Future without Nuclear Energy: Is it Feasible, Is it Sensible?

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Abstract

Considering the necessity and future role of nuclear energy as relevant to the climate problem, we have focused on the period to the year 2065. For quantification of the required emission reduction we have used IEA WEO 2009 and WEO 2011 data as presented in their Reference strategies predicting emissions with business as usual practices, and WEO 450 Energy strategies which show the time development of allowed emissions consistent with a limit on the global temperature increase of 2 ºC and the peak CO_2 concentration of 450 ppm. By extrapolating these data to the year 2065 we obtain 77.4 $GtCO_2$-eq for Reference emission and 10 $GtCO_2$-eq for WEO 450 strategy allowing emission, resulting in 67.4 $GtCO_2$-eq reduction required to come down to sustainable WEO 450 trajectory. The large contributions to emission reduction from fusion energy and fossil fuel with carbon separation and storage are not likely. Main carbon non-emitting sources assumed in the years up to 2065 are proven technology nuclear fission and renewable sources. In our specified strategy aimed to achieve WEO 450 target we assumed an energy mix including nuclear power build-up in the period 2025-2065 to the level of 3300 GW in 2065. With the resulting nuclear contribution of 25.2 $GtCO_2$ to the total required emission reduction of 67.4 $GtCO_2$, what remains for renewable sources, energy saving and increased efficiency of energy use to contribute are prodigious 42.2 $GtCO_2$-eq. Assuming that energy saving and more efficient energy use will by 2065 effect an annual reduction between 10 to 16 $GtCO_2$-eq, remaining 26.2 to 32.2 $GtCO_2$, respectively 27290 and 33540 TWh would be the task for renewable energy sources. Our estimates about contribution of renewable sources going as far as 2065 are based on EREC prediction for EU and on our extension to world total with EREC and GWEC prediction as a guide. Our high, but still credible estimates of predicted world renewable energy contribution by 2065 come to the similar figures between 29260 and 36180 TWh. However, without nuclear contribution in 2065, renewable energy contribution would have to be doubled, practically impossible task in the time period in consideration and in view of their generous predictions. Resulting contributions by renewable sources, probably their upper limits, allow some conclusions about the role of nuclear energy in future decades. By combining highest contributions from energy saving, efficiency increase and other measures to reduce emission, apart from energy production, with highest prediction for renewable sources contribution, we obtain the minimum nuclear energy requirement of about 2190 GW in 2065. This minimum nuclear strategy should be planned and prepared for, unless there is strong evidence that other carbon free energy sources (CCS or fusion) could be developed in time. Expansion of nuclear power by about 1800 GW by 2065 would come from different and already developed industrial sector, which can give its contribution to the energy mix, without obstructing the build-up of renewable sources. It would not be wise to forfeit nuclear contribution at least in the period to 2065, critical for the control of climate change.

1. Introduction

The future of nuclear energy will be essentially determined by its role in reduction of carbon emission and prevention of associated unacceptable climate changes. In trying to assess the role of nuclear energy in resolving the carbon emission problem we focus on the several next decades when the choice of carbon free energy sources will not include large scale energy production by nuclear fusion or coal power plants with carbon sequestration and storage (CCS). Starting with generally accepted recommendations by IPCC about carbon emission reductions, the question about the future of nuclear (fission) energy is really the question whether required emission reduction in the next decades can be achieved with renewable sources alone, or the contribution from nuclear power must also be included. First step towards the answer is to quantify the emission reduction target. Present consensus is that global temperature increase be limited to 2 degrees Celsius. This limit was adopted in Copenhagen Accord [1] and in EU energy strategy [2]. Global endorsement reflecting IPCC recommendations was given at the UN climate change conference in Cancun in December 2010 [3, 4]. In order to obtain a quantitative guidance on the carbon emission reduction required to keep global temperature increase below 2 ºC we use the WEO 2009 and subsequent WEO 2011 energy strategy designed to achieve this target by limiting the increase of GHG concentration below 450 parts per million of CO_2-eq. That strategy was presented in the International Energy Agency annual report in 2009, WEO 2009 [5] as WEO 2009 450 Energy Strategy, and further elaborated in WEO 2011[6]. According to the IEA WEO 2011 Reference Scenario, by continuing present trends, global anthropogenic greenhouse-gases (GHG) emission from all sectors of human activity would reach 56.5 $GtCO_2$-eq by 2020 and 64.4 $GtCO_2$-eq by 2035, increasing from 47.1 $GtCO_2$-eq in 2009. Continuation of this trend would increase long-term CO_2-eq concentration in excess of 1000 ppm and increase average temperature by up to 6 ºC, leading almost certainly to the irreparable damage to the planet. The environmentally sustainable WEO 2011 450 Energy Strategy, in line with the Copenhagen Accord and EU energy policy, aims to stabilize concentration at 450 ppm and limit temperature increase to 2 ºC. In WEO 2009 and later in WEO 2011, strong arguments are presented for this scenario. According to WEO 2009 450 scenario the estimated allowed limits on total GHG emission in 2030 and 2050 would be 37.1 and 21 $GtCO_2$-eq respectively, whilst consistent figures in WEO 2011 450 strategy are 47.1 $GtCO_2$-eq for 2020 and 32.6 for 2035. They are lower than Reference scenario in 2035 by 31.8 $GtCO_2$-eq and in 2050 by as much as 50.4 $GtCO_2$-eq. The time scale appears to be too short for several carbon non-emitting technologies. Carbon capture and storage (CCS) technology is in the development stage for future applications, which will have to grow from the present experimental level of million tons per year to the scale of billion tons per year. Many hundreds (thousands) of safe non-leakage storage locations would be required. The future success of applications on such a scale cannot be taken for granted, at least not in next few decades. It could be many years before more definite predictions become possible. No solution can be seen in nuclear fusion, either. Even should the tokamak concept of nuclear fusion develop successfully physically and commercially, which is by no means certain, a significant contribution by nuclear fusion to the world energy production cannot be expected before 2065. This is evident from the dynamics of ITER and the follow-up projects (DEMO) before the first commercial plants could be constructed [7, 8]. Plasma ignition may be achieved at the laser fusion National Ignition Facility of Lawrence Livermore National Laboratory (LLNL) this year, or very soon, but the technological problems on the road to commercial power are so formidable that the predictions about energy production cannot be more optimistic [9,10]. As for the solar energy in spite of its large physical potential, it is less ready for large-scale deployment than wind energy. Some authors estimate two or three decades as a time needed to achieve economic competitiveness [11]. However, even when renewable sources of energy, such as wind and solar, become technically and economically ready for large-scale deployment, their intermittent nature of energy production would limit their share in total energy production, barring the development of energy storage at an acceptable cost, not in sight at present. Heat storage can resolve day-night cycle for concentrated solar energy installations in sunny periods, but not in winter or for several cloudy days. Very large grids connecting wind and solar installations would smooth the variations, but would also remove independence on big systems, perceived as one advantage of renewable energy. Energy field is in transition and the picture depends on how far in the future we look. We have to understand that the rate of change in the field of energy differs from that of, say, communication gadgets which become obsolete in a year. Big energy installations take years to build and operate for decades. Change of energy technology is correspondingly slow process. We consider the period up to the year 2065, critical from the climate point of view, during which large contributions from CCS and fusion are not likely, while a large build-up of nuclear fission energy could be accomplished. In this period substantial contribution is expected from wind and solar energy, although still with economic limitations. Another important point to note is, if the aim is to reduce carbon emissions, as required by 2 ºC increase limit, build-up of carbon free sources should be as fast as possible. Nuclear fission, as developed energy source, can take the main burden while other non-carbon sources are not yet available on a large scale. The selected year 2065 is a present judgment, a compromise between what is desirable and what seems technically feasible, regardless of current limited nuclear plans and present levels of renewable energy sources. Reduced nuclear strategies that would reach a high nuclear share later, by 2080 or as late as 2100, would, of course, provide more time for the development of the technical and political prerequisites for nuclear build-up, but their contribution to the urgent problem of CO_2 emission would be diminished or too late, if we take the IPCC recommendations seriously. The next few years will tell us whether we can afford delays. Climatologists are warning us that we cannot [12, 3, 4]. Optimists generally believe that future is uncertain and that black climate change forecasts are still inadequately researched and even disputed. On the other hand, should the climate situation develop in an alarming way, demanding urgent measures and an earlier contribution of carbon-free energy, the final year of nuclear build-up could be moved back to about the year 2060, or even earlier. It would mean a correspondingly greater challenge to international nuclear industry.

In order to be able to gain some quantitative insight about the necessity and potential of nuclear contribution for achievement of emission reduction in accordance with WEO 2011 450 Energy strategy, we base our discussion on the energy strategy which achieves this aim with an energy production mix inclusive nuclear power [13, 14, 15]. Nuclear share in the mix is determined as a maximum attainable with established light-water nuclear technology, under constraints of consuming presently (2008) estimated uranium resources by 2065, and by abstaining from reprocessing of spent fuel and from introduction of fast breeders at least until that year. These technology and safety constrains on nuclear power are chosen having in mind the political problems associated with nuclear power and nuclear fuel cycle and with the need for public acceptance of nuclear contribution. The point of this exercise was not to propose this particular nuclear strategy, but to see whether under these constraints, which respect public concerns about nuclear technology, nuclear power can still give a substantial reduction of carbon emission. Postponement of fuel reprocessing and plutonium use at least until 2060 would offer the time for development of political institutions and efficient international control measures to prevent nuclear proliferation. As witnessed by Fukushima events, even the technologies with many years of experience can surprise, therefore postponement of introduction of breeder reactors or other not sufficiently proven technologies is advisable, in the interest of nuclear industry and would respond to general public attitude towards nuclear energy.

2. Emission Reduction Targets

The ‘‘Business-as-Usual’’ WEO 2009 Reference Scenario gives the energy-related carbon emission of 40.2 $GtCO_2$ for 2030, and anthropogenic GHG emission of 56.5 $GtCO_2$-eq. The total anthropogenic GHG emission according to the WEO 2009 Reference Scenario in 2050 is 68.4 $GtCO_2$-eq. WEO 2011 Business-as-Usual Reference scenario starts in 2009 with total anthropogenic emission amounting to 47.1 $GtCO_2$-eq and runs few $GtCO_2$ above the WEO 2009 Reference scenario. Predicted emissions for the years 2020 and 2035 are 56.5 and 64.4 $GtCO_2$-eq, respectively. For the years 2050 and 2065, we extrapolate by following general trend and allowing for expected decrease of growth rate. Continuing on the increase of 7.9 $GtCO_2$-eq in the period 2020 to 2035 with increases of 7 and 6 $GtCO_2$-eq in the next two 15 years intervals we obtain 71.4 and 77.4 for the total anthropogenic emission in 2050 respectively in 2065. To obtain the WEO 450 emission limit for the year 2065 we could extrapolate from the WEO 2009 450 total allowed anthropogenic GHG emission of 21 $GtCO_2$-eq in 2050 to the year 2065 continuing with the 2030/50 rate of decline, from 37.1 $GtCO_2$-eq to 21 $GtCO_2$-eq, into the 2050–2065 period. The extrapolated allowed anthropogenic GHG emission for 2065 would then come to 13.7 $GtCO_2$-eq. However, with emission rate for early years in WEO 2011 being higher than predicted in WEO 2009, emissions in the later of WEO 2011 years 2050 should be lower than in WEO 2009 if the integral emission should remain the same. Difference demonstrates the effects of delay in carbon emission mitigation measures. Recent analysis by Meinshausen et al. [16] puts the integral CO_2 emission limit to keep the probability of 2 ºC temperature rise below 0.25% at 1000 $GtCO_2$ in the years 2000-2050, consistent with the earlier IPCC limit of 1800 $GtCO_2$ for period 2000-2100 [17]. Any delay in reduction in early years must be compensated with sharper reduction in later years. So the revised values for WEO 450 trajectory for years 2050 and 2065 should be below 21 and 13.7 $GtCO_2$ figures in WEO 2009, close to 19 and 10 $GtCO_2$-eq, which we take as working assumptions. Resulting WEO Reference and WEO 450 trajectories are shown in figure 1. To reduce the emission from the Reference Scenario level of 77.4 $GtCO_2$-eq to the WEO 450 Scenario level of 10 $GtCO_2$-eq, an emission reduction of 67.4 $GtCO_2$ would be needed. This would be a reduction of 87%. Several countries have already adopted drastic emission cuts as the basis for their energy strategies, at least as a declaration of understanding what should be done. Great Britain is committed to 80% cuts by 2050 relative to 1990 emission.

3. Nuclear Contribution in an Energy Mix Scenario

We use above considerations of required total reduction from WEO Reference scenario to WEO 450 Scenario to get some quantitative insight on the required non-nuclear contributions. As we determine maximum nuclear contribution under conditions specified below, non-nuclear contribution which follows would be a minimum required to reach WEO 450 requirements. Figure 1 presents two WEO scenarios, reference, “business as usual”, and WEO 450 up to the year 2065. Our specified “maximum” nuclear scenario with a build-up in the years 2025-2065 would reach 3300 GW by 2065. This level of nuclear power would be reached by linear nuclear power build-up starting in the year 2025 and proceeding until 2065. Rate of growth is obtained requiring that uranium resources as estimated in 2008 Red Book [18] be consumed by 2065.

Second constraint defining maximum nuclear strategy is postponing of spent fuel reprocessing, respectively introduction of fast breeders until 2065, at least. Under these constraints maximum linear nuclear growth compatible with prescribed constraints is a constant growth by 71.8 GW/year, and the resulting nuclear power of 3300 GW by 2065 is the maximum attainable under specified constraints. Linear growth was assumed as it gives larger emission reductions in earlier years than exponential growth. With determination and international effort such nuclear build-up could start by 2025. More discussion on that point can be found in [13]. This maximum nuclear contribution, not to be mixed with actual construction rate, serves to determine minimum non-nuclear contribution required to reach the total emission reduction of 67.4 $GtCO_2$-eg by 2065. Lower nuclear growth would imply increased requirements on non-nuclear contributions to carbon emission reduction in order to come down from WEO Reference scenario to the WEO 450 Scenario. Nuclear carbon emission reduction in the year 2065 from operation of 3300 GW amounts to 25.2 $GtCO_2$, assuming that nuclear power plant replace worst emitters, coal power plants. This would be 37.4% of required reduction, leaving remaining 42.2 $GtCO_2$-eq , respectively 62.6% of total reduction required 67.4 $GtCO_2$-eq, to be achieved by energy saving, increased efficiency of energy use, forestry management, renewable energy sources, and a range of present and future methods and ways to cut carbon emission. Task is so enormous that no reasonable contribution should be neglected.

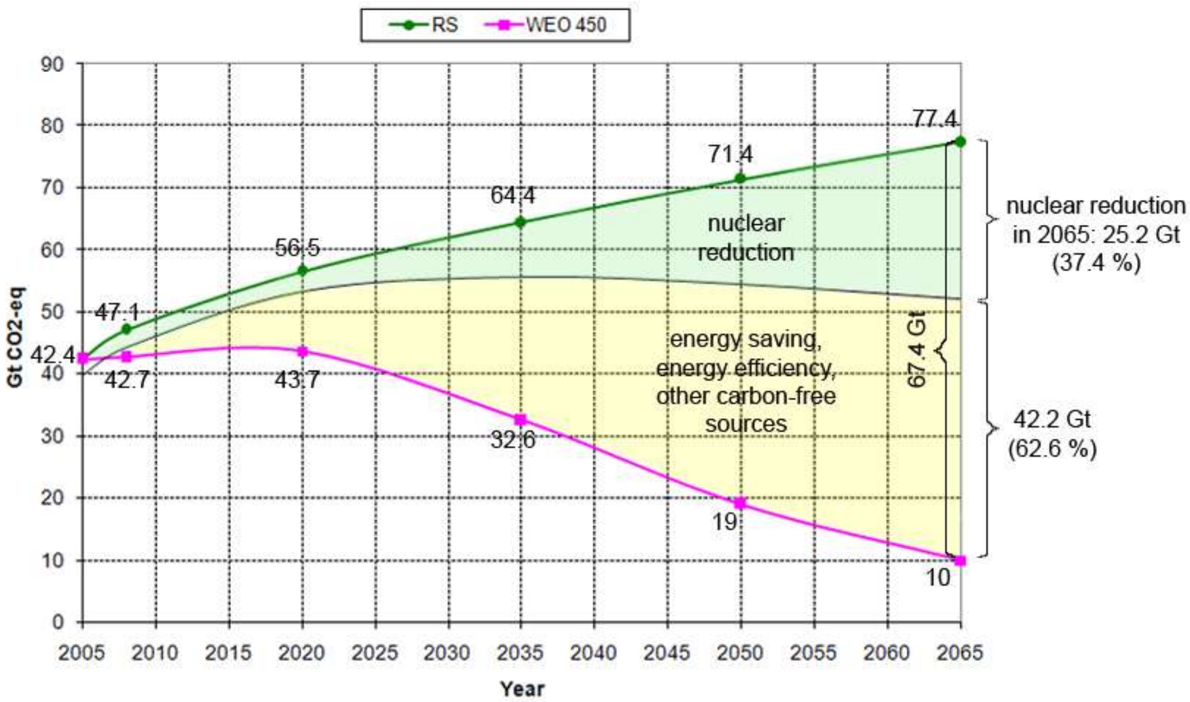

Figure 1: Emission reduction by linear nuclear build-up to 3300 GW in $GtCO_2$... The upper and bottom curve are the total anthropogenic emissions according the WEO 2011 Reference Scenario and the WEO 450 Scenario. The 2065 values were extrapolated from predictions for up to 2050 from WEO 2009 and WEO 2011.

Undoubtedly, with nuclear reduction greater than one-third, reduction of the remaining two thirds would be much easier to achieve. The question we aim to clarify is whether it is possible to forfeit or essentially decrease nuclear contribution and correspondingly increase burden on the non-nuclear sources. For that we have to compare required reductions with the predictions or extrapolations of non-nuclear sources growth. Year 2065 is too distant for a reliable predictions about relatively fast developing renewable sources and many methods of energy saving. Yet, if we want to have some bases for creating comprehensive long term energy strategy with a mix of energy sources we must make some estimates about all of them. Attempting this we face first a difficult problem of quantifying effects of increased efficiency of energy use and of reduced energy use. Progress in this direction is going to take place in all sectors of energy use, industry, housing, transport, in countless small steps and innovations impossible to predict. Many more creative minds are working now on the energy problems than in the past era of cheap energy without climate problem. At present we have to make a guess on how much emission reduction can be expected from improvement of energy efficiency, from energy saving, from reduced deforestation and many other measures, some unknown today, that can reduce carbon emission.

Without sufficient certainty about future development, we shall put our estimate into a wide range between 10 and 16 $GtCO_2$-eq by 2065, respectively between 14.8 % and 23.7 % of the emission reduction required to come down from world anthropogenic emission in WEO Reference scenario to WEO 450 scenario in 2065. This range is supported by estimate for emission abatement by energy use efficiency and saving for the year 2035 as given in WEO 2011, figure 6.4. Emission reduction in 2035 amounts to about 6.4 $GtCO_2$, respectively about 20% of the requirement for reaching WEO 450 trajectory from the anthropogenic emission WEO 2011 reference trajectory. As is recognized, efficiency and saving emission reductions are cost effective and expected to be introduced in early years, whilst new energy generating technologies are expected to dominate in later years. Both trends will act to reduce the share of energy efficiency and saving in emission reductions in the years after 2035, probably well below 20%, consistent with our selected range for 2065. The required contribution from renewable sources would consequently have to be between 26.2 and 32.2 $GtCO_2$/year in order to sum up to a total non-nuclear share of 42.2 $GtCO_2$-eq.

4. Predictions of Wind and Solar Energy Contribution for the year 2065

Assuming that renewable sources replace the coal power plants the required amounts of 26.2 to 32.2 $GtCO_2$ of annual emission reduction can be expressed as the corresponding amount of renewable electricity, again assuming replacement of coal power plants, (we use figure of 0.96 kg CO_2/kWh for coal plants emission) from 27290 to 33540 TWh/year. These figures are the minimum required. When replacing gas power plants for a given amount of emissions more renewable power would be needed. With global average of wind energy conversion efficiency of 25%, which is probably overestimated, and with 15% for solar installations, we would come to the global average of about 20% for a system of about the same amount of wind and solar power. What will be the real ratio of these two main renewable sources contributions by 2065 depends on future developments, especially of solar materials. From our assumption of about equal contributions we obtain required installed power of these installations between 15500 GW to 19200 GW for 26.2 respectively 32.2 $GtCO_2$ of required emission reduction. How this requirement compares with the predictions on the future developments of renewable sources? Predictions as far in future as 2065 do not exist, although 40 years is a not a long period compared with the working life of a large power station. One reason is that some technologies, such as solar, are still rapidly evolving.

5. Renewable sources in EU

For European Union there is a prediction of renewable energy growth prepared by European Renewable Energy Council (EREC) [19] which goes up to 2050. Global prediction for wind energy is given by Global Wind Energy Council up to 2050 [20].

Table 1 Predictions of renewable energy capacities (GW) by EREC in the "RE-thinking 2050", forecasts for European Union (2011) up to 2050 with our linear extension to 2065 (last column)

	2007	2020	2030	2050	2065
Wind	56	180	288.5	462	592
Hydro	102	120	148	194	228
PV	4.9	150	397	962	1386
Biomass	20.5	50	58	100	131
Geothermal	1.4	4	21.7	77	118
CSP	0.011	15	43.4	96	135
Ocean		2.5	8.6	65	107
Total RES-Capacity (GW)	185	521.5	965.2	1956	2697

Table 2 EREC: Contribution of renewable sources to electricity production (TWh) to 2050. Figures for 2065 are our linear extrapolation from the 2030-2050 period

	2007	2020	2030	2050	2065
Wind	104	477	833	1552	2091
Hydro	325	384	398	448	485
PV	5.4	180	556	1347	1940
Biomass	102	250	292	496	649
Geothermal	5.8	31	169	601	925
CSP	0.8	43	141	385	568
Ocean		5	18	158	263
Total RES-Energy (TWh)	543	1370	2407	4987	6921

As our purpose is to judge the need for nuclear energy we include also the possibility of rapid growth of such renewable sources as wind and solar beyond 2050 up to 2065, in order to see whether in that case renewable energy could be sufficient. By extending EREC predictions exponentially the rapid growth from the period 2030-2050 up to the year 2065 we expect to obtain a very generous upper limit on the renewable energy production capacities in European Union for the year 2065.

Table 3 EREC predictions of total renewable energy capacities in EU until 2050 and exponential extrapolation to the year 2065, installed capacity in GW

Year	2020	2030	2050	2065
EREC prediction GW	521.5	965.2	1965	3000 Estimate

First doubling occurs in 2020/30 period, in 10 years, second doubling in 2030/50 period in 20 years. Our estimate assumes continuing 2030/50 rate with doubling in 2050/70 period, so 3000 GW in 2065 is the result of exponential growth up to 2065. So we proceed with linear extrapolation of 2700 GW and with 3000 GW as the range for the upper limit of extension of EREC predictions for EU up to the year 2065.

6. Some technical limits on the wind energy potential in EU

Simple calculation [21] as well as examples of built wind farms (Whitelee wind farm, Scotland, 322 MW peak power on 55 square km, average power $2W/m^2$, and London Array, offshore wind farm, 1 GW peak on 245 km^2, average power 1.5 W/m^2) show that, due to physical and technical criteria on a distance between windmills, average power on the wind farms is not above 2 W/m^2. Assuming that in densely populated European Union area about 10% of 4 500 000 km^2 area were covered with wind farms we obtain rough estimates of EU wind power potential. Building wind farms on some 450 000 km^2, i.e. on the 10% of total EU area, and with 2 W/m^2 , i.e., 450x10 to 9 m^2 x 2 W/m^2, we would obtain average wind power of 900 GW. Required installed peak power would be about 3500 GW, at 25% efficiency, as for such mass construction efficiency value of best location cannot be assumed. It should be noted that this technical limit is much higher figure then EREC extrapolation for 2065 which is below 1000 GW of installed power. All the same, is it realistic to see wind power in EU as replacement for nuclear power in the period up to 2065?

Our global strategy assumed construction of 3300 GW of nuclear power by 2065 resulted in 37% reduction of carbon emission required to reach WEO 2009 450 strategy. At present with about 140 nuclear reactors in operation in EU, i.e. approximately one third of world number, one would expect that EU share in future global nuclear expansion be not less then one third. Clearly, in spite of present Fukushima conundrum, international solidarity would ask that main burden of nuclear development for carbon reduction falls on industrialized regions of the world; EU, US, and Far East regions which posses already developed nuclear industries. One would therefore expect from EU a share of at least 1100 GW of the global nuclear program of 3300 GW, on the level of present EU share in global nuclear power. If we extrapolate exponentially EREC prediction of installed wind power for 2050 of 462 GW to 2065, resulting 900 GW peak would certainly not suffice to replace 1100 GW of nuclear power. With an average to peak power ratio of 25%, additional installed wind power would have to be some 4400 GW in order to replace 1100 GW of nuclear power, almost five times the EREC based (exponential) wind power prediction for 2065. It is also larger than the total wind power estimate for EU should wind farms cover 10% of EU area resulting in average power of about 900 GW and corresponding installed power about 3500 GW.

7. Global estimates of wind power

To obtain an idea on the upper limits of the wind power development for the world, we look at the Global Wind Energy Council and Greenpeace 2010 predictions given to the year 2050 [20]. WEC Survey of energy resources [22] does not give predictions for installed capacities in 2050 but discusses conditions which are important for wind power development. Highest prediction by GWEC-Greenpeace for the year 2050, designed as "advanced" variant, is 4.5 times above their "reference prediction" (880 GW), and amounts to 4000 GW of installed wind power. By extrapolating advanced variant with the 2% increase assumed before 2050, we obtain about 5400 GW of installed power in 2065. Even this highest prediction, with optimistic assumption on average energy conversion efficiency (25%), and corresponding annual production of about 14000 TWh, leaves a large space to be covered by other renewable energy sources in order to reach the required renewable energy carbon free energy production between 27290 and 33540 TWh remaining after contributions from 3300 GW of nuclear power and from the energy saving and increased efficiency of energy use, equivalent to 10 to 16 $GtCO_2$-eq of emission reduction. It should be also noted that in case of very high expansion of wind power some material limitations may occur. One of these may be the scarcity of neodymium and dysprosium, rare earth elements needed in production of permanent magnets.

8. Solar contribution in EU and globally

According to EREC, again, solar photovoltaic and CSP installed power in EU in 2050 would be some 1000 GW (peak) producing close to 2000 TWh of electricity. If, again, we assume doubling in the years from 2050 to 2070, we reach the figure of about 1500 GW peak in 2065 and the electricity production on the level of 3000 TWh. With capacity factor of 0.8 one GW of nuclear power produces 7 TWh per year, so 3000 TWh could be produced by 430 GW of nuclear power. To estimate the physical limits on solar power in EU we can again use the value for solar energy density for EU region. Taking average solar power per m2 of 100 W, a figure for Britain which cannot be far from average for EU [21] and energy conversion efficiency of 15% for mass produced solar photovoltaic cells we get the average solar power of 15 W/m^2, much larger then the average wind power. With an area of 9000 m^2 per person in EU and with solar farms on the 10% of total area (which includes buildings, roads, water, arable land etc) we obtain average solar power per person in EU on the level of 15x900 = 13500 W, and energy production of 324 kWh per day per person. By transforming EU total energy consumption of 1800 Mtoe [23] into equivalent amount in kWh, we obtain the considerably smaller figure of 115 kWh/day for the average of primary energy consumption in 2010. Our physical limit on solar energy production would come to the high figure of about 59 000 TWh/year, while the total energy consumption in 2010 in EU amounted to 21 000 TWh. No doubt, even for relatively densely populated EU theoretical physical potential of solar energy is abundant enough to replace 1/3 of the nuclear reactors (EU share) from the global 3300 GW nuclear strategy shown in figure 1, i.e. 1100 GW which would produce about 8000 TWh/year. Thus, in order to judge what could be real contribution of solar energy in the years to 2065 we must look into economic and technical parameters which limited the production of solar energy in 2007 in EU to only 6.2 TWh (EREC, PV + CSP) and to about double the figure in the world. Can solar energy production be increased at least thousand times by 2065 in order to replace nuclear contribution of about 26000 TWh (figure 1) to carbon emission reduction? There is a very rapid increase from the present low level of solar power but sustained high growth and an increase by a factor 1000 in the course of 50 years cannot be taken as granted without consideration of essential developments of solar materials towards higher efficiency and lower costs. If such sustained high growth is to take place then also energy required to produce solar installations should come into consideration. If the installed power is to double in approximately every five years, as implied by growth with a factor of 1000 in 50 years, then each operating solar installation in five years should produce at least the amount of energy for production of materials and construction of another installation. Energy balance or yield of an energy installation is expressed with the ratio between lifetime production of energy and the energy needed to produce required materials and construct the installation. For roof mounted solar installations yield would be in the range 5 to 10 depending on the technology and location [24, 25]At the lower yield limit, applicable for developed northern world regions, and the lifetime of 20 years, 4 years would be needed to cover the energy for materials and construction. Applying this estimate to an expanding solar system with doubling time of five years we see that available net energy will be significantly reduced relative to the nonexpanding system. In our example about 80% of energy produced would be used to support the expansion of the system. The point we wish to make is that however large be the potential of solar energy it cannot be reached in a very short time. An increase by high factor (significantly larger than 1000 in 50 years) would pose a problem at least in the regions of lower yield factors. Another issue is economy. At present solar installations costs economic burden on EU of building at least 4000 GW peak of solar photovoltaic installations in order to replace 1100 GW of nuclear power would be staggering. Even with the cost per unit peak power at the level of nuclear power, due to efficiency factor not above 0.2, the cost of solar installations per unit produced energy would be about 4 times higher. In production of large amounts of energy economic considerations have been decisive in the past, there is no reason to expect much change in the future. Globally the theoretical sufficiency of solar energy is even more evident, as EU is not optimal location considering the intensity of solar radiation. However, for many regions where physical conditions for solar energy use are better, economic constraints are stronger, limiting development. Investments from developed industrial countries could help, but this is not an immediate future. Important point in this discussion is that we look at the period up to the year 2065, critical for the climate control. In spite of a large and in the long run abundant potential of solar energy, its contribution in coming decades is limited by economic constraints. With intensive development of solar materials this may change. This will certainly be a very welcome development. However, the known times from scientific discovery to the very large scale applications do not warrant that this will take place in the years up to 2065, early enough to abandon nuclear contribution. As we have noted, there is a physical limit on the rate of growth of solar installations beyond which the effect on carbon emission reduction becomes negative.

9. Renewable energy on the world scale

In view of cost disadvantage of renewable sources it can be expected that their large scale deployment will be undertaken largely by the developed industrial countries; EU as leading region, North America, but also by rapidly developing countries such as China and India where conventional fossil sources pose serious problems to environment. However, some relevant well founded predictions, rather than wishful thinking, for world renewable sources do not exist. It is however very important to have some picture about energy scene up to 2065. Large thermal power stations built now may be still operating in sixties. One generation in conventional energy production is much longer then in communication technology, while renewable sources technology is somewhere in between. We cannot answer the question on the need or not of nuclear power in 2065 without some estimate on the probable or possible contributions from renewable sources. We venture to make a guess on the future of renewable sources fully aware of very large uncertainties. In view of this, our approach is to choose somewhat easier task, to make an upper limit estimate. Should the upper limit contribution from renewable sources turn out to be insufficient for coming down to WEO 450 strategy from the WEO reference strategy argument will stand for nuclear contribution. To obtain estimate for global contribution of renewable energy we start from EREC (European Renewable Energy Council) predictions for EU and use it as guidance, trusting that their predictions do not underestimate the prospects for renewable energy. For North America we assume approximately equal contribution of renewable sources per capita as in EU; prediction analogous to EREC for North America would then come between 1800 and 2300 GW, figures corresponding to prediction range for EU region of 2700 and 3000 GW, respectively.

For Asian region predictions are rather more uncertain. So globally we estimate probable upper limit of world renewable power in 2065 capacities (GW) and contribution to energy production (table 2) by equating contributions of North America with that of India, and of China with EU:

Table 4 Projection of world renewable energy installed power in 2065

Population millions	500	350	1300	1400		7000 (present)
Region	EU	North Amer.	India	China	Rest**	World
Estimated renewable power GW	2700-3000*	1800-2300	1800-2300	2700-3000	2000-3000	11000-13600

* prediction range results from linear and exponential extrapolation of EREC values for 2050 to 2065 **main contributors South Korea, Japan, Brazil, Indonesia

In adopting these figures considerations were made of starting positions, population, rate of development, and of awareness of environmental problems. With all that figures can be only tentative. So far economic science was reasonably good in explaining past events, but rather less successful in predictions. If the world had time to wait, better data would be available. Using the EREC average ratio between installed power and energy production (2.66 TWh/GW) i.e. the same average efficiency of, we obtain in the last column a range of estimate for the upper limit of world renewable sources installed power. Corresponding values of annual energy production are 29 260 TWh and 36 180 TWh.

10. Required And Predicted Renewable Sources Production

These figures can be now compared with the required contributions of non nuclear energy sources as shown in figure 1 in order to reach WE0 450 values of allowed emission. Within the analysis presented in figure 1 when nuclear contribution of 25.2 $GtCO_2$ is subtracted from the total reduction to WEO 450 trajectory amounting to 67.4 $GtCO_2$-eq we obtain 42.2 $GtCO_2$-eq to be covered by renewable sources, energy efficiency, energy saving. As elaborated above impossibility to predict energy saving and of increased efficiency is reflected in a wide range for our prediction; from 10 $GtCO_2$-eq to 16 $GtCO_2$-eq of emission reduction in 2065. The reduction which would remain as a task for renewable sources would be, consequently, in the range from 26.2 $GtCO_2$ to 32.2 $GtCO_2$. If these emissions were produced by coal power plants corresponding quantities of energy would be 27290 TWh and 33540 TWh. To replace coal plants this amount of energy would have to be produced by renewable energy sources. It would increase if the thermal power plants included gas plants. However, for our discussion we are interested in a minimum demand on renewable energy required to reach WEO 450 trajectory from the WEO Reference trajectory in 2065. However, we see that these values of required contributions from renewable sources correspond reasonably well with the figures for predicted renewable energy production in the range from 29260 to 36180 TWh, especially as we cannot be sure to reach highest emission reduction of 16 $GtCO_2$-eq from the energy efficiency and saving sector, and highest production of 36180 TWh by renewable energy sources.

Table 5 Balance of emission reductions from the WEO 2011 Reference scenario to the WEO 450 strategy.

Emission reduction from operation of 3300 GW of nuclear power in 2065	25.2 $GtCO_2$ (26250 TWh)	25.2 $GtCO_2$ (26250 TWh)
Emission reduction by energy saving and increased efficiency in 2065	10 GtC02-eq	16 $GtCO_2$-eq
Required reduction by renewable sources in 2065	32.2 $GtCO_2$	26.2 $GtCO_2$
Renewable sources; corresponding required production in TWh and in average power in GW	33540 TWh 3830 GW	27290 TWh 3120 GW
Upper limit estimate of global production by renewable sources in 2065, TWh and corresponding emission reduction in $GtCO_2$*	29260-36180 TWh 3340 – 4130 GW 28.1-34.7 $GtCO_2$	29260-36180 TWh 3340 – 4130 GW 28.1-34.7 $GtCO_2$

Total required reduction to reach WEO 450 Strategy trajectory from WEO Reference strategy emission in 2065 amounts to 67.4 $GtCO_2$-eq. (fig.1). Figures refer to total anthropogenic emissions. Required contribution from renewable sources is obtained by subtraction of nuclear and energy saving and efficiency increase emission reduction from the total, third and fourth row. Two values given in the table 5 for renewable sources production (last row) are linear and exponential extrapolation of EREC and GWEC data from the year 2050 to 2065 determining a range for predicted upper limit of renewable energy contribution.

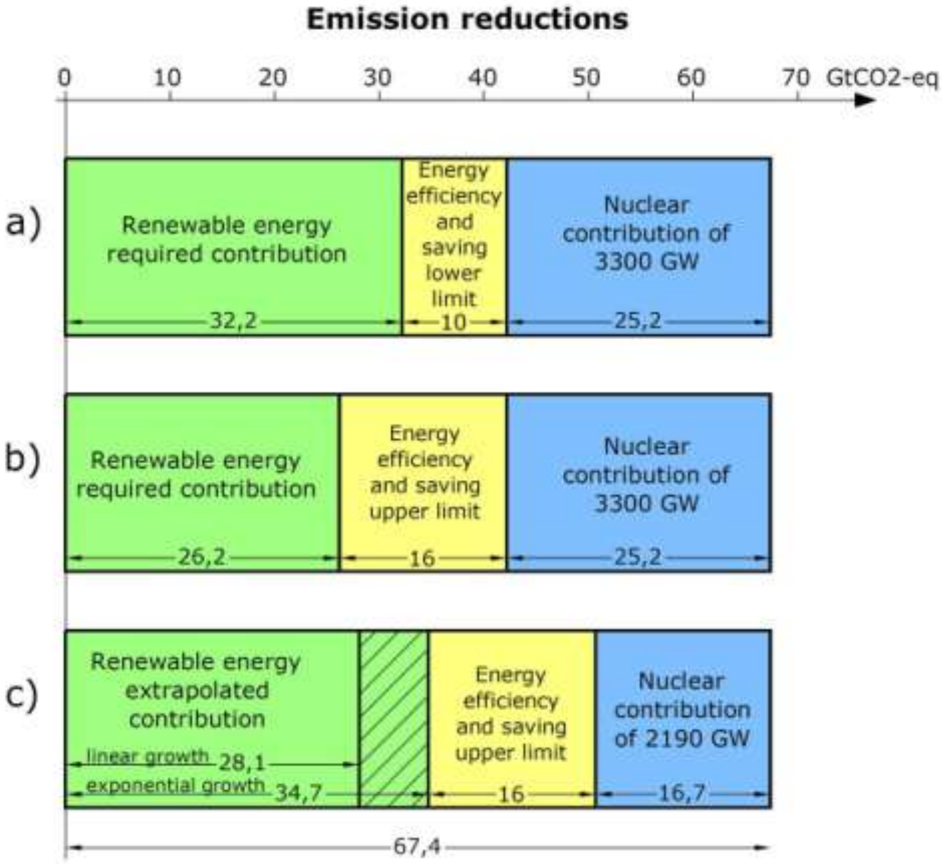

Figure 2: Graphic presentation of contributions to carbon or equivalent emission reduction by 2065

Shadow belt is the range for the high prediction of contribution from renewable sources. Range is determined by linear, respectively exponential extrapolation from 2050 values. Box a) depicts a situation with lower limit of reduction by energy saving and other ways of reducing emission outside power production sector.

Case of high limit is depicted in box b). Contribution from power sector are given in $GtCO_2$, while contributions from energy saving etc are given in $GtCO_2$-eq. Case c) presents a minimum nuclear contribution required, resulting when maximum contributions from renewable sources and upper limit of energy saving and efficiency increase are combined.

11. Discussion

A look at the table 5 gives some quantitative insights about the energy strategy that could by 2065 fulfil the aim of reducing the carbon emission from the unacceptable WEO 2009(2011) Reference strategy down to the WEO 2009(2011) 450 strategy. With nuclear energy contribution defined by specific constraints and reaching 3300 GW of power by 2065, we obtain the required production of renewable energy by the year 2065. This is important as it can be compared with the predictions for build-up of renewable sources and offers an answer on the role of nuclear power in the same time period. We see that renewable energy predicted production could match the requirement, but only after nuclear power has given its contribution. Smaller nuclear contribution would require increased contribution of renewable energy. Without nuclear contribution production of renewable sources would have to be about doubled, which must be considered completely unrealistic in view of generous optimistic estimate of their production in 2065.

Whilst these conclusions should be of importance for future structuring of energy plans and strategies, one should be aware of unavoidable limitations and several caveats should be given. The figures presented in table 5 are, of course not predictions, they are an attempt to guess now about the future 50 years ahead. Nuclear build-up to 3300 GW by 2065 reducing CO_2 emission by 25.2 $GtCO_2$ is a maximum based on the conventional uranium resources known in 2007, with conventional reactor technology and without fuel reprocessing and plutonium recycle. The point of selecting this nuclear strategy was to show what can be achieved with these, in our opinion, very desirable constraints. More detailed discussion on the reality of such nuclear contribution with the constraints imposed is given in our earlier study [13]. It also discusses the fuel sufficiency after 2065. Further details which show that with advanced nuclear technologies of Generation 4 sufficiency of nuclear fuel should not be a problem are given in [13,26]. We could not have the same confidence in predicting the contribution to emission reduction from energy saving, from increased efficiency of energy use and from many other ways, some unknown today, which could reduce carbon emission. In evaluation of nuclear contribution adopted constraints of conventional technology, fuel cycle and uranium resources help predictions, whilst the amount of emission reduction through energy saving and better use of energy will be determined by future developments and innovations. Thus, there is large range from 10 to 16 $GtCO_2$-eq for reductions from that sector. Graphic presentation on figure 2 should help to offer some further insights about future energy mix. In estimation of future contribution from renewable sources we adopted high predictions based on European Renewable Energy Council and on Global Wind Energy Council, as shown in box c). From the box c) of the figure 2 we see that by combining the high production of renewable energy, corresponding to emission saving of 34.7 $GtCO_2$ with the upper value of emission reduction by energy saving of 16 $GtCO_2$-eq, required nuclear contribution would be reduced to 16.7 $GtCO_2$, respectively to about 2190 GW in terms of installed power in 2065. With maximum contributions from renewable energy and from energy saving etc, 2190 GW of nuclear power would be needed and sufficient to cover the required reduction of 67.4 $GtCO_2$-eq. However, if with high predictions on contributions from both renewable sources and from energy saving, the need for nuclear contribution still remains, then a very important conclusion about the nuclear energy future follows. That is, 2190 GW of nuclear power seems to be the minimum required to reach the WEO 450 trajectory in 2065. This would require about 1800 GW in addition to present about 380 GW. We pointed out that physical limits exist on the wind energy capacity and on the solar energy rate of growth. Should, hopefully, through intense international efforts high predictions on renewable sources be realized, then together with nuclear contribution with additional 1800 GW and with contributions from energy saving, efficiency increase etc, on the level of up to 16 $GtCO_2$-eq, World could succeed in coming down from WEO 2011 Reference scenario to WEO 450 scenario by 2065. Clearly, only future developments will give more certainty. However, before we have more certainty this analysis tells us that abandoning nuclear contribution would be a risky game with the future of our planet.

Neither CCS, nor nuclear fusion is likely to give essential contribution before 2065, although it is impossible at present to foresee the role of these technologies in later years. Developments of photovoltaic materials are faster and situation would be different with drastic reduction of their costs. That may or may not happen soon enough. If delayed it may not be possible to benefit fully from it in the period up to 2065. Whilst physical potential of solar energy is undisputed, actual deployment is much lower, limited by economic considerations. Should future developments of solar materials remove economic disadvantages, there would still remain a physical limit on the rate of growth preventing a very rapid build-up of solar power. If we cannot be sure of timely and favourable developments, we must plan for less favourable and the technologies we now have at our disposal. Nuclear technology is one of these. Whilst one can place solar installations in a number of sun-rich countries, nuclear contribution should come primarily from industrialized countries and regions which have industry, knowledge and experience in the field required to build reliable and safe nuclear power plants. This may be one lesson of Fukushima accident. EU is one such region, and is also a region with high intensity of carbon emission. If we accept that climate problem will not be resolved without nuclear energy then EU would fail in its responsibility and in solidarity with the less developed regions of the world by not contributing to carbon emission reduction in the critical period to 2065 with its nuclear energy sector for which EU possesses an outstanding potential and capabilities. With all the unavoidable uncertainties we hope this study offers some guidance for the future energy strategies.

12. Summary

Considering the necessity and future role of nuclear energy as relevant to the climate problem, we have focused on the period to the year 2065. The reasons for this choice are twofold; first, this is a critical period for achieving the essential 80% CO_2 emission reductions and, secondly, this is the period during which large contributions from fusion and carbon separation and storage are not likely. For quantification of the required emission reduction we have used IEA WEO 2009 and WEO 2011 data as presented in their Reference strategies predicting emissions with business as usual practices, and WEO 450 Energy strategies which show the time development of allowed emissions consistent with a limit on the global temperature increase of 2C and the peak CO_2 concentration of 450 ppm. From the 2035 and 2050 values of total anthropogenic CO_2eq emissions given in WEO 2011 and WEO 2009 we extrapolated the Reference strategy and WEO 450 strategy to the year 2065. With Reference emission in 2065 reaching 77.4 $GtCO_2$-eq and WEO 450 strategy allowing emission of 10 $GtCO_2$-eq we obtain the reduction required by 2065 amounting to 67.4 $GtCO_2$-eq in order to come down to sustainable WEO 450 trajectory. Main carbon non-emitting sources assumed in the years up to 2065 are proven technology nuclear fission and renewable sources. Shorter period, more desirable from the climate control view, would correspondingly increase technical and economic demands in development of required carbon free energy production capacities. Even with the year 2065 as a compromise there is a giant task facing renewable sources in the mixed energy strategy which includes nuclear power, if by that year total anthropogenic GHG emission is to be reduced to 10 $GtCO_2$–eq. In our specified strategy aimed to achieve WEO 450 target we assumed an energy mix including nuclear power build-up in the period 2025-2065 to the level of 3300 GW in 2065. With the resulting nuclear contribution of 25.2 $GtCO_2$ to the total required reduction down from the WEO 2009 reference strategy amounting to 67.4 $GtCO_2$ in 2065, what remains for renewable sources, energy saving and increased efficiency of energy use to contribute are prodigious 42.2 $GtCO_2$-eq. In the absence of estimates about contribution of renewable sources going as far as 2065, we had to make reasonable guesses trying not to underestimate their possible contributions. Relevant energy policy cannot be deduced by looking only two or three decades in advance when construction and the lifetime of energy installations can be 50 years or more. Our estimates are based on EREC prediction for EU and on our extension to world total with EREC and GWEC prediction as a guide. Resulting contributions by renewable sources, probably their upper limits, allow some conclusions about the role of nuclear energy in future decades. Assuming that energy saving and more efficient energy use will by 2065 effect an annual reduction between 10 to 16 $GtCO_2$-eq, remaining 26.2 to 32.2 $GtCO_2$, respectively 27290 and 33540 TWh would be the task for the renewable energy sources as presented in table 5 and in figure 2. Our high, but still credible estimates of predicted world renewable energy contribution by 2065 come to the similar figures between 29260 and 36180 TWh. However, as is evident from table 5 and figure 2, even so without nuclear contribution in 2065, renewable energy contribution would have to be doubled, practically impossible task in the time period in consideration and in view of their generous predictions. By combining highest contributions from energy saving, efficiency increase and other measures to reduce emission, apart from energy production, with highest prediction for renewable sources contribution, we obtain the minimum nuclear energy requirement of about 2190 GW in 2065. This minimum nuclear strategy should be planned and prepared for, unless there is strong evidence that other carbon free energy sources (CCS or fusion) could be developed in time. Expansion of nuclear power by about 1800 GW by 2065 would come from different and already developed industrial sector, which can give its contribution to the energy mix, without obstructing the build-up of renewable sources. It would not be wise to forfeit nuclear contribution at least in the period to 2065, critical for the control of climate change.

13. Conclusions about the future of nuclear power

1. After combining a reasonably largest prediction of carbon emission reduction from the renewable sources (36180 TWh, respectively 34.7 $GtCO_2$ in 2065) with a maximum predicted reduction from energy saving, efficiency increase and other non-energy methods of carbon emission reduction (16 $GtCO_2$-eq in 2065), about 16.7 $GtCO_2$ of further reduction is still missing in order to reach a total of 67.4 $GtCO_2$-eq required to bring in the year 2065 the WEO Reference energy strategy down to the WEO 450 energy strategy limiting the global temperature increase to 2C.

2. Gap could be closed by operating about 2190 GW of nuclear power in 2065. In view of the assumed high predictions for renewable energy and for energy saving, this figure should be considered a minimum future need. Plans for about 1800 GW of nuclear power, additional to presently operating about 360 GW should be discussed and coordinated. For political, technical and public reasons, plans should be realized with proven conventional technology and with once through fuel cycle, while the new technologies can be prepared for the years after 2065.

3. Whilst the need for nuclear (fission) power appears to be clear for the period to about 2065, its long term future will be determined by developments of alternatives such as CCS or nuclear fusion, and whether the period up to 2065, during which conventional nuclear technology without reprocessing can be adequate, will be used for development of political and technical institutions and technologies for the safe use of U238 and Th 232, that would make nuclear fission practically inexhaustible source of energy.

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