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Nuclear power generation as a reasonable option for energy strategies

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1. Introduction

Main challenge of the 21st century is to find the ways of sustainable development for the world's growing population. The development of world economy, the energy need of growing population in developing countries, rapid increase of consumption of emerging economies result in 40% increase of energy consumption by 2030, which reflects both the impact of the recent economic crisis and of new government policies introduced over the last years (IEA, 2009). Increase of energy consumption, which is essential for global development, affects the environment and the climate irreversibly and adversely. The World Energy Outlook (IAEA, 2009) sets out a timetable of actions needed to limit the long-term concentration of greenhouse gases in the atmosphere to 450 parts per million of carbon-dioxide equivalent and to keep the global temperature rise to around 2° Celsius. This goal might be achieved by enormous investments into energy sector, by increasing the effectiveness of energy utilisation and deployment of emission-free technologies, using of renewable and nuclear energy. Because of the complexity of the issue complex energy strategies have to be developed on country, region and global level.

The global concern is expressed in the establishment of United Nations Framework Convention on Climate Change (UNFCCC), which is the international environmental treaty aimed at fighting global warming. The global policy is expressed in Kyoto Protocol, (UNFCCC, 1998) continuation of which is endorsed by the Copenhagen Accord in 2009, (UNFCCC, 2009). The European Union is committed to achieve at least a 20% reduction of greenhouse-gas emission by 2020, while the primary energy use should be decreased by 20% and utilisation of renewable energy sources increased also by 20%, (European Commission, 2007). Nuclear power generation is accepted by the EU policy as one of low-emission technologies. The US energy policy is also targeted on reduction of greenhouse gas emission and emphasises the role of nuclear energy, see (DoE EIA, 2009). China and the emerging economies are also intending to develop nuclear power generation for covering the rapidly growing needs of their economy. Although growing energy consumption drives the development of these countries, the environmental and climate protection goals are also respected, (DoE EIA, 2009). Energy import dependence and security of the supply became also a serious issue for many countries and regions. In case of European Union the reliance

on imports of gas is expected to increase from 57% to 84% by 2030, (European Commission, 2007).

Representative studies highlight the effective solutions for avoiding severe climate change, while also enhancing energy security. Essential contribution should come from energy efficiency, while the role of low carbon technologies will also be critical (IEA, 2006; IEA, 2008; IAEA, 2009). The studies show that the use of renewable sources is one, but not the only solution due to the low energy density, large land demand on the one hand, and immaturity of some technologies and operating limitations of electrical grid system on the other hand. Clean coal is a secure source for long term. However the deployment of clean technologies and industrial implementation of CO₂ capture have to be waited for quite a long time.

One of possible option for clean generation of electricity is the utilisation of nuclear energy. According to the International Atomic Energy Agency data, currently 436 nuclear power reactors in operation in the world with a total net installed capacity of 370.407 GW(e), which provide the half of CO₂ emission-free production of electricity; 56 nuclear power units are under construction (IAEA PRIS, 2009). In 2009 construction of 13 units were started and two new units have been connected to the grid. Nuclear power plants provided 13.8% of generation worldwide and 21.4% in OECD countries in 2007 (IEA, 2009).

The status of development of nuclear power generation industry worldwide might be characterized by the following:

1. The existing nuclear power plants will be kept in operation as long as safe and economically reasonable (for example operational licence of more than half of plants operated in the U.S. are already renewed and extended for 20 years in addition to the 40 years of licensed term).
2. New nuclear power plants are under construction or preparation. In majority of OECD countries – in addition to utilisation of renewable sources – the use of nuclear energy is considered as acceptable emission-free electricity production methods for the future, see e.g. (UK, 2007). Moreover in some countries, such as in the USA, the same preferences are given to nuclear as the other emission-free technologies (US, 2005). Germany seems to be the only exception, where the phase-out of nuclear is still in force, while in some other countries like Italy radical changes of the political and public opinion could be observed.
3. Development of new nuclear reactors have been restarted in the vendor countries (Canada, France, Japan, Russia, South Korea and the USA); other countries like China and India are intensively developing own industrial capacities;
4. Some 60 countries worldwide that do not yet operate nuclear power plants have expressed an interest in including nuclear in the future energy mix, and more than 30 countries launched programmes for developing national infrastructure or are preparing national nuclear programmes.

Energy policy and the strategy of development of energy sector is subject of public interest. Although the views are changing in positive direction regarding nuclear energy, the use of nuclear energy is a matter of public debates in connection with sustainable development (Eurobarometer, 2008; OECD NEA, 2010). The critical opinion on nuclear power generation is mainly linked to controversial views on generating technologies, misleading representation of benefits of some technologies, which have deceiving effects on public opinion.

A quite detailed but rather simple assessment of nuclear power generation is attempted below, which demonstrates that the nuclear power generation should be part of the solution for ensuring the energy needs of a sustainable development and it should be accounted in the definition of the strategy for development of the power generating capacity mix.

2. Comparative assessment of power generation technologies

Adequate decision on the energy strategy and composition of energy mix of a country has to be based on realistic assessment of available technologies. Large number of studies has been published on the future perspectives of the nuclear power generation referring to or based on complex comparison of generating options; see for example the most recent publications (OECD NEA, 2008; IAEA, 2009; MIT, 2009).

OECD NEA Nuclear Energy Outlook (OECD, 2008) covered the following aspects of nuclear power generation:

- Nuclear power's current status and projected trends;
- Environmental impacts;
- Uranium resources and security of supply;
- Costs, safety and regulation;
- Radioactive waste management and decommissioning;
- Non-proliferation and security;
- Legal frameworks;
- Infrastructure;
- Stakeholder engagement;
- Advanced reactors and advanced fuel cycles.

The study of Massachusetts Institute of Technology (MIT, 2009) covers practically the same areas as above, with main message regarding economic chances of nuclear power generation:

- Status of nuclear power deployment;
- Nuclear generation economics;
- Government incentives and regulations;
- Safety;
- Waste management;
- Fuel cycle issues;
- Non-proliferation;
- Technology opportunities and R&D needs.

Other studies assess the environmental impact of nuclear power generation comparing with other generating technologies. Life cycle emissions and environmental impact of utilisation of different energy sources and generating technologies have been studied which demonstrate the environmental advantages of nuclear power generation (IAEA, 1999) and (Vattenfall, 1999). A comprehensive life cycle assessment (LCA) for the whole energy sector is given in (WEC, 2004). More recent and comprehensive study on sustainability of utilisation of nuclear energy is given in (ISA, 2006). This type of analyses of sustainability with respect to complex and “cradle-to-grave” approach is supported by standards ISO 14040:2006 and 14044:2006, which standardize the LCA methodology for complex assessment of different production activities. Recently a new update of LCA methodology has been published for complex assessment of production and generation activities

(Goedkoop, M. et al., 2009). This method provides a synthesis of the baseline LCA and the “eco-indicator 99” endpoint approach and assess the midpoint level impact, like climate change, human toxicity, land use, mineral resources depletion, etc to three endpoint category: damage to human health, ecosystem and resource availability.

The mentioned above studies and methods are comprehensive and providing very valuable results. However for justification of decisions regarding energy strategy and composition of energy mix of power generation industry aggregation of some characteristics might be needed on one hand, and on the other, the analysis should be extended to some new features.

The methodology outlined and applied below is an integration of approaches with focus on decision on energy strategy and integration of capacities into energy system. The logics of this approach is based on the study of OECD NEA titled as ‘Risks and Benefits of Nuclear Energy’ (OECD NEA, 2007) and is an amendment of the method applied in (Katona, 2008).

In the method followed below, attributes of production technologies are aggregated into three main endpoints or areas of consideration/judgement: economical, environmental and social.

Decision on energy strategy and long-term plans for development of energy mix should not be considered as a decision on an isolated investment project, it should be based on considerations on integration and co-operation of technologies in energy system. Therefore it might need two further areas of consideration/judgement: what kind features, limitations should be taken into account while integrating that technology into the energy system and what is the development potential of a given technology in long term.

Considerations regarding possibility and limitations for integration of a generation technology into energy system should be an obligatory part of energy strategy development and establishment of an optimum capacity mix with respect to primary sources, technologies, etc. Integration has several aspects: integration into energy market, integration regarding grid stability and integration various technologies together into the system for ensuring its diversity which decrease the vulnerability against diversity of disturbances. These aspects are usually not considered in representative studies mentioned above. Technical aspects and limitations for integration of a generation technology into the energy system is a typical issue of countries with relative small total capacity of electric energy system or pour cross-border integration and co-operation. These aspects might be very important for developing countries. Policy measures intervening into the industry for ensuring diversity of energy system are also not emphasised in the representative studies: they seem to be inadequate in a deregulated market economy, although preferences and non-preferences exist like clean-air policy and CO₂ penalties.

The listed five areas of judgement are complex, integrating several features and considerations. The assessment of technologies in each area is dominated by certain parameter. Nevertheless for the comprehensive assessment all related to the area features have to be accounted. The areas of judgement could not be separated completely, there are interactions between the areas, which should be identified and analysed from all relevant aspects.

There are features of generating technologies, which become importance only if they cross some level (e.g. the share of wind generating capacities in an energy system, or the maximum unit size). In the decision on the composition of energy production capacities of a country the features with scale effect might be also identified and analysed. Some of the

indicators for characterising the different generation technologies are qualitative, which might be and have to be assessed and compared without exact measures and still very realistic.

3. Features of nuclear power generation

3.1 Economic dimension

Regarding economic area, first attribute to be considered is the competitiveness, which is defined by the costs of nuclear power generation. A nuclear power plant is the most investment demanding technology, with high operation and maintenance cost and very low fuel cost. The nuclear power generation costs are dominated by high up-front capital costs. Comparison of cost structure of different generation technologies is given in Table 1. (Hydroelectric power plants are not included in the table; they need also very high investment costs like the nuclear.)

Cost contributor, %	Nuclear	Gas/CCGT	Coal	Wind
Investment	50-60	15-20	40-50	80-85
Operational and maintenance	30-35	5-10	15-20	10-15
Fuel	15-20	70-80	35-40	0

Table 1. Cost components of electricity generation technologies (WEC, 2007)

The study (IEA, 2006) estimated the average specific construction costs of nuclear power plant as 1500 USD/kW (10% interest rate and 5-year construction period) and gave the cost range as 1300-2000 USD/kW, where the upper limit is the price of demonstrations/prototypes. The range of investment cost estimation is much higher recently. Nevertheless even a relative small 'penalty' imposed due to CO₂ emissions or encouragement of emission-free electricity generation will make new nuclear power plants far competitive against the gas-fired ones. The (IEA, 2006) study estimated the operational costs as 0.021-0.031 USD/kWh, assuming 5% interest rate, 50% investment, 30% operational and maintenance, and 20% fuel components. As maximum values of the estimation, assuming 10% interest rate, 70% investment, 20% operational and maintenance, and 10% fuel components the operational costs were estimated for 0.03-0.05 USD/kWh. Consequently, nuclear power plants were assessed to be competitive compared with gas-fired plants, if the gas price is higher than 5.70 USD/MBtu or the oil price is higher than 40-45 USD/barrel. This was one of the reasons of the recent break-through in development of nuclear power generation.

According to the MIT update study the levelized cost might be considered as an integrating characteristic with respect of costs and competitiveness (MIT, 2009).

Since the up-front capital costs are dominating in the cost structure the levelized cost varies very sensitive with discount rate and with the risk-premium associated to nuclear investments. With respect to the possibility of reduction of penalising rates, the experience of preparation and implementation of new nuclear projects is controversial: In the US improvement of the assurance of investors is expected due to rationalised regulatory requirements and governmental loan guaranty. In case of Finland Olkilouto Unit 3 the changing regulatory practice together with improper project preparation and management

lead to delay and costs overruns, which seems to be a justification of investment risk of nuclear projects. There are only a few positive examples for implementation of nuclear projects in time and budget (Japan, South-Korea), which might change the opinion of the financial sector. As it is stated in (MIT, 2009) avoiding only the risk premium to capital cost would make the nuclear option competitive even without emission penalty. Recently the ranges of levelized costs of electricity from natural gas, coal and nuclear sources largely overlap between 2 to 9 US cents/kWh. Besides the risk premium and emission penalty the preferences of particular countries depend on local circumstances, such as the lack or availability of cheap domestic fossil resources. Similar conclusions have been made earlier in (OECD NEA, 2005).

Recent study of World Nuclear Association on economics of nuclear power is investigating the capital, finance and operating costs (WNA, 2010). The study demonstrates the generating price advantage of nuclear power compared for majority of countries. There is an obvious strong dependence of the generating costs on discount rate, construction time and operational lifetime. Increase of the discount rate from 5% to 10% may increase of generating costs of nuclear power by nearly 50%. The shorten construction time (5 versus 7 years) and the longer operation lifetime (40 versus 60years) also may decrease the generation cost about 20%. The bare plant costs (i.e. the engineering, procurement and construction costs) are very much depending on the country of supply and where the plant is built. It may vary between 1500-4000USD/kW; see also (OECD NEA, 2005).

There are features of the nuclear power generation, which have economic nature and not covered by levelized costs. These are the following:

- effect on the security of supply,
- stabilisation of the market - low price volatility due to low fuel price dependence,
- geopolitical aspect of accessibility of fuel,
- long-term availability of the fuel.

Nuclear power generation has an overwhelming advantage compared to other conventional generation technologies with respect to the security of supply. In short term any disturbances in fuel supply can be managed by stockpiling of fresh fuel. Stockpiling of the fresh fuel at the nuclear power plants ensuring quite long period of operation is feasible due to the high energy-concentration of fuel. For generation 1GWyear of electricity 2.5 million tons of coal, 1.6 million tons of oil and 3.9 million tons of natural gas would be required approximately. The same amount of electricity requires about 20 tons of nuclear fuel. In some countries stockpiling of fresh fuel sufficient for two years of operation is obligatory. Import dependent countries established alternative fuel supply for fresh nuclear fuel.

Low fuel cost sensibility of nuclear power generation ensures stable market position for nuclear and it affect also the stability of the electricity market; production cost increments less than 10%, if the fuel price will double.

The availability and accessibility of nuclear fuel generates issues of technical, economical and geopolitical nature. It is rather obvious that any limitations on the availability and accessibility of fuel will increase the generation costs and destabilize the market. The geopolitical aspects of accessibility are part of social area. However the geopolitical aspect of accessibility of fuel has direct impact on the economy; any limitation of the accessibility of fuel will cause economical uncertainty, price-increase (and political tensions). From geopolitical point of view the nuclear fuel seems to be much less critical compared to oil and gas due to distribution of Uranium resources over the world.

The long-term availability of nuclear fuel might become a more critical issue. The identified uranium reserves being used in the existing light-water reactors are sufficient just for less than one hundred years. In these reactors about one percent of the fissile isotopes burns up and the remaining fissile part can be reprocessed. Establishing a system with fast breeder reactors and closed fuel cycle, the known conventional Uranium reserves will be sufficient for more than three thousand years (more than twenty thousand years if the non-conventional resources are accounted), see e.g. (OECD NEA, 2008).

There are advantages of nuclear power generation compared to the other generation technologies, which are not or not explicitly addressed by levelized cost.

Assessments of the role of a given technology in the energy system, ideally, should be based upon comparisons of full costs to society. Therefore some other costs are also worth to consider while assessing the economic area, e.g.

- the external costs,
- the relative societal cost for greenhouse gas (GHG) saving,
- need for subsidies for research and development, deployment or operation.

Comprehensive analysis of external costs of different power generating technologies has been performed in the frame of ExternE research project of the European Commission. Summary and comparison of generating technologies regarding external costs is given in (WEC, 2004). The study demonstrates that nuclear power is favourable compared with other technologies. Most health and environmental costs of nuclear power generation are already internalised. It may take more than 20% of production costs. If these costs were included, the European Union price of electricity from coal would double and that from gas would increase 30%. These are without attempting to include the external costs of global warming, which might be considered as delayed penalty for the uncontrolled emission from fossil fuel use. All studies on the subject agree that the nuclear power generation is the least cost solution for reduction of GHG emission (IAEA, 2009).

Research and development, deployment (sometimes also the operation) of low-emission technologies need state subsidies. Nuclear power generation is a mature low-emission technology, which does not need state subsidies. In the same time the state has very important role with respect to the development of nuclear industry, but it is limited to establishment of stable regulatory framework and equal to other low-emission technologies treatment of the nuclear electricity generation. It has to be underlined, that the low-emission technologies might be subsidised only within the capability of society, i.e. even the very developed countries could not afford today a replacement of conventional power generation technologies with emissions-free one.

Considering the existing nuclear power plants, they represent major corporate assets. The reason for long-term operating the existing nuclear power plants is economic triviality, since they are not imposed by capital costs and still operable for a long time (totally about 60 years), considered as the cheapest and most reliable producers (load factor 85÷93%), competitiveness might be improved by power up-rates, see (IAEA-TECDOC-1309, 2002). Business evaluation of nuclear power plants has been done for example in (EPRI, 2001).

3.2 Environmental dimension

The environmental impact of different technologies has to be considered with respect to the following main aspects:

- real and potential environmental impact of operation,

- waste issue, waste management,
- natural resource management.

It is an unquestionable fact that negative environmental effects exist in the case of all energetic technologies, even in the case of the so-called green technologies.

Regarding real environmental impact, today the 439 operating nuclear power plants provide the half of GHG emission-free electricity generation. In comparison to other technologies, the GHG emission of nuclear power plants is negligible, even if the whole life cycle, including uranium mining, is taken into account. It is hardly believable but a fact that generation of one kWh electricity in a photovoltaic or wind power plant results in more greenhouse gas (GHG) emissions than in nuclear power plants, if the whole life cycle (manufacturing, operation, decommissioning) is included, see (OECD NEA 2008; ISA, 2009). The regional environmental impacts caused by nuclear power plants are neutral or fully negligible. In majority of cases the only reportable environmental load during normal operation is the heat load due to cooling to air or aquatic environment. All types of effluents to the environment are controlled under strict norms at nuclear power plants.

Waste is generated unavoidable during electricity production. In nuclear power plants considerably less industrial wastes are produced per kWh than in other power plants. Waste management practice of nuclear industry is based on the principle of 'collect, control and confine' contrary to the 'dilute and release' practice of other technologies. Techniques for management and final disposal of radioactive wastes are available; existing problems in this field are of political and social nature.

Considering the potential impact, safety of power generation has been essentially improved during last twenty years. The probability of early large release of radioactive substances to the environment due to accidents is less than 10^{-6} /years. It means that the risk of nuclear power generation should be more than an order of magnitude less compared to any other industrial activity.

Further improvements of safety features are in progress in case of newly designed Generation III and III+ reactors, due to implementation of high quality, and reliability components and proven techniques. The Generation IV reactors will have very high safety level due to principally new design features based on passive and inherently safe solutions.

Nuclear power plants are high unit power production capacities with operational lifetime 60 years and the capacity factor about 86-92%. These parameters of nuclear power plants essentially affect all characteristics, which are related to the total energy produced during operational lifetime, e.g. (1) the energy intensity coefficient, which is equal to the ratio of total energy needed for construction, operation, decommissioning, etc. to the produced by the plant energy during the whole lifetime; (2) use of resources per unit power (MW) or for the total production (MWh), e.g. materials (steel, concrete, copper, etc.), land etc.

Mentioned above parameters are adequate also for comparison of rational use of resources. With this respect nuclear is the most favourable technology compared to any other, including technologies utilising renewable energy sources. This statement is justified in all representative studies (ISA, 2009; WEC, 2004).

3.3 Social dimension

Development any energy strategy should start with evaluation of the needs and expectations of the society and with the social impact of the strategy when implemented. Evaluation of generating technologies in the social dimension is very complex. Practically all

features mentioned above characterising economical and environmental acceptability of technologies have social connotation.

In the social dimension the technologies have to be evaluated from point of view of direct risk (mortality under normal operation) and potential risk, i.e. frequency of incidents and their consequences (fatality), including risk due to severe accidents.

Contrary to the public opinion frequency of severe accidents is the lowest at nuclear power plants; it is less than 10^{-6} /years. After TMI accident and the severe Chernobyl accident safety reviews have performed at all nuclear power plants in the world and significant safety improvements programs have been implemented. For example at Paks NPP, Hungary the core damage probability has been improved by more than one order of magnitude (i.e. the probability of core damage decreased) due to safety improvement measures. This value is $\sim 10^{-5}$ /year now, as illustrated in Fig. 1. It has been a typical tendency at each nuclear power plant for the last two decades.

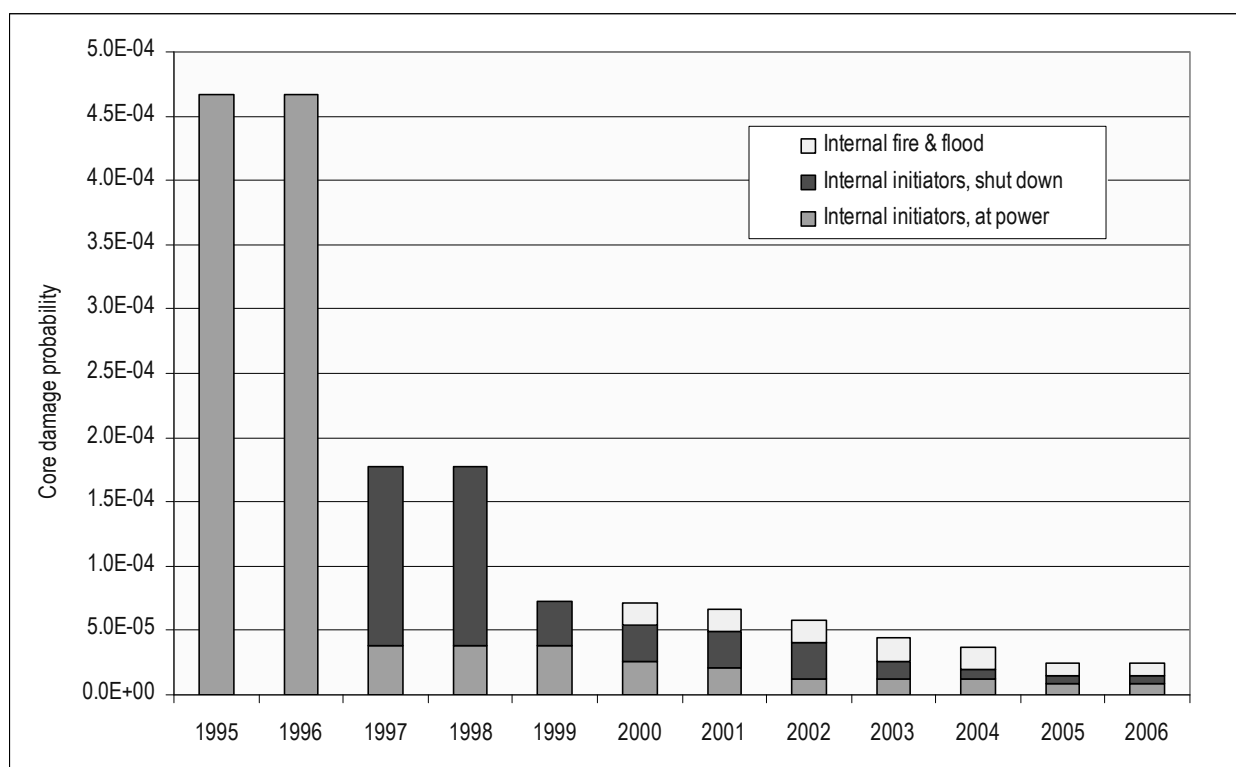


Fig. 1. Decrease of core damage probability at Paks NPP as a consequence of safety upgrading measures

The risk of serious accidents at nuclear power plants accompanied by health effects is negligible; its frequency is less than 10^{-7} /year.

Concerning the mortality under normal operation nuclear power generation has better statistics compared to the traditional generating technologies. This can be easily understood since the operation and maintenance of nuclear power plants require high level of generic technical and safety culture, the operational processes are formalized, licensed and controlled in accordance with the regulatory requirements.

Waste generation, use of land and other resources, security of supply, availability and accessibility of primary sources, and also the public conceptions on these aspects of energy

system affect the acceptance of energy strategy with different composition of primary energy sources and generating capacities in it.

In the social dimension the responsibility of the society regarding waste management has to be considered. The responsibility of society is specific in case of nuclear power generation due to necessity of safe and long-time isolation of radioactive waste from the environment. In the case of low- and medium-level radioactive wastes this time-span is 600 years (at least 20 half-times, when the activity of dominating isotopes will decline to the level of natural background).

In the case of high-level radioactive wastes the halftime of isotopes can be very long. The researches launched for disposal of high-level radioactive wastes and the current international practice have clearly justified that disposal of radioactive wastes and spent fuel can be implemented technically with maximal safety of the society and environment. The current ongoing researches promise to provide more effective methods for management and disposal of spent fuel and radioactive wastes. Technologies suitable for burning actinides exist and are currently under development, which will be discussed in connection with the development potential of nuclear generation later. The high-level radioactive wastes (not spent fuel, which can be reprocessed) can be finally disposed in deep geologic storage facilities.

Accessibility of resources and the possible geopolitical tensions might be conflicting with social interests from both economical and security point of view. Land use is not only an environmental issue, but can be the source of serious social conflicts. Given that the size of crop lands and food production may decrease due to the climate change, while the global population will increase, then starving people will compete for the croplands with biomass and bio fuel producers.

The social dimension covers for example the human capital, institutional framework, non-proliferation, public participation and political aspects. Nuclear energy is one of the great scientific discoveries of the 20th century. It constitutes achievements of the state-of-the-art scientific and technical development, and requires highly developed technical-scientific background, high-level professional and safety culture and complex institutional infrastructure. The nuclear power plant operating countries have effective and independent regulation, backed by strong legislation. It ensures that the nuclear energy activities are carried out in compliance with high safety and radiation protection standards.

Like waste issue the proliferation issue requires high social responsibility. Obviously, nuclear power generation should not contribute to the proliferation of nuclear weapons on one hand and renouncing nuclear energy would not eliminate the risk of nuclear weapon proliferation on the other.

Policies for sustainable development require not only public support, but also certain immolation of the society. Financial support required for deployment nuclear power generation technologies is negligible small compared to other clean technologies; it is mainly limited for establishment of scientific support and developing safety related researches for regulatory institutions. However, the regulation should recognise the emission-savings due to nuclear power generation and should not apply different from other environmental-friendly technologies policy. There are already positive examples for the balanced policy, see (US, 2005).

For nuclear energy most concerns arise from the public perceptions of the risks involved. Recent developments in many countries, e.g. Sweden, Italy, UK, Germany data show the

improving acceptance of nuclear power due to better communication and greater participation by the public. However a better demonstration of benefits of nuclear in comparison with other technologies seems to be needed. For example, the promotion programs for renewable energy technologies do not even mention that hazardous wastes generating during the whole lifecycle of wind or solar energy production have to be managed in a similar way than radioactive wastes of nuclear power plants. It is not even discussed under the topic of the social issues. Because of the low shear of such technologies in the whole system, the issue is not recognised by the society and does not alert social concern.

4. Integration into energy system

The electricity market is a deregulated competitive market. Contrary to this, the competing electricity producers are integrated into an energy system, which is linking the producers together and forcing them to co-operate, otherwise the stability of supply could not be ensured from the point of view of operation of the electrical distribution system. There are technical conditions and limitations for the integration into the electrical grid. While comparing the technologies and integrating each technology into the system of energy supply the effects of introduction of the new capacity on the stability of the electricity grid has to be considered. For example the maximum rated power of a new capacity should be fitted to the total capacity and structure of the whole system. An optimum size of new capacity exists from technical point of view (similar to the optimum size from business point of view), which depends on the total grid capacity, level of regional, cross-border integration, reserving in the system, types of co-operating capacities. This issue might be marginal, if such technologies are present in the system with a small weight, but it might be essential, when the contribution of a technology approaches a certain limit, and the stability of the system is endangered.

Considering the nuclear power generation, integration into the grid might be difficult in case of countries with small system capacity since the rated power of Generation III and III+ reactors is over 1000MWe. For ensuring the required system back-up capacities pumping storage hydroelectric plants might be very appropriate, they may essentially improve the system quality and they are really emissions-free solutions. Similar problem may arise, while incorporating wind power plants into the electrical system. The predictability of availability of wind plants is limited therefore the system backup capability will limit the shear of wind capacities in the system.

Configuration of a diverse energy system seems to be an important aspect of energy strategies. An optimal energy system should be divers regarding technologies, sources of primary energy, import markets. The diversity decreases the system vulnerability to technical disturbances. Diversity of energy system might be important also for those countries, which have essential fossil resources (for example United Arab Emirates).

5. Development potential of nuclear power generation

The current needs for nuclear construction are satisfied by the so-called Generation III and III+ reactor types, which have been developed using the design, manufacturing and operational experiences gained during the previous decades. They represent high-level

safety and availability due to proven solutions. Some inherent safe characteristics appear, which use gravitation drive and natural circulation cooling to the safety functions, and do not require actuating resources. There are design features for management of some classes of beyond design base accidents and mitigation of their consequences (design base extension). Reactor containment buildings are designed to be impervious to catastrophes. Nuclear power plants containment structures have been designed to withstand the impact of hurricanes, tornadoes, floods, missiles and large aircraft impacts. The plants can be operated in load follow regime. Fuel burn-up is high compared to Generation 2 reactors, which results in relatively lower radioactive waste production per kWh and per kg of fresh fuel. Operational lifetime of these plants is >60 years. The load factor is around 90%. Standardised design and manufacturing will decrease the construction time and costs. For example, the Advanced Boiling Water Reactors (ABWR), European Pressurised Water Reactors (EPR), the US designed AP-1000 and the Russian designed AES-2006, the South Korean designed APR-1400 pressurised water reactors represent the Generation III reactors. These reactors are mature for the market.

The innovative, new trends in reactor technology are represented by the Generation IV nuclear reactors, which are under intensive development; see for example (DoE, 2002). They will represent the state-of-the-art in XXI. Century.

According to (DoE, 2002) the goals of development of Generation IV reactors are as follows:

- The Generation IV systems will provide sustainable energy generation with respect to minimum life cycle GHG emission, effective use of fuel and other resources, while generation of waste will be minimized and the long-term stewardship burden notably reduced, thereby improving protection for the public health and the environment.
- The Generation IV nuclear energy systems will have a clear lifecycle cost advantage over other energy sources and business as usual financial risk.
- The Generation IV nuclear energy systems shall have very high reliability and safety with a very low likelihood and degree of reactor core damage without any need for offsite emergency response.
- The Generation IV systems shall have proliferation resistance and physical protection capability.

Large variety of types of reactors is under development:

- Sodium-cooled fast reactors (SFR)
- Very high temperature reactors (VHTR)
- High temperature gas-cooled fast reactors (GFR)
- Lead-cooled fast reactors (LFR)
- Molten salt reactors (MSR)
- Supercritical water-cooled reactors (SCWR)

Development potential of new generation of nuclear reactors can be demonstrated by the diversity of applications. Diversity of the reactor and power plant types being under development is extremely remarkable.

The Generation IV reactors cover a very wide range of features:

- Considering the unit size: they are small (a few hundred) to very large (2000 MW) plants: The LFR might have power level less than 100MW, the GFR, SFR, VHTR might be medium and also large size, the SCWR is a large size reactor.

- With respect of the reactor temperature: they are of moderate temperature for conventional steam-turbine power generation (SCWR and SFR) to very high supercritical temperatures and also with parameters applicable for Hydrogen energy system (GFR, LFR, MSR, VHTR).
- With respect to the neutron physics the types vary from thermal to fast-neutron reactors, with fuel breeding or even actinides burning
- Regarding fuel cycle the types vary from reactors with open fuel cycle (VHTR) like the recent light water reactors (Generation II, III and III+), to different types of fast breeders and reactors able to burn the actinides (GFR, MFR, LFR, SFR).

This is shown in Fig. 2 where the versatility of utilisation of Generation IV reactors is illustrated in the dimensions of neutron-physics, i.e. capability of reactor to work in closed fuel cycle, or even to burn actinides, reactor rated power from small to huge capacity plants, producing electricity or Hydrogen.

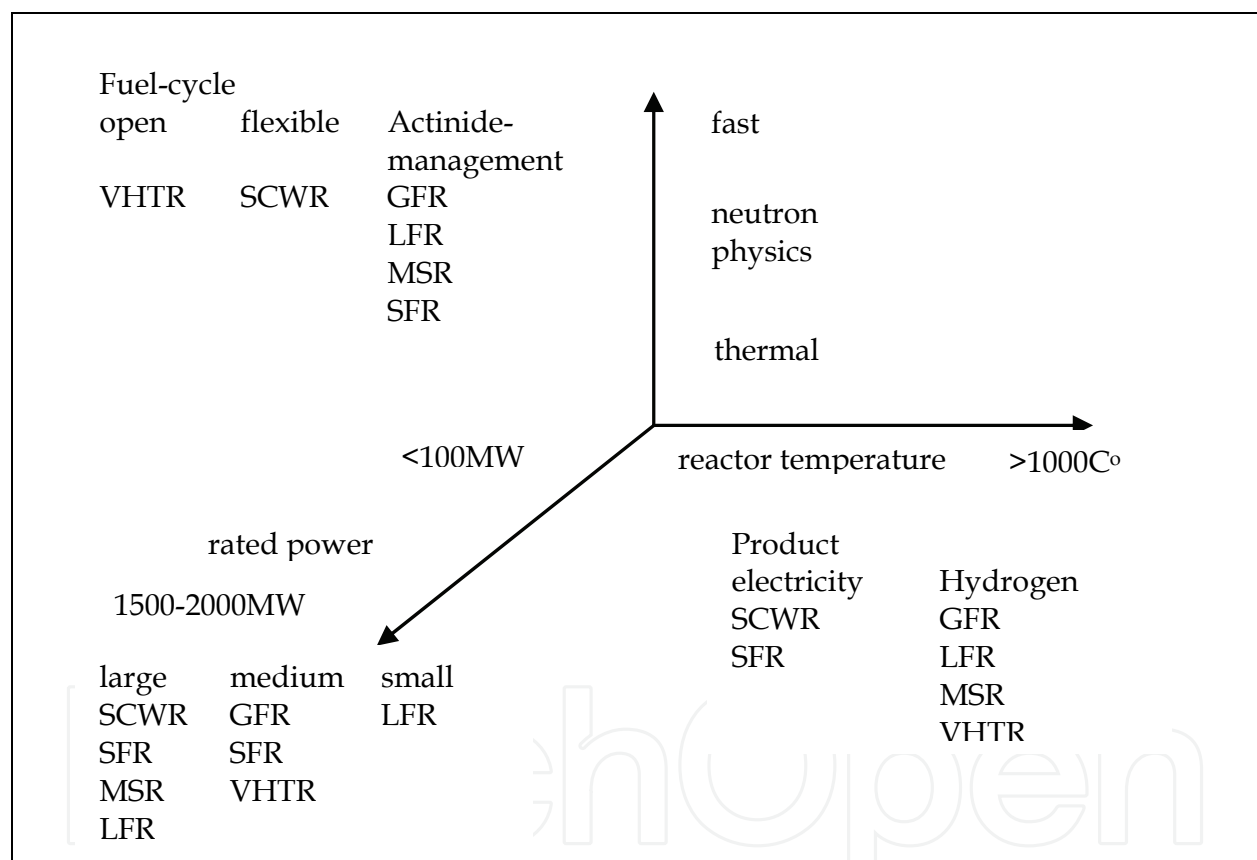


Fig. 2. Development potential of the fourth generation of nuclear power plants

Such a versatile energetic technology can be easily adjusted to a modern energy supply system, where the plants utilising renewable sources and nuclear energy can be used for electricity generation and hydrogen production. Hydrogen is a new fuel for transport, and oxygen can be used for modern burning of coal with CO₂ capture. This high variety of types may cover wide spectrum of needs of future costumers and allow integration of nuclear power generation into the complex frame of industrial technologies. However the highest efficiency of nuclear power can be achieved not in electron-Hydrogen but in electron-economy, where for example the electrical energy is directly used in transportation.

Development potential of new generation of nuclear reactors can be demonstrated by the viability of deployment of new types. It is worth mentioning also the time of industrial application of the new types, which is expected to be between 2015 (sodium-cooled fast reactors) and 2025 (gas, molten salt or lead-cooled fast reactors and supercritical water-cooled reactors). Some intermediate types like the gas-cooled pebble-bed reactors might be constructed within coming decade.

7. Conclusion

Decision on the development of power generation industry has to be derived from the visions of a country regarding own overall development perspectives and goals. It requires consideration and assessment of economical and ecological benefit from development of different generation technologies manifesting in security of supply and emission saving. Financial and technical aspect of feasibility of different development options and also the expected generation costs are decisive as well as the total societal costs. However for the development of an optimal power generating system adjusted to the condition of a country configuration of a diverse production capacity mix is needed, which is divers regarding technologies, sources of primary energy, import markets. There are technical conditions and limitations for the integration into the electrical grid, which define the size of generating units as well as the optimum contribution of each technology from the point of view of the stability of the electrical grid. While assessing the role and contribution of different generating technologies in the production mix also the development potential of different technologies has to be considered. Comparative studies based on assessment of complexity of aspects show that the nuclear energy is a clean, safe and affordable alternative to other power generating technologies including those using renewable energy sources.

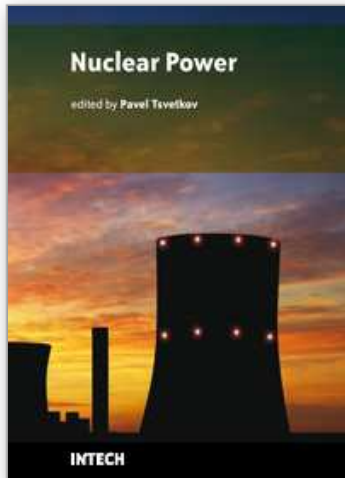
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The world of the twenty first century is an energy consuming society. Due to increasing population and living standards, each year the world requires more energy and new efficient systems for delivering it. Furthermore, the new systems must be inherently safe and environmentally benign. These realities of today's world are among the reasons that lead to serious interest in deploying nuclear power as a sustainable energy source. Today's nuclear reactors are safe and highly efficient energy systems that offer electricity and a multitude of co-generation energy products ranging from potable water to heat for industrial applications. The goal of the book is to show the current state-of-the-art in the covered technical areas as well as to demonstrate how general engineering principles and methods can be applied to nuclear power systems.

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