Also small scale and micro generation should cover 1-2% of electricity. The UK has introduced the Renewable Obligation (RO) and feed-in tariffs in order to reach the goals.

In Germany the feed in tariffs for renewable energy sources has increased the solar and wind capacity very rapidly. The country aims to produce 35% of electricity by 2020 and 80% by 2050 by using renewable sources.

Many of the US states have same kind of system, called the Renewable Portfolio Standard (RPS), targeted to raise the renewable share in electricity generation by 2020 to 33% in California, 30% in Colorado, 27% in Connecticut and 20% in Kansas. Most of the US states similar targets.

Also China has now set a target to increase its renewable energy share to 15% by 2020. China has a program to install 500 GW of renewable electrical capacity by 2020. Hydro capacity additions will be 300 GW, wind 150 GW, biomass 30 GW and solar 20 GW. This will make China the biggest producer of renewable power.

It should be noted that nuclear plants are not favored by most countries. Several countries have programs to close down the existing nuclear plants. However, China has a program to increase its nuclear capacity to 80 GWe by 2020, to 200 GWe by 2030 and to 400 GWe by 2050. Thus China's nuclear power capacity in 2050 would be about the same as in the whole world today. However, this is much less than the target of 500 GWe renewable plants by 2020.

5.2.2 Capacity planning

In the next chapters a forecast of future generation in different parts of the world until 2100 will be given. The forecast have been made using a capacity planning model developed by the author. It includes capacity additions and retirements and the optimum running of the operating plants.

In the capacity planning of electricity systems for the years 2050 and 2100 it is therefore assumed that renewable energy sources have first priority. Combined heat and power plants will be built after renewable plants as second priority. Nuclear plants come after CHP plants in third priority.

Fossil fired plants will be built after nuclear plants in fourth priority starting with gas and oil plants. Coal plants will be built only if there will still be a need for additional capacity after all the other plants.

PRIORITIES IN CAPACITY PLANNING

- 1 Renewable plants (hydro, wind, bio, solar)
- 2 Combined heat and power plants
- 3 Nuclear power plants
- 4 Fossil power plants

5.3 Hydro

The main sources of renewable electricity are hydro, wind, biomass and solar. Hydro energy has been the biggest renewable source of electricity up to now. The world's hydro generation was 3200 TWh in 2009 (Figure 5.3.1). The forecasted hydro generation will increase to 5300 TWh in 2050 and to 6500 TWh in 2100 (Table 5.3.1).

Table 5.3.1 Generation of hydro electricity

	Hydro	generation		Hydro sha	re of generat	neration	
Area	2009	2050	2100	2009	2050	2100	
	TWh	TWh	TWh	(%)	(%)	(%)	
North America	700	816	906	13,9 %	11,8 %	11,5 %	
European Union	323	327	327	10,2 %	8,4 %	9,0 %	
Japan	477	499	515	25,3 %	15,4 %	16,4 %	
Rest of Europe	74	74	74	6,7 %	5,9 %	8,2 %	
Latin America	682	1 197	1 313	63,0 %	48,2 %	39,4 %	
Middle East	12	21	29	1,6 %	0,8 %	0,5 %	
Africa	99	384	1 088	15,7 %	17,3 %	27,9 %	
China	585	1 467	1 639	15,7 %	12,3 %	12,3 %	
India	115	252	324	13,2 %	10,9 %	11,3 %	
Rest of Asia Pacific	159	238	262	8,8 %	4,9 %	4,2 %	
Total	3 232	5 274	6 475	16,1 %	12,6 %	12,8 %	

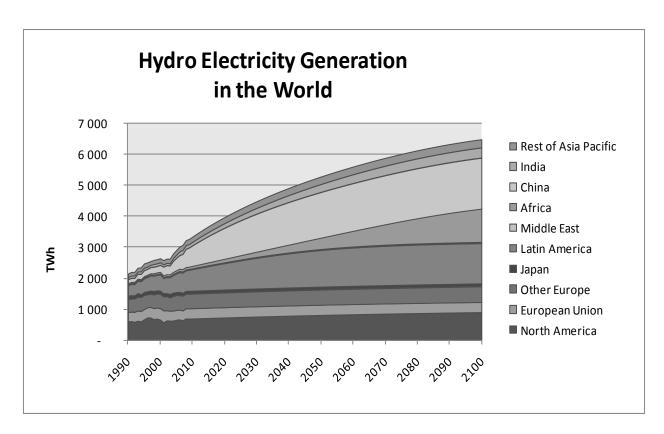


Figure 5.3.1 The forecast for hydro generation

The share of hydro power will decrease from 16% to 13% of electricity generation. The highest hydro share in 2100 will be in Latin America (39%). The hydro share will increase to 28% of generation in Africa, when most of the available resources will be built.

Hydro resources have been exploited in most European and North American countries. There are, however, a lot of economical hydro resources in South-America, Africa, China, India and in the Rest of Asia. China has the largest construction program with more than 60 GWe of new hydropower capacity under construction. There are also several large above 1000 MW hydro plants under construction in Argentina, Venezuela, India and Russia.

Hydro plants require large investments into power plants and transmission lines. Additionally the hydro storage reservoirs sometime require relocations of several cities or villages. Because hydro years have great variations, also reserve capacity for dry years is needed to be built.



Figure 5.4.1 Wind power has became the most important source of renewable electricity in Germany

5.4 Wind power

Wind energy has now the biggest growth potential of all renewable energy until 2050. The technology is already commercial in high wind areas, where the average wind speed is more than 7 m/s. It is also coming commercial in offshore installations, if conditions are good.

Investments into wind energy are now increasing at a rapid speed. In 2009 about 38 000 MWe of new wind power capacity was added into power system (Figure 5.4.2). The largest investors were North America, the European Union and China. In 2009 China was the biggest investor with 13 000 MWe of new wind power capacity.

The cumulative wind power capacity in the world is now about 200 GW. Thus wind power can generate about 400-500 TWh of electricity. The share of wind of power generation was 1.6% of electricity generation in 2009. Denmark generates about 20% of its electricity with wind power and has plans to increase the wind share to 30%. It has very favorable winds in the coastal areas of the North Sea.

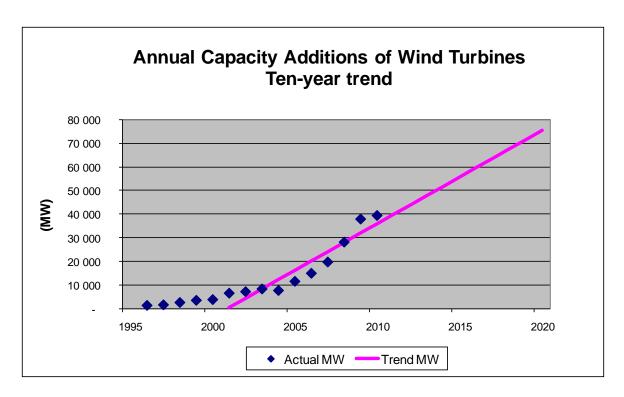


Figure 5.4.2 The capacity additions of wind power plants (Source: BP Energy Statistic 2011)

The US has also made plans to reach a 30% wind share. The best wind areas are in the Midwest on the eastern side of the Rocky Mountains. In the US the investments have been fluctuating depending on the tax benefits of the Federal Government.

It has been estimated that annual wind and wave capacity additions will reach 160 GW by 2100 (Figure 5.4.3). Wind power generation will then grow to 5 000 TWh by 2050 and 12 000 TWh by 2100 (Table 5.4.1). Wind will generate about 13% of electricity in 2050 and 24% in 2100.

Table 5.4.1 Wind and wave electricity generation

	Wind and Wave Generation Win					
Area	2009	2050	2100	2009	2050	2100
	TWh	TWh	TWh	(%)	(%)	(%)
North America	56	1 346	2 176	1,1 %	19,5 %	27,7 %
European Union	127	751	1 041	3,8 %	19,4 %	28,6 %
Japan	5	206	604	0,3 %	6,4 %	19,3 %
Rest of Europe	4	48	150	0,3 %	3,8 %	16,7 %
Latin America	2	177	730	0,2 %	7,1 %	21,9 %
Middle East	0	104	620	0,0 %	3,8 %	11,5 %
Africa	1	150	884	0,2 %	6,8 %	22,6 %
China	24	1 835	3 528	0,7 %	15,4 %	26,4 %
India	19	304	553	2,3 %	13,2 %	19,2 %
Rest of Asia Pacific	5	362	1 846	0,3 %	7,4 %	30,0 %
Total	244	5 284	12 134	1,2 %	12,6 %	24,0 %

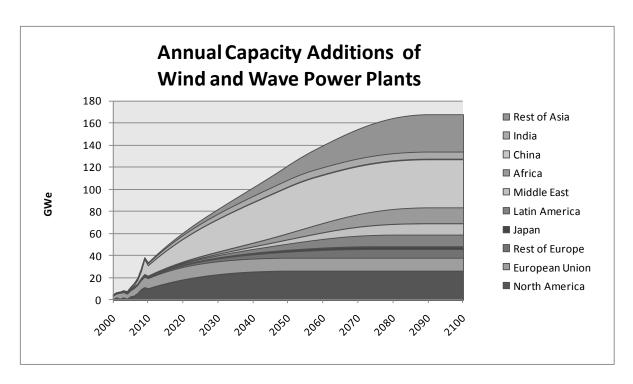


Figure 5.4.3 The forecasted capacity additions of wind and wave power

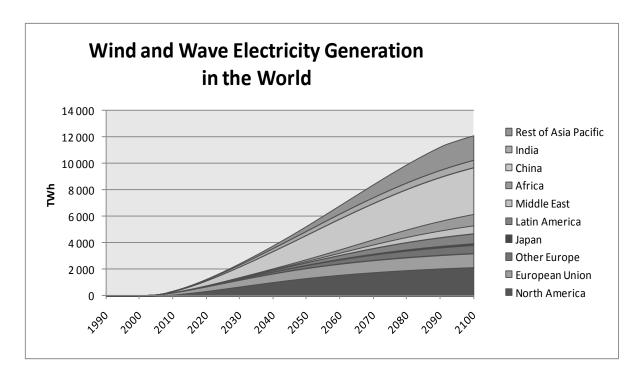


Figure 5.4.4 The forecasted wind and wave electricity generation (TWh)

5.5 Biomass

The largest potential source for the biomass energy is the forests. However, the forest area in world has reduced from 4160 million in 1990 to 4030 million hectares in 2010 (Table 5.5.1). The largest reductions have been in Latin America and Africa.

Table 5.5.1 Forest area (FAO 2010)

Forest area (Mha)	History			CI	Change from 1990		
	1990	2000	2010		2000		2010
North America	676,8	677,1	679,0		0,3		2,2
Latin America	978,1	932,7	890,8	-	45,4	-	87,3
Europe exl Russia	180,5	189,0	196,0		8,5		15,5
Russia	809,0	809,2	809,0		0,2		-
Africa	749,2	708,6	674,4	-	40,6	-	74,8
Asia	576,1	570,2	592,5	-	5,9		16,4
Oceania	198,7	198,4	191,4	-	0,3	-	7,3
Total	4 168	4 085	4 033	-	83	-	135

If the wood removal rate in the whole world would be the same as in Finland (Table 5.5.2), the world would be using 11.2 billion m³ of wood. This is the ultimate potential of biomass resource utilization in the future.

Electricity generation from wood biomass in Finland was 10.1 TWh in 2005. This corresponds specific electricity generation of 0.46 MWh/ha. If all of the world's forests would be developed to reach the same specific electricity generation as in Finland, the biomass electricity generation from wood fuels would be 1840 TWh. This is considered to be the potential electricity generation in 2100.

Table 5.5.2 Wood removal in Finland (FAO 2010)

Removal rate in Finland		1990	2000	2005
Forest area	Mha	21,90	22,50	22,16
Wood removal				
Roundwood	Mm3	43,84	55,72	55,15
Fuelwood	Mm3	3,37	5,11	5,93
Total	Mm3	47,21	60,83	61,08
Removal rate	m3/ha	2,16	2,70	2,76

Wood fired biomass power plants have been built for several decades by the paper industry companies for making pulp, where about 50% of the energy contents of the wood will be burned. The steam was used in the paper making process and also to generate electricity.

Today, also municipal power companies have built CHP plants, which generate heat for the district heating network. CHP plants generate about 30% of all electricity and about 50% of the heat needed in Finland and Denmark. The latest biomass plant was taken into commercial operation in Finland in Lappeenranta in 2010. The plant can generate 125 MWe of electricity, 152 MW of steam for paper mills and 110 MW of hot water for the district heating network of Lappeenranta city.

Also liquid biofuel (LBF) power plants have been built in EU countries, which have introduced feed in tariffs. One of the latest plants is the 50 MWe Unigrá LBF plant in Italy. It has three 16 MWe diesel engines and a 6 MWe steam turbine. The main fuel is palm oil. The benefit of palm oil is that it has the best yield per hectare of any vegetable oils. The best sites in Malesia give four tons of palm oil per hectare. A 50 MWe plant running 8000 h/a would generate 400 GWh of electricity. The palm oil need for the plant, which has 48% of electrical efficiency, is 83 000 tons annually. This can be produced with 20 000 hectares of palm tree forest. The electricity generation will then be about 20 000 kWh per hectare.

Biomass power plants have also been built by using biogas. The typical installation uses landfill gases in 0.1-5 MWe gas engines. The largest biogas plant in Finland has a 15 MWe output. The largest short term potential for biomass energy comes from forest wood removals, which have been about 3 Gm³ annually in the world. This corresponds to about 5000 TWh of primary energy. However, only 1.4 Gm³ (2400 TWh) of wood is used directly for energy production.

The estimated capacity additions of biomass plants will grow from 6 GWe in 2010 to 12 GWe in 2030 (Figure 5.5.1). The forecasted electricity generation by biomass will reach 1200 TWh in 2050 and 1570 TWh in 2100 (Table 5.5.1).

Table 5.5.1 Share of biomass and waste in electricity generation in 2050

	Biomass electricity generation			Share of biomass			
Area	2008	2050	2100	2008	2050	2100	
	TWh	TWh	TWh	(%)	(%)	(%)	
North America	32	110	142	0,6 %	1,6 %	1,8 %	
European Union	36	251	227	1,1 %	6,5 %	6,3 %	
Japan	3	132	271	0,2 %	4,1 %	8,7 %	
Rest of Europe	21	93	23	1,7 %	7,5 %	2,6 %	
Latin America	25	166	111	2,3 %	6,7 %	3,3 %	
Middle East	-	-	-	0,0 %	0,0 %	0,0 %	
Africa	0	36	48	0,1 %	1,6 %	1,2 %	
China	9	221	448	0,2 %	1,8 %	3,4 %	
India	5	70	94	0,6 %	3,0 %	3,3 %	
Rest of Asia Pacific	17	110	204	0,9 %	2,2 %	3,3 %	
Total	148	1 189	1 570	0,7 %	2,8 %	3,1 %	

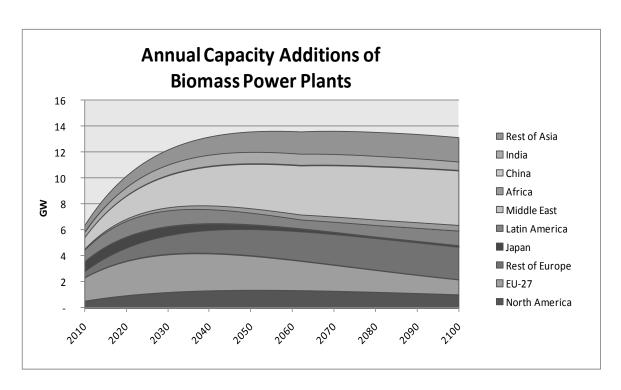


Figure 5.5.1 The forecasted biomass capacity additions

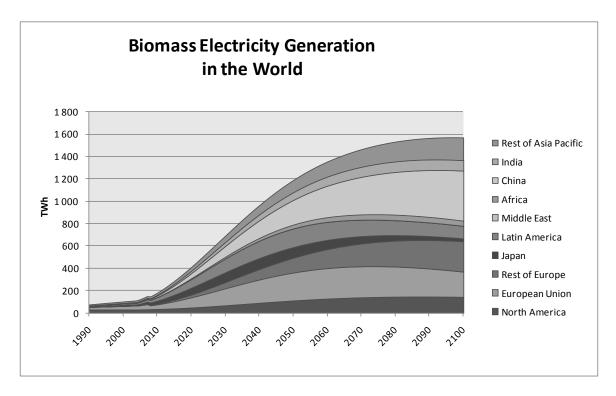


Figure 5.5.2 The forecasted electricity generation by biomass and waste will grow to 1600 TWh by 2100.

The growing stock of the living forests has diminished by 2.9 Gm^3 during the last twenty years (Table 5.5.2). The biggest losses have happened in Latin America and Africa. This loss has been caused mainly by reducing the forest areas. The specific stock of living forest has been growing from $127 \text{ m}^3/\text{ha}$ to $131 \text{ m}^3/\text{ha}$.

Table 5.5.2 The biomass stock in the world's growing forests in Gm³ (Source FAO 2010)

Growing stock (Gm3)		History	Change from 1990		
	1990	2000	2010	2000	2010
North America	74,9	76,9	82,9	2,0	8,0
Latin America	195,7	187,9	180,7	- 7,8 -	15,0
Europe exl Russia	23,8	27,5	30,5	3,7	6,7
Russia	80,0	80,3	81,5	0,2	1,5
Africa	83,0	79,9	77,0	- 3,1 -	6,1
Asia	51,3	52,5	53,7	1,2	2,3
Oceania	21,3	21,4	20,9	0,1 -	0,4
Total	530,1	526,5	527,2	- 3,6 -	2,9
Specific (m3/ha)	127,2	128,9	130,7	1,7	3,5

Biomass energy generation today also includes waste plants. In long term a biomass source will also be various sea bacteria, which could generate hydrogen, methane or other biomass energy sources by using sunlight. It has been estimated that now about 1 % of energy sun radiation has been converted into biomass. With the new plantation this ratio can be increased to nearly 10%.

5.6 Solar power

Solar power is also coming onto the market place. It has been used commercially in small scale in off grid applications for a long time. Photo voltage (PV) cells have been excellent source of electricity in off-grid summer cottages. They have been used in Finland for some twenty years and some 10% (50 000) of all Finnish summer cottages have solar electricity.

Now also grid connected PV-systems have been built (Figure 5.6.1) by utilities. Most of the small installations have been built on the roof tops of residential and commercial buildings. Some countries have established special programs that give subsidies or feed-in tariff for 20 years. Germany and Spain have been leading the development in Europe. They both have more than 20 large (>20 MW) PV power plants on the grid. In 2009 capacity of the new PV power plants connected on the grid was 7300 MWe.



Figure 5.6.1 A large solar PV power plant

Table 5.6.1 The share of solar electricity generation in 2050 and in 2100

Area	Solar electricity generation			Solar share of generation		
	2009	2050	2100	2009	2050	2100
	TWh	TWh	TWh	(%)	(%)	(%)
North America	2,6	199	2 089	0,0 %	2,9 %	26,6 %
European Union	24,1	572	804	0,7 %	14,7 %	22,1 %
Japan	0,4	15	298	0,0 %	0,4 %	9,5 %
Rest of Europe	3,9	49	146	0,3 %	3,9 %	16,3 %
Latin America	0,4	15	299	0,0 %	0,6 %	9,0 %
Middle East	0,4	28	1 425	0,1 %	1,0 %	26,4 %
Africa	0,2	14	713	0,0 %	0,6 %	18,3 %
China	0,5	80	2 164	0,0 %	0,7 %	16,2 %
India	0,6	27	567	0,1 %	1,2 %	19,7 %
Rest of Asia Pacific	0,6	30	979	0,0 %	0,6 %	15,9 %
Total	34	1 026	9 484	0,2 %	2,4 %	18,8 %

The largest solar power plants are concentrating solar thermal (CST) plants, where solar radiation is concentrated into a steam boiler plant, which generates steam for a conventional thermal power plant. Spain has now seven large (>20 MW) solar thermal plants on the grid. The largest plant has a 354 MW capacity and it has been built in the Mojave Desert in California. The total installed CST capacity in the world is now about 1000 MW and there is 1900 MW of new capacity under construction.

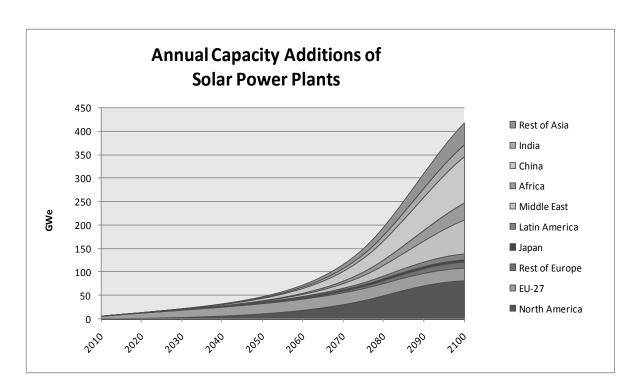
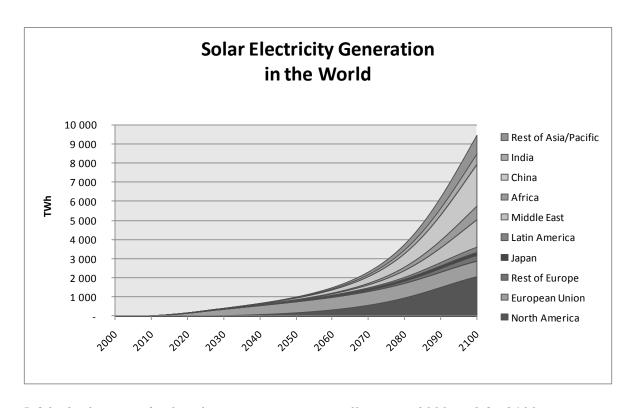


Figure 5.6.2 The forecasted annual Solar capacity additions



5.6.3 The forecasted solar electricity generation will grow to 9000 TWh by 2100.

There are now plans to build mega-size plants in the Sahara desert in Africa and transfer the electricity to Europe. Some are also thinking that solar PV plants could be built in outer space and transmit the electricity with micro waves or laser beams. They are both possibilities that will need further studies.

According to my forecast solar electricity generation will grow to 1000 TWh and will cover about 2.4 % of electricity in 2050 (Table 5.6.1). The biggest growth of solar power will happen after 2050, when the best sites of hydro and wind have been built. In 2100 solar electricity will cover 9500 TWh and 19 % of electricity consumption.

5.7 Municipal CHP

Municipal combined heat and power (CHP) plants generate district heat and electricity. They have been built mainly in Northern Europe and Russia, where the winter is long and district heating networks have been built in most cities.

In Finland district heating covers 47% of overall heat energy consumption. About 90 % of the people in Helsinki live in the houses that have district heating. The total consumption of district heat in Finland in 2009 was 34.2 TWh or 6.4 MWh/person. The electricity generated with CHP plants was 14.8 TWh or 2.8 MWh/person.

The electricity per heat value, alpha, was 0.43, which shows that it is still possible to construct new CHP plants in many Finnish cities. I have evaluated the CHP potential in my earlier book (*Planning of Optimal Power Systems*) that there is still possibility to increase the Finnish municipal CHP capacity from 3100 MWe to 4000 MWe or to 750 W/capita.

The biggest potential for municipal CHP plants is however in Russia and China, which can in theory satisfy their short term electricity needs with municipal CHP plants. The municipal CHP potential in Russia's largest cities (with more than 50 000 inhabitants) is 169 GWe (1180 W/capita). These plants can generate 844 TWh of electricity (Table 5.7.1). Thus about 80% of electricity in Russia could be generated by municipal CHP plants and all large cities could be independent of outside electricity.

Table 5.7.1 CHP potential of the large cities (above 50 000 inhabitants) in Russia

CHP potential of	Popu-	Heat	CHP	CHP	CHP
the largest cities	lation	demand	electr.	electr.	electr./cap
in Russia	1000	TWh	GWe	TWh	kWh/cap.
Large cities >100000	68 424	821	151	753	11 000
<100000 but>50000	10 982	110	18	92	8 333
Total	79 406	931	169	844	10 631

This is theory, but because of the organizational limitations, the potential cannot be fully realized. I was working for the utility company Imatran Voima in 1990, when we planned to build a 450 MW gas CHP plant in Saint Petersburg. The plant was commissioned during the 1990's but it took about ten years before the heat could be connected to the district heating network.

In Russia the district heating companies and power generation companies have different owners and they have difficulties to make energy purchases with each other. In Finland most of the district heating companies and local power producers are owned by the same city and thus several cities are independent of outside electricity.

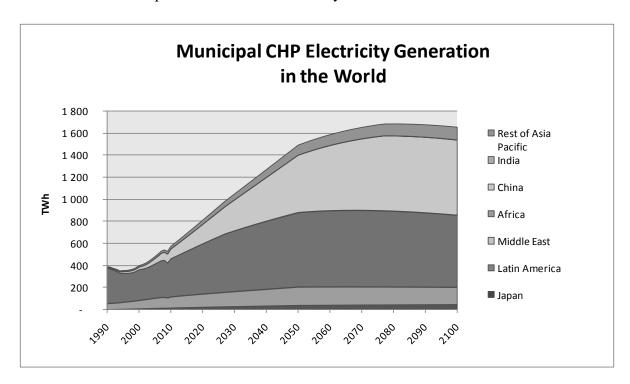


Figure 5.7.1 The forecast for municipal CHP electricity generation until 2100

The typical CHP potential in cities that have natural gas available is about 2 kW/capita. All cities which have more than 5 000 inhabitants living in the district heating houses can build CHP plants. The typical gas engine CHP plant for a small city has a 10 MW electrical output and a 9 MW heat output. The plant generates 50 GWh of electricity and 45 GWh of heat.

The global municipal CHP generation is forecasted to increase to 1700 TWh by 2100 (Figure 5.7.1). The share of municipal CHP electricity will increase to 3.3% by 2100 (Table 5.7.1). The largest share, 21% of municipal CHP electricity generation will be in Europe outside European Union. This includes Russia, which has the largest CHP potential in Europe.

Table 5.7.2 The forecast of municipal CHP generation

	Municip	al CHP gene	eration	Share of municipal CHP			
Area	2009	2050	2100	2009	2050	2100	
	TWh	TWh	TWh	(%)	(%)	(%)	
North America	17,0	42,3	49,8	0,3 %	0,6 %	0,6 %	
European Union	90,9	165,2	155,1	2,9 %	4,3 %	4,3 %	
Rest of Europe	316,1	674,4	653,5	16,7 %	20,8 %	20,9 %	
Japan	0,9	1,9	1,4	0,1 %	0,2 %	0,2 %	
Latin America	-	-	-	0,0 %	0,0 %	0,0 %	
Middle East	-	-	-	0,0 %	0,0 %	0,0 %	
Africa	-	-	-	0,0 %	0,0 %	0,0 %	
China	79,8	518,2	680,2	2,1 %	4,3 %	5,1 %	
India	-	-	-	0,0 %	0,0 %	0,0 %	
Rest of Asia Pacific	23,7	90,2	115,6	1,3 %	1,8 %	1,9 %	
Total	528	1 492	1 656	2,6 %	3,6 %	3,3 %	

Also China and the EU will increase their municipal CHP share to 5% of electricity generation. The municipal CHP plants are almost totally missing in North America because the natural gas is delivered into most of the houses in large cities. The consumption of gas is still increasing and it is still used in the most of the new houses. However, micro CHP generation has the largest potential in North America, because of the existing gas network.

In southern countries heating is needed only for less than half the year and district heating networks would hardly be economical. However, micro generation has some potential in all areas that have a natural gas network available.

5.8 Industrial CHP generation

Industrial combined heat and power plants generate mostly process steam and electricity. Typical plants in Finland are being used in the pulp and paper industry, where heat is generated from wood in the pulp mill and the generated electricity and steam of the CHP plant is used by the paper machines. Same kind of CHP plants have been used in chemical factories and refineries, both of which need a lot of steam. Also smaller scales of CHP plants have been built in bakeries, glass factories etc.

CHP electricity can cover the electricity needs of many industrial companies. The biggest industrial CHP generation is now in North America and China (Figure 5.8.1). The share of industrial CHP electricity is increasing from 8 % today to about 9 % in 2100 (Table 5.8.1). Very large potential is in the Middle East, which will build refineries and will need a lot of heat in desalination plants in the future.

Table 5.8.1 The forecast of industrial CHP generation

Indusrial CHP	Industr	ial CHP gene	ration	Industrial CHP share			
Generation	2009	2050	2100	2009	2050	2100	
	TWh	TWh	TWh	(%)	(%)	(%)	
North America	426	704	799	8,5 %	10,2 %	10,2 %	
European Union	236	365	342	7,4 %	9,4 %	9,4 %	
Rest of Europe	203	299	288	10,7 %	9,2 %	9,2 %	
Japan	48	65	47	4,3 %	5,2 %	5,2 %	
Latin America	24	67	115	2,2 %	2,7 %	3,5 %	
Middle East	27	326	858	3,5 %	11,8 %	15,9 %	
Africa	3	15	26	0,5 %	0,7 %	0,7 %	
China	432	1 497	1 570	11,6 %	12,5 %	11,8 %	
India	48	155	194	5,5 %	6,7 %	6,7 %	
Rest of Asia Pacific	75	240	299	4,2 %	4,9 %	4,9 %	
Total	1 523	3 733	4 539	7,6 %	8,9 %	9,0 %	

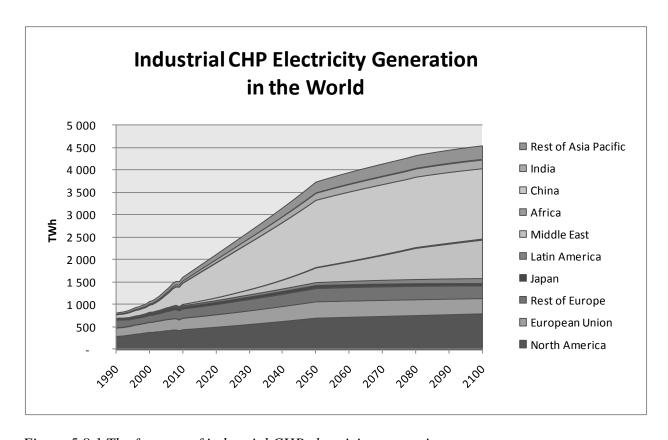


Figure 5.8.1 The forecast of industrial CHP electricity generation

5.9 Summary

5.9.1 Renewable energy sources

The renewable electricity generation could reach 30 000 TWh in 2100 (Figure 5.9.1) and cover 59% of all electricity. Wind power will be the biggest contributor of renewable electricity in 2100 and generate 23% of world electricity. Solar power will be the second and generate about 18% of electricity. Renewable electricity will grow in each of the areas (Figure 5.9.2).

Hydro, wind and solar power can cover the growth after 2050. Thus before 2050 also other new capacity, such as nuclear and CHP-power plants will be needed to reduce the CO₂-emissions. CO₂-separation has not been introduced yet, thus its use is speculative. The only real alternative today in order to cut the emissions is to build more nuclear power, which is also the most cost effective alternative.

In 2050 the share of renewable electricity share in the world will be 31% (Table 5.9.1) and the highest in Latin America (63%) and the European Union (49%). By 2100 the renewable share in the world will rise to 58% and to 74% in Latin America.

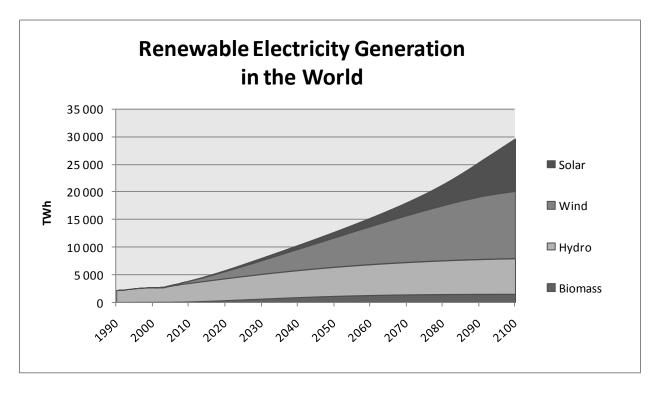


Figure 5.9.1 Renewable energy could generate 30 000 TWh in 2100

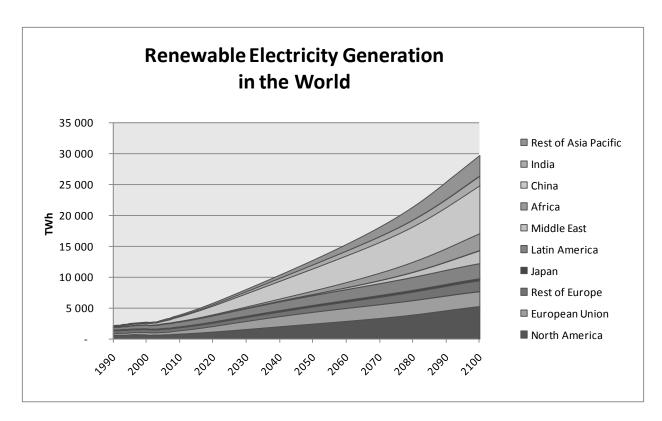


Figure 5.9.2 The forecast of renewable electricity generation in different areas

Table 5.9.1 The forecast of renewable electricity shares in 2050 and 2100

	Renewable	electricity	generation	Ma	rket Share	
Area	2009	2050	2100	2009	2050	2100
	TWh	TWh	TWh	%	%	%
North America	813	2 471	5 314	16,1 %	35,7 %	67,6 %
European Union	537	1 901	2 400	16,9 %	49,0 %	66,0 %
Rest of Europe	489	851	1 688	25,9 %	26,3 %	53,9 %
Japan	105	264	393	9,4 %	21,2 %	43,8 %
Latin America	732	1 554	2 454	67,6 %	62,6 %	73,7 %
Middle East	12	153	2 074	1,6 %	5,5 %	38,4 %
Africa	100	584	2 732	15,9 %	26,2 %	70,0 %
China	678	3 604	7 779	18,2 %	30,2 %	58,3 %
India	135	652	1 538	15,5 %	28,4 %	53,5 %
Rest of Asia Pac	189	740	3 291	10,5 %	15,1 %	53,5 %
Total	3 790	12 773	29 662	18,9 %	30,5 %	58,7 %

5.9.2 CHP electricity generation

CHP electricity generation is also increasing and it could reach 6200 TWh in 2100 (Figure 5.9.3). The CHP share in the world is increasing from 10% in 2009 to about 12% in 2100.

In 2100 the largest CHP electricity generator will be China with 2250 TWh (Table 5.9.2), because China will be the biggest industrial producer and will also have municipal CHP

generation. The rest of Europe will be in second place after China, and will generate 940 TWh of electricity by using CHP plants. Russia has been the biggest market for municipal CHP, which will make it larger than the European Union or North America.

The largest CHP share will be in Eastern Europe, including Russia, which will generate 30% of its electricity by using CHP power plants. China and the Middle East could get 16% of electricity from CHP plants by 2100.

Table 5.9.2 The forecast of total CHP electricity generation

	CHP ele	ectricity gene	ration	CHP electricity share			
Area	2009	2050	2100	2009	2050	2100	
	TWh	TWh	TWh	(%)	(%)	(%)	
North America	443	746	849	8,8 %	10,8 %	10,8 %	
European Union	327	530	497	10,3 %	13,7 %	13,7 %	
Rest of Europe	519	973	941	27,5 %	30,1 %	30,1 %	
Japan	49	67	48	4,4 %	5,4 %	5,4 %	
Latin America	24	67	115	2,2 %	2,7 %	3,5 %	
Middle East	27	326	858	3,5 %	11,8 %	15,9 %	
Africa	3	15	26	0,5 %	0,7 %	0,7 %	
China	512	2 015	2 250	13,7 %	16,9 %	16,9 %	
India	48	155	194	5,5 %	6,7 %	6,7 %	
Rest of Asia Pacific	99	330	415	5,5 %	6,7 %	6,7 %	
Total	2 051	5 225	6 194	10,2 %	12,5 %	12,3 %	

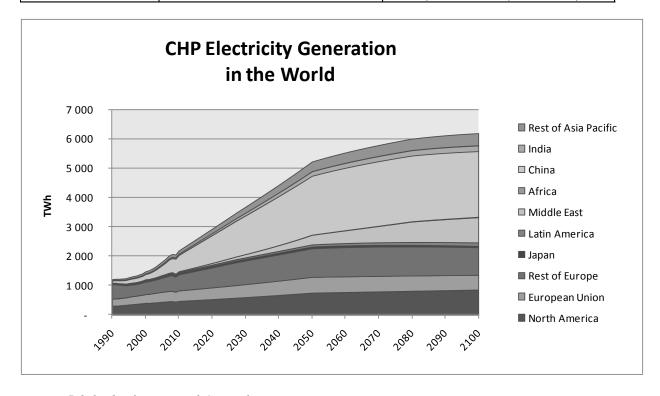


Figure 5.9.3 The forecast of CHP electricity generation

5.9.3 Preferable electricity generation

The preferable electricity generation sources including renewable and CHP power plants, can satisfy the growth of electricity needs only after 2050. In 2100 they could cover 71% of the electricity generation in the world (Figure 5.9.4). The rest of the consumption can be satisfied with nuclear and fossil fired power plants. With nuclear power plants the CO₂-emissions can be reduced already before 2050.

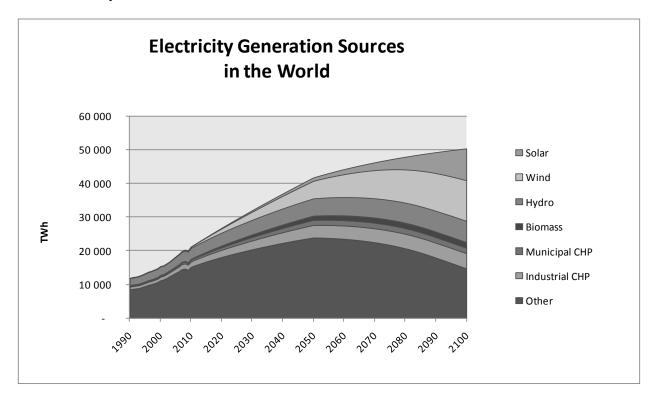


Figure 5.9.4 Hydro, wind, biomass, solar and CHP power plants could cover 71% of electricity consumption in 2100. These sources will satisfy the growth in electricity consumption only after 2050

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6 NUCLEAR ELECTRICITY PLAN UNTIL 2100

6.1 Uranium resources

6.1.1 History

Uranium-235 has been the main resource for nuclear power until now and it also will continue to be for the near future. Also thorium-232 can be used in nuclear reactors, but it will require breeding to uranium-233. Plutonium-239 is the third nuclear energy source, but it will require the reprocessing of spent fuel.

Natural uranium has mainly two isotopes, U-235 and U-238. The fissionable fraction is U-235, which content is 0.71 % in natural uranium. The rest, 99.29 %, is U-238. Five billion years ago, when the earth was created, the both isotopes were equally common. U-238 has a half life of 4.5 billion years and its concentration is now in half of that in the beginning of birth of earth.

U-235 has been splitting to lighter atoms as its half life is 700 million years. As a matter of fact after some billion years from now U-235 isotopes will be disappearing, even if it will not be used in reactors at all. U-238 is more stable and 140 times more abundant. But the fission of U-238 can be caused practically only with fast neutrons and fast reactors.

Uranium was found in the **Joachimsthal** silver mine near Prague in 1850. The silver mine was in use from the 16th century and its product were used for silver coins. Actually the names of dollar, daler (Sweden) and taaleri (Finland) originate from the name Joachinsthaler, of which Thaler is an abbreviation and was used to measure the value of the coin. The uranium from this mine was used by Marie Curie in her experiments with radioactivity. From this ore she could isolate radium and polonium. Also first loadings of the German nuclear experiments used the uranium from the Joachimsthal mine.

Uranium was also found in the Belgian Congo before the Second World War. Most of the Belgian uranium was evacuated from Belgium to the US before the Germans occupied the country in 1940. The same uranium was then used in the development of nuclear bombs. In the US uranium was also found in Colorado. Canadian uranium was also used during the war time. Today the main uranium resources are in Australia, Kazakhstan and Canada.

6.1.2 Uranium consumption in LWR

The uranium need of a nuclear reactor can be optimized by using the typical 1500 MWe light water reactor parameters and estimated prices of uranium and enrichment (Table 6.1.1). The burn up of fuel in new reactors will be about 50 MWd/kgUHM, where MWd is the energy unit (Megawattdays, 24 MWh) and kgUHM is the kilograms of heavy metal or uranium in the fuel.

Table 6.1.1 Need for uranium in Light Water Reactor (LWR) power plants

Reactor type		Old LWR	New LWR				
Uranium price	USD/kgU	65	65	130	130	260	260
Tails assay	%	0,30 %	0,30 %	0,30 %	0,20 %	0,20 %	0,15 %
Electrical output	MWe	1 500	1 500	1 500	1 500	1 500	1 500
Load factor	%	80 %	90 %	90 %	90 %	90 %	90 %
Electricity generation	TWh/a	10,52	11,83	11,83	11,83	11,83	11,83
Efficiency	%	32 %	34 %	34 %	34 %	34 %	34 %
Reactor output	MWt	4 688	4 412	4 412	4 412	4 412	4 412
Thermal energy	GWh	32 873	34 806	34 806	34 806	34 806	34 806
Thermal energy	GWd	1 370	1 450	1 450	1 450	1 450	1 450
Burn up	MWd/kgUHM	36,0	50,0	50,0	50,0	50,0	50,0
Fuel load fractions	number	3	4	4	4	4	4
Enrichment	%	3,2%	4,0%	4,0%	4,0%	4,0%	4,0%
Enriched uranium need	kgUHM/a	38,0	29,0	29,0	29,0	29,0	29,0
Natural uranium need	kgU/kgUHM	6,8	9,2	9,2	7,4	7,4	6,7
Natural uranium need	tU/a	260	266	266	214	214	195
Enricment need	tSWU/a	137	157	157	188	188	211
Uranium price	USD/kgU	65	65	130	130	260	260
Conversion price	USD/kgU	8	8	8	8	8	8
Enrichment price	USD/kgSWU	150	150	150	150	150	150
Fabrication price	USD/kgU	300	300	300	300	300	300
Waste disposal	USD/kgU	1 000	1 000	1 000	1 000	1 000	1 000
Uranium costs	kUSD/a	18 632	19 087	38 174	30 704	61 407	55 934
Conversion costs	kUSD/a	2 293	2 349	2 349	1 889	1 889	1 721
Enricment costs	kUSD/a	21 532	24 803	24 803	29 544	29 544	33 258
Fabrication	kUSD/a	11 696	8 916	8 916	8 916	8 916	8 916
Back end	kUSD/a	38 047	29 005	29 005	29 005	29 005	29 005
Total	kUSD/a	92 199	84 161	103 248	100 058	130 762	128 835
Total	EUR/MWhe	7,01	5,69	6,98	6,76	8,84	8,71

Thus 50 MWd/kgU corresponds to 1200 000 kWh/kgU. The heat value of crude oil is 11.62 kWh/kg. Thus one kilogram of uranium gives 100 000 times more energy than crude oil. With today's prices the fuel cost of electricity produced by a LWR plant is €5.7/MWh. This can be compared with the fuel cost of a modern coal plant, which is about €20/MWh.

The natural uranium need of a 1500 MWe LWR plant with 90 % load factor is 266 tons annually with 0.3 % tails assay. Tails assay is the U-235 content in the waste uranium in an enrichment plant. Tails assay will be optimized this depending on the price of uranium. If the price of uranium rises it will be economical to lower the tails assay and take more U-235 from the ore. If the price of uranium will rise to \$130/kgU, the tails assay will be dropped to 0.20 %. Thus with a higher uranium price the uranium can be utilized more thoroughly and less uranium is needed. The same power plant will consume 214 tons of uranium annually. It can also be noted that if the uranium prices rise by 100 %, the fuel costs will rise to €6.8/MWh or by 20 %.

If the price of uranium will rise to \$260/kgU, the tails assay will be dropped to 0.15 %. The fuel costs will rise to €8.7/MWh. The fuel costs are then only 29 % higher than with \$130/kgU. The natural uranium need will drop to 195 tons of uranium annually.

6.1.3 Resources of uranium

The uranium resources with cost less than \$130/kgU have been identified to be 5.5 million tons (Table 6.1.2). There are also additional conventional resources, which are about 10.5 million tons. With the present consumption levels the resources will last for about 240 years. If new 1500 MWe LWR plants will be built and the uranium tails assay is 0.2 %, they uranium resources can support 1870 GWe of nuclear capacity for 60 years.

Table 6.1.2 Uranium resources and nuclear capacity supported by the \$130/kgU resources

Basic data (2008)		
Nuclear power capacity	365	GWe
Nuclear generation	2 739	TWh
Uranium consumption	67	kt/a
Resources *		
Identified resources	5 500	kt
Other resources	10 500	kt
Total conventional resources	16 000	kt
Depletion time with present capacity		
Identified resources	82	years
Other resources	157	years
Total conventional resources	239	years
Capacity supported for 60 years		
Identified resources	643	GWe
Other resources	1 227	GWe
Total conventional resources	1 869	GWe

^{*} Source: INEA Position Paper 2008

However, the fuel costs of a LWR plant are moderate also with \$260/kgU resources. Those resources have not been identified, but will be much higher than \$130/kgU resources given in Table 6.1.2. With a \$260/kgU price also several new sources of uranium will become profitable. These include uranium from rock or sea water.

The resources in the land can be estimated by using the formula $R = 15 \text{ MtU x } (P/130)^3$, where P is the price of uranium (\$/kgU). If the price of uranium is \$260/kgU, the resources could be 8x16 or 96 million tons of U. Additionally the uranium resources in sea water are about 5 billion tons of U, but the costs of separation are not known.

6.2 Breeder reactors

6.2.1 Plutonium breeder reactors

Breeder reactors can convert U-238 into plutonium-239 (Pu-239) in neutron radiation. Liquid metal fast reactors (LMFBR) are already in operation in Russia and very many other fast reactor types are in the development. They have been planned to continue the nuclear generation after the uranium resources have been used.

The population of the world will be stabilized at 9 billion in 2100 and global electricity consumption will be stabilized at 50 PWh. Assuming 30% of future electricity will be generated by nuclear sources, 15 PWh of nuclear electricity is needed. This can be generated by breeder reactors with a capacity of 2000 GWe.

Assuming that a breeder reactor consumes 1/60 of the uranium of the light water reactor, then a 1500 MW plant will need about 200 tU/60 or 3.3 tons annually. The capacity of 2000 GWe therefore needs about 4 400 tons of uranium annually. The uranium need for the next thousand years is thus about 4.4 billion tons. The uranium consumption is only 1/60 of that of the LWR, thus the price of uranium can be ten times higher. If the price of uranium is \$1300/kgU, the resources could be 15 billion tons of U.

However, plutonium breeder reactors need reprocessing, where the plutonium is separated from the waste fuel. This is a safety issue as the plutonium might be used for making nuclear weapons. This is the reason why the forecasts made in this book assume that the breeders will be only built in existing nuclear weapon countries that have the necessary nuclear waste reprocessing facilities available.

In 2050 when the plutonium breeder reactors should be available also many renewable technologies will be competing with the nuclear plants. Solar plants may have become competitive during this time. Also thorium breeder reactors may replace plutonium breeders.

It is very difficult to say whether the breeder reactors will come commercial. Today the investment costs would be much higher than those of LWR reactors. The extra investment costs of breeder reactors have been estimated to be 30-100% at the moment.

If breeder reactor power plants have $\[mathcal{\in}\]1000\]$ kWe higher investment costs than the LWR plants, then the generation costs of electricity will be $\[mathcal{\in}\]12\]$ MWh higher than with LWR's, other costs being equal. If the price of uranium will rise from \$130 to \$260\]kgU, the fuel costs of LWR plant will increase from $\[mathcal{\in}\]6.8$ to $\[mathcal{\in}\]8.7\]$ MWh or with $\[mathcal{\in}\]1.9\]$ MWh (Table 6.1.1). Thus it is more economical to use the $\[mathcal{\in}\]260\]$ kgU uranium than build breeder plants, which have more than $\[mathcal{\in}\]1.75$ kWe higher investment costs than the LWR plants.

6.2.2 Thorium breeder reactors

The thorium resources have been estimated to be about four times of uranium resources. The content of thorium in the earth's crust is 10 grams per ton. Thorium can be used as fertile material in uranium or plutonium reactors, where thorium-232 is converted into uranium-233 by capturing one neutron.

The low cost thorium resources (<\$80/kg price) are 3.8 million tons (Table 6.2.1). One 1000 MWe reactor uses 1 ton of thorium annually. Thus the 3.8 million tons of known thorium reserves can fuel 3800 GWe capacity for thousand years. If the price increases tenfold (to \$800/kg), the resources will be about 4 billion tons. With these resources all electricity needed in the world could be generated with thorium reactors for a million years.

Table 6.2.1 Reasonable assured resources (RAR) and estimated additional resources (EAR) of thorium in some countries in kilotons (kt)

Thorium resources	RAR	EAR	TOTAL
	kt	kt	kt
Brazil	606	700	1306
Turkey	380	500	880
India	319		319
United States	137	295	432
Norway	132	132	264
Greenland	54	32	86
Canada	45	128	173
Australia	19		19
South Africa	18		18
Egypt	15	309	324
Total	1725	2096	3821

Source: Thorium Fuel Cycle. IAEA 2005

Thorium is a good alternative for fast reactors with plutonium cycles. Thus it could come after light water reactors as the next choice before the fast breeder reactors. In the following analysis the breeder reactors will be combined under one name, Breeder Reactors (BR), but they can be any of the types discussed.

It is very difficult to see which of the different breeder reactors become commercially available by 2050. It is also possible that none of them will, if other technologies develop faster. However, there will be plenty of thorium, uranium and spent fuel resources available to support electricity generation for the next million years.

India has already built a thorium test plant (**Kakrapar-1**) and has a 300 MW heavy water thorium nuclear plant under construction. India's thorium resources are about 319 000 tons. These resources could be enough for a Indian 319 GWe nuclear power program for a thousand years.

6.3 A plan until 2100

The electricity generation of the existing nuclear power plants peaked at 2800 TWh in 2006 (Figure 6.3.1). After this date the electricity generation by existing nuclear plants has been going down because many of the plants are old and they will be decommissioned. By 2060 almost all of the existing plants will be decommissioned.

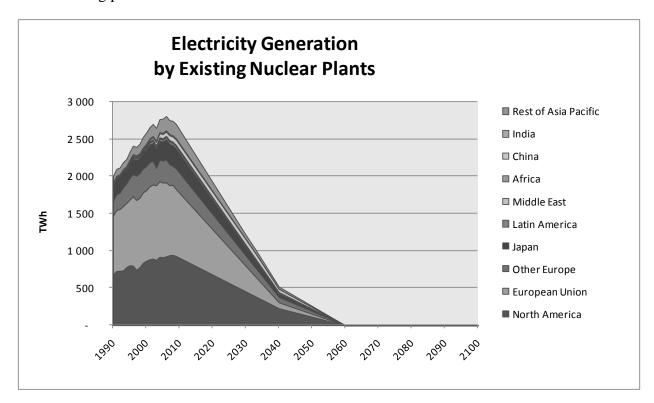


Figure 6.3.1 The electricity generation forecast of the existing nuclear power plants

The capacity additions of new nuclear plants until 2100 have been estimated in Figure 6.3.2. The annual capacity additions should reach a 65 GWe level by 2030 in order to close down the old coal fired plants as soon as possible. However, after 2050 capacity additions should be reduced because new renewable capacity will be gaining market share in North America and the European Union.

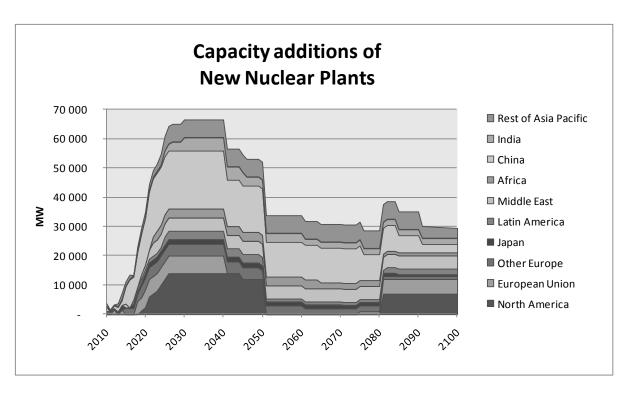


Figure 6.3.2 Forecast of capacity additions of new nuclear power plants globally

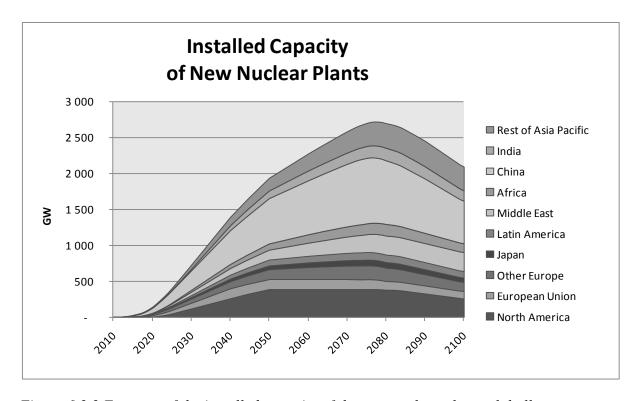


Figure 6.3.3 Forecast of the installed capacity of the new nuclear plants globally

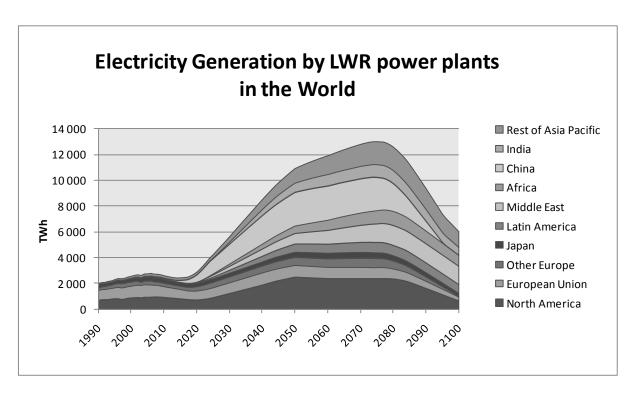


Figure 6.3.4 Forecast of electricity generation using LWR power plants

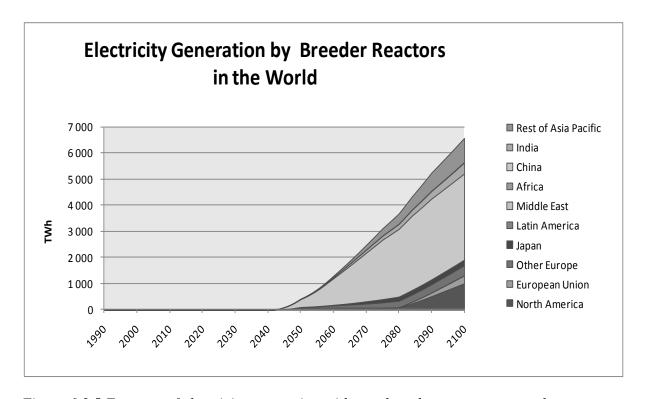


Figure 6.3.5 Forecast of electricity generation with new breeder reactor power plants

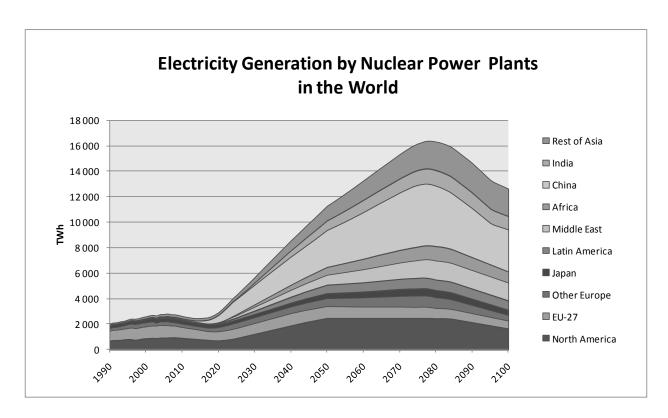


Figure 6.3.6 Forecast of nuclear electricity generation in the world until 2100

If the new nuclear plants will have a 60 year operation time, the installed capacity of the new nuclear power plants will peak at 2700 GWe in 2080 (Figure 6.3.3). Thereafter the capacity will start to decrease, while renewable generation will start to increase its market share also in the developing countries and nuclear power will not be needed as urgently.

The electricity generation of LWR power plants will peak at 13 000 TWh in 2080 (Figure 6.3.4). The new breeder reactor power plants will start operation in 2050 and will reach 5500 TWh by 2100 (Figure 6.3.5).

The electricity generation of nuclear power plants (LWR's and Breeders) will peak at 16 000 TWh in 2080 (Figure 6.3.6). Thereafter nuclear electricity generation will go down, as renewable electricity sources will start gaining market shares.

The nuclear share of electricity generation is forecasted to rise from 13% in 2009 to 27% in 2050 and to 34% in 2075; when nuclear plants will be the biggest contributor of electrical energy (Table 6.3.1). The nuclear share will then decrease to 25% by 2100 as renewable energy sources gain market shares.

Table 6.3.1 Forecast of nuclear power generation and the nuclear share of electricity

	Nuclear electricity generat				Nuclear share				
Area	2009	2050	2075	2100	2009	2050	2075	2100	
	TWh	TWh	TWh	TWh	%	%	%	%	
North America	944	2 460	2 460	1 637	18,0%	35,6%	33,3%	20,8%	
EU-27	940	941	886	631	28,0%	24,3%	23,3%	17,4%	
Other Europe	283	386	906	445	14,3%	11,9%	27,3%	14,2%	
Japan	252	647	552	428	21,3%	51,9%	50,7%	47,6%	
Latin America	31	635	801	694	2,9%	25,5%	27,1%	20,9%	
Middle East	-	804	1 424	1 415	0,0%	29,0%	34,6%	26,2%	
Africa	13	605	1 052	870	2,1%	27,2%	34,8%	22,3%	
China	68	2 909	4 856	3 308	2,0%	24,3%	36,6%	24,8%	
India	15	739	1 147	1 034	1,8%	32,1%	43,1%	36,0%	
Rest of Asia	194	1 137	2 067	2 151	10,8%	23,2%	36,6%	34,9%	
Total	2 741	11 261	[*] 16 151	12 613	13,5%	26,9%	34,2%	25,0%	

The nuclear share of electricity in 2100 will remain at about the same level as today in North America. In the EU the nuclear share will decrease because of extensive programs for renewable electricity. The biggest share of nuclear power (50%) is forecasted to be in Japan, which does not have large renewable energy sources in the short term.

China will be the biggest generator of nuclear power by 2050 and the nuclear share in China will be 24%. The nuclear electricity generation in China in 2100 (3300 TWh) will be more than the total world is generating today. China has large potential to generate up to 50% of its electricity by using nuclear plants, but this requires that the breeder reactors will become competitive by this time.

6.4 Consumption of uranium

A nuclear program was planned in chapter 6.3 by building 65 GWe of new nuclear capacity annually. This is equivalent of 43 new units annually with 1500 MW each. Then after 2050 the new LWR reactors should be followed by breeder reactors which will use the spent fuel of LWR reactors as a primary fuel and depleted uranium-238 or thorium as the fertile material. After 2050 both LWR and breeder power plants will be built in parallel with gradually increasing the share of breeders (Figure 6.4.1).

Nuclear power capacity would peak at 2500 GWe in 2080 (Figure 6.4.2). Nuclear generation would reach 19 000 TWh in 2080 (Figure 6.4.3). By then about 20% of the nuclear capacity should be breeder reactors. In 2100 the nuclear power capacity will be 2000 GWe and about 30% of the capacity would be breeders.

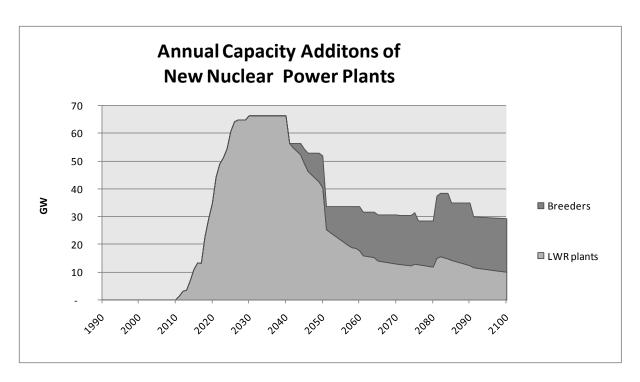


Figure 6.4.1 Forecasted capacity additions of nuclear plants could reach 50 GWe/a

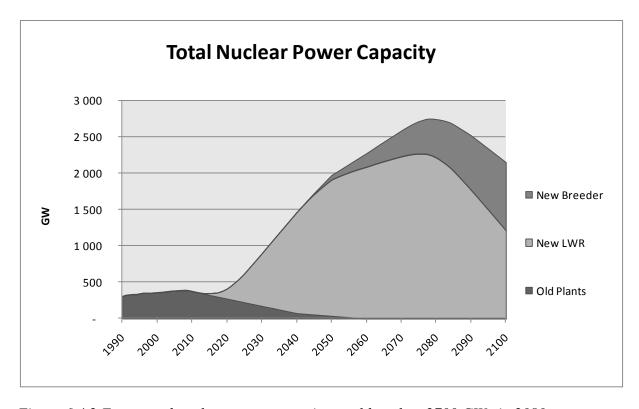


Figure 6.4.2 Forecasted nuclear power capacity would peak at 2700 GWe in 2080

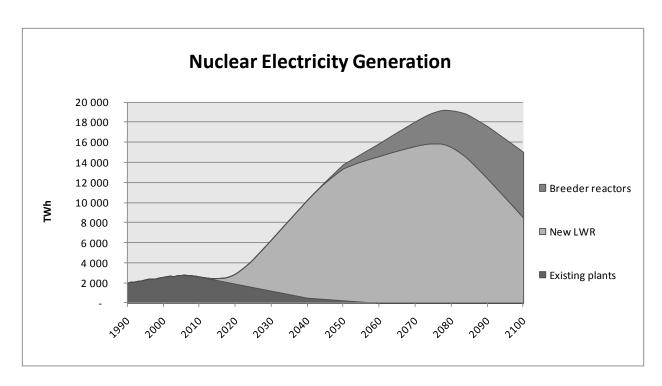


Figure 6.4.3 Forecasted nuclear power generation will peak at 19 000 TWh in 2080

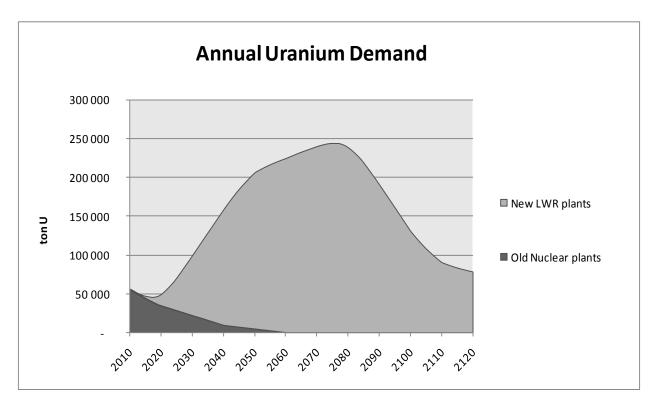


Figure 6.4.4 Forecasted annual uranium demand until 2120

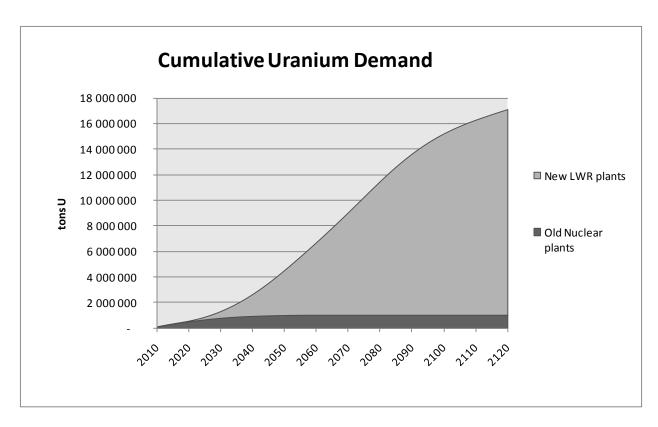


Figure 6.4.5 Forecasted cumulative uranium demand until 2120

The annual uranium demand will peak at 240 000 tons/a in 2080 (Figure 6.4.4). This is four times the present level. The cumulative uranium demand for LWR reactors for the given program has been evaluated in Figure 6.4.5. The low costs (<\$130/kgU) uranium resources of 16 million tons will be used by 2100.

6.5 The electricity plan after nuclear generation

If the given program would be realized, nuclear power would be the number one source of electricity and the world will go to **nuclear age** in 2041 (Figure 6.5.1). The nuclear age would last until 2100, when wind/wave power would overtake the nuclear as the largest source of electricity.

The use of nuclear power would make a radical change in fossil electricity, which would start decreasing after 2020. Without nuclear power the fossil electricity generation would increase until 2050. According to the plan the fossil share of electricity generation would go down rapidly from 66% in 2009 to 30% in 2050 (Table 6.5.1). However, the absolute generation of fossil fired electricity would be remain at a 12 000 TWh level until 2050. Then after 2050 the fossil generation would decrease to 2000 TWh in 2100.

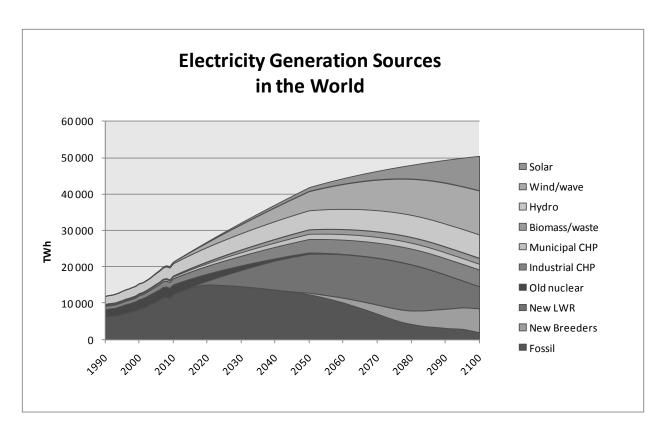


Figure 6.5.1 Forecasted electricity generation mix with nuclear power plants

Table 6.5.1 Forecasted sources of electricity generation

	Sou	urces of Ele	ctricity Ge	neration	Market shares				
Source	2009	2050	2075	2100	2009	2050	2075	2100	
	TWh	TWh	TWh	TWh	%	%	%	%	
Preferable source	es								
Solar	34	1 026	2 955	9 814	0,2%	2,4%	6,3%	19,3%	
Wind/wave	321	5 284	9 197	12 134	1,8%	12,6%	19,5%	23,9%	
Hydro	3 272	5 274	6 000	6 475	18,8%	12,6%	12,7%	12,7%	
Biomass/waste	164	1 189	1 503	1 570	0,9%	2,8%	3,2%	3,1%	
CHP	2 051	5 225	5 900	6 194	11,8%	12,5%	12,5%	12,2%	
Total	5 841	17 998	25 555	36 186	33,6%	43,0%	54,1%	71,1%	
Other sources									
New Breeders	-	418	3 103	6 556	0,0%	1,0%	6,6%	12,9%	
New LWR	-	10 698	13 048	6 056	0,0%	25,5%	27,6%	11,9%	
Old nuclear	2 698	259	0	0	15,5%	0,6%	0,0%	0,0%	
Fossil	11 554	12 521	5 548	2 072	66,4%	29,9%	11,7%	4,1%	
Total	14 252	23 896	21 698	14 685	81,9%	57,0%	45,9%	28,9%	
Total	17 395	41 895	47 254	50 871	100,0%	100,0%	100,0%	100,0%	

Preferable electricity sources are increasing in the plan from 33% in 2009 to about 43% by 2050, and to 71% by 2100. The biggest increase is happening in wind and solar electricity generation, which would generate 24% and 19% of electricity respectively in 2100.

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7 FOSSIL ELECTRICITY PLAN FOR 2100

7.1 Planning process

Fossil plants should cover the remaining electricity generation after the preferable sources of renewable, CHP and nuclear electricity. The fossil electricity generation have increased from 6000 TWh in 1990 to 12 000 TWh in 2009 (Figure 7.1.1, Table 7.1.1). The fossil generation will peak at 15 000 TWh in 2020 and thereafter the generation will go down and reach 1990 level before 2075.

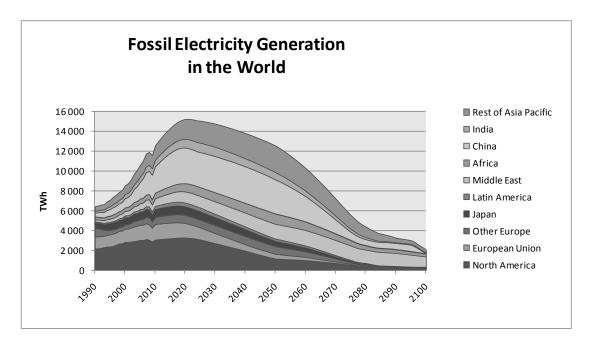


Figure 7.1.1 Forecasted electricity generated by fossil fired power plants

The CO₂-emissions of fossil plant can still be reduced by improving the efficiencies of power plants and by increasing the share of oil and gas fired plants and decreasing the share of coal fired power plants. This can be achieved as most of the new fossil fired power plants will use gas and oil as their primary fuel. The coal fired plants will then only be built for the base load generation at sites where natural gas is not available. The goal is to reach the emission target of 690 kgCO₂/capita by 2050 and 140 kgCO₂/capita by 2100 in each of the areas separately.

The economic incentive to build gas fired plants instead of coal fired plants should be favored by CO₂-emission allowances or clear emission standards. If the emission standards allow only a 500 gCO₂/kWh emission, then coal fired plants will not be built without carbon capture and storage (CCS). Because of the high costs of CCS the other plants would replace the coal plants in the most cases. However, CCS will be also needed in China and USA to reach the emission targets.

Table 7.1.1 Forecasted electricity generation of fossil power plants and market shares

	F	ossil Power	Generatio	neration Share of Fossil Power Plan					
Area	2009	2050	2075	2100	2009	2050	2075	2100	
	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)	
North America	2 854	1 122	491	66	56,6 %	16,2 %	6,6 %	0,8 %	
European Union	1 423	504	112	108	44,7 %	13,0 %	2,9 %	3,0 %	
Rest of Europe	606	766	167	56	32,1 %	23,7 %	5,0 %	1,7 %	
Japan	685	528	147	29	61,5 %	42,4 %	13,5 %	3,2 %	
Latin America	296	228	86	65	27,4 %	9,2 %	2,9 %	2,0 %	
Middle East	718	1 487	1 467	1 057	94,9 %	53,7 %	35,6 %	18,4 %	
Africa	515	1 022	533	276	81,6 %	45,9 %	17,6 %	7,1 %	
China	2 465	3 423	808	7	66,2 %	28,6 %	6,1 %	0,1 %	
India	670	752	327	109	77,1 %	32,7 %	12,3 %	3,8 %	
Rest of Asia Pacific	1 322	2 688	1 410	298	73,3 %	54,9 %	25,0 %	4,8 %	
Total	11 554	12 521	5 548	2 072	57,5 %	29,9 %	11,7 %	4,1 %	

The prices of CO₂-allowances should be so high that gas fired plants have lower variable costs than coal plants. If the fuel prices of gas and coal are ϵ 20/MWh and ϵ 10/MWh respectively, then the price of CO₂-allowances should be more than ϵ 30/tCO₂ (Table 7.1.2) and the variable costs of both plants are about ϵ 56/MWh.

At the moment the CO_2 -price allowance is about £15/MWh and coal fired plants have about 10% lower variable costs than gas plants. The coal plants come before the gas plants in the dispatch order. It is forecasted that by 2020 the prices of CO_2 -allowances will increase to £30/t CO_2 , which corresponds to a 7% annual change. By 2050 the allowance price could reach a £50/t CO_2 level, which will make also gas plants more expensive than wind or solar plants.

Table 7.1.2 The variable costs of gas and coal power plants

		2011		2020)	2050	
Power plant ty	γpe	Gas plant	Coal plant	Gas plant	Coal plant	Gas plant	Coal plant
Emission price	!	15 eur/t	15 eur/t	30 eur/t	30 eur/t	50 eur/t	50 eur/t
Performance							
Efficiency	%	50 %	40 %	52 %	42 %	54 %	44 %
CO2/content	kg/MWh	198	340	198	340	198	340
Emission	kg/MWh	396	850	381	810	367	773
Fuel costs							
Fuel price	eur/MWh	20,0	10,0	20,0	10,0	20,0	10,0
Fuel costs	eur/MWh	40,0	25,0	38,5	23,8	37,0	22,7
CO2-costs							
CO2-price	eur/t	15,0	15,0	30,0	30,0	50,0	50,0
CO2-costs	eur/MWh	5,9	12,8	11,4	24,3	18,3	38,6
O&M costs	eur/MWh	6,0	8,0	6,0	8,0	6,0	8,0
Variable costs	eur/MWh	51,9	45,8	55,9	56,1	61,4	69,4

7.2 Oil and gas fired plants

For 25 years natural gas has been the most favored fuel in new power plants after the Chernobyl accident in 1986. Typical gas plants are used at base load as combined cycle plants and at peak load and reserve applications as simple cycle gas turbines or diesel and gas engines.

Most of the new plants have been combined cycle gas turbine (CCGT) plants, which have one or two gas turbines in the topping cycle and one steam turbine in the back end. Thus the steam turbine can utilize the waste heat from the gas turbines and generate typically 50% more electricity. If the gas turbine has a 36% efficiency then the combined cycle plant has typically $1.5 \times 36\%$ or 54% net electrical efficiency.

The orders of large gas turbines have been changing around 40 000 MW (Figure 7.2.1). There have been large changes in the orders depending on the economic cycle. The total volume of the large plants has been about 60 000 MWe annually, if also the steam turbines of the CCGT plants are included.

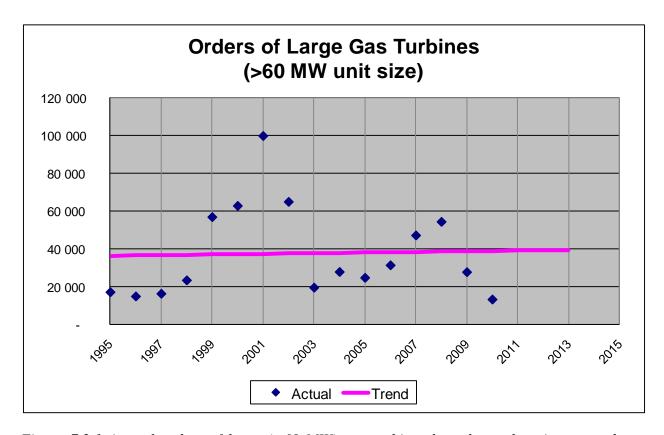


Figure 7.2.1 Annual orders of large (>60 MW) gas turbines have been changing around 40 000 MW (Source: Diesel and Gas Turbine World Wide)

Peaking power plants use gas engines that typically have a 40-45% electrical efficiency and aeroderivative gas turbines with 36-42% efficiency. These plants will also be needed to balance the generation changes of renewable wind and solar plants. Typically the balancing plants should cover about 25% of the installed capacity of wind and solar power plants.

The orders for internal combustion engines (0.5-60 MW unit size) have been changing around 35 000 MW depending on the economic cycle (Figure 7.2.2). The orders for small (1-60 MW) gas turbines have stayed between 5000 MW and 10 000 MW level during the same period.

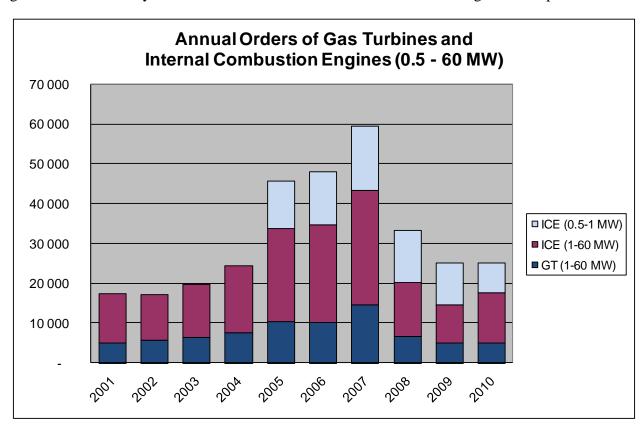
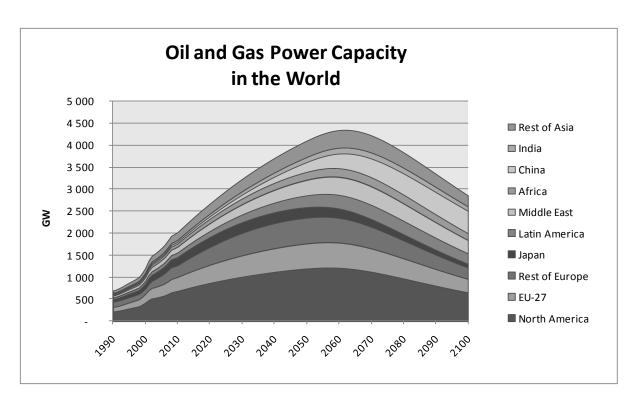


Figure 7.2.2 The orders of internal combustion engines and gas turbines (0.5-60 MW unit size) have changing around 35 000 MW (Source: Diesel and Gas Turbine World Wide)

The installed capacity of oil and gas power plant is increasing from 2000 GWe in 2009 to about 4000 GWe by 2050 and then decreasing to 2800 GWe by 2100 (Figure 7.2.3). The peak load of electricity consumption is developing from 4000 GWe by 2009 to 8000 GWe in 2050 and to 10 000 GWe by 2100 (Figure 7.2.4).

In 2100 the oil and gas fired power plants will be cover 27% of the peak load capacity and they are mainly used for system services. Typically about 20-30% capacity is needed for system services including peaking, regulating and reserve power plants.



7.2.3 Forecasted installed capacity of oil and gas fired power plants in the world

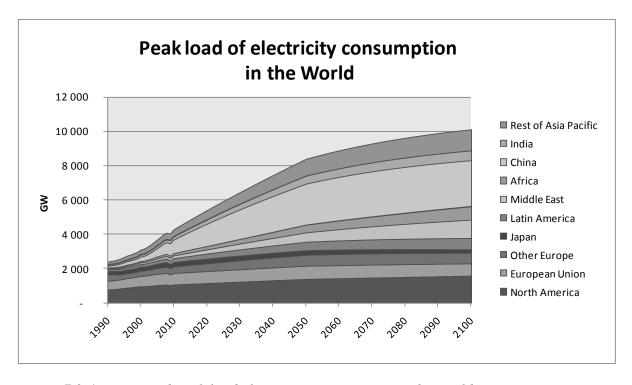


Figure 7.2.4 Forecasted peak load electricity consumption in the world

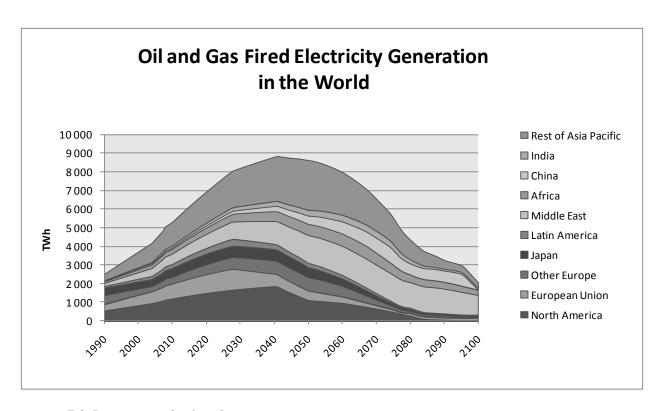


Figure 7.2.5 Forecasted oil and gas power generation

Electricity generation with oil and gas power plants is growing from 5100 TWh in 2009 to 8600 TWh by 2050 (Figure 7.2.5). Then after 2060 the renewable and nuclear plants will cover the growth. Oil and gas fired plants were generating 26% of electricity in 2009 (Table 7.2.1). Their share will then gradually decline to 21% by 2050 and to 4% by 2100.

Table 7.2.1 Forecasted electricity generation with oil and gas plants

	Oil and Gas Electricity Generation				Share of Oil and Gas			
Area	2009	2050	2075	2100	2009	2050	2075	2100
	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)
North America	1 174	1 122	491	66	23,3 %	16,2 %	6,6 %	0,8 %
European Union	770	504	112	108	24,2 %	13,0 %	2,9 %	3,0 %
Rest of Europe	360	718	167	56	19,1 %	22,2 %	5,0 %	1,7 %
Japan	448	528	147	29	40,2 %	42,4 %	13,5 %	3,2 %
Latin America	218	228	86	65	20,2 %	9,2 %	2,9 %	2,0 %
Middle East	542	1 487	1 467	1 057	71,7 %	53,7 %	35,6 %	18,4 %
Africa	246	607	533	276	39,1 %	27,3 %	17,6 %	7,1 %
China	85	459	808	7	2,3 %	3,8 %	6,1 %	0,1 %
India	112	311	327	109	12,9 %	13,5 %	12,3 %	3,8 %
Rest of Asia Pacific	1 235	2 674	1 410	298	68,5 %	54,6 %	25,0 %	4,8 %
Total	5 191	8 638	5 548	2 072	25,8 %	20,6 %	11,7 %	4,1 %

7.3 Coal fired power generation

Coal has been the major fuel in power generation for about hundred years. But, it is also the biggest source of carbon dioxide emissions. The CO₂-emissions of a typical coal plant are 850 gCO₂/kWh, when a gas plants emits only 400 g CO₂/kWh (Table 7.1.2). Because the emissions should be reduced, this can be most easily done by replacing the coal fired plants with renewable or nuclear plants in the long term, or with gas fired plants in the short term.

Coal fired electricity generation can be forecasted by subtraction all other power generation sources from the total electricity generation (Figure 7.3.1). Coal power generation will peak at 8500 TWh in the year 2020, when the new plants that are now under planning and construction phases will be connected to the grid. After 2020 coal fired electricity generation will then start to decline after new renewable and nuclear plants will be connected to the grid.

There are many countries that have already stopped building new coal plants. One of them is Finland, which has built its last coal fired power plant in 1994. Hardly any new coal fired plants will be built in the future in Europe. At the moment coal power's share in Finland's electricity generation is about 20%. It will decline to less than 5% by 2020 as three new nuclear and many renewable plants will be connected into the network. Then in about 2034 all the coal fired plants will have been decommissioned.

However, there are countries such as China and India that are building new coal fired power plants. The coal share of electricity generation in China and India was about 64% in 2009. In 2050 the coal share will still be about 20% in both the countries (Table 7.3.1).

Table 7.3.1 Forecasted coal share of power generation will reduce from 32% in 2009 to 9% by 2050 and to near zero by 2075

	Electricity generation by coal plants				Share of Coal Electricity			
Area	2009	2050	2075	2100	2009	2050	2075	2100
	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)
North America	1 680	-	-	-	33,3 %	0,0 %	0,0 %	0,0 %
European Union	653	-	-	-	20,5 %	0,0 %	0,0 %	0,0 %
Rest of Europe	246	48	-	-	13,0 %	1,5 %	0,0 %	0,0 %
Japan	237	-	-	-	21,3 %	0,0 %	0,0 %	0,0 %
Latin America	78	-	-	-	7,2 %	0,0 %	0,0 %	0,0 %
Middle East	176	1	-	-	23,2 %	0,0 %	0,0 %	0,0 %
Africa	269	415	-	-	42,6 %	18,7 %	0,0 %	0,0 %
China	2 380	2 964	-	-	63,9 %	24,8 %	0,0 %	0,0 %
India	559	442	-	-	64,2 %	19,2 %	0,0 %	0,0 %
Rest of Asia Pacific	87	14	-	-	4,8 %	0,3 %	0,0 %	0,0 %
Total	6 363	3 884	-	-	31,7 %	9,3 %	0,0 %	0,0 %

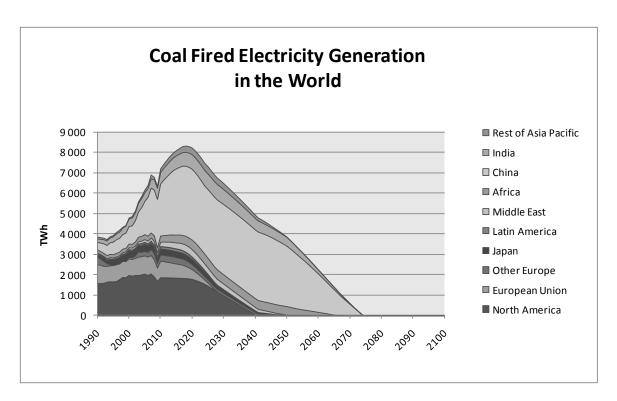


Figure 7.3.1 Forecasted coal fired power generation will peak in the year 2020 at 8500 TWh

7.4 The CO₂-emissions of electricity generation

The CO₂-emissions are still increasing as fossil fired power generation is increasing. The emissions will peak at 13 Gt/a in 2020 and then decrease to 2 Gt/a in 2100 (Figure 7.4.1). The cumulative CO₂-emissions will reach 900 Gt by the year 2100. They include 500 Gt emissions from coal and 400 Gt from oil and gas power plants (Figure 7.4.2).

The specific CO₂-emissions of power generation in the world will reduce to about 1 ton/capita by 2050 (Figure 7.4.3) and to 0.2 t/capita by 2100 (Figure 7.4.4). There are still great variations in the per capita emissions between the countries and continents. It seems that the US, China, Japan and Eastern Europe could not meet the general target (690 kg/capita) set in chapter 4.6 by 2050.

Middle East will also have difficulties in reaching the target (140 kg/capita) for 2100. China could reach the targets for 2100, if it creates an ambitious program to do so. However, there are several countries in which the emissions will be lower than the targets. Thus it will be possible to reach the general targets if those countries will sell the emission rights to others.

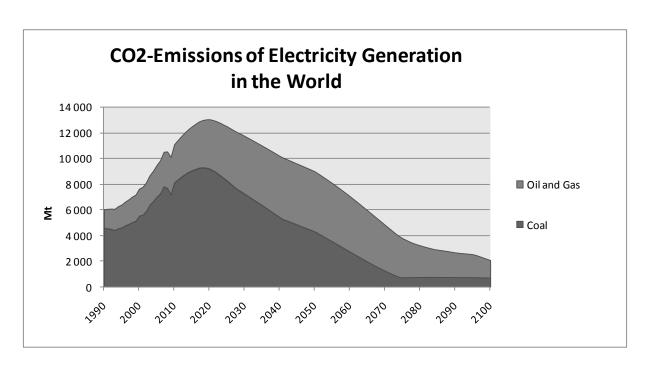


Figure 7.4.1 The forecasted CO₂-emissions of electricity generation

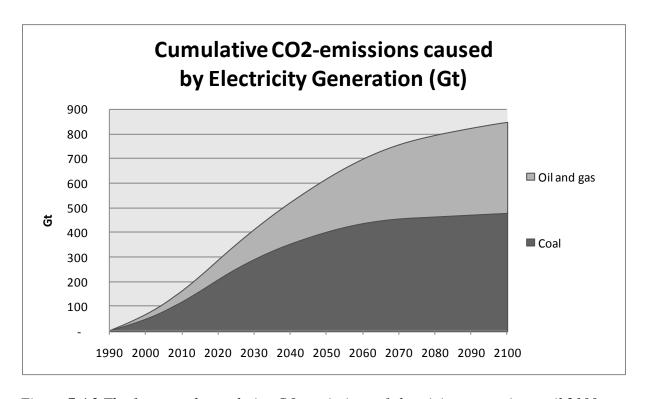


Figure 7.4.2 The forecasted cumulative CO₂-emissions of electricity generation until 2100

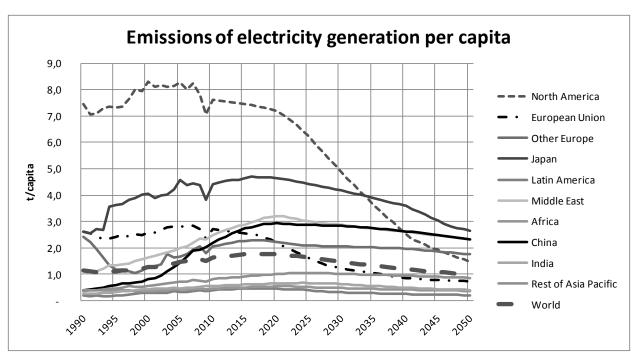


Figure 7.4.3 The forecasted CO_2 -emissions from electricity generation of the world will increase from the 1 t/capita in 1990 and reduce back to it by 2050

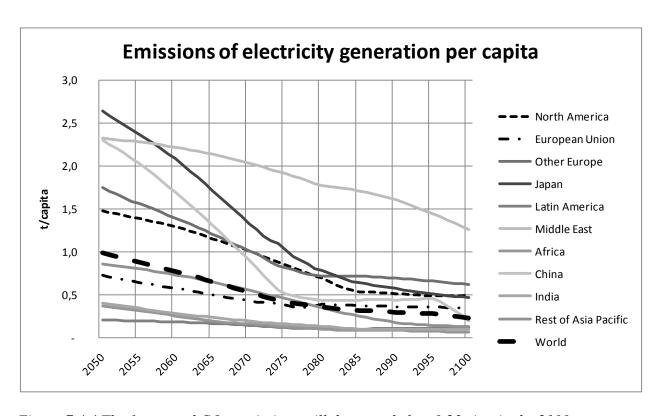


Figure 7.4.4 The forecasted CO₂- emissions will decrease below 0.23 t/capita by 2100

7.5 Global warming caused by power generation

The CO₂-emissions of electricity generation by fossil fired power plants are about 34% of the total emissions of energy industry. The forecasted emissions of electricity generation until 2100 were estimated to be 900 Gt. If this relation remains the same, the emissions of the energy industry until 2100 will be 2800 Gt (Figure 7.5.1).

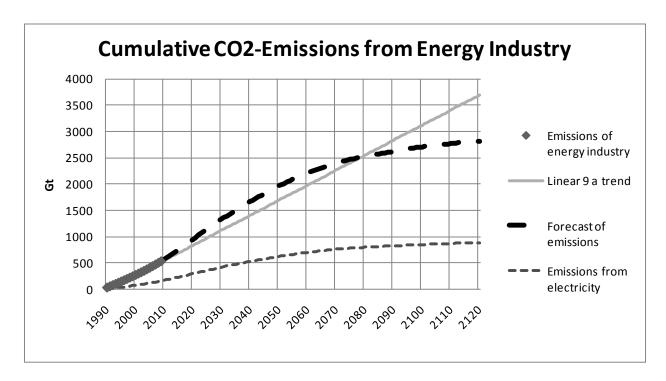


Figure 7.5.1 Forecasted CO₂-emission from energy industry

If the CO₂-concentration in the atmosphere will follow the past correlation with CO₂-emissions, the concentration in Mauna Loa will increase to 550 ppm by 2100 (Figure 7.5.2). The concentration will increase faster than the linear trend until 2050, because the emissions are increasing faster than the trend. After 2080 the concentration will increase quite moderately and it is possible that the critical value of 560 ppm will never be reached.

Global warming is partly caused by the CO₂-emissions. Finnish measurements have shown that 1000 Gt of CO₂-emissions have caused temperature increase of 0.79 °C (maximum sensitivity see Chapter 4.5). Myles R. Allen et. al. Nature (April 30, 2009) have evaluated that 3670 Gt emissions cause a 2 °C increase (minimum sensitivity).

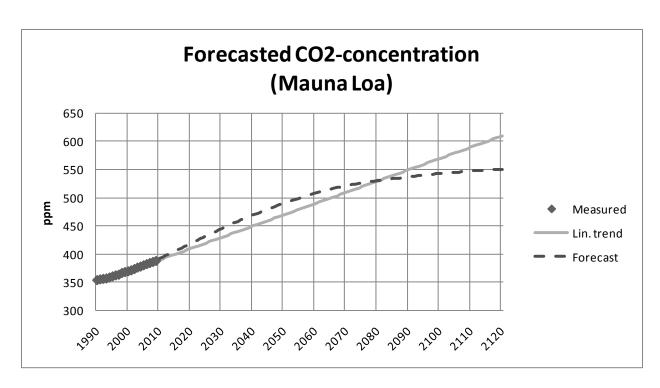


Figure 7.5.2 The forecasted CO₂-concentration at Mauna Loa

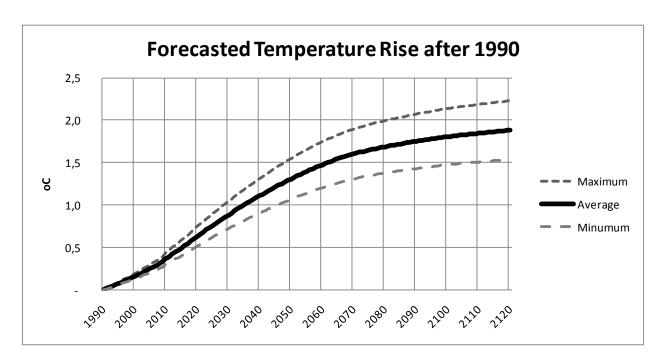


Figure 7.5.3 The forecasted temperature rise after 1990, if the emissions of the energy industry will be approaching 2800 GtCO₂ until 2120 (Figure 7.5.1)

The emissions caused by the energy industry have been about 700 Gt during the years 1900-1990. This has caused an increase in the global temperature of 0.38 °C (minimum sensitivity of Myles R. Allen) or 0.55 °C (maximum sensitivity by the author).

The forecasted temperature rise after 1990 has been estimated by using the minimum sensitivity and the maximum sensitivity has been estimated to be 1.54–2.23 °C by 2120 (Figure 7.5.3). The temperature rise from 1900 to 2120 will then be 1.92–2.78 °C, and the probable increase would be 2.35 °C.

7.6 Fossil fuel resources

The cumulative coal consumption for power generation is forecasted to achieve 120 Gtoe (120 billion tons of oil equivalent) by 2120 (Figure 7.6.1). The coal reserves were estimated by British Petroleum (*BP 2010 energy statistics*) to be 862 Gt, which would be approximately 575 Gtoe. Thus the coal reserves are about five times the need for power generation. However, coal is also needed for heat generation, for the production of iron and for other industrial uses.

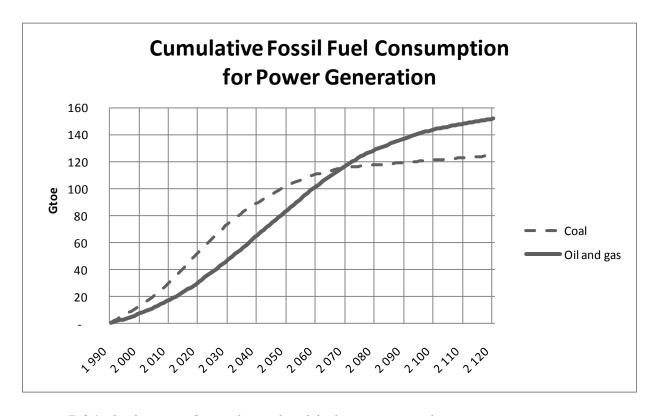


Figure 7.6.1 The forecasted cumulative fossil fuel consumption for power generation

The cumulative oil and gas consumption for power generation will reach 150 Gtoe by 2120. The proven reserves for oil have been estimated to be 1333 trillion barrels or 181 Gtoe by British Petroleum. The proven reserves for natural gas are 187.5 Gm3, which corresponds to 169 Gtoe. The total reserves of oil and gas are then 350 Gtoe and 43 % of them are needed for electricity generation.

About 20-30% of oil and gas is used for power generation today. 20-30% of the available reserves correspond to 70-105 Gtoe. This is less than is needed for power generation. However, in many sectors oil and gas will be switching to electricity. Cars will be switching from gasoline to electric or hybrid cars. Households are switching from natural gas and heating oil to electric heating and cooling, but switching to electricity will be more difficult in marine and air traffic.

References

/7.1/ Power Generation Survay 2011. Diesel and Gas Turbine World Wide. May 2011

/7.2/ Statistical Review of World Energy. British Petroleum. http://www.bp.com/sectionbodycopy.do?categoryId=7500&contentId=7068481

8 FROM COAL TO NUCLEAR AGE

8.1 Electricity generation in the world

The electricity generation sources can now be summed up from each sector in chapters 5, 6 and 7 (Figure 8.1.1). The market shares of each source have been given in Figure 8.1.2. We can define the ages given the name by the source that has the largest market share in the defined period.

From this data we can say that we are now living in a **coal age**. Coal fired electricity generation is still growing and it will peak by 2020. However, the market share of coal will decline from 32% in 2009 to 25% in 2025. The coal fired power generation will decrease to nearly zero by 2100, but coal will still be used in CHP generation then.

The coal age will end by 2025, when the oil and gas power plants or hydrocarbons will be the have the highest market shares in electricity generation (Figure 8.1.2). **The hydrocarbon age** will continue from 2025 until 2041, when nuclear electricity will overtake the hydrocarbons.

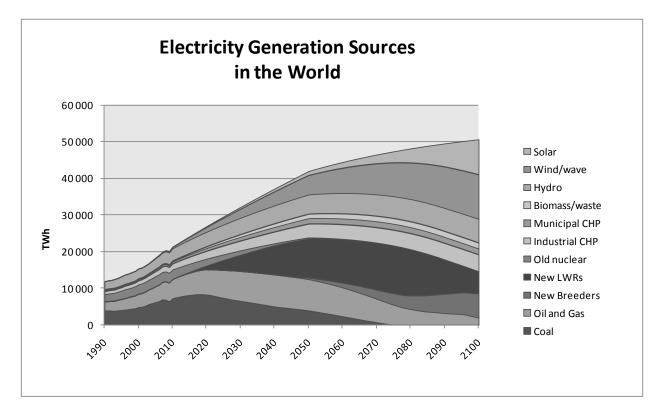


Figure 8.1.1 The forecasted electricity generation sources in the world

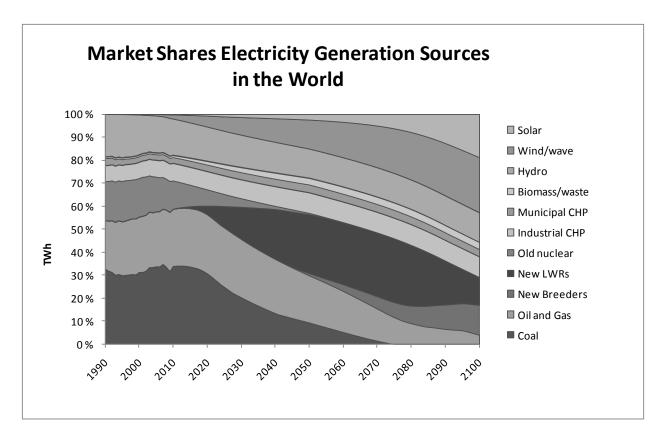


Figure 8.1.2 The forecasted market shares of electricity sources

Table 8.1.1 The forecasted sources of electricity generation

Sources of Electricity	Sources of electricity				Market shares			
Generation	2009	2050	2075	2100	2009	2050	2075	2100
in the World	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)
Coal	6 363	3 884	-		31,7 %	9,3 %	0,0 %	0,0 %
Oil and Gas	5 191	8 638	5 548	2 072	25,8 %	20,6 %	11,7 %	4,1 %
Total Fossil	11 554	12 521	5 548	2 072	57,5 %	29,9 %	11,7 %	4,1 %
New FBR	-	418	3 103	6 556	0,0 %	1,0 %	6,6 %	13,0 %
New LWR	-	10 698	13 048	6 056	0,0 %	25,5 %	27,6 %	12,0 %
Old nuclear	2 698	259	0	0	13,4 %	0,6 %	0,0 %	0,0 %
Total Nuclear	2 698	11 375	16 151	12 613	13,4 %	27,2 %	34,2 %	25,0 %
Industrial CHP	1 523	3 733	4 224	4 539	7,6 %	8,9 %	8,9 %	9,0 %
Municipal CHP	528	1 492	1 677	1 656	2,6 %	3,6 %	3,5 %	3,3 %
Total CHP	2 051	5 225	5 900	6 194	10,2 %	12,5 %	12,5 %	12,3 %
Biomass/waste	164	1 189	1 503	1 570	0,8 %	2,8 %	3,2 %	3,1 %
Hydro	3 272	5 274	6 000	6 475	16,3 %	12,6 %	12,7 %	12,8 %
Wind/wave	321	5 284	9 197	12 134	1,6 %	12,6 %	19,5 %	24,0 %
Solar	34	1 026	2 955	9 484	0,2 %	2,4 %	6,3 %	18,8 %
TotalRenewable	3 790	12 773	19 655	29 662	18,9 %	30,5 %	41,6 %	58,7 %
Total	20 094	41 895	47 254	50 541	100,0 %	100,0 %	100,0 %	100,0 %

Hydrocarbons will still be needed in the year 2100 because of peaking and reserve power generation still, when the oil and gas plants will have a 4% share (Table 8.1.1). CHP plants will have a 12% share by then and gas will still have the largest share in CHP power generation.

The nuclear share will decrease from 13% in 2009 to its lowest share of 10% in 2017. Thereafter the nuclear share will start to increase again, when the many new plants under construction will be connected to the grid.

Nuclear generation will overtake the hydrocarbons in 2041, when the nuclear share will reach a 24% market share and the world will be in the **nuclear age**. The nuclear share will then peak at 36% during the years 2075-80. The nuclear age will end by 2110 when wind power generation will overtake nuclear and both will generate about 24% of electricity.

The wind age will last from 2110 to about 2130-40, when solar electricity will be the biggest source of electricity. The world will enter into the **solar age**, which could last forever.

Capacity additions

The capacity additions in the world's electricity market will be changing ahead of the generation markets (Figure 8.1.3). The capacity additions will grow from 200 GWe in 2010 to about 350 GWe in 2050 and 650 GWe in 2100.

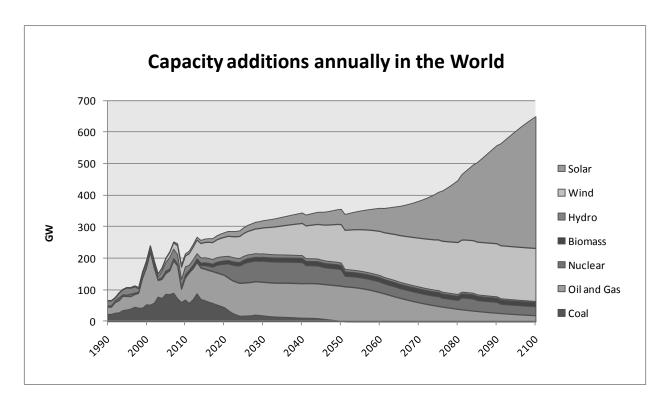


Figure 8.1.3 The forecasted power plant capacity additions annually in the world

Oil and gas fired power plants have taken the lead in annual capacity addition and now almost 100 GWe/a of new oil and gas capacity will be built annually after the year 2010. Wind capacity additions will overtake oil and gas capacity additions between years 2040-50.

If nuclear capacity additions will grow to 65 GWe/a by 2030, this will make nuclear power generation the number one source of electricity after 2040. Finally, solar power capacity additions will overtake wind plants between 2080-2100. This will happen some 30-40 years before solar will become the largest source of electrical energy around 2120-2150.

8.2 North America

The main source for electricity generation in North America will develop from coal to oil and gas then via nuclear to renewable sources similar to the global development (Figure 8.2.1). Coal power will be main source for electricity and North America will be living in the **coal age** until 2025.

The **hydrocarbon age** will follow from 2025 until 2040, when the oil and gas share will drop below 29% and nuclear electricity will take the lead. This will be the time when local sources of oil and gas will also be exploited and the North America will be depended on imported oil and gas.

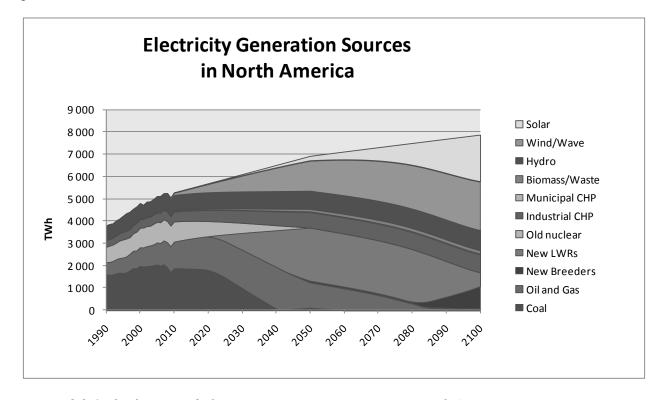


Figure 8.2.1 The forecasted electricity generation sources in North America

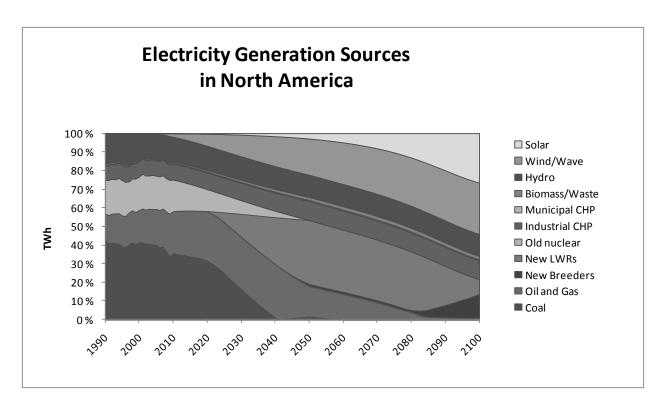


Figure 8.2.2 The forecasted market shares of electricity sources in North America. Oil and gas age will be between the years 2025-2040 and the nuclear age between the years 2040-2090

North America will come into the **nuclear age** in 2041, when the nuclear share will reach 27% of electricity generation. According to the plan nuclear capacity additions will increase to 14 000 MW by 2025, which corresponds to ten large nuclear plants annually. Nuclear investments should continue at this level until 2050 to get rid of coal fired power plants and CO₂-emissions.

The nuclear age will last until 2090, when the wind and wave share will reach 27% of generation and North America will be enter the **wind age**. Wind energy is already very profitable in the US in the Mid West, where favorable winds blow throughout the year. Solar power generation would take the lead from wind around 2120-2140 and the **solar age** will then last until the unknown future.

The CO₂-emissions from electricity generation in North America will continue at the present level until 2020 (Figure 8.2.3). After 2020 nuclear power and renewable sources will start to gain market shares, which will drop the share of coal and CO₂-emissions. The emissions will still be 660 MtCO₂ in 2050 (1.5 tCO₂/capita), which is more than the target of 0.69 tCO₂/capita.

In 2100 the CO₂-emissions will be 250 Mt/a (490 kgCO₂/capita). This will be above the target of 140 kg/capita and North America should buy emission rights from the countries that have lower than target emissions.

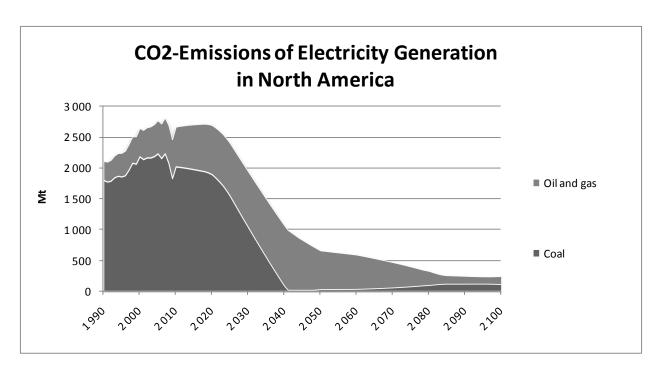


Figure 8.2.3 The forecasted CO₂-emissions from electricity generation in North America

8.3 The European Union

Electricity consumption has been growing moderately in the European Union and it reached 3180 TWh (6700 kWh/capita) in 2009 (Figure 8.3.1). The forecasted electricity generation will reach 3880 TWh in 2050 (7750 kWh/capita) and 3640 TWh (8600 kWh/capita) in 2100.

Electricity generation sources in the EU are developing ahead of the rest of the world. Nuclear power became the number one electricity source already in 1993, when it reached 32% market share of electricity sources and overcome coal (Figure 8.3.2). The nuclear share was above 30% until 2005.

In the future the nuclear share will decrease below 24% and hydrocarbons will overcome nuclear by 2012. However, the nuclear share will start increasing again and will reach a 25% share in 2034 and be the major source of electricity until 2070, when wind electricity generation will reach 26% of electricity generation and end the nuclear age. Thus the **first nuclear age** was during the years 1993-2012 and the **second nuclear age** during the years 2034-2070.

The **hydrocarbon age** will be between the nuclear ages from 2012 to 2034. The **wind age** will follow the nuclear age after 2070 and finally EU will end into **solar age** by 2120-50.

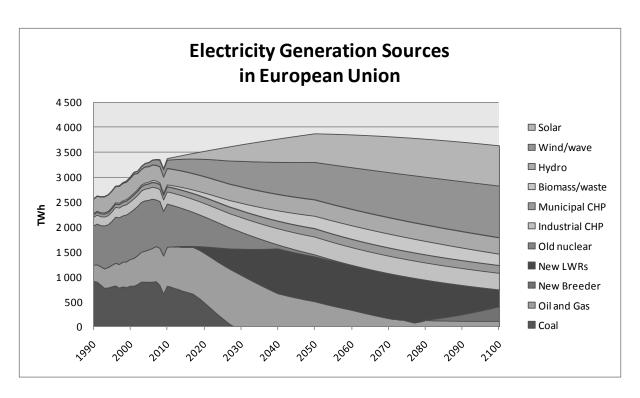


Figure 8.3.1 The forecasted electricity generation sources in European Union

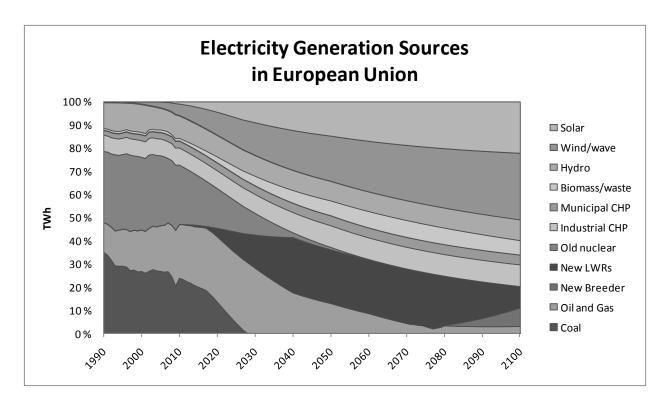


Figure 8.3.2 The forecasted market shares of electricity sources in European Union

Electricity generation with fossil fuels in the EU has increased from 1230 TWh in 1990 to 1430 TWh in 2009. It is still increasing and peaking at 1600 TWh in 2015. The peak in CO₂-emission in EU was reached in 2007, when emissions were 1400 MtCO₂ or 2.8 tCO₂/capita (Figure 7.3.3).

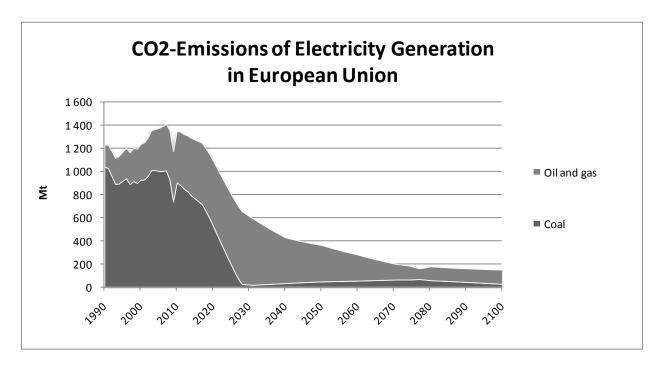


Figure 7.3.3 The forecasted CO₂-emissions of electricity generation in the EU

The forecasted CO₂-emissions of electricity generation will decrease to 360 MtCO₂ by 2050 and 150 MtCO₂ by 2100. The specific CO₂-emissions will reach 700 kg/capita by 2050 and 300 kg/capita by 2100. The figure of 2050 will be near the target of 690 kgCO₂/capita, but the 2100 figure of 300 kg CO₂/capita is far from target of 140 kgCO₂/capita. Thus also Carbon Capture and Storage (CCS) program will be needed.

8.4 The rest of Europe (Transitional Economics)

The electricity generation in the rest of Europe was decreasing after 1990, when the Former Soviet Union countries started liberalization. The lowest electricity consumption figures of 1554 TWh were achieved in 1997. The consumption is now 2000 TWh and will reach 3200 TWh in 2050 and 3300 TWh in 2100 (Figure 8.4.1).

The largest source of electricity generation in the rest of Europe has been the combined heat and power (CHP), which generate 25-27% of electricity (Figure 8.4.2). Most cities have district heating systems and the largest cities also have CHP generation.

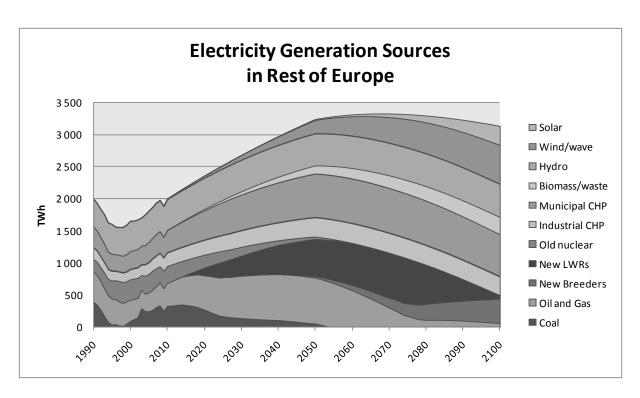


Figure 8.4.1 The forecasted electricity generation sources in the rest of Europe

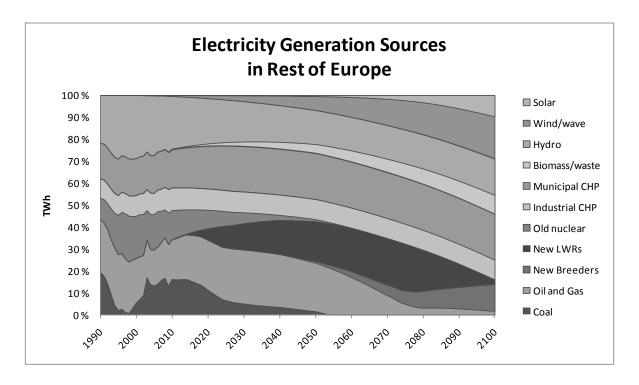


Figure 8.4.2 The forecasted market shares of electricity sources in the rest of Europe

There is still large potential for CHP plants in smaller cities and it is forecasted that the CHP share will reach 30% in 2027.

Natural gas condensing power plants have been the second largest source of electricity and most of the CHP plants use natural gas. Natural gas condensing plants have about a 20% share, which will decrease as more and more natural gas will be used for CHP generation in the future.

The share of nuclear power has been increasing from 10% in 1990 to about 15% in 2009. It will reach 20% by 2050 and will peak at 27% in 2075. The main source of electricity has been natural gas and the rest of Europe has been living in the **hydrocarbon age** since 1990.

The **nuclear age** will be starting in 2055, when nuclear power will overcome the hydrocarbons. The nuclear age will continue until 2100, if the largest cities will have nuclear CHP plants. The first nuclear CHP plant (Akademik Lomonosov) will be start its operation in 2012.

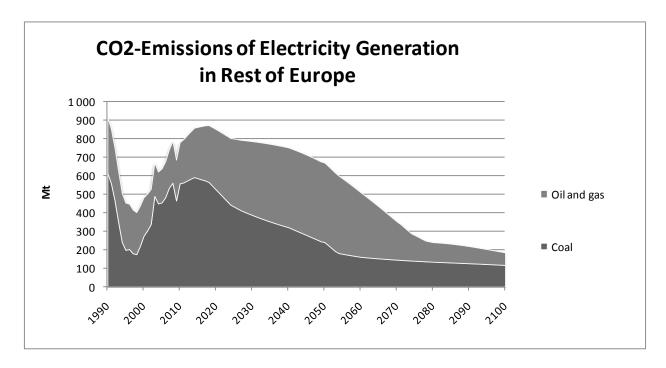


Figure 8.4.3 The forecasted CO₂-emissions of electricity generation in the rest of Europe

When the electricity consumption was decreasing the generation of fossil fired electricity was reducing from 46% in 1990 to 24% in 1997. This reduced the CO₂-emissions from 900 Mt to 400 Mt in 1997 (Figure 8.4.3).

Fossil fired plants generate today about 32-35% of electricity, and as most of the CHP plants use natural gas the CO₂-emissions are increasing. The emissions will peak at 850 Mt in 2020 and will then reduce to 670 Mt by 2050 and to 190 Mt by 2100. Thus the rest of Europe would need a CCS program to reach the targets.

The specific emissions of electricity generation were 1800 kgCO₂/capita in 2009. The emissions will decrease to 1750 kg/capita by 2050 and to 620 kg/capita by 2100. The both figures are more than 100% above the targets of 690 kg/capita by 2050 and 140 kg/capita by 2100. Thus also the CCS will be needed.

8.5 Japan

Electricity generation in Japan has increased from 840 TWh in 1990 to 1115 TWh in 2009. It will still be increasing to peak at 1300 TWh in 2030 (Figure 8.5.1). After 2030 the population of Japan will start to decline and thus also electricity consumption will start to decrease.

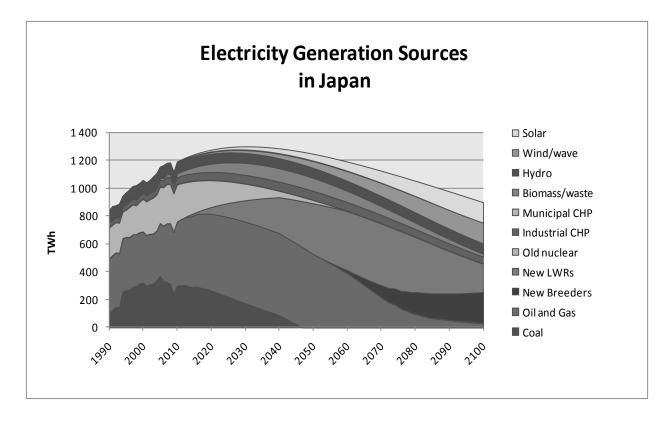


Figure 8.5.1The forecasted electricity generation sources in Japan

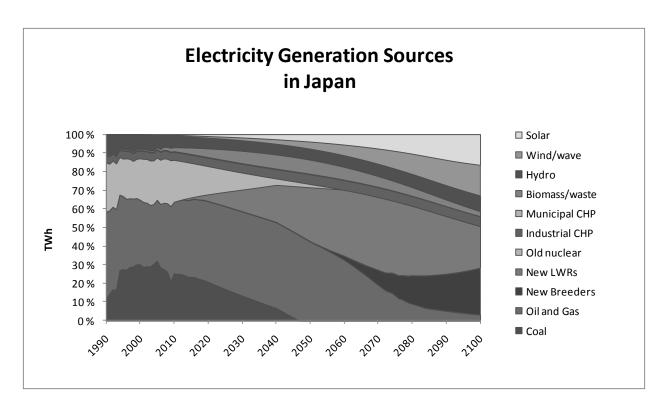


Figure 8.5.2 The forecasted market shares of electricity generation in Japan

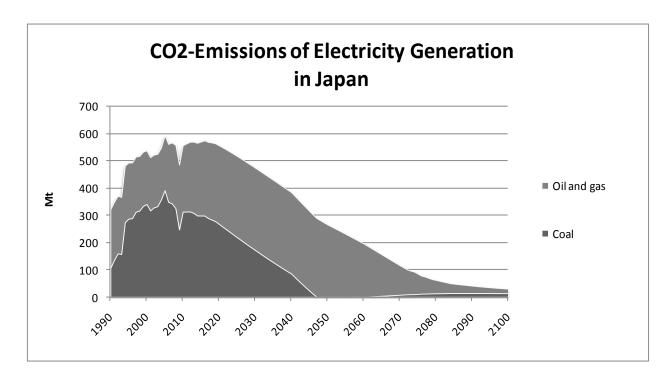


Figure 8.5.3 The forecasted CO₂-emissions of electricity generation in Japan

Japan has been living in the **hydrocarbon age** for a long time. Oil and gas fired power plants have had a 47% market share of electricity generation in Japan in 1990 and 40% in 2009 (Figure 8.5.2).

In 2058 the nuclear electricity market share will reach 36% and nuclear power will be the number one electricity source in Japan. The **nuclear age** will then last from 2058 until 2120, when wind or solar plants will overcome nuclear generation.

The CO₂-emissions of electricity generation in Japan have peaked at 570 MtCO₂ in 2007 (Figure 8.5.3). The emissions will decrease to 270 MtCO₂ by 2050 and to 30 Mt by 2100. The emissions per capita will reduce from 3800 kgCO₂/capita in 2009 to 2600 kgCO₂/capita by 2050 and to 500 kgCO₂/capita by 2100. The both figures are far from the target of 690 kgCO₂/capita by 2050 and 140 kgCO₂/capita by 2100. Japan would need in addition a massive CCS program.

8.6 Latin America

Electricity generation in Latin America has increased from 500 TWh in 1990 to 1080 TWh in 2009. It will still continue to increase to 2480 TWh by 2050 and 3330 TWh by 2100 (Figure 8.6.1).

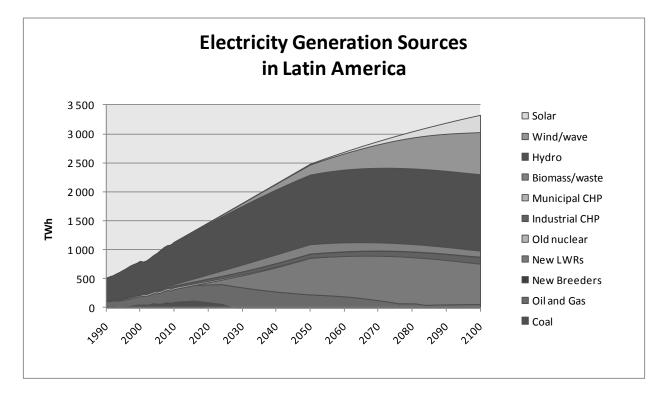


Figure 8.6.1 The forecasted electricity generation sources in Latin America

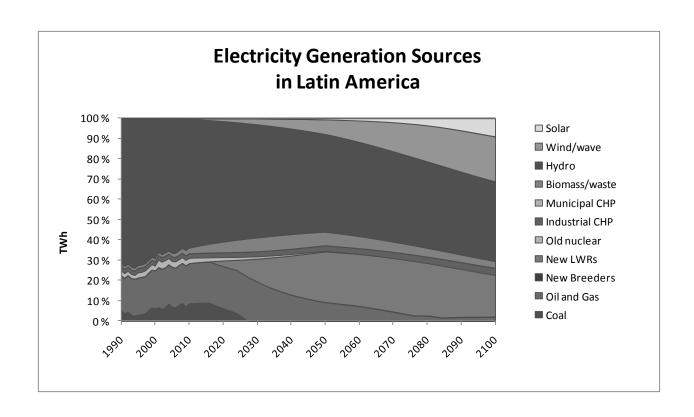


Figure 8.6.2 The forecasted market share of electricity sources in Latin America

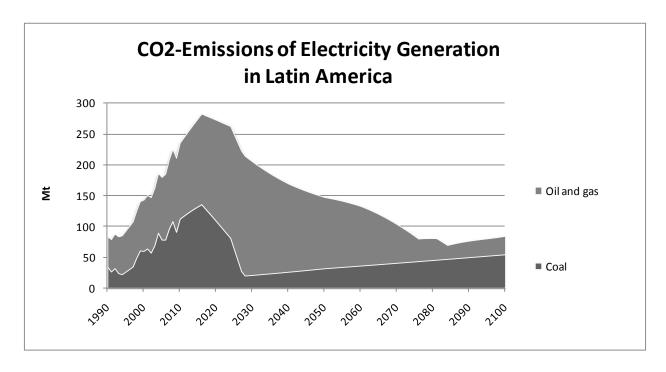


Figure 8.6.3 The forecasted CO₂-emissions of electricity generation in Latin America

The main source of electricity generation has been hydro, which has a 65% market share in 2009 (Figure 8.6.2). The hydro share will go down to 48% by 2050 and 40% by 2100. Thus Latin America continues to live in the **hydro age** also in the future. Nuclear will be the second largest source by 2050, when the nuclear share has increased to 25% of generation. In 2100 both wind and nuclear will have 20-22% market share.

CO₂-emissions have been increasing as more fossil fuel power plants have been constructed. The emissions are now 210 MtCO₂ annually (Figure 8.6.3). The emissions will peak at 280 MtCO₂ in 2016, if the new nuclear plants will replace coal in electricity generation. The specific emissions will be 200 kgCO₂/capita in 2050 and 120 kgCO₂/capita in 2100. The both figures are below the targets of 690 kgCO₂/capita in 2050 and 140 kgCO₂/capita in 2100.

8.7 The Middle East

Electricity generation in the Middle East has grown from 240 TWh in 1990 to 760 TWh in 2009. It will reach to 2770 TWh by 2050 and 5400 TWh by 2100 (Figure 8.7.1). The major reason for the growth is the population, which will increase to more than 500 million by 2100.

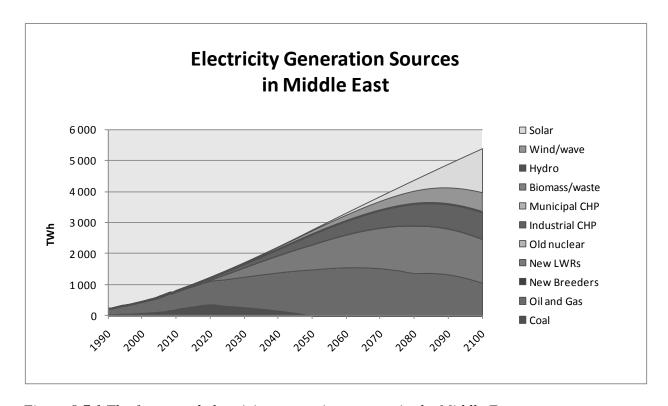


Figure 8.7.1 The forecasted electricity generation sources in the Middle East

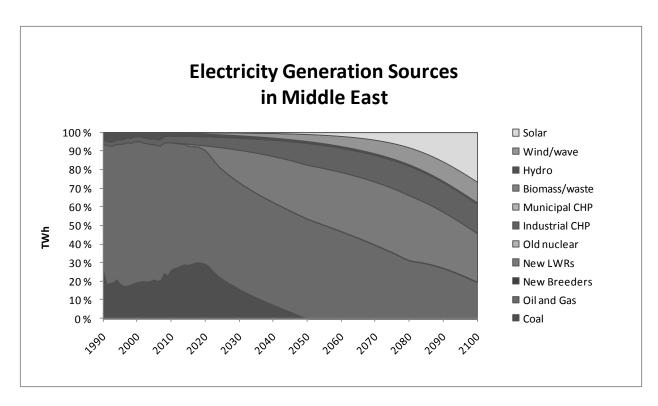


Figure 8.7.2 The forecasted market shares of electricity generation sources in Middle East

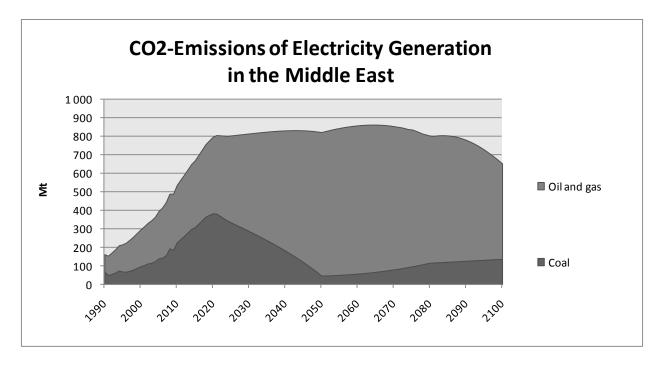


Figure 8.7.3 The forecasted CO₂-emissions of electricity generation in the Middle East

The main sources of electricity in the Middle East have been oil and gas (Figure 8.7.2), and the countries have been living in the **hydrocarbon age** for a long time. Hydrocarbons have had about 70% share from the electricity generation. Nuclear generation will achieve a 35% share by 2050 and will overcome oil and gas by then. The **nuclear age** in the Middle East will then last from 2050 until 2100.

The Middle East will need quite a large nuclear program in order to cut the CO₂-emissions. The capacity additions after 2030 should be 4500 MWe annually, which corresponds to three 1500 MW nuclear plants. At the moment there are two plants under construction in Iran and four plants in the planning stage in the United Arab Emirates. It would very profitable to sell the oil and gas to the world market rather than use it for base load power generation.

The Middle East will be entering into the **solar age** in 2100, when solar will be the main source of electricity. The Middle East is one of the best places for solar power throughout the year and the solar age will probably start from there in the future.

The CO₂-emissions of electricity generation in the Middle East have been growing rapidly from 160 Mt in 1990 to 490 Mt in 2009 (Figure 8.7.3). The CO₂-emissions will then rise to 800 Mt by 2020 and continue at this level until 2080. They will then start to decrease as the Middle East is approaching the solar age. The emissions will go down to 440 Mt by 2100. The specific emissions in 2100 will be 1250 kgCO₂/capita, which is nearly ten times the target value of 140 kgCO₂/capita (2100). Thus the Middle East will need a massive CCS program to reach the target.

8.8 Africa

Electricity consumption in Africa has increased from 320 TWh in 1990 to 630 TWh in 2009 (Figure 8.8.1). The growth will continue in the future and reach 2220 TWh by 2050 and 3900 TWh by 2100. The specific consumption will grow from 560 kWh/capita in 2009 to 1150 kWh/capita in 2050 and by 1750 kWh/ capita by 2100.

Coal has had the largest market share until now and Africa will continue to live in the **coal age** until 2030. **Hydrocarbons** will overtake coal by 2030 as the largest source of electricity.

The **nuclear age** will start in 2051, when nuclear will reach a 27% share and overtake the hydrocarbons. The nuclear age will then last until 2090, when hydro power will achieve a 27% share and overtake nuclear. Nuclear capacity additions could start at 2022 with 3000 MW of new capacity connected to the grid annually. This corresponds to two 1500 MW nuclear plants each year.

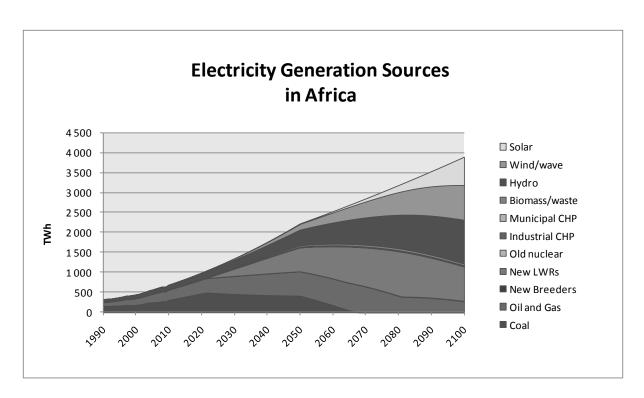


Figure 8.8.1 The forecasted electricity generation sources in Africa

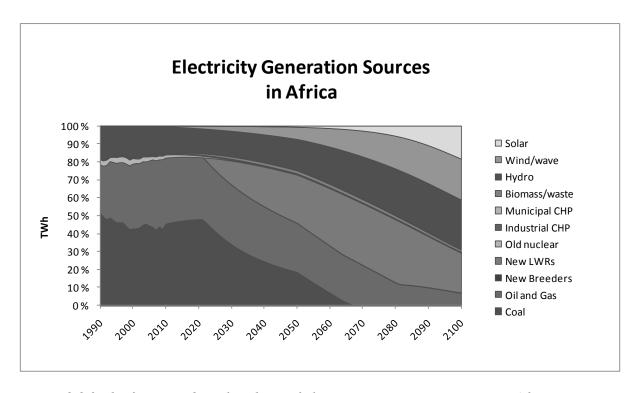


Figure 8.8.2 The forecasted market share of electricity generation sources in Africa

There are already some plants in operation in South Africa and several more in the planning stage. Also Egypt is planning to build nuclear power plants. However, there are large potential of renewable capacity available.

The CO₂-emissions of electricity generation have been increasing from 220 Mt in 1990 to 410 Mt in 2009. The emissions will be increasing to 690 Mt by 2020 and peaking at 700 Gt in 2050. After the new nuclear and renewable power plant gain market share, the CO₂-emissions will decline to 140 Gt by 2100.

The specific emissions were 440 kgCO₂/capita in 2009. The emissions will be 370 kg CO₂/capita by 2050 and 60 kg CO₂/capita by 2100. The both figures are lower than the target of 690 kgCO₂/capita (2050) and 140 kg CO₂/capita (2100).

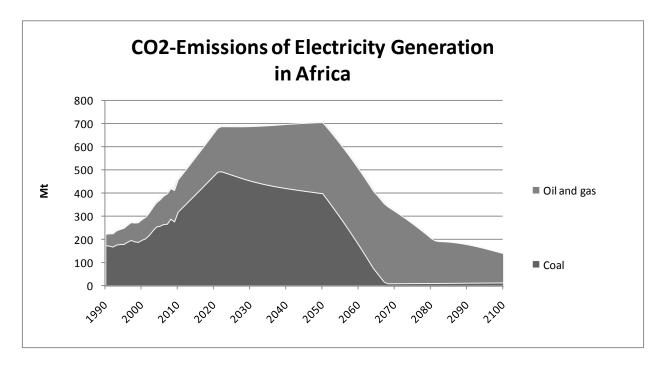


Figure 8.8.3 The forecasted CO₂-emissions of electricity generation in Africa

8.9 China

Electricity generation in China has increased from 620 TWh in 1990 to 3720 TWh in 2009. The growth will continue and consumption will be 12 000 TWh by 2050 and 13 300 TWh by 2100. The growth in consumption has been 9% annually since 1990. It will slow down to 3% from 2009 to 2050, because the population growth will be quite moderate in the future.

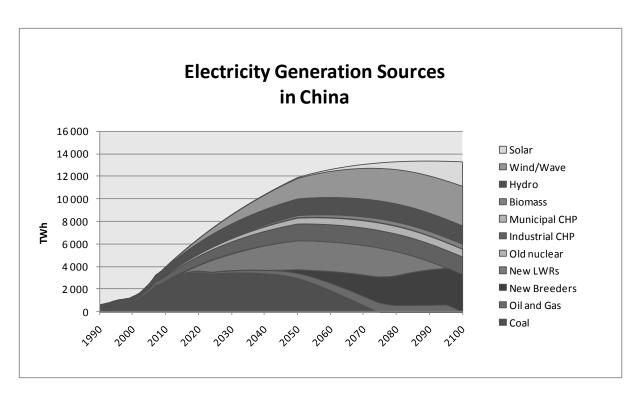


Figure 8.9.1 The forecasted electricity generation sources in China

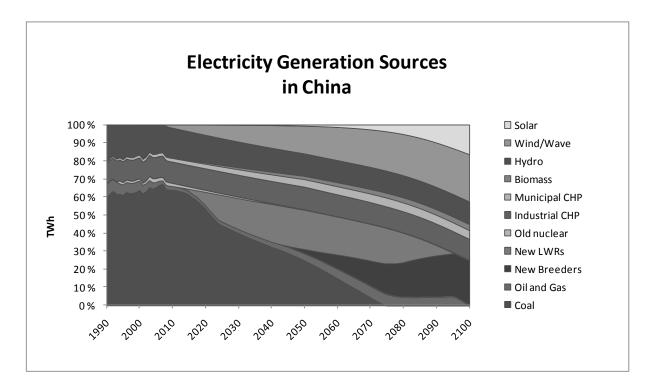


Figure 8.9.2 The forecasted market shares of electricity generation in China

China has been living in the **coal age** and coal has a 60% share of electricity generation (Figure 8.9.2). The **nuclear age** will start in 2050, when the nuclear share will increase to 25% and overtake coal as the number one electricity source in China. The nuclear age will end in 2095, when wind power will reach a 25% share and overtake nuclear power as the market leader.

China will need a massive nuclear program to get rid of coal fired power plants. The nuclear capacity additions should be 20 000 MWe annually starting from 2021. This is about 30% of all nuclear capacity additions in the world. However, this is much less than the about 50 000–70 000 MWe of coal plants that China has built annually during the last ten years

Between the years 2050 and 2100 about 50% of new nuclear plant should be built as nuclear CHP plants. This requires that a new type of nuclear plants will be developed by 2050. The plants should be inherently safe so that they can be located in the vicinity of population centers. The plants could be use breeder reactor technology, which China is developing at the moment.

The CO₂-emissions have been increased from 450 MtCO₂/a in 1990 to 2700 MtCO₂/a in 2009 (Figure 8.9.3). The emissions will peak at 4000 Mt in 2020 and will decrease to 3200 Mt/a by 2050 and 240 Mt/a by 2100. The specific emissions were 2000 kgCO₂/capita in 2009. The emissions will reach 2300 kgCO₂/capita by 2050 and then go down to 200 kgCO₂/capita by 2100. The both figures are above the targets of 690 kgCO₂ (2050) and 140 kgCO₂ (2100). To reach the targets China would need an additional CCS program..

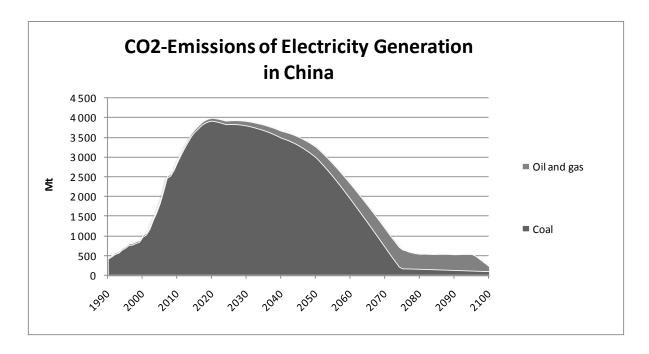


Figure 8.9.3 The forecasted CO₂-emissions of electricity generation in China

8.10 India

Electricity consumption in India has grown from 280 TWh in 1990 to 870 TWh in 2009. The growth will continue in the future and consumption will reach 2300 TWh by 2050 and 2880 TWh by 2100. The specific consumption was 730 kWh/capita in 2009 and will increase to 1400 kWh/capita by 2050 and 2000 kWh/capita by 2100.

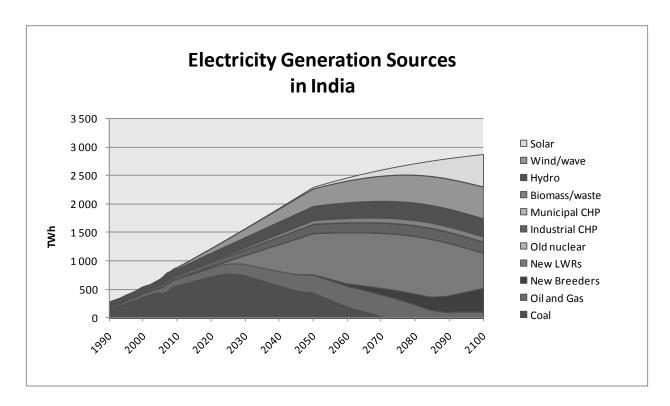


Figure 8.10.1 The forecasted electricity sources in India

The main source of electricity in India has been coal. **The coal age** in India will end in 2042, when the nuclear share will increase to 25% and it will overtake coal as the number one source of electricity. The **nuclear age** will then last from 2041 until 2120, when solar power will overtake nuclear. The **solar age** will then last from 2120 to the unknown future.

India will need a massive nuclear and renewable power program to get rid of coal in the future. The capacity additions of nuclear power should be 4500 MWe/a, starting in 2030. This will also include breeder reactors, which are under development in India. The breeders may include thorium breeders, which are breeding fertile thorium-232 into fissile uranium-233.

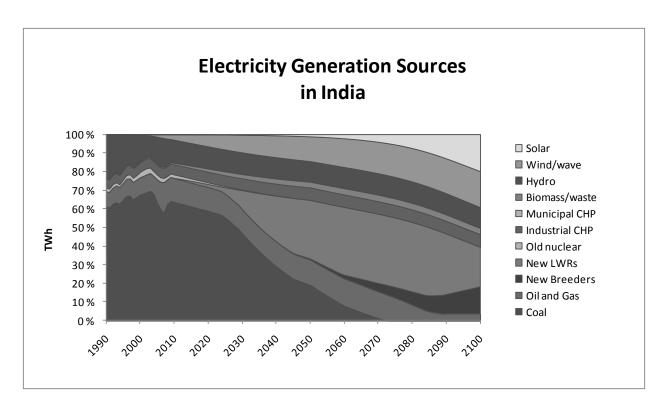


Figure 8.10.2 The forecasted market share of electricity sources in India

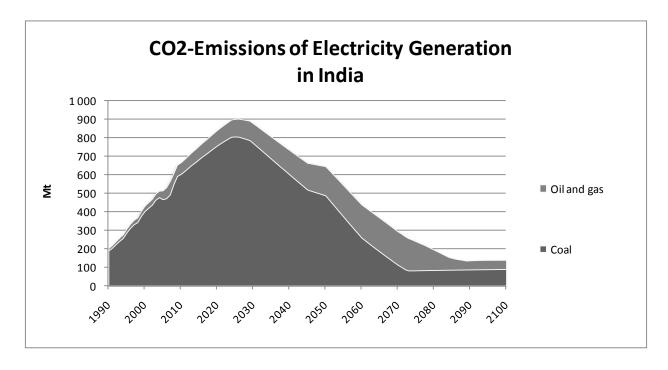


Figure 8.10.3 The forecasted CO₂-emissions of electricity generation in India

India is also a very good area for wind power development. The capacity additions of wind power will increase to 5000 MWe/a by 2030 and to 6000 MWe/a by 2050. However, solar power will be the best solution for electricity generation in the future, because of good solar conditions. Solar power capacity additions in India are increasing continuously and will reach a 25 000 MWe/a level by 2100.

The CO₂-emissions of electricity generation in India are increasing very rapidly. The emissions were 200 MtCO₂/a in 1990 and 660 MtCO₂/a in 2009 (Figure 8.10.3). They will peak at 900 Mt/a in 2025. Thereafter the emissions will decrease to 650 Mt/a by 2050 and to 140 Mt by 2100. The specific emissions were 550 kgCO₂/capita in 2009. They will reach 400 kgCO₂/capita by 2050 and 100 kgCO₂/capita by 2100. These figures are lower than the targets of 690 kgCO₂/capita (2050) and 140 kgCO₂/capita (2100).

8.11 The rest of Asia and Oceania

The electricity consumption in the rest of Asia and the Pacific has increased from 680 TWh in 1990 to 1800 TWh in 2009 (Figure 8.11.1). The consumption will continue to increase to 4900 TWh by 2050 and to 6160 TWh by 2100. The specific consumption was 1400 kWh/capita in 2009. It will grow to 2930 kWh/capita by 2050 and to 3900 kWh/capita by 2100.

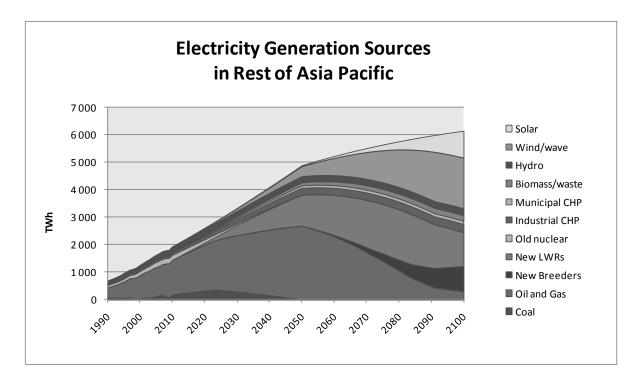


Figure 8.11.1 The forecasted electricity generation sources in rest of Asia and the Pacific

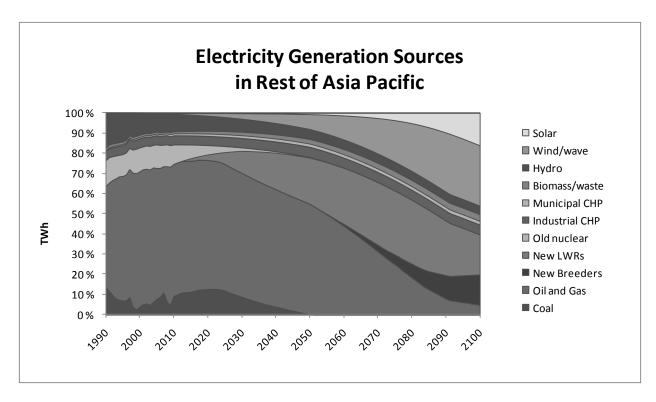


Figure 8.11.2 The forecasted market sharea of electricity generation sources in rest of Asia and the Pacific

The main electricity sources in the rest of Asia and the Pacific have been oil and gas plants. The **hydrocarbon age** will continue until 2069, when the nuclear share will increase to 36% and overtake oil and gas. The **nuclear age** will last from 2070 to 2100 until wind and wave plants will take the leading role in power generation. The **wind age** will then continue until solar electricity will take the lead in around 2120-50.

Nuclear power capacity additions will increase to 6000 MWe/a by 2026, which corresponds to four 1500 MWe plants annually. Most of the investment will be made in South Korea, but new nuclear plants will also be built in Bangladesh and in Vietnam, which have signed contracts to build two 1000 MWe plants each by 2020. Other nuclear countries include Pakistan, Thailand, the Phillipines and Indonesia.

The CO₂-emissions of electricity generation in the rest of Asia and the Pacific have increased from 300 MtCO₂/a in 1990 to 800 MtCO₂/a in 2009 (Figure 8.11.3). The emissions will peak at 1400 MtCO₂/a during the years 2027–2050. Thereafter the emissions will degrease to 200 MtCO₂/a by 2100. The specific emissions in the rest of the Asia and the Pacific are now 710 kgCO₂/capita. They will reach 860 kgCO₂/capita by 2050 and go down to 120 kgCO₂/capita by 2100. The 2100 figure will be below the target of 140 kgCO₂/capita.

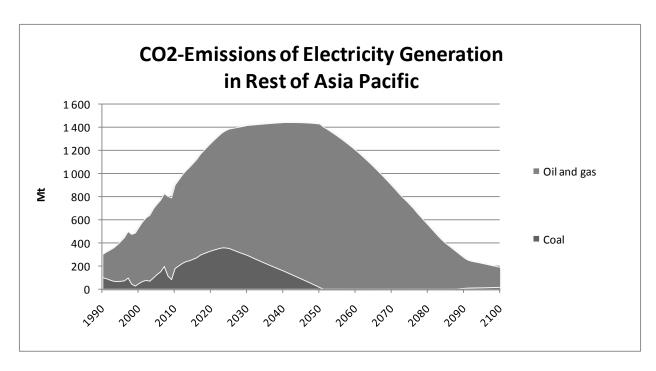


Figure 8.11.3 Forecasted CO₂-emissions of electricity generation in Rest of Asia Pacific

9 THE FEASIBILITY OF NUCLEAR POWER

9.1 Planning of a nuclear project

Nuclear project presents one of the most complicated and large industrial projects that have ever been implemented. The success of the project depends very much on the experience of the project people and on organized project planning.

A nuclear project can be divided into six phases: the feasibility study phase, supplier selection phase, designing phase, the implementation phase, the operation phase and the decommissioning phase (Figure 9.1.1). It will typically take four years before state approval for the site has been obtained (Figure 9.1.2). After state approval it will take about ten years before the plant will be handed over into commercial operation.

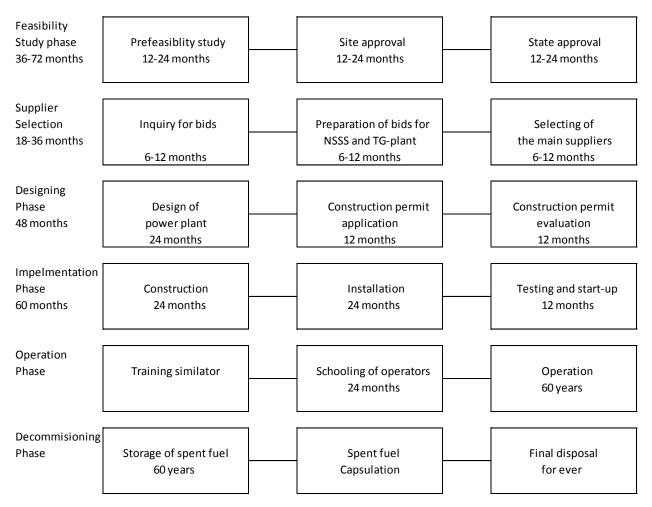


Figure 9.1.1 The phases in a nuclear project

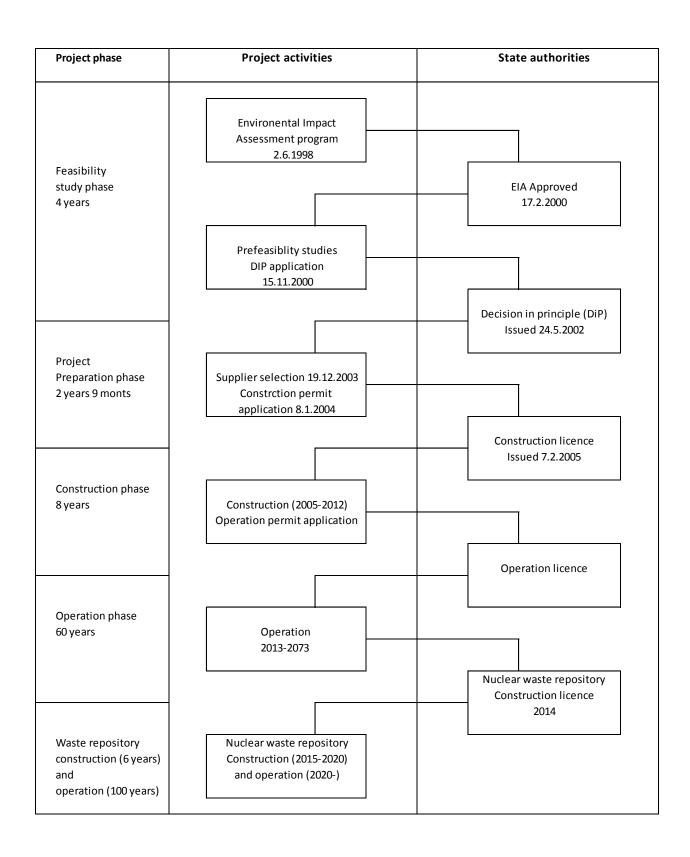


Figure 9.1.2 The main decisions made in the Olkiluoto-3 nuclear project

The operation phase should be prepared carefully during the project execution phase and the operators should be trained with a training simulator. If a training simulator is not available, it should be built before the training can be effectively executed.

Finally the decommissioning phase should be planned. This should include a plan for interim storage and final repository of the high level nuclear waste and a plan for decommissioning of the nuclear plant after the operation phase

9.2 Prefeasibility studies

Nuclear project will actually start when the future owner of the nuclear plant starts studying the alternative nuclear power plants in his future generation mix. These studies have been thoroughly described in my earlier book "*Planning of optimal power systems*".

These studies include cost estimates for each of the alternative power plants and simulating the costs and profitability of the power plants in the utility system. The result of the optimization should give the optimal sizes of the power plants and schedules to connect each of the plants to the grid. They should also include the necessary grid and reserve power investments. If the size of the power plant increases, the reserve power needs and network investments will increase as well.

9.2.1 Investment costs

The cost estimates for power plants in this phase could be generated by using the experiences of former nuclear investments. The investment costs should be converted into current cost level by using cost index (Table 9.2.1). The costs of the Loviisa-1/2 and the Olkiluoto-1/2 plants were €1393 and €1528/kWe respectively. The total investment costs of the Olkiluoto-3 plant will be about €3500/kWe or twice the costs of the old plants. However, the plant was sold at a fixed price of €2000/kWe. The losses of Areva are therefore about €1500/kWe or about 75% of the sales price.

Table 9.2.1 The investment costs of Finnish nuclear power plants

	Loviisa-1	Loviisa-2	Total	Olkiluoto-1	Olkiluoto-2	Total	Olkiluoto-3
Output MWe	488	488	976	880	860	1740	1600
Grid connection	1977,2	1979,5		1978,8	1980,2		2013
Cost index (2010 = 100)	22,2	28		25,4	30,8		100
Investment costs Meur	167	170	337	324	426	750	5600
Costs at 2010 level Meur	752	607	1359	1276	1383	2658	5600
Eur/kWe	1542	1244	1393	1450	1608	1528	3500

The Finnish costs of a small nuclear plant do not predict the present costs of a large plant. There are several factors which influence costs. The new safety features, such as protection against an aircraft crash and core meltdown, increase costs.

In my opinion the lowest specific costs would be obtained at a 600-1000 MW size. The cost estimates in plant over the 1000 MW size seem to have scaling factor of 1.2-1.5, which means that the specific costs at the 1600 MW size would be higher than at 1000 MW size. The factors that tend to raise the costs, are for example the turbine speed. Above 1000 MW size the speed should 1500 r/min (or 1800 r/min in the US). Low rotation speed makes the turbine much more heavier and expensive than the full speed (3000 r/min) turbines.

Larger size also will increase construction time and the interests during construction (IDC). Larger size means more powerful transmission lines and more reserve power plants. The trip of the plants also requires more regulation reserve power, which should replace the loss of nuclear power within 15 seconds and then restore the system back to be ready for a second disturbance. These external costs, if caused by the nuclear plant, have to be paid by the nuclear plant's investor.

9.2.2 Generation costs

The generation costs of alternative power plants should be evaluated in the prefeasibility study phase. If a nuclear plant gives the lowest costs, then the investment can be justified. The main competitor for a nuclear plant is not today the coal fired plant, but a gas fired CHP plant and a wind power plant can generate power at the lowest cost.

The investment costs of a nuclear plant are at 2011 cost level $\[\le 2500 - 3500 \]$ (Table 9.2.2). The generation costs of nuclear plants are typically $\[\le 40 - 55 \]$ MWh, if the utilization time of the power plant is 7000-8000 h/a. A wind power plant can also generate electricity at the costs of $\[\le 35 - 52 \]$ MWh at good sites, where the full power hours reach 2000-3000 h/a. The generation costs of a gas combined cycle plant and a low cost nuclear plant are the same at full power hours of $\[T_1 \]$:

$$T_1 = (175.5-60.6) \text{ kWa/} (55.5-17.5) \text{ MWh} = 114.9/38.0 \text{ h/a} = 3020 \text{ h/a}$$

A combined cycle plant and a gas engine plant will generate power at the same cost at T₂:

$$T_2 = (60.6-40.1) \notin /kWa / (68.4-55.5) \notin /MWh = 20.5/12.9 h/a = 1590 h/a$$

At the intermediate power range (1590–3020 h/a) gas combined cycle plants generate the lowest cost electricity. At the peaking power range (0–1590 h/a) the lowest costs will be generated by a gas engine plant. During the old days the base load was planned with coal fired power plants. A coal plant and a gas engine plant will generate electricity at the same costs at T_3 :

$$T_3 = (107.6-40.1) \notin /kW / (68.4-48.6) \notin /MWh = 67.5/19.8 h/a = 3410 h/a$$

Thus if coal plants will be built, they would be economical at 3410–8765 h/a. Gas or diesel engines are more economical than coal plants, if the full power hours would be 0–3410 h/a.

Table 9.2.2 Preliminary generation cost evaluation (discount rate 5 %)

Туре		Nuclear	Nuclear	Coal	Gas Comb.	Gas	Wind	Wind
		low	high		Cycle	Engine	low	high
Concept	MW	1x1000	1x1000	2x500	2x500	20 x 10	40x3	40x3
Output	MW	1 000	1 000	1 000	1 000	200	120	120
Capital costs								
Mechanical systems	Meur	1 000	1 300	600	300	60	70	90
Electrical systems	Meur	300	500	150	100	20	15	20
Buildings	Meur	500	650	200	100	10	20	25
Indirect costs	Meur	360	490	190	100	9	21	27
Fuel storage	Meur	40	50	67	77	-		
Basic costs	Meur	2 200	2 990	1 207	677	99	126	162
Construction time	Years	5	7	4	3	1	2	2
Interests during constr.	Meur	275	523	121	51	2	6	8
Total costs	Meur	2 475	3 513	1 327	728	101	132	170
Specific costs	eur/kWe	2 475	3 513	1 327	728	507	1 103	1 418
Discount rate	%	5%	5%	5 %	5%	5%	5%	5%
Operation time	years	60	60	30	30	30	25	25
Annual costs	eur/kWa	130,7	185,6	86,3	47,3	33,0	78,2	100,6
Fixed O&M costs								
Number of operators		200	200	80	60	20	10	10
Wages / operator	keur	100,0	100,0	100,0	100,0	100,0	100,0	100,0
Wages	eur/kWa	20,0	20,0	8,0	6,0	2,0	8,3	8,3
Other fixed costs	eur/kWa	24,8	35,1	13,3	7,3	5,1	11,0	14,2
Total fixed O&M	eur/kWa	44,8	55,1	21,3	13,3	7,1	19,4	22,5
Variable O&M costs		<u> </u>	,	<u> </u>	•	,	· ·	· · · · · ·
Maintenance	eur/MWh	9,8	13,5	5,6	5,0	6,0	2,1	2,8
Consumables	eur/MWh	2,0	2,0	2,0	0,5	0,5	0,1	0,1
Total	eur/MWh	11,8	15,5	7,6	5,5	6,5	2,2	2,9
Fuel costs	,	,,-	-,-	,-		-,-	,	,-
Efficiency	%	35 %	35 %	42 %	52 %	42 %		
Fuel price	eur/MWh	2,0	2,0	7,0	20,0	20,0		
Fuel costs	eur/MWh	5,7	5,7	16,7	38,5	47,6		
CO2-price	eur/t	-,	-,	30,0	30,0	30,0		
CO2-emissions	g/kWh			810	385	476		
CO2-costs	eur/MWh			24,3	11,5	14,3		
Total fuel costs	eur/MWh	5,7	5,7	41,0	50,0	61,9	_	_
Total fixed costs	eur/kWa	175,5	240,7	107,6	60,6	40,1	97,6	123,1
Total variable costs	eur/MWh	17,5	21,2	48,6	55,5	68,4	2,2	2,9
Generation costs		,,-	,			,	,	,-
at 8000 h/a	eur/MWh	39,4	51,3	62,0	63,1	73,4		
at 7000 h/a	eur/MWh	42,5	55,6	64,0	64,2	74,1		
at 6000 h/a	eur/MWh	46,7	61,3	66,5	65,6	75,1		
at 5000 h/a	eur/MWh	52,6	69,4	70,1	67,6	76,4		
at 4000 h/a	eur/MWh	61,3	81,4	75,5	70,7	78,4		
at 3000 h/a	eur/MWh	76,0	101,5	84,5	75,7	81,8	34,8	43,9
at 2500 h/a	eur/MWh	-,-	/-	- ·/-	79,7	84,4	41,3	52,1
at 2000 h/a	eur/MWh				85,8	88,4	51,0	64,4
at 1500 h/a	eur/MWh				95,9	95,1	67,3	84,9

9.2.3 System costs

The operation of the alternative power plants can then be simulated in the real system for one week (Figure 9.2.1). If all weeks would be the same, the system would need 73 TWh of electricity annually. In the traditional system (Case 1, Table 9.2.3) the base load would be generated with 9000 MWe capacity of coal fired plants (500 MWe unit size) and the peak and reserve needs with 500 MWe diesel or gas engines.

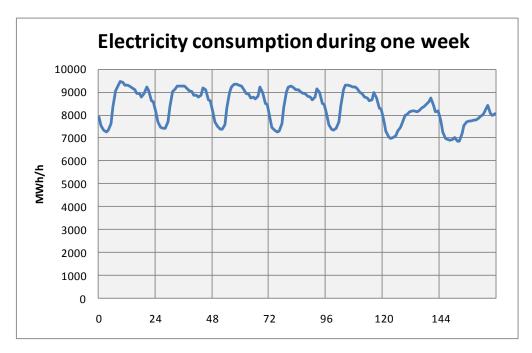


Figure 9.2.1 Hourly electricity consumption during one week in September 2010 in Finland

Additionally a 1000 MWe capacity of gas or diesel engine plants is needed for fast reserves to cover trip of two 500 MWe coals. The total costs, assuming that all weeks are the same, would be $\[\in \]$ 4592 million or $\[\in \]$ 62.9/MWh (Table 9.2.3). The total emissions would be 59 MtCO₂ or 807 gCO₂/kWh.

If two 1000 MWe nuclear plants will be added to the system (Case 2), then 7000 MWe remains to be generated by coal plants and 500 MWe by diesel or gas engine plants. Additionally, 2 x 1000 MWe diesel or gas engine capacity would be needed for reserves. The first 1000 MWe plant capacity would be needed for reserves to cover a trip of the first nuclear plant. The second 1000 MWe is needed to cover the trip of the second nuclear plant.

The annual costs of a system with two 1000 MW nuclear plants would be €4390 million or €60.1/MWh. The two unit nuclear plant would make the annual costs €200 million lower than in Case 1 without the nuclear plants. The annual CO₂-emissions would be 44.2 MtCO₂ or 605 gCO₂/kWh

Table 9.2.3 Simplified evaluation of the Finnish power system using the data given in Figure 9.2.1

		Case 1	Case 2	Case 3
Generation mix				
Nuclear capacity	MW	0	2000	7000
Coal capacity	MW	9000	7000	0
Gas CC capacity	MW	0	0	2000
Gas or diesel engines	MW	1500	2500	2500
Total capacity	MW	10500	11500	11500
Annual generation	TWh	73	73	73
Generation costs				
Annual costs	Meur	4592	4390	3669
Specific costs	eur/MWh	62,9	60,1	50,3
Index		100 %	96 %	80 %
Emissions				
Annual emissions	MtCO2	58,9	44,2	4,6
Specific emissions	gCO2/kWl	807	605	63
Index		100 %	75 %	8%

If the system would be optimized to get the lowest costs (Case 3, Table 9.2.3), then the base load should be generated with 7×1000 MW of nuclear plants, the intermediate load with 2000 MW of gas fired combined cycle plants and the peak and reserve load with 500 MW of gas engine plants. Additionally 2×1000 MW of reserves are needed to cover the trips of two 1000 MW nuclear units.

The total annual costs would then be €3669 million or €50.3/MWh. The annual costs would be €923 million (20%) lower than without nuclear power in the Case 1. The annual CO₂-emissions of electricity generation would come down to 4.6 MtCO₂ or to 63 gCO₂/kWh. This would be 92% lower than in the Case 1, with the coal fired base load generation.

The Finnish power system today has 2400 MW of nuclear capacity in operation, one 1600 MW plant under construction and two 1500 MW plants in supplier selection phase. In the year 2020 the total nuclear capacity in Finland would be about 7000 MW. The nuclear capacity will be 1.3 kW/capita and the largest specific nuclear capacity of any country. Additionally Finland has about a 5000 MW capacity of CHP power plants, which will be needed mostly during the winter time to cover the 16 000 MW peak load during the coldest winter days. There is also 2000 MW of hydro capacity and 2000 MW capacity of condensing power plants.

9.3 Site studies

A very critical task is to find the sites for the new nuclear plants. The site has to have good cooling water conditions, and not very far from the high voltage network. Additionally, within a 5-20 km radius from the site there should be practically no permanent population, because during accident situations this population should be evacuated.

Another critical factor is the ground conditions at the site. The best soil for the site is granite rock, where the basement can be built without massive concrete structures. The bad seismic conditions could increase the costs of nuclear power plant investments. In Finland a nuclear plant should be designed to withstand earthquake acceleration of 0.1 g (g=9.81 m/s²). However, there are sites abroad, where 0.25 g is required.

The site has to be approved by the local municipality. A municipal council has typically some 30-60 members that should approve the nuclear plant to be built. The author has been a member of the Espoo city council, but during the years 1986-1992 nuclear power was out of the question because of the Chernobyl accident. Espoo has had the first research reactor (Triga) in operation since 1962 and possibilities of a heating reactor were studied during years 1979-85.

There are municipalities that favor nuclear power. A nuclear power plant would generate tax revenues for the community, jobs for local people and service companies. But it will also make the neighborhood of the plant risky because of possible radiation releases. However, the radiation releases of the core meltdown accident at the Three Mile Island in 1978 did not cause any danger for the local population. If the design includes a core catcher, the risks will be even lower than in 1978.

Electrical grid connections to the site have to be strong. They should allow the trip of the nuclear plant without causing a blackout of the grid. On the other hand a blackout in the national power system should not cause the trip of the power plant. The power plants should reduce its load to house load conditions, which is some 5-10% of the gross output of the plant.

Additionally, the nuclear plant should have a priority power supply from a separate local plant. The local plant may be a hydro plant, which could operate during the blackout of the main grid. It could also be built by using one or two 8-16 MW diesel engines, which will be started by using pressurized air. The blackout in 2003 in North-East USA stopped 10 nuclear power plants within three minutes from the start of the blackout. Nine of the nuclear plants had to use the emergency diesels and one used its priority power supply until the grid was restored within 2 to 14 hours. After this blackout many nuclear stations installed new priority electricity supply systems.

Another question will be the transportation possibilities. A very good harbor and roads will be necessary for transportation of the reactor pressure vessel, which might have a weight of 300 tons. The main transformers and generators of a nuclear plant might have the same weight.

9.4 State approval

If the nuclear project is found to be feasible, it will need an approval by the state. In Finland the decision in principle will be made by the Finnish Government, and the Parliament has to approve the decision before the project can be started.

The application for the state includes feasibility aspects and site evaluations. It will also describe which reactors may be selected and their safety features. The safety authorities should also review that the reactor candidates fulfill the local safety rules.

In Finland perhaps the most critical issue has been the disposal of the spent fuel. In 1993 the Parliament said no to new reactors because the spent fuel question was open. Since then the utilities have established a separate company, Posiva, to prepare the disposal of spent fuels. When the decision of the Olkiluoto-3 reactor was made in 2002, the disposal methodology and site was approved at the same time. We will discuss this more thoroughly in Chapter 12.

When the decision is made, it will have many effects on energy policies. A nuclear project will have a large influence on the CO₂-emissions and on alternative energy sources. The goals of renewable energy and nuclear energy might be competing with each other. The aspects for economy, local industry and employment should also be considered.

Nuclear power has many sides. Some people are against nuclear power for many reasons. Some think it s the best energy technology available. This kind of discussion has been going on since the Three Mile Island accident. Several books about this have been published. In my opinion the best book was Michio Kaku's and Jennifer Trainer's Book, Nuclear Power: Both Sides /9.2/. It includes the main thoughts about nuclear power by the US leading nuclear scientist and opponents.

References

/9.1/ Asko Vuorinen. Planning of Optimal Power Systems. Ekoenergo Oy. 2008

/9.2/ Michio <u>Kaku</u> and Jennifer <u>Trainer</u>. *Nuclear Power: Both Sides. The best Arguments For and Against the Most Controversial Technology*. W.W. Norton & Company 1982

10 SELECTION OF THE REACTOR SUPPLIER

10.1 Splitting the project into contracts

A nuclear power plant can be purchased with one main Engineering and Procurement Contract (EPC) or by splitting the project into several contracts. Most nuclear projects have been executed by big national utility companies, which have established a nuclear project team to manage the planning and contract management.

A split package contract requires a project team of some 150-300 engineers in the project's main office and about 50-100 engineers at the site for supervision and management. The amount of engineering in the Loviisa "Atomic project group" was about 1000 man-years for the Loviisa-1 project and 600 man-years for the Loviisa-2 project (Figure 11.2.1).

Some of the engineers had experience on coal power plant projects, but most of the staff, including the author, was young (25 years old), and my experience was only from big refinery project. The whole project staff, including many foreign consultants, was located just in one building, which eased communication.

The staff had in average about three years of engineering experience. In addition most of the engineers had been about one year in obligatory Finnish army service, where they had been trained to work in organized teams. The army service has been obligatory for all men for age at 20 years. The project reminded me about the time in the army and I think that the secret of the success was that the engineers were committed to act like in army times. The project was divided for groups and each of the group was led by a group leader. The biggest engineering group was process and instrumentation, which included 40-50 people.

The EPC contract approach can be recommended for an inexperienced utility, which does not have the project staff. However, there are not many nuclear power plant vendors, who are competent EPC contractors. Thus they will hire a separate contractor to do the engineering and construction for them. Most of the US nuclear projects were managed by an architect engineering company, which was hired by the utility. Each of the architect engineering companies had their own designs even the reactor vendor was the same.

TVO has had EPC approach in Olkiluoto projects. However, in the Olkiluoto-1 and -2 projects the contractors were Finnish and they knew the Finnish norms and practices. In the Olkiluoto-3 EPR case the main EPC contractor was Areva and they used mostly foreign contractors and foreign labor.

This has caused several problems, because the local conditions were not known by the foreign engineers. The engineering works was purchased from several countries, which made communication more difficult.

10.2 Prequalified suppliers

The most critical decision in a nuclear project is the selection of the reactor or nuclear steam supply system's (NSSS) vendor. The most careful buyer will accept only the NSSS vendor, which has had operation experience with the offered reactor. Some require that at least two reactors have been operating successfully.

Additionally, local safety requirements should be noted. Do the reference plants have the required safety systems? In Finland the plant should have a core catcher and outer protection against a possible aircraft crash. These requirements would mean a completely new design of the reactor building. This would mean a two year design project before the construction can begin.

10.3 Boiling water reactor plants

The Finnish utilities have prequalified three boiling water reactors and four pressurized water reactors (Experts Statement to the EIA report, June 2008). The boiling water reactors include ABWR from General Electric/Toshiba/Hitachi, ESBWR from GEH and Kerena by Areva (Table 10.3.1).

10.3.1 ABWR

ABWR reactor plants have been built in Japan, where the **Kashiwazaki-Kariwa** plant is the first of this kind of power plants in operation. Advanced boiling water reactor has internal circulating pumps for the first time in GE reactors. They were already introduced in the Olkiluoto-1 nuclear plant by Asea Atom in 1979.

The author had the possibility to visit the Kashiwazaki-Kariwa site in 1991, when the construction was in progress. It was impressive to see the modular construction, which was in progress by then. The rebars of the containment structures were prefabricated and the total construction time was about four years.

In the US, the ABWR plant planned in South Texas will be the first plant in the US in thirty years. The pressure vessel has already been ordered to be ready by 2012. The construction could start in 2011 and the plant could be ready for operation by 2015.

10.3.2 ESBWR

The ESBWR plant has no operating references, but one plant in the US is in the planning phase. It will have natural circulation in the reactor and thus the reactor pressure vessel (RPV) has a height of 27.6 meters. The large water volume means that the reactor is safe, because the thermal capacity of water can take the extra energy during the transients.

The passive heat removal system has been designed to cool the reactor for 72 hours without external electricity (Figure 10.3.1). This kind of design satisfies the new station blackout (SBO) criteria that have been developed after Fukushima accident. This kind of passive heat removal system has not been proven in practice.

The plant has also some safety equipment in turbine hall, which is not allowed by the Finnish safety standards. The design for a possible aircraft crash has not been completed. However, design changes can be made to satisfy the Finnish standards.

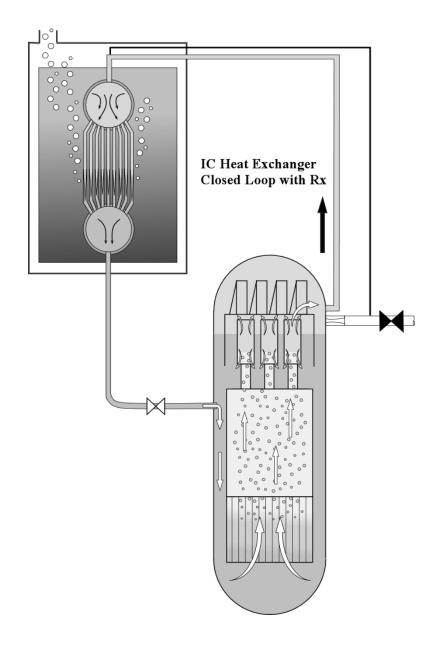


Figure 10.3.1 Passive IC cooling system of the ESBWR reactor plant can cool the reactor for 72 hours without external electricity

Table 10.3.1 Boiling water reactors prequalified by the Finnish utilities

Boiling Water Reactors		ABWR General Electric	ESBWR GE/Hitachi	Kerena SWR-1000
		Hitachi /Toshiba	(GEH)	Areva
		US/Finland		
Prequalified in Finland	ру	TVO/Fortum/FV	TVO/Fortum	Fennovoima (FV)
Design features				
-Reactor thermal output		3992/4300	4300	3370
-Electrical output	MWe	1371/1650	1500/1650	1250-1300
-RPV inner diameter	m	7,1	7,1	7,12
-RPV height	m	20	27,6	23,8
-RPV Pressure	bar	71,7	71,7	
-Reactor power density	kW/l	51	54	51
-Burn-up	MWd/kgU	45	45	
-Enrichment	%	4 %		5 %
-Circulating pumps	number	10	zero	8
Containment				
-type		Pressure supression	Pressure supression	Pressure supression
-construction		Reinforc.concrete	Reinforc.concrete	Reinforc.concrete
-pressure	bar	4,1	4,1	
Safety				
-Core damage frequency	/	1,6E-07	2,0E-08	1,2E-07
-Core catcher		no	no (RPV cooling)	no (RPV cooling)
-Safety systems pumps		18	zero	
-Redundace		3x100 %	4x50%/2x100%	4x50%/2x100%
-Emerg. diesel gener.	MW	3x7	zero	2x100%
-Auxiliary power supply		4X50 %	2x100%	
-Aircraft crash protection	n	Yes	Yes	Yes?
-Seismic design		0.3 g/ 0.4 g	0.3 g	0.23 g
Operating reference pla	nt	Kashiwazaki-		Gundremmingen
		Kariwa 6/7		Germany 1999
		Japan 1996/1997		
		Hamaoka 5		
		2004		
		Shika 2		
		2006		
Rerences on the constru	ction	Lungmen		
		Taiwan		
		Shimane 3		
		Japan 2005-11		
References on the planr	ning	South Texas 3/4	Fermi	
stage	-	USA	USA	

10.3.3 Kerena

The third boiling water reactor **Kerena** (**SWR-1000**) is based on the German Gundremmingen power plant design, which has been updated to have passive safety features against possible station blackout events. The problem with the plant is that Germany cannot build new nuclear plants according to the present energy law. The plant has a good design, but it would be risky to buy the first plant, which is just on the drawing board.

10.3.4 ABB BWR

In my opinion the **ABB BWR** plant in Olkiluoto would be a perfect BWR plant to be constructed even today. Unfortunately, the plant design was sold to Toshiba Westinghouse, which is not promoting this technology any more. They have put all of their efforts into the AP1000 plants, which are still in the development phase and cannot be licensed in Finland today. However, pressurized water reactors are now leading the markets.

10.4 Pressurized water plants

The pressurized water reactors prequalified by the Finnish utilities include the European Pressurized Reactor (EPR) by Areva, the APR-1400 by Korean Hydro&Nuclear Company (KHNC), the AES-2006 (VVER-1200) by Atomstroyexport (ASE) and the EU-APR by Mitsubishi (Table 10.4.1).

10.4.1 EPR by Areva

The EPR reactor has been designed to satisfy the European Utility requirements, which were developed in 1992. The recent requirements include aircraft crash and core meltdown protection features. There are now four EPR units under construction, one in Finland, the second in France and two in China.

The Finnish plant was ordered in 2003 and construction started in 2005. The plant is expected to start commercial operation in 2013 or ten years after the contract was made. The contract price was about €3200 million, but the actual costs have overrun to about €5600 million. The costs have risen from €2000/kWe to about €3500/kWe, which have caused losses for the contractor. However, the references are the key to get future orders.

The problems at the Olkiluoto-3 came from being the first of this kind of design. The construction was started before the design was completed. Now the construction has already lasted six years and the last concrete was poured in summer 2011. The installation of the primary components will take another two or three years. Thus the total construction time will be about eight or nine years. It seems now that its sister unit in Flamanville will also have eight or nine year's construction time.

10.4.1 Prequalified pressurized water reactors for Finland

Pressurized Water Read Vendor	ctors	EPR Areva	APR-1400 Korea Hydro&Nucl.	AES-2006 Atomstoyexport	EU-APWR Mitsubishi
			Power Company	(ASE)	
Prequalified in Finland		TVO/Fortum/FV	TVO/Fortum	Fortum	TVO
Reactor thermal output	MWt	4500	4000	3200	4451
Electrical output	MWe	1650	1450	1200	1700
Number of loops		4	2/4	4	4
-RPV inner diameter	m	4,9		4,25	
-RPV height	m	12,7		11,185	
-RPV Pressure	bar	154	155	162	155
-Hot leg temperature	оС		324	329,7	
-Uranium in Reactor	tUO2	128			
-Burn-up	MWd/kgU	45	45-55	45	45-55
-Enrichment	%	4 %	4-5%	4 %	4-5%
-Circulating pumps	number	4	4	4	4
-Safety systems pumps		4x100%		4x50%	3x100%
-Diesel engines	MW	4 x 7		4x6	3x100%+2x100%
-Auxiliary generators					2x100%
-Containment		dry	dry	dry	dry
		presressed concr.		prestressed concr.	
- inner diameter	m			44,0	
-Containment pressure	bar	5,3	5,7	5,0	5,7
- Outer containment				renforced concr.	
- inner diemater	m			50,0	
-Core damage frequence	у	1,80E-06	2,25E-07	1,00E-07	1,00E-07
-Core catcher		Yes		Yes	
-Aircraft crash protectio	n	Yes		Yes	
-Seismic design				0,25 g	
Operating references				Tianwan 1/2	
				China 2006/7	
Rerences on the constru	ıction	Olkiluoto 3	Shin Kori 3/4	Tianwan 3/4	Tsuruga 3/4
		Finland 2005-13	Korea 2009-13	China 2011-16	Japan 2012-17
		Flamanville		Leningrad II-1/2	
		France 2007-15		Russia 2008-15	
		Taishan 1-2			
		China 2008-2016			

10.4.4 The APR-1400 by KHNC

The Korean pressurized water reactor **APR-1400** (Advanced Pressurized water reactor) has been developed based on its smaller version, the **OPR-1000** (Optimized Power Reactor). The design was based on US Combustion Engineering System 80+ with two steam generators. The design of System 80 was certified in the US by the NRC in 1997.

The first of the two System 80 PWRs were commissioned at the Yonggwang site in 1995 and 1996. Seven OPR-1000 units are now in operation and three more under construction. Two APR-1400 units are under construction at Shin Kori site in South Korea.

Four APR-1400 units were ordered by the United Arab Emirates in December 2009. The price of the EPC contract was \$20.4 million or \$3640/kWe. The first of the reactors is planned to start commercial operation in 2017.

APR-1400 design has some features which need to be considered. The design offered today is a two unit design, where the turbine halls are side by side. Most of the modern concepts are today such that the units are independent of each other. The System 80 plant in Palo Verde has three units and each of them have turbine axes in the same line.

The second problem for the European countries is the American measurement units, which use inches and other non-ISO units. This means that for the European plants the units should be converted into millimeters. The third problem is the lack of a core catcher, which is required or the heat recovery from the reactor after melt down should be otherwise proved.

Within app. six years the experience from the first operating plants will be available. Then the concept should be mature enough for the international markets. However, the new designs to cope with aircraft crash and core melt down have to be done by then.

10.4.5 AES-2006

The Russian VVER-1000 reactors have several design concepts that have been used around the world. The latest plants built at Tianwan in China use the VVER-91 concept, which was designed by IVO Engineering for the Loviisa-3 plant during years 1976-91.

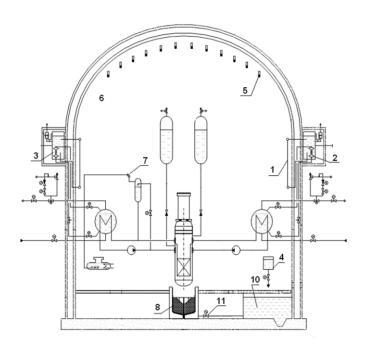


Figure 10.41 The containment structure of AES-2006 plant aimed for the Loviisa-3 includes: 1 Passive cooling of the containment, 2 SG passive cooling, 3 Emergency water tanks, 4 Emergency chemical supply, 5 Hydrogen recombiners, 6 Hydrogen monitoring, 7 Pressurizer safety valves, 8 Core catcher, 10 Borated water tanks, 11 Valves for the cooling of the core catcher (Source: Vitaly Ermolaev)

The design of Loviisa-3 plant was updated after the Chernobyl accident to include a core catcher, which was implemented in the Tianwan plant in China for the first time in the history of any light water reactor.

The new reactor under construction in the Leningrad-II-1/2 units use new the AES-2006 concept, which uses a 3200 MWt four loop reactor. The design includes some passive containment cooling after sever accidents. The cooling tanks on the containment walls could cool the containment without external power. However, there are four emergency diesel generators, which will power the emergency cooling pumps. The AES-2006 plant has a core catcher and double containment to cope with aircraft crash.

10.4.6 The EU-APR

The Mitsubishi designed EU-APR (European Union Advanced Pressurized Water Reactor) plant uses a four loop reactor. The first plant is under construction in Tsuruga in Japan. The design is based on earlier Westinghouse four loop reactor plants. As Westinghouse was sold to Toshiba, Mitsubishi is now offering this design alone.

The Tsuruga plant should be in commercial operation by 2017. The construction has been delayed because of earthquake analysis. The Japanese authorities have updated the requirements because the earthquake in Kashiwazaki-Kariwa in 2007 caused more acceleration than expected.

The same kind of APR design has been modified for the US market under the name US-APR. The US-APR design will be approved by the USNRC at the earliest in 2012.

10.5 Technical evaluation

The technical evaluation starts by calculating the performance values of the planned power plant at the site conditions. The main idea is to try to evaluate the construction period and operation period as realistically as possible. The evaluation of the construction period should give the main dates of the project execution and fixed the date by which the plant will be generating electricity.

The evaluation of the plant operation should estimate the electricity generated each year, the maintenance periods and an estimate for the forced outage rate. It should also evaluate the safety aspects by calculating reliability of the safety systems and the probability of a core meltdown.

There are also possibilities to secure core cooling through passive systems, which have higher reliability than active or electricity depended systems. The reliability of passive systems is dependent on the opening of valves, which are typically more reliable than active emergency diesel generators. It is also possible to increase the volumes of the pressurizer and emergency water tanks, which would allow longer starting times for the diesel engines.

Additionally the Finnish safety standards require that after a core meltdown the core will be collected on the bottom of the containment in such a way that the radioactive release will be limited. Thus a core catcher should be built below the reactor pressure vessel. There are also other designs that claim that the core can be cooled continuously without a core catcher, but this has yet to be proved. However, the preliminary evaluation of the probability of core meltdown and large releases should be done before the supplier will be selected.

10.6 Economical evaluation

10.6.1 Revenues

The revenues depend on the electricity generation, which is dependent on the size of the plant, its reliability and its maintenance periods. The revenues also depend on the price of electricity. Typically the price changes month by month and hour by hour. Thus if more nuclear power is built, it will also influence the price of electricity. If the nuclear capacity is smaller than the summer load, then the price will not reduce to zero.

There was too much nuclear power in Finland during the summer of 1982, when four units went online at the same time. The nuclear share was 38% of electricity in 1982 and there was also a lot of hydro electricity available. No other condensing power was needed during the summer and there were hours when the price of electricity was zero. The utilities installed electrical boilers free of charge into district heating networks to convert the extra electricity into heat.

The execution of a nuclear project may also have a large influence on the price of electricity for the owners. If the plant is four years late from its original commissioning date as Olkiluoto-3, it may raise the price of electricity in the whole country. The replacing power has to be bought from more expensive sources, typically from a coal fired condensing power plant. It might also raise the price of CO₂-allowances, if the use of coal increases above the planned level.

The delay may also influence the security of the power supply system. Missing generation has to be generated by other means also during the peak hours. The nuclear unit is in most cases the largest unit in the system and the deficit may be 10-20 % of capacity. The capacity deficit of the Finnish power system was 2800 MW, or 19 % of the peak load during the peak hour in February 2011. Fortunately, Finland belongs to the Nordic power system, which had some excess power to cover the deficit in Finland.

The electricity prices in Finland have actually been about €2/MWh higher than the system prices in the Nordpool, because Finland has been importing electricity from Sweden for most of the time. If Finland had more nuclear power, it would be exporting electricity to Sweden and would

have lower prices within the country. This would depend very much on the hydro conditions in the Nordic area, where 75% of the electricity is generated by hydro.

10.6.2 The costs

The construction costs of a nuclear plant have the biggest influence on the profitability of the nuclear plant. The cost figures can be fixed with bidding offers from the contractors. The cost estimates will depend very much on the design and the materials needed. If the buildings need 100 000 m³ or 250 000 m³ of concrete, the costs may differ considerably.

Additionally the amount of concrete will influence the construction schedule, because the concrete manufacturing rate is limited. The reinforcing bars can be pre-manufactured and installed as modules, as was done in the Kashiwazaki-Kariwa plant in Japan in 1995.

The construction time can be reduced if the inner containment is made of steel. Steel containments have been used in the Loviisa-1 and -2 and many German plants. They are also in use in the AP1000 plants in China. The steel plates can be constructed as large modules, which can then be joined together at the site much faster.

10.6.3 Cash flow models

Selecting of the reactor supplier will be done after the economical evaluation, where all the aspects of the power plant are taken into account. The economical analysis uses a cash flow analysis, where the electricity generation is converted into revenue and the investment and operation costs as negative cash flows.

A cash flow model should be developed by using spread sheet programs. Examples of cash flow models have been given in the book "*Planning of Optimal Power Systems*". The models also include ancillary services, which should be taken into account when large units are added into the system. Ancillary services needed include spinning and non-spinning reserves.

The system should be planned in such a way that a trip of the nuclear plant will be compensated immediately by the spinning reserves. The spinning reserves should be released within 5-10 minutes from the trip by the non-spinning reserves, and the costs of those reserves should be taken into account in the evaluation.

A simplified cash flow evaluation of a 1200 MW nuclear project has been given in Tables 10.6.1-3. With a discount rate of 5% and an operation time of 50 years the cumulative generation would be 173 TWh (Table 10.6.1).

The levelised generation costs would be €29.6/MWh, which is the ratio of discounted costs of €7908 and discounted generation of 173 TWh (Table 10.6.2). With an electricity price of €50/MWh the cumulative discounted net cash flow would be €15 221million and the internal rate of return (IRR) 10.0%.

Table 10.6.1 Discounted cash flow analysis of a 1200 MW plant (Page 1)

PROFITABILITY E	VALUA	ΓΙΟΝ	Electric	50 €/MWh	3 %	Page	1
Unit size	1200	MWe	Fuel	4,0 €/MWh	3 %	Date	11.4.2011
Number	1	pcs	O&M	8,0 €/MWh	2 %	Cost level	1/2011
Output	1200	MWe	Waste	2.4 €/MWh	2 %	Disc. rate	5 %

	Outpu	t	1200	MWe		Waste	2,4	€/MWh	2 %			5 %	
			Gener	ation		Disc.		ctricity			ruction	costs	i
Year		2	3	4	Total	ounted		Revenu	1	2	3	4	Investm.
	TWh	TWh	TWh	TWh	TWh	TWh	€/MWh	Meur	M€	M€	M€	M€	M€
-10					-	-	50		-10				-10
-9					-	-	52		-20				-20
-8					-	-	53		-25				-25
-7					-	-	55		-50				-50
-6					-	-	56		-200				-200
-5					-	-	58		-250				-250
-4					-	-	60		-300				-300
-3					-	-	61		-400				-400
-2					-	-	63	0	-500				-500
-1					-	-	65	0	-700				-700
0					-	-	67	0	-700				-700
1	8,4				8,4	8,0	69	581	-58				-58
2	8,6				8,6	7,8	71	616					
3	9,0				9,0	7,8	73	661					
4	9,6				9,6	7,9	76	726					
5	9,6				9,6	7,5	78	748					
6	9,6				9,6	7,2	80	770					
7	9,6				9,6	6,8	83	793					
8	9,6				9,6	6,5	85	817					
9	9,6				9,6	6,2	88	842					
10	9,6				9,6	5,9	90	867					
11	9,6				9,6	5,6	93	893					
12	9,6				9,6	5,3	96	920					
13	9,6				9,6	5,1	99	947					
14	9,6				9,6	4,8	102	976					
15	9,6				9,6	4,6	105	1005					
16 17	9,6				9,6	4,4	108	1035					
18	9,6 9,6				9,6 9,6	4,2 4,0	111 114	1066 1098					
19	9,6				9,6 9,6		114	1131					
20	9,6				9,6 9,6	3,8 3,6	121	1165					
21	9,6				9,6	3,4	125	1200					
22	9,6				9,6	3,4	129	1236					
23	9,6				9,6	3,1	133	1273					
24	9,6				9,6	3,0	137	1311					
25	9,6				9,6	2,8	141	1351					
	:				:	:		1001					
	- :					:							
						:							
44	;				;	;	247	2260					
44	9,6				9,6	1,1	247	2368					
45	9,6				9,6	1,1	254	2439					
46	9,6				9,6	1,0	262	2513					
47	9,6				9,6	1,0	270	2588					
48	9,6				9,6	0,9	278	2666					
49	9,6				9,6	0,9	286	2746					
50	9,6				9,6	0,8	295	2828					
Total					477	173		75	-3213	0	0	0	-3213
											€/kWe	2	2677,5

Table 10.6.2 Discounted cash flow analysis of a 1200 MW plant (Page 2)

PROFITABILITY EVALUATION Unit size 1200 MWe

Number 1 pcs
Output 1200 MWe

 Page
 2

 Date
 11.4.2011

 Cost level
 1/2011

 Disc. rate
 5 %

	Output		MWe						Disc. rate	5 %	
	Fuel	Fuel	O&M	Waste	Other c		Total co		Net Cash	Discou	
Year	Price	Costs	Price	fee	О&М	Waste	Sum	Disc.	Flow	Cash flow	
	€/MWh	M€		€/MWh	M€	M€	M€	M€	M€	M€	M€
-10	4,0	0	8,0	2,4			-10	-16	-10	-16	-16
-9	4,1	0	8,2	2,4			-20	-31	-20	-31	-47
-8	4,2	0	8,3	2,5			-25	-37	-25	-37	-84
-7	4,4	0	8,5	2,5			-50	-70	-50	-70	-155
-6	4,5	0	8,7	2,6			-200	-268	-200	-268	-423
-5	4,6	0	8,8	2,6			-250	-319	-250	-319	-742
-4	4,8	0	9,0	2,7			-300	-365	-300	-365	-1106
-3	4,9	0	9,2	2,8			-400	-463	-400	-463	-1569
-2	5,1	0	9,4	2,8			-500	-551	-500	-551	-2121
-1	5,2	88	9,6	2,9	-42		-654	-687	-654	-687	-2807
0	5,4	45	9,8	2,9	-84		-738	-738	-738	-738	-3546
1	5,5	48	9,9	3,0	-84	-25	-119	-113	463	441	-3105
2	5,7	51	10,1	3,0	-88	-26	-63	-57	553	502	-2603
3	5,9	56	10,3	3,1	-93	-28	-65	-56	596	515	-2088
4	6,1	58	10,6	3,2	-101	-30	-74	-61	652	537	-1552
5	6,2	60	10,8	3,2	-103	-31	-75	-58	673	528	-1024
6	6,4	62	11,0	3,3	-105	-32	-75	-56	695	518	-506
7	6,6	63	11,2	3,4	-108	-32	-76	-54	717	510	4
8	6,8	65	11,4	3,4	-110	-33	-77	-52	740	501	505
9	7,0	67	11,7	3,5	-112	-34	-78	-50	764	492	997
10	7,2	69	11,9	3,6	-114	-34	-79	-49	788	484	1481
11	7,4	71	12,1	3,6	-116	-35	-80	-47	813	475	1956
12	7,7	74	12,4	3,7	-119	-36	-81	-45	839	467	2423
13	7,9	76	12,6	3,8	-121	-36	-82	-43	866	459	2882
14	8,1	78	12,9	3,9	-124	-37	-83	-42	893	451	3333
15	8,4	80	13,1	3,9	-126	-38	-83	-40	922	443	3777
16	8,6	83	13,4	4,0	-129	-39	-84	-39	951	436	4212
17	8,9	85	13,7	4,1	-131	-39	-85	-37	981	428	4640
18	9,2	88	13,9	4,2	-134	-40	-86	-36	1012	421	5061
19	9,4	90	14,2	4,3	-136	-41	-87	-34	1044	413	5474
20	9,7	93	14,5	4,3	-139	-42	-88	-33	1077	406	5880
21	10,0	96	14,8	4,4	-142	-43	-88	-32	1112	399	6279
22	10,3	99	15,1	4,5	-145	-43	-89	-31	1147	392	6671
23	10,6	102	15,4	4,6	-148	-44	-90	-29	1183	385	7057
24	10,9	105	15,7	4,7	-151	-45	-91	-28	1220	378	7435
25	11,3	108	16,0	4,8	-154	-46	-92	-27	1259	372	7807
	:			:							
	:		:	:							
			- :								
44	: 19,7	189	: 23,3	: 7,0	-224	-67	-101	-12	2267	265	13748
45	20,3	195	23,3	7,0 7,1	-228	-68	-101	-12	2338	260	14008
46	20,3	201	24,2	7,1 7,3	-228	-08 -70	-102	-11 -11	2411	256	14008
									l .	l .	
47	21,6	207	24,7	7,4	-237	-71	-102	-10	2486	251	14515
48	22,2	213	25,2	7,6	-242	-73	-102	-10	2564	247	14761
49	22,9	220	25,7	7,7	-247	-74	-102	-9	2644	242	15003
50	23,6	0	26,2	7,9	-252	-76	-328	-29	2500	218	15221
		5894			-8174	-2415	-7908	-5121	66842	15221	
								29,6	€/MWh	10,0 %	IRR

Table 10.6.3 Discounted cash flow analysis of a 1200 MW plant (Page 3, Financing)

	Unit size	1200	MWe	Loan rat	io	80 %		Date	11.4.2011
	Number	1				20	2	Cost level	1/2011
			pcs	Loan per			d		· · ·
	Output	1200	MWe	Interest		3 %	5	Disc. rate	5 %
	Total		ancing	Total cos		Net Cash		unted	Discount
Year	Costs	Loans	Inter.	Sum	Disc.	Flow	Cash fl.	Cumulat.	factor
	M€	M€	M€	M€	M€	M€	M€	M€	5 %
-10	-10			-10	-16	-10	-16	-16	1,629
-9	-20			-20	-31	-20	-31	-47	1,551
-8	-25			-25	-37	-25	-37	-84	1,477
-7	-50	40		-10	-14	-10	-14	-98	1,407
-6	-200	160	-1	-41	-55	-41	-55	-154	1,340
-5	-250	200	-6	-56	-71	-56	-71	-225	1,276
-4	-300	240	-12	-72	-88	-72	-88	-313	1,216
-3	-400	320	-19	-99	-115	-99	-115	-427	1,158
-2	-500	400	-29	-129	-142	-129	-142	-569	1,103
-1	-654	560	-41	-135	-142	-135	-142	-711	1,050
0	-738	560	-58	-236	-236	-236	-236	-947	1,000
1	-119	46	-74	-147	-140	435	414	-533	0,952
2	-63	-126	-76	-265	-240	351	319	-215	0,907
3	-65	-126	-72	-263	-227	398	344	129	0,864
4	-74	-126	-68	-268	-221	458	377	506	0,823
5	-75	-126	-64	-265	-208	483	378	884	0,784
6	-75	-126	-61	-262	-196	508	379	1263	0,746
7	-76	-126	-57	-259	-184	534	379	1642	0,740
8	-77	-126	-53	-257	-174	561	379	2022	0,677
9	-77	-126	-33 -49	-254	-174	588	379	2401	0,645
_						1			1
10	-79	-126	-45 -42	-251	-154	616	378	2779	0,614
11	-80	-126		-248	-145	645	377	3156	0,585
12	-81	-126	-38	-245	-136	675	376	3532	0,557
13	-82	-126	-34	-242	-128	705	374	3906	0,530
14	-83	-126	-30	-239	-121	737	372	4278	0,505
15	-83	-126	-27	-236	-114	769	370	4648	0,481
16	-84	-126	-23	-233	-107	802	367	5015	0,458
17	-85	-126	-19	-230	-101	836	365	5380	0,436
18	-86	-126	-15	-227	-95	871	362	5741	0,416
19	-87	-126	-11	-224	-89	907	359	6100	0,396
20	-88	-126	-8	-222	-83	944	356	6456	0,377
21	-88	-126	-4	-219	-78	981	352	6808	0,359
22	-89		0	-89	-31	1147	392	7200	0,342
23	-90			-90	-29	1183	385	7585	0,326
24	-91			-91	-28	1220	378	7964	0,310
25	-92			-92	-27	1259	372	8336	0,295
									:
									:
44	-101			-101	-12	2267	265	14277	0,117
45	-102			-102	-11	2338	260	14537	0,111
46	-102			-102	-11	2411	256	14792	0,106
47	-102			-102	-10	2486	251	15043	0,101
						1			
48	-102			-102	-10	2564	247	15290	0,096
49	-102			-102	-9	2644	242	15532	0,092
50	-328			-328	-29	2500	218	15750	0,087
		0	-1036	-8944	-4592	65806	15750		
					26,6	€/MWh	20,3 %	IRR	İ

If the project is financed with 80% suppliers credit (a 3% interest rate and 20 year loan period) the cumulative discounted costs decrease to €4592 million and the generation costs drop to €26.6/MWh (Table 10.6.3). The cumulative net cash flow would increase to €15750 million and the internal rate of return to 20.3 %.

The result can also be presented in a cumulative discounted cash flow diagram (Figure 10.6.1). It also shows the payback time of the investment as a break even value of the discounted cash flow. In this case the payback time of the investment without financing is 8 years.

If the plant is owned by an investor type utility, they might have an internal rate of return (IRR) as the main criteria for making investments. Some investors require that all investments should yield at least 12% IRR. Thus the nuclear investment with a 20.0% IRR will be enough for them to make the final investment decision.

If the power plant is owned by industrial companies, whose the main target is to secure the long term supply of electricity, then the costs of electricity might be the key to make the investment. They could be very happy to achieve electricity at a €30.0/MWh price after financing.

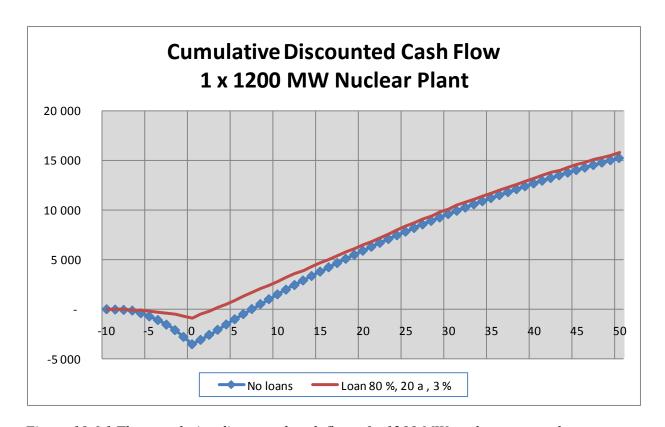


Figure 10.6.1 The cumulative discounted cash flow of a 1200 MW nuclear power plant

11PROJECT EXECUTION

11.1 The preliminary design

The preliminary design of the nuclear power plant will follow the selection of the reactor supplier. During this phase also many other main components will be purchased. The heat balance diagrams can then be made and the performance values of the power plant can be evaluated at the site conditions.

The preliminary design will also include the layout drawings of the plant, which can be designed by using the design data of the process diagrams and components. The architect engineers design layout of buildings and constructor engineers will then evaluate the dimensions of the structures. From this data the main drawings of the buildings for the construction permit can be done.

Another big issue is the core catcher. The first core catcher was designed for the Loviisa-3 plant in about 1991, because the Finnish safety norms required it in the first time. The plant was not approved by the Finnish Parliament, but the similar Loviisa-3 (VVER-91) plant was built in Tianwan, China. The updated design of the core catcher in AES-2006 plant aimed for Loviisa-3 was presented by Atomstroyexport (ASE).

The next core catchers will be built in the EPR plants at the Olkiluoto-3 and Flamanville-3 plants, which will be in operation in 2013-16. Other suppliers have still to make the design that could be approved in Europe.

The site conditions should be taken into account. The seismic and ground conditions determine how thick concrete structures are needed in the basement. In Finnish conditions there is no need for several meters of concrete slab, because of the rock foundation.

The construction volumes of the Finnish PWR plants in Loviisa 1/2 and Olkiluoto-3 are about the same, but the Olkiluoto-3 plant has 1.6 times higher output (Table 11.1.1). The specific volume is therefore much lower. However, the specific amount of concrete is the same, because Olkiluoto-3 plant has been protected to withstand a large aircraft crash.

Table 11.1.1 Construction volumes and concrete volumes in the Finnish PWR plants

Plant		Loviisa 1	Loviisa 2	Loviisa 1+2	Olkiluoto 3
Output	MW	488	488	976	1600
Building volume	1000 m3	510	390	900	950
	m3/MW	1045	799	922	594
Concrete volume	1000 m3	86	64	150	250
	m3/MW	176	131	154	156

The table shows that the large size of the nuclear plant tends to decrease specific volume, but not necessarily the construction costs. It will on the other hand tend to increase the project schedule, because the injection rate of concrete is limited.

11.1.1 The preliminary safety analysis report

One of the main tasks during this phase is to prepare the Preliminary Safety Analysis Report (PSAR). The PSAR describes the functional design of the nuclear power plant and how normal operation and possible failures are controlled.

Most nuclear reactor suppliers have done this design already in the bidding phase, because many of the plants have already been licensed for other sites. However, usually some modifications are needed to meet the local safety requirements. The Finnish norms require a core catcher and aircraft protection and these features have not been designed by many suppliers for other sites.

My first task in July 1971 at the Loviisa Atomic Project Group was to describe the emergency core cooling systems in the first PSAR of Loviisa plant. It was done by using the PSAR of Westinghouse reference plant (Donald C. Cock) and the process data of a VVER-440 plant.

Wärtsilä supplied the steel containment under license from Westinghouse and Westinghouse did the safety evaluation for the containment building. The first PSAR had about 600 pages by this time. The construction works in the reactor building could be started after the PSAR was accepted by the Finnish safety authority.

Today the PSAR would be a multi volume description. Many of the pages can be copied from earlier projects, but there are always country and site related matters that would need to be written once again. The EPR plant for Olkiluoto was originally designed to fulfill the European Safety standards, but the Finnish requirements differ from them and thus many design features had to be changed.

11.1.2 The probabilistic safety assessment

The PSAR today should also include Probabilistic Safety Assessments (PSA), where the probabilities of different failures are mathematically evaluated. The main target is to limit the probability of the core damage frequency (CDF) below a given limit.

The Rasmussen report (Wash-1400) in 1975 evaluated that the CDF was about 1:20 000, i.e. $5x10^{-5}$. In utility requirements this limit is now $1x10^{-5}$ (1:100 000) in Europe and the US. However, each country can apply its own limits, which also depend on the site conditions. If the plant will be near population centers the requirements can be more demanding.

In the future if the number of reactors is more than 1000, CDF of 1:100 000 would mean a nuclear accident every hundred years. This level can be achieved by installing redundant 4x50%, 5x50% or 3x100% safety systems instead of the earlier 2x100% systems.

In Europe the German, Swedish and Finnish nuclear plants have been using the four redundant concepts already in the 70's. They all have four redundant emergency diesel engines (EDG). If the plant has two diesel engines and each have a 99% reliability, then the probability (P) of operation that no one of the two diesel engines will start will then be $P = 0.01 \times 0.01 = 0.0001$, or 10^{-4} .

In a 3x100% redundant system the probability that none of the three EDGs will start is then P=0.01 x 0.01 x 0.01=0.000 001 or 1 x 10^{-6} . With the 4x50% system the probability will be between these two or P = 0.000 004 or 4 x 10^{-6} (reliability Tables in the Appendix C4).

My proposal would be a 5x50 % system, where one of the EDGs can be in maintenance and probability that at least two diesels would start would be better than 0.999999. This would also improve the availability of nuclear plant, because there would be no need to shut down the whole plant, if one of the EDGs is undergoing maintenance. In addition, the reliability of all of the engines can be kept at a high level, if maintenance can be done without restrictions.

Today the most of the plants should additionally have a priority power supply system, which operates independently from the high voltage network. Some plants also have special blackout diesel that can provide power for the essential safety systems even if all other electrical systems are out of operation.

The PSA of the existing Loviisa VVER-440 plants give CDF values of $2x10^{-4}$ (STUK Report 395/1991). Today the CDF value of Loviisa units is $5.2x10^{-5}$ (STUK report 12/2010). This corresponds to the values given in the Rasmussen report ($5x10^{-5}$ or 1:20 000).

The evaluations for the new Olkiluoto-3 EPR plant give CDF values of 1.8×10^{-6} or 1:550~000 (STUK report 21.1.2005). Thus the new EPR reactors will be about 30 times better than the existing PWRs in Finland, and the safety status can be improved if the old reactors will be replaced by new ones.

The safety authorities will then review the application. The PSA review of the Olkiluoto-3 EPR safety has evaluated that the following factors will have the highest influence on the probability of core damage (STUK 21.1.2005):

- -Transients 45% (loss of feed water and component cooling system failures being the most important)
- Loss of Coolant Accidents (LOCA) 24% (small LOCA being the most important)
- Loss of off-site power supply 5%
- Fires 2%
- Floods 2%
- External events 16%
- *Other* 6%
- Low power and shutdown (internal) 6%

11.1.3 Construction license

The PSAR will then form one part of the construction application, which will be asked from the government. If the safety authority has positive opinion about safety of the plant the government will grant the construction license without delay. Also independent consultants may be used to evaluate, whether the design will fulfill the safety requirements in the country. However, this process may last one year from the application.

Another construction permit will also be needed from the local municipal authorities. They monitor the construction of all kinds of buildings in the area and thus want to know, if the constructed building will be fulfilling the technical and esthetic norms in the community. A nuclear plant will in most cases be the most visible buildings within the community and it should be esthetically pleasing.

The local authorities also look at some environmental and safety aspects, such as warm up of local sea water, sewage, roads and fire protection. The local fire stations have to be prepared for possible fires in the power station, both in the construction and in the operation phases. They want to know, which kind of fire preventive means are used. What will be the materials in each of the buildings and how long time can they resist fire?

11.2 The detailed design

The detailed design can then be started after the process design has been accepted by the authorities. The tasks will include three dimensional layout models of each building, including the main equipments, piping, cable trays etc.

Each of the buildings require at least one process designer, one layout designer, one piping designer and one electrical designer, which will work together by using the same three dimensional layout model. They will need two years to complete the drawings ready for construction.

The detailed design requires a component identification system, where all the components will get individual codes, starting from the process diagrams and continuing to cover each electrical and control diagram. The coding helps in making a detailed list of equipment that could be used in computerized project control and monitoring.

If the detailed design is done properly, the work at the site could proceed very well. On the other hand, the installation of pipes and cables might be problematic, if the piping engineers and electrical engineers have planned piping and cable trays exactly into the same space. The best idea is that there is only one architect engineer, who is making the model of a building. Then he can put all equipment, piping and cables in different spaces. More than half of the project people in the Loviisa-1 and -2 projects were designers (Figure 11.2.1).

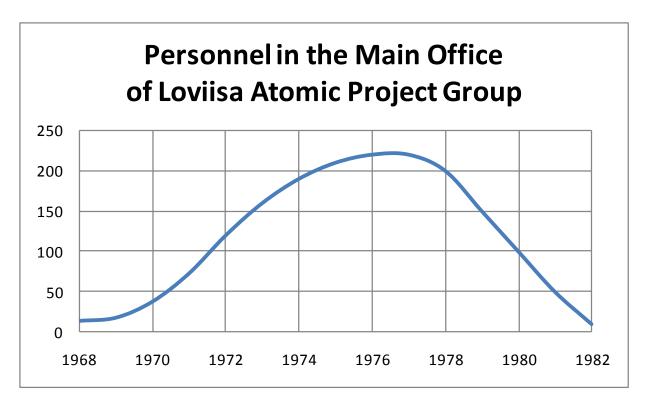


Figure 11.2.1 Project personnel in the Loviisa-1 and -2 project office

11.3 Site preparation

The preparation works at the site should be started at the same time as the preliminary design is done. The roads for the site are needed, through them the excavated land can be transported away. Typically some 500 000–1000 000 m³ of soil and 100 000–200 000 m³ of rock has to be removed and restored.

The preparation works should also include housing for some one thousand construction workers. Many of the site workers come from abroad and need accommodation, shops and other facilities for free time activities. The workers' housing also needs a construction permit from the local municipality.

The preparatory works should include a concrete manufacturing station, which should produce about $50\,000-100\,000\,\text{m}^3$ of concrete annually for two years. This is $1000-2000\,\text{m}^3$ per week.

Typically two years are needed for the site preparation. The preparation can be performed simultaneously with the plant design phase and thus they are not in the critical path in the schedule.

11.4 Construction

The concrete works at the nuclear plant can actually start only after the construction permit has been received. The construction can last up to six years, if the design is such that installation and construction progress is proceeding in level by level. The Loviisa reactor building had to use this kind of stepwise approach, because of reactor building has several levels.

The concrete works at the Olkiluoto-3 EPR plant started in August 2005 by pouring the three meter thick base slab of the reactor building. They have lasted until July 2011, six years. The outer containment was without a roof in February 2011 (Figure 11.4.1). The inner containment was ready in April 2010, but the pre-stressing cables and pressure tests have to wait until the concrete has been drying.



Figure 11.4.1 Olkiluoto-3 site in February 2011

If any of the large components are delayed, the construction has to be stopped to wait for its arrival. This would mean waiting hours for the construction workers and a waste of time and money. Delays will always happen. In the Olkiluoto-3 project some cracks were found already in the factory and new components had to be manufactured. Thus the separation of the installation and construction would be useful.

It is possible to separate concrete works from installation works. In an ideal construction sequence all of the buildings would be ready within two years of the start. The building workers would disappear before the installation people will come to the site. This can be achieved if the containment building has such a large equipment hatch that the components can be installed through that.

The site workforce at the Loviisa-1 and -2 and Olkiluoto-3 sites was about the same. The maximum head count in the Olkiluoto-3 site has been 4000 men (Figure 11.4.2) and totally about 40 million man-hours will be needed at the site, before the Olkiluoto-3 unit will produce electricity. The manpower demand is about 25 h/kWe. If the labor costs are €40/h, site's manpower will cost €1000/kWe.

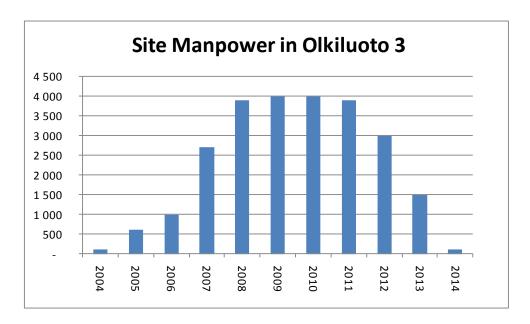


Figure 11.4.2 A predicted head count at the Olkiluoto-3 site

Time can also be saved if steel is used instead of concrete. The inner building can be made of steel and thus prefabricate it at a factory. Also prefabricated building modules can be used in many buildings. The components and piping can then be installed into the building modules in factory conditions.

The construction works should be almost ready when the pressure test of the containment is done. This happened 21 months after the start of the construction of the Loviisa-1 plant. The schedule was short because of the steel inner containment. At the Olkiluoto-3 unit this test can be made only after the tensioning of the pre-stressing cables have been made. This pre-stressed containment needs therefore very long construction time.

Modular construction has also been utilized at the Kashiwazaki-Kariwa (KK) nuclear plant in Japan, where the reinforced steel bars of the containment were manufactured as large modules. The ABWR plants were built in less than five years from the laying of the first concrete. The first criticality was achieved in 52 months at the KK-6 and in 49 months at the KK-7.

In this case the supplier and customer were in Japan and also most of the constructors and workers. The reinforced containment structure was used without pre-stressing. The containment size at the ABWR plant is also very much smaller than at the EPR-plant. The Kashiwazaki-Kariwa units do not have the aircraft crash shielding outer containment.

The most effective construction is done by the ship industry, where the ship is divided into app. 10 meter modules, into which all equipment and electrical cubicles are installed. The modules are then joined together on by one in a dry dock. The modular construction is discussed in detail in chapters 13 and 14.

11.5 The installation and startup

The real milestone is the placement of the reactor pressure vessel (RPV). In the Loviisa-1 project the RPV was delivered 42 months after the start of the construction. A 32 month installation and testing period followed, before full power could be delivered in April 1977. The total project lasted 74 months from the start of the construction and it was one year behind its original schedule.

At the Olkiluoto-3 unit the delivery of the RPV happened in June 2010 or 46 months after the start of the construction. The plant is expected to deliver full power 36 months later or in June 2013. Thus the total construction time will last about 82 months. The Olkiluoto-3 unit is three times the size of the Loviisa-1 unit, which could also explain the longer project schedule.

The operation of the plant requires that the Final Safety Analysis Report (FSAR) has been accepted by the authorities and the operation license has to be granted. The FSAR would be describing the actual plant as it has been built and it could also include descriptions of the tests that have been done.

References

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/11.2/ Compliance of Loviisa Nuclear Plant with Decision STUK Report 395/1991 http://www.stuk.fi/english/convention/compliance_lo.html

/11.3/ Nuclear Safety at TVO units. http://www.tvo.fi/www/page/3535/

12 PLANT OPERATION AND WASTE DISPOSAL

12.1 Operation and maintenance

The operation phase should be prepared by hiring the plant operators and maintenance staff at the same time, when the construction works will start. The training time of the operators should be about five years. They need to be trained at the reactor suppliers training sites and at some of the similar nuclear power stations.

Additionally, a training simulator should be built near the nuclear power station. This allows training of handling transient and accident situations that nobody wants to happen. There the teacher can simulate failures in the plant and then the operators can try to control the plant in transient situations to restore the plant back into a safe state.

The training of the fighter jet pilots lasts about five years. They fly other types of airplanes and simulators before they can start flying the fighter jets. The nuclear plant operators should be trained equally well. Any mistake in the operation can become costly and violate nuclear safety. The operators in the Three Mile Island could not manage a quite usual transient that damaged the whole plant.

The number of operation staff can be estimated based on existing nuclear companies. The privately owned nuclear utility company TVO now has two 880 MW BWR plants and a 560 MW coal plant in operation, and one 1600 MW PWR under construction. The total number of personnel was 530 (228 persons/GWe) in 2001, when only two units were operating and none were under construction. Today the number persons is 840 (214 persons/GWe).

The personnel costs for the 840 operating personnel are now €56 million (€24/kWe). Other fixed costs were €81 million or €35/kWe. The total fixed O&M costs were €59/kWe or €9.8/MWh. The nuclear fuel costs in 2010 were €50 million or €3.6/MWh.

The nuclear plant should also collect funds for the waste disposal. In Finland the average costs collected are &2.4/MWh. This includes the direct disposal of nuclear fuel starting from 2020 and ending in 2120. The costs should cover interim storage, building of the encapsulation plant and the final repository of low and high level nuclear waste. Thus the total costs from operation, fuel and waste disposal at the Olkiluoto nuclear plants were &15.8/MWh in 2010. The average price of electricity in the Nord Pool was &56.6/MWh in 2010. Thus the operating profit was &40.8/MWh or &570 million.

One of the reasons for low generating costs of the Finnish nuclear plants has been the high energy availability factor. Finland tops the world ranking with 91.1% availability (Figure 12.1.1). An average annual maintenance and fuel loading period takes four weeks, where two weeks will be needed to reload the reactor with new fuel each year. The overhaul periods vary from year to year depending on the scope of the maintenance.

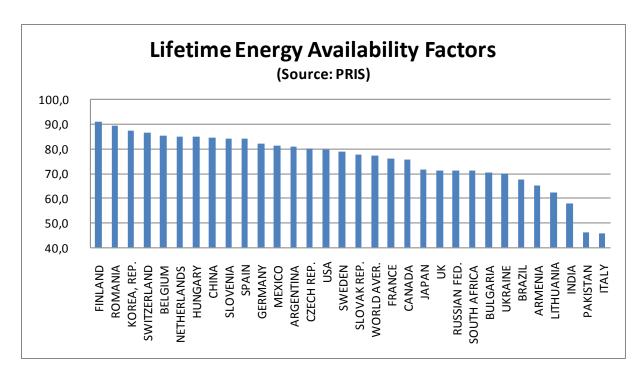


Figure 12.1.1 Lifetime energy availability factors of 32 nuclear countries (Source. PRIS)

The world average energy availability of 32 countries from the beginning of commercial operation was 77.2% in the end of 2010. The high availability factors of the Finnish nuclear plants indicate that the design of the plants has been sound and the preventive maintenance works have been done properly.

One can note that the energy availability in Sweden has been 79%. Sweden has mostly same type of reactors, which have supplied by Asea-Atom. One explanation to this might be the large hydro resources in Sweden and the operation of nuclear plants is not always profitable.

12.2 Medium and low level waste disposal

The waste from nuclear power plants has been one of the main problems that should be solved before large scale expansion of nuclear programs in the world.

Typical liquid waste comes from the water purification plants which distillate radioactive water to be recycled. The waste from the distillate plants is then reprocessed, mixed with bitumen and stored in canisters. The canisters are then disposed underground at the site (Figure 12.2.1).

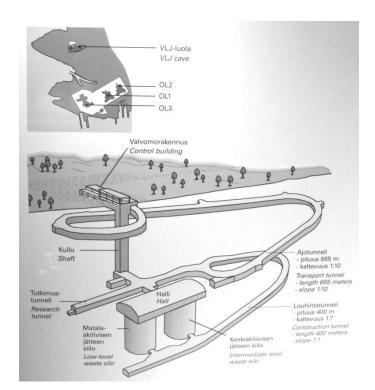


Figure 12.2.1

In Olkiluoto underground tunnels lead to the vertical repository of medium and low level waste

Table 12.3.1 Activity of spent fuel in kCi per GWa

			Years afte	r unload fro	m reactor			
Isotope	Half life	1	10	100	1 000	10 000	100 000	1 000 000
Plutonium-241	14	4 400	2 800	37				
Cesium-137	30	3 600	2 900	370				
Strontium-90	29	2 500	2 000	230				
Yttrium-90	<<1	2 500	2 000	230				
Krypton-85	11	280	160					
Americium-241	432	12	6	140	33			
Plutonium-240	6 560	16	16	16	15	5,7		
Plutonium-239	24 100	10	10	10	10	5,7	0,58	-
Uranium-233	159 000						0,02	0,03
Technetium-99	211 000				0,5	0,5	0,33	0,02
Total		74 000	13 900	1 440	60	14,9	1,82	0,15

12.3 High level waste disposal

The high level waste comes from the used nuclear fuel, which has a very high radioactivity level. The used fuel can be reprocessed; the uranium-235 and plutonium-239 can be recycled for use in nuclear reactors. Another method is to use the once through cycle, where the waste fuel is stored and then after some years encapsulated and put into the final repository. The activity in the spent fuels declines as the short living isotopes disappear. Within a hundred years only about 2% of the original activity in the spent fuel is left (Table 12.3.1).

After 1000 years the most active isotopes are americium-241 and plutonium-240 and -239. After 10 000 years plutonium-239 and -240 will determine the activity of spent fuel. Since plutonium-239 is a fissionable reactor fuel, it can be used after reprocessing in breeder reactors. The activity in reprocessed waste will then become much lower. The plutonium-239 is available in the in the repository more than 1000 years and can be used in breeders also later.

12.4 Intermediate storage

The method for spent fuel disposal adapted in Finland and Sweden is direct disposal. The spent nuclear fuel is first installed into an interim storage (Figure 12.4.1) for cooling for some 20-50 years and then encapsuled in copper canisters and disposed underground.

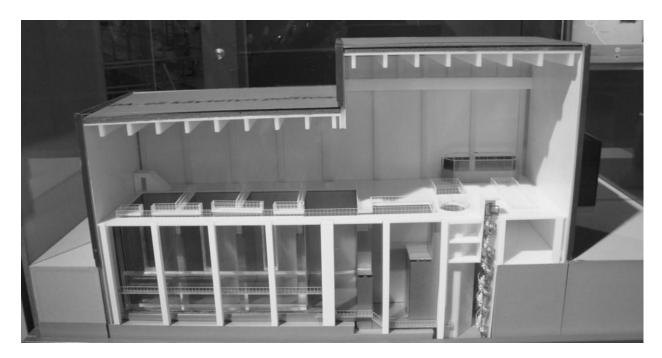


Figure 12.4.1 Scale model of intermediate storage of spent fuel in Olkiluoto Finland

12.5 Final disposal

The schedule for final disposal has been planned so that the final disposal will start when the first reactor in Finland has been operating for 43 years in 2020 (Table 12.5.1). Waste processing will then last for a hundred years, until all the waste from the five reactors has been stored in 2120. There is a reserve place for the fuel of the Loviisa-3 reactor, which is in planning stage by Fortum. The fuel from Loviisa-3 will be stored probably between the years 2120-30.

Table 12.5.1 Schedule for final disposal in Finland

Year	Task
1977	Reactor operation starts at Loviisa 1
1978	Start of geological studies for radioactive waste
1983	Decisions by the Finnish Government of spent fuel schedule
2001	Selection of site for final repository
2004	Start of construction of test facility Onkalo
2012	Application for construction of the final storage
2018	Application for operation of the final storage
2020	Start of disposal of Loviisa 1/2 and Olkiluoto 1/2 fuel
2070	Start of disposal of Olkiluoto 3 fuel
2080	Start of disposal of Olkiluoto 4 fuel
2120	Closing of the final storage

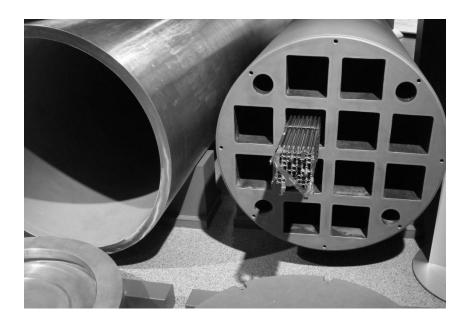


Figure 12.5.1 A fuel canister contains 12 fuel assemblies for Loviisa 1 and 2 and Olkiluoto 1 and 2 plants.

12.5.1 Fuel canisters

The canisters used in Finland will be based on the **KSB-3** vertical design created by **Svensk Kärnbrenselhantering Ab** (Figure 12.5.1). The spent fuel will be packed in fuel canisters, which include about 12 fuel assemblies each. The encapsulation plant will be located above the site of the final repository.

12.5.2 Final storage

The canisters will then be disposed into a rock about 400-500 meters below ground level in vertical holes (Figure 12.5.2). The canisters will then be sealed by using betonite, which isolates the canister from ground water. Ground water leakage to the hole can be 0.1 liter/minute (max). Finally the cavern will be filled to prevent access to the spent fuel

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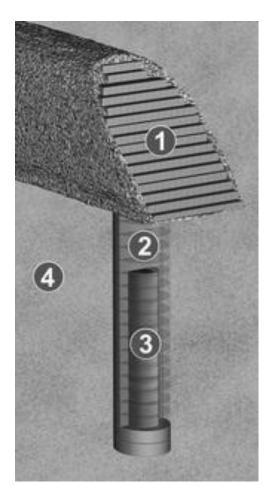


Figure 12.5.2 The final repository: canisters (3) will be filled with betonite (2), in a rock cavern (4). The tunnel (1) will be filled after the canisters have been buried

The construction of the test site **Onkalo** is already in progress and has reached 400 m below ground level (Figure 12.5.3). The test site will later on be used as the final repository after the final studies have been done and the necessary permits have been obtained.

These tests include testing the real thermal conductivity of rock, which in turn determines the distance between the canisters, because each of them still generates about 1.7 kW of heat. Another test includes ground water leakage, which could be controlled by injecting water resistant substance into the leaking holes.



Figure 12.5.3 The constriction of the spent fuel disposal test site (Onkalo) has reached 400 m depth below ground level in January 2011

The final evaluation of the repository will be done in 2012, when the application to construct the waste disposal is presented. The Swedish spent fuel nuclear waste storage plant in Forsmark is in about the same phase. It now seems that Finland will be the first to start the capsulation and disposal of spent fuel in the world.

12.6 Spent fuel reprocessing

Spent nuclear fuel contains typically 94.2% of uranium-238, 0.9% of plutonium-239 and 0.5% of uranium-235, which can be recycled in thermal or fast reactors. The rest of the waste i.e. about 4% cannot be recycled and should be stored as high level waste. Thus if the same final storage in Olkiluoto can store the waste of seven reactors, with reprocessing it could store the waste of 175 reactors. However, the problem of recycling is the high cost of reprocessing and fabrication of recycled fuel.

The costs of a nuclear fuel reload with a 50 MWd/kgU burn-up using \$130/kgU natural uranium were evaluated (Table 6.1.1) to be €82 million for 29 tU reload. Thus the costs of fresh fuel are €2900 /kgU.

The reprocessing costs of spent fuel are typically \$1000-2000/kgU and the costs of manufacturing mixed oxide fuel are also \$1000-2000/kgU. Thus the total costs of recycled fuel are on the same level as the costs of fresh fuel using natural uranium at \$130 /kgU.

The evaluations given by the John F. Kennedy School of Government in 2003 (**Matthew Bunn** et. al) indicate that the breakeven price of the natural uranium should be \$340/kgU, where reprocessing would become competitive. The uranium resources at this price are so large that there are no needs for processing in the near future.

Uranium and plutonium recycling for fast breeder reactors is another story. Matthew Bunn (et. al.) have evaluated that reprocessing will become economical in utility reactors, if the uranium price is \$134/kgU, and if the investment costs of FBR and LWR plants are the same.

If the investment costs of a FBR plant are \$500/kWe more than these of a LWR plant, then the breakeven uranium price would be \$560/kgU. Thus the feasibility of the fast breeder reactors depends on the investment costs, which should be at about the same level as for LWR reactors.

The Russians are now building an 800 MW sodium cooled fast breeder reactor in Beloyarsk. Also two more similar reactors are planned to be built in China. However, the cost figures have not been given. Safety is another problem, as sodium leaks and fires have been the major reason to abandon the reactors in France.

12.7 Financing nuclear waste disposal

The nuclear energy act in Finland requires that the operator of a nuclear power plant is responsible for managing the nuclear waste and financing its costs. In other countries this responsibility has been transferred to the government. In Finland the two existing nuclear utility companies, Fortum and TVO, have established a separate spent fuel company, **Posiva**, who takes care of the necessary operations.

The costs of spent fuel processing of the operating four reactors and the new unit Olkilluoto-3 have been estimated to exceed €3 billion. This includes €650 million for construction, €2100 for operation and €250 million for closure of the repository. The money needed for all the activities of Posiva have been collected from Fortum and TVO into the State Nuclear Waste Management Fund. The fund will then invest the money to grow the capital for future needs and will give the money back to Posiva for actual waste disposal when needed.

Each year the fund evaluates the money needed for future nuclear waste disposal and determines the fees for both nuclear utilities. At the moment the fee is ϵ 2.4/MWh for electricity generation for each reactor. This corresponds to about 5% of the market price of electricity (ϵ 50/MWh) in Finland.

The nuclear electricity generation in Finland has been in average about 23 TWh annually and each year about €60 million is saved for nuclear waste disposal. At the moment €1400 million has been collected.

If the fund fee is $\[\in \]$ 2.4/MWh, then a 1000 MWe plant should invest $\[\in \]$ 20 million annually. If this money is invested with a 2.5 % interest rate, then after 30 years the fund capital will be $\[\in \]$ 1000 million and within 60 years $\[\in \]$ 3000 million (Figure 12.7.1). Without any interest rate the fund will reach to $\[\in \]$ 600 or $\[\in \]$ 1200 million, respectively.

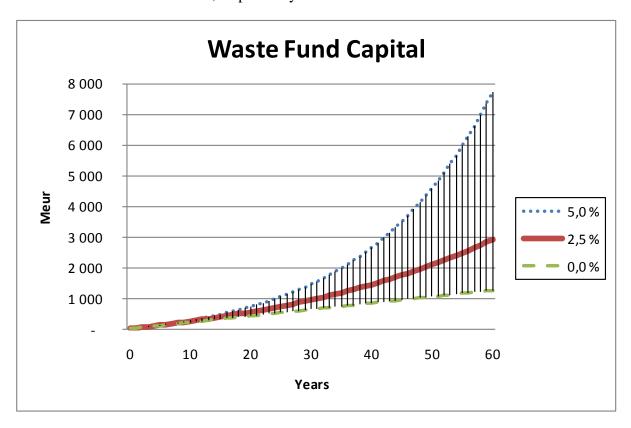


Figure 12.7.1 Nuclear waste fund capital with \pounds 2.4/MWh fee depending on the interest rate

References

/12.1/ Power Reactor Information System PRIS. IAEA. http://www.iaea.org/programmes/a2/

/12.2/ Total Costs and Funding for Final Disposal. http://www.posiva.fi/en/posiva

13 ADVANCED NUCLEAR PLANTS

13.1 Construction experiences

Large plants have had very high construction costs. Thus many vendors are now looking at smaller plant sizes. Only China has been building both medium and large plants at the same time. The costs of the Chinese design nuclear plants have been about €1700/kWe (Figure 13.1). The specific costs do not change much with the output if the output in within 600-1000 MWe.

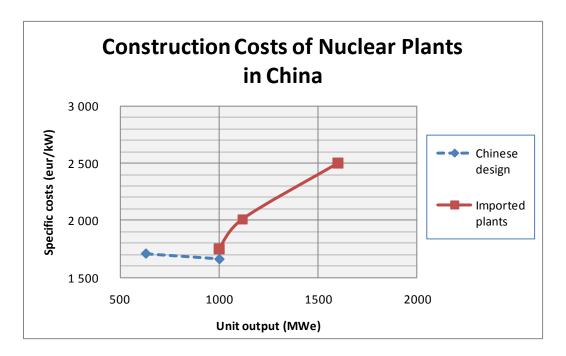


Figure 13.1.1 Construction costs of Chinese nuclear plants

The costs of imported plants have varied from €1700 to €2500/kWe and the average costs being about €2100/kWe. The specific costs seem to be increase with higher output. The 1000 MW VVER-1000 plants have had the lowest costs (€1750 /kW) and the 1600 MW EPR plants the highest (€2500 /kWe).

Thus there seems to be no economics of scale above 1000 MW unit sizes. On the contrary, the cost (C) of nuclear plants seems to increase according to the formula $C = (P/P_o)^S$, where the scaling exponent (S) is 1.5. The evidence from China shows that the lowest costs plants will be near 1000 MW unit size. There are three 1000-1100 MW plants under construction. The lowest costs will have the Chinese design CNP-1000 plants (€1650/kW). The costs of the AP1000 plant in Sanmen have been estimated to be about €2000/kWe.

13.1.1 AP1000

Westinghouse has designed an AP1000 plant that has only two steam generators (Figure 13.1.2). The plant uses passive safety systems and does not need emergency diesel generators. The containment building has inner steel containment and a reinforced concrete outer containment. This older design does not have the protection for aircraft crash.

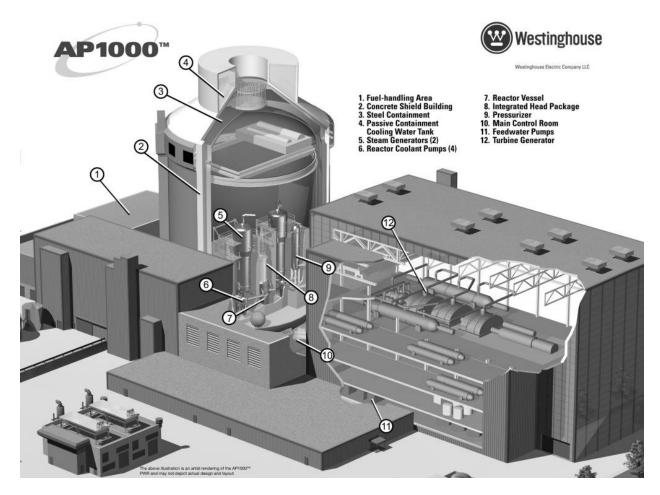


Figure 13.1.2 The Westinghouse standard AP1000 plant has a steel containment (3), a concrete outer containment (2), a passive containment cooling water tank (4) and two steam generators (5). There are two auxiliary diesel generators (left), but no emergency diesel generators

The first two units are under construction at the Sanmen site in China, based on the older design. The updated design for the UK is under safety evaluation. The UK plant will have aircraft protection and some kind of a core catcher arrangement. There are also 14 plants under design review in the US. Thus the AP1000 plant could be the market leader in the near future.

Table 13.1.1 New midsize reactors types

New reactor types		AP1000 Toshiba/	Atmea1 Areva/Mitsubishi	ACR-1000 Advanced Candu
		Westinghouse		AECL
Туре		PWR	PWR	HWR
Reactor thermal output	MWt	3415	2860-3150	3187
Electrical output	MWe	1117	1000-1150	1200
Number of steam genera	ators	2	3	4
-RPV inner diameter	m	3,988		7,5
-RPV height	m			
-RPV Pressure	bar	155		111
-Hot leg temperature	оС	321	326	319
- Uranium load	tU	84,5		
-Burn-up	GWd/tU			20
-Enrichment	%	4.95 %	5 %	1.5%-2.0 %
-Circulating pumps	number	4	3	4
-Safety systems pumps				
-Diesel engines	MW	2x4	3x100%	4x50%
-Containment type		steel vessel	pre-sressed concr.	pre-sressed concr.
-Containment diameter	m	30,6		56,5
-Containment pressure	bar	4,07		
-Core melt frequency		5.1xE-7		3.4xE-7
-Core catcher		?	Yes	Yes
-Concrete	1000m3	100		
-Aircraft crash protection	1	Yes	Yes	
-Seismic design		0,3-0.5 g	0,3 g	
Operating references				
Rerences plants		Sanmen 1-2		
		China 2009-14		
		Haiyang 1-2		
		China 2011-2016		
References on the plann	ing	14 units in USA		
stage				

13.1.2 ATMEA 1

Areva offered the EPR plant in bid a competition for the United Arab Emirates (UAE), and found that the EPR was too expensive. After this Areva started to look for methods to reduce the capital costs. Downsizing was seen as the best method to reduce costs. Areva is now designing

1100 MW size Atmea plant based on EPR technology and using three steam generators instead of four in the EPR. The plant will have the same design features as the EPR, but now the containment will be smaller and the steam turbine will be at economical size. The expected construction time will also be shorter.

13.1.3 ACR-1000

The ACR-1000 (Advanced Candu Reactor) is a new type of Canadian Candu (Canadian deuterium uranium) nuclear reactor. It has been designed for an 1100-1200 MWe output and to include modern safety features. It will be available for export markets only after the Canadian utilities will have built the first prototype of the reactor.

The reactor is a vertical pressure tube reactor, and has a continuous fuel loading. This makes the reactor difficult for developing countries, as they might use the reactor for producing plutonium for nuclear weapons. The first Indian atomic bomb has been said to be developed based on the first heavy water reactors supplied by the Canadians.

13.2 Marine derived reactors

If the nuclear programs will grow to the level of 50-70 GWe of new plants annually, then much better construction methods should be developed. The model can be taken from the shipyards, future plants should be built as ready-made plants in factory conditions. This will mean smaller plants, less concrete and more steel structures.

During my years in Imatran Voima (IVO) in the 80's I was preparing a licentiate thesis of a 190 MW size gas fired **modular combined cycle** (MCC) power plant. A four unit MCC plant was then offered by IVO at a fixed price for the Norwegian state utility company **Statkraft**. The plant would have been built by using four 190 MWe modules in Finland and transported on a barge to near Trondheim. There the modules would have been lifted on land like ships are in canals.

The project was not realized, because the Norwegian parliament did not accept gas plants due to their CO₂-emissions. The description of the 760 MWe plant can be found in the **Modern Power System Magazine** (November 1991). However, I joined Wärtsilä after this and the development of the plant in IVO ceased.

Wärtsilä has used modular technology in the building of several floating power plants. About ten floating power plants have been constructed by now by using reciprocating engines. The size of the plants starts from 30 MWe and ends at the 150 MWe size. Some floating plants have been delivered in six months from the order by using ocean going barges.

Large projects have been executed on cruising ships. The largest passenger steamship of its time was the **RMS Titanic**, which was planned for 3500 passengers and crew members. It was 290

meters long and 29 meters wide, and had a 52 300 ton displacement. It included four 12 MW (15 000 hp) reciprocating steam engines and one 13 MW steam turbine.

The world's largest luxury cruising ship today is the **M/S Oasis of the Seas**. It was ordered from the Turku Shipyard in Finland in February 2007 (Figure 13.2.1) and handed over in November 2009, two years after the order.



Figure 13.2.1 M/S Oasis of the Seas is the largest luxury cruising ship in the world

The Oasis of the Seas is 361 meters long, 47 meters wide and 64.9 meters high. The displacement is 100 000 tons, two times the size of the Titanic. The ship has three 13 MW and three 18 MW reciprocating engines by Wärtsilä. The price of the ship was €900 million, or €9000/kWe, if divided by the 100 MW engine output.

13.2.1 The Russian icebreaker derived KLT-40 reactor

Nuclear plants have been built in shipyard conditions for icebreakers. Wärtsilä Marine (Helsinki shipyard) has launched two 20 000 ton displacement nuclear icebreakers, the *N/S Taymyr* 1989 and the *N/S Vaykach* 1990.

Each of the ships had one 135 MWth KLT-40 reactor and two 18 MWe steam turbines. The project lasted for about three years. It was one of the biggest projects at the time and the price of each ships was €160 million. If divided by the output the specific costs were €4000/kWe.

Table 13.2.1 Marine derived reactors

Marine reactors		mPower	KLT-40	SVBR-100	Hyperion
Vendor		Babcock Wilcock	Rosatom	AKME Engineering	
Plant type		Modular plant	Floating plant	Modular plant	Modular plant
Reactor type		PWR	PWR	LMFBR	LMFBR
Reactor thermal output	MWt		2x150	265-280	70
Electrical output	MWe	115	2x35	100	25
Refuelling period	years		2	8	8-10
Dimensions					
- Length	m		144,4		
- Width	m		30		
- Displacement	t		21 500		
First Project			Severodvinsk		
- Construction started			April 2007		
- Launced			June 2010		
- Start of operation			Sept. 2012		
Reference vessel		N/S Savannah	N/S Taimyr	Alpha Submarine	
- Reactor			KLT-40M		
- Owner		US Maritime Ad.	Rosatom	Russian Navy	
- Ship type		Cargo Vessel	Icebreaker	Submarine	
Dimensions					
- Length	m	181	150.2	81.4	
- Beam	m	23.77	29.2	9.5	
- Displacement	t	9900	20 000	2 300	
Performance					
-Reactor output	MW	70	135	155	
- Steam turbines	MW	2x8	2x18,4	32	
- Speed	knots	21	18,5	41	
Project					
- Ordered		1955			
- Launched		July 1959	June 1989		
- Start of operation		Dec 1961			
- Project duration		80			
- Shipyeard		NY Shipbuilding	Wärtsilä Marine		

The Russians have now developed a 70 MWe floating nuclear plant based on two 35 MWe *KLT-40S* reactors. The development was started in 1990 and IVO was asked to participate in the design, because we had the MCC concept available by this time. However, we refused mainly because of the turbulent times in Russia during the beginning of the 90's.

The size of the floating nuclear plant is 144 x 30 meters and its displacement is 21 500 tons (307 kg/kWe). The specific weight of the whole plant can be compared to the 600 000 t or 375 kg/kWe weight of the concrete structures in the Olkiluoto-3 plant. The plant will be delivered to

the arctic areas, where fuel transportation to fossil fired plants would be difficult because of the ice conditions.

The construction of the first plant, the *Akademik Lomonosov*, was started in April 2007 and the plant was launched in June 2010, about three years later at the St Petersburg shipyard. It will start commercial operation in 2012 at Severodvinsk, five years after the start of its construction. However, the safety of the floating nuclear plants does not meet European standards. They could be achieved if the plant would be surrounded by a containment building, which could be built at the power plant site before the delivery.



Figure 13.2.2 Babcock and Wilcocks **mPower** reactor (Courtesy of Babcock and Wilcocks)

13.2.2 Merchant ship derived reactors by Babcock Wilcocks

The first commercial nuclear powered ship was the *N/S Savannah*. The ship was ordered in 1955 and launched in July 1959. The ship was 191 m long and it weighed 9900 tons. It was powered by a 70 MWth pressurized water reactor, which generated heat to two 8 MWe steam turbines.

The project was started in 1955 and the ship started operation in 1962. It also had a sister vessel Otto Hahn, which was built in Germany by Deutsche Babcock.

Nuclear merchant chips did not become a commercial success, because most cities did not let them to enter into the harbor. It was a question of fulfillment of the local nuclear safety standards.

Babcock and Wilcocks has been using the same technology to design a **mPower** reactor plant, which will use the same kind of reactor in a larger scale (Figure 13.2.2). The plant will be built by using 125 MWe modules. A typical plant can have eight modules and a 1000 MWe output.

The design of the plant is such that the reactor, the steam generator and the pressurizer are integrated into one vertical vessel. Thus the installation time at the site is minimized. The plant is now under NRC review. Tennessee Valley Authority (TVA) is planning to build the first prototype plant before 2020.

13.2.3 NP-300 by Technicatome

Techniatome has also developed a 300 MWe modular PWR plant based of the French nuclear submarine technology. The plant can also produce heat.

13.3 Modular Fast Breeders

13.3.1 SVBR-100

Russian submarines have been using lead-bismuth fast reactors because they are much lighter than the pressurized water reactors. The fast reactors have been used by alpha class nuclear submarines, which had a maximum speed of 40 knots submerged. The first vessel was launched in 1971.

The lead-bismuth eutectic alloy has a high boiling temperature (1670 °C) and thus a high reactor outlet temperature (480 °C) can be achieved. Then superheated steam can be fed into the steam turbine, which can have a higher efficiency. The thermal output of the reactor is 280 MWt and the electrical output of one module is then 100 MWe.

The most difficult problem with the lead-bismuth coolant is the melting point of 123.5 °C, in which temperature the reloading of new fuel becomes difficult. If the temperature drops below the melting point the metal becomes solid. This is why lead-bismuth submarine reactors do not have refueling. The reactor is loaded for appr. ten years and after this the existing submarine reactors have been decommissioned.

In the power plant applications the **SVBR-100** plants will be refueled once every eight years. This can also be done by replacing the whole reactor. The lead-bismuth mixture is very corrosive

material and thus the reactor internals might be worn out by the same time and should be replaced with new ones.

The lead-bismuth coolant also has another problem, because the bismuth-209 can capture neutrons in neutron radiation and become bismuth-210. Bismuth-210 will then emit beta radiation and become polonium-210. Polonium-210 is one of the most toxic materials, and it can cause health problems if the polonium-210 concentration in the air is 0.2 Bq/m³. Polonium has a half life of 158 days and thus it would cause health problems during refueling.

13.3.2 Hyperion

Another lead-bismuth cooled reactor concept under design is the 25 MWe **Hyperion**, which is based on the same kind of design as the Russian submarine reactors. A test loop for lead-bismuth eutectic (LBE) has been built in the Los Alamos laboratory, where the materials of reactors have been tested since 2001.

The Hyperion reactor module has a 70 MWt thermal output. The temperature in the outlet of reactor is 500 °C and the electrical efficiency of the plant is 36%. The reactor module will be used for 7 to 10 years and then replaced with a new one. The prototype reactor is planned to be built at the Savannah River site.

13.4 Other modular reactors

13.4.1 IRIS

The International Reactor Innovative and Secure (IRIS) nuclear plant is under development by a team, which includes Westinghouse. The reactor output is 1000 MWt and the net electrical output is 335 MWe. The reactor plant is similar to the Babcock and Wilcocks **mPower** plant, described in chapter 13.2.2.

The reactor, the steam generator primary circulating pumps and the pressurizer are in one large vessel, which eliminates problems with reactor pipe leaks. The fuel enrichment is 4.95 % and the reloading interval is three to four years. The fuel assemblies use the standard Westinghouse 17 x 17 fuel design.

Westinghouse has applied for design certification of the IRIS plant from the NRC in 2009 and is expecting to get the license by 2012.

13.4.2 VK-300

The Russian designed **VK-300** nuclear plant includes a 750 MWt boiling water reactor, which has been designed for district heating and desalination applications. In condensing power mode the electrical output of the plant will be 250 MWe and in desalination applications the output will be reduced to 150 MWe.

The design of the reactor is based on the reactor pressure vessel of a VVER-1000 reactor. The amount of uranium in the reactor is 31.5 tU. The enrichment is 4% and the average fuel burn-up is 43.5 MWd/kg. The reactor includes a core catcher. The reactor has negative temperature and void coefficients. The primary circulating pumps have been eliminated and the reactor has natural circulation. The reactor containment building will be made of reinforced concrete. The volume of the containment is 2000 m³. It will include a pressure suppression pool.

The probability of core damage is estimated to be 2 x 10⁻⁷ by the designer. A prototype plant, the VK-50, has been built in Dimitrov. The first VK-300 plant has been proposed to be built in Kola to replace the existing VVER-440 units.

13.4.3 VBER-300

The Russian designed pressurized water reactor **VBER-300** has a 917 MWt reactor output. The electrical power output is 325 MWe. The reactor will use the same fuel as the VVER-1000 reactors. The enrichment is 4.95 % and 100 % of the fuel will be changed after six years, or the half of fuel will be changed every three years.

13.4.4 SSBWR by Hitachi and INET

The **SSBWR-200** reactor has been designed by the Institute of Energy Technology (INET) in China. The name SSBWR comes from 'small, simplified boiling water reactor'. The reactor has been planned for thermal output of a 630 MWt and electrical output of 200 MWe. The plant can also be used for heat generation. The reactor pressure vessel diameter is 5 m and the height is 18 m. There are 384 fuel assemblies.

13.4.5 LSBWR by Toshiba

The **LSBWR** is a conceptual design of a BWR plant by Toshiba. The electrical output of the plant is 306 MWe. The reactor output is 900 MWt. The containment has a pressure suppression pool and a passive containment cooling system.

The reactor has been designed for a long operating cycle, up to 15 years. The design is simplified and reactor cooling is managed with natural circulation. The letters LS come from Long cycle and Simplified design.

Reference

/13.1/ Asko <u>Vuorinen</u> 190 MW Modular Combined Cycle (MCC) Power Plant. Modern Power Systems. November 1991.

14 CONCEPTUAL DESIGN OF A MODULAR NUCLEAR PLANT

14.1 Serial production

14.1.1 Car manufacturing

Henry Ford (1863-1947) was one of the pioneers of car manufacturing. He started his career by making demonstration cars for racing. One of his cars won a car race in 1901 in Detroit, when his car was the only one that could keep its full speed to the end. Seven weeks after the race Henry Ford could get partners and the Ford Motor Company was established for the first time.

After several manufactured prototypes the company sold its first serially manufactured A-model for \$850 in 1903. Ford could manufacture 25 cars each day. In 1908 the Ford T-model was sold for \$825 and 1000 cars were made each month. The manufacturing capacity had risen to 18 000 cars by 1910, to 34 000 cars by 1911 and to 78 000 cars by 1912.

The volume also doubled in 1913 and in 1914, when the serial production of cars was really invented. In 1914 the price of a car was set to \$440 and in 1915 it was reduced to \$345. The wage for a worker in the Ford factory was \$5/day and thus the price of a car could be earned for working 69 days. Mass production was really needed in 1920, when Ford manufactured 933 000 cars and became the world's biggest manufacturer.

One of the pioneers of manufacturing science was **Fredrik Taylor** (1856-1915), who helped Henry Ford to build the assembly lines. One of the key things of mass production was the separate manufacturing of parts, which could be assembled into any of the cars, because the accuracy of manufacturing had been improved.

Another invention was the cylinder block, which was now manufactured by using one piece of metal for the first time. The four cylinder engine had four holes in the cylinder block and the cylinders were put in a vertical position for the first time. The engine included a cylinder head, which could be removed for overhaul of the cylinders.

Today, car manufacturing has reached several millions of cars. One can buy a car with a 100 kW engine at price of €15 000. The specific price is then €150/kW. The costs of the engine itself are about €50/kW. This shows that small scale power plants could also be manufactured with lower specific costs than the large ones, if serial production was used.

One can buy 1-10 kW generator sets at the price of €100/kWe. These could be used in homes during blackouts and peaking hours. Small scale engines have very high rotation speeds, which make them weigh less. However, the efficiency is low and the cost of electricity would be too high for continuous power supply if electricity from the grid is also available.

14.1.2 Power plant manufacturing

Serial production is in use in manufacturing diesel engine power plants. The bestselling engine of my former employer Wärtsilä has been a 9 MW diesel engine. About a thousand units have been manufactured after 2004 at the Vaasa factory in Finland. The engines have been used in the construction of 5–200 MW power plants by installing several engines in the same building. The same engine can be used for emergency diesel generating sets for nuclear power plants.

The basic construction of the diesel engine for power plants is the same as in the Ford factory. Because the cylinder diameter is 320 mm, the machining of the cylinder blocks is done by automatic robots. The robots work day and nights without breaks. However, also lot of manpower is still needed on the assembly lines.

Today, a 100 MW plant with 10 diesel engines can be built at the specific costs of €500 /kWe. The costs are the same or lower than the costs of a 100 MWe gas turbine plant, which do not have so large series as the diesel engines. This is one of the reasons why diesel engines have about 90% of all megawatts ordered in the world market of oil fired power plants. Other reasons include higher efficiency and faster startup time.

The engine manufacturing will then be continued using a modular power plant construction. The most productive manufacturing can be made, if the power plant will be built in a shipyard. Then engines will be installed on an ocean going barge, which has been designed for floating applications. This method can also be used in nuclear plant manufacturing. The first floating nuclear plant, **Akademik Lomonosov**, was launched in Saint Petersburg shipyard in 2010 (see 13.2.1).

14.2 Selection of a reactor for the modular plant

The reactor for the modular plant should be a conventional type of LWR, which can be licensed in most countries. Thus only pressurized and boiling water reactors are qualified. Heavy water reactors, which could be used for plutonium production, cannot be introduced in unstable countries. Fast reactors are too expensive with today's prices of uranium. Gas cooled reactors are far from commercial maturity.

The reactor could in principle be a pressurized water reactor (PWR) or a boiling water reactor (BWR). However, the containment buildings of the BWR are much smaller because they use the pressure suppression pool. Thus an advanced BWR with internal circulating pumps and with the pressure suppression pool containment would be ideal for this compact plant. At least three companies have this size BWR on the planning stage: the SSBWR by Hitachi, the LSBWR by Toshiba and the VK-300 by Atomstroyexport. The problem with BWR plants is the very small water volume in the reactor pressure vessel, and thus fast actions are needed in accident situations before the water level decreases below the fuel elements.

The PWR reactors would normally have separate steam generators, which would make the containment building larger than in the BWR plants. Some manufacturers have also introduced more compact nuclear steam supply systems (NSSS) for PWR plants. One of them is the B&W 125 MWe modular plant, but it could be designed to reach 300 MWe size. The three 300 MWe size PWR plants include the VBER-300 reactor from Atomstroyexport in Russia, the NP-300 reactor from Technoatome in France and the 335 MWe IRIS reactor from Westinghouse.

14.3 Conceptual design of the modular plant

It would be best if all the vendors would standardize their designs based on the concept given below. Then the vendors could benefit from the same component manufacturers and the architect engineers could design the plants in modules.

The 300 MWe size plant has been selected because of the possibility to build the units in a shipyard and transport them trough the Suez channel to Asian countries. Thus the width of the plant should be 40-45 m. This size ships could be sailing through the canal and many shipyards are able to build this size vessels.

The reactor building module should then be $60 \times 40 \times 50 \text{ m}$ (LxWxH) or $120\ 000\ \text{m}^3$. If the plant output is 300 MWe, the specific volume will be $400\ \text{m}^3$ /MWe. The turbine module could be $80 \times 40 \times 40 \text{ m}$ or $128\ 000\ \text{m}^3$ ($427\ \text{m}^3$ /MWe). The total volume of the main buildings would then be $248\ 000\ \text{m}^3$ and the specific volume would be $827\ \text{m}^3$ /MWe. The plant would be $140\ \text{m}$ long, which is about half of the size of the M/S Oasis of the Seas.

If the modular plant is manufactured in a shipyard, the plant site should be designed so that the each of the modules can be towed into its final place. The best layout is achieved if the units are placed in a row one after the other (Figure 14.3.1). The turbine axes are in the same line and thus the possibility that a turbine missile could hit an operating unit is eliminated.

The electrical module is located near the switchyard and it could also be manufactured in a shipyard. The emergency diesel generator modules are on different sides of each unit and thus a single external incident cannot destroy them all. The EDG buildings include auxiliary control rooms for emergency situations.

The planned installation of the modules can be seen from the Figure 14.3.2. The lifting canal is filled with seawater and a module will be towed through the canal. Then seawater is pumped into the canal and modules will be lifted on the upper canal, which is about five to fifteen meters above sea level. When the water level will be decreased the modules would be standing on the concrete basement. The lifting canal could then be used as cooling water inlet tank to smooth the fluctuations of the level of the seawater.

The modules can be towed in the same way into an underground rock cavern, which could give the plant physical protection against aircraft crash. The rock cavern concepts would eliminate the building of the outer containment. It would be also possible to build the outer containment by using a concrete structure, if the rock cavern type construction is not possible.

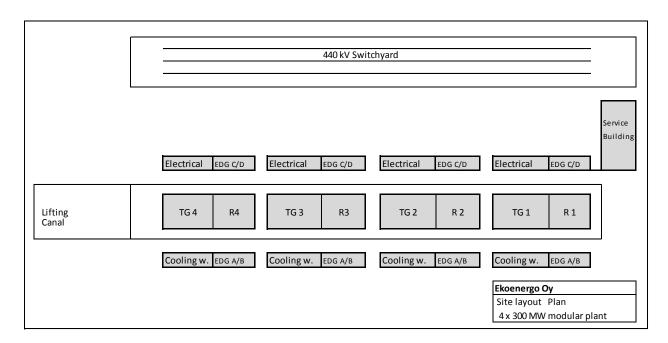


Figure 14.3.1 The site layout of a 4×300 MWe Modular Plant. The reactors (R1-R4) are in the same canal. The emergency diesel generators are on both sides of the buildings

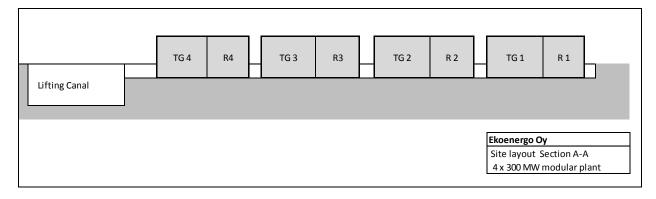


Figure 14.3.2 The site layout of a 4 x 300 MWe Modular Plant. Section A-A shows the lifting canal, by which the modules will be lifted to the upper canal

14.4 Cost reduction trough serial production

Cost reductions of serial production can be achieved by using Henderson's law:

(14.4.1) $C_n = C_1 \times n^{-e}$, where $C_n = \cos t$ of n:th unit, $C_1 = \cos t$ of the first unit, n = number of unit and e = elasticity

The cost factor has been evaluated in Table 14.4.1 in function of the size of the series and elasticity factor. Serial production has been used in nuclear plant manufacturing, but the size of the series has been smaller. The size of the series of the earlier 1300 MWe PWR units by Framatome was 20. However, only four 1450 MWe plants have been built. Now, the EPR plants could have larger series.

The costs of the first EPR nuclear plant, the Olkiluoto-3 in Finland, will be about €3500/kWe. The typical elasticity in serial production in the manufacturing industry is 0.15. Thus if the first unit will cost €3500/kWe, then the tenth unit will cost 0.71 x 3500 or €2500/kWe. It could be possible to manufacture nuclear plants in large series, if the plant sizes will come down to 300 MWe.

Table 14.4.1 The unit costs of manufacturing depending on the number of units and the elasticity

Number of units			Elasticity			
manufactured	0,05	0,10	0,15	0,20	0,25	0,30
1	1,00	1,00	1,00	1,00	1,00	1,00
2	0,97	0,93	0,90	0,87	0,84	0,81
3	0,95	0,90	0,85	0,80	0,76	0,72
4	0,93	0,87	0,81	0,76	0,71	0,66
5	0,92	0,85	0,79	0,72	0,67	0,62
10	0,89	0,79	0,71	0,63	0,56	0,50
20	0,86	0,74	0,64	0,55	0,47	0,41
30	0,84	0,71	0,60	0,51	0,43	0,36
40	0,83	0,69	0,58	0,48	0,40	0,33
50	0,82	0,68	0,56	0,46	0,38	0,31
100	0,79	0,63	0,50	0,40	0,32	0,25
200	0,77	0,59	0,45	0,35	0,27	0,20
300	0,75	0,57	0,43	0,32	0,24	0,18
400	0,74	0,55	0,41	0,30	0,22	0,17
500	0,73	0,54	0,39	0,29	0,21	0,15
1000	0,71	0,50	0,35	0,25	0,18	0,13
2000	0,68	0,47	0,32	0,22	0,15	0,10
3000	0,67	0,45	0,30	0,20	0,14	0,09
4000	0,66	0,44	0,29	0,19	0,13	0,08
5000	0,65	0,43	0,28	0,18	0,12	0,08
10000	0,63	0,40	0,25	0,16	0,10	0,06

After one hundred units the costs could decline by 50%. If the first plant costs €3500 /kWe, then after a hundred units the price would be €1750/kWe. Thus it is possible to reach the same cost level with small plants as with large plants.

14.5 Estimating investment costs

Another factor in investment planning is the scaling factor. The costs of a power plant tend to increase with the size according to the following formula (14.5.1):

(14.5.1) $C(P) = C_r \times (P/P_r)^S$, where C(P) = cost of unit with output P (MWe), $C_r = costs$ of the reference unit, P = costs of the reference unit,

The scaling exponent (S) has typically been 0.75 in the power plant industry. Thus if the size increases with a factor of two, the costs will increase with $2^{0.75}$ or 1.68 times. But if the size increases above 1000 MW, the exponent seems to be 1.2-1.5.

Thus the minimum costs are at the 1000 MWe size depending on the site conditions. The cost estimates of the single unit nuclear plants have been estimated in Table 14.5.1. The scaling factor of 0.75 has been used below the 1000 MW and 1.2 above the 1000 MW size of the units.

The construction time increases with the size of the plant and the interest costs during the construction will also increase. It has been estimated that a 300 MWe plant will need four years from the order to generate electricity. A1600 MW plant will take seven years for the first electricity. The first 1600 MWe EPR plant in Olkiluoto will take about eight years.

The total investment costs of a 1000 MWe plant have been estimated to be €2970/kWe. The costs of a 300 MWe, 600 MWe and 1200 MWe plant will be €3837/kWe, €3300/kWe and €3100/kWe respectively (Table 14.5.1).

However, if a 1200 MWe plant will be built by using four 300 MW units, the cost will decline according to the serial production with formula (14.4.1). If the elasticity is 0.15 for the mechanical system, electrical equipment and buildings, then the investment costs of a 4 x 300 MWe plant are $\[\in \]$ 330 /kWe (Table 14.5.2).

Additionally the smaller units will have smaller system costs, which can make the small plants more competitive than large plants. The operating reserves would include spinning reserves and non-spinning reserves. The spinning reserves should compensate trip of the largest unit and the non-spinning reserves should restore the spinning reserves within 10 minutes. The spinning reserves are typically covered by coal or gas fired plants, which increase their output from 90% to 100% within 15 seconds to fill the deficit in generation.

A 1200 MWe unit size plant will need 900 MW more spinning reserves than a 300 MWe nuclear plant. If this is covered by investing in gas fired capacity, the costs are 900 MWe x €800/kW or €720 million.

Table 14.5.1 Investment costs of the first unit of nuclear power plant

INVESTMENT COST ESTIMATES OF NUCLEAR POWER PLANTS

Output	MWe	300	600	800	1000	1200	1400	1600
		(Meur)						
Mechanical systen	ns							
NSSS		240	403	500	591	736	885	1 039
Turbine		182	306	380	449	559	673	790
Auxilaries		43	72	89	105	131	157	184
Total		464	781	969	1 146	1 426	1 715	2 014
Electrical equipme	ents							
Electrical syste	ms	59	100	124	147	182	219	258
Instrumentatio	n	69	116	143	170	211	254	298
Total		128	215	267	316	393	473	555
Buildings								
Buildings		118	198	246	291	362	435	511
Structures		19	32	40	47	59	71	83
Total		137	230	286	338	420	506	594
Indirect costs								
Site manageme	ent	92	156	193	228	284	342	401
Design		59	99	122	144	180	216	254
General costs		55	92	114	135	168	203	238
Total		206	346	430	508	632	761	893
BASIC COSTS		935	1 573	1 952	2 307	2 871	3 455	4 055
Contingency		94	157	195	231	287	345	406
Spare parts		18	30	37	44	55	66	77
OVERNIGHT COSTS	S	1 047	1 760	2 184	2 582	3 213	3 866	4 538
Specific costs	eur/kWe	3 488	2 933	2 730	2 582	2 678	2 761	2 836
Construction ti	me	4	5	5,5	6	6,5	7	7,5
Interests DC		105	220	300	387	522	677	851
POWER PLANT INV	/ESTMENT	1 151	1 980	2 484	2 969	3 735	4 543	5 389
	eur/kWe	3 837	3 300	3 105	2 969	3 113	3 245	3 368

Non-spinning reserves are needed to restore the spinning reserves within ten minutes to be ready for a possible trip of another 300 MWe unit. They are typically constructed using gas and diesel engines or gas turbines. The costs of the extra capacity of non-spinning reserves will be 900 MW $\times 600 \, \text{kW}$ of $6540 \, \text{million}$.

Thus the total extra costs for the operating reserves of a 1200 MWe unit size plant are €1260 million or €1050/kWe. The total costs of 1200 MWe plant would then be €3113/kWe + €1050/kWe or 4160/kWe. The costs of a 4 x 300 MWe nuclear plant were €3327/kWe, which are €830/kWe lower than the costs of a 1200 MWe plant.

Table 14.5.2 Investment costs of a 4 x 300 MW nuclear power plant

INVESTMENT COST ESTIMATES OF A 4 X 300 MW NUCLEAR POWER PLANT

Unit number		1	2	3	4	Total
	elasticity	(Meur)	(Meur)	(Meur)	(Meur)	(Meur)
Mechanical systems						
NSSS	0,15	240	216	203	195	854
Turbine	0,15	182	164	154	148	649
Auxilaries	0,15	43	38	36	35	151
Total		464	419	394	377	1 654
Electrical equipments						
Electrical systems	0,15	59	54	50	48	212
Instrumentation	0,15	69	62	58	56	245
Total		128	115	109	104	456
Buildings						
Buildings	0,15	118	106	100	96	419
Structures	0,15	19	17	16	16	68
Total		137	123	116	111	488
Indirect costs						
Site management	0,30	92	75	67	61	295
Design	0,30	59	48	42	39	187
General costs	0,30	55	45	39	36	175
Total		206	167	148	136	657
BASIC COSTS		935	825	767	728	3 255
Contingency		94	82	77	73	325
Spare parts	0,50	18	13	10	9	49
OVERNIGHT COSTS		1 047	920	854	810	3 630
Specific costs	eur/kWe	3 488	3 065	2 845	2 700	3 025
Construction time		4	4	4	4	
Interests DC		105	92	85	81	363
POWER PLANT INVESTM	ENT	1 151	1 012	939	891	3 993
	eur/kWe	3 837	3 372	3 130	2 970	3 327

14.6 Cash flow analysis

If the project is financed with an 80% loan for 20 years at a 3% interest rate, the generation costs will decrease to €25.8/MWh (Table 14.6.3). This can be compared with the generation costs of the 1200 MWe plant, which were €26.6/MWh.

The internal rate of return of the 4 x 300 MWe plant is 10.9% without financing and 26.4% with financing. This can be compared with the internal rate of return of the 1200 MWe plant, which was 10.0% without financing (Table 10.6.2) and 20.3% with financing (Table 10.6.3).

The cumulative discounted cash flow diagram of the 4 x 300 MWe plant has been compared with the 1200 MWe plant in Figure 14.6.1. The figure shows that the smaller plant will start to generate electricity sooner. Thus the project does not need as much financing as the large plant.

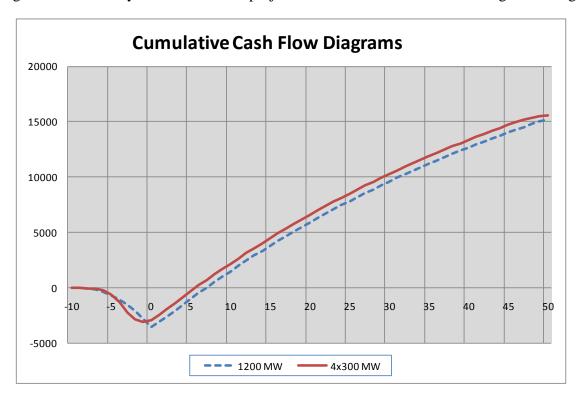


Figure 14.6.1 Cumulative discounted cash flow of 1200 MW and 4 x 300 MW nuclear plant

Table 14.6.1 The cash flow of a 4 x 300 MW nuclear power plant (Page 1)

PRO	FITAB	ILITY I	EVALU.	ATION		Electric	5	0 €/MWh	3 %		Page		1
	Units		300	MWe		Fuel		0 €/MWh	3 %		Date		11.4.2011
	Numb	oer	4	pcs		о&м	8,	0 €/MWh	2 %		Costlev	/el	1/2011
	Outp	ut	1200	MWe		Waste	2,	4 €/MWh	2 %		Disc.rat		5 %
			Gener			Disc-		ectricity		Constri	uction co		
Year	1	2	3	4	Total	ounted		Revenue	1	2	3	4	Total
	TWh	TWh	TWh	TWh	TWh	TWh		/h Meur	M€	M€	M€	M€	M€
-10					-	0,0	50		-10				-10
-9					-	0,0	52		-20				-20
-8					-	0,0	53		-25				-25
-7					-	0,0	55		-30				-30
-6					-	0,0	56		-80	-26			-106
-5					-	0,0	58		-200	-68	-24		-292
-4					-	0,0	60		-300	-170	-63	-23	-556
-3					-	0,0	61		-350	-255	-158	-60	-823
-2	2,1				2	2,3	63	133	-32	-298	-237	-150	-717
-1	2,2	2,1			4	4,5	65	280		-27	-277	-225	-529
О	2,3	2,2	2,1		7	6,5	67	439			-25	-263	-288
1	2,4	2,3	2,2	2,1	9	8,5	69	619				-24	-24
2	2,4	2,4	2,3	2,2	9	8,4	71	657					
3	2,4	2,4	2,4	2,3	9	8,2	73	694					
4	2,4	2,4	2,4	2,4	10	7,9	76	726					
5	2,4	2,4	2,4	2,4	10	7,5	78	748					
6	2,4	2,4	2,4	2,4	10	7,2	80	770					
7	2,4	2,4	2,4	2,4	10	6,8	83	793					
8	2,4	2,4	2,4	2,4	10	6,5	85	817					
9	2,4	2,4	2,4	2,4	10	6,2	88	842					
10	2,4	2,4	2,4	2,4	10	5,9	90	867					
11	2,4	2,4	2,4	2,4	10	5,6	93	893					
12	2,4	2,4	2,4	2,4	10	5,3	96	920					
13	2,4	2,4	2,4	2,4	10	5,1	99	947					
14	2,4	2,4	2,4	2,4	10	4,8	102	976					
15	2,4	2,4	2,4	2,4	10	4,6	105	1 005					
16	2,4	2,4	2,4	2,4	10	4,4	108	1 035					
17	2,4	2,4	2,4	2,4	10	4,2	111	1 066					
18	2,4	2,4	2,4	2,4	10	4,0	114	1 098					
19	2,4	2,4	2,4	2,4	10	3,8	118	1 131					
20	2,4	2,4	2,4	2,4	10	3,6	121	1 165					
21	2,4	2,4	2,4	2,4	10	3,4	125	1 200					
22	2,4	2,4	2,4	2,4	10	3,3	129	1 236					
23	2,4	2,4	2,4	2,4	10	3,1	133	1 273					
24	2,4	2,4	2,4	2,4	10	3,0	137	1 311					
25	2,4	2,4	2,4	2,4	10	2,8	141	1 351					
26	2,4	2,4	2,4	2,4	10	2,7	145	1 391					
27	2,4	2,4	2,4	2,4	10	2,6	149	1 433					
28	2,4	2,4	2,4	2,4	10	2,4	154	1 476					
29	2,4	2,4	2,4	2,4	10	2,3	158	1 520					
30	2,4	2,4	2,4	2,4	10	2,2	163	1 566					
46	2,4	2,4	2,4	2,4	10	1,0	262	2 513					
47	2,4	2,4	2,4	2,4	10	1,0	270	2 588					
48	,-	2,4	2,4	2,4	7	0,7	278	1 999					
49		-,-	2,4	2,4	5	0,7	286	1 373					
50			_,-	2,4	2	0,2	295	707					
Total				_,.	477	186		71,6	-1047	-843	-784	-745	-3419

Table 14.6.2 The cash flow of a 4 x 300 MW nuclear power plant without financing (Page 2)

PRO	FITABI	LITY	EVAL	UATIO	NC								Page		2
	Unitsiz	e	300	MWe		300	MWe						Date		11.4.2011
	Number	r	4	pcs		4	pcs						Costle	/el	1/2011
	Output		1200	MWe		1200	MWe						Disc.ra	te	5 %
	Fuel		Fuel	costs		Fuel	0&M	Waste	Other	costs	Total o	costs	Net Cas	Disc	ounted
Year	Price	1	2	3	4	Costs	Price	fee	0&М	Waste	Sum	Disc.	Flow	Cash f	k Cumulat.
	€/MWh	М€	M€	M€	М€	M€	€/MWh	€/MWh	M€	M€	M€	M€	M€	M€	M€
-10	4,0					0	8,0	2,4			-10	-16	-10	-16	-16
-9	4,1					0	8,2	2,4			-20	-31	-20	-31	-47
-8	4,2					0	8,3	2,5			-25	-37	-25	-37	-84
-7	4,4					О	8,5	2,5			-30	-42	-30	-42	-126
-6	4,5					О	8,7	2,6			-106	-141	-106	-141	-268
-5	4,6					0	8,8	2,6			-292	-372	-292	-372	-640
-4	4,8					О	9,0	2,7			-556	-676	-556	-676	-1316
-3	4,9		21			21	9,2	2,8			-802	-929	-802	-929	-2244
-2	5,1		11	22		32	9,4	2,8			-684	-755	-551	-608	-2852
-1	5,2	25	11	11	22	70	9,6	2,9	-44		-504	-529	-224	-235	-3088
О	5,4	13	12	12	11	48	9,8	2,9	-89		-329	-329	110	110	-2977
1	5,5	13	13	12	12	51	9,9	3,0	-89	-27	-89	-84	530	505	-2472
2	5,7	14	14	14	13	54	10,1	3,0	-93	-28	-68	-61	589	534	-1938
3	5,9	14	14	14	14	56	10,3	3,1	-98	-29	-71	-61	623	538	-1400
4	6,1	15	15	15	15	58	10,6	3,2	-101	-30	-74	-61	652	537	-863
5	6,2	15	15	15	15	60	10,8	3,2	-103	-31	-75	-58	673	528	-336
6	6,4	15	15	15	15	62	11,0	3,3	-105	-32	-75	-56	695	518	183
7	6,6	16	16	16	16	63	11,2	3,4	-108	-32	-76	-54	717	510	693
8	6,8	16	16	16	16	65	11,4	3,4	-110	-33	-77	-52	740	501	1193
9	7,0	17	17	17	17	67	11,7	3,5	-112	-34	-78	-50	764	492	1686
10	7,2	17	17	17	17	69	11,9	3,6	-114	-34	-79	-49	788	484	2169
11	7,4	18	18	18	18	71	12,1	3,6	-116	-35	-80	-47	813	475	2645
12	7,7	18	18	18	18	74	12,4	3,7	-119	-36	-81	-45	839	467	3112
13	7,9	19	19	19	19	76	12,6	3,8	-121	-36	-82	-43	866	459	3571
14	8,1	20	20	20	20	78	12,9	3,9	-124	-37	-83	-42	893	451	4022
15	8,4	20	20	20	20	80	13,1	3,9	-126	-38	-83	-40	922	443	4465
16	8,6	21	21	21	21	83	13,4	4,0	-129	-39	-84	-39	951	436	4901
17	8,9	21	21	21	21	85	13,7	4,1	-131	-39	-85	-37	981	428	5329
18	9,2	22	22	22	22	88	13,9	4,2	-134	-40	-86	-36	1012	421	5750
19	9,4	23	23	23	23	90	14,2	4,3	-136	-41	-87	-34	1044	413	6163
20	9,7	23	23	23	23	93	14,5	4,3	-139	-42	-88	-33	1077	406	6569
21	10,0	24	24	24	24	96	14,8	4,4	-142	-43	-88	-32	1112	399	6968
22	10,3	25	25	25	25	99	15,1	4,5	-145	-43	-89	-31	1147	392	7360
23	10,6	25	25	25	25	102	15,4	4,6	-148	-44	-90	-29	1183	385	7745
24	10,9	26	26	26	26	105	15,7	4,7	-151	-45	-91	-28	1220	378	8124
25	11,3	27	27	27	27	108	16,0	4,8	-154	-46	-92	-27	1259	372	8495
26	11,6	28	28	28	28	111	16,3	4,9	-157	-47	-92	-26	1299	365	8861
27	11,9	29	29	29	29	115	16,6	5,0	-160	-48	-93	-25	1340	359	9220
28	12,3	30	30	30	30	118	17,0	5,1	-163	-49	-94	-24	1382	353	9572
29	12,7	30	30	30	30	122	17,3	5,2	-166	-50	-95	-23	1426	346	9918
30	13,0	31	31	31	31	125	17,3	5,3	-170	-51	-95	-23	1471	340	10259
	10,0		J +	J.	J.			٥,٥		<u> </u>				340	10233
46	20,9	50	50	50	50	201	24,2	7,3	-233	-70	-102	-11	2411	256	14952
47	21,6	0	52	52	52	155	24,7	7,4	-237	-71	-153	-15	2435	246	15198
48	22,2	0	0	53	53	107	25,2	7,6	-182	-54	-130	-12	1870	180	15378
49	22,9	0	0	0	55	55	25,7	7,7	-124	-37	-106	-10	1267	116	15494
50	23,6	0	0	0	0	0	26,2	7,9	-63	-19	-82	-7	625	55	15548
		1320	1389	1431	1474	5614			-7825	-2307	-7937	-5400	63616	15548	
	-					-					-	29,0	€/MWh	10,9 %	IRR

Table 14.6.3 The cash flow of a 4×300 MW nuclear power plant with financing (Page 3)

PROFI	TABILITY E	VALUATIO	ON					Page	3
	Unit size	300	MWe	Loan rat	io	80 %		Date	11.4.2011
	Number	4	pcs	Loan pei	riod	20	a	Cost level	1/2011
	Output	1200	MWe	Interest	rate	3 %	,	Disc.rate	5 %
	Total	Financing		Total cos	sts	Net Cash	Discounte	ed	Discount
Year	Costs	Loans	Inter.	Sum	Disc.	Flow	Cash fl.	Cumulat.	factor
	M€	M€	M€	M€	M€	M€	M€	M€	5 %
-10	-10			-10	-16	-10	-16	-16	1,629
-9	-20			-20	-31	-20	-31	-47	1,551
-8	-25			-25	-37	-25	-37	-84	1,477
-7	-30	24		-6	-8	-6	-8	-93	1,407
-6	-106	84	-1	-22	-29	-22	-29	-122	1,340
-5	-292	233	-3	-62	-79	-62	-79	-201	1,276
-4	-556	445	-10	-121	-148	-121	-148	-348	1,216
-3	-802	659	-24	-167	-194	-167	-194	-542	1,158
-3 -2	-684	573	-43	-154	-170	-21	-24	-565	
-2 -1	-504		-43 -61						1,103
-1		423		-141	-148	139	146	-420 153	1,050
	-329	231	-73	-172	-172	268	268	-152	1,000
1	-89	19	-80	-150	-142	469	447	295	0,952
2	-68	-135	-81	-283	-257	374	339	634	0,907
3	-71	-135	-77 	-282	-244	412	356	990	0,864
4	-74	-135	-73	-281	-231	445	366	1356	0,823
5	-75	-135	-69	-278	-218	470	368	1724	0,784
6	-75	-135	-65	-275	-205	496	370	2094	0,746
7	-76	-135	-61	-271	-193	522	371	2465	0,711
8	-77	-135	-57	-268	-182	549	371	2836	0,677
9	-78	-135	-52	-265	-171	577	372	3208	0,645
10	-79	-135	-48	-262	-161	605	371	3579	0,614
11	-80	-135	-44	-259	-151	634	371	3950	0,585
12	-81	-135	-40	-256	-142	664	370	4320	0,557
13	-82	-135	-36	-253	-134	695	368	4688	0,530
14	-83	-135	-32	-249	-126	726	367	5055	0,505
15	-83	-135	-28	-246	-118	759	365	5420	0,481
16	-84	-135	-24	-243	-111	792	363	5783	0,458
17	-85	-135	-20	-240	-105	826	361	6144	0,436
18	-86	-135	-16	-237	-98	862	358	6502	0,416
19	-87	-135	-12	-233	-92	898	355	6857	0,396
20	-88	-135	-8	-230	-87	935	352	7209	0,377
21	-88	-135	-4	-227	-82	973	349	7558	0,359
22	-89		0	-89	-31	1147	392	7950	0,342
23	-90			-90	-29	1183	385	8336	0,326
24	-91			-91	-28	1220	378	8714	0,310
25	-92			-92	-27	1259	372	9086	0,295
26	-92			-92	-26	1299	365	9451	0,281
27	-93			-93	-25	1340	359	9810	0,268
28	-94			-94	-24	1382	353	10162	0,255
29	-95			-95	-23	1426	346	10509	0,243
30	-95			-95	-22	1471	340	10849	0,231
									3,232
46	-102			-102	-11	2411	256	15543	0,106
47	-153	1		-153	-15	2435	246	15788	0,101
48	-130	1		-130	-12	1870	180	15968	0,096
49	-106			-106	-10	1267	116	16084	0,092
50	-82			-82	-7	625	55	16139	0,087
		0	-1143	-9080	-4810	62473	16139		,
							+		

15 LIVING IN A POLLUTED WORLD

15.1 Life expectancy

Life expectancy can be used as one measure of the living standard. The life expectancy is more than 80 years in 27 countries (Table 15.1.1). 19 of them belong to the European Union and 13 of them have introduced nuclear power.

Table 15.1.1 Life expectancy by WHO (Nuclear countries highlighted)

no	country	years	no	country	ears/	no	country	years	no	country	/ears
1	Japan	83	48	Bosnia and Herz	75	95	Latvia	71	142	Papua New Guine	62
2	San Marino	83	49	Colombia	75	96	Saint Vincent a	71	143	Timor-Leste	62
3	Australia	82	50	Saint Lucia	75	97	Suriname	71	144	Botswana	61
4	Iceland	82	51	Slovakia	75	98	Tonga	71	145	Sao Tome and Pr	61
5	Italy	82	52	Tunisia	75	99	Armenia	70	146	Comoros	60
6	Monaco	82	53	Uruguay	75	100	Belarus	70	147	Gabon	60
7	Switzerland	82	54	Venezuela (Boliv	75	101	Fiji	70	148	Madagascar	60
8	Canada	81	55	Antigua and Barl	74	102	Honduras	70	149	Djibouti	59
9	France	81	56	Barbados	74	103	Philippines	70	150	Gambia	59
10	Israel	81	57	China	74	104	Solomon Island	70	151	Marshall Islands	59
11	New Zealand	81	58	Dominica	74	105	Thailand	70	152	Senegal	59
12	Norway	81	59	Estonia	74	106	Trinidad and To	70	153	Togo	59
13	Singapore	81	60	Hungary	74	107	Egypt	69	154	Ethiopia	58
14	Spain	81	61	Maldives	74	108	Grenada	69	155	Mauritania	58
15	Sweden	81	62	Montenegro	74	109	Guatemala	69	156	Rwanda	58
16	Austria	80	63	Nicaragua	74	110	Micronesia (Fed	69	157	Benin	57
17	Belgium	80	64	Oman	74	111	Moldova	69	158	Sudan	57
	Cyprus	80	65	Paraguay	74	112	Sri Lanka	69	159	Côte d'Ivoire	56
	Finland	80	66	Serbia	74	113	Vanuatu	69	160	Congo	54
20	Germany	80	67	The former Yugo	74	114	Azerbaijan	68	161	Guinea	54
	Greece	80	68	Turkey	74	115	Mongolia	68	162	Kenya	54
22	Ireland	80	69	Albania	73	116	Russian Feder	68	163	Liberia	54
	Luxembourg	80	70	Brazil	73	117	Samoa	68	164	Myanmar	54
	Malta	80	71	Bulgaria	73	118	Ukraine	68	165	Cameroon	53
	Netherlands	80	72	Dominican Repu	-	119	Uzbekistan	68	166	Equatorial Guinea	
_	Republic of Kore	80	73	Ecuador	73	120	Bolivia (Plurinat	67	167	Malawi	53
	United Kingdom	80	74	Libyan Arab Jam		121	Democratic Per		168	South Africa	53
	Denmark	79	75	Malaysia	73	122	Indonesia	67	169	United Republic o	
_	Portugal	79	76	Mauritius	73	123	Kiribati	67	170	Niger	52
	Slovenia	79	77	Romania	73	124	Tajikistan	67	171	Uganda	52
	Chile	78	78	Saint Kitts and N	73	125	Kyrgyzstan	66	172	Burkina Faso	51
_	Costa Rica	78	79	Viet Nam	73	126	Bangladesh	65	173	Mozambique	51
	Kuwait	78	80	Belize	72	127	Eritrea	65	174	Burundi	50
	United Arab Emira	78	81	El Salvador	72	128	Guyana	65	175	Guinea-Bissau	49
	United States of	78	82	Georgia	72	129	India	64	176	Mali	49
	Cuba	77	83	Iran (Islamic Re		130	Kazakhstan	64	177	Nigeria	49
	Czech Republic	77	84	Jamaica	72	131	Yemen	64	178	Sierra Leone	49
	Argentina	76	85	Jordan	72	132	Bhutan	63	179	Central African Re	_
	Brunei Darussalar	76	86	Lebanon	72	133	Iraq	63	180	Somalia	48
	Croatia	76	87	Lithuania	72	134	Namibia	63	181	Swaziland	48
	Mexico	76	88	Morocco	72	135	Nepal	63	182	Zambia	48
	Panama	76 76	89	Palau	72	136	Pakistan	63	183	Lesotho	40 47
	Peru	76 76	90	Saudi Arabia	72	137	Turkmenistan	63	184	Angola	46
	Poland	76 76	90		72	138	Cambodia	62	185	Chad	46
	Qatar	76 76	91	Seychelles	. –	138	Ghana	62	186	Afghanistan	46 42
_		76 75	92 93	Syrian Arab Rep	72	139	Gnana Haiti	62	186	O .	42 42
_	Bahamas			Algeria	1				107	Zimbabwe	42
	Bahrain	75	94	Cape Verde	71	141	Lao People's De	62	1		
18			8			6			Т		

The top countries in the list are all democratic and also have high living standards. Nuclear power has also been introduced in many low income countries, where the life expectancy is still much lower. India and Pakistan are among the nuclear countries with a 63 to 64 years life expectancy. However, none of the countries with a less than 50 year life expectancy have introduced nuclear power.

15.2 Causes of death

Life on earth has always been dangerous. Many things can cause an early death: famine, wars, accidents and sickness, which may be caused by pollution in air, water or in food. The statistics given by the World Health Organization (WHO) indicate that about 80% of deaths are caused by six reasons: heart and infectious diseases, cancer, respiratory infections and diseases as well as by unintentional injuries (Figure 15.2.1).

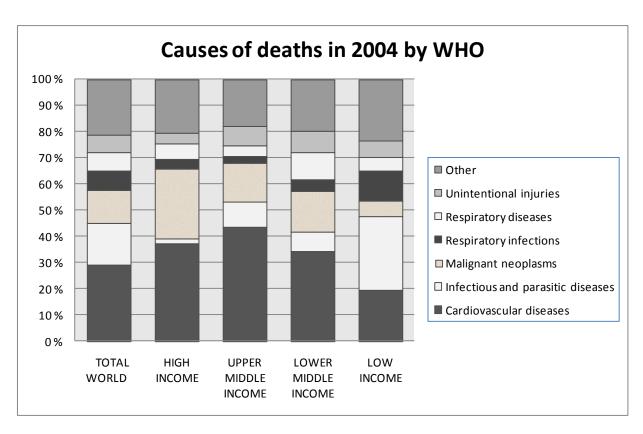


Figure 15.2.1 Causes of deaths according to income groups of countries in 2004 by the World Health Organization (WHO)

Unintentional injuries cause about 7% of deaths. They are mainly road accidents, which will be discussed in chapter 16. Respiratory diseases and infections cause 14% of the deaths. They could be caused by air pollution. It should be noted that respiratory diseases are relatively more common in low income countries, where they cause about 16% of deaths.

Various cancers (*malignant neoplasms*) cause 13% of deaths in the world and 26% of deaths in high income countries. They can also have been caused by pollution and radiation in air, food and water. Air, food and water may contain several types of harmful particles, which can contaminate human body. Processed food also has several chemicals that can cause cancers.

The most common causes of death (28%) in low income countries are infections and parasitic disease, which may be caused by polluted drinking water and the general hygiene of inhabitants. In higher income countries heart diseases (*cardiovascular diseases*) cause 30-42% of deaths.

15.3 Radiation

15.3.1 X-rays

The effects of ionized radiation on health were noticed for the first time when X-rays were used for health inspections. Later it was noted that X-rays are electromagnetic radiation, which has a very short wave length. However, one of the victims of X-rays was **Nikola Tesla**, who got his fingers burned in 1896, but he did not understand that the cause was the X-rays. Tesla was the inventor of the alternating current. The genetic effects and cancer risks of X-rays were found in 1927 by **Herman Müller**.

X-rays have been used for medical inspection since then, but the dangers of radiation were actually found much later. In the 50's X-rays were used in my home town of **Jyväskylä** by shoe shops for studying how the shoes fit onto the foot. I remember having at least once being looking at my foot with an X-ray machine. The machines disappeared very rapidly and in the 60's no machines could be found in shoe shops.

It was also common to examine all women with X-rays (mammography) to detect breast cancer. This was found later that X-rays may have caused new cancers through these examinations. The examinations for all the Finnish population were stopped in about 1985. However, they are still in use by doctor's orders for some age groups. X-rays could detect many illnesses and thus save lives.

The average annual dose rate from the X-rays is 0.4 millisieverts (mSv) per person in the world today. This is about 25% of the average annual dose of 2.8 mSv received by average persons. The total dose rate from X-rays in the world's population is 2.4 million manSv annually. **Sievert** is the unit measuring the biological effects of radiation on the human body.

Sieverts can be evaluated from the absorbed energy of radiation, which is measured in **Grey** (Joule/kg). The same amount of absorbed radiation has different biological effect, which is measured in quality factors (Q). X-rays, gamma rays and beta particles (electrons) have Q-value of 1, but alpha particles have a Q-value of 20.

15.3.2 Radioactivity

Radioactivity was discovered in 1896 by **Henri Becquerel**, who was studying fluorescent lighting of uranium. He found that the radiation from uranium could expose photographic plates. Today his name has remained in history as the unit of radiation, **Becquerel (Bq)**. One Bq of radiation corresponds to one nucleus decays per second (1/s). Becquerel is a very small unit to measure the radiation caused by a nuclear accident. The nuclear accident in Chernobyl released 140×10^{15} Bq of radioactivity in cesium.

Another unit to measure of radiation is **Curie** (**Ci**), which was used earlier. One Curie is equivalent of one gram of radium and it corresponds to 37 GBq (3.7 x 10¹⁰ Bq). The Chernobyl explosion produced about 400 000 Curies of cesium radioactivity. **Marie Curie** discovered radium, when she was separating radium from uranium ore. At the same time she discovered that the real activity in uranium ore was in radium, but the uranium itself was not very radioactive.

The radioactivity scale is large and thus the measurement units of Mega (MBq= 10^6 Bq), Giga (GBg = 10^9 Bq), Tera (TBq= 10^{12} Bq), and Peta (PBq= 10^{15} Bq) are used. The radioactive cesium releases from the Chernobyl accidents were 140 000 TBq.

15.3.3 Radon-222

Radon is a decay product of uranium. The average concentration of uranium in the earth's crust is 2.8 parts per million (ppm). Uranium-238 has a half life of 4.4 billion years, thus radon will be formed forever. Uranium decays into radium-226, which has a half life of 1600 years. Radium will then decay into **radon-222** gas, which has a half life of 3.8 days.

Radon-222 is in the air of most houses and in drinking water, if the water comes from ground water sources. The total release of radioactivity from radon-222 has been estimated to be 90 TBq annually. The total dose of radon is about 8 MSv annually, and the average radon dose of world population is about 1.26 mSv per year. This is 46% of the average annual dose of the people.

The maximum value of the radon concentration in new houses is set to 200 Bq/m³ in Finland. But there are many old houses where the concentration exceeds 1000 Bq/m³. The concentration can be easily decreased by a factor of ten, if the ventilation of air in the buildings is increased. Thus the contaminated inside air is changed to cleaner outside air.

Some energy activists are still proposing to save energy by closing the ventilation. However, this kind of saving could lead to much higher exposures of radiation than in the nuclear plants.

Another method used in new houses is the ventilation of the basement of the buildings. In addition the construction materials can contain radium and thus they will emit radon. Concrete buildings have about 30-100 Bq/m³ larger radium content in inside air than wooden houses. In addition wooden houses can be used as carbon sinks, because they will store the CO₂ captured from the air for several decades.

Radon-222 in the air inside a home can be carcinogenic. Radon can increase the risk of lung cancer and it has been considered to be the second biggest reason for lung cancer after smoking. A European study (British Medical Journal, 330, 23-227) has estimated that concentration of 700 Bg/m³ in air adds the risks of lung cancer by 100%.

If the average concentration of radon in homes is 140 Bq/m³, then about 20% of lung cancers are caused by radon. The average levels of radon concentration in houses is in Finland 123, in Sweden 108, in Norway 106, in Denmark 77, in France 66, in Germany 50 and in UK 20 Bq/m³. However, in Finland there are about 1% of houses, which have more than 800 Bq/m³ of radon in the air.

15.3.4 Polonium-210

Polonium-210 was discovered by Marie Sklodowska-Curie and Pierre Curie in 1898. It is a decay material of uranium-238 and it can be found from uranium ore. Polonium-210 is highly radioactive (166 TBq/gram).

Polonium became famous when a Russian agent, **Alexander Litvinenko**, was probably murdered with polonium-210 in 2006. As little as 50 nanograms of polonium can be a deadly dose. Most of polonium-210 has been produced by lead-bismuth fast reactors, which were used in Russian nuclear submarines. Bismuth-209 becomes polonium-210 in neutron radiation.

Polonium-210 can also cause large radioactive doses among smoking people. The US EPA informs about the radioactivity from polonium-210 as follows: *Phosphate fertilizers, favored by the tobacco industry, contain radium and its decay products (including lead-210 and polonium-210).* When phosphate fertilizer is spread on tobacco fields year after year, the concentration of lead-210 and polonium-210 in the soil rises.

15.3.5 Cesium-137

Cesium-137 is a fission product of nuclear reactors and nuclear bombs. Cesium-137 is highly radioactive and one gram of cesium has 3200 GBq of radioactivity. Cesium-137 has a half life of 30 years and will decay with beta radiation into **barium-137**.

The radioactivity of cesium-137 and barium-137 is mainly gamma radiation, thus the radioactivity in the clouds can cause radioactive victims on the ground or inside buildings.

There are still some traces of cesium left from the nuclear tests done 50 or 60 years ago. The nuclear tests done at the Bikini Atolls 50 years ago made the area uninhabitable to this day. Even though Cesium has decayed from the ground and water, it can still be found to contaminate the cocoa nuts, which people used to eat. Cesium acts like potassium (Ka), which is needed by the cocoa trees.

Now, 25 years after Chernobyl, cesium-137 activity can still be found in the land and water, therefore it can contaminate food. The release caused a greater than 37 kBq/km² (1 Curie/km²) deposition of cesium-137 in a land area of 191 000 km².

Finland had 11 500 km² of this kind of contaminated land. Today, the average dose caused by the Chernobyl accident and nuclear tests is 0.02 mSv annually for the Finns and 0.007 mSv for the whole world. These figures cause a 0.5% addition to the annual dose for the Finns and a 0.25% addition for average population of the world.

However, one can still find some groups of people that have very high amounts of cesium in their body. These risk groups are the people who eat fish from contaminated small lakes. Another risk group is the people who eat mushrooms from the contaminated areas. However, the biological half life of cesium-137 in the human body is only 70 days. Thus it is possible to become clean after some months after stopping eating of the contaminated food.

The EU has given a 600 Bq/kg maximum limit of cesium-137 for mushrooms and for fish. In 2005 about 50% of the samples of mushrooms exceeded this limit and were between 50 and 5400 Bq/kg in Finland. About 20% of fish samples taken from the lakes exceeded the EU-limit and the measurements being between 3 and 2000 Bq/kg. Thus, there is still a recommendation to eat fish only once a week from those lakes. However, there still are fishermen who eat fish almost every day. That is why they may be getting much higher doses than the average people.

15.3.6 Cesium-134

Cesium-134 is formed in a nuclear reactor in a neutron flux as a fission product of **cesium-133**. Thus it cannot be found from the releases of nuclear bombs. Cesium-133 is a stable isotope and it is used in atomic clocks.

Cesium-134 is a radioactive material, which has a half life of 2.0 years. Thus in the beginning of the release it has the same activity level as cesium-137. After some years, it will disappear from nature, while cesium-137 remains there much longer.

15.3.7 Iodine-131

Radioactive **iodine-131** should be separated from normal **iodine-127**, which is added to salt to satisfy the need of iodine by the thyroid. Iodine-131 is one of the fission products of uranium in a reactor or in nuclear bomb explosions.

If iodine-131 has contaminated air or water it will accumulate in the thyroid in the same way as normal iodine-127. Because iodine-131 is radioactive, it will cause a concentrated radioactive exposure in the thyroid and it may be one of the reasons for thyroid cancer.

Iodine-131 has a half life of eight days, and thus for the first days after nuclear releases it is very important to protect the people. The best protection for radioactive iodine-131 can be obtained by eating iodine-127 pills 1-6 hours before the radioactive clouds arrive. One pill is needed for adults and above 12 year old children, 1/2 pill for 3-12 years, 1/4 for 1 month-3 years and 1/8 pill for children less than 1 month old.

The authorities determine when iodine pills should be taken. However, iodine pills should be bought and stored by the house owners before anything has happened. They would not be available after accident has happened. Very soon after the Fukushima accident in 2011 people went to buy iodine pills and they were sold out within one day in Finland. However, Fukushima had no radioactive fallout in Finland.

If cows are outside during the exposure of radioactive clouds, iodine-131 can be found in the milk and meat of the cows. Thus also cows should be kept inside for several days after radioactive fallout. Because of its 8 hour half life, iodine-131 will have practically disappeared after one year from the exposure.

15.3.8 Strontium-90

Strontium-90 is one of the metals that are formed during nuclear fission. It was found for the first time in the ground after the first nuclear tests in the atmosphere. Because strontium-90 has a half live of 28 years, it can still be found from the ground near the test sites. Also the Chernobyl accident released strontium-90 and distributed it all over Europe.

The biological effects of strontium-90 are difficult, because it will act like calcium in the human body. **Dr Louis Reiss** found in 1963 high strontium-90 levels in children's teeth in the US. This helped the US to stop atmospheric tests.

15.4 Other pollutants

15.4.1 Particle emissions

The three most difficult impurities in outdoor air include particulates (PM10), nitrogen oxide and sulfur oxide. PM10-particles that have less than 10 μ m diameter have been measured long time. Their average concentrations vary from 20 to 60 μ g/m³ in North America and 40 to 150 μ g/m³ in Africa (Table 15.4.1).

Table 15.4.1 Concentration of PM10, nitrogen oxide and sulfur dioxide in $\mu g/m^3(WHO)$

Region	PM10	Nitrogen	Sulfur
		dioxide	dioxide
Canada/USA	20-60	35-70	9-35
Europe	20-70	18-57	8-36
Austrailia/New Zealand	28-127	11-28	3-17
Latin America	20-129	30-82	40-70
Asia	35-220	20-75	6-65
Africa	40-150	35-65	10-100

Particle emissions are caused mainly by traffic, where particle emissions come from diesel engine cars and street dust. In rural areas the main causes are firewood heating and cooking. The basic concentration comes from the power plants, which spread particles for long distances from the high stacks.

In Europe the average concentration of PM10 has been 21.7 $\mu g/m^3$, 26.3 $\mu g/m^3$ in urban background and 32.0 $\mu g/m^3$ in the streets. The largest concentration of particulates can be found in large cities (Figure 15.4.1). Most of the cities with a more than 100 $\mu g/m^3$ PM10 concentration are in Asia and Latin America. In Europe there are several cities in which the concentration exceeds 50 $\mu g/m^3$. The concentrations in cities in the US and Canada are lower because of less diesel cars.

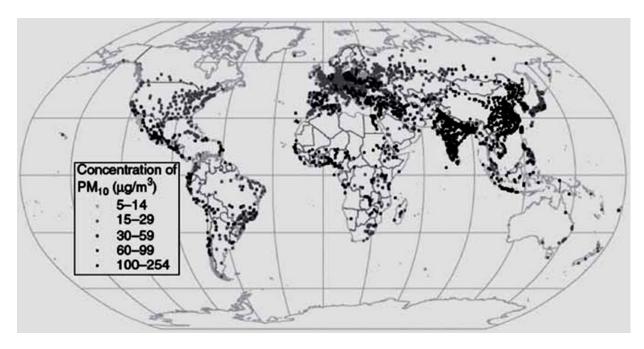


Figure 15.4.1 PM10 concentration in world cities (Air guidelines 2005 update, WHO)

WHO estimates that at least 40 million people in the 115 largest cities in Europe are exposed to higher values of air pollutants than the values recommended by the WHO guidelines (Table 15.4.2). In Europe the rural background concentration of PM2.5 has been 11 to 13 $\mu g/m^3$ and urban levels 15 to 20 $\mu g/m^3$. The average PM2.5 concentration in the United States has been 12.5 $\mu g/m^3$.

The PM emissions have been going down by emissions standards. The most important factor has been the emission standards for new cars. Euro-5 standards limit emissions of new diesel engine cars to less than 5 mg/km after beginning of the year 2011. This is 80% less than emissions in Euro 4 standard for diesel cars. Thus the new diesel engine cars should have particulate filters.

Table 15.4.2 Some cities with more than 50 μ g/m³ PM10 concentration

Region	>150 μg/m3	100-150 μg/m3	50-100 μg/m ³		
Asia	Karachi	Kathmandu	Ho Chi Minh	Busan	
	New Delhi	Dakha	Mumbai	Seul	
		Calcutta	Colombo	Manila	
		Sanghai			
		Beijing			
Latin America		Lima	Meddelin	San Salvador	
		Arequipa	Fortalza	Guatemala City	
			Santiago	Havana	
			Bogota	Mexico City	
			Cochabamba	Rio de Janeiro	
Africa	Cairo				
Europe			Praque	Milano	
			Turin	Rome	
			Bucharest	Cracow	
			Barcelona		
USA			San Diego		

Particulate emissions of large power plants (>50 MWt) in the EU area were 200 000 tons annually in 2006. In a list of ten of the most polluting power plants two are in Greece, two in Estonia, two in Bulgaria, two in Poland and one in Slovakia and one in Romania. All of them emit more than 3000 tons of dust annually. One diesel engine car (Euro-5) emits about 100 g of particles annually. Thus one power plant can emit as much as particles as 30 million diesel engine cars annually. The ten largest power plants emit 49 000 tons of dust annually. This is the equivalent of 490 million diesel engine cars.

The average dust emissions of power plants in the EU were 12.8 g/GJ in 2006. However, higher than 50 g/GJ emissions can be found in Bulgaria, Estonia, Greece, Romania and Slovakia. The new IPPC standard will set the maximum dust emission limit to 20 mg/Nm³ for large solid, liquid and biomass plants, excluding gas turbines.

Thus very effective dust filters will be required in all large solid fuel plants. In practice many of the old plants will be decommissioned due to the costs of installing the filters.

The particulate concentration in the air could increase the risk of lung cancer. Lung cancer causes 1.2 million additional deaths annually in the world. Outdoor air contamination causes 62 000 lung cancers annually. Particularly the PM2.5 concentration has been found to be the main risk factor in outside air. Each $10 \,\mu\text{g/m}^3$ addition of PM2.5 concentration increases the lung cancer risk by 8 to 14% according to WHO studies.

Another risk caused by the PM10 concentration is cardiovascular disease. A $50 \mu g/m^3$ increase of the PM10 concentration could increase the risk for cardiovascular disease by 3 to 8% according to WHO. Additionally the PM10 concentration is a risk factor for asthma and chronic obstructive pulmonary disease (COPD). However, smoking remains the highest risk factor for COPD.

15.4.2 Nitrogen oxides

Nitrogen oxides are formed in high temperature combustion. The biggest nitrogen oxide emitters are diesel engine cars and buses in cities, which can cause large concentrations in inner city areas. The largest cities in Asia, Latin America and the US have the highest concentrations (Table 15.4.3). The highest nitrogen oxide concentration could be more than 80 μ g/m³ (Sao Paulo).

Most of the NO_x emissions in the cities come from cars and buses. The Euro-5 emission standard limits the NO_x emissions for diesel cars to 180 g/km and for gasoline cars to 60 g/km. Thus if there are one million cars in a city and each of them drives 10 000 km annually, they causes 0.6 to 1.8 million tons of NOx emissions.

A part of the emissions come from power plants and ships, but those emissions spread to a larger area. The NO_x emission limit for large (>300 MWt) coal, biomass and other solid fuel plants is 200 mg/Nm^3 and 150 mg/Nm^3 for liquid fuel plants. Gas fired plants have a 50 mg/Nm^3 limit for gas turbines and combined cycle plants and a 100 mg/Nm^3 limit for gas engines.

The NO_x emissions for power generation in the EU were 2 million tons in 2006. The NO_x emissions of the ten largest polluters were 227 000 tons. Among the ten most polluting plants six were in the United Kingdom, two in Poland and two in Spain. The most polluting plant, the Drax in the UK, had 58 000 tons of NO_x emissions.

The average NO_x emissions of all power plants in the EU were 123 g/GJ. The average NO_x emissions were higher than 200 g/GJ in Bulgaria, Malta, Portugal, Romania and Slovenia.

Table 15.4.3 The average annual concentration of nitrogen dioxide in some cities (WHO)

Region	>60 μg/m3	40-60 μg/m3	30-40 μg/m3	20-30 μg/m ³
Asia	Beijing	Taipei	Osaka	Singapore
	Lahore	Pusan	Ho Chi Minh	Dakha
	Gangzhou	Hongong	New Delhi	Mumbai
	Sanghai		Bangkok	Hanoi
	Seoul			
	Jakarta			
	Calcutta			
	Tokyo			
Latin America	Sao Paulo			
	Mexico City			
	Pogota			
Africa	Cairo	Johannesburg	Capetown	
Europe		Paris	Oslo	Warsaw
		Athens	Brussels	Prague
		Barcelona	Vienna	Berlin
		Rome	Zurich	Helsinki
		Munich	London	Copenhagen
USA /Canada	Los Angeles	Boston	Houston	
	Chicago		Montreal	
	New York		Vancouver	

15.4.3 Sulfur oxides

Sulfur oxides derive from the sulfur in coal and heavy fuel oil. Coal and heavy fuel oil are used in power plants and heavy fuel oil also in ship engines and heating boilers.

Sulfur oxide emissions come mainly from coal fired power plants, which do not have sulfur purification systems. In the 70's the coal fired plants in the UK and Poland caused high concentration levels of sulfur and acid rains in Scandinavian countries. The acid rain spoiled many lakes in Scandinavia.

Today, the sulfur oxide concentration is very high in China, which generates most of its electricity by using coal fired power plants (Table 15.4.4). There are also several cities in Africa and South America which have a higher than $60 \, \mu \text{g/m}^3$ concentration.

Today most coal plants have sulfur purification systems in exhaust gas treatment. Thus the lakes are returning back to normal again. The IPPC standards in Europe limit the exhaust gas concentration of sulfur oxide in large boilers (>300 MWt) to 200 mg/Nm³.

The problem is still acute in many developing countries, such as India, Pakistan and China, in which electricity production is based on coal and heavy fuel oil power plants. Many of those

plants do not have exhaust gas treatment systems. However, there are also areas in the US and the South Europe where the concentration is still quite high.

Table 15.4.4 The sulfur oxide concentration in some major cities (WHO)

Region	>60 μg/m3	40-60 μg/m3	20-40 μg/m3	10-20 μg/m ³
Asia	Beijing	Ganzhou	Hanoi	Colombo
	l	Lahore	Islamabad	Busan
	l	Karachi	Mumbai	Seoul
	l	Shanhai	Ho Chi Minh	Hong Kong
	l			Bangkok
	l			Singapore
	l			New Delhi
	L			
Latin America	Mexico City	Sao Paulo		
	Bogota			
Africa	Harare	Cairo		Johannesburg
	Kitwe			Garbone
	<u> </u>			Durban
Europe	l		Sofia	Brussel
	l		Athens	Berlin
	L			Kiel
USA /Canada			Pittsburg	Vancouver
	l		New York	Los Angeles
	l		Philadelphia	Seatle
	l		Washington DC	Montreal

15.4.4 Heavy metals and other difficult substances

The heavy metals are very difficult impurities in nature. Radioactive materials such as cesium decay in time, but heavy metals remain in nature practically forever. The most difficult materials are mercury and lead.

Mercury spreads trough the exhaust gases of coal and oil fired power plants and crematories. Some batteries can contain mercury or cadmium even today and when they are burned in waste incinerator plants the emissions can harmful. Additionally the new energy saving lamps can contain mercury.

After being burned mercury spreads in the air and comes down on the ground and lakes with the rain. It will then bioaccumalate in fish, which people then eat. In the human body mercury could cause damage to the nervous system.

Lead was used as an additive in gasoline for a long time to help the lubrication of valves of the engines. It was found to be dangerous and today's gasoline is unleaded. However, it still exists in nature and there are other sources, such as metals and the battery industry, which cause lead emissions.

In the smoke of fossil fired plants there are also many other metals. Radioactive substance such as cesium and strontium, which once contaminated the ground, can be found from peat and wood, which are used in power plants. Thus the radioactive emissions of these plants can be even larger than the emissions of nuclear plants in normal operation.

Perhaps the biggest risk today comes from heavy metal impurities and some chemical waste, which can cause infertility in men. It was discovered twenty years ago that white-tailed eagles were disappearing from the Finnish coastal areas. The eagles were eating sea fish, which was contaminated with mercury, PCB and DDT. Only 17 nestlings were found in 1980.

Today men's fertility has also diminished to a half, because of contaminated food. It is possible that this might be one reason for the population in the most polluted countries will start to diminish like the eagles in Finland. However, today in Finland the eagles have more than 200 nestlings annually because the impurities in fish have decreased.

The biggest environmental risk in industrialized countries today comes from smoking. The US Environmental Protection Agency (EPA) has estimated that 20% of all preventable deaths are caused by smoking. The EPA has estimated the number of lung cancer deaths caused by smoking to be 123 000 annually in the US.

Very harmful substances in tobacco are the radioactive materials polonium-210 and lead-210. Polonium-210 has a half life of 138 days, but it is highly radioactive. Lead-210 has a half life of 22.3 years and it will remain in the body even if one has stopped smoking at a young age. The polonium-210 and lead-210 in tobacco has its origin from the phosphate that is used in the tobacco fields. Phosphates contain uranium and its other decay products.

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16 NUCLEAR POWER ACCIDENTS AND THEIR CONSEQUENCES

16.1 Nuclear accidents

There have been eleven accidents in nuclear facilities, which have caused releases of radioactivity (Table 16.1.1).

Table 16.1.1 Doses of radioactivity caused by major accidents (man Sieverts)

Year	Site	USSR/Russia	Japan	UK	Mexico	Brasil	USA	Spain
1957	Windscale			2 000				
1957	Mayak	1 200						
1964	SNAP (U6)							
1966	Palomares							6
1979	Tree Mile Island						40	
1983	Ciudad Juares				150			
1986	Chernobyl	320 000						
1987	Goiania					60		
1993	Tomsk	0,02						
1999	Tokai Mura		0,6					
2011	Fukushima		30 000					
	Total	321 200	30 001	2 000	150	60	40	6

The **Windscale** accident was the first one to be noted around the world. The reactor was moderated by graphite and cooled by air. The graphite was in a solid block, where the uranium had been inserted into horizontal holes. The reactor was designed to produce plutonium for nuclear bombs. There was a fire that caused the release of 740 TBq of iodine-131 and 22 TBq of cesium-137. The releases caused milk to become contaminated in the nearby farms and milk could not be used for several months. It has been estimated that the accident caused 240 additional cancer deaths.

The **Mayak** accident happened in September 1957 in the Kyshtum reprocessing plant. It was not known by public during the time of the accident because of the iron curtain and the whole nuclear site was in a closed city. The accident was caused by chemical reactions which started to form ammonium nitrate, which exploded and caused the release of the reprocessing materials from the facility. The accident caused the contamination of the neighborhood areas, but the inhabitants were evacuated only after a month later.

Both the Windscale and the Majak accidents were connected to nuclear weapons production programs. The three well documented accidents connected with power generation are the Three Mile Island in 1979, Chernobyl in 1986 and Fukushima in 2011. They will be discussed in more detail in the next three chapters.

16.2 Three Mile Island

The Three Mile Island accident in the US was caused by operator and instrumentation errors in TMI-2 pressurized water reactor on March 28th, 1979. The accident started with a trip of one of the condensing pumps in the non-active secondary circuit. This caused the automatic starting of the emergency feedwater pumps, which were aimed to keep the water level in the steam generators. However, the valves of the emergency feedwater pipes were closed. The indicator lights showed that the valves were closed, but the operators did not notice this.

The water flow to the steam generators stopped and the temperature and pressure in the primary started to rise and after a while the pilot operated relief valve (PORV) opened and started to release primary circuit water into the relief tank. The reactor tripped from the high pressure signal and the control rods were dropped. Then the PORV valves should have automatically closed, but they were stuck open. However, the indicator lights in the control room showed that the PORV were closed. Thus the primary circuit was leaking water and caused Loss of Coolant Accident (LOCA).

The steam generators were boiled out within two minutes and all the decay heat was heating the primary water, which was leaking through the PORV. The PORV was closed only 2.5 hours after the start of the accident. The water level in the reactor pressure vessel started to sink and after three hours radioactive releases were noticed and "the state of emergency" was declared. The fuel of the core had partially melted down and caused releases of the radioactive fission products.

The accident was noted all over the world. At the time we were designing the Loviisa-3 PWR plant and I had the preliminary safety analysis report of Babcock & Wilcocks (B&W) reactor in our office room at Imatran Voima. Thus I invited Jukka Laaksonen from the Finnish Safety authority (STUK) to study the accident to our office and it was very difficult to understand what had happened. However, this was the first time when a PWR reactor started to boil-off and fuel had melted.

B&W stopped its large nuclear reactor program. Their design had used less water in the steam generators, which means a faster response time of the operators is needed. The Loviisa-1 and -2 VVER reactors, on the other hand, had a very large water volume, which gave the operator more time for actions. Another feature, which was found good in the Loviisa-1 and -2 power plants, was the extensive amount of instrumentation measurements, which helped the operators to understand what is happening in the plant.

Many utilities started to do a probabilistic safety analysis (PSA) in their plants. STUK started to consider how to prevent radiation releases after a core meltdown accident. In 1984 STUK made its first draft criteria to prevent releases after core meltdown accidents. After this core catchers were studied by the utilities.

16.3 The Chernobyl Accident

The Soviet nuclear program was using RBMK reactors for power production. The RBMK reactors were moderated by graphite and cooled by light water. The reactors have continuous fuel loading and they have been used for plutonium-239 production.

Additionally, the reactors have a positive void coefficient and thus they could not be licensed in Finland. If the water in the pressure tubes starts to boil, the reactivity starts to increase. In normal water moderated and water cooled reactors (VVER, PWR or BWR) the boiling of water will have a negative effect on reactivity, because boiling will decrease the moderation of neutrons.

The largest RBMK power plants were the Leningrad 4 x 925 MW plant near Saint Petersburg, the Kursk 4 x 925 MW plant near Kursk and the Chernobyl 4 x 925 MW plant near Kiev in the Ukraine. The operators had found one big problem of electrical power supply after a turbine trip in the RBMK plants.

The Russian made diesel generators could supply electricity only 40-50 seconds after a trip for some unknown reason. Thus the inertia of the turbine-generators should be used to generate power for the reactor circulating water pumps until the diesel generators were available. In western plants the emergency diesel generators can supply power within 10-15 seconds.

In 1986 the voltage control system in the Chernobyl-3 generator was changed so that it could be able to supply electricity after a generator trip. The preparations for the test were started at 01:06 on Friday, 25th of April with a gradual reduction of the power level to 50% during the dayshift. But the grid control center did not allow the operators to reduce the power further and complete the test because the demand for electricity had started to grow during the Friday evening and one large unit had tripped. Thus the test could be done only after the day shift operators had left and the night shift operators were in charge. The reduced power started xenon poisoning, which decreased the reactivity of the reactor core.

The test was started on **Saturday night on 26th of April** at 01:23:04 AM, when the operator closed the turbine steam valves. The generator was still rotating for some time and supplying power to the Main Circulating Pumps (MCP). The MCP speed was decreasing and the water flow into the reactor was decreasing, which increased the steam bubbles in the reactor core. The water level in the steam drums started to decrease. The emergency water pumps could not start to pump water into the reactor because the diesel generators required 40-50 seconds to generate power.

Because of the positive void coefficient the reactor output started to increase. At 01:23:40 a reactor trip was actuated because of the increased reactor output. However, the reactor control rods were withdrawn too far because of the xenon poisoning and the rods had graphite displacers

at their ends. Thus the trip started to reduce the reactivity only after a delay and the power level increased in the beginning because of the graphite displacers and boiling in the reactor.

Thus the reactor became promptly critical at 01:23:43 and caused a steam explosion after the reactor output reached 33 GW, which was the last reading recorded in the control room. A second explosion was caused by hydrogen, which happened after 2-3 seconds after the first one. This destroyed the whole reactor and the reactor building and graphite started to burn spreading radioactivity all over Europe.

The release was first noticed at the **Forsmark** nuclear power station in Sweden about 1100 km distance from Chernobyl on the following Monday morning on April 28th. The operators were tested after coming from the night shift and found to be radioactive. They thought that the Forsmark plants had a radioactive release and informed of this to other countries, including Finland. During the next day the radiation clouds spread over Finland. The radiation was analyzed by the Swedish and Finnish authorities and they concluded that it was coming from a nuclear plant in the Soviet Union.

The Soviet Union remained silent and only told about the accident on Monday evening on April 28th at 19:00, when the authorities in the west already knew that the accident had happened there. On Wednesday evening the Finnish Nuclear Society (ATS) arranged a meeting on the accident and we tried to figure out what had happened and how the Finnish population should be protected.

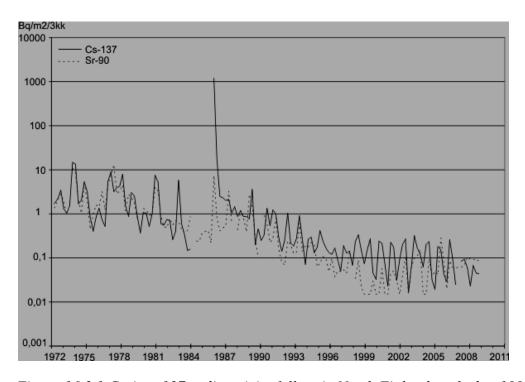


Figure 16.3.1 Cesium-137 radioactivity fallout in North Finland peaked at 1000 Bq/m2 (STUK)

The cesium-137 radioactivity concentration in the air of Helsinki had increased from 1 to $100~000~\mu Bq/m^3$ (microbecquerel per cubic meter). It had been more than $100~\mu Bq/m^3$ only during the nuclear tests some years earlier. However, the average concentration of radon in normal Finnish houses is about $120~Bq/m^3$, which is still about thousand times higher than in the outside air in 1986.

The radioactive clouds had a peak gamma radiation dose rate of 5 μ Sv/h (microsievert per hour). This was about 50 times the normal background radiation dose rate of 0.04 - 0.30 μ Sv/h, but much less than the level of 100 μ Sv/h in which people should go inside of the buildings. Sheltering actions were not required. After some time the radiation levels in some food substances were found to have too much activity and some of them (mainly fish and mushrooms) were restricted to be used only once in a week. This recommendation is still valid in some parts of the country, which has had the largest fallouts.

The Chernobyl accident contaminated large areas in Europe with more than 37 kBq/m² (Table 16.3.1). Also large parts of Sweden and Finland were contaminated and many preventive measures to decrease the radiation were executed.

Table 16.3.1 The largest contaminated areas after Chernobyl accident

Contaminated areas after Chernobyl accident									
in square kilometers (>1 Ci/km2 or >37 kBq/m2)									
1	Russia	57 900	6	Austria	8 600				
2	Belarus	46 500	7	Norway	5 200				
3	Ukraine	41 900	8	Bulgaria	4 800				
4	Sweden	12 000	9	Switzerland	1 300				
5	Finland	11 500	10	Greece	1 200				

The Chernobyl accident was caused by many defective design features of the RBMK reactors, which happened at the same time. The primary reason for the extra test was the slow start-up time of the emergency diesel generators. The positive void coefficient of the reactor and the wrong design of the control rods of the RBMK reactor caused the instability of the reactor during the transients.

Additionally the graphite moderator fire caused the fallout of fission products spreading through Europe. This kind of reactors should not be built and all of the existing reactors should be decommissioned as soon as possible. The Leningrad power plant is about 60 km from St Petersburg and 120 km from the Finnish city of Kotka. If one of the reactors explodes, it is possible that the whole city of St Petersburg with five million inhabitants could be in danger.

The possibility of a nuclear accident at the Leningrad RBMK plant was evaluated by the Finnish State Research institute (VTT). The report made by **Dr. Seppo Vuori** from the VTT estimated the possible fallout of the Leningrad plants very well some five years before the Chernobyl accident.

After the accident in Chernobyl some people from the Leningrad nuclear plant visited the VTT laboratories in Finland. They said to **Prof. Björn Wahlström**, at the time the director of the VTT electrotechnical laboratory, that the authorities had asked the operators of the Leningrad plant to make the blackout tests, but they had refused and claimed that this test would mean a risk to the reactor.

Actually, a similar explosion at the Leningrad plant could have caused protective actions in Finland. However, at the time the Soviet authorities did not inform people about accidents. Unfortunately, at the same time the state servants were in strike on Finland and the radioactive readings were not collected by the authorities.

However, high readings (90 μ R/h, microröntgen per hour=0.9 μ Sv/h) were measured already on Sunday evening (27th of April) by the Finnish army people, who were monitoring radioactive levels in the North Finland. They informed about the increased level to the army headquarter on Monday morning. The radiation was about six times the background radiation level (0.1-0.2 μ Sv/h) and did not cause any immediate actions.

Today in Finland there are more than two hundred public automatic on-line radioactivity measurement instruments, where people can read the measured values on the display or through the internet (www.stuk.fi). The alarm limit is set to 0.4 μ Sv/h (microsievers per hour) and at a 100 μ Sv/h (0.1 mSv/h millisieverts per hour) dose rate level people should go indoors.

16.4 The Fukushima accident

The first nuclear accident in the internet age started on **Friday 11th of March** 2011 in Japan, when an earthquake of 9.0 magnitude occurred on the bottom of the sea near Honsu main island at 14.46 (JET). The IAEA safety center sent a warning of the earthquake and noted that a tsunami alert had been sent to 50 countries. The sequence of events has been documented in the Japanese Government report to the IAEA in June 2011.

The Fukushima Dai-ichi nuclear plant on the coast had three reactors (units 1, 2 and 3) on-line generating power and three other reactors (units 4, 5 and 6) in shut down conditions for maintenance. The earth quake caused excess acceleration, which was detected by the reactor protection system and it stopped the three operating reactors at 14:46. Connection to the outside power grid was lost because the power lines were broken.

The emergency diesel generators (EDG) in the power plant were started at 14:52 and they were able to supply emergency cooling water for the residual heat removal (RHR) pumps. 14-15 meter tsunami waves hit the coast at 15:27 (41 minutes after the earthquake). All the EDG's stopped at 15:37-15:41, 51-55 minutes after the earthquake, except at unit 6, which was cooled by air.

The cooling of the reactors 1, 2 and 3 was stopped, when all the reactors were still generating about 1.5 % of heat, which was about 22 MW in unit 1 and 33 MW in units 2 and 3. The temperature in all the reactors started to increase rapidly and the excess heat converted the primary circuit water into steam. The steam was dumped into the primary containment by the relief valves. The water level in the reactor pressure vessel started to sink and very soon the fuel started to melt down and accumulated on the bottom of the reactor pressure vessel (RPV).

Table 16.4.1 The sequence of events at the Fukushima Dai-ichi plant during the first eighteen days

Date	Reactor 1	Reactor 2	Reactor 3	Reactor 4	Radiation
					at border
Friday	Electricity generation	Electricity generation	Electricity generation	Unit in maintenance	mSv/h
11 March	Reactor trip	Reactor trip	Reactor trip	No fuel in reactor	0.0001
	Reactor cooling stopped	Reactor cooling stopped	Reactor cooling stopped	Fuel pool cooling stopped	
Saturday	Hydrogen explosion				1.0
12 March	Radioactive leaking				
Sunday					0.02
13 March					
Monday			Hydrogen explosion		12
14 March					
Tuesday		Hydrogen explosion		Hydrogen explosion	11.9
15 March				Fire in reactor building	
Wednesday				New fire	3.4
16 March				Spend fuel pool dry	
Thursday			Helicopters drop water		0.18
17 March			into reactor building		
Friday			Cooled with fire trucks		
18 March					
Sarturday		Grid power available	Cooled with fire trucks	Cooled with fire trucks	
19 March		Cooled with sea water			
Sunday	Grid power available	20 tons of sea water	Cable installed	Cable installed	
20 March	Cooled with sea water	pumped into fuel pool			
Monday	Cooled with sea water	Cooled with sea water	Cooled with sea water		
21 March					
Tuesday		18 tons of sea water		Concrete pump truck	
22 March		pumped into fuel pool		starts pumping water	
Friday	RPV cooled with	RPV cooled with	RPV cooled with		
25 March	fresh water from trucks	fresh water from trucks	fresh water from trucks		
Tuesday	Cooled by fresh water	0.2			
29 March	with electric pumps	with electric pumps	with electric pumps	with concrete pumps	

On **Saturday 12th of March** venting of the wet well was carried out at 14:30 in reactor No. 1. At 15:36 a hydrogen explosion destroyed the roof of the reactor building in unit No. 1. Hydrogen formation started, when the reactor fuel bundles were not fully covered with water and the

zirconium cladding of the fuel started to react with water and generate hydrogen at 1200 °C. The hydrogen was ignited by some unknown external heat source. Radioactivity started to spread into the neighborhood of the plant site. At 18:25 **the Prime Minister Naoto Kan** asked for the evacuation of all people living within 20 km from the reactor site

On **Monday 14th of March** at 05:20 the venting of the primary containment vessel in unit 3 was started. At 11:01 a second explosion happened in reactor building No. 3.

On **Tuesday 15th of March** between 6:00 and 7:00 a third explosion happened in the reactor building No. 2 and the specialists figured out that the containment was broken and radiation levels started to rise sharply.

"We are on the brink. We are now facing the worst-case scenario," said **Hiroaki Koide**, a senior reactor engineering specialist at the Research Reactor Institute of the Kyoto University. "We can assume that the containment vessel at Reactor No. 2 is already breached. If there is heavy melting inside the reactor, large amounts of radiation will most definitely be released."

On **Tuesday 15th of March** the roof of the reactor building in reactor No. 4 was on fire, which could have been stopped, but the building had the pool of spent fuel. The water level in the pool was falling and the spent fuel started to emit gamma radiation above the area. The radiation level near the building was 400 mSv/h, which was 4000 times higher than the level in which people should go inside their homes. The utility company **Tepco** informed that 750 of the plant's 800 workers had been evacuated. Only 50 of the workers were still at the site. At 11:00 Prime Minister urged all people within a 20-30 km distance to keep inside and wait for further instructions. There were about 140 000 people living within the 30 km zone. Also a 30 km no-fly zone was set around the nuclear site.

On **Wednesday 16th of March** the radiation level at the site was peaking at 10 mSv/h, which is 10 times the level (1 mSv/h) at which people should go into shelters.

On **Thursday 17th of March** the most critical reactor was No. 3, which was cooled by dropping water from the helicopters. Also the spent fuel pool in reactor No. 4 was without water, but helicopters could not drop water there because of strong gamma radiation above the fuel pool. The number of workers at site was raised to 320.

On **Friday 18th of March** an electric cable was installed at the site, but it could not be connected to powering the cooling pumps, because they should first be examined. The third reactor was now cooled by spraying water by fire trucks. Three workers were transported to a hospital due to an excessive radiation dose.

On **Saturday 19th of March** a cable was installed to supply power to reactors No. 1 and 2, but the reactors were still cooled with sea water. Reactors No. 3 and 4 were cooled by using fire trucks. The two diesel generators in reactor No. 6 were ready for operation, which could then

power the cooling pumps of units 5 and 6. The activity in the sea water had risen to 1250 times above the normal values. 30 000 people were reported to be dead or missing because of the tsunami. The costs of the tsunami were estimated to reach €200 billion.

On **Sunday 20th of March** a cable was installed to supply power to reactors No. 3, 4, 5 and 6. The temperature in reactors No. 5 and 6 was stabilized at 30 $^{\circ}$ C. The pressure was rising in containment of reactor No. 3. The radiation level at the Fukushima site was in average 3000 μ Sv/h and in the Tokio area 0.05 μ Sv/h. All the Finnish visitors in Japan were given iodine pills by the Finnish embassy, but they were not asked take them.

On **Monday 21st of March** reactors No. 1-3 were cooled by injecting sea water. The residual heat was removed by releasing the boiled steam into the containment. The containments were said to be tight, but steam had to be released to the atmosphere through relief valves to keep the pressure in the containment below the design pressure. Steam had been seen to be discharged from unit No. 2 and smoke had seen in unit No. 3. Reactor No. 4 had no fuel in the pressure vessel.

On **Tuesday 22nd of March** sea water was pumped into the reactor pressures vessel in units 1-3. The temperature in reactor No. 1 pressure vessel water had been risen to 400 °C.

On **Wednesday 23rd of March** radiation level at the gate of Fukushima plant was measured to be 230 µSv/h. Smoke was coming from the reactor No. 3. Workers were evacuated from the unit. Small amount of radioactive iodine-131 had been measured in Finland.



Figure 16.4.1 Fukushima Dai-ichi nuclear reactors 1-4 were damaged by accident and taken out of service. The reactor buildings of units 1, 3 and 4 were without roofs

On **Wednesday 30th of March** it was announced that the containment vessels of unit 2 and 3 had lost their pressure and were damaged. Tepco informed that four of its six reactors would be decommissioned. The share price of Tepco had dropped by 75% and the state of Japan was considering taking over the company.

Many countries reported that they would delay their nuclear programs. Germany stopped seven reactors for inspections. The Finnish STUK asked the utilities about their readiness for external occurrences. Also China was considering postponing some of its new reactors. The opinion poll made after Fukushima showed that about 48% of Finns still wanted to build more nuclear plants and 48% were against of the new plants.

16.5 Fatalities caused by nuclear accidents

The radiation doses for people are mainly caused by iodine-131, cesium-134 and cesium-137 releases. Iodine-131 releases are most dangerous during the first days after an accident, because the half life or iodine-131 is 8.04 days. The isotopes cesium-134 and -137 will have the biggest influence in the long term, because their half lives 2.1 and 30.0 years respectively.

Ionized radiation will cause cancer. Iodine-131 will cause thyroid cancer, which can be prevented by eating iodine pills before the radioactive iodine-131 releases contaminate the ambient air. Cesium-137 isotopes will contaminate milk, beef, pork, fish and mushrooms. The maximum level of annual dose for individuals was set to 5 mSv and the intake of the cesium-137 to 200 000 Bq in Finland. This could be achieved if the maximum values of radiation are 1000 Bq/kg in pork and beef and 1000 Bq/l in milk.

Radiation can cause cancer. The risk estimate by the authorities is that population dose of 100 person-Sieverts (0.1 millisievert to each of one million people) could cause one cancer in population. If 20% of cancers can lead to death, then twenty person-Sieverts could cause one cancer death. These estimates assume that also low level radiation can cause cancer deaths, but this has not been proved in practice.

Total population dose caused by the three accidents, the Three Mile Island, the Cernobyl and the Fukushima (Table 16.5.1), has been about 370 000 person-Sieverts. Fatalities caused by them have been estimated to be about 19 500, if they are calculated using the conservative values.

Most of the fatalities will be caused by later cancer deaths and only 30 by acute deaths. About 19 000 of the cancer deaths will happen far from the Chernobyl site. However, they could not be detected from the background cancer deaths of the 605 million people living in the affected areas.

The cumulative electricity generation by nuclear energy has been about 70 000 TWh and the three reactor accidents have caused or will cause about 19 500 deaths. Thus the accidental fatality rate of nuclear electricity has been about 0.28 /TWh.

Table 16.5.1 The radioactive doses and fatalities of nuclear accidents

Accident		Three Mile	Chernobyl	Fukushima	Total
		Island	1)		
		USA	Ukraine	Japan	
Year of occurence		1979	1986	2011	
Releases				2)	
- Iodine-131	TBq	1	1 776 000	160 000	1 936 001
- Cesium -134/137	TBq		140 600	15 000	155 600
Liquidators	number		530 000	100 000	630 000
- average dose	mSv		117	30	103
- total dose	manSv		62 010	3 000	65 010
- cancer deaths	number		3 000	300	3 300
- acute deaths	number	-	28	2	30
Evacuees	number		116 000	140 000	256 000
- average dose	mSv		31	10	20
- total dose	manSv		3 596	1 400	4 996
- cancer deaths	number		180	140	320
Residents	number	2 000 000	270 000	200 000	2 470 000
- average dose	mSv	0,01	60	3,00	7
- total dose	manSv	20	16 200	600	16 820
- cancer deaths	number	2	800	60	862
East Europe	number		105 000 000		105 000 000
- average dose	mSv		1,3		1
- total dose	manSv		136 500		136 500
- cancer deaths	number		9 000		9 000
Other Europe	number		500 000 000		500 000 000
- average dose	mSv		0,3		0
- total dose	manSv		150 000		150 000
- cancer deaths	number		6 000		6 000
Total people affecte	d number	2 000 000	605 916 000	440 000	608 356 000
- average dose	mSv	0	0,6	11	1
- total dose	manSv	20	368 306	5 000	373 326
- cancer deaths	number	2	18 980	500	19 482
- acute deaths	number	-	28	2	30

¹⁾ Vendla Paile /STUK 2011

However, these fatalities are dominated by the Chernobyl accident and the Chernobyl plant did not fulfill western safety standards. If Chernobyl is omitted, then the fatality rate would be dominated by the Fukushima accident (about 500 fatalities). Thus the accidental fatality rate of the western type reactors has been about 0.007 /TWh, or about 0.06 per one 1000 MW reactoryear.

²⁾ Japanese Governement report to IAEA. June 2011

This accidental fatality rate can be used to estimate the future fatality rate. According the forecasts nuclear electricity generation during the next 90 years will increase from 2550 TWh in 2011 to 12 600 TWh by 2100 (Chapter 6). The cumulative generation of 960 000 TWh until 2100 would give 6 700 fatalities from nuclear accidents by using the present safety level of reactors excluding the Russian RBMK reactors.

16.6 Fatalities in coal production

The accidental fatalities in coal mining are 6000-10 000 per year or about 0.56 per million tons of coal mined (Table 16.6.2) or about 0.08 per TWh (thermal) of primary energy. The total power generation by coal plants was 6363 TWh in 2009. If the average efficiency has been 35%, the coal consumption was 18 180 TWh. The fatal accident rate 0.08 /TWh (thermal) of coal would mean that coal electricity generation would cause 1540 accidental fatalities annually in world. The fatality rate of coal fired electricity would be then 0.24 /TWh of electricity generated.

Table 16.6.2 The accidental fatalities in coal mining in the three largest producer countries

Country	Population	Coal	Coal	Mining	Fatalities	Fatalities
		mining	per capita	fatalities	per capita	per coal t
	millions	Mt	t/capita	number	1/million	1/Mt
China	1 336	3 050	2,3	2 631	1,97	0,86
United States of America	306	1 154	3,8	30	0,10	0,03
India	1 169	558	0,5	100	0,09	0,18
Total	2 811	4 762	1,7	2 761	0,98	0,58

The fatality rate of coal power generation (0.24 /TWh) can be compared with the nuclear fatalities caused by the three nuclear accidents during the last forty years. If only the western reactors are counted, the coal power accidents would then cause 0.24/0.007 or 34 times more fatalities than nuclear power accidents.

16.7 Accidental fatalities in normal life

Perhaps the most common risks to people in the industrialized countries are caused by the traffic. The reported fatalities in the world were 661 000 in 2008 / 16.1 / . The fatality rate depends on the number of vehicles per capita. In industrialized countries, where the vehicle rate is more than 500 per 1000 inhabitants, the fatality rate is 80 - 200 fatalities per million vehicles (Figure 16.7.1).

In developing countries the fatality rate is 300–3000 per million vehicles. It is interesting to note that Finland and the US have more vehicles than others (882 and 822 /1000 people), but their fatality rate varies from 82 fatalities in Finland to 169 fatalities per million vehicles in the US.

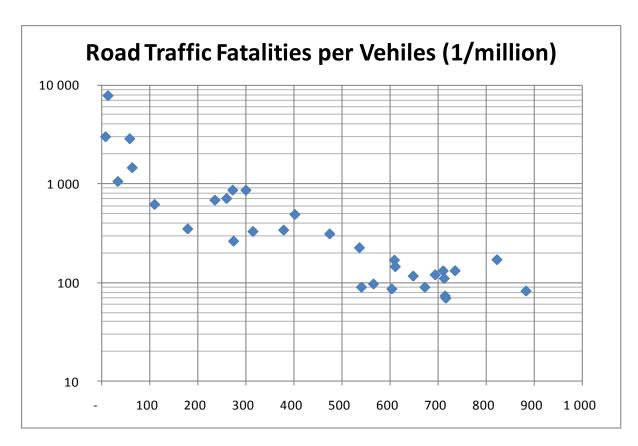


Figure 16.7.1 The road traffic fatalities per million vehicles, depending on the number of vehicles per 1000 inhabitants (Source WHO /16.1/)

If the fatality rate in the road traffic in the world was at the same level as it is in Switzerland (69 per million vehicles), then the 1200 million vehicles would mean in average 82 000 fatalities. Now the total fatality rate is 661 000 or seven times higher. There really are many things to do for traffic safety.

The road transportation sector is using about 1922 Mtoe or 22 350 TWh energy. Thus the average traffic accident fatality rate is 30 fatalities /TWh of primary energy in the world and about 5 fatalities /TWh in the industrialized countries. Because the efficiency of vehicles is about 20%, the average fatality rate per final energy of vehicles is five times larger, or 150 fatalities/TWh of final energy. This can be compared with the accidental fatality rate of electricity production, which was evaluated to be 0.007/TWh in western type nuclear reactors and 0.24/TWh in coal power.

Major aircraft accidents have caused about 19 000 casualties since 1980 (Figure 16.7.2). The number of casualties has been about the same as in nuclear accidents during the same years. The trend in casualties has been increasing and is now about 700 each year because air traffic is increasing.

Table 16.7.1 Registered traffic fatalities and vehicles in some countries listed by vehicles per capita

Country	Population	GDP	Registered	Vehicles	Traffic	Fatalities	Fatalities
		per capita	vehicles	per capita	fatalities	per capita	per vehicles
	millions	USD	millions	1/1000	number	1/million	1/million
Bangladesh	158,7	470	1,1	7	3 160	20	2 998
Uganda	30,9	340	0,4	12	2 838	92	7 818
Pakistan	163,9	870	5,3	32	5 565	34	1 053
Egypt	75,5	1 580	4,3	57	12 295	163	2 859
India	1 169,0	950	72,7	62	105 725	90	1 454
China	1 336,3	2 360	145,2	109	89 455	67	616
Turkey	74,9	8 020	13,3	178	4 633	62	348
Mexico	106,5	8 340	25,0	234	17 003	160	681
Brazil	191,8	5 910	49,6	259	35 155	183	708
Russian Federation	142,5	15 440	38,7	272	33 308	234	861
Indonesia	231,6	1 650	63,3	273	16 548	71	261
Saudi Arabia	24,7	7 560	7,4	299	6 358	257	859
Argentina	39,5	6 050	12,4	314	4 063	103	328
Republic of Korea	48,2	19 690	18,2	378	6 166	128	339
Thailand	63,9	3 400	25,6	401	12 492	196	488
Poland	38,1	9 840	18,0	474	5 583	147	310
Czech Republic	10,2	14 450	5,5	536	1 222	120	224
Netherlands	16,42	45 820	8,86	540	791	48	89
United Kingdom	60,8	42 740	34,3	565	3 298	54	96
Sweden	9,12	46 060	5,50	603	471	52	86
Belgium	10,5	40 710	6,4	608	1 067	102	168
Canada	32,9	39 420	20,1	610	2 889	88	144
France	61,6	38 500	39,9	648	4 620	75	116
Germany	82,6	38 860	55,5	672	4 949	60	89
Austria	8,4	42 700	5,8	693	691	83	119
Spain	44,3	29 450	31,4	710	4 104	93	131
Australia	20,7	35 960	14,8	712	1 616	78	109
Japan	128,0	37 670	91,4	714	6 639	52	73
Switzerland	7,5	59 880	5,4	716	370	49	69
Italy	58,9	33 540	43,3	735	5 669	96	131
United States of America	305,8	46 040	251,4	822	42 642	139	170
Finland	5,28	44 400	4,66	883	380	72	82
Other countries	1 785,7		75,4	42	219 554	123	2 914
World	6 544,6		1 200,0	183	661 319	101	551

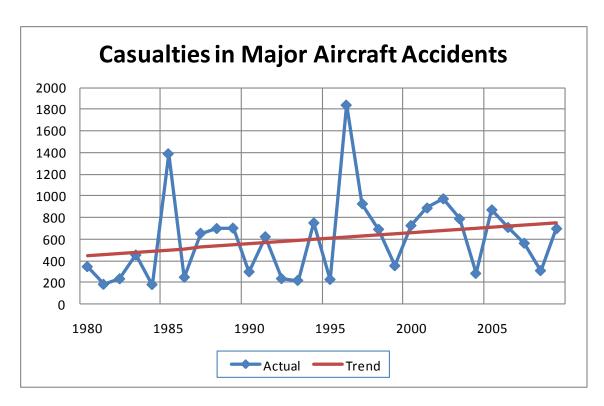


Figure 16.7.2 The casualties of major aircraft accidents since 1980 show an increasing trend

16.8 The economic costs of accidents and insurance

The economic consequences of the Three Mile Island accident for the population have been evaluated to be about \$90 million. This is not much compared with the value of the power plant, which could have been \$500 and \$1000 million at the same time.

The costs for outside people were compensated by the pool of nuclear companies in the US. According to the Price Anderson Act nuclear plant owners cover claims up to \$12.6 billion. Claims above \$12.6 billion will be covered by the Congress. The claims of up to \$375 million are covered by the insurances made by the individual utility, who owns the nuclear plant. The 104 nuclear plants cover \$111.9 million each, which contributes to \$12.22 billion all together.

The operators in Finland and Sweden today have a liability limit of \in 300 million. This will be raised to \in 700 million after the OECD Paris convention protocols done of 2004 come into force. In addition the state contribution is \in 500 million and the collective state contribution is \in 300 million. The total coverage of damage is then \in 1500 million.

In Germany each operator has unlimited liability and they have to deposit a €2.5 billion security for each plant. In Japan the liability is absolute and operators have to deposit a JPY120 billion

(about €1 billion) security by 2010. Ukraine has also signed the Paris protocols, but today the limit of liability of operators has been set to €180 million.

The costs that the Fukushima accident has caused to the public have not been evaluated. The costs can be counted by the number of people evacuated, which has been about 140 000. If the floor space per capita has been 30 m^2 and the average value of homes has been 600 m^2 , the value of houses has been 900 m^2 .

16.9 Learning from the nuclear accidents

16.9.1 Core catcher

There have been several reports after each accident, which can give recommendations. After Three Mile Island, Finnish Safety authority, the STUK in Finland developed new standards. The Safety as High as Reasonable Achievable (SAHRA) principle was adopted according to Dr. Antti Vuorinen, who was the Director General of STUK during 1984-1997. New safety culture was adopted and the new norms required systems to take care of core meltdown. At the same time also intensive Probability Safety Assessments (PSA) were started by the utilities. The PSA helped to decrease the probability of core meltdown frequency considerably.

Civil nuclear power has been in operation for 14 500 reactor-years up to May 2011. During this time four reactor cores have been melted in accidents of western type reactors. The core melt probability has been then once every 3600 reactor years. Three of the reactors have caused radioactive releases, thus the probability of releases is 1:4600 reactor years. Additionally, the Fukushima reactor No. 4 has caused release from the spent fuel pool in the reactor building.

Some of the existing old 385 plants will be in operation until the year 2060. They will generate about 51 000 TWh of electricity and will have about 7000 reactor-years. If the past core damage frequency (CDF = 1:3600) continues, there will be two accidents by 2060 with a 50% probability. This is too much and the target should be less than one. If the target is to have no accidents with 90% probability, then the meltdown frequency should be 1:70 000 reactor-years (1.4×10^{-5}) .

An independent PSA analysis of each of the plants should be made with frequent intervals and, if deficits are found, corrective actions should be initiated. The CDF value of the Olkiluoto-1 and - 2 units is today about 1.2×10^{-5} or 1:80~000 reactor-years. From 1990 the improvement of CDF value in the Olkiluoto units has been with a factor of 20.

The first analysis of CDF of the Loviisa-1 and -2 was evaluated to be about 1×10^{-3} in 1980. Today the CDF of Loviisa units is between 3 and 5 x 10^{-5} , because of continuous improvements. Many improvements have been made during the annual maintenance periods. There is still much to be done to reach the same CDF value (1.2×10^{-5}) than in the Olkiluoto-1 and -2 units.

16.9.2 Aircraft protection

An aircraft crash came into Finnish safety standards after the September 2001 in the US, when two large airliners were crashed into the World Trade buildings in New York and one into the Pentagon main building in Washington DC. After this incident new norms were given where new nuclear plants should withstand aircraft crash. Thus the Olkiluoto-3 plant is the one of first nuclear plants that has been planned to survive a big aircraft crash.

16.9.3 Blackout protection

Third notable incident was the North-East blackout, which lasted for about 24 hours in August 2003 in the US. The blackout left 50 million people without electricity. 80 power plants stopped, including 10 nuclear power plants. Most of the nuclear plants tripped because their connection to the network was lost. Nine of the plants used their emergency diesel generators and one could get power from an outside source. Seven nuclear plants were tripped in Canada and four plants could reduce their loads to level of house load without trip.

After this incident several safety authorities discussed the reliability of electrical power systems /16.2/. In Finland the owner of Olkiluoto plant (TVO) together with the transmission grid operator (Fingrid) have built a 100 MW reserve power plant at the Olkiluoto site. The reserve power would be needed when the new 1600 MW nuclear plant will come into operation and the same nuclear site would need more reliable backup electricity to cope with blackout situations.

My personal worries concerning nuclear safety have been about an electrical blackout in a nuclear plant. The worries were realized in the Fukushima accident, when the three operating reactors and the spent fuel pool of the fourth reactor remained without electricity and cooling for many days. The easiest thing to do to improve safety would be installing at least one reserve diesel generator near the site and connect it to the plant by using cables. Then it could be connected to any of the safety trains that have lost their voltage.

Fast reserve plants would be needed in any electricity systems to cover a trip of the largest unit in the system within 10 minutes. If the largest unit is a 1000 MW nuclear plant, then it will need at least 1000 MW capacity of fast starting diesel engines. To secure the electricity supply for a nuclear plant the reserve plants should be built near the nuclear plants. Each of the nuclear sites could have a 100 MW reserve plant. It does not cost anything, because reserve capacity is needed anyway, but it would need an agreement between the nuclear plant operator and the transmission grid operator.

A 100 MWe diesel engine plant with 10 generators could generate at least 50 MWe with a probability of 0.999997, if each of the engines has a reliability of 95% (see Appendix C2). I would build a 100 MW reserve plant by having two independent 50 MW plants, which would be built in two different buildings. Then each of the plants would generate at least 30 MW with the probability of 0.999 (three nines).

Also the US Task Force of Fukushima /16.3/ recommends that the station blackout (SBO) capability of existing nuclear plants should be improved. The minimum coping time without AC power should be 8 hours. In addition, the task force recommends "an extended coping time of 72 hours" for core and spent fuel cooling. The task force assumes that after 8-hour coping time with permanent equipment AC power can be supplied by using movable equipment up to 72 hours. Within 72 hours (3 days) AC power could then be restored.

There are many ways to restore power within 8 hours. In Scandinavian countries it is possible to use the icebreakers, which are during the summer time in Helsinki harbor. All of them are have electrical generators for propulsion and can be sailed to any part of the Baltic Sea within 24 hours. If the icebreakers will relocated in different places they could be available within eight hours near any nuclear plant in the Baltic Sea. In Japan, there are several LNG ships which have typically 100 MWe electrical generators, which could supply power for the nuclear plants.

16.9.4 Safety culture

"Three Mile Island, Chernobyl and Fukushima have shown the lack of a safety culture" said Jukka Laaksonen, director general of STUK, at a meeting of the Finnish Nuclear Society (ATS) in April 2011. The operators could not keep the plants under control during the accidents. There were also large deficiencies in plant design. The Chernobyl type plant would not have got the license to be built in any western countries.

The Government Report to the IAEA in June 2011 /16.4/ discussed several points that should be improved. The last point (28) was the "Nuclear Safety Culture", which has been given in the IAEA report Fundamental Safety Principles (SF-1. 3.13). The new culture means that "organizations and individuals should be seriously addressing new knowledge on safety in a responsive and prompt manner, not leaving any doubts in terms of safety"

The Fukushima plant was not planned to withstand large tsunamis, which were known to happen. Additionally the operators did not take fast actions to pump seawater into the reactors, because this would damage the reactors anyway. The private company was possibly thinking of their shareholders interests instead of thinking about the safety of the public.

The design of emergency power supply system was not diversified to external effects, where one failure could destroy all the emergency diesel generators at the same time. There were no station blackout diesels that could keep the cooling on when all of the emergency diesels were out of

operation. Additionally the emergency diesel generators were cooled by seawater, which needed outside electricity.

Independent safety authorities should be given absolute power to cool the reactors, if public safety is under danger. Safety authorities should determine the corrective actions, if safety problems are found. In the Fukushima case IAEA staff had made an inspection and proposed some corrections, but they were not done.

16.9.5 Safety rules

Nuclear accidents will happen every now and then. The consequences could be limited by selecting the sites for new plants far from population centers. Today, the exclusion zone of 5 km has been used in Finland. However, a 30 km zone had to be evacuated in case of the Chernobyl and a 20 km zone in Fukushima. It would be possible to find sites for new plants at this distance. Then the consequences in any accident scenario would be minimal.

One of the old nuclear plants near population center is the Indian Point plant in the US. It is located 38 miles north from the New York City and 272 000 people are living within 10 miles from the plant. If something happens there, it is possible that all those people should be evacuated. Within fifty miles from the plant is Manhattan, which could be also in danger, if the winds will blow from the north during radioactive releases. NRC has made new evacuation rules for 10 mile radius for the Indian Point plant after Fukushima accident. Additionally, the seismic capability of Indian Point-2 unit is now under evaluation.

New international safety standards would be needed. They should be developed by IAEA and used in all countries that are generating electricity by using nuclear power. If the old plants do not meet the standards, they should be improved to meet them or taken out of operation. It is much easier to build a new plant according to present standards than to improve old plants to the same level. Additionally, new siting and evacuation rules for new nuclear plants should be introduced.

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17 LIVING UNDER THREAT OF NUCLEARS WEAPONS

17.1 The iron curtain

World War II was not over, when the leaders of the Allied forces had a meeting in February 1945 in Yalta. President **Franklin D. Roosevelt**, Prime Minister **Winston Churchill** and General Secretary **Joseph Stalin** were dividing Europe into Western and Eastern blocks. The war between Finland and the Soviet Union had ended and this time Finland remained in the neutral zone with Sweden. However, many neighboring countries such as Estonia, Latvia, Lithuania, Poland and East-Germany were joined to form the eastern block and to the eastern side of the iron curtain. The Soviet forces occupied the eastern countries and promised them free elections. However, this never happened and in practice the Soviet occupation continued there for 45 years.

The western army forces formed the **North Atlantic Treaty Organization (NATO)** in April 1949. The eastern countries made the Warsaw pact in May 1955. Both parties started to expand their military forces. The Warsaw Pact countries had more capacity in tanks and NATO countries tried to keep the balance by collecting more nuclear weapons and missiles.

In the **Potsdam conference** in July-August of 1945 the Korean peninsula was divided between the Soviet and the US at 38° with the Soviet forces ruling the north sector and the US the southern sector. After the nuclear bombs in Hiroshima and Nagasaki in August 1945 the Japanese war was over, but Japan had occupied the Korean peninsula. The Soviet Red army occupied the northern part of Korea and the USA the southern part. The Soviet and the US forces were withdrawn from Korea in 1948 and 1950 respectively.

The **Korean War** broke out in June 1950 and the armed forces of North Korea marched south. North Korea took control of almost entirely South Korea in September 1950. South Korea, backed with the United Nations (basically using US military forces) started to fight back. The UN forces took control of South Korea, as well as large parts of North Korea by October 1950.

China intervened in the battles to help North Korea and the troops started to march south again. In January 1951 the Chinese troops took control of Seoul. Nuclear weapons were planned by **General MacArthur** to be used for the first time after Nagasaki. The radioactive fallout could interrupt the service chains to the military forces. The battles stabilized near the 38° line and by 1953 about 33 000 Americans, 200 000 Chinese and 300 000 North Korean soldiers were killed in the battles.

The Cold War period had started between the communist block and the western countries. Both block tried to develop a nuclear weapons arsenal, which would be bigger than that of the other side.

17.2 Nuclear tests and crises

Nuclear weapons started to spread from the US to other countries very soon after the explosions in Hiroshima and Nagasaki. The first nuclear test in the Soviet Union was done in 1949, in the UK in 1952, in France in 1960 and in China in 1964. Finally, India did its first test in 1974, Pakistan in 1998 and North Korea in 2009. There are now eight nuclear weapons countries and additionally Israel is known to have nuclear weapons capability.

From 1950 to 1962 a total of 442 atmospheric tests were done (Figure 17.2.1). This was three tests per month. Then atmospheric testing was stopped in the US and the USSR based on an agreement between those countries. However, France and China continued atmospheric testing.

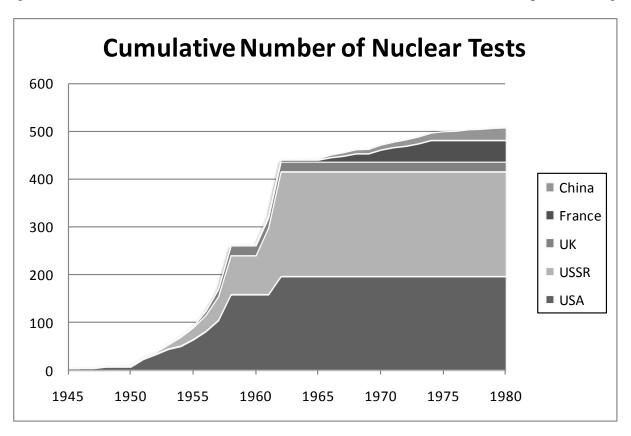


Figure 17.2.1 Cumulative atmospheric nuclear tests

The total yield of the tests was 440 Mt. The Soviet Union did 247 Mt of tests and 240 Mt of those were done at Novaya Zemlya in the northern hemisphere. The test by the US had a 154 Mt yield and 77 Mt of the tests were done at the Bikini test site on the Marshal Islands in the southern hemisphere. The US has also tested in Nevada with a yield of 1 Mt.

The tests in Novaya Zemlya have caused the main radioactive fallout in the northern hemisphere and in Finland (Figure 17.2.2). The radioactive releases in the southern hemisphere were about 80% lower, but they continued for a longer time.

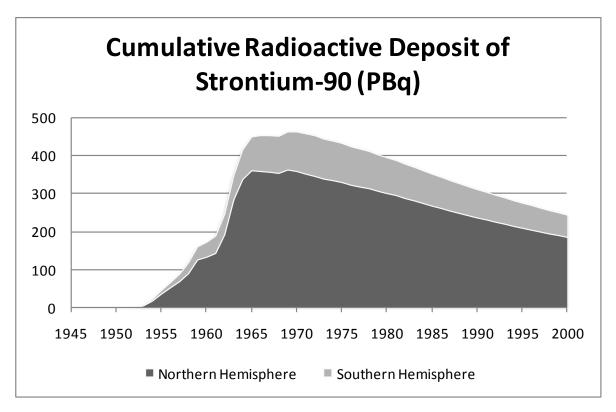


Figure 17.2.2 The cumulative radioactive deposit of strontium-90 from nuclear tests

The released strontium-90 from the tests can still be found in drinking water and food. The average dose of strontium-90 is about $0.5~\mu Sv$ annually by ingestion. This is about 10~% of the total dose from nuclear tests for the average person. However, the total dose from the tests today is about 0.1 to 1.0% of the annual dose of radon and other natural sources.

The average annual doses from the nuclear tests have peaked at 125 μ Sv in the northern hemisphere and at 17 μ Sv at the southern hemisphere in 1963 (Figure 17.2.3). The peak values in the north in 1963 caused about a 10% addition to the natural level of radiation.

The nuclear testing experience of 508 explosions shows that the world will probably survive of a local nuclear war. However, the casualties of any nuclear war would be enormous. The 12 kiloton nuclear bomb dropped on **Hiroshima** killed between 70 000 to 100 000 people. However, today, 65 years later, the city is inhabited and has about 1.1 million people. During the Fukushima accident in 2011 the Finnish embassy was transferred from Tokyo to Hiroshima for safety reasons.

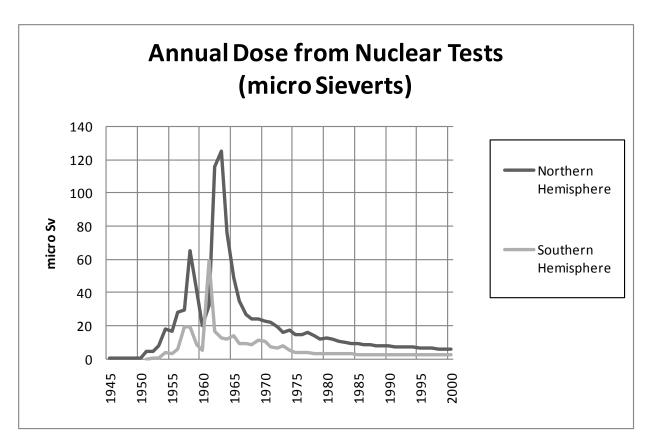


Figure 17.2.3 The annual average dose from nuclear tests peaked in 1962-63

The test site at **Bikini** is still today, 50 years from the last explosions, without inhabitants. However, the radiation levels on the ground are not dangerous any more. Only the eating of some vegetables and fish may cause doses, which might exceed the safety limits. There were 23 nuclear tests made on Bikini during the years from 1948 to 1956. The test's yield was 42.2 million tons from fission and 34.6 million tons from fusion bombs.

The world was different in 1962 and 1963, when the radioactive fallout from nuclear weapons testing peaked. Actually, in 1962 a total of 118 atmospheric nuclear tests were done. The US had installed more than 100 nuclear war head missiles by 1961 in Italy and Turkey, targeted at Moscow.

The Soviets were building a nuclear missile base in Cuba to target US cities. A US Air Force plane (U-2) had detected a missile base in October 14th, 1962. **President Kennedy** asked the Soviets to remove the missiles, but nothing happened. Several options were considered including the occupation of Cuba, but the US feared that the Soviet army would occupy West-Berlin. The option selected was a blockage of Cuba by US military vessels.

On October 19th US planes detected four missile launching sites in Cuba. The US demanded in the UN Security Council meeting on October 25th that the missiles should be removed. On October 26th the US declared a state **DEFCON-2** and US Air force B-47 and B-52 bombers were ready to fly and drop bombs on Cuba. The US had by this date about 5000 strategic nuclear warheads ready to be launched, but the Soviets had only 340 warheads.

After discussions between the US and Soviet leaders an agreement was made. **Nikita Khrushchev** announced on the Moscow Radio on October 27th that the Soviet Union would remove the missiles from Cuba. However, no one said that the US missiles would also be removed from Turkey, which was part of the agreement. It seemed that President Kennedy had won the case.

During the negotiations on the Cuban crisis it took 12 hours to deliver messages from Washington to Moscow by airplane. During those days the world was watching the crises live on television and hoped that the nuclear war would not break out. However, the message from Moscow was heard instantly through the television and radio channels everywhere.

After the Cuban missile crises the **Hot Line** between Washington and Moscow was created. The telephone line goes under water from Washington to London and from London to Stockholm and via Helsinki to Moscow. The line was then used for the first time in 1967, when the war between Israel and Egypt broke out.

17.3 Shelters for nuclear war

During the whole sixties everyone was worried about the possibility of nuclear war. Helsinki was 400 km from the former capital of the Soviet Union, Saint Petersburg. The nuclear war would certainly ruin the city of Saint Petersburg and spread the radioactive fallout to Finnish cities.

All new larger buildings had to build a nuclear shelter, where the inhabitants would go after nuclear war had broken out. This was built typically in a cellar with a 30 to 50 cm thick concrete roof and walls, which should protect from radioactive fallout. The shelters had to have water and supplies enough for living one week in the shelter.

Today, the city of Helsinki has shelters underground in public places. The shelters are used as parking lots during normal times. Several shelters can take 1000 cars for parking, which helps people to come shopping in the city by car.

The shelters might be needed because of radioactive fallout from nuclear power plants. The nearest Chernobyl-type power plant is the Leningrad plant near Saint Petersburg and a Chernobyl type accident could happen there any time. There is no containment that could withhold the releases. However, evacuation of the area is the recommended protection measure after the radioactive clouds have passed through. The last time Helsinki was evacuated was in 1944, when the Soviet army started bombing the city.

In the sixties I was in the Finnish army, which gave all soldiers basic knowledge about nuclear arms and radioactive fallout. They were teaching us how to use raincoats and masks during fallout. We also practiced using dose counters and washing our clothing and skin, if radioactive substances were detected.

The Finnish intelligence knew that there were several missile bases near the Finnish borders at he time and the best policy against them was diplomacy. The aim of the Finnish leaders was to keep Finland out of any conflict between the East and West. In 1963, **President Urho Kekkonen** made his initiative to create a nuclear weapons free zone in the Nordic countries and Baltic areas. It was feared that the Nordic countries could be used as a route for the cruising missiles of both sides.

17.4 Nuclear weapons

17.4.1 The plutonium bomb

One way of nuclear weapons production is through plutonium, which will be produced in a normal fission reactor. In addition reprocessing technology is needed to separate the plutonium-239 from waste fuel.

Plutonium-239 is formed from uranium-238 in a neutron flux in a thermal reactor. But if plutonium-239 stays in the neutron flux for a long time, it could then absorb a neutron and convert to plutonium-240. The plutonium-239 content decreases if the burn-up will increase (Table 17.4.1).

Table 17.4.1 Plutonium-239 isotope content depends on burn-up

Material	Pu-238	Pu-239	Pu-240	Pu-241	Pu-242
Super grade		98 %	2 %		
Weapons grade (1 GWd/t)		93.8 %	5.8 %	0.3 %	
LWR spent fuel (33 GWd/t)	1.3 %	60.3 %	24.3 %	9.1%	5.0 %

Weapons grade plutonium can be made, if the fuel is taken out of the core within 10 to 30 days. After about two months (2 GWd/t) the plutonium-239 content will decrease below 90% and it cannot be used for nuclear weapons any more.

The production rate of plutonium-239 depends on the reactor type. Light water reactors can produce 0.18 kg/MWt, while graphite and heavy water reactors can produce 0.31-0.35 kg/MWt

annually. Thus a 10 MWt reactor can make materials for one bomb in three years time. Additionally, reprocessing of spent fuel is needed to separate the plutonium from other materials.

Plutonium-239 fission will have more free neutrons and thus it needs less fissile material (8-12 kg) than uranium bomb (15-25 kg). But the plutonium bomb is more difficult to design. This is why the plutonium bomb dropped in Nagasaki was tested in Alamogordon, while the uranium bomb dropped in Hiroshima was not tested at all. The plutonium bomb should have less than 6% of plutonium-240, which has a very high spontaneous fission rate (415 000 fissions/s/kg). Thus it cannot be produced from LWR spent fuel.

The Indian nuclear program was started by using a 40 MWt heavy water reactor, which was supplied by Canada and the heavy water by the US. India then built a reprocessing facility, which produced the first 15 kg of plutonium for the first Indian nuclear device, which was exploded in 1974.

North-Korea has also been using this method. They have had from 1980 a gas cooled graphite reactor, which can produce plutonium. At the end of the 80's they had built a reprocessing plant that was separating the plutonium for the bombs. They had a 5 MWt reactor for plutonium production, but the reactor was taken out of operation in 2008. Today, North-Korea has a 100 MWt reactor under construction. By 2008 North-Korea had produced 34 kg of plutonium.

In October 2006 North-Korea tested its first plutonium bomb. The estimated strength of the weapon was between 1 and 15 kt. In April 2009 North-Korea launched an experimental communication satellite, which proves that they have rockets capable to carry warheads. The nuclear program in North-Korea is going on today with uranium bombs.

17.4.2 The uranium bomb

Enrichment by centrifuges was used in building the first uranium bomb by Pakistan. Pakistan and India have not signed the NPT-protocol. Pakistan used the drawings of a centrifuge, which were copied from the URENCO enrichment plant in Almelo in the Netherlands.

The drawings were copied by **Abdul Qadeer Khan**, who was working in the plant. In 1984 Khan was sentenced to four years in prison for espionage by the Amsterdam court. Khan was then celebrated as being the father of the Islamic bomb, which was exploded in 1998 in Pakistan.

The centrifuge drawings have also been used by Libya and Iran, and although it is not clear where those countries have got their centrifuges, but Pakistan has been suspected. Libya abandoned its plans to make enriched uranium in 2003, but Iran has continued its program up to now.

Iran now has new centrifuges with the code name IR-2m that can produce 6.2 kgSWU/year. The enrichment factor of the centrifuges is 1.27 and the rotor length is 1100 mm. They will operate in

cascade and enrich U-235 in first stage from 3.5% to 20%, in the second stage from 20% to 60% and in the third stage from 60% to 90% highly enriched uranium (HEU).

In 2009 North-Korea started building an enrichment plant that would use centrifuges. The North-Korean centrifuges can produce about 40 kg of HEU annually, starting from 2011. One nuclear weapon needs 15-25 kg of HEU.

17.5 Nuclear Non-Proliferation Treaty (NPT)

The three nuclear weapons states (NWS): the US, the United Kingdom and the Soviet Union signed the Nuclear Non-Proliferation Treaty (NPT) in 1968. The other two NWS were China and France, who signed the NPT in 1992. But there are four other nuclear weapon states: India, Pakistan, North Korea and Israel, who have not signed the treaty.

The treaty included three basic subjects: non-proliferation, disarmament and peaceful uses of nuclear technology. Non-proliferation means that the NWS countries would not help the non nuclear weapons states (NNWS) to make nuclear weapons. The disarmament meant the obligation to limit the nuclear arms race and encourage the possible disarmament of nuclear weapons. Peaceful uses of nuclear technology meant that the countries which would sign the NPT would have the right to use nuclear technology for power generation and other peaceful uses.

The treaty was opened for signatures in 1968 and Finland was the first country who signed the treaty in February 1968. Finland was followed by other the Nordic countries. Today, 140 countries have signed the treaty.

The NPT treaty was used for the first time in practice when Finland ordered the Russian VVER-440 reactor in 1970. The agreement made in the beginning of the project was made bilaterally between the exporting countries, which were the Soviet Union and the US. The Soviet Union supplied the reactor and Westinghouse gave the license to build the containment. However, there was no general international model agreement available. This is why the first NPT-agreement was made with the IAEA concerning the Loviisa-1 project. This was no longer bilateral, but the inspectors of IAEA would have authority to follow the balances of nuclear materials at the site.

The NPT-control performed by the IAEA has since been one of the cornerstones of nuclear materials controls in every country. The most famous incident happened in Iraq, which was said by the USA to have weapons of mass destruction. Inspection missions were sent to Iraq to study possible materials that could be used for nuclear weapons in 2003. The mission was headed by **Hans Blix,** who was heading the inspection team in Iraq.

No stockpiles of nuclear weapons were found by the Hans Blix team, but the war against Iraq was started by the **Georg Bush** administration and its allies.

The main problems with the NPT inspection have been its inability to detect centrifuges and other equipment, which could be used to make enriched uranium. The NPT-inspectors have concentrated on finding enriched uranium and plutonium. However, the owning of centrifuges has been until now a shortcut to nuclear weapons, because they enable the making of enriched uranium.

One of the most urgent tasks of the UN is to try to get all the nuclear countries under the NPT agreement. The most important countries are North Korea and Iran. Both of them have uranium enrichment and missile programs. With uranium bombs and missiles both countries can cause a threat to their neighbor countries.

17.6 The peace making process

The NPT inspection is not all that is needed in making peace between countries. There are also other means of peace making, which should be developed. This is one of the reasons why a special peace mission group visited the North-Korean leaders in April 2011. The group included former **President Jimmy Carter** from the USA and **President Martti Ahtisaari** from Finland. Both men are winners of the Nobel Peace Prize.

The policy against North Korea has been denying all help to the country unless it will stop aggressions. This has lead to hunger within the country according to the reports from the above mission. Ahtisaari said that food help should be sent to North Korea by the EU, because one third of the population is starving. Peacemaking can be started with friendly communication with the neighbors.

Finland has been living in peace with its neighborsfor sixty seven years now after the war with the Soviet Union was over. The position has not been easy, because Finland lost large parts of its land and 500 000 people lost they homes. After less than ten years most of the refugees built new houses for themselves with the help of the government. It is strange that so many people have been living in refugee camps for tens of years in the Middle East.

President Ahtisaari has said long ago that the unemployment of young people is one of the biggest threats to peace in the Middle East. **Mohamed Bouazizi** was a 27 year old street vendor, who had university education in Tunisia. He was selling goods in the market place of the city of Sidi Bouzid, which had a 30% unemployment rate and where the police was corrupted. Because of the constant difficulties with local police, Muhammed Bouazizi openly burned himself in the street in December 2010.

This fire sparked protests in Tunisia and Egypt, where their leaders had to step down. The revolution has spread to Libya, Syria and many other Arab countries, where the people want to have freedom. Democracy in the Middle East could be the best way to world peace. When

people are ready to throw away their dictators, they would rather make peace with their neighbors than to put their sons into war.

However, there are still many dictatorships ruling in many parts of the world. Some of them have been ruling for more than 40 years, which is the normal working life of people. In my opinion no ruler should be in place for more than 12 years altogether. Additionally, the leaders should be put into pension at the age of 70 in the same way as ordinary people.

Democracy needs educated people. Thus schools and universities should be free for everyone, who passes their exams. Finland tops in the rankings of affordability of education. The next five countries are Norway, Germany, Denmark, Sweden and the Netherlands. All of them are countries with long democratic experience and a very high life expectancy (Table 15.1).

Today, the US **President Barak Obama** has a vision of nuclear weapons free world. This could be started by making nuclear weapons free Europe. He has won the Nobel Peace Prize and could really earn with his initiative. He has proposed that the amount of strategic nuclear warheads should be reduced below the level of 1700 - 2300, which was allowed by the Moscow Treaty in 2002.

Reference

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18 NUCLEAR ENERGY POLICY

18.1 Energy without CO₂-emissions

Global warming has been seen to be the biggest threat to mankind during the next hundred years. It has been estimated that electricity consumption will increase from 20 000 TWh in 2009 to 47 000 TWh in 2075. The target to decrease CO₂-emissions means that all kinds of carbon free technologies including nuclear power plants, should be invested in.

The nuclear share could increase to 34% (Table 6.3.1) and the renewable share to 42% of electricity generation by 2075. The share of hydro, wind, biomass and solar could then be 13%, 20%, 3% and 6% respectively.

Fossil fired plants should be minimized and all coal plants should be decommissioned by 2075, because they are the main cause of the CO₂-emissions. Oil and gas power plants could be in use to fulfill the peaking and balancing power needs of renewable power plants, as well as in CHP-applications.

About 80% of the world's CO₂-emissions from the energy industry are coming from 20 countries which could have nuclear power (Table 18.1.1). However, some of them such as Turkey, Greece and Indonesia are located in seismic areas, which are not suitable for nuclear plant construction. But there are countries such as Saudi Arabia, Poland and Kazakhstan, which could use nuclear power to reduce their emissions.

Wherever possible, renewable sources should be preferred especially in developing countries. Many countries in southern latitudes can cover 100 % of their electricity by hydro, wind, solar and biomass plants. Thus nuclear power is not needed to reduce the CO₂-emissions of electricity generation to reach the tarrgets, which are less than 690 kgCO₂ per capita by 2050 and less than 140 kgCO₂ per capita by 2100.

The nuclear plants should, on the other hand, be built in countries which have the high engineering skills to be able to build and operate the nuclear plants and handle the nuclear waste. Those countries include the present nuclear countries and some new countries, which will fill the development conditions.

There will be 65 countries in 2050 that have large enough power systems to be able to build nuclear plants (Table 18.1.2). The twenty largest countries generate about 80% of the world's electricity in 2050 and almost all of them have nuclear plants. But there are 18 large electricity producers (>100TWh) that have not built nuclear plants by now. Additionally, 15 medium-size producers (16-100 TWh) could introduce a nuclear plant within the next 40 years.

Table 18.1.1 CO₂-emissions listed by the largest emitters in 2009 in MtCO₂ (Source BP 2010)

1 China	7518	21 Taiwan	320	41 China Hong Kong (78	61 Peru	35
2 US	5942	22 Ukraine	281	42 Philippines	71	62 Ecuador	31
3 India	1539	23 Thailand	274	43 Chile	70		25
4 Russian Federation	1535	24 Netherlands	265	44 Qatar	70	64 Lithuania	15
5 Japan	1222	25 Turkey	264	45 Austria	69	65 Iceland	4
6 Germany	796	26 Kazakhstan	209		63	·	
7 South Korea	663	27 Egypt	198		63		
8 Canada	603	28 United Arab Emirates	192	48 Colombia	58		
9 Iran	540	29 Singapore	180	49 Turkmenistan	58		
10 Saudi Arabia			ŀ		56 57		
	538	30 Belgium & Luxembourg	173 164		54		
11 United Kingdom	529	31 Argentina		51 Hungary			j
12 South Africa	469	32 Pakistan	160	52 Finland	52	1	j
13 Mexico	437	33 Malaysia	148		51	1	
14 Italy	435	34 Venezuela	147	54 Denmark	50	1	
15 Brazil	409	35 Uzbekistan	123		44		
16 France	399	36 Czech Republic	109	56 Bulgaria	44		j
17 Indonesia	388	37 Algeria	105	57 Republic of Ireland	40	1	j
18 Australia	387	38 Greece	100	58 Norway	40	1	j
19 Spain	339	39 Kuwait	87	59 Slovakia	38	1	
20 Poland	320	40 Romania	84	60 New Zealand	36		
Total	25008	Total	3585	Total	1107	Total	110

Table 18.1.2 Forecasted electricity generation in 2050 in TWh. Countries having >30 % nuclear share are highlighted. Non-nuclear countries have squares

1 China	11 951	21 Indonesia	434	41 Romania	111	61 Hungary	47
2 US	6 913	22 Thailand	403	42 Sweden	103	62 Denmark	38
3 India	2 299	23 Egypt	397	43 Finland	102	63 Azerbaijan	36
4 Russian Federation	1 781	24 Argentina	325	44 Greece	101	64 Slovakia	18
5 Japan	1 245	25 Malaysia	315	45 Singapore	94	65 Lithuania	16
6 South Korea	1 200	26 Venezuela	305	46 Austria	92		
7 Brazil	1 083	27 United Arab Emirates	294	47 Peru	92		
8 Germany	925	28 Ukraine	270	48 China Hong Kong SAR	79		
9 Canada	913	29 Pakistan	232	49 Bangladesh	79		
10 Spain	716	30 Poland	224	50 New Zealand	70		
11 France	697	31 Kazakhstan	218	51 Portugal	69		
12 Iran	619	32 Netherlands	202	52 Belarus	66		
13 Saudi Arabia	582	33 Norway	174	53 Uzbekistan	66		
14 Turkey	575	34 Chile	170	54 Qatar	66		
15 South Africa	558	35 Czech Republic	153	55 Bulgaria	62		
16 Mexico	541	36 Kuwait	147	56 Switzerland	58		
17 Taiwan	533	37 Philippines	145	57 Ecuador	58		
18 Italy	488	38 Belgium & Luxembo	116	58 Republic of Ireland	52		
19 Australia	470	39 Algeria	116	59 Iceland	51		
20 United Kingdom	440	40 Colombia	113	60 Turkmenistan	49		
Total	34 530	Total	4 752	Total	1 520	Total	156

If all of the present nuclear countries could make 40% of their electricity with nuclear plants by 2050, the nuclear electricity generation would be 13 800 TWh and take a 33% share of the world's electricity generation. Many countries have already in 2010 reached the 40% share, including France, Slovakia, Belgium, Ukraine and Hungary. Finland will reach the 40% share in 2013. Countries with a higher than 30% share are now Armenia, Sweden, Switzerland, the Czech Republic, Bulgaria and South Korea.

However, the four largest electricity generators in 2050, China, the US, India and Russia, have now only 2%, 18%, 3% and 17% nuclear shares respectively. But all of them have large scale nuclear programs and if the programs will proceed as planned their nuclear share will be increasing in the future.

There is also a moral question: Can industrialized countries be without nuclear energy? If their electricity generation is based on fossil fuels, they will cause most of the damages of global warming to the less developed countries.

Global warming has been seen to cause the biggest problems between the 40° south and 40° north latitudes, where the weather will become dry and the crops will become smaller. In Finland, between 60° and 70° north latitudes, the summers will be longer and there will be more rain and large crops. Should we help the southern countries to keep the climate cooler, even though the warmer temperature would be better for us? Yes, we should.

18.2 New nuclear safety standards

18.2.1 Meltdown probability

Now, after the Fukushima Dai-ichi nuclear accident, governments are evaluating the safety level of existing and new reactors. The calculated probability of a core meltdown accident has been about once in 20 000 years for most of the plants, which were built between 1970 and 80. This was evaluated by the **Rasmussen report** (WASH-1400) in 1974.

The actual meltdown rate has been once every 3600 years. The Fukushima Dai-ichi plant was built according to those standards, but the plant had not been updated according to the recent knowledge of accident scenarios.

According to the nuclear electricity plan in chapter 6.3, the new nuclear plants, which start operation after 2011, would generate 900 000 TWh electricity and will have about 100 000 reactor-years. If the core meltdown probability of the new reactors is 1×10^{-5} , the probability that one core meltdown accident will happen before the year 2100 is 50 %.

18.2.2 Large release probability

The new plants should additionally have a core catcher, which would retain the releases with at least 90% probability. Additionally, containment cooling systems and spent fuel cooling systems are needed. The probability of a large release is then 1×10^{-6} , or once in a million reactor years. Thus the large release probability before 2100 would be less than 10%.

There are two specific problems during core meltdown accidents: A hydrogen explosion and steam explosions. Both explosions should be prevented. A hydrogen explosion could happen, if the hydrogen released forms a dangerous hydrogen-air mixture. This can be avoided if the containment is filled with nitrogen. This is possible in boiling water reactors.

The steam explosion can be avoided if there is no water in the reactor vessel vault. This design has been adopted by the EPR and VVER reactors. Additionally, it is possible to construct the containment vessel to withstand the possible pressure peak caused by the steam explosion.

Table 18.2.1 List of the largest earthquakes since 1896

Asia	n Conti	inent	Asian C	ontine	nt/China	Ameri	ican cor	ntinent	Other areas		eas
1896	8,5	Japan				1902	7,5	Quatemala			
1905	7,5	India				1906	8,8	Equador			
1907	8,1	Central Asia				1906	7,7	Usa			
			1917	7,5	China	1906	8,6	Chile			
1923	7,9	Japan	1920	7,8	China						
1927	7,6	Japan	1927	7,6	China						
1933	8,4	Japan	1931	8,0	China						
1934	8,1	India	1933	7,5	China						
1935	7,6	Pakistan				1939	7,8	Chile	1939	7,8	Turkey
1945	8,0	Pakistan							1943	7,6	Turkey
1946	8,1	Japan									
1949	7,5	Taijkistan									
1950	8,6	India				1960	9,5	Chile			
						1964	9,2	Alaska			
			1970	7,7	China	1970	7,9	Peru			
1976	7,9	Philippines	1976	7,5	China	1976	7,5	Guatemala			
1977	8,0	Indonesia							1978	7,8	Iran
1979	8,1	Indonesia							1980	7,7	Algeria
1984	8,4	Japan				1985	8,0	Mexico			
1990	7,7	Philippines									
1992	7,5	Indonesia									
1995	7,5	Sahalin									
1999	7,6	Taiwan							1999	7,6	Turkey
2001	7,6	India									
2004	9,1	Indonesia									
2005	8,8	Indonesia									
2009	7,5	Indonesia	2008	7,9	China						
2011	9,0	Japan				2010	8,8	Chile			
25	8,0		8	7,7		11	8,3		5	7,7	

18.2.3 Siting rules

There are also some possible sites where the building of nuclear power would be too big a risk. Those include sites where large earthquakes and tsunamis could happen. The dangerous zone of earthquakes starts from Indonesia and goes through the east coast of Japan to the west coast of the US and then down to Chile and Peru.

There have been 49 earthquakes with a higher than 7.5 in magnitude after 1896 (Table 18.2.1). 33 of them have happened within Asia: eight in China, seven in Japan, six in Indonesia and three in India. Eleven have happened on the west coast of the Americas. Three earthquakes have happened in Turkey. No large earthquakes have happened in the eastern part of the Americas and in the North, East or West Europe.

Additionally the sites of the future plants should be selected to be far from the population centers. The present exclusion zone of nuclear site has been 5 km. Thus within this limit there are practically no permanent houses or factories. However, the experience of large releases has shown that people should be evacuated within a 20 km radius. Thus the new sites of nuclear plants should be selected so that within a 20 km radius there is practically no permanent housing.

If the average housing area is 40 m² and houses cost €2500/m², then 10 000 people living within 20 km range from a nuclear plant would have one billion euro's capital in houses. The nuclear operators should have full responsibility to compensate these one billion costs of new houses for those 10 000 people. The population near the nuclear plant should therefore be so small that the nuclear operator is capable of paying the costs of resettlement.

18.3 New nuclear plants

Several PWR and BWR nuclear plants can fulfill the modern safety standards. The problems with plants are economic. The costs of the plants are quite high because plants are each one of a kind. In the year 2010 the construction of 14 new nuclear units was started. Of those plants seven were Chinese type PWRs, two Russian VVER-1000s, two Indian HWRs, one European EPR in China, one American AP1000 in China and one Japanese ABWR.

Only two of the fourteen plants (EPR and AP1000) were aimed for export markets. However, also the VVER, the ABWR, the Kerena by Areva, the APWR by Mitsubishi and the Korean APR-1400 plants are offered for export markets. The year 2010 was the best in 40 years in the amount of new construction starts, which means about 13 000 MWe capacity and €40-50 billion investment.

According to the nuclear electricity plan given in chapter 6, the annual nuclear capacity additions could increase to 60 000 MWe during the years 2025-2040. If the unit size is 1500 MW, it would

mean 30 plants annually. And if the market is divided between about ten vendors, each could have three plants annually. However, typically the three largest companies will take 80% of the market. One of them could be a Chinese company, because they operate in the home markets. The other two vendors could be the Westinghouse AP1000 and the VVER by Atomstroyexport (ASE), which have been the two major export companies on the international markets.

Most of the new plants should be built with an EPC contract. This will require much new skills, which the nuclear vendors should be developing. The first EPR was sold to Finland at a €2000 /kWe at fixed price, but the actual costs will be about €3500/kWe for the vendor.

The biggest reason for the high costs is the long schedule and high manpower needs at the site. The 25 h/kWe manpower at the site will mean €1000/kWe costs (40 €/h). The future price level should be about €2500/kWe and the manpower level should be less than 10 h/kWe.

The site manpower consumption could be decreased to less than 5 h/kWe if the new plants are built in shipyards (see chapter 14). Thus the site labor costs could be about €250/kWe. The saving in costs is based on the fact that one hour at the site will costs about the same as two hours in the shipyard.

Even if the manpower would be 20 h/kWe, in both cases the manpower costs saving in the shipyard would be 15 h/kWe x 30 = €450/kWe. This corresponds to a 10-12% saving in investment costs. Another 10-12% saving will come from shorter schedule.

Large (20-50%) savings could also be achieved with the serial production of nuclear plants. Additionally, if the unit size would be decreased to 300 MWe, the costs for spinning and non-spinning reserves would be considerable in small networks.

18.4 Nuclear power and democracy

Some critics are saying that nuclear power is no good for democracy. In Finland the last decisions to build the three nuclear plants have been made by the Finnish parliament. Additionally, the two sites have been approved by the local city councils. When the decision in principle for the two new plants was granted in the summer of 2010, the site of the final nuclear spent fuel disposal in Olkiluoto was also approved.

The three leading countries in nuclear power generation per capita are Finland, France and Sweden. All of them are democracies. The EU generates about 30% of its electricity by using nuclear power. Most of the EU's nuclear countries have been run by a democratic government for a long time.

The world's largest democracy, India, has also accepted a program for several nuclear power plants. The other giant, China, is still on its way to democracy, but I would guess that it is following the way of Russia and will find its way to democracy.

To make a democratic decision about nuclear power plants the Members of Parliament have many factors to consider:

- 1. How to decrease CO₂-emissions?
- 2. How to provide industries and households with low cost energy?
- 3. How to develop technology and industries?
- 5. How to control the quality of the nuclear plant?
- 6. Are there good sites available?
- 7. Can we finance the project?
- 8. Do we have nuclear engineers?
- 9. Do we have strong utility companies?
- 10. Where to bury the nuclear waste and who will pay the costs?

We have to remember that all energy forms have both plus and minus sides. The benefit of nuclear power is its ability to provide low cost electricity with low CO₂-emissions. On the other hand, nuclear power may cause radiation leakages during accidents. These can be eliminated by good safety standards and siting the plants far from populations centers.

The electricity prices for households were the lowest in Finland (FI) and France (FR) in 2010 (Figure 18.4.1). The both countries have a high nuclear share in their electricity generation. The prices in Sweden (SE) also are lower than average. In the other end is Germany (DE), which has nuclear plants, but has decided to decommission all nuclear plants by 2022 and invest in renewable electricity.

However, nuclear power should be used only after all low cost renewable energy sources have been exhausted. Electricity generation should be started from hydro power. Then there might be possible to build wind power capacity as much as hydro. Hydro power can balance the deficit of wind power. There are now large possibilities for wind power in many countries. It is possible that the costs of wind power are lower than costs of nuclear power.

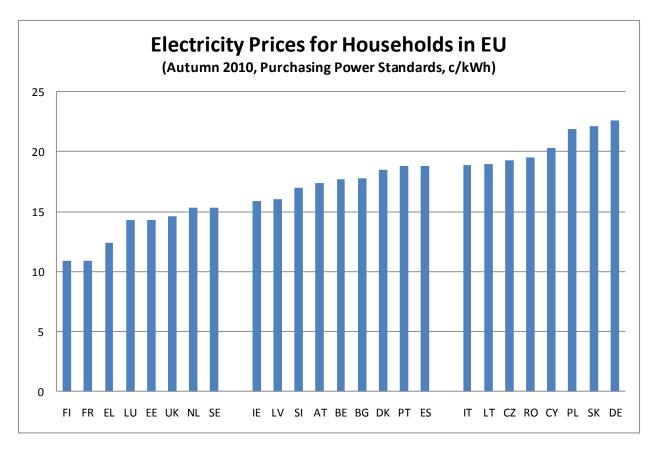


Figure 18.4.1 Electricity prices in EU countries (Source: Eurostat. 46/2010)

EU countries: Belgium (BE), Bulgaria (BG), Czech Republic (CZ), Denmark (DK), Germany (DE), Estonia (EE), Ireland (IE), Greece (EL), Spain (ES), France (FR), Italy (IT), Cyprus (CY), Latvia (LV), Lithuania (LT), Luxembourg (LU), Hungary (HU), Malta (MT), the Netherlands (NL), Austria (AT), Poland (PL), Portugal (PT), Romania (RO), Slovenia (SI), Slovakia (SK), Finland (FI), Sweden (SE) and the United Kingdom (UK).

Also CHP plants might be more economical than nuclear plants, if the heat load is available. The Finnish sources include 30% of renewable electricity, 30% of CHP, 30% of nuclear and 10% of imports and fossil plants. This is quite near the optimum, but the CO₂-emissions of electricity are about 200 gCO₂/kWh. Nuclear or renewable sources are needed to decrease the emissions below 100 gCO₂/kWh.

However, the costs of renewable energy might become so high that consumers will not choose renewable electricity, if other energy sources can be bought at a lower price. Only some 5% to 10% of consumers select green energy in Finland. Renewable electricity can be bought by the grid companies through feed-in tariffs and the costs can then be distributed to all uses through distribution charges.

In democratic countries the opinion of the people will be taken into account. Opinion polls on energy forms have been done since the 1980. The latest poll made in 2010 shows that wind, bio and hydro power are the three most favored sources of energy (Figure 18.4.2).

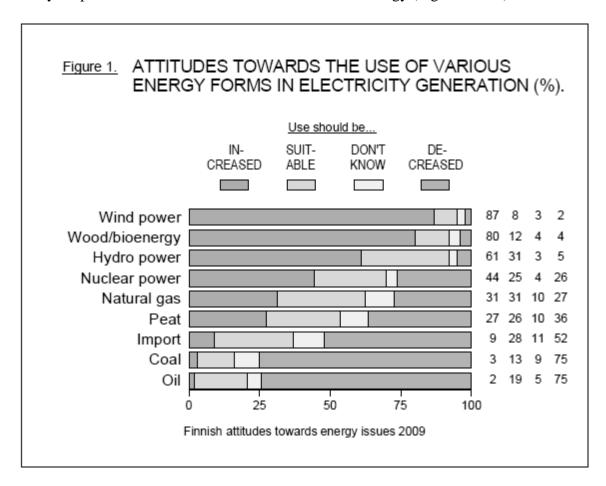


Figure 18.4.2 Attitudes of Finns towards the use of various energy forms in electricity generation (Source: **Pentti Kiljunen** Yhdyskuntatutkimus. 2010)

Today, after Fukushima, the people still favor nuclear power, but consider the renewable energy sources as being the best of all. 44% of people want to have more, and 26% less, nuclear power. Nuclear power is preferred more than natural gas. 31% of people want more, and 27% less natural gas. Electricity imports, coal and oil are the energy forms which should be decreased.

The share of those in favor of nuclear power in Finland has been increasing almost constantly after the Chernobyl accident (Figure 18.4.3). In 2003 more than 50% of the population wanted to have more nuclear power. About 48% of the population favored nuclear power in 2010, when the decision to build two more reactors was made.

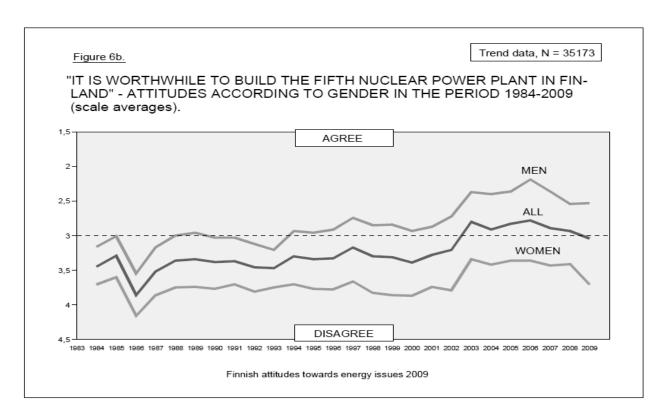


Figure 18.4.3 Favor of nuclear power in Finland (Source: Pentti Kiljunen 2010)

Open information about all energy forms is the key to the success of nuclear power in Finland. All energy forms have both positive and negative sides. They should be openly discussed. Living here in the latitudes between 60° and 70° without electricity would mean dark and cold days for us all.

19 SUMMARY AND CONCLUSIONS

The energy transition is going from fuels to electricity. Today about 34% of primary energy is used to generate electricity in industrialized countries. After 2050 this figure will rise to 40-50% and by 2100 about 50% of energy will be used for electricity generation. Today many houses are already heated and cooled by heat pumps. After 2050 also road transportation will be using electric vehicles.

Nuclear and renewable energy sources can together help to solve the climate change problem, which is probably the biggest threat to mankind during the next hundred years. Both of them can reduce the consumption of fossil fuels. CO₂-emissions can simply be decreased, if use of fossil fuels is decreased.

In Finland, about 50% of electricity will be generated by nuclear and 30% by renewable sources in 2020. If most of the fossil electricity will be generated by gas fired CHP-plants, then the CO₂-emissions of electricity generation will be about 50 gCO₂/kWh. If the electricity consumption will be 19 000 kWh/capita, then the specific emissions of electricity generation will be less than 1 tonCO₂/capita. However, the target of emissions for electricity generation was set to 690 kgCO₂/capita by 2050 and to 140 kgCO₂/capita by 2100.

The whole world can achieve 1 ton CO_2 /capita in electricity generation by 2050 and about 200 kg CO_2 /capita by 2100. This will mean that the nuclear share will be raised from 14% today to 26% in 2050 and the renewable share from 19 % today to 30 % in 2050. The nuclear share could peak at 37 % in 2075.

In the year 2100 electricity generation should be practically CO₂-free. Low cost fossil and uranium resources have been exploited by then and renewable electricity will be the main sources of electricity. There are also new nuclear technologies coming into market after 2050, including fusion and breeder reactors. They have to compete with wind and solar, which will be mature technologies by then.

Wind and solar are the fastest growing technologies today and they will reach about 20-30% market share in electricity generation by 2100. Although, the world will be making the transition to renewable energy, nuclear energy is the other big technology, which has a large potential to reduce greenhouse gas emissions.

According to the plans made in this book the world is going from the **coal age** to **hydrocarbon age** in 2025. The hydrocarbon age could last until 2040, when the world will be moving into the **nuclear age.** The nuclear age could start in 2041 and last until 2100. The nuclear power could be then the number one source of electricity and generate 25 to 35% of world electricity.

APPENDIX A. ELECTRICITY GENERATION SOURCES IN DIFFERENT AREAS

Appendix A1 Electricity generations sources in the world

Sources of Electricity	Sources of electricity generation							
Generation	1990	2000	2009	2025	2050	2075	2100	
in the World	TWh	TWh	TWh	TWh	TWh	TWh	TWh	
Coal	3 880	4 815	6 363	7 339	3 884	-		
Oil and Gas	2 514	3 711	5 191	7 678	8 638	5 548	2 072	
Total Fossil	6 394	8 526	11 554	15 017	12 521	5 548	2 072	
New FBR	-	-	-	-	418	3 103	6 556	
New LWR	-	-	-	2 697	10 698	13 048	6 056	
Old nuclear	2 002	2 582	2 698	1 568	259	0	0	
Total Nuclear	2 002	2 582	2 698	4 265	11 375	16 151	12 613	
Industrial CHP	820	1 079	1 523	2 375	3 733	4 224	4 539	
Municipal CHP	390	399	528	933	1 492	1 677	1 656	
Total CHP	1 210	1 477	2 051	3 308	5 225	5 900	6 194	
Biomass/waste	76	102	164	549	1 189	1 503	1 570	
Hydro	2 162	2 652	3 272	4 237	5 274	6 000	6 475	
Wind/wave	2	37	321	1 845	5 284	9 197	12 134	
Solar	0	3	34	317	1 026	2 955	9 484	
TotalRenewable	2 241	2 794	3 790	6 948	12 773	19 655	29 662	
Total	11 847	15 380	20 094	29 538	41 895	47 254	50 541	

Appendix A2 Market shares of electricity sources

Sources of Electricity			Market sh	nares		
Generation	1990	2000	2009	2050	2075	2100
in the World	(%)	(%)	(%)	(%)	(%)	(%)
Coal	32,8 %	31,3 %	31,7 %	9,3 %	0,0 %	0,0 %
Oil and Gas	21,2 %	24,1 %	25,8 %	20,6 %	11,7 %	4,1 %
Total Fossil	54,0 %	55,4 %	57,5 %	29,9 %	11,7 %	4,1 %
New FBR	0,0 %	0,0 %	0,0 %	1,0 %	6,6 %	13,0 %
New LWR	0,0 %	0,0 %	0,0 %	25,5 %	27,6 %	12,0 %
Old nuclear	16,9 %	16,8 %	13,4 %	0,6 %	0,0 %	0,0 %
Total Nuclear	16,9 %	16,8 %	13,4 %	27,2 %	34,2 %	25,0 %
Industrial CHP	6,9 %	7,0 %	7,6 %	8,9 %	8,9 %	9,0 %
Municipal CHP	3,3 %	2,6 %	2,6 %	3,6 %	3,5 %	3,3 %
Total CHP	10,2 %	9,6 %	10,2 %	12,5 %	12,5 %	12,3 %
Biomass/waste	0,6 %	0,7 %	0,8 %	2,8 %	3,2 %	3,1 %
Hydro	18,3 %	17,2 %	16,3 %	12,6 %	12,7 %	12,8 %
Wind/wave	0,0 %	0,2 %	1,6 %	12,6 %	19,5 %	24,0 %
Solar	0,0 %	0,0 %	0,2 %	2,4 %	6,3 %	18,8 %
TotalRenewable	18,9 %	18,2 %	18,9 %	30,5 %	41,6 %	58,7 %
Total	100,0 %	100,0 %	100,0 %	100,0 %	100,0 %	100,0 %

Appendix A3 Electricity generation sources in North America

Sources of Electricity		Sources	of electricit	y	M	arket share	es	
Generation	2009	2050	2075	2100	2009	2050	2075	2100
in North America	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)
Coal	1 689	114	-	-	33,5 %	1,7 %	0,0 %	0,0 %
Oil and Gas	1 174	1 122	491	66	23,3 %	16,2 %	6,6 %	0,8 %
Total Fossil	2 863	1 236	491	66	56,8 %	17,9 %	6,6 %	0,8 %
New FBR	-	77	77	1 005	0,0 %	1,1 %	1,0 %	12,8 %
New LWR	-	2 382	2 382	632	0,0 %	34,5 %	32,2 %	8,0 %
Old nuclear	922	-	-	-	18,3 %	0,0 %	0,0 %	0,0 %
Total Nuclear	922	2 460	2 460	1 637	18,3 %	35,6 %	33,3 %	20,8 %
Industrial CHP	426	704	751	799	8,5 %	10,2 %	10,2 %	10,2 %
Municipal CHP	17	42	46	50	0,3 %	0,6 %	0,6 %	0,6 %
Total CHP	443	746	798	849	8,8 %	10,8 %	10,8 %	10,8 %
Biomass/waste	33	110	142	142	0,7 %	1,6 %	1,9 %	1,8 %
Hydro	700	816	867	906	13,9 %	11,8 %	11,7 %	11,5 %
Wind/wave	78	1 346	1 873	2 176	1,5 %	19,5 %	25,3 %	27,7 %
Solar	3	199	763	2 089	0,1 %	2,9 %	10,3 %	26,6 %
TotalRenewable	813	2 471	3 645	5 314	16,1 %	35,7 %	49,3 %	67,6 %

Appendix A4 Electricity generation sources in European Union

Sources of Electricity		Sources o	f electricity	у		Market sha	ares	
Generation	2009	2050	2075	2100	2009	2050	2075	2100
in European Union	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)
Coal	653	-	-	-	20,5 %	0,0 %	0,0 %	0,0 %
Oil and Gas	770	504	112	108	24,2 %	13,0 %	2,9 %	3,0 %
Total Fossil	1 423	504	112	108	44,7 %	13,0 %	2,9 %	3,0 %
New FBR	-	-	2	296	0,0 %	0,0 %	0,0 %	8,1 %
New LWR	-	902	884	336	0,0 %	23,3 %	23,3 %	9,2 %
Old nuclear	895	39	0	0	28,1 %	1,0 %	0,0 %	0,0 %
Total Nuclear	895	941	886	631	28,1 %	24,3 %	23,3 %	17,4 %
Industrial CHP	236	365	357	342	7,4 %	9,4 %	9,4 %	9,4 %
Municipal CHP	91	165	162	155	2,9 %	4,3 %	4,3 %	4,3 %
Total CHP	327	530	519	497	10,3 %	13,7 %	13,7 %	13,7 %
Biomass/waste	40	251	276	227	1,2 %	6,5 %	7,3 %	6,3 %
Hydro	327	327	327	327	10,3 %	8,4 %	8,6 %	9,0 %
Wind/wave	146	751	935	1 041	4,6 %	19,4 %	24,6 %	28,6 %
Solar	24	572	739	804	0,8 %	14,7 %	19,5 %	22,1 %
TotalRenewable	537	1 901	2 278	2 400	16,9 %	49,0 %	60,0 %	66,0 %
Total	3 182	3 876	3 795	3 637	100,0 %	100,0 %	100,0 %	100,0 %

Appendix A5 Electricity generation sources in Rest of Europe

Sources of Electricity		Electricity	generatio	n		Market	shares	
Generation	2009	2050	2075	2100	2009	2050	2050	2100
in Rest of Europe	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)
Coal	246	48	-	-	13,0 %	1,5 %	0,0 %	0,0 %
Oil and Gas	360	718	167	56	19,1 %	22,2 %	5,0 %	1,8 %
Total Fossil	606	766	167	56	32,1 %	23,7 %	5,0 %	1,8 %
New FBR	-	25	199	384	0,0 %	0,8 %	6,0 %	12,3 %
New LWR	-	586	707	61	0,0 %	18,1 %	21,3 %	2,0 %
Old nuclear	275	36	0	0	14,5 %	1,1 %	0,0 %	0,0 %
Total Nuclear	275	647	906	445	14,5 %	20,0 %	27,3 %	14,2 %
Industrial CHP	203	299	305	288	10,7 %	9,2 %	9,2 %	9,2 %
Municipal CHP	316	674	691	653	16,7 %	20,8 %	20,9 %	20,9 %
Total CHP	519	973	996	941	27,5 %	30,1 %	30,1 %	30,1 %
Biomass/waste	4	132	217	271	0,2 %	4,1 %	6,5 %	8,7 %
Hydro	477	499	508	515	25,3 %	15,4 %	15,3 %	16,4 %
Wind/wave	7	206	442	604	0,4 %	6,4 %	13,3 %	19,3 %
Solar	0	15	78	298	0,0 %	0,4 %	2,3 %	9,5 %
TotalRenewable	489	851	1 244	1 688	25,9 %	26,3 %	37,5 %	53,9 %
Total	1 888	3 237	3 313	3 131	100,0 %	100,0 %	100,0 %	100,0 %

Appendix A6 Electricity generation sources in Japan

Sources of Electricity		Electricity	Generati	on	M	arket share	es	
Generation	2009	2050	2075	2100	2009	2050	2075	2100
in Japan	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)
Coal	237	-	-	-	21,3 %	0,0 %	0,0 %	0,0 %
Oil and Gas	448	528	147	29	40,2 %	42,4 %	13,5 %	3,2 %
Total Fossil	685	528	147	29	61,5 %	42,4 %	13,5 %	3,2 %
New Breeders	-	-	123	224	0,0 %	0,0 %	11,3 %	25,0 %
New LWR	-	363	428	203	0,0 %	29,1 %	39,3 %	22,6 %
Old nuclear	276	23	- 0	- 0	24,7 %	1,8 %	0,0 %	0,0 %
Total Nuclear	276	386	552	428	24,7 %	31,0 %	50,7 %	47,6 %
Industrial CHP	48	65	57	47	4,3 %	5,2 %	5,2 %	5,2 %
Municipal CHP	1	2	2	1	0,1 %	0,2 %	0,2 %	0,2 %
Total CHP	49	67	59	48	4,4 %	5,4 %	5,4 %	5,4 %
Biomass/waste	23	93	56	23	2,0 %	7,5 %	5,1 %	2,6 %
Hydro	74	74	74	74	6,6 %	5,9 %	6,8 %	8,2 %
Wind/wave	4	48	105	150	0,4 %	3,8 %	9,6 %	16,7 %
Solar	4	49	97	146	0,4 %	3,9 %	8,9 %	16,3 %
TotalRenewable	105	264	331	393	9,4 %	21,2 %	30,4 %	43,8 %
Total	1 115	1 245	1 089	899	100,0 %	100,0 %	100,0 %	100,0 %

Appendix A7 Market shares of electricity generation in Latin America

Sources of Electricity		Electricity	Generatio	n		Market	shares	
Generation	2009	2050	2075	2100	2009	2050	2075	2100
in Latin America	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)
Coal	78	-	-	-	7,2 %	0,0 %	0,0 %	0,0 %
Oil and Gas	218	228	86	65	20,2 %	9,2 %	2,9 %	2,0 %
Total Fossil	296	228	86	65	27,4 %	9,2 %	2,9 %	2,0 %
New Breeders	-	-	-	-	0,0 %	0,0 %	0,0 %	0,0 %
New LWR	-	626	801	694	0,0 %	25,2 %	27,1 %	20,9 %
Old nuclear	31	9	0	0	2,8 %	0,4 %	0,0 %	0,0 %
Total Nuclear	31	635	801	694	2,8 %	25,5 %	27,1 %	20,9 %
Industrial CHP	24	67	90	115	2,2 %	2,7 %	3,1 %	3,5 %
Municipal CHP	-	-	-	-	0,0 %	0,0 %	0,0 %	0,0 %
Total CHP	24	67	90	115	2,2 %	2,7 %	3,1 %	3,5 %
Biomass/waste	28	166	139	111	2,6 %	6,7 %	4,7 %	3,3 %
Hydro	700	1 197	1 293	1 313	64,7 %	48,2 %	43,7 %	39,4 %
Wind/wave	3	177	473	730	0,3 %	7,1 %	16,0 %	21,9 %
Solar	0	15	78	299	0,0 %	0,6 %	2,6 %	9,0 %
TotalRenewable	732	1 554	1 984	2 454	67,6 %	62,6 %	67,0 %	73,7 %
Total	1 082	2 484	2 961	3 329	100,0 %	100,0 %	100,0 %	100,0 %

Appendix A8 Electricity generation sources in the Middle East

Sources of Electricity		Electricity	Generatio	n		Market	shares	
Generation	2009	2050	2075	2100	2009	2050	2050	2100
in Middle East	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)
Coal	176	1	-	-	23,2 %	0,0 %	0,0 %	0,0 %
Oil and Gas	542	1 487	1 467	1 057	71,7 %	53,7 %	35,6 %	19,6 %
Total Fossil	718	1 487	1 467	1 057	94,9 %	53,7 %	35,6 %	19,6 %
New Breeders	-	-	-	-	0,0 %	0,0 %	0,0 %	0,0 %
New LWR	-	804	1 424	1 415	0,0 %	29,0 %	34,6 %	26,2 %
Old nuclear	-	-	-	-	0,0 %	0,0 %	0,0 %	0,0 %
Total Nuclear	-	804	1 424	1 415	0,0 %	29,0 %	34,6 %	26,2 %
Industrial CHP	27	326	622	858	3,5 %	11,8 %	15,1 %	15,9 %
Municipal CHP	-	-	-	-	0,0 %	0,0 %	0,0 %	0,0 %
Total CHP	27	326	622	858	3,5 %	11,8 %	15,1 %	15,9 %
Biomass/waste	-	-	-	-	0,0 %	0,0 %	0,0 %	0,0 %
Hydro	11	21	25	29	1,4 %	0,8 %	0,6 %	0,5 %
Wind/wave	1	104	344	620	0,1 %	3,8 %	8,4 %	11,5 %
Solar	0	28	236	1 425	0,1 %	1,0 %	5,7 %	26,4 %
TotalRenewable	12	153	605	2 074	1,6 %	5,5 %	14,7 %	38,4 %
Total	756	2 770	4 119	5 404	100,0 %	100,0 %	100,0 %	100,0 %

Appendix A9 Electricity generation sources in Africa

Sources of Electricity		Electricity	Generatio	n		Market	shares	
Generation	2009	2050	2075	2100	2009	2050	2075	2100
in Africa	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)
Coal	269	415	-	-	42,6 %	18,7 %	0,0 %	0,0 %
Oil and Gas	246	607	533	276	39,1 %	27,3 %	17,6 %	7,1 %
Total Fossil	515	1 022	533	276	81,6 %	45,9 %	17,6 %	7,1 %
New Breeders	-	-	-	-	0,0 %	0,0 %	0,0 %	0,0 %
New LWR	-	603	1 052	870	0,0 %	27,1 %	34,8 %	22,3 %
Old nuclear	12	1	0	0	1,9 %	0,1 %	0,0 %	0,0 %
Total Nuclear	12	605	1 052	870	1,9 %	27,2 %	34,8 %	22,3 %
Industrial CHP	3	15	20	26	0,5 %	0,7 %	0,7 %	0,7 %
Municipal CHP	-	-	-	-	0,0 %	0,0 %	0,0 %	0,0 %
Total CHP	3	15	20	26	0,5 %	0,7 %	0,7 %	0,7 %
Biomass/waste	1	36	51	48	0,1 %	1,6 %	1,7 %	1,2 %
Hydro	97	384	754	1 088	15,4 %	17,3 %	25,0 %	27,9 %
Wind/wave	2	150	492	884	0,3 %	6,8 %	16,3 %	22,6 %
Solar	0	14	118	713	0,0 %	0,6 %	3,9 %	18,3 %
TotalRenewable	100	584	1 414	2 732	15,9 %	26,2 %	46,8 %	70,0 %
Total	631	2 225	3 019	3 904	100,0 %	100,0 %	100,0 %	100,0 %

Appendix A10 Electricity generation sources in China

Sources of Electricity		Electricity	/ Generation	n		Market	shares	
Generation	2009	2050	2075	2100	2009	2050	2075	2100
in China	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)
Coal	2 380	2 964	-	-	63,9 %	24,8 %	0,0 %	0,0 %
Oil and Gas	85	459	808	7	2,3 %	3,8 %	6,1 %	0,1 %
Total Fossil	2 465	3 423	808	7	66,2 %	28,6 %	6,1 %	0,1 %
New Breeders	-	303	2 277	3 308	0,0 %	2,5 %	17,2 %	24,8 %
New LWR	-	2 585	2 578	-	0,0 %	21,6 %	19,5 %	0,0 %
Old nuclear	70	21	-	-	1,9 %	0,2 %	0,0 %	0,0 %
Total Nuclear	70	2 909	4 856	3 308	1,9 %	24,3 %	36,6 %	24,8 %
Industrial CHP	432	1 497	1 565	1 570	11,6 %	12,5 %	11,8 %	11,8 %
Municipal CHP	80	518	670	680	2,1 %	4,3 %	5,1 %	5,1 %
Total CHP	512	2 015	2 235	2 250	13,7 %	16,9 %	16,9 %	16,9 %
Biomass/waste	11	221	360	448	0,3 %	1,8 %	2,7 %	3,4 %
Hydro	616	1 467	1 593	1 639	16,5 %	12,3 %	12,0 %	12,3 %
Wind/wave	52	1 835	2 906	3 528	1,4 %	15,4 %	21,9 %	26,4 %
Solar	0	80	497	2 164	0,0 %	0,7 %	3,7 %	16,2 %
TotalRenewable	678	3 604	5 357	7 779	18,2 %	30,2 %	40,4 %	58,3 %
Total	3 725	11 951	13 256	13 344	100,0 %	100,0 %	100,0 %	100,0 %

Appendix A11 Electricity generation sources in India

Sources of Electricity	Electr	icity Gene	ration		M	arket share	es	
Generation	2009	2050	2075	2100	2009	2050	2075	2100
in India	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)
Coal	559	442	-	-	64,2 %	19,2 %	0,0 %	0,0 %
Oil and Gas	112	311	327	109	12,9 %	13,5 %	12,3 %	3,8 %
Total Fossil	670	752	327	109	77,1 %	32,7 %	12,3 %	3,8 %
New Breeders	-	13	150	417	0,0 %	0,5 %	5,6 %	14,5 %
New LWR	-	725	997	618	0,0 %	31,5 %	37,5 %	21,5 %
Old nuclear	17	2	- 0	- 0	1,9 %	0,1 %	0,0 %	0,0 %
Total Nuclear	17	739	1 147	1 034	1,9 %	32,1 %	43,1 %	36,0 %
Industrial CHP	48	155	179	194	5,5 %	6,7 %	6,7 %	6,7 %
Municipal CHP	-	-	-	-	0,0 %	0,0 %	0,0 %	0,0 %
Total CHP	48	155	179	194	5,5 %	6,7 %	6,7 %	6,7 %
Biomass/waste	6	70	94	94	0,7 %	3,0 %	3,5 %	3,3 %
Hydro	106	252	306	324	12,2 %	10,9 %	11,5 %	11,3 %
Wind/wave	22	304	462	553	2,5 %	13,2 %	17,4 %	19,2 %
Solar	1	27	146	567	0,1 %	1,2 %	5,5 %	19,7 %
TotalRenewable	135	652	1 007	1 538	15,5 %	28,4 %	37,9 %	53,5 %
Total	870	2 299	2 661	2 875	100,0 %	100,0 %	100,0 %	100,0 %

Appendix A12 Electricity generation sources in Rest of Asia Pacific

Sources of Electricity		Electricity	Generation	on		Market	shares	
Generation	2009	2050	2075	2100	2009	2050	2075	2100
in Rest of Asia Pacific	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)
Coal	87	14	-	-	4,8 %	0,3 %	0,0 %	0,0 %
Oil and Gas	1 235	2 674	1 410	298	68,5 %	54,6 %	25,0 %	4,8 %
Total Fossil	1 322	2 688	1 410	298	73,3 %	54,9 %	25,0 %	4,8 %
New Breeders	-	-	273	923	0,0 %	0,0 %	4,8 %	15,0 %
New LWR	-	1 123	1 794	1 228	0,0 %	22,9 %	31,8 %	19,9 %
Old nuclear	192	14	- 0	- 0	10,7 %	0,3 %	0,0 %	0,0 %
Total Nuclear	192	1 137	2 067	2 151	10,7 %	23,2 %	36,6 %	34,9 %
Industrial CHP	75	240	275	299	4,2 %	4,9 %	4,9 %	4,9 %
Municipal CHP	24	90	106	116	1,3 %	1,8 %	1,9 %	1,9 %
Total CHP	99	330	381	415	5,5 %	6,7 %	6,7 %	6,7 %
Biomass/waste	18	110	168	204	1,0 %	2,2 %	3,0 %	3,3 %
Hydro	164	238	254	262	9,1 %	4,9 %	4,5 %	4,2 %
Wind/wave	6	362	1 164	1 846	0,3 %	7,4 %	20,6 %	30,0 %
Solar	1	30	203	979	0,0 %	0,6 %	3,6 %	15,9 %
TotalRenewable	189	740	1 790	3 291	10,5 %	15,1 %	31,7 %	53,5 %
Total	1 802	4 895	5 648	6 155	100,0 %	100,0 %	100,0 %	100,0 %

APPENDIX B. SHARE OF ELECTRICITY SOURCES

Appendix B1 Share of hydro in electricity generation in the world

	Hy	dro genera	ation		Hydr	8,4 % 8,6 % 9,0 % 15,4 % 15,3 % 16,4 % 5,9 % 6,8 % 8,2 %			
Area	2009	2050	2075	2100	2009	2050	2075	2100	
	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)	
North America	700	816	867	906	13,9 %	11,8 %	11,7 %	11,5 %	
European Union	323	327	327	327	10,2 %	8,4 %	8,6 %	9,0 %	
Rest of Europe	477	499	508	515	25,3 %	15,4 %	15,3 %	16,4 %	
Japan	74	74	74	74	6,7 %	5,9 %	6,8 %	8,2 %	
Latin America	682	1 197	1 293	1 313	63,0 %	48,2 %	43,7 %	39,4 %	
Middle East	12	21	25	29	1,6 %	0,8 %	0,6 %	0,5 %	
Africa	99	384	754	1 088	15,7 %	17,3 %	25,0 %	27,9 %	
China	585	1 467	1 593	1 639	15,7 %	12,3 %	12,0 %	12,3 %	
India	115	252	306	324	13,2 %	10,9 %	11,5 %	11,3 %	
Rest of Asia Pacific	159	238	254	262	8,8 %	4,9 %	4,5 %	4,2 %	
Total	3 232	5 274	6 000	6 475	16,1 %	12,6 %	12,7 %	12,8 %	

Appendix B2 Share of wind and wave in electricity generation

		Wind/Wav	e Genera	tion		Wind and Wave share 2009 2050 2050 2100 (%) (%) (%) (%) 1,1 % 19,5 % 25,3 % 27,7 %			
Area	2009	2050	2075	2100	2009	2050	2050	2100	
	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)	
North America	56	1 346	1 873	2 176	1,1 %	19,5 %	25,3 %	27,7 %	
European Union	127	751	935	1 041	3,8 %	19,4 %	24,6 %	28,6 %	
Rest of Europe	5	206	442	604	0,3 %	6,4 %	13,3 %	19,3 %	
Japan	4	48	105	150	0,3 %	3,8 %	9,6 %	16,7 %	
Latin America	2	177	473	730	0,2 %	7,1 %	16,0 %	21,9 %	
Middle East	0	104	344	620	0,0 %	3,8 %	8,4 %	11,5 %	
Africa	1	150	492	884	0,2 %	6,8 %	16,3 %	22,6 %	
China	24	1 835	2 906	3 528	0,7 %	15,4 %	21,9 %	26,4 %	
India	19	304	462	553	2,3 %	13,2 %	17,4 %	19,2 %	
Rest of Asia Pacific	5	362	1 164	1 846	0,3 %	7,4 %	20,6 %	30,0 %	
Total	244	5 284	9 197	12 134	1,2 %	12,6 %	19,5 %	24,0 %	

Appendix B3 Share of biomass in electricity generation

	Biom	ass electri	city genera	ation		Share of b	oiomass	
Area	2008	2050	2075	2100	2008	2050	2075	2100
	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)
North America	32	110	142	142	0,6 %	1,6 %	1,9 %	1,8 %
European Union	36	251	276	227	1,1 %	6,5 %	7,3 %	6,3 %
Japan	3	132	217	271	0,2 %	4,1 %	6,5 %	8,7 %
Rest of Europe	21	93	56	23	1,7 %	7,5 %	5,1 %	2,6 %
Latin America	25	166	139	111	2,3 %	6,7 %	4,7 %	3,3 %
Middle East	-	-	-	-	0,0 %	0,0 %	0,0 %	0,0 %
Africa	0	36	51	48	0,1 %	1,6 %	1,7 %	1,2 %
China	9	221	360	448	0,2 %	1,8 %	2,7 %	3,4 %
India	5	70	94	94	0,6 %	3,0 %	3,5 %	3,3 %
Rest of Asia Pacific	17	110	168	204	0,9 %	2,2 %	3,0 %	3,3 %
Total	148	1 189	1 503	1 570	0,7 %	2,8 %	3,2 %	3,1 %

Appendix B4 Share of solar in electricity generation

	Sc	lar electric	city genera	tion	Sola	r share of g	generation	
Area	2009	2050	2075	2100	2009	2050	2075	2100
	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)
North America	2,6	199	763	2 089	0,0 %	2,9 %	10,3 %	26,6 %
European Union	24,1	572	739	804	0,7 %	14,7 %	19,5 %	22,1 %
Rest of Europe	0,4	15	78	298	0,0 %	0,4 %	2,3 %	9,5 %
Japan	3,9	49	97	146	0,3 %	3,9 %	8,9 %	16,3 %
Latin America	0,4	15	78	299	0,0 %	0,6 %	2,6 %	9,0 %
Middle East	0,4	28	236	1 425	0,1 %	1,0 %	5,7 %	26,4 %
Africa	0,2	14	118	713	0,0 %	0,6 %	3,9 %	18,3 %
China	0,5	80	497	2 164	0,0 %	0,7 %	3,7 %	16,2 %
India	0,6	27	146	567	0,1 %	1,2 %	5,5 %	19,7 %
Rest of Asia Pacific	0,6	30	203	979	0,0 %	0,6 %	3,6 %	15,9 %
Total	34	1 026	2 955	9 484	0,2 %	2,4 %	6,3 %	18,8 %

Appendix B5 Share of municipal CHP in electricity generation

	Munici	pal CHP el	ectricity ge	eneration	Share	of municip	al CHP ele	ctricity
Area	2009	2050	2075	2100	2009	2050	2075	2100
	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)
North America	17,0	42,3	46	50	0,3 %	0,6 %	0,6 %	0,6 %
European Union	90,9	165,2	162	155	2,9 %	4,3 %	4,3 %	4,3 %
Rest of Europe	316,1	674,4	691	653	16,7 %	20,8 %	20,9 %	20,9 %
Japan	0,9	1,9	2	1	0,1 %	0,2 %	0,2 %	0,2 %
Latin America	-	-	-	-	0,0 %	0,0 %	0,0 %	0,0 %
Middle East	-	-	-	-	0,0 %	0,0 %	0,0 %	0,0 %
Africa	-	-	-	-	0,0 %	0,0 %	0,0 %	0,0 %
China	79,8	518,2	670	680	2,1 %	4,3 %	5,1 %	5,1 %
India	-	-	-	-	0,0 %	0,0 %	0,0 %	0,0 %
Rest of Asia Pacific	23,7	90,2	106	116	1,3 %	1,8 %	1,9 %	1,9 %
Total	528	1 492	1 677	1 656	2,6 %	3,6 %	3,5 %	3,3 %

Appendix B6 Share of industrial CHP in electricity generation

	Industria	I CHP elec	tricity gene	eration	Indust	rial CHP el	ectricity sh	are
Area	2009	2050	2075	2100	2009	2050	2075	2100
	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)
North America	426	704	751	799	8,5 %	10,2 %	10,2 %	10,2 %
European Union	236	365	357	342	7,4 %	9,4 %	9,4 %	9,4 %
Rest of Europe	203	299	305	288	10,7 %	9,2 %	9,2 %	9,2 %
Japan	48	65	57	47	4,3 %	5,2 %	5,2 %	5,2 %
Latin America	24	67	90	115	2,2 %	2,7 %	3,1 %	3,5 %
Middle East	27	326	622	858	3,5 %	11,8 %	15,1 %	15,9 %
Africa	3	15	20	26	0,5 %	0,7 %	0,7 %	0,7 %
China	432	1 497	1 565	1 570	11,6 %	12,5 %	11,8 %	11,8 %
India	48	155	179	194	5,5 %	6,7 %	6,7 %	6,7 %
Rest of Asia Pacific	75	240	275	299	4,2 %	4,9 %	4,9 %	4,9 %
Total	1 523	3 733	4 224	4 539	7,6 %	8,9 %	8,9 %	9,0 %

Appendix B7 Share of nuclear in electricity generation

	Nuclear e	electricity	generation			Nuclear st	nare	
Area	2009	2050	2075	2100	2009	2050	2075	2100
	TWh	TWh	TWh	TWh	%	%	%	%
North America	944	2 460	2 460	1 637	18,0%	35,6%	33,3%	20,8%
EU-27	940	941	886	631	28,0%	24,3%	23,3%	17,4%
Other Europe	283	386	906	445	14,3%	11,9%	27,3%	14,2%
Japan	252	647	552	428	21,3%	51,9%	50,7%	47,6%
Latin America	31	635	801	694	2,9%	25,5%	27,1%	20,9%
Middle East	-	804	1 424	1 415	0,0%	29,0%	34,6%	26,2%
Africa	13	605	1 052	870	2,1%	27,2%	34,8%	22,3%
China	68	2 909	4 856	3 308	2,0%	24,3%	36,6%	24,8%
India	15	739	1 147	1 034	1,8%	32,1%	43,1%	36,0%
Rest of Asia	194	1 137	2 067	2 151	10,8%	23,2%	36,6%	34,9%
Total	2 741	11 261	16 151	12 613	13,5%	26,9%	34,2%	25,0%

Appendix B8 Share of oil and gas in electricity generation

	Oil and	d Gas Elect	ricity Gene	ration	Shar	e of Oil and	d Gas	
Area	2009	2050	2075	2100	2009	2050	2075	2100
	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)
North America	1 174	1 122	491	66	23,3 %	16,2 %	6,6 %	0,8 %
European Union	770	504	112	108	24,2 %	13,0 %	2,9 %	3,0 %
Rest of Europe	360	718	167	56	19,1 %	22,2 %	5,0 %	1,7 %
Japan	448	528	147	29	40,2 %	42,4 %	13,5 %	3,2 %
Latin America	218	228	86	65	20,2 %	9,2 %	2,9 %	2,0 %
Middle East	542	1 487	1 467	1 057	71,7 %	53,7 %	35,6 %	18,4 %
Africa	246	607	533	276	39,1 %	27,3 %	17,6 %	7,1 %
China	85	459	808	7	2,3 %	3,8 %	6,1 %	0,1 %
India	112	311	327	109	12,9 %	13,5 %	12,3 %	3,8 %
Rest of Asia Pacific	1 235	2 674	1 410	298	68,5 %	54,6 %	25,0 %	4,8 %
Total	5 191	8 638	5 548	2 072	25,8 %	20,6 %	11,7 %	4,1 %

Appendix B9 Share of coal in electricity generation

	Electri	icity genera	ation by co	al plants	Sh	are of Coa	I Electricit	у
Area	2009	2050	2075	2100	2009	2050	2075	2100
	TWh	TWh	TWh	TWh	(%)	(%)	(%)	(%)
North America	1 680	-	-	-	33,3 %	0,0 %	0,0 %	0,0 %
European Union	653	-	-	-	20,5 %	0,0 %	0,0 %	0,0 %
Rest of Europe	246	48	-	-	13,0 %	1,5 %	0,0 %	0,0 %
Japan	237	-	-	-	21,3 %	0,0 %	0,0 %	0,0 %
Latin America	78	-	-	-	7,2 %	0,0 %	0,0 %	0,0 %
Middle East	176	1	-	-	23,2 %	0,0 %	0,0 %	0,0 %
Africa	269	415	-	-	42,6 %	18,7 %	0,0 %	0,0 %
China	2 380	2 964	-	-	63,9 %	24,8 %	0,0 %	0,0 %
India	559	442	-	-	64,2 %	19,2 %	0,0 %	0,0 %
Rest of Asia Pacific	87	14	-	-	4,8 %	0,3 %	0,0 %	0,0 %
Total	6 363	3 884	•	-	31,7 %	9,3 %	0,0 %	0,0 %

n	1	2	3	4	5	10	20	50	100
n	0,900000	0,810000	0,729000	0,656100	0,590490	0,348678	0,121577	0,005154	0,000027
n-1		0,990000	0,972000	0,947700	0,918540	0,736099	0,391747	0,033786	0,000322
n-2			0,999000	0,996300	0,991440	0,929809	0,676927	0,111729	0,001945
n-3				0,999900	0,999540	0,987205	0,867047	0,250294	0,007836
n-4					0,999990	0,998365	0,956826	0,431198	0,023711
n-5						0,999853	0,988747	0,616123	0,057577
n-6							0,997614	0,770227	0,117156
n-7							0,999584	0,877855	0,206051
n-8							0,999940	0,942133	0,320874
n-9								0,975462	0,451290
n-10								0,990645	0,583156
n-11								0,996780	0,703033
n-12								0,998995	0,801821
n-13								0,999715	0,876123
n-14									0,927427

Appendix C2 Probability that at least n - m units are in operation (R = 95 %)

n	1	2	3	4	5	10	20	50	100
n	0,950000	0,902500	0,857375	0,814506	0,773781	0,598737	0,358486	0,076945	0,005921
n-1		0,997500	0,992750	0,985981	0,977408	0,913862	0,735840	0,279432	0,037081
n-2			0,999875	0,999519	0,998842	0,988496	0,924516	0,540533	0,118263
n-3				0,999994	0,999970	0,998972	0,984098	0,760408	0,257839
n-4					1,000000	0,999936	0,997426	0,896383	0,435981
n-5						0,999997	0,999671	0,962224	0,615999
n-6							0,999966	0,988214	0,766014
n-7							0,999997	0,996812	0,872040
n-8							1,000000	0,999244	0,936910
n-9								0,999841	0,971812
n-10								0,999970	0,988528
n-11								0,999995	0,995726
n-12									0,998536
n-13									0,999537
n-14									0,999864

Appendix C3 Probability that at least n-m units are in operation (R=97%)

n	1	2	3	4	5	10	20	50	100
n	0,970000	0,940900	0,912673	0,885293	0,858734	0,737424	0,543794	0,218065	0,047553
n-1		0,999100	0,997354	0,994814	0,991528	0,965493	0,880162	0,555280	0,194622
n-2			0,999973	0,999894	0,999742	0,997235	0,978992	0,810798	0,419775
n-3				0,999999	0,999996	0,999853	0,997331	0,937240	0,647249
n-4						0,999995	0,999742	0,983189	0,817855
n-5							0,999980	0,996264	0,919163
n-6							0,999999	0,999296	0,968772
n-7								0,999886	0,989376
n-8								0,999984	0,996784
n-9								0,999998	0,999126
n-10									0,999785
n-11									0,999952
n-12									0,999990
n-13									0,999998
n-14									1,000000

Appendix C4 Probability that at least n-m units are in operation ($R=99\ \%$)

0,990000	0,980100	0,970299	0,960596	0,950990	0,904382	0,817907	0,605006	0,366032
	0,999900	0,999702	0,999408	0,999020	0,995734	0,983141	0,910565	0,735762
		0,999999	0,999996	0,999990	0,999886	0,998996	0,986183	0,920627
				1,000000	0,999998	0,999957	0,998404	0,981626
					1,000000	0,999999	0,999854	0,996568
						1,000000	0,999989	0,999465
							0,999999	0,999929
							1,000000	0,999992
								0,999999
								1,000000
	0,990000		0,999900 0,999702	0,999900 0,999702 0,999408	0,999900 0,999702 0,999408 0,999020 0,999999 0,999996 0,999990	0,999900 0,999702 0,999408 0,999020 0,995734 0,999999 0,999996 0,999990 0,9999886 1,000000 0,999998	0,999900 0,999702 0,999408 0,999020 0,995734 0,983141 0,999999 0,999999 0,999990 0,999886 0,998996 1,000000 0,999998 0,999997 1,000000 0,999999	0,999900 0,999702 0,999408 0,999020 0,995734 0,983141 0,910565 0,999999 0,999999 0,999990 0,999886 0,998996 0,986183 1,000000 0,999998 0,999957 0,998404 1,000000 0,999999 0,999989 1,000000 0,999999 0,999989 0,999999 0,999999

CONVERSION FACTORS

Prefix fac	tors		
Prefix	Symbol		
Exa	Е	10+E18	1 000 000 000 000 000 000
Peta	Р	10+E15	1 000 000 000 000 000
Tera	T	10+E12	1 000 000 000 000
Giga	G	10+E9	1 000 000 000
Mega	М	10+E6	1 000 000
kilo	k	10+E3	1 000
		10+E	1
milli	m	10-E3	0,001
micro	μ	10-E6	0,000001
nano	n	10-E9	0,00000001
pico	p	10-E12	0,00000000001
femto	f	10-E15	0,00000000000001
otto	0	10-E18	0,00000000000000001

ENERGY SOURCES

Energy source	Energy content	
Nuclear fuel (4% U-235)	1 200 000 000	kWh/kg
Natural uranium (0.7% U-235)	150 000 000	kWh/kg
Uranium in the sea water (3 mg/m3)	0,45	kWh/l
Crude oil	11,62	kWh/kg
Coal	7,08	kWh/kg
Wood (standard cord)	1,70	kWh/l
Wood chips (loose volume)	0,90	kWh/l
Natural gas	10,0	kWh/m3

With 10 g of natural uranium a PWR plant can generate 500 000 kWh of electricity

HALF LIFES OF SOME ISOTOPES

Half lifes of som	ne isotopes		
Americium -243	7 400 a	Cerium-144	285 d
Americium -241	430 a	Cesium-137	30 a
Plutonium-240	6 600 a	lodium-131	8 d
Plutonium-239	24 400 a	Strontium-90	28 a
Neptunium-237	2 200 000 a	Krypton-85	11 a
Uranium-238	4.5 x E12	Cobolt-60	5.2 a
Uranium-235	0.7 x E12	Cobolt-58	71 d
Thorium-232	14 x E12	Tritium (Hydrogen-3)	12 a

UNITS OF RADIATION DOSES

1 rad = 0,01 Gy 1 rem = 0,01 Sv rem/h =0,01 Sv/h
1 1

rem = röntgen equivalent man

Some examples of radiation doses

Dose	What the rate causes /1/
6000 mSv	The dose which may lead to death when received all at once
1000 mSv	The dose which may cause symptoms of a radiation sickness (e.g. tiredness and nausea) if received within 24 hours
100 mSv	The highest permitted dose for a radiation worker over a period of five years
4 mSv	The average annual radiation dose for Finns caused by indoor radon, X-ray examinations, etc
2 mSv	The annual dose of cosmic radiation received by a person working in an airplane
0,1 mSv	The radiation dose received by a patient having his/her lungs X-rayed
0,01 mSv	The radiation dose received by a patient having his/her teeth X-rayed

Some examples of external dose rates

Dose 1	ate.

- 100 μSv/h It is necessary to take protective measures (e.g. to shelter indoors)
- 30 $\mu Sv/h$ The dose rate measured at a distance of one meter of a patient that has undergone isotope treatment. When the dose rate is less than 30 $\mu Sv/h$, the patient can be discharged.
- $5~\mu Sv/h~$ The highest dose rate measured in Finland during the Chernobyl accident
- $5 \mu Sv/h$ The dose rate in an airplane flying at an altitude of 12 kilometers
- $0.4~\mu Sv/h$ If this dose rate limit is exceeded, the automatic radiation meter of the Finnish radiation monitoring network triggers an alarm.
- 0,04-0,30 µSv/h Natural background radiation in Finland

^{*} Source: STUK. http://www.stuk.fi/sateilyvaara/en_GB/esim_annos/