SUSTAINABLE NUCLEAR ENERGY DILEMMA

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Sustainable energy development implies the need for the emerging potential energy sources which are not producing adverse effect to the environment. In this respect nuclear energy has gained the complimentary favor to be considered as the potential energy source without degradation of the environment.
The sustainability evaluation of the nuclear energy systems has required the special attention to the criteria for the assessment of nuclear energy system before we can make firm justification of the sustainability of nuclear energy systems.
In order to demonstrate the sustainability assessment of nuclear energy system this exercise has been devoted to the potential options of nuclear energy development, namely: short term option, medium term option, long term option, and classical thermal system option. Criteria with following indicators are introduced in this analysis: nuclear indicator, economic indicator, environment indicator, and social indicator. The sustainability index is used as the merit for the priority assessment among options under consideration.

Key words: *sustainability, nuclear energy, nuclear dilemma, nuclear energy systems, sustainability index, safety, proliferation, radioactive waist*

Introduction

The vast majority of world's energy in the coming centuries will come from a few sources: fossil fuels, the Sun, biomass, wind, geothermal sources, nuclear fission, and (potentially) nuclear fusion. Because the anticipated demand is high and because different technologies are better for different applications, it is likely that all of these sources will be tapped. There are four major issues which are of the special importance in the assessment of nuclear energy.

Sustainable fission energy

One of the criteria for the fission energy assessment is amount of the available nuclear fission material. The known economically recoverable 3.3 million metric tons of uranium and 4 to 6 million metric tons of thorium could produce 250 zetta Joule (ZJ) and 350 to 500 ZJ, respectively, if used to their full potential. Thus, more than 600 ZJ of potential nuclear fission energy – 1,500 times the current total worldwide annual energy consumption – is readily available. Much more easily recoverable thorium will surely be found if a demand develops. Fission power uses little land and requires modest construction inputs (mainly concrete and steel) per unit of energy produced – lower than the construction inputs for wind and solar energy by factors of 10 and 100, respectively. Thus, as far as inputs are concerned, fission power has the potential to provide a large fraction of the world's energy for many, many centuries. However, tapping the full potential energy of uranium and thorium resources will require changes from current fission-en-

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ergy practice, including the use of “high-conversion” reactors and the recycling of fissionable isotopes. The output from fission power includes modest amounts of chemical and low-level radioactive wastes, which are relatively easy to handle, as well as used (“spent”) fuel, which is the main disposition challenge. Spent fuel from today’s power reactors contains approximately 5% fission products (atoms produced by splitting another atom or by radioactive decay of another fission product), 2% “fissile” material (including ^{235}U, ^{239}Pu, and ^{241}Pu), and 1% other actinides (including ^{238}Pu and ^{241}Am), with ^{238}U comprising most of the remaining mass. Note that fission power produces a very small volume of spent fuel. With current technology, six years of operation of a 1-GW$_e$ plant yields spent fuel that could fit inside a 4-meter cube, and the vast majority of this material is recyclable. This implies that the nuclear energy is an important energy source in modern society [1].

It has been recognized that there are three major problems in peaceful utilization of nuclear energy, namely: safety, radioactive waste, and nuclear proliferation.

Safety

The safety of nuclear reactor is an imminent problem of nuclear chain reaction control. Nuclear reactor is controlled by delayed neutrons representing only 2.1% of total population of neutron produced in the fission chain reactions. The major part of neutron population belongs to the so called prompt neutron. Since the prompt neutrons have a zero time between the neutron generations, the number of fission chain reaction is almost infinite producing enormous energy. This brings the question if the present man made control system can guaranty the safe energy production in nuclear reactor to be utilized for heat and electricity production. There have been several attempts to design so called the inherently safe nuclear reactor without success. In this respect the most promising is the Accelerator Driven System [2, 3]. The potential possibility to design a nuclear reactor system with the inherently safe characteristic may open new path for the nuclear energy utilization.

Radioactive waste

It is important to realize the benefit which has been gained by the utilization of nuclear power systems. In 2006 the total installed nuclear capacity in the world was 370 GW$_e$, or 15% of electricity production capacity in the world. Nuclear power plants electricity production is contributing to local electricity production in 15 countries. In this moment there are 26 new nuclear power plants in construction. Presently, by the operation nuclear power plants there is production about 14 000 t per year of radioactive waste [4]. Under assumption that the same type of reactor will be utilized in 2050 the total amount of radioactive waste will be about 30 000 t per year. It is of the great importance to accept that the high potential of the nuclear energy is envisaged in the long term energy strategy.

No separation technology is 100% efficient; thus, even with actinide recycling, some fraction of the actinides will remain with the fission products for disposal. The efficiency of the separations will determine the long-term (>1,000 years) radiotoxicity of the waste from fission power. Thus, the efficiency of separation of actinides has a significant impact on the waste-isolation time and thus on the difficulty of the waste-isolation problem. Research and development continues to improve the technology for actinide separation; thus, it seems reasonable to expect that highly efficient (99.9%) separation of key actinides will be economically achievable eventually.

Nuclear proliferation

As it is expressed in the Non Proliferation Treaty [5] there are horizontal and vertical proliferations. The horizontal proliferation is the transfer of present nuclear technologies to the parties which did not have it. The vertical proliferation is the development of new nuclear weapon based on the higher fissile actinides.

Even if it's anticipated that the horizontal proliferation is aimed to prevent dissemination of the nuclear technologies: ore processing, enrichment and spent fuel reprocessing the number of countries which have developed these technologies has increased. The sustainability concept of nuclear energy should include the nuclear proliferation merits in the evaluation of the future energy strategy.

Nothing threatens sustainability more than nuclear weapons. These weapons are rarely considered in the discussions of sustainability, which tend to focus on resources and environmental degradation.

Nuclear power development

Nuclear power economy

For the evaluation of the economy of nuclear power generation (fig. 1) it is of interest to use comparison with other energy sources and the cost in different countries [6-8]. As shown tabs. 1 and 2.

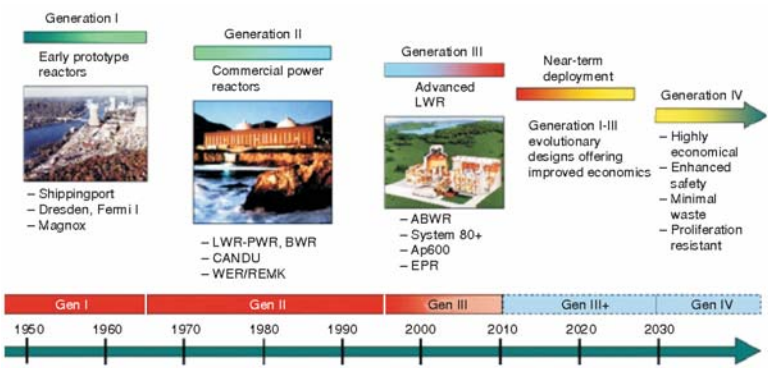

Figure 1. Evaluation of nuclear power

Table 1. Comparative electricity generating cost projection for period 2005-2010*

Country	Nuclear	Coal	Gas
France	3.22	4.64	4.74
Russia	2.69	4.63	3.54
Japan	5.75	5.58	7.91
Korea	3.07	3.44	4.25
Spain	4.10	4.22	4.75
USA	3.33	2.48	2.33
Canada	2.47	2.92	3.00
China	2.54	3.18	–

* US 1997 cents/kWh. Discount rate 5%, 30 years lifetime, 75% load factor, OECD 1998

Table 2. Representative proportion of electricity generating cost [%]

	Nuclear	CCGT	Renewable (wind)
Construction capital (including interest during construction)	60-75	30-40	85-90
Fuel	5-10	50-65	0
O&M	8-15	5-10	5-15

Source adapted from International Energy Agency (2001), Nuclear Power in the OECD, Paris, p. 124

Nuclear fuel cycles

Natural uranium contains 0.7% U-235 and 99.3% U-238. It is enriched up to 5% U-236 for fresh light water reactor (LWR) fuel. Spent nuclear fuel contains about 95% uranium (mostly U-238) more than 3% fission products, and less than 2% transuranic elements. All actinides present in the spent fuel have potential value for energy generation [9, 10].

As the world dependence on nuclear energy increases the open fuel cycle will not meet long-term sustainability goals. The limitation for the long term sustainability goals are:
- use only a small fraction of the energy available in the original mined uranium,
- discharge into the environ- ment long-term radiotoxic elements that mast be contained for hundred thousand years, and
- the construction and licensing of geological repository for finale disposal.

These difficulties can be overcome by adapting a close fuel cycle in which irradiated fuel is reprocessed, and constituent elements are separated in streams to be recycled into a reactor or disposed of in appropriate waste form.

There are three fuel cycle schemes as shown in fig. 2

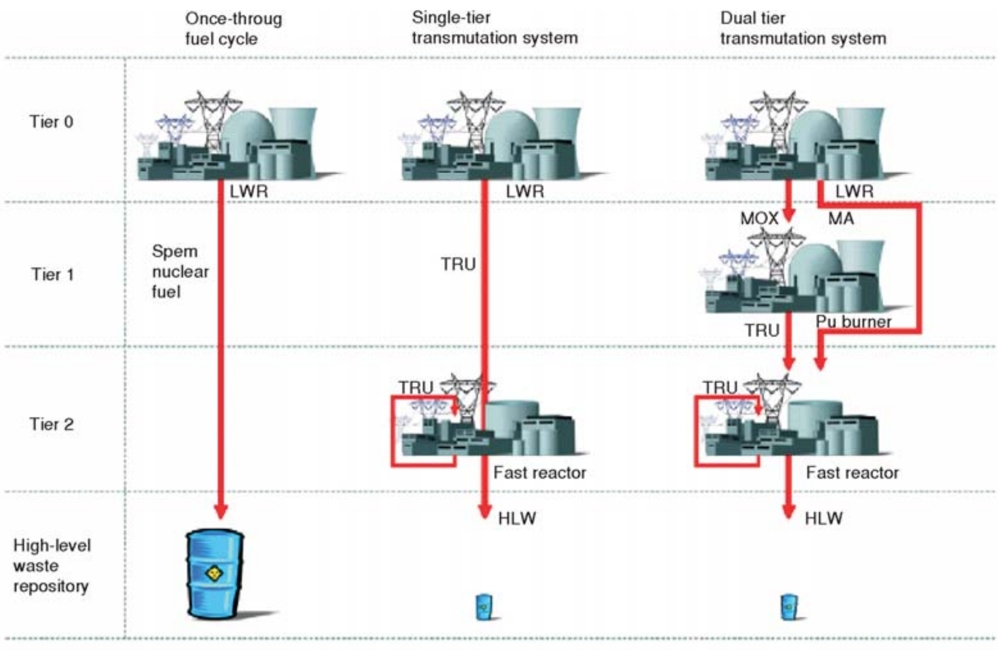

Figure 2. Nuclear fuel cycles

ITER – International Thermonuclear Experimental Reactor, MOX – Mixed oxide, MA – Molten acid, TRU – Thru pass, HLW – Heavy liquid waste

Forecast of nuclear power capacity in the world

The nuclear energy production forecast, as shown in fig. 3, takes into a consideration potential need as presented by the IAEA document [8]. In 2004 the capacity of nuclear power plants in the world was 368 GW_e with total electricity production 2625.9 TWh per year. In 2006 there was 442 nuclear power plants in operation.

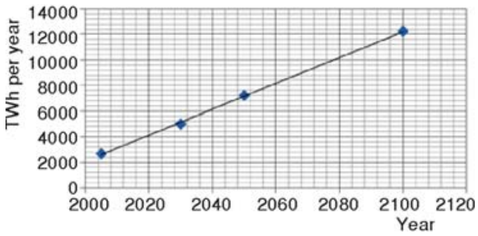

Figure 3. Nuclear energy production forecast

Table 3. New nuclear power production and capacity

	Nuclear power production [TWh per year]	Nuclear power capcity [GW]
2005-2030	2300	266
2030-2050	2500	289
2050-2100	5000	578

From tab. 3, we can notice that in the period 2005-2030 a new capacity has to be put in operation to meet the increased demand of 2300 TWh per year corresponding to 266 GW. Also in the period 2030-2050 a new capacity will be 2500 TWh per year corresponding to 289 GW, and in period 2050-2100 a new demand will increase for 5000 TWh per year or 578 GW of new capacity. In this exercise the new nuclear power capacity will be estimated as shown in tab. 3.

In term of the future nuclear power development strategy, we have introduced in the analysis three potential options, namely: the short term nuclear energy, the medium term nuclear energy source and the long term sustainable energy source.

Sustainability concept

The United Nations Conference on Environment and Development held in Rio de Janeiro from June 3 to 14, 1992, has adapted the Rio Declaration on Environment and Development [11] with the Principle 1: *Human beings are at the centre of concerns for sustainable development*. They are entitled to a healthy and productive life in harmony with nature. Agenda 21 [12] is a global program that committed 118 countries to the environmental restoration, preservation and social development. Their aims are to meet the challenge of global warming, pollution, biodiversity and the inter-related social problems of poverty, health, and population. The sustainability was introduced as the global concept for the environment preservation and development.

"10 years after Rio" the Johannesburg 2002 Conference [13] was the next UN conference devoted to plan of implementation of the Rio Declaration focused to the elaboration of the concrete measures of the sustainable development. The sustainable development encompasses the economic, social, and ecological perspectives of conservation and change. In correspondence with the WCED, it is generally defined as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*." [11]. This definition is based on the ethical imperative of equity within and between generations. Moreover, apart from the meeting basic needs of all, sustainable development implies sustaining the natural life-support systems on Earth, and extending to all the opportunity to satisfy their aspirations for a better life. Hence, the sustainable development is more precisely defined as a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspiration.

Sustainability assessment

This analysis is based on the multi-criteria evaluation of selected options which are defined for the specific time period. It comprises nuclear options which are defined by the nuclear reactor type and associated nuclear fuel cycle. It is anticipated that each time period reflects the specific nuclear reactor technology in accordance with the expected development [14]. The selection of the five potential possibilities is based on the road map of nuclear technology development anticipated as the future strategies of nuclear energy development. In the light of potential options the nuclear energy utilization road map is defined for the short, medium, and long term nuclear strategy. In this assessment we will focus our attention on five different nuclear concepts, namely: thermal reactor with once through fuel cycle, thermal reactor with closed fuel cycle, fast breeder reactor with closed fuel fusion reactor accelerated driven system.

Thermal reactors are based on the fission U-235 isotope. The fast reactors are based on the transmutation of U-238 to new fission isotopes. Fusion reactors are based on the D-D fusion reaction. Special attention is focused on the Accelerator Driven System [2, 3]. For all these nuclear reactor options the quality assessment is based on four indicators reflecting specific criteria: nuclear energy indicator, economic indicator, environment indicator, and social indicator.

Criteria for the sustainability assessment

Nuclear energy indicator

In the design of nuclear energy indicator it is anticipated to define following sub-indicators: participation of the nuclear energy in the electric energy production in the world, radioactive waste produced by nuclear power systems, and nuclear fuel utilization in the respective fuel cycle systems. The participation of nuclear energy in the electricity generation is defined as the number of GW of the nuclear power plant in the total electric power generation [16]. Radioactive waste is determined in accordance with the specific nuclear fuel cycle and respective nuclear power system expressed in m^3/GWh.

Economic indicator

The economic indicator [17] for the justification of nuclear energy system comprises two sub-indicators, namely: electricity cost and investment cost. The electricity cost sub-indicator comprise the electricity cost per unit electricity produced and is expressed in €/MWh; the investment cost of the plant is expressed in €/MW.

Environment indicator

The environment indicator [18] comprises the amount of compensation of the CO_2 emission by nuclear energy, expressed in Mt per year in the respective period. It is anticipated that 1 GW coal fired power plant is producing 6 Mt CO_2 per year.

Social indicator

The social sub-indicator [19, 20] is the public acceptance measurement parameter. The public acceptance sub-indicator is expressed in man/total public taken into a consideration. It is determined by author's assessment.

Nuclear options

In the assessment of potential of nuclear power options to be the sustainable nuclear energy source following systems are taken into the consideration. Also, the coal fired power plant is used as the power system for the comparison with nuclear options.

Short term option – light water reactor with once through fuel cycle (LWR OTFC, fig. 4)

The short term option includes the period between 2005-2030 [21]. It is anticipated that the nuclear energy participation in this period will be the same as in the previous period, namely 14% or about 266 GW. This will lead to the additional 15 m^3 per GWh of radioactive waste. It is assumed to have a OTFC with the utilization of enriched uranium in LWR. The natural uranium use in this type of nuclear reactors is about 1% of available uranium reserves. In order to verify the uranium resource availability by this nuclear power system it is anticipated that the total potential uranium resources will be sufficient for 85 years. The electricity cost from these power reactors is anticipated as 40 €/MWh and the investment cost is 1200 €/kW. The use of nuclear power plant for the electricity production affects the decrease of CO_2 generation resulting from the electricity generation by fossil fuels.

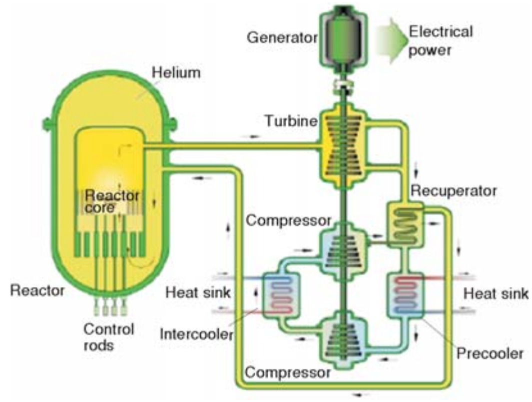

Figure 4. LWR with OTFC

For this option the decrease of CO_2 emission is 2017 t/MWh. Safety of nuclear power plant and nuclear proliferation are the imminent public concern. It is usually defined as the percentage of the public acceptance (tab. 4).

Table 4. Short term option – LWR with open fuel cycle (OFC)

Option	Period	Nuclear energy indicator			Economic indicator		Environment indicator	Social indicator
		NE capacity [GW]	Radioactive waste [m^{3}per GWh]	Fuel reserve utilization [years]	Electricity cost [€ per MWh]	Investment cost [€ per kW]	CO_2 emission [Mt per year]	Public acceptance [%]
LWR OTFC	2005-2030	266	15	85	40	1000	1586	70

Medium term option – LWR with open fuel cycle (LWR OFC)

The medium term option includes the period 2030-2050 [22]. It is assumed that the nuclear power in this period participate in the total energy consumption by about 19%. The total nuclear electric energy production will be about 2500 TWh per year by the LWR with single pass fuel cycle. The radioactive waste will be 5 m^3/GWh [3] and the available uranium reserve will be utilized within the period of 270 years. The economy of this LWR can be defined by the electricity cost and investment cost. The electricity cost is estimated to be 60 €/MWh and the investment cost will be 1500 €/MW. Power generated by the LWR in the period 2030-2050 will compensate 2192 Mt CO_2 per year if the same amount of energy will be produced by HC fuel. The public acceptance indicator will be defined by the arbitrary assumption of the author estimate (tab. 5).

Table 5. Medium term option – LWR OFC

Option	Period	Nuclear energy indicator			Economic indicator		Environment indicator	Social indicator
		NE capacity [GW]	Radioactive waste [m^{3}GW^{-1}h^{-1}]	Fuel reserve utilization [years]	Electricity cost [€ per MWh]	Investment cost [€ per kW]	CO_2 emission [Mt per year]	Public acceptance [%]
LWR OFC	2030-2050	286	5	120	60	1520	1780	60

Long term option with FBR with closed fuel cycle (FBR CFC, fig. 5)

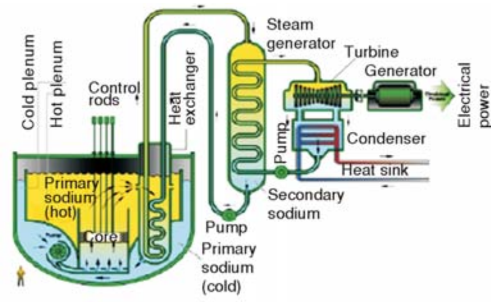

Figure 5. FBR with closed fuel cycle

The long term option is based on the assumption that the nuclear energy participation in the period 2050-2100 will be generated by the fast breeder reactors (FBR) with closed fuel cycle [23]. In this case the amount of uranium reserves will be available for 270 year. According the energy forecast scenario the participation of nuclear energy in the period 2050-2100 will be 50%. Due to the high utilization of uranium and thorium reserves there will be a substantial smaller amount of radioactive waste in comparison with the thermal reactor radioactive waste. Economic indicator is based on the electricity cost – 100 €/MWh and the investment cost – 3200 €/kW. In the FBR CFC, there is the great amount of high level radioactive waste which by itself self protected. Namely, there are beside U-235 the substantial amounts of other fissionable isotopes which are easily accessible as the weapon grade material (tab. 6).

Table 6. Long term option with FBR CFC

Option	Period	Nuclear energy indicator			Economic indicator		Environment indicator	Social indicator
		NE capacity [GW]	Radioactive waste [m^3 per GWh]	Fuel reserve utilization [years]	Electricity cost [€ per MWh]	Investment cost [€ per kW]	CO_2 emission [Mt per year]	Public acceptance [%]
FBR CFC	2050-2100	580	0.5	275	100	3200	3520	50

Long term option with fusion power plant (FPP, fig. 6)

Fusion power is having a large resources, low environment impact and high level of intrinsic safety [24, 25]. Taking a conservative power plant concept design which has the same as ITER parameters, the cost of electricity produced by FPP is estimated to be lower than photovoltaic and wind power plant at the same level of technological potential. The internal cost of the electricity produced in the FPP is between 6-10 €/MWh, while external cost is 0.7-0.9 €/MWh. It is assumed that the internal cost for fusion plant is 6 €/MWh. Under assumption that total electricity cost is coming from the investment cost with 15 years pay of, than the investment cost is $75 \cdot 10^6$ €/MW. The external cost for the fusion reactor is assumed to be 0.08 €/MWh so it can be assumed to be very small in comparison with fossil and nuclear power plant (tab. 7).

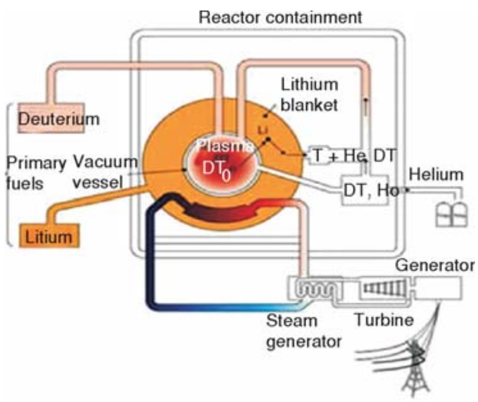

Figure 6. Fusion power plant

In general it can be stated that the FPP has high availability, is safe and environment friendly and economically acceptable. Figure 6 shows ITER fusion plant concept.

Table 7. Long term option with FPP

Option	Period	Nuclear energy indicator			Economic indicator		Environment indicator	Social indicator
		NE capacity [GW]	Radioactive waste [m^3 per GWh]	Fuel reserve utilization [years]	Electricity cost [€ per MWh]	Investment cost [€ perkW]	CO_2 emission [t per year]	Public acceptance [%]
FPP	2050-2100	0	0	120	4	666	0	60

Long term option with accelerator driven system (ADS, fig. 7)

The essence of a conventional nuclear reactor is the controlled fission chain reaction of U-235 and Pu-239. This produces heat which is used to make steam which drives a turbine.

For many years there has been interest in utilizing thorium (Th-232) as a nuclear fuel, since it is three to five times as abundant in the Earth's crust as uranium. A thorium reactor would work by having Th-232 capture a neutron to become Th-233 which decays to uranium-233, which fissions.

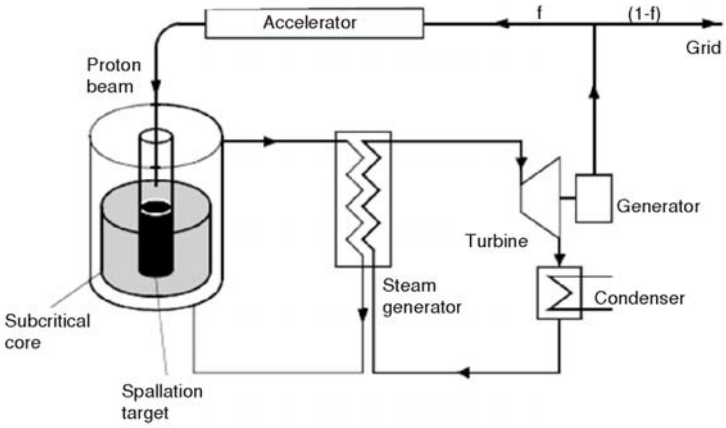

Figure 7. Accelerator driven system – ADS

More recently there has been interest in transmuting the long-lived transuranic radionuclides (actinides – neptunium, americium and curium particularly) formed by neutron capture in a conventional reactor and reporting with the high-level waste.

Accelerator-driven systems (ADS) [26] address both these issues. They are seen as safer that a normal fission reactor because they are sub-critical and stop when the input current is switched off. This is because they burn material which does not have a high enough fission-to-capture ratio for neutrons to enable to be critical and maintain a fission chain reaction. An ADS can only run when neutrons are supplied to it. The capability of high-current, high-energy accelerators to produce neutrons by spallation from heavy elements has been used in the structural research of such materials. In this process a beam of high-energy protons (usually >500 MeV) is directed at a high-atomic number target (*e. g.* tungsten, tantalum, depleted uranium, thorium, zirconium, lead, lead-bismuth, mercury) and up to one neutron can be produced per 25 MeV of the incident proton beam.

If the spallation target is surrounded by a blanket assembly of nuclear fuel, such as fissile isotopes of uranium or plutonium (or thorium-232 which can breed to uranium-233), there is a possibility of sustaining a fission reaction. This is described as an ADS. In this, up to ten percent of the neutrons could come from the spallation, though it would normally be less, even where actinide incineration is the main objective.

The concept of using an ADS based on the ^{232}Th-^{233}U fuel cycle was first proposed by Professor Carlo Rubbia, but at national level; India is the country.

ADS option in this analysis is designed with the following parameters. The period is defined within the 2030-2100. The reserves of the fuel resources are estimated to be 120 years. The total capacity build in the prescribed period will be 586 GW, tab. 8.

Table 8. Long term option with ADS

Option	Period	Nuclear energy indicator			Economic indicator		Environment indicator	Social indicator
		NE capacity [GW]	Radioactive waste [m^3 per GWh]	Fuel reserve utilization [years]	Electricity cost [€ per MWh]	Investment cost [€ per MW]	CO_2 emission [Mt per year]	Public acceptance [%]
ADS	2030-2100	586	0.5	120	100	3200	3250	80

Long term option with coal fired power plants (CFPP, fig. 8)

This option is designed with assumption that in the period 2010-2100 the total electricity will be produced by the fossil fuel power plants. Under this assumption the available fossil fuel reserves will meet electricity demand for the next 120 years.

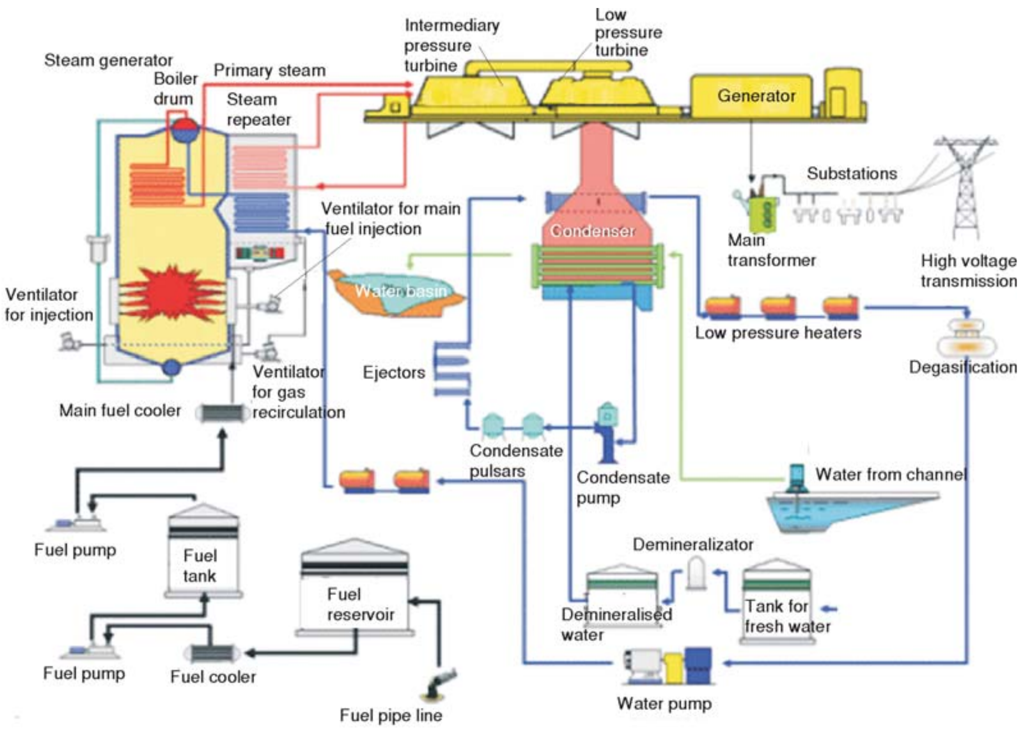

Figure 8. Thermal power plant

As the option in this analysis the modern coal fire power plant is used to represent fossil fuel power plants [27]. For this plant the efficiency is 39% and the electricity cost is 4 €/MWh The investment for this type of power plant is assumed 666 €/kW. CO_2 emission is 300 g/MWh, tab. 9.

Table 9. Long term option with coal fired power plants – CFPP

Option	Period	Nuclear energy indicator			Economic indicator		Environment indicator	Social indicator
		NE capacity [GW]	Radioactive waste [m^3 per MWh]	Fuel utilization [years]	Electricity cost [€ per MWh]	Investment cost [€ per MW]	CO_2 emission [Mt per year]	Public acceptance [%]
CFPP	2010-2100	2103	0	150	34	666	0	60

Nuclear dilemmas

Nuclear dilemma is the result of the multi-dimensional problem generated through the different aspect of nuclear energy development. It implies the need for the assessment of complex issues including nuclear energy indicator, economic indicator, environment indicator, and social indicator. The complexity of each of these indicators requires the introduction of the sub-indicators associated with the specific attributes related to individual sub-indicators. It is obvious that the nuclear indicator is the essential parameter which describes a nuclear quality of the nuclear power system. It is of particular importance to emphasize the nuclear quality reflecting safety, radioactive waste and proliferation [27-29].

It is of the particular interest to analyze several potential dilemmas which are to be important in evaluation the complex issue of the sustainable nuclear energy dilemma. Among those dilemmas are sustainability – unsustainability, economic – uneconomic, and dangerous – safe, proliferation and non-proliferation. These dilemmas are complex issues with mutual interaction. Sustainability dilemma is by itself the multidimensional issue which agglomerates all other dilemmas by assuming their interactive dependence.

Sustainability – unsustainability

In the evaluation of the sustainability and unsustainability dilemma of the energy system, it is of the primary interest to verify quality of the system under consideration and its potential possibility to change the main indicators which are reflecting specific characteristic of the system. The economic crisis is visualized as the warning of the sustainability decease of the company sustainability.

Economic – uneconomic

The economic and uneconomic dilemma is commonly resulting of the crisis which is affecting economic quality of the system. The recession is one of the economic process which shows the tendency to reach the intensity level of this process in global space it diffusing its effect in the domain of the potential ecological and social events. It is also, needed to recognize that these processes in global space that beside the increase in intensity of interaction with other processes can lead to unexpected instability which is characterized with hazard events. Obviously, it has to be emphasized that mutual interaction of different processes will lead to the catastrophic events. In the history of our planet we can find time period in which the cataclysm happens on our planet.

Dangerous – safe

The resilience of any system is characteristic parameter which define eventual dilemma of the stability of the system. The sudden change of the main economic, environmental and social indicators is the potential instability of the system leading to the catastrophic events. Typical examples of these events are the nuclear reactor accidents.

Proliferation – non-proliferation

Potential possibility to lose control of the fission material is imminent for the misuse of the nuclear material quality. Even the world proliferation system is controlled by the International Atomic Energy Agency as the United Nation organization, its capacity and qualification is far from being perfect. This leaves space to the different terroristic and criminal organizations to gain control over the nuclear quality fission material to be used for the nuclear weapon design. In this respect it is of paramount importance of the modern world to be averred of the potential hazard which may lead by the lost of the control of the proliferation process.

Nuclear weapons can be built only if enough weapon-usable nuclear material is available. The weapon-usable nuclear materials include all isotopes capable of being assembled into a fast critical mass which then undergoes explosive prompt fission reactions. A civilian nuclear power program can potentially be linked to all of these routes if uranium enrichment or spent fuel reprocessing is involved. It has been shown that the reactor-grade plutonium from civilian nuclear reactors is a potentially explosive material and that the difficulties of developing an effective design of the most straightforward types of weapon.

In order to deal with these dilemmas we have to be able to make the assessment of the complexity of the problem with the respective tools. One of the potential tools to be used for the assessment of the advantage and disadvantages of the energy systems is the quality assessment of the potential options for the future nuclear energies strategies. In this respect the general index of sustainability can be utilized as a new tool for the verification of the potential strategy for the nuclear energy development option.

General index of sustainability

In the evaluation of the sustainability of nuclear energy the General Sustainability Index is defined as the parameter for the sustainability assessment of the option under consideration [30-33]. The rating among options will be anticipated as the scale for the sustainability of nuclear energy systems. The adapted procedure for the calculation of the General Sustainability Index is based on the formation of the linear additive function of normalized value of indicators multiplied with the corresponding weight coefficient (fig. 9).

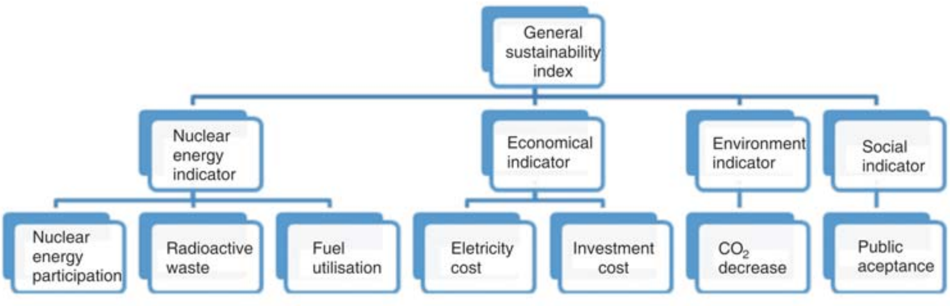

Figure 9. Graphic scheme for general sustainability index

The procedure for normalization of indicators is based on the linear function, defined by:

$$q_i(x_i) = \begin{cases} 0, & \text{if} \quad x_i \le \min.(i) \\ \left(\dfrac{x_i - \min(i)}{\max(i) - \min(i)} \right)^{\lambda} & \text{if } \min.(i) < x_i \le \max.(i) \\ 1, & \text{if} \quad x_i > \max.(i) \end{cases} \tag{1}$$

for the increasing function $q_i(x_i)$.

Agglomerated indicators

As it is shown the individual sub-indicators are subset of indicator reflecting attributes in the description of objects. Under the constrain that the set of sub-indicators belong to the set of general indicators as defined by the attributes, it is allowed to use the linear agglomeration function to define the agglomerated indicators represented as:

$$I_{\text{agg}} = \sum_{i=1}^{m} w_i q_i \tag{2}$$

where I_{agg} is the aggregated indicator, w_i – the weighting coefficient for sub-indicator i, and q_i – the normalized value of sub-indicator i.

The average value of weight coefficients is obtained as the specific set of sub-indicator satisfying imposed constrain. The new set formed will allow determining the average value of weight coefficient for each sub-indicator. This is the finale result of the procedure for the determination of weight coefficients used in the aggregated indicator calculation.

The same procedure is used in the determination of agglomerated values for nuclear indicator, economic indicator, environmental indicator, and social indicator under specified constrains reflecting the priority of sub-indicators, tab. 10.

Table 10. Indicators for the sustainability assessment of nuclear power systems

Option	Period	Nuclear energy indicator			Economic indicator		Environment indicator	Social indicator
		NE capacity [GW]	Radio waste [m^3 per MWh]	Fuel utilization [years]	Electricity cost [€ per MWh]	Investment cost [€ per MW]	CO_2 emission [Mt per year]	Public acceptance [%]
LWR OTFC	2005-2030	266	15	85	40	1000	1586	70
LWR OFC	2030-2050	286	5	120	60	1520	1760	60
FBR CFR	2050-2100	586	0.5	235	100	3200	3520	50
FPP	2100-2200	1000	0	100000	100	5000	6000	90
ADS	2030-2100	586	5	120	100	3200	3250	80
CFPP	2005-2100	2103	0	150	34	666	0	60

Agglomerated nuclear energy indicators

The formation of agglomerated nuclear indicator is aimed to express individual indicator in form which will synthesize sub-indicators nuclear energy (NE) participation, radioactive waste, and fuel utilization under non-numerical constrains. There are three cases which are including priorities given to NE participation, radioactive waste, and fuel utilization sub-indicators. The aim of this prioritization is to emphasize change in the agglomerated nuclear indicator by the change of the sub-indicator priority. Also, it can be noticed that each case proves the strong dependency on the priority list of the sub-indicators, tab. 11.

Table 11. Agglomerated nuclear energy indicators under constrains

Option	Nuclear energy indicator		
	NE participation > Radiactive waste = Fuel utilization	Radiactive waste > NE participation = Radiactive waste	Fuel Utilization > NE participation = Radiactie waste
LWR OThFC	0.00	0.00	0.00
LWR OFC	0.11	0.45	0.11
FBR CFC	0.27	0.68	0.18
FPP	0.59	0.90	0.90
ADS	0.22	0.48	0.13
CFPP	0.184	0.84	0.32

Table 12. Agglomerated economic indicators under constrains

Option	Economic indicator
	Electricity cost > investment cost
LWR OThFC	0.91
LWR OFC	0.77
FBR CFR	0.20
FPP	0.000
ADS	0.20
CFPP	1.00

Agglomerated economic indicators

The agglomerated economic indicator is composed of two sub-indicators, namely: electricity cost sub-indicator and investment sub-indicator. Two cases are taken into a consideration. The case with priority given to the electricity cost sub-indicator and the Investment cost sub-indicator, tab. 12.

Sustainability index of nuclear energy systems

The sustainability index of nuclear energy systems is the synthesizing parameter for the quality assessment of the system under consideration. The four indicators are used as the parameters for the specific criteria. They are agglomerated indicators for the cases with constrains reflecting priority of the single indicators with others indicators having the same values. It is of interest to emphasize that the priority of individual indicators selected in this analysis is only limited number of the potential cases which may contribute to the final assessment of the quality of the systems under consideration, tab. 13.

Table 13. Indicators under specified constrains

Option	Nuclear energy indicator	Economic indicator	Environment indicator	Social indicator
	NE participation > Radiactive waste = Fuel utilization	Electricity cost > investment	CO_2 emission	Public acceptance
LWR OThFC	0.16	0.72	0.73	0.50
LWR OFC	0.26	0.68	0.70	0.25
FBR CFR	0.37	0.21	0.41	0.00
FPP	0.76	0.76	0.00	1.00
ADS	0.37	0.76	0.41	0.75
CFPP	0.31	0.88	0.00	0.25

Sustainability Index of nuclear system is expressed as the additive linear function of the product of average weight coefficient and respective indicator reflecting specific constrains as defined in for the individual case.

In this exercise individual indicators are defined with respective constrains for agglomerated sub-indicators (Nuclear Energy Indicator, Economic Indicators) and Environment Indicator and Social Indicator. Weight coefficient for every indicator is obtained as the average of all cases which satisfies predefined priority of the case. In this analysis the priority is given to the Nuclear Energy Indicators with other weight coefficients having the same values as shown for the Case NEI > EI = EnI = SI, fig. 10.

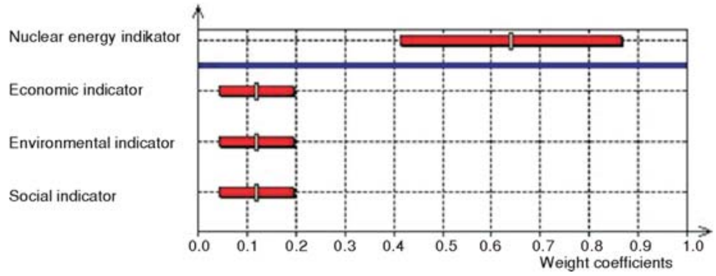

Figure 10. Weight coefficient for case: NEI > EI = EnI = SI

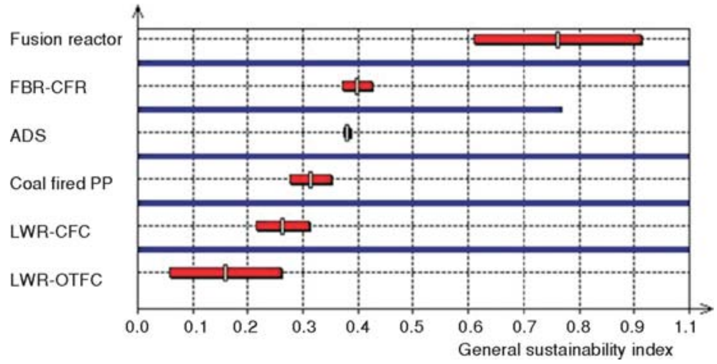

Figure 11. General sustainability index for case: NEI > EI = EnI =SI

The finale results for the General Sustainability Index as the numerical values of the every option taken into a consideration in this exercise. It should be mentioned that there are a large number of potential cases which are suppose to be determined before the finale case is selected. Figure 11 shows the results obtained for the General Sustainability Index and Case reflecting priority of the indicators.

The General Option Rating List presented in this analysis is determined by the General Sustainability Index. In particular column there is Option Rating List The sensitivity of the obtained result is not defined due to limited accuracy of the data obtained in this execise, tab. 14.

Table 14. Option rating list

Option	Summe of sustainability index	Option rating list
LWR OThFC	0.16	6
LWR OFC	0.26	5
FBP CFR	0.39	2
FPP	0.76	1
ADS	0.37	3
CFPP	0.32	4

Discussion

The final results obtained in the form of rating list lead to the conclusion that the Fusion power plant option is the best choice in the sustainability assessment of potential nuclear energy systems. This analysis is based on the agglomerated indicators which are defined by the priority within the respective group. This implies that there are a great number of potential cases which may be used in the decision making procedure. It is of interest to notice that the method of multi-criteria assessment is only a tool for the evaluation of the potential decision making options which are available to the decision makers. Also, it is of interest to mention that the evaluation method comprise unbiased approach which is of the great importance for the decision making process.

The assessment of the sustainability nuclear energy dilemma defined by the sustainability index has shown the possibility to use this validation procedure as the tool for the justification of the potential road map for the long term nuclear energy strategy. Even this analysis has limited validation in enlightening the sustainability dilemma due to the qualitative merits in the justification of the individual option under consideration. The main pillars for the assessment of the potential dilemmas are of the great importance for the future development of nuclear energy. It should be kept in mind that potential break trough based on the new scientific achievements may open an a new venue in overriding present limitation in the further nuclear energy development.

As it was emphasized, the safety and non-proliferation are the milestones of limitation for the further development of the reactor system. In the assessment of the indicators contribution it can be visualized that the nuclear energy indicators are important parameters. The economic indicators are defined in the monetary scale and their contribution to the overall assessment is limited to systems under consideration. Limited quality of the data for the assessment is one of the limitation of the method used in the in this evaluation.

Conclusions

This analyses fail to come up with any 100-year scenario based on sustainable development principles which does not depend significantly on nuclear fission to provide large-scale, highly intensive energy system. The alternative is either to sqeander fossil carbon resources or denies the aspirations of hundred of millions of people in our grandchildren's generation.

Nuclear energy's opponents have yet to credibly suggest how we should produce most of our future electricity. Certainly all the reputable energy scenarios show the main load being carried by coal, gas, and nuclear, with the balance among them depending on economic factors in the context of various levels of greenhouse constraints.

Nuclear power can contribute significantly to sustainable development. Before we can consider nuclear energy as the potential source of energy for the future it is necessary to justify or to validate potential strategy of the nuclear development. Most of them are based on the logical justification of the potential scenarios.

The selected options for the analysis of the potential routes of nuclear energy prove that there is a number of possibilities to be taken into the consideration. The differences in the technologies to be used in the future nuclear development proved to be the important factor influencing a future rout of the nuclear energy development. The safety and proliferation are milestones for the nuclear energy development. The inherent safety is highly needed quality of the future nuclear energy demand.

The multi-criteria evaluation method demonstrated in the assessment of the potential nuclear energy path and development is the efficient tool for the quantitative evaluation of the potential options. It is based on the selected number of criteria with respective indicators. With non-numerical parameters the probabilistic method is developed to determine weighting coefficients for the definition of the contribution of individual indicators to the General Sustainability Index.

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