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How much can nuclear energy do about global warming?

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Abstract: The framework MESSAGE from the IIASA fulfills the IPCC requirement RCP 2.6. To achieve this, it proposes the use of massive deployment of Carbon Dioxide Capture and Storage (CCS), dealing with tens of billion tons of CO_2. However, present knowledge of this process rests on a few experiments at the annual million tons level. MESSAGE includes three scenarios: 'Supply' with a high energy consumption; 'Efficiency' which implies the end of nuclear energy and the intermediary 'MIX'. We propose, as a variant of the MESSAGE framework, to initiate a sustained deployment of nuclear production in 2020, reaching a total nuclear power around 20,000 GWe by the year 2100. Our scenarios considerably reduce the interest or necessity for CCS. Renouncing nuclear power requires an energy consumption reduction of more than 40% compared to the 'Supply' scenario, without escaping the need to store more than 15 billion tons of CO_2.

Keywords: 2100 energy scenarios; carbon dioxide; nuclear power; carbon capture storage; fast breeder reactors; CANDU reactors; cost; sustainability; risks; wastes.

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1 Introduction

The recent IPCC (2014) report (AR5) stresses, once more, the seriousness of global warming. In order to make the climate models' results comparable and to give the same objectives to the various emission scenarios, IPCC has selected four 'Representative Concentration Pathways' (RCPs), encapsulating the full range of likely Greenhouse Gas (GHG) concentrations evolution. Each of the four RCPs is labelled according to the value of radiative forcing obtained in 2100 by the specific integrated model[1] emissions profile. RCP2.6 (W/m^2 radiative forcing) scenarios are the only ones which could limit the increase of global temperature to less than 2°C. The Integrated Assessment Modeling Consortium (IAMC) has stressed two scenario frameworks, IMAGE and MESSAGE. Both are described in detail on the IIASA website (GEA Scenario database, Version 2.0.2, http://www.iiasa.ac.at/webapps/ene/geadb/dsd?Action=htmlpage&page=regions). These frameworks are subdivided into three scenarios 'Supply', 'Mix' and 'Efficiency' that refer to decreasing energy consumption levels.

1.1 The Carbon Capture and Storage bet

All of these scenarios rely upon capture and storage of large quantities of CO_2, as can be seen in Table 1.[2] Rates of Carbon Capture and Storage (CCS) reach yearly values of as much as 50 Gt/yr in 2100. By comparison, present experience with this technique is of the order of a few million tons.

Table 1 CO_2 mass yearly stored in 2100 (million tons) for the scenarios of IMAGE and MESSAGE frameworks. In 2010, annual CO_2 world emissions value was 31 billion tons (14 related to coal, 11 to oil and 6 to gas). Present CCS experiments deal with only a few million tons

	Supply	*Mix*	*Efficiency*
MESSAGE	23,900	15,200	15,200
IMAGE	50,000	43,200	26,500

Source: IIASA website (http://www.iiasa.ac.at/webapps/ene/geadb/dsd?Action=htmlpage&page=regions)

Table 1 compares the CO_2 masses yearly stored, in 2100, for the MESSAGE and IMAGE scenarios.

Storage needs of the IMAGE framework are much larger than those of the MESSAGE ones. Indeed, the IMAGE framework relies much more on a persistent use of fossil fuels. Since our primary goal is to decrease the need of yet unproved CCS, we focus on the MESSAGE framework and its three scenarios.

1.2 CCS in China

Since China is, by far, the world's largest user of coal, the prospects of CCS in China are of utmost importance. In China, coal consumption is proportionally high, representing 66% of the primary energy supply. The level of coal use severely impacts China's GHG emissions and air pollution, in particular smog.

CCS has been considered by many research institutions as the only possible and available solution for mitigating carbon emissions from coal-fired power production. However, over many years there has been very little investment in CCS worldwide. For emerging economies, the high costs of CCS R&D have been a barrier for achieving significant progress. China has been involved in a couple of small carbon capture utilisation experimental projects, but no project has been extended to storage. Several factors will likely limit China's further efforts in coming years:

- Heavy investment costs for individual plant investors R&D.
- Concerns related to unreliable safety measures for storage; plants are too close to the power load centre.
- China has not mastered *integrated gasification combined cycle* technology.
- CCS application will reduce power plant efficiency and add to production costs.

In addition, it is difficult to foresee any further CCS technological breakthroughs that would realistically lead to commercialisation, at least in the absence of a very strong and sustained carbon price. Therefore, for China, nuclear power is the only reliable, practical and mature energy source which could reduce China's massive coal-fired reliance while maintaining grid stability.

1.3 Main features of MESSAGE framework

The main features of the three MESSAGE scenarios are energy consumption, CO_2 capture and energy mix.[3] Table 2 shows the values of the main aggregates retained by the three scenarios in 2100. We note that all scenarios imply the same world population and the same world income.

Table 2 Main parameters of the MESSAGE RCP2.6 scenarios in 2100 and corresponding 2010 values. Net CO_2 emissions equal the difference between gross emissions (mostly due to fossil combustion) and stored CO_2 including from biomass combustion

	Final energy (EJ/yr)	*Primary energy (EJ/yr)*	*CO_2 captured and stored (Mt/yr)*	*Electricity (EJ/yr)*	*Net CO_2 emissions (Mt)*	*Gross CO_2 emissions (Mt)*	*PIB (G$)*	*World population (millions)*
2010	343	470	0	73	36,000	36,000	45,237	6900
Supply	755	1061	23,900	677	–18,350	55,50	366,139	9500
Mix	616	856	15,175	487	–13,288	1887	366,139	9500
Efficiency	427	617	15,198	297	–14,630	548	366,139	9500

Source: IIASA website (http://www.iiasa.ac.at/webapps/ene/geadb/dsd?Action=htmlpage&page=regions)

The scenarios differ by their energy consumption and energy mix, and, as a consequence, by their CO_2 emissions. Table 3 summarises the contribution of the main sources to primary energy in 2100.

Table 3 World energy mix in 2100 for the three MESSAGE scenarios (primary, secondary and final energies[a] in EJ[b]). For solar production, numbers between brackets correspond to electricity production, the complements being used for direct heat production. For comparison, we have given nominal installed power in 2100, for nuclear, wind and solar PV plants for the supply scenario

	Total	*Coal*	*Natural gas*	*Oil*	*Nuclear*	*Biomass*	*Hydro*	*Wind*	*Solar*
2010	470	136	100	165	10	45	12	1	1
Supply (EJ)	1061	75	64	2	251	221	33	89	326(289)
Supply (GWe)					8600			9750	81300
Mix (EJ)	856	18	100	4	138	221	33	70	272(235)
Efficiency (EJ)	617	41	46	3	0	221	23	34	249(220)

Notes: [a]For definitions of primary, secondary and final energies, see Appendix 1.
[b]1 EJ = 10^{18} J = 277 TWh = 24 Mtep.

Source: IIASA website (http://www.iiasa.ac.at/webapps/ene/geadb/dsd?Action=htmlpage&page=regions)

Note the importance of solar production. With present photovoltaic cell performances, the foreseen production of 289 EJ corresponds to a surface coverage of 1 million km^2.

Table 4 Cumulated use and remaining workable stocks of fossil fuels in 2010 (GEA, 2012, Table 7.1) for the three MESSAGE scenarios

	Coal ZJ	*Oil ZJ*	*Natural gas ZJ*
Cumulated use 2100 'Supply'	13.6	12.1	14.9
Cumulated use 2100 'MIX'	10.04	11.9	15.1
Cumulated use 2100 'Efficiency'	10.8	12.1	11.9
Reserves 2010	21	7.1	7.6

Note: 1 zetajoule (ZJ) = 1000 EJ = 24 Gtep

Sources: http://www.iiasa.ac.at/webapps/ene/geadb/dsd?Action=htmlpage&page=regions; http://www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/Chapter1.en.html

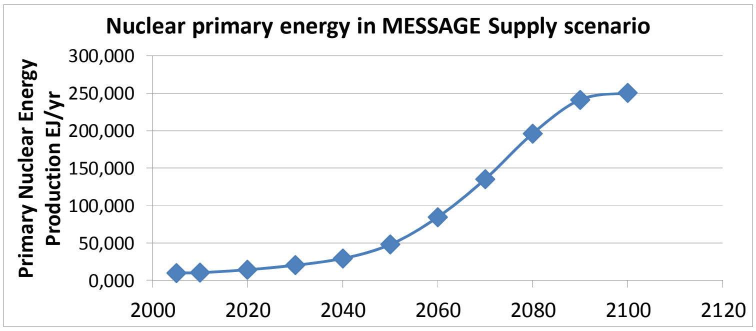
Table 4 gives the cumulated use and the workable remaining stocks of fossil fuels. By 2100, oil reserves will be practically exhausted, and natural gas significantly reduced. Only coal will remain plentiful. In practice, its use will be restricted by the climatic constraint.

2 The MESSAGE scenarios

2.1 The MESSAGE 'Supply' scenario

The MESSAGE 'Supply' scenario foresees a nuclear electricity contribution of 251 EJ, i.e. 69,000 TWh, which could be produced by 8600 1-GWe reactors. The time evolution of nuclear production is shown in Figure 1. It is seen in this figure that almost all the new nuclear power would start operation between 2050 and 2090.[4] For the original Supply scenario, the type of reactors and uranium resources management are not specified.

Figure 1 Evolution of nuclear electricity production in the MESSAGE 'Supply' scenario (supply nuclear) (see online version for colours)



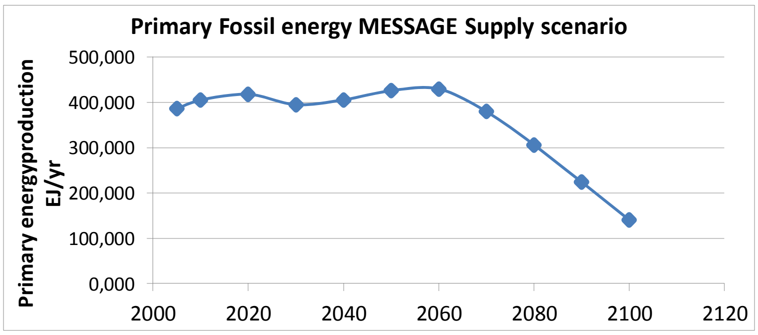
Source: Supply nuclear, http://www.iiasa.ac.at/web-apps/ene/geadb/dsd?Action=htmlpage&page=regions

During this period, nuclear production would increase by 200 EJ, corresponding to that of 7000 1-GWe reactors. This increase corresponds to a factor of 5.2 in nuclear production in 40 years, i.e. an annual increase of 4.2%.

Most of the increase of the nuclear production is supposed to take place in Asia, as can be seen in Figure B1 in the Appendix 2 (A.2.2).

In the original MESSAGE Supply scenario, the share of electricity as a percentage of final energy use jumps from 21% in 2010 to 89% in 2100. This sharp increase is related to a revolution in the nature of car motorisation, switching from gas to electricity or hydrogen (itself produced by electrolysis). We have kept this feature of the original Supply. Our work is based on the development of nuclear power 40 years earlier and includes a discussion of the physical possibility of such development with respect to uranium reserves, not present in the original scenario.

Figure 2 Evolution of the fossil production in the MESSAGE 'Supply' scenario (supply fossil) (see online version for colours)



Source: Supply fossil, http://www.iiasa.ac.at/web-apps/ene/geadb/dsd?Action=htmlpage&page=regions

Figure 2 shows the evolution of the fossil production in the original Supply scenario. It decreases by a factor of 4 between 2050 and 2100 when the nuclear production increases rapidly.

We suggest starting the nuclear reactor implementation program in 2020 rather than 2060. Thus, CO_2 emission reduction will start earlier and the amount of CO_2 in the atmosphere will be considerably reduced, hence alleviating considerably the need of CCS, a technique still not well mastered and currently very expensive. It might also allow a more moderate contribution of solar energy. The key point is to evaluate whether such an acceleration in nuclear energy development is physically, technically and economically realistic. We specifically concentrate on a 'nuclear' variant of the 'Supply' scenario which we label 'Supply-N'. We shall also evaluate the effect of such an earlier start of nuclear energy development on a 'MIX-N' scenario.

2.2 The supply-N scenario

2.2.1 Uranium reserves and breeding

The possibility of a strong increase of nuclear production depends on the uranium reserves and on the extension of breeding processes. The rate of development of a breeder reactor fleet depends on the breeding coefficient and on the plutonium amount present in the fuel cycle. As for the breeding coefficient, we use values observed in the 'Superphénix' case (https://fr.wikipedia.org/wiki/Superph%C3%A9nix#Bilan_neutronique_de_Superph.C3.A9nix), a 1240 MW sodium-cooled fast-neutron reactor which worked in France at full power during 1 year before being stopped in 1998 for political reasons. Normalised to a 1 GWe reactor, the mass of plutonium in the core is 4 tons, while the net production of plutonium is 0.2 ton/yr. Based upon the PUREX (https://fr.wikipedia.org/wiki/PUREX) aqueous phase reprocessing technique, about 4 tons of plutonium are present in the fuel cycle. This corresponds to a doubling time (time after which one breeder reactor produces enough plutonium to start another one) of 40 years.[5]

Use of current thermal neutron reactors is allegedly limited by the uranium reserves, but this is highly questionable on at least a century timescale. Many new mines are being developed, and it should be noted that there are already technologies that can tap the essentially inexhaustible uranium reserves in seawater. The Nuclear Energy Agency (NEA) gives an estimate for 'classical' reserves around 16 million tons (OECD NEA, 2010).[6] Standard PWR reactors require 120 tons of uranium per year per GW (Nifenecker, 2011). For a production of 250 EJ/yr, the number of production years assured with such reserves would be limited to approximately 16 years. Thus, for a sustainable development of nuclear energy, the standard reactors should, essentially, build the plutonium stock necessary for developing the breeder fleet. Full fuel recycling using fast neutron reactors can increase energy utilisation from uranium by more than a factor of 100, providing many millennia of potential electricity production.

2.2.2 Available technologies

Reactors supposed to be used in our proposal are PWR, PHWR and Liquid Sodium Fast Breeder Reactors (FBR or SFR). Experience is quite large with PWRs and PHWRs with 278 PWRs and 42 PHWRs active in the world.

Table 5 Present and past fast breeder characteristics

Country	*Name*	*Years operation*	*Power (MWe)*	*Breeding coefficient*	*Fuel*	*Core*
USA	EBR 2	1964–1994	20		Metallic	
France	Phénix	1973–2009	260	1.12	Mox	Plutonium
Russia	BN600	1980–	560		Mox	^{235}U
France	Superphenix	1987–1998 (political stop)	1240	1.2	Mox	Plutonium
Russia	BN800 (2 sold to China)	2015–	830		Mox	Plutonium
India	PFBR	End of 2016	500	1.05		
China	CEFR	2014–	20			

Only a few FBR are active in the world although several have operated for extended periods of time in the past. Over 300 reactor-years of experience have been accumulated with SFRs, and the large commercial BN-800 reactor has recently begun operating in Russia, so this technology is far from speculative, as can be seen in Table 5

In most cases, nuclear fuel used in FBR is a mixture of uranium and plutonium oxides. Reprocessing facilities in France, UK, Japan and Russia are able to process used fuels from reactors with a total power of 120 GWe, extracting approximately 30 tons of plutonium yearly, enough for starting seven FBR. These are used for the fabrication of mixed uranium–plutonium oxides fuels used in PWR reactors.

The USA used metallic uranium–plutonium fuel for the EBR-2 reactor. Reprocessing of this metallic fuel was repeatedly tested successfully. A commercial-scale facility capable of recycling both metal and oxide spent fuel, based on the pyroprocessing technology demonstrated at the EBR-2, is currently being designed at Argonne National Laboratory in the USA.

2.2.3 Implementation of nuclear development

Our proposal, which shifts forward in time the accelerated development of nuclear production by approximately 40 years, foresees nuclear production of around 500 EJ/yr in 2100, allowing a complete renouncement of fossil energies. Thus, in 2100, the totality of energy needs will be provided by renewable and nuclear sources. An energy production of 500 EJ, corresponding to 140,000 TWh would require 17,000 1-GWe reactors. If these reactors were PWR, uranium reserves would be exhausted after 8 years![7] Therefore, before 2100 all nuclear reactors should be breeders. A similar approach was previously followed by Nifenecker et al. (2003) and Nifenecker (2011) and by a Karlsruhe Institute of Technology (KIT) researchers group (as documented in Romanello et al., 2012 and OECD, 2013). In Appendix C4, it is shown that the required number of FBR could be obtained by varying two parameters, the plutonium inventory and doubling time of the FBR and the fraction of PHWR reactors in the initial nuclear mix. Figure 3 was obtained under the following assumptions:

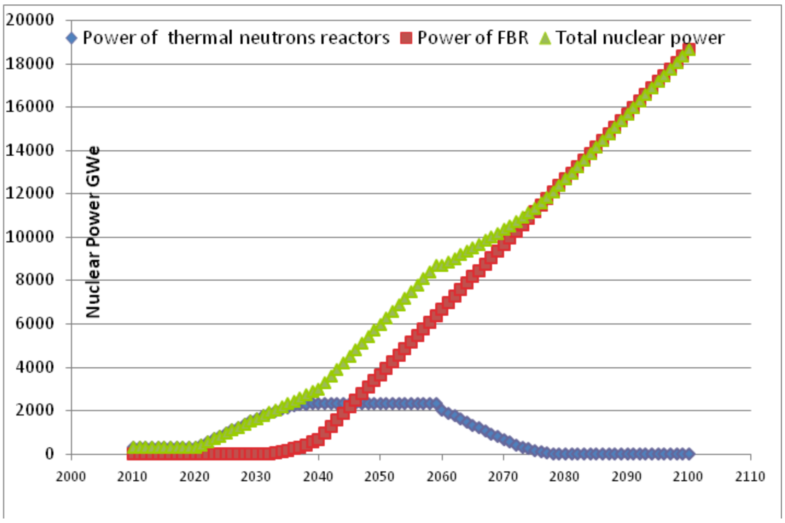
- Annual electricity production: 7.9 TWh/GWe of nuclear power.
- Plutonium production by PWR: 250 kg/yr/GWe, used for building up the initial FBR inventory

- Natural uranium annual needs per 1 GWe PWR reactor: 120 tons/GWe.
- Plutonium production by FBR in addition to that used for core replacement: 200 kg/yr/GWe.
- Total plutonium inventory of a 1-GWe FBR: 5.5 tons of plutonium.

The PWR power plateau is constrained by two conditions:

- Uranium consumption less than 16 million tons, estimated reserves by the NEA.
- Reach 19,000 GWe FBR in 2100.

Figure 3 Evolution of the nuclear installed power for scenario 'Supply-N'.



Note: The details of the calculation is given in Appendix C (Section C5)

Figure 4 Cumulated consumption of uranium in the supply-N scenario

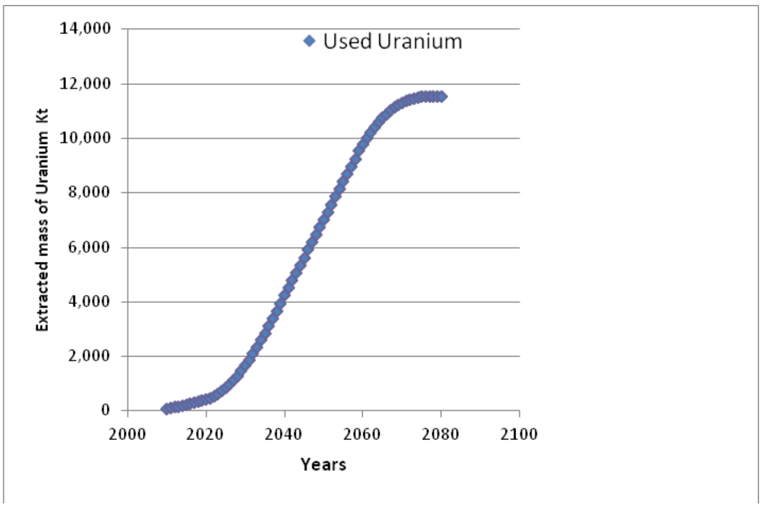
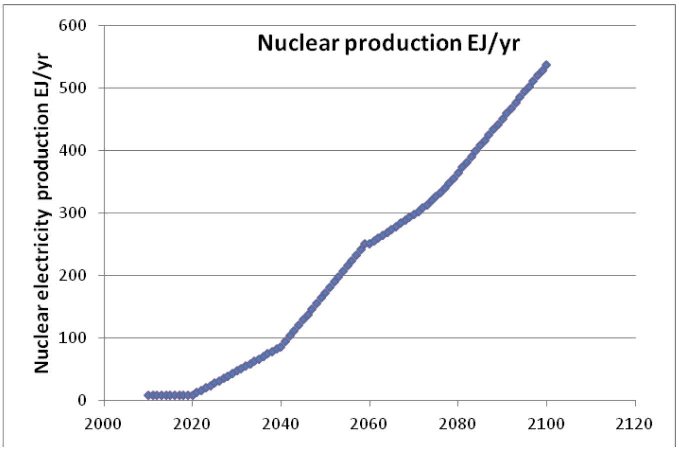


Figure 3 shows the evolution of nuclear power up to year 2100. Thermal neutron reactors are supposed to operate during 50 years.[8] Their total power goes through a plateau of 2325 GWe. The evolution of the consumed uranium is given on Figure 4. It reaches 12 million tons, compatible with the reserve estimates by the NEA.

The total nuclear energy production is shown on Figure 5. It corresponds to the objective of an annual production of 500 EJ/yr. Our article gives the first demonstration that such an objective for nuclear energy in 2100 is possible and to give the conditions required in terms of breeding rates and plutonium inventory.

Figure 5 Evolution of nuclear annual energy production (see online version for colours)



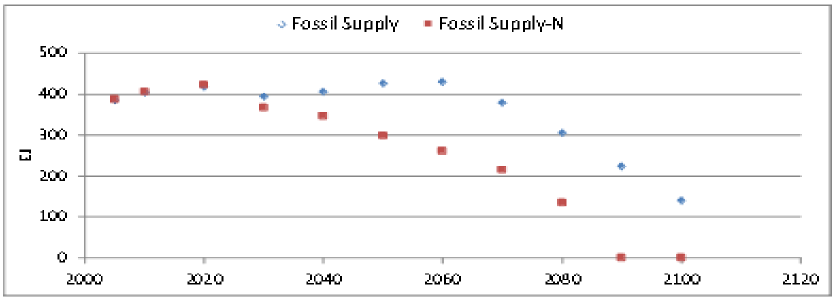
The evolution of nuclear electric power is shown in Figure 5 and peaks at 540 EJ in 2100.

Our approach is to use, primarily, nuclear production for reducing fossil fuels consumption.

2.2.4 *Fossil evolution in supply and supply-N*

Figure 6 compares the fossil consumption of scenarios 'Supply' and 'Supply-N'. In 2090, the Supply scenario still has a consumption of 200 EJ of fossil fuels, while the Supply-N is able to eliminate it.

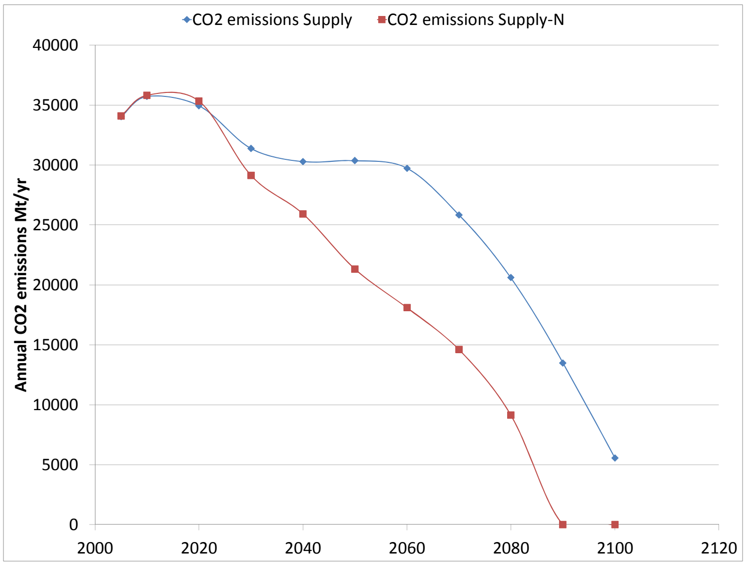
Figure 6 Comparison of fossil fuels consumptions of scenarios 'Supply' and 'Supply-N' scenarios



2.2.5 CO_2 emissions in supply and supply-N

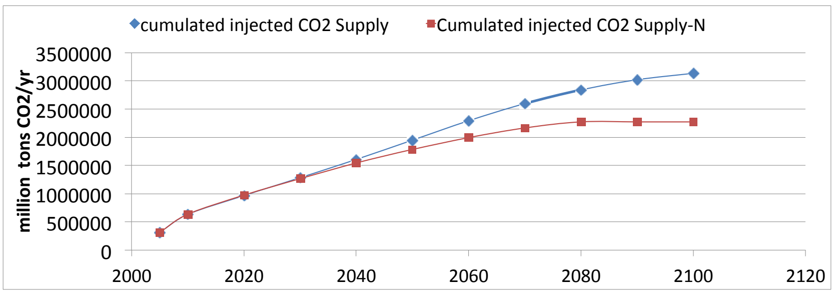
As a consequence of the reduced fossil consumption of the 'Supply-N' scenario, this scenario has lower annual CO_2 emissions, as can be seen on Figure 7, to the point that they vanish in 2090. The integrated emissions are clearly much smaller in the Supply-N scenario.

Figure 7 Comparison of CO_2 annual emissions between the 'Supply' and the 'Supply-N' scenarios



The 40 year shift of the curves leads to an earlier stabilisation of cumulated CO_2 quantities injected in the atmosphere as seen on Figure 8.

Figure 8 Cumulated injected CO_2 quantities for the 'Supply' and 'Supply-N' scenarios



In order to follow the RCP2.6, the IPCC estimates that no more than 1000 Gt of CO_2 should be added to the atmosphere.

These quantities of CO_2 injected in the atmosphere are not compatible with the RCP2.6 path. Without CCS, the Supply scenario would add 3100 Gt CO_2 to the atmosphere, which is 2100 Gt CO_2 more than allowed, and the Supply-N 2300 Gt CO_2, 1300 Gt CO_2 more than allowed. Figure 9 shows that, in order to fulfil the RCP2.6 requirements, the Supply scenario requires storing 25 Gt CO_2 in 2100, while in the 'Supply-N' scenario the CCS needs are limited to 10 Gt.

Figure 9 CO_2 storage needs comparison between 'Supply' and 'Supply-N' scenarios

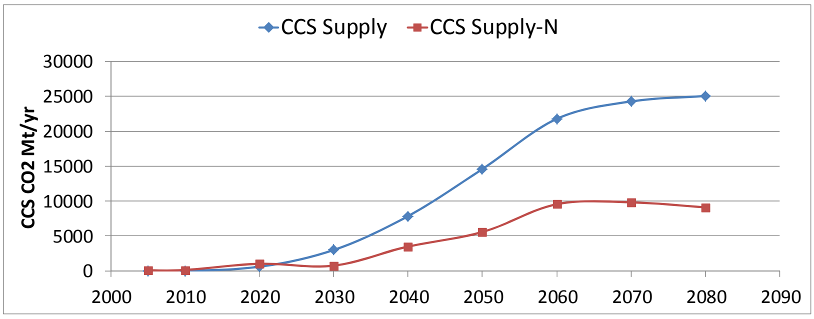


Figure 7 shows that, in the 'Supply-N' scenario, CO_2 emissions are suppressed in 2090. This happens for a nuclear production of 450 EJ. Extending the trend of nuclear production, as done in Figure 5, leads to a value of 540 EJ in 2100. Thus, it would be possible to limit the nuclear production to 450 EJ or to use the 'excess' nuclear production of 90 EJ for reducing further the need for intermittent renewable energy production, such as solar electricity.

2.3 *The 'Mix-N' scenario*

The 'MIX' scenario foresees 137 EJ of nuclear electricity production, equivalent to the production of 4700 GWe of nuclear power. Similar to the 'Supply' scenario, the decrease of fossil use is strongly correlated to the increase in nuclear electricity production. We follow an approach similar to that used for the 'Supply' scenario to modify the MIX into a 'MIX-N' scenario. We assume an increase of nuclear power as given in Figure 5. The fossil production decreases rapidly as can be seen on Figure 10. After the year 2080, no further increase of nuclear production is needed for decreasing fossil fuel consumption. It might be used for relaxing the need for wind or solar production as seen on Table 6.

Figure 10 Comparison of fossil fuels consumptions in the 'MIX' and 'MIX-N' scenarios

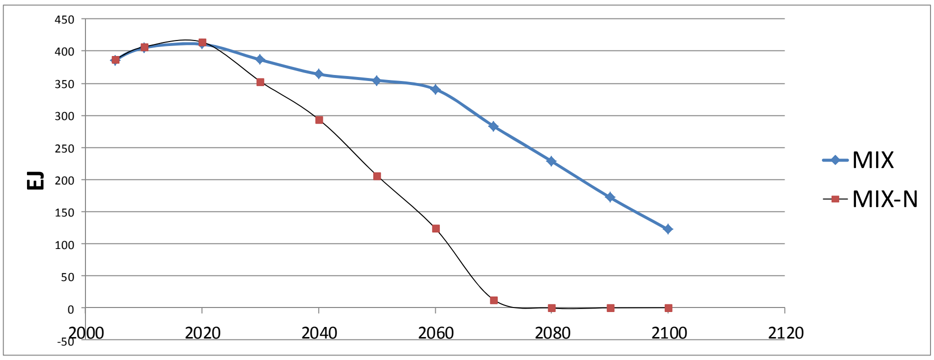


Table 6 World primary energy mix in 2100 for scenarios 'Supply' and 'Supply-N'. The numbers in bracket correspond to the case when nuclear is limited to 450 EJ in 2100

	Total	*Fossils*	*Nuclear*	*Biomass*	*Hydro+geothermal*	*Wind*	*Sun*
2010 (EJ)	470	401	10	45	12	1.2	1
Supply (EJ)	1071	141	251	221	43	89	326
Supply-N (EJ)	1071	0	540 (450)	221	43	89	178 (268)

Table 7 shows the comparison of the energy mix between MIX and MIX-N scenarios. There the excess nuclear production between 2080 and 2100 was used to decrease the contribution of wind and, especially, solar energy, whose intermittent nature may be difficult to manage.

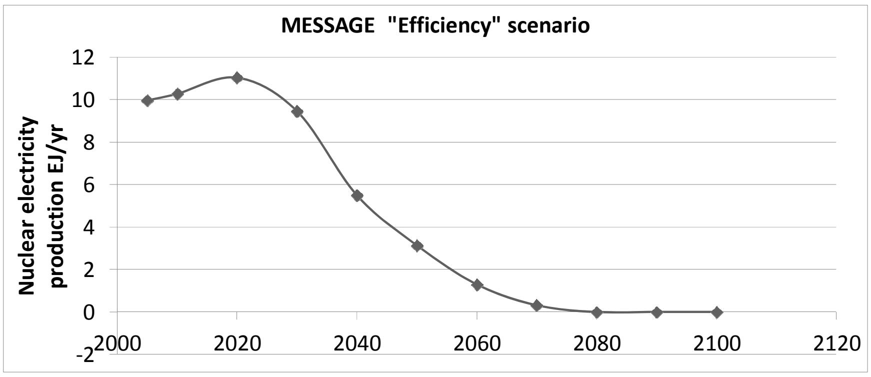
Table 7 World energy mix in 2100 or scenarios 'MIX' and 'MIX-N'

EJ	*Total*	*Fossils*	*Nuclear*	*Biomass*	*Hydro*	*Wind*	*Solar*
2010	470	401	10	45	12	1.2	1
MIX	850	0	137	221	33	70	272
MIX-N	850	0	500	217	33	40	60

2.4 The efficiency scenario

The MESSAGE 'Efficiency' scenario implies a progressive decrease and eventual exit of nuclear energy production by the latter decades of this century, as can be seen on Figure 11.

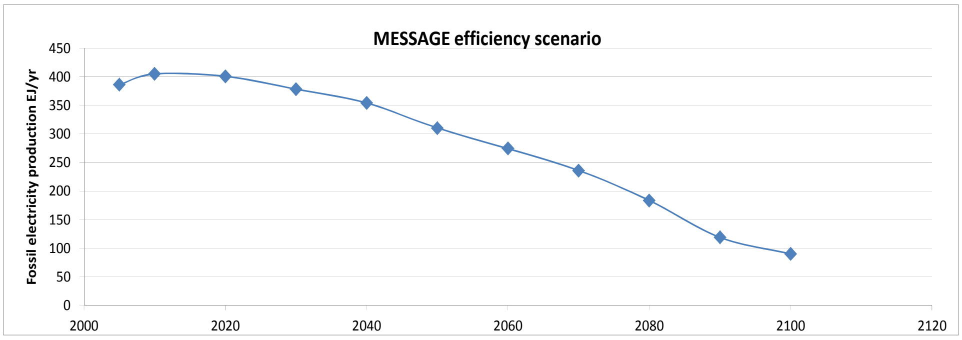
Figure 11 Evolution of nuclear production in 'Efficiency' scenario



However, even in 2100, a fossil electricity production amounting to 100 EJ remains, equivalent to a production by 3500 GWe nuclear power.

The simultaneous decrease of nuclear and fossil consumption is made possible by a serious cutback in final energy consumption and a high proportion of renewable energies in the energy mix (86%).

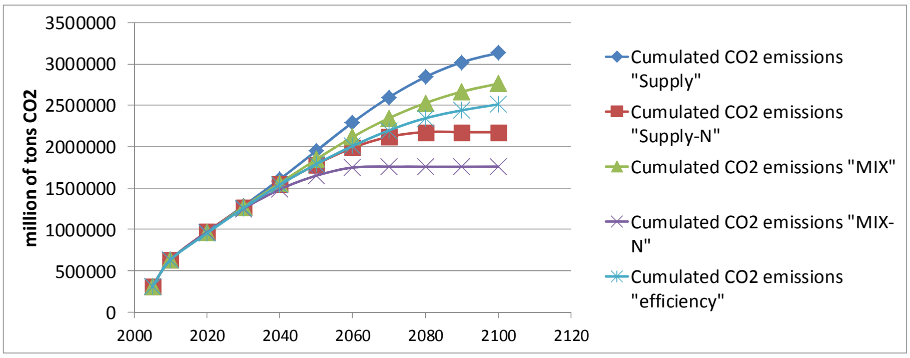
Figure 12 Evolution of fossil electricity production in 'Efficiency' scenario (see online version for colours)



3 CO_2 emissions

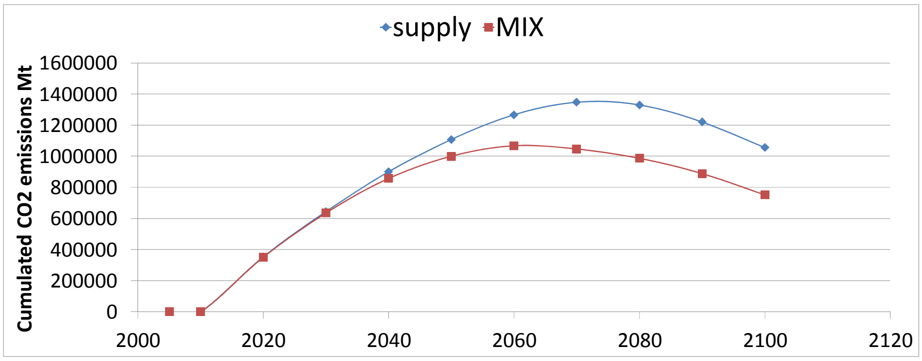
Figure 13 shows the accumulated quantities of emitted CO_2 between 2010 and 2100, calculated for the different scenarios. These quantities are calculated from the fossil consumptions assuming a CO_2 emission intensity of 317 kg/MWh,[9] as observed for 2010. CCS was not taken into account in the calculations of either absorption by oceans or biomass.

Figure 13 Evolution of integrated CO_2 emissions for scenarios Supply, Mix and Efficiency between 2010 and 2100, with and without acceleration of nuclear production. No CCS was assumed. CO_2 reabsorption by oceans and biomass is not included



Since fossil contributions do not vanish by 2100 (140 EJ for the Supply scenario), the standard MESSAGE scenarios are unable to stabilise the CO_2 concentration in the atmosphere before 2100. On the contrary, scenarios with an accelerated increase of nuclear production and vanishing contributions of fossils reach stabilisation between 1700 and 2100 Gt of CO_2.[10]

Figure 14 Evolution of integrated CO_2 emissions between 2010 and 2100 for scenarios supply-N and Mix-N with CSS applied to biomass combustion



MESSAGE scenarios cannot comply with the RCP2.6 criterion without intensive CCS. This technique applied to the combustion of biomass allows a decrease of atmospheric CO_2 concentration.[11] If achievable, it can be, equally well, applied to 'Supply-N' and 'MIX-N' scenarios. The result is shown in Figure 14.

Table 8 shows that, with the nuclear option, the cumulative CO_2 emissions decrease by approximately 1000 Gt, and increase no further thereafter.

Table 8 Values of cumulated CO_2 emissions in 2100 for the three standard MESSAGE scenarios and the two X–N scenarios. The observation of a stabilisation of the CO_2 content of the atmosphere in 2100 is indicated

	Supply	*Supply-N*	*MIX*	*MIX-N*	*Efficiency*
Cumulated CO_2 emissions (Gt), in 2100	3100	2200	2700	1700	2500
Stabilisation	No	Yes	No	Yes	No

Without CCS, the Supply-N and MIX-N scenarios, although they have much better performances than the original ones, are not able to fulfil the 1000 Gt limit required by IPCC RCP2.6. Figure 14 shows that adding CCS only to biomass energy sources, as proposed by the original MESSAGE scenarios, allows the RCP2.6 criterion to be achieved.

4 Comparison between scenarios with and without nuclear

Within the MESSAGE standard scenarios, 'Efficiency' assumes a phasing out of nuclear electricity production, but relying on a massive deployment of CCS, manages to follow an RCP2.6 path owing to reduced energy consumption, as shown in Figure 15.

The 'Efficiency' scenario final energy consumption is close to half that of 'Supply'.

Figure 16 shows a comparison of annual gross CO_2 emissions (without taking into account CCS) for the 'Supply', 'Efficiency' and 'Supply-N' scenarios. While the emission rates of the 'Efficiency' scenario are clearly less than that of 'Supply', the

‘Supply-N’ emissions are very close to those of ‘Efficiency’. It follows that, as far as CO_2 emissions are concerned, there is an equivalency to either decreasing the energy consumption by 50% or to have 50% nuclear energy in the energy mix.

Figure 15 Ratio of final energy consumption of the ‘Efficiency’ scenario to that of the ‘Supply’ scenario

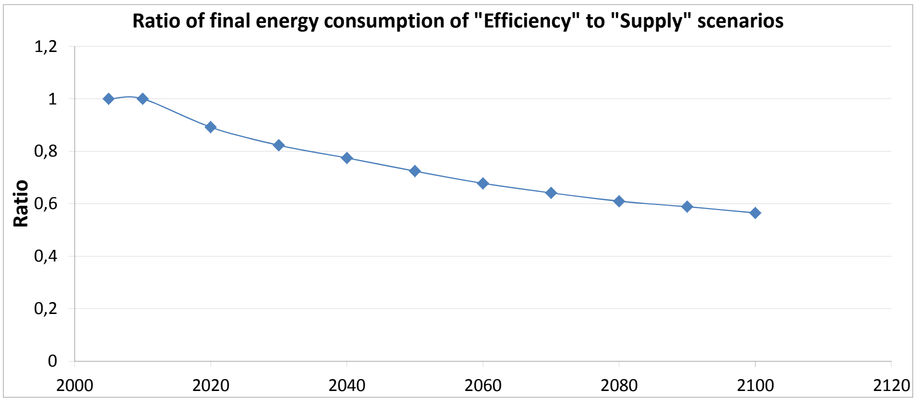
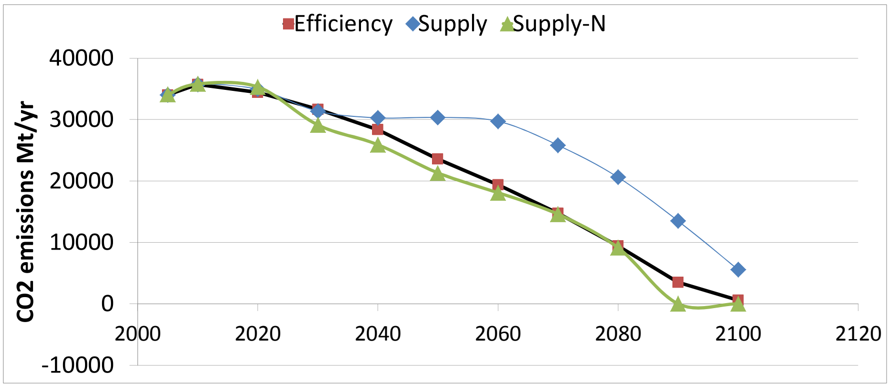


Figure 16 Comparison of CO_2 gross emissions for ‘Supply’, ‘Supply-N’ and ‘Efficiency’ scenarios



4.1 Climatic ranking of the scenarios

Table 9 shows the climatic consequences of various scenarios. They do not make use of CCS except at the end of the century, for biomass combustion, when specified. Under these conditions, the MIX-N scenario with an accelerated development of nuclear power is the only one which might reach the RCP2.6 criterion without extensive use of CCS, except for biomass.

Table 9 Values of RCPs and global temperature increases for various scenarios. Correspondences between CO_2 atmospheric concentrations, RCP and temperature increases are given in the IPCC report AR4

Scenario	*Integrated emissions ($GtCO_2$)*	*Forcing (ppm CO_2)*	*RCP(W/m^2) Earth energy unbalance in 2100*	*Temperature increase in °C with respect to pre-industrial values*
Supply	3100	650	5.8	4.8
Supply-N	2200	510	4.2	3.5
Supply-N+CSS biomass	1055	410	3.2	2.5
MIX	2700	580	5.1	4.1
MIX-N	1700	460	3.7	3
MIX-N+CSS biomass	751	370	**2.7**	2.2
Efficiency+CSS biomass	1535	440	3.6	2.8

Sources: IPCC AR4, https://www.ipcc.ch/publications_and_data/ar4/wg3/en/contents.html; https://www.ipcc.ch/publications_and_data/ar4/wg3/en/spmsspm-d.html#table-spm-5

5 Costs

The average number of 1-GWe reactors completed every year in the 'Supply-N' scenario amounts to 100 PWR between 2020 and 2040, and 300 FBR between 2050 and 2100. Most reactors will be built predominantly in China, India and Southeast Asia. A reasonable cost estimate is based on Chinese costs.

For future PWRs and PHWRs, China claims a cost of \$2000/kW, which might decrease to \$1600/kW. We have kept a conservative cost of \$2500/kW. During the first 20 years, most of the reactors built will likely be PWR. This leads to an annual total investment cost of \$250 billion.

After 2050, most reactors built are likely to be FBRs. Cost estimates are very uncertain. Russian builders give extremely low costs of \$1000/kW. GE-Hitachi estimates (in 2014 dollars) about \$2000/kW for mass-producible metal-fuelled fast reactors with on-site fuel recycling. On the other hand, the cost of the European fast breeder reactor was foreseen to be 50% more expensive than PWRs (EFR cost; Marth, 1993). Here again, we have chosen an extremely conservative cost of 4000 \$/kW. The total annual investment, at the end of the century, would, thus, be \$1200 billion. This would correspond to less than 1% of the gross world product. It may also be compared to electricity production industry turnover at around \$10,000 billion/yr in 2060.

In 2010, the Nuclear Energy Agency (NEA OECD) carried out a cost comparison between different electricity production techniques in OECD countries and in China. The results of this comparison are shown in Table 10. It is seen that nuclear electricity may be competitive with coal-produced electricity with CCS. Following NEA, it is seen that CCS is assumed to increase the cost of electricity by 57%. We have assumed a similar increase of electricity cost due to CCS in China.

Table 10 Levelised kWh costs of electricity for OECD and China (NEA costs). A 5% discount rate was assumed

Techniques	*OECD (US$/MWh)*	*China (US$/MWh)*
Nuclear	50-82	30–36
Coal with CCS	85	(54)
Coal without CCS	54	34
Wind on shore	90–146	51–86
Wind off shore	138–188	
Photovoltaic	287–410	123–186

Source: OECD/IEA-NEA (2010, Table 3.7)

The nuclear electricity production cost under Chinese conditions for FBR would be around $80/MWh (based on our conservative assumptions), while that obtained with coal plants equipped with CCS is estimated around $60/MWh. Assuming a total cost of electricity including transmission and distribution of $100/MWh, we see that the cost increase caused by the substitution of coal plants by FBRs would be around 20%, while there would be no more need to store tens of billions of tons of CO_2.

6 Workforce and industrial resources

The possibility to reach an annual rate of building of a 100 GWe/yr nuclear power between 2020 and 2040, and 300 GWe/yr at the end of the century, may seem to be unrealistic. However, there exists an interesting model of a rapid transition towards a nuclear electricity. In 1973, during the oil crisis, the French government decided to switch from electricity produced primarily by fossil-fuel-driven electric plants towards nuclear-generated electricity. In 1973, only one reactor project was started, four in 1974 and nine in 1975. France has a population of 60 million. Countries which already have a nuclear program and are able to accelerate it have a population close to 3 billion, i.e. 50 times more than France. Applying a proportional scaling based on population, jumping to a new reactor construction rate of 450 units within 2 years is theoretically possible. World electricity production amounts to 23,000 TWh, more than 40 times that of France. The average power of electric plants is close to 3000 GW worldwide, 50 times greater than that of France. Since France was able to launch nine reactors in 1975, we find again, using the electricity production capacity as scaling factor, that at the world level, it should be possible to launch 450 reactors within 2 years from now. In fact, only 100 PWR reactors per annum would be necessary between 2020 and 2040 and 300 FBR at the end of the century.

7 Environmental burden

7.1 Mining

A fleet amounting to 20,000 GWe of FBR power consumes 20,000 tons of natural uranium or thorium each year. These fuels are used with a gain in efficiency of 100 as compared to the present nuclear production based, essentially, on PWR. While, for PWR, the cost of uranium represents approximately 5% of the total cost of nuclear electricity, it would represent 100 times less with the FBR. In practice, existing uranium mines with production close to 60,000 tons/yr would be largely sufficient to fuel the FBR fleet, notwithstanding the existing uranium and plutonium present in used fuels or as depleted uranium, which is equivalent to 2 million tons of uranium. This means that a 20,000 GWe FBR fleet will not need new mining.

Coal plants with equivalent energy output would require extraction of 80 Gt/yr. As an example of surface mining, we take the German Hambach opencast mine with a surface of 40 km^2 and annual production of 40 Mt of coal, enough for powering 10 GWe electric plants. This implies that each 1 GWe coal plant requires a surface of opencast coal mine of 4 km^2 (and two times more for hard coal).

7.2 Surface footprint and biodiversity

Nuclear plants have a surface footprint around 2 km^2/GWe, most of which is normally empty green space surrounding the power plants. The surface of photovoltaic cells necessary for producing the same amount of energy (albeit intermittently) is 50 km^2 (Footprint, http://www.nei.org/News-Media/News/News-Archives/Nuclear-Power-Plants-Are-Compact,-Efficient-and-Re), that for wind turbines 300 km^2 and that of biomass, 2500 km^2. The footprint is the surface over which biodiversity is strongly affected. For example, it is known that the surface at the foot of wind mills may accept some farming activity, but not wild animal life or forest habitat. It should be noted that there are several nuclear reactor design projects that call for mounting nuclear power plants on either hulls or floating platforms such as those designed for the North Sea and siting them up to 50 km offshore.

Table 11 gives an estimate of the footprint for various techniques of electricity production of 500 EJ/yr.

Table 11 Footprint (surface over which the biodiversity is gravely impacted) for various techniques for electricity production of 500 EJ/y

	Nuclear	*Fossil*	*PV*	*Wind*	*Biomass*
Footprint (km^2)	40,000	100,000	2,000,000	12,000,000	50,000,000

7.3 Raw material needs

As an example, the European Pressurised Reactor (EPR, 1650 MWe) requires 500,000 m^3 of concrete and 110,000 tons of steel. CO_2 emissions due to the EPR construction are calculated to amount to approximately 1 million tons (Materials EPR, http://quille-industrie.com/metiers/nucleaire/centrale-electronucleaire-epr-flamanville).
Over a lifetime of 60 years, the EPR will produce 720 TWh. This leads to a CO_2 emission from construction materials of 0.5 g CO_2/kWh. With present technologies, wind turbines require eight times more concrete per kWh and 12 times more steel per kWh than EPR. This is telling, because the EPR is the worst of the new reactor designs when it comes to raw material needs. Other designs are considerably more frugal in that respect.

8 Incentive

Without special incentives, coal- and gas-fired electric plants are more profitable than nuclear plants. Those are, also, more investment intensive and very sensitive to financial costs. Therefore, some kind of incentive is necessary for the transition away from fossil fuels. It is not the object of this paper to give an in-depth discussion of this matter. We only cite two methods widely advocated by specialists:

1. The regulatory approach consists in setting limits on the amount of CO_2 emitted by kWh produced, e.g. 100 g CO_2/kWh. This standard should be applied to all new electricity plants. The electricity facility operator will have the choice of building a wind or solar farm, a nuclear or a fossil plant with CCS. A few examples of CO_2 emissions/kWh are given in Table 12.

   With a standard of 100 g CO_2/kWh new coal electricity plants would be forbidden unless they were equipped with a 90% efficient CCS. Under these constraints, it is plausible that operators will choose nuclear or renewable electricity plants. Assuming a lifespan of 30 years for fossil plants, the complete transition to a CO_2-free electricity production could, thus, be obtained after 30 years.

2. Introduce an emission trading scheme or a Carbon Fee and Dividend, as described by James Hansen et al. (Hansen Tax, see, for example, http://www.worldwatch.org/node/5962).

Table 12 CO_2 emissions in gCO_2/kWh for different electricity production techniques (Hirshberg)

Technique	*Coal*	*Gas CCG*	*Hydro*	*Wind*	*Solar PV*	*Nuclear*
Emission (gCO_2/kWh)	1024	491	6	15	45	16

Sources: http://www.sfen.org/fr/nuclear-for-climate and http://www.sauvonsleclimat.org/images/articles/pdf_files/ec_2008/Hirschberg.pdf (slide 12)

9 Safety issues

9.1 Reactor accidents

With 20,000 fast reactors operational in 2100, it is legitimate to be particularly concerned about the safety of such a large fleet. The present rule enforced by safety authorities corresponds to a probability of core melting less than 10^{-5} per year per reactor, and a further reduction by 10 for the probability for a significant radioactivity release to the atmosphere.[12] This means that one might expect two nuclear accidents with significant radioactivity release per century for the entire fleet. Equivalently, one would expect a probability for such an event of 10^{-4} for an electricity production of 1000 TWh. Based upon the results of the European Union study on the lethality of electricity-producing techniques, ExternE (*Forbes Magazine*) has published the comparison shown on Table 13. This table shows that nuclear electricity is the least dangerous of all, with a 2000 times lower death rate than coal and 250 less than biomass.

Table 13 Number of deaths per 1000 TWh of final energy for different energy production techniques. For nuclear energy, Chernobyl and Fukushima victims were accounted for

Technique	*Deaths per 1000 TWh*
Coal (world)	170,000
Coal (China)	280,000
Coal (USA)	15,000
Oil	36,000
Natural gas	4000
Biomass	24,000
Solar PV	440
Wind	150
Hydroelectricity	1400
Nuclear	90

Source: Data from ExternE (*Forbes Magazine*, http://www.forbes.com/sites/jamesconca/2012/06/10/energys-deathprint-a-price-always-paid/)

Along the same line, Kharecha and Hansen (2013) have shown that due to airborne pollution of displaced fossil energy sources, the historical use of nuclear power has saved 1.8 million lives if compared to the present coal-dominated electricity production.

9.2 Nuclear fear

One of the main problems facing nuclear energy is its image among the general public. For most people, radioactivity and radioactive elements are extremely dangerous, whatever the dose of radiation received. It seems important to make the evaluation of radioactive risk commonplace and scientifically realistic. A pedagogical approach towards this goal may be found in a recent article (Nifenecker, 2015) written by one of us. As an example, living in a background radiation of 20 mSv/yr, a maximum limit for return in the Fukushima neighbourhood, is equivalent, as far as cancer development is concerned, to smoking three cigarettes per day. The number of years of life lost in a background of 100 mSv/yr is equivalent to that related to chronic micro-particle pollution in Paris.

9.3 Nuclear wastes

A standard 1 GWe PWR reactor produces approximately 30 tons of high-level nuclear wastes, which include fission products, depleted uranium, plutonium and minor actinides, while an FBR produces only 1 ton (essentially fission products) since uranium, plutonium and minor actinides are recycled. Therefore, 20,000 FBR would produce a nuclear waste mass equivalent to that produced by 700 PWR, not far from the present value. And that nuclear waste would have a radiotoxicity level that would diminish below that of natural uranium ore within a few hundred years. FBRs with recycling, in effect, will solve the so-called ‘million-year waste problem’.

9.4 Proliferation issues

Might the very important development of nuclear power lead to a corresponding increase of proliferation of nuclear armaments?

A first remark is that proliferation (defined as the spread of nuclear weapons to new states) is, obviously, not a problem with countries which already have a nuclear arsenal: USA, Russia, China, India, Pakistan, Israel, North Korea, France, UK, which represent 3.8 billion people, more than half the total world population. These countries are also those where most of the development of nuclear power will need to take place.

Setting up a nuclear armaments program does not imply a link with nuclear electricity production. Nuclear armament requires either highly enriched uranium of good quality or plutonium with an extremely high proportion of the 239 plutonium isotope. Uranium highly enriched in isotope 235 is obtained with gas centrifuges which are difficult to detect by the inspectors of the International Atomic Energy Agency (IAEA), contrary to the massive gas diffusion plants previously used. Furthermore, ^{235}U explosive devices are rather straightforward to build, while, due to the presence of the non-fissile ^{240}Pu isotope, plutonium devices require the delicate use of timed chemical implosion before atomic explosion can take place. In order to minimise the presence of ^{240}Pu isotope, the irradiation of ^{238}U necessary for production of ^{239}Pu should be as short as possible. On the contrary, PWR and FBR, when used in commercial electricity generation settings, require long irradiation times and are not suitable for 'military' plutonium production. PHWRs are equipped with continuous fuel discharge mechanisms and, theoretically, can be used to produce very good 'military'-grade plutonium. However, it would involve discharging fuel at a low burn-up and would involve high frequency of fuel loading and unloading. Fuelling machines of PHWRs are not designed for that kind of duty and producing weapon-grade plutonium from PHWRs is not a practical proposition. Moreover, whenever a proliferation risk in a specific country exists, it is clear that inspectors of the IAEA will be especially watchful concerning PHWRs operating in that country.

At present, one can say that a country can obtain the material necessary for building nuclear explosive devices if it has competent physicists and engineers. However, the example of Iran shows that it will have to pay a high price due to the international sanctions that might result. The development of nuclear electric power would not have a significant effect here.

9.5 Terrorist attacks

A kamikaze-style attack against a reactor cannot be completely excluded. In order to cause significant radioactive emissions, the terrorist group has to ruin the confinement, a concrete barrier several meters thick. Chernobyl, which had no confinement, is the worst example of what might be achieved in a true war action. Such an attack would be quite ineffective as far as lethality is concerned: at most a few dozen dead, essentially among the operators and rescuers. Only after several years would the true scale of the catastrophe appear, notwithstanding never-ending controversies on its true extent. By that time, the motivation of the attack will be forgotten. We just recently saw, in Paris, that with two determined terrorists it is possible to kill more than hundred people in a few seconds. And still, one cannot exclude an attack on a nuclear reactor. This is because terrorists know that such an attack would cause immense panic. This is an illustration that the main risk of nuclear is not that associated with the reality of radiation, but that associated with the fear we have of it. Development of nuclear power has to be accompanied by truthful information on the nature and magnitude of its risks. As a rule, people living close to nuclear reactors are less afraid of nuclear energy than the general public. Despite the Chernobyl catastrophe, Ukraine did not renounce nuclear power, but Germany did. Paradoxically, the very highly demanding safety rules increase the fear of the public. Following the rule set by most safety authorities, the acceptable 'human-made' dose delivered to the public is limited to 1 mSv/yr. Most people believe that being irradiated at a dose 100 times that much would be deadly in the short term. They find it hard to believe that, as far as cancer probability is concerned, the risk of an irradiation of 100 mSv/yr is equivalent to smoking a little less than one pack of cigarettes per day.

10 Conclusion

An accelerated development of nuclear electricity production, starting as soon as 2020, would significantly alleviate the constraints required to stabilise global temperatures before 2100. The CO_2 volume to be stored would be divided by at least a factor of 2.5 and might even prove unnecessary. The constraints on the development of expansive and intermittent renewable electricity techniques might also be lessened.

Achieving a global nuclear power deployment of 20,000 GWe in 2100 is possible if the world relies on breeding with improved reprocessing techniques, deploying thorium-fuelled reactors, and/or increasing the contribution of PHWR reactors. Nuclear production would then reach close to 60% of final energy consumption, the complement being met by renewable energy sources.

It seems physically and economically possible to multiply by 50 the production of nuclear energy by 2100, leading to a complete elimination of fossil fuels. Together with the use of renewable energy, this would both answer the climate challenge and give a perennial solution to humanity's energy needs for thousands of years. Furthermore, in its breeding form, nuclear energy is probably the most benign way to produce energy as far as the protection of biodiversity is concerned (Brook and Bradshaw, 2015).

Following a study published in *Forbes Magazine* (http://www.forbes.com/sites/jamesconca/2012/06/10/energys-deathprint-a-price-always-paid/), when compared to those related to global warming, the risks associated with nuclear electricity production are small. Including the Chernobyl and Fukushima death tolls (nobody died at Fukushima due to radioactivity, nor is anyone expected to have negative health effects from the radioactivity released by this accident), lethality of electricity production by nuclear energy is less than 1/1000 that of coal and 1/20 that of biomass.

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Appendix A: energy conventions

Final energy: Energy bought by the final user, e.g. natural gas or electricity.

Secondary energy: Energy output from the production plant, e.g. electricity, hydrogen, gasoline, etc. Electricity sources are specified (coal, nuclear, wind, etc.)

Primary energy: Energy necessary for producing secondary or final energies.

Two conventions are used by IIASA:

- 'Primary energy by substitution' corresponds to the quantity of fossil fuels necessary to produce the same quantity of final or secondary energies. For electricity production with thermal plants, the ratio between secondary and primary energies is about 33%. The same ratio is chosen for nuclear and renewable energies.
- 'Direct primary energy' is the same as above for fossil fuels but, for nuclear and renewable energies, primary and secondary energies are equal. IIASA generally uses this definition of primary energy and we follow the same convention.

Appendix B: regional developments in the MESSAGE scenarios

B1 Definition of the 11 regions used by IIASA

AFR: Sub-Saharan Africa – Angola, Benin, Botswana, British Indian Ocean Territory, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Comoros, Cote d'Ivoire, Congo, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mali, Mauritania, Mauritius, Mozambique, Namibia, Niger, Nigeria, Reunion, Rwanda, Sao Tome and Principe, Senegal, Seychelles, Sierra Leone, Somalia, South Africa, Saint Helena, Swaziland, Tanzania, Togo, Uganda, Zaire, Zambia, Zimbabwe

CPA: Centrally planned Asia and China: Cambodia, China (incl. Hong Kong), Korea (DPR), Laos (PDR), Mongolia, Vietnam

EEU: Central and Eastern Europe – Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, the (former Yugoslavia) Republic of Macedonia, Latvia, Lithuania, Hungary, Poland, Romania, Slovak Republic, Slovenia, Yugoslavia.

FSU: Former Soviet Union – Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Russian Federation, Tajikistan, Turkmenistan, Ukraine, Uzbekistan (the Baltic republics are in the Central and Eastern Europe region).

LAC: Latin America and the Caribbean – Antigua and Barbuda, Argentina, Bahamas, Barbados, Belize, Bermuda, Bolivia, Brazil, Chile, Colombia, Costa Rica, Cuba, Dominica, Dominican Republic, Ecuador, El Salvador, French Guyana, Grenada, Guadeloupe, Guatemala, Guyana, Haiti, Honduras, Jamaica, Martinique, Mexico, Netherlands Antilles, Nicaragua, Panama, Paraguay, Peru, Saint Kitts and Nevis, Santa Lucia, Saint Vincent and the Grenadines, Suriname, Trinidad and Tobago, Uruguay, Venezuela.

MEA: Middle East and North Africa – Algeria, Bahrain, Egypt (Arab Republic), Iraq, Iran (Islamic Republic), Israel, Jordan, Kuwait, Lebanon, Libya/SPLAJ, Morocco, Oman, Qatar, Saudi Arabia, Sudan, Syria (Arab Republic), Tunisia, United Arab Emirates, Yemen.

NAM: North America – Canada, Guam, Puerto Rico, USA, Virgin Islands.

PAO: Pacific OECD – Australia, Japan, New Zealand.

PAS: Other Pacific Asia – American Samoa, Brunei Darussalam, Fiji, French Polynesia, Gilbert-Kiribati, Indonesia, Malaysia, Myanmar, New Caledonia, Papua, New Guinea, Philippines, Republic of Korea, Singapore, Solomon Islands, Taiwan (China), Thailand, Tonga, Vanuatu, Western Samoa.

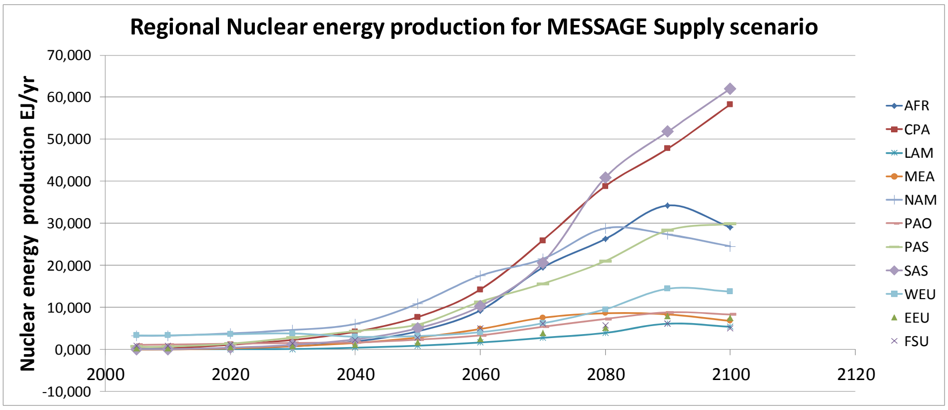
SAS: South Asia – Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, Pakistan, Sri Lanka.

WEU: Western Europe – Andorra, Austria, Azores, Belgium, Canary Islands, Channel Islands, Cyprus, Denmark, Faeroe Islands, Finland, France, Germany, Gibraltar, Greece, Greenland, Iceland, Ireland, Isle of Man, Italy, Liechtenstein, Luxembourg, Madeira, Malta, Monaco, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland, Turkey, UK.

B2 Regional development of nuclear energy following the MESSAGE supply scenario

Figure B1 illustrates a possible regional development of nuclear energy as proposed in the MESSAGE Supply scenario. Most development would take place in China (CPA), India (SAS), USA (NAM), South Korea and other East and Southeast Asian States (Taiwan, Thailand, Indonesia).

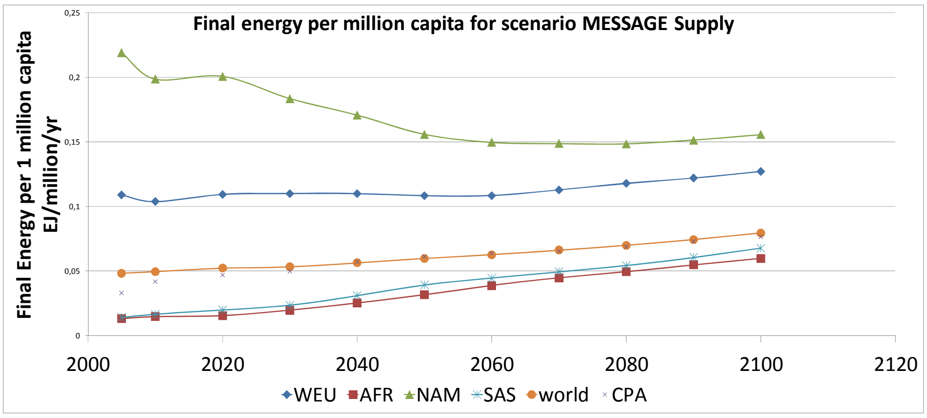
Figure B1 Evolution of nuclear electricity production in various geographic regions according to the MESSAGE ‘Supply’ scenario. The definition of regions is given in Section B1



B3 Regional evolution of the final energies per million capita in the supply scenario

Figure B2 shows that, even in the Supply scenario, a tendency towards equity of the final energy consumption per capita is present.

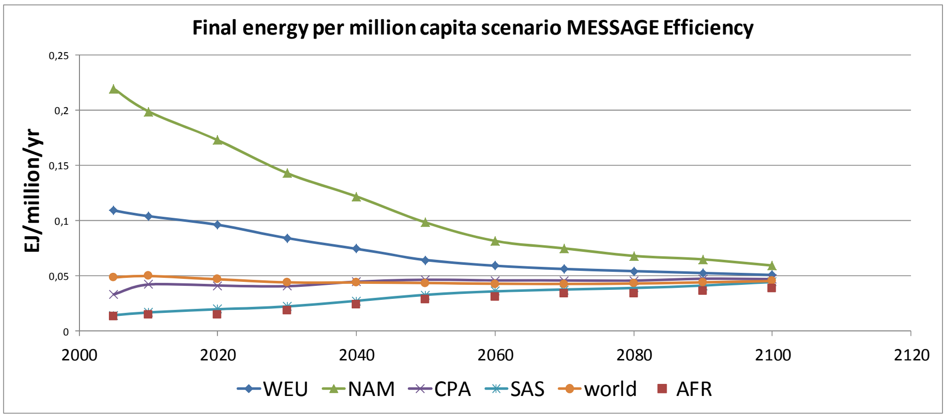
Figure B2 Evolution of final energy per capita for different regions given by the scenario MESSAGE 'Supply'. Note a tendency for equalisation. However, developed countries in 2010 have still higher consumption in 2100



B4 Regional evolution of the final energies per million capita in the efficiency scenario

Figure B3 shows that in the Efficiency scenario a tendency towards even more equity than in the Supply of the final energy consumption per capita is looked for.

Figure B3 Evolution of final energy per capita for different regions given by the scenario MESSAGE 'Efficiency'. Note a tendency for equalisation. A strong decrease is observed for developed countries with more than a factor of 4 for USA and 2 for Western Europe



Appendix C: Assumptions on nuclear electricity production

We give some explanation for the choice of important parameters in the calculations of the nuclear power and energy production, which are assumed in the scenario MESSAGE Supply-N.

C1 Annual energy production per GWe nuclear power

We have assumed a load factor of 0.9 of the reactors and a thermo-dynamical efficiency of 33%. If nuclear power has to compensate for the intermittency of wind and solar production, the load factor will decrease. By comparison, Generation 3 (GEN 3, like advanced PWR and PHWR) reactors are supposed to have 36% thermo-dynamical efficiency and FBR up to 45% due to higher outlet temperatures.

C2 Annual uranium needs

A typical 1 GWe PWR reactor produces 950 kg of fission products corresponding to fission of 1 ton of heavy metal (actinides). About two-thirds correspond to fission of ^{235}U and the remaining to fast fission of ^{238}U and fission of ^{239,241}Pu produced from neutron capture on ^{238}U. The annual consumption of a 1 GWe reactor is about 27 tons of uranium enriched to 3%, which corresponds to 115 tons of natural uranium. Thus, we have chosen an annual uranium need of 120 tons/GWe PWR. This has to be compounded by enrichment tails on the one hand and re-enrichment of these tails and of reprocessed depleted uranium, on the other. We assume the same uranium consumption for PHWR reactors where 30% of the fissions are produced by plutonium. Uranium needs of FBRs with recycling, on the other hand, would require merely about 1 ton of depleted uranium per gigawatt per year, and the amount of depleted uranium currently in inventory around the world assures that a world powered solely by FBRs would have enough fuel for several centuries before any mining would be required.

C3 PHWR reactors

As compared to PWR, in PHWR, light water is replaced by heavy water for slowing down neutrons and heat extraction. The capture cross-section of heavy water (deuterium, D_2O) is 600 times smaller than that of light water. Owing to their superior neutron utilisation, PHWR reactors produce 2.4 times more plutonium than PWR (Guillemin, 2009).

C4 Plutonium inventory of fast breeder reactors

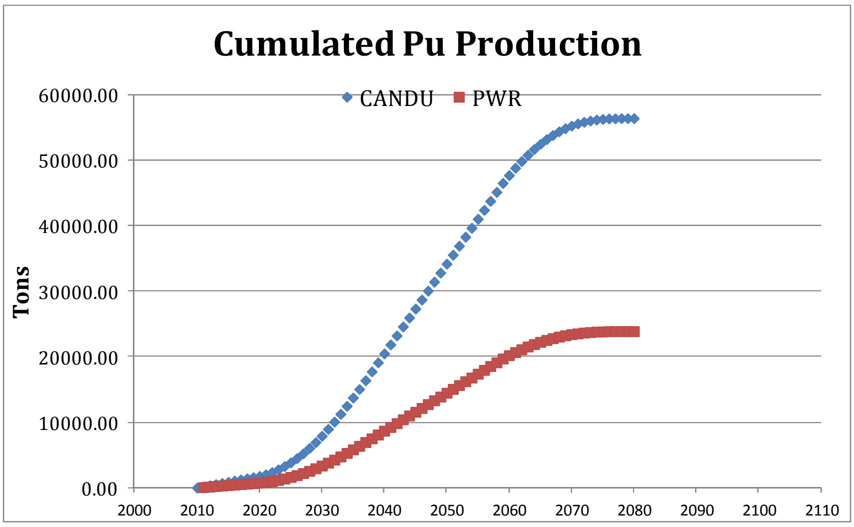
Typical plutonium core inventory is 4 tons/GWe. However, fuel elements are extracted periodically from the reactor and need to be processed in order to separate plutonium and uranium (and other actinides) for further fabrication of new fuel elements. At present, this process lasts about 4 years. This leads to a total inventory of FBR of 8 tons. However, shorter durations seem to be possible. For example, US nuclear engineers proposed the concept of the Integral Fast Reactor (IFR, https://en.wikipedia.org/wiki/Integral_fast_reactor) where reprocessing is carried out at the reactor site and uses a hot, dry electro-refining method called pyroprocessing. Metallic fuels rather than oxide are used in this concept and allow shorter reprocessing of higher activity fuels, with no possibility for isolation of specific fissile isotopes. It is possible to obtain a duration of the processing as short as 1.3 year.

In case a significant decrease of the plutonium inventory of FBR appears not feasible, an alternative would be to include more PHWRs in the thermal neutron reactor fleet. Indeed, while a 1 GWe PWR needs to operate 40 years before producing the plutonium inventory of an FBR, only 13 years are necessary for a 1 GWe PHWR. Thus, after

40 years, 2000 PWR reactors will allow starting 2000 FBR, which themselves will give rise to 4000 FBR after another 40 years. In contrast, after 40 years, 2000 PHWR allow starting 5700 FBR, i.e. 11,400 FBR after 40 more years.

Figure C1 compares the plutonium production of a 2325 GWe PWR fleet to that of the same PHWR power. The life time of the reactors was assumed to be 50 years.

Figure C1 Comparison of cumulated plutonium productions of a 2325 fleet of PWRs or PHWRs. The PWR production is equivalent to the inventory of 3000 FBR, that of the PHWRs to that of 7100 FBR



With the standard values of 8 tons of plutonium for the inventory of a 1 GWe FBR and an exclusively PWR reactor fleet (2325 PWR consuming more than 11.5 million tons of uranium) for building the initial inventories, we find it impossible to exceed 3800 FBR by 2100 producing 177 EJ, much below our 500 EJ objective. This objective can only be obtained by optimising the initial inventory and the proportion of PHWRs in the thermal reactor fleet. Table 14 shows how introducing a proportion of PHWRs would allow for keeping of present reprocessing methods.

Table C1 Equivalence between the total plutonium inventory (core + fuel cycle) for a 1 GWe FBR and the proportion of PHWR reactors in the thermal reactors fleet (PHWRs + PWRs) necessary in order to reach the objective power of FBR in 2100

Total Pu inventory (GWe tons)	*Proportion of PHWR in the thermal fleet %*
8	50
7	37
6	14
5.5	0

C5 Details of the calculation of Figure 3

The calculations were done using an EXCEL program. We assume all reactors to deliver a power of 1 GWe and an energy production of 7.9 TWh/yr. The Pu production of PWR is chosen to be 0.25 tons/yr, that of PHWRs to be 0.59 tons/yr and the net production of Pu by FBR to be 0.2 tons/yr.

The core inventory of FBR is assumed to be 4 tons of plutonium. The fuel is supposed to stay 4 years in the reactor. Concerning the out-of-reactor plutonium inventory, we made two calculations: one with 4 tons and the other with 1.5 tons. Thus, in one case the total plutonium inventory is 8 tons and 5.5 tons in the other.

Starting at year 0 we assume a constant building rate of 135/yr until 20 years after the starting year; at that time the building rate increases to 300/yr. The number of thermal reactors (PWR or PHWRs) being built is 135/yr at the beginning and starts levelling off 10 years after year 0 to vanish in year 20. The complement to 135/yr before year 40 and to 300/yr after is made of FBR. After 80 years, the number of FBR (the only ones left) reaches 15,000 for an energy production of 430 EJ, as seen in Figure 5, to be compared to the total primary energy of 1060 EJ in the Supply scenario.

The amount of natural uranium needed for running PWR is around 120 tons/GWe/yr and that for running PHWRs is around 80 tons/GWe/yr. In our calculation, we have used an average value of 100 tons/GWe/yr. Using the evolution of the number of thermal neutrons of Figure 3, one gets the natural uranium consumption of Figure 4.

The possibility to produce enough plutonium for a fleet of 19,000 FBR in 2100 is, of course, crucial and not easy. It depends on the initial stock of plutonium built up by thermal neutron reactors and on the doubling time of the reactors. The plutonium production of existing FBR is 0.2 tons/yr. For an inventory of 8 ton/GWe, the total inventory for 19,000 FBR amounts to 150,000 tons. With a 0.2 ton/yr production and an inventory of 8 tons, the doubling time of the FBR fleet is 40 years. This means that by 2050 the plutonium stock should be close to 27,000 tons. For PWR the cumulated plutonium production is only 12,000 tons. For PHWRs, it reaches 34,000 tons.

If the inventory is reduced to 5.5 tons/GWe, the total inventory for 19,000 FBR amounts to 105,000 tons with a need of 19,000 tons in 2050.

Figure C2 is an example of the evolution of the available plutonium stock for various choices of the percentage of PHWRs in the thermal neutron reactor fleet with two different values of the plutonium inventory of the FBRs. We note that the combination of a 100% PWR fleet and an FBR plutonium inventory of 8 tons/yr leads to a negative stock, which means an impossibility to reach the objective of 19,000 FBR reactors.

An important part of the stock rests in the used fuels since, after the rate of FBR construction is stabilised at 300/yr, the yearly processing rates are 2400 tons of plutonium with an 8 ton inventory and 1650 tons for a 5.5 ton inventory. The rise of the plutonium inventory after 2080 can easily be controlled by limiting the breeding coefficient. By 2100, the annual plutonium production of the 19,000 reactors would be 3800 tons/yr, allowing the construction of 475 reactors with 8 t/GWe inventory and of 690 FBR with 5.5 tons/GWe inventory. This means that the FBR fleet will be easily at equilibrium. Some natural uranium will still be necessary at a rate of 19,000 tons/yr.

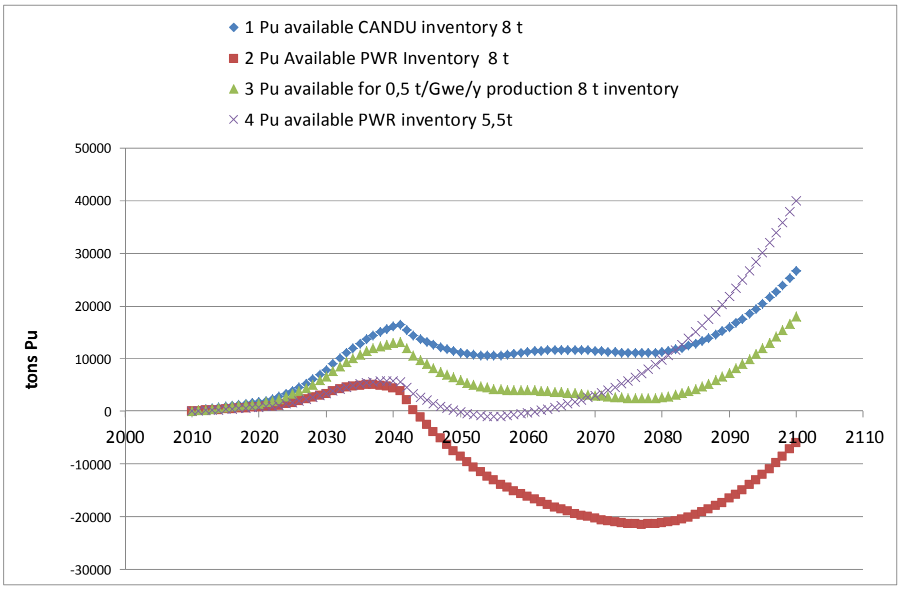
Figure C2 Evolution of the available plutonium stock for different assumptions on the thermal neutron reactors fleet and on the FBR plutonium inventory:

1 Assumed a 100% PHWR thermal reactors fleet and an FBR plutonium inventory of 8 tons/GWe.

2 Assumed a 100% PWR thermal reactors fleet and an FBR plutonium inventory of 8 tons/GWe.

3 Assumed a mixed thermal reactors fleet with 73% PHWRs and an FBR plutonium inventory of 8 tons/GWe.

4 Assumed a 100% PWR thermal reactors fleet and an FBR plutonium inventory of 5.5 tons/GWe.



Notes

1 Models selected by the IPCC originate from the work of the following groups: IMAGE led by the 'Netherlands Environmental Assessment Agency', MiniCAM led by the 'Pacific Northwest National Laboratory's Joint Global Change Research Institute (JGCRI)', AIM led by the 'National Institute for Environmental Studies (NIES), Japan', and MESSAGE led by the 'International Institute for Applied Systems Analysis (IIASA), Austria'.

2 Here we simply report the results from the Excel tables available on the IIASA site: http://www.iiasa.ac.at/web-apps/ene/geadb/dsd?Action=htmlpage&page=regions

3 The data of the MESSAGE scenarios are found in the IIASA website (http://www.iiasa.ac.at/webapps/ene/geadb/dsd?Action=htmlpage&page=regions) and their justification in GEA (2012).

4 From 2010 to 2050, nuclear power was multiplied by 4.

5 It should be noted that metal-fuelled fast reactors of the IFR type might achieve a doubling time of 7–8 years. If such reactors are deployed in large numbers (as exemplified by GE-Hitachi's PRISM reactor), that would obviously greatly accelerate even the most ambitious nuclear scenarios described here.

6 OECD NEA (2010) Identified resources at a cost <$260/kg: 6.3 million tons. Reasonable assured resources <$260/kg: 4 million tons. Inferred resources <$260/kg: 2.3 million tons. Prognosticated resources <$260/kg: 3 million tons. Speculative resources: 7.5 million tons.

7 If thorium-fuelled reactors are deployed, as planned by many new reactor designers, the much greater reserves of thorium would create a substantial cushion to allow more time for the shift to breeder reactors.

8 AP1000 and EPR have, respectively, design lifetimes of 80 and 60 years.

9 In 2010, a CO_2 emission of 35.7 Gt was observed for a total fossil primary energy of 405 EJ, i.e. a CO_2 intensity of 318 kg/MWh. Because of a shift from coal to gas, this intensity would decrease during the century to 286 kg/MWh in 2030 and 257 kg/MWh in 2050. We have ignored this slight decrease.

10 About half of the emissions might be absorbed by the ocean and biomass growth.

11 Under the assumption that burnt biomass is replaced by plantations, it is generally assumed that biomass burning is CO_2 neutral. If CCS is applied to the fumes, it results in decreasing the amount of CO_2 in the atmosphere. In practice, biomass is mostly used for biofuel synthesis and CCS takes place at this stage.

12 Neither Chernobyl nor Fukushima reactors obeyed this type of safety requirements, especially for lack of a true confinement and hydrogen explosion prevention. TMI had good confinement and, although core melting occurred, there was no significant radioactive release.