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How much can nuclear energy do about global warming?

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Abstract

The reference framework MESSAGE devised by the « International Institute for Applied Systems Analysis (IIASA), Austria » is one of the two frameworks reported by the Intergovernmental Panel on Climate Change (IPCC) as potentially able to limit the global surface temperature increase to 2 degrees Celsius (RCPⁱ 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 CO₂. However, present knowledge of this process rests on a few experiments at the annual million tons level, with global storage capacity not yet established as being adequate.

The use of CCS is limited to 24 billion tons/y, based on the assumption of either a large-scale development of nuclear energy between 2060 and 2100 or else a severe contraction of energy supply. It includes three potential scenarios: « Supply » with a high energy consumption, « Efficiency » which implies the end of nuclear energy, paid for by a decrease in energy consumption of 45% with respect to the “Supply scenario”, and the intermediary « MIX » scenario. All three scenarios propose a high contribution of solar energy and biomass. In the “Supply” scenario 7000 GWeⁱⁱ nuclear power start operation between 2060 and 2100.

ⁱ Representative Concentration Pathways

ⁱⁱ GWe : Giga Watt electric

Since technical requisites for nuclear energy exist today (which is the case neither for massive CCS nor for extensive use of intermittent renewable electricity production), here we propose, as a variant of the MESSAGE framework, to initiate a sustained deployment of nuclear production in 2020, rather than 2060, reaching a total nuclear power around 20,000 GWe by the year 2100. We study in detail how such a deployment is physically possible with the generalization of breeder reactors. It appears that such a large-scale deployment needs significant improvement in the throughput of reprocessing or a switch from a PWRⁱ dominated nuclear fleet to a fleet equilibrated between PWR and PHWRⁱⁱ reactors.

Our « nuclearized » « Supply » and « MIX » scenarios reduce considerably the interest in or necessity for CCS, making it even possible to achieve stabilization of atmospheric CO₂ concentration before 2100 without using this technology. It is also possible to limit the contribution of intermittent renewable electricity production to a more feasible level.

It is to be stressed that renouncing nuclear power (« Efficiency» scenarios) 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 CO₂, and without stabilization of its atmospheric concentration before 2100.

A strong nuclear development, by comparison, allows for a reasonable level of energy consumption, as well as a stabilization of atmospheric CO₂ concentration as soon as 2060, reducing considerably the needs of CO₂ storage, and permitting total suppression of fossil fuels several decades before the end of the century.

ⁱ PWR : Pressurized Water Reactor

ⁱⁱ PHWR: Pressurized Heavy Water also called CANDU (Canadian Deuterium Uranium)

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1. Introduction

The recent IPCC (AR5)¹ report 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 emissions scenarios, IPCC has selected 4 RCPs "Representative Concentration Pathways", encapsulating the full range of likely greenhouse gases (GHG) concentrations evolution. Each of the 4 RCPs is labeled according to the value of radiative forcing obtained in 2100 by the specific integrated modelⁱ emissions profile. RCP 2.6 (W/m² radiative forcing) scenarios are the only ones which could limit the increase of global temperature to less than 2 °C. The IAMC (Integrated Assessment Modeling

ⁱModels selected by the IPCC originate from the work of the 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 ».

Consortium) has stressed two scenario frameworks, IMAGE and MESSAGE. Both are described in detail on the IIASA WEB site (IIASA WEB site)². These frameworks are subdivided into three scenarios « Supply », « Mix » and « Efficiency » which refer to decreasing energy consumption levels.

1.1 The Carbon Capture and Storage (CCS) bet

All of these scenarios rely upon capture and storage of large quantities of CO₂, as can be seen in Table 1ⁱ. Rates of CCS reach yearly values of as much as 50 Gt/yr in 2100. By comparison, present experience with this technique are of order of a few million tons.

Table 1 compares the CO₂ masses yearly stored, in 2100, for the MESSAGE and IMAGE scenarios.

	SUPPLY	MIX	EFFICIENCY
MESSAGE	23900	15200	15200
IMAGE	50000	43200	26500

Table 1

CO₂ mass yearly stored in 2100 (million tons) for the scenarios of IMAGE and MESSAGE frameworks (IIASA WEB site). In 2010, annual CO₂ 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.

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 greenhouse gas 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 CCU (Carbon Capture Utilization) 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 center
- China has not mastered IGCC (integrated gasification combined cycle) technology

ⁱ 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>

- 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 commercialization, 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 3 MESSAGE scenarios are: energy consumption, CO₂ capture and energy mixⁱ. 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.

	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	36000	36000	45237	6900
Supply	755	1061	23900	677	-18350	5550	366139	9500
Mix	616	856	15175	487	-13288	1887	366139	9500
Efficiency	427	617	15198	297	-14630	548	366139	9500

Table 2

Main parameters of the MESSAGE RCP 2.6 scenarios in 2100 and corresponding 2010 values. Net CO₂ emissions equal the difference between gross emissions (mostly due to fossil combustion) and stored CO₂ including from biomass combustion (IIASA WEB site).

The scenarios differ by their energy consumption and energy mix, and, as a consequence, by their CO₂ emissions. Table 3 summarizes the contribution of the main sources to primary energy in 2100.

	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)

Table 3

World energy mix in 2100 for the three MESSAGE scenarios. (Primary energyⁱⁱ, exajoules EJⁱⁱⁱ). 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 (IIASA WEB site)

Note the importance of solar production. With present photovoltaic cell (PV) performances, the foreseen production of 289 EJ corresponds to a surface coverage of one million km².

ⁱ The data of the MESSAGE scenarios are found in reference (IIASA WEB site) and their justification in reference (GEA, 2012)

ⁱⁱ For definitions of primary, secondary and final energies see Appendix 1.

ⁱⁱⁱ 1 EJ= 1 exajoule=10¹⁸ Joules = 277 TWh = 24 Mtep

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.

	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 ⁱ	21	7.1	7.6

Table 4

Cumulated use (IIASA_WEB_site)² and remaining workable stocks of fossil fuels in 2010 (GEA 2012)³ for the 3 MESSAGE scenarios.

1 zetajoule ZJ = 1000 EJ = 24 Gtep

2. The MESSAGE scenarios

2.1 The Message “Supply” scenario

The MESSAGE “Supply” scenario foresees a nuclear electricity contribution of 251 EJ, i.e. 69000 TWh which could be produced by 8600 1 GWe reactors. The time evolution of nuclear production is shown on Figure 1. It is seen on this figure that almost all the new nuclear power would start operation between 2050 and 2090ⁱⁱ. For the original Supply scenario the type of reactors and uranium resources management are not specified.

During this period, the nuclear production would increase by 200 EJ, corresponding to that of 7000 one 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 on Figure 17 in the Appendix 2 (A.2.2)

ⁱ See <http://www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/Chapter1.en.html>

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

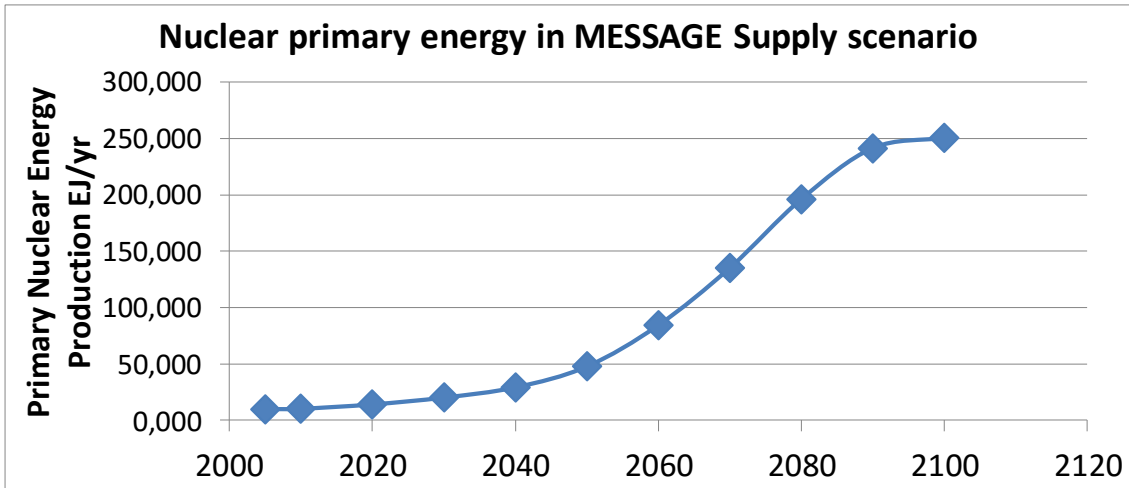


Figure 1

Evolution of nuclear electricity production in the MESSAGE "Supply" scenario (Supply nuclear)⁴.

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

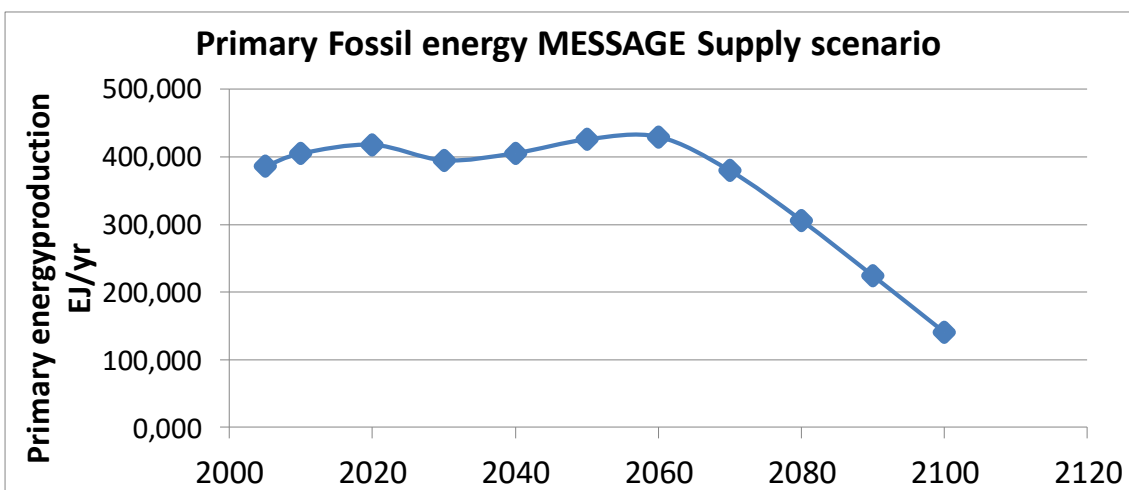


Figure 2

Evolution of the fossil production in the MESSAGE "Supply" scenario (Supply fossil)⁵

We suggest starting the nuclear reactor implementation program in 2020 rather than 2060. Thus, CO₂ emissions reduction will start earlier and the amount of CO₂ in the atmosphere will be considerably reduced, hence alleviating considerably the need of carbon capture and storage (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 “Super Phenix” case (Super Phenix Wikipedia)⁶, a 1240 MW sodium-cooled fast-neutron reactor which worked in France at full power during one year before being stopped in 1998 for political reasons. Normalized 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 (Purex Wikipedia)⁷ 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 yearsⁱ.

Use of current thermal neutron reactors is allegedly limited by the uranium reserves, but this is highly questionable on at least a century time scale. 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 gives an estimate for “classical” reserves around 16 million tons (OECD NEA 2009)⁸. Standard PWR reactors require 120 tons of uranium per year per GW (Nifenecker 2011)⁹. For a production of 250 EJ/y, the number of production years assured with such reserves would be limited to approximately 16 years. Thus, for a sustainable

ⁱ It should be noted that metal-fueled fast reactors of the Integral Fast Reactor type (IFR) 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.

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 utilization 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.

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

Country	Name	Years operation	Power MWe	Breeding coefficient	fuel	core
USA	EBR 2	1964-1994	20		Metallic	
France	Phenix	1973-2009	260	1.12	Mox	Plutonium
Russia	BN600	1980-	560		Mox	U235
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			

Table 5

Present and past fast breeder characteristics

In most cases nuclear fuel used in FBR are mixed uranium-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 7 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/y 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 140000 TWh would require 17000 1 GWe reactors. If these reactors were PWR Uranium reserves would be exhausted after 8 yearsⁱ! Therefore, before 2100 all nuclear reactors should be breeders. A similar approach was previously followed by H.Nifenecker et al. (Nifenecker 2003)¹⁰ (Nifenecker 2011)¹¹ and by a Karlsruhe Institute of Technology (KIT) researchers group (as documented in “Sustainable Nuclear Fuel Cycles and World Regional Issues” Sustainability 2012, 4(6), 1214-1238, and in the Nuclear Energy Agency Report “TRANSITION TOWARDS A SUSTAINABLE NUCLEAR FUEL CYCLE”, NEA No. 7133, © OECD 2013). In Appendix 3 (A.3.4), 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: 250kg/y/GWe, used for building up the initial FBR inventory
- Natural Uranium annual needs per one GWe PWR reactor: 120 tons/GWe
- Plutonium production by FBR in addition to that used for core replacement: 200 kg/y/GWe
- Total plutonium inventory of a one 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 Nuclear Energy Agency.
- Reach 19000 GWe FBR in 2100

ⁱ If thorium-fueled 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.

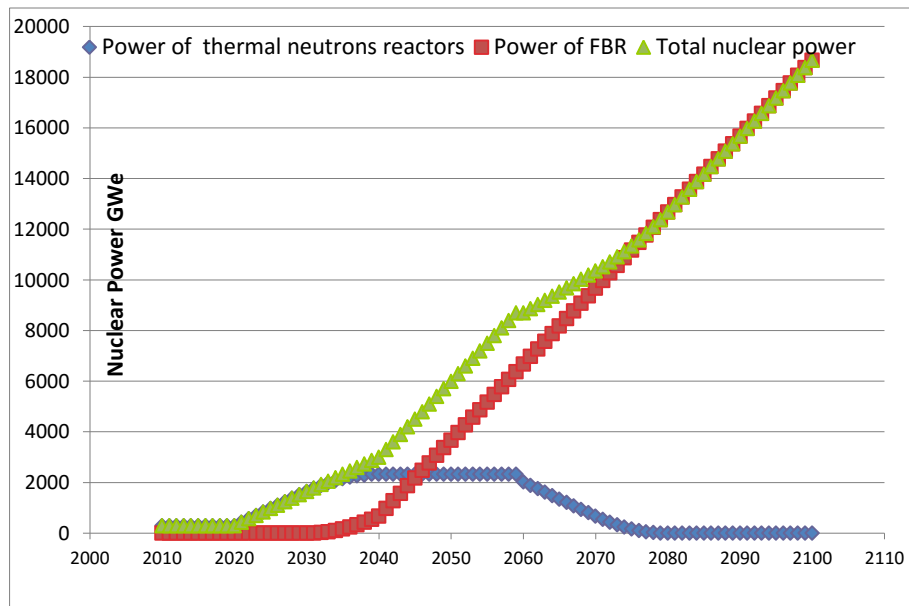


Figure 3

Evolution of the nuclear installed power for scenario "Supply-N".

The details of the calculation is given in Appendix 3 (A.3.5)

Figure 3 shows the evolution of nuclear power up to year 2100. Thermal neutron reactors are supposed to operate during 50 yearsⁱ. 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/y. 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.

ⁱ AP1000 and EPR have, respectively, design lifetime of 80 and 60 years

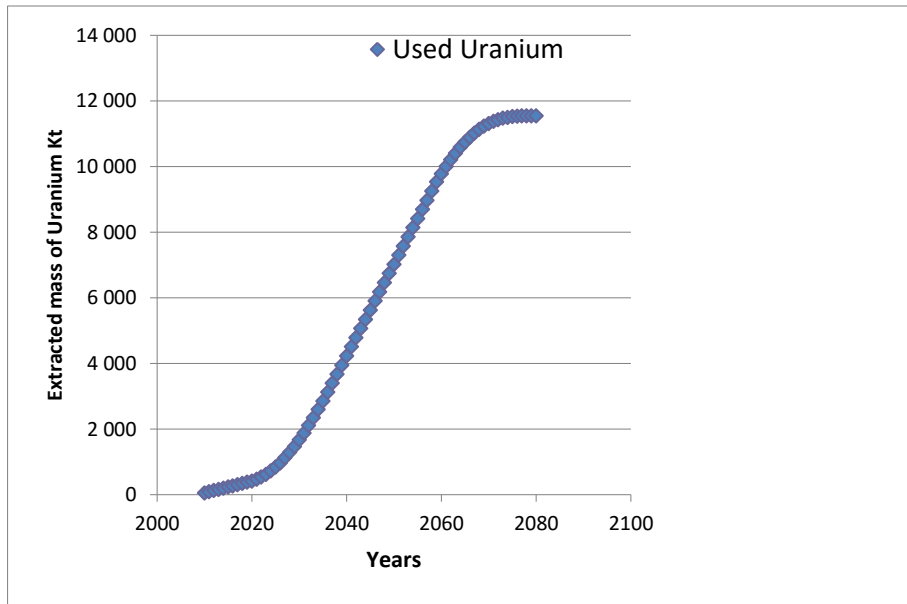


Figure 4

Cumulated consumption of uranium in the Supply-N scenario

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

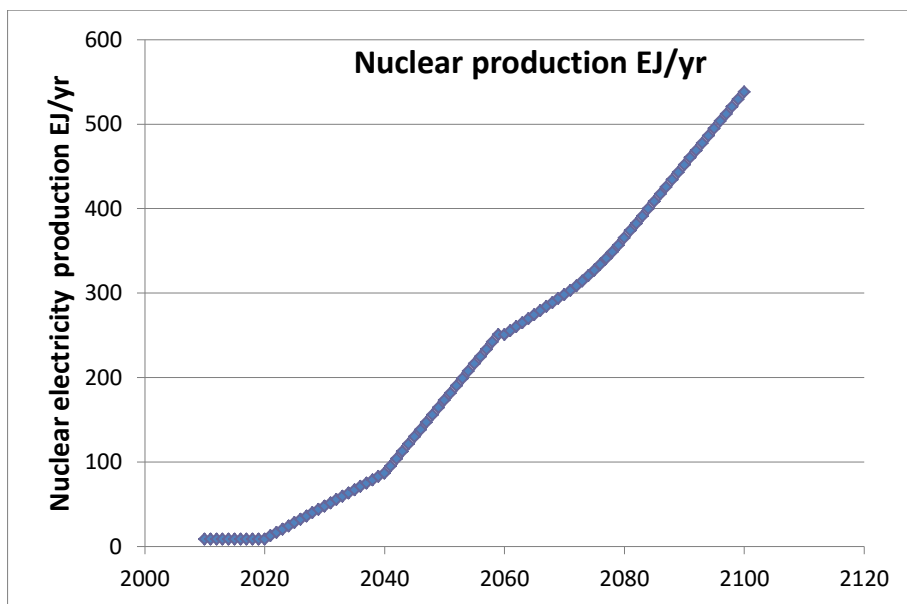


Figure 5

Evolution of nuclear annual energy production

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

2.2.4 Fossil evolution in Supply and Supply-N

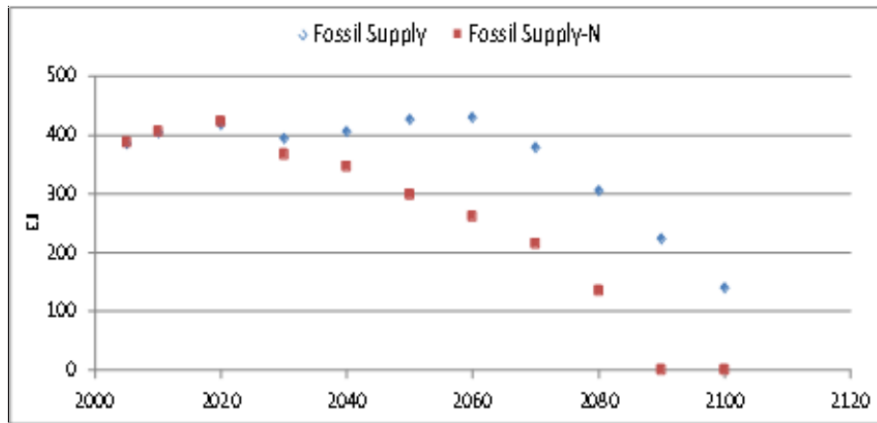


Figure 6

Comparison of fossil fuels consumptions of scenarios "Supply" and "Supply-N" scenarios

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.

2.2.5 CO2 emissions in Supply and Supply-N

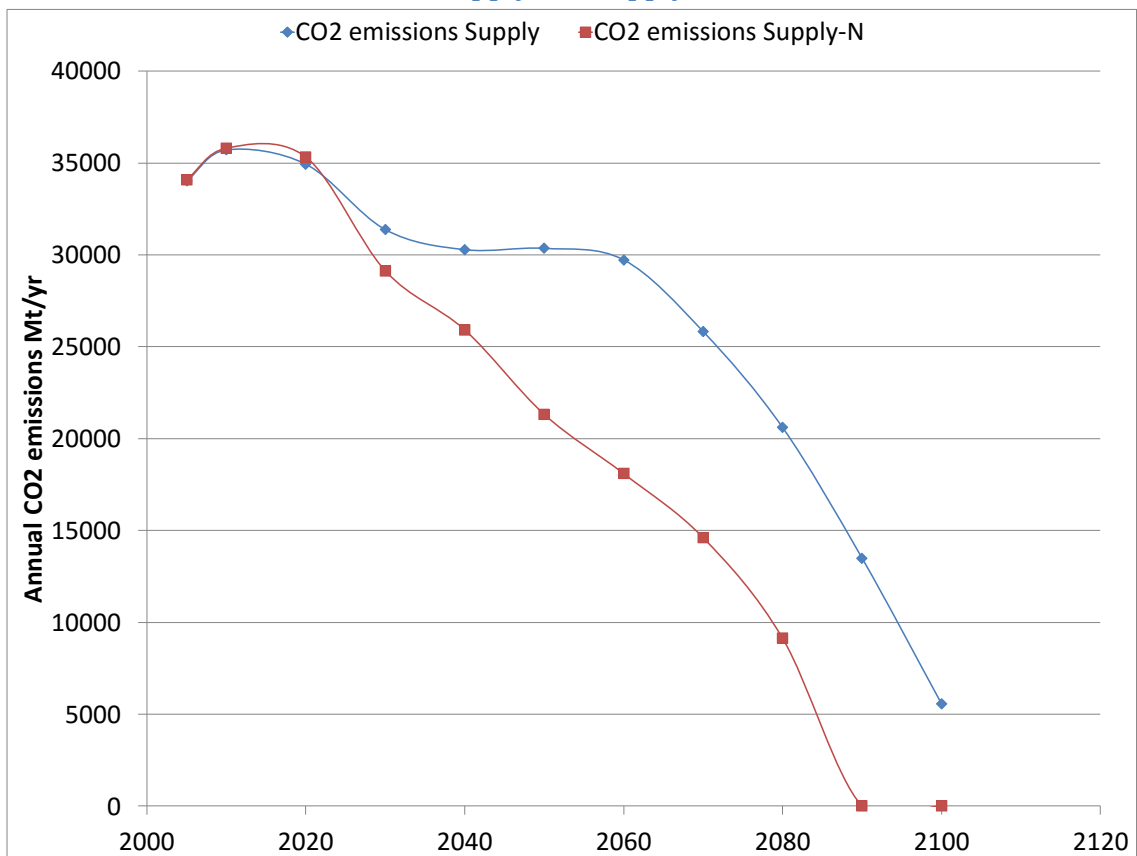


Figure 7

Comparison of CO₂ annual emissions between the "Supply" and the "Supply-N" scenarios

As a consequence of the reduced fossil consumption of the “Supply-N” scenario, this scenario has lower annual CO₂ 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.

The 40 year shift of the curves leads to an earlier stabilization of cumulated CO₂ quantities injected in the atmosphere as seen on Figure 8.

In order to follow the RCP 2.6 , the IPCC estimates that no more than 1000 Gt of CO₂ should be added to the atmosphere.

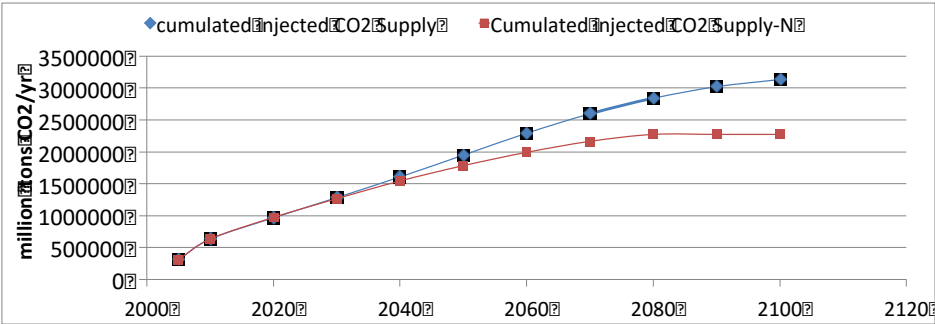


Figure 8

Cumulated injected CO₂ quantities for the “Supply” and “Supply-N” scenarios

These quantities of CO₂ injected in the atmosphere are not compatible with the RCP2.6 path. Without CCS, the Supply scenario would add 3100 Gt CO₂ to the atmosphere, which is 2100 Gt CO₂ more than allowed, and the Supply-N 2300 Gt CO₂, 1300 Gt CO₂ more than allowed. Figure 9 shows that, in order to fulfill the RCP 2.6 requirements, the Supply scenario requires storing 25 Gt CO₂ in 2100 while in the “Supply-N” scenario the CCS needs are limited to 10 Gt.

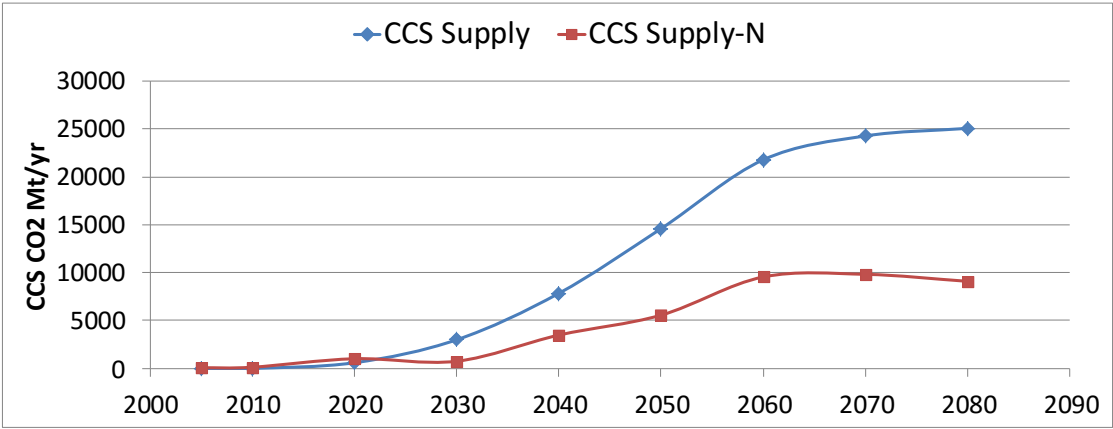


Figure 9

CO₂ storage needs comparison between « Supply » and « Supply-N » scenarios

Figure 7 shows that, in the “Supply-N” scenario, CO₂ 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.

	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 6

World primary energy mix in 2100 for scenarios « Supply » and « Supply-N ». The bracketed numbers correspond to the case when nuclear is limited to 450 EJ in 2100.

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.

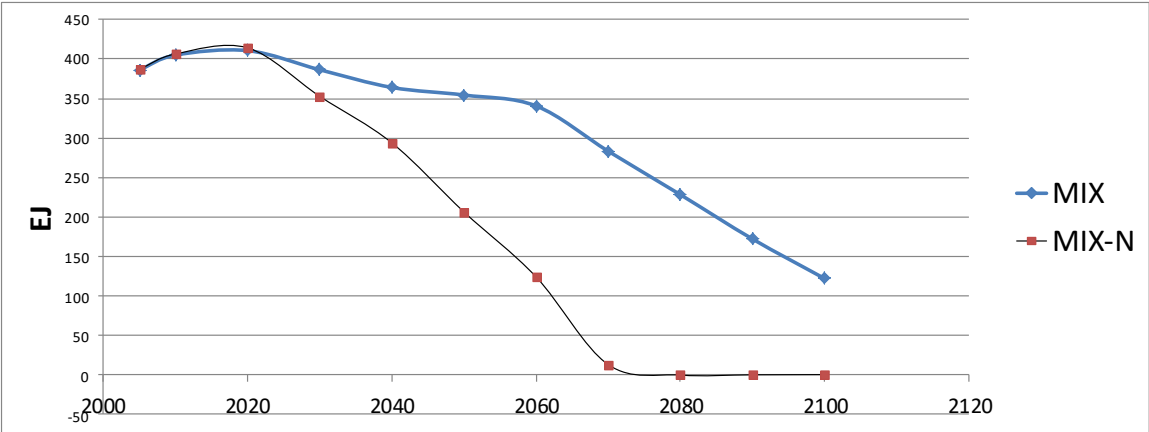


Figure 10

Comparison of fossil fuels consumptions in the “MIX” and “MIX-N” scenarios

Table 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.

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

Table 7

World Energy Mix in 2100 or scenarios "MIX" and "MIX-N"

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.

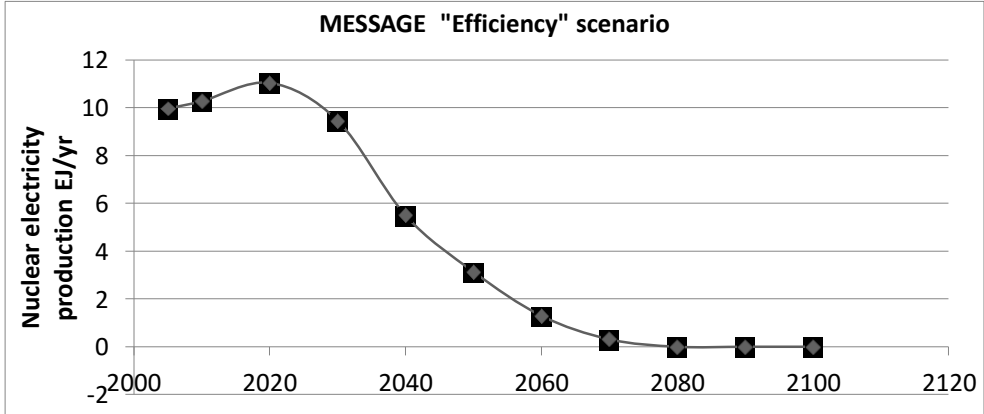


Figure 11

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.

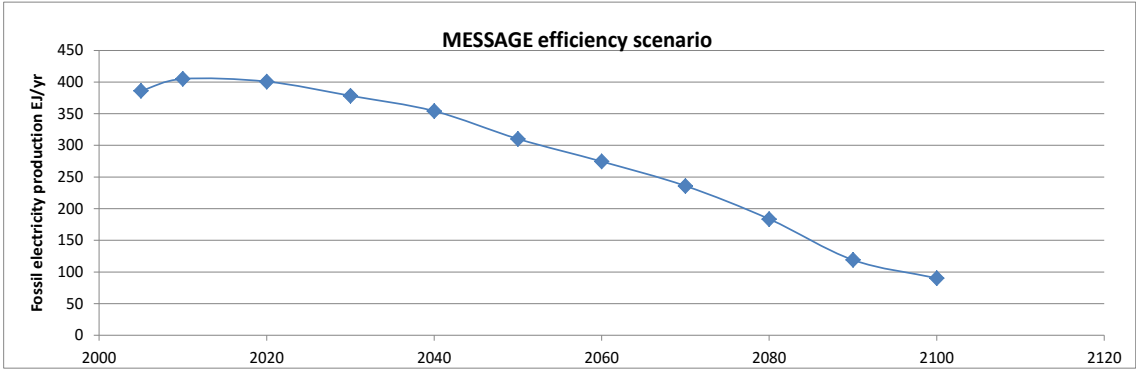


Figure 12

Evolution of fossil electricity production in "Efficiency" scenario

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

3. CO₂ emissions.

Figure 13 shows the accumulated quantities of emitted CO₂ between 2010 and 2100, calculated for the different scenarios. These quantities are calculated from the fossil consumptions assuming a CO₂ emission intensity of 317 kg per MWhⁱ, as observed for 2010. CCS was not taken into account in the calculations of either absorption by oceans or biomass.

Since fossil contributions do not vanish by 2100 (140 EJ for the Supply scenario) the standard MESSAGE scenarios are unable to stabilize the CO₂ concentration in the atmosphere before 2100. On the contrary, scenarios with an accelerated increase of nuclear production and vanishing contributions of fossils reach stabilization between 1700 and 2100 Gt of CO₂ⁱⁱ.

MESSAGE scenarios cannot comply to the RCP 2.6 criterion without intensive CCS. This technique applied to the combustion of biomass allows a decrease of atmospheric CO₂ concentrationⁱⁱⁱ. If achievable, it can be, equally well, applied to “Supply-N” and “MIX-N” scenarios. The result is shown on Figure 14.

	Supply	Supply-N	MIX	MIX-N	Efficiency
Cumulated CO ₂ emissions Gt Year 2100	3100	2200	2700	1700	2500
Stabilization	No	Yes	No	Yes	No

Table 8

Values of cumulated CO₂ emissions in 2100 for the three standard MESSAGE scenarios and the two X-N scenarios. The observation of a stabilization of the CO₂ content of the atmosphere in 2100 is indicated.

Table 8 shows that, with the nuclear option, the cumulative CO₂ emissions decrease by approximately 1000 Gt, and increase no further thereafter.

ⁱ In 2010 a CO₂ emission of 35.7 Gt was observed for a total fossil primary energy of 405 EJ i.e. a CO₂ 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.

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

ⁱⁱⁱ Under the assumption that burnt biomass is replaced by plantations it is generally assumed that biomass burning is CO₂ neutral. If CCS is applied to the fumes it has the result of decreasing the amount of CO₂ in the atmosphere. In practice, biomass is mostly used for biofuel synthesis and CCS takes place at this stage.

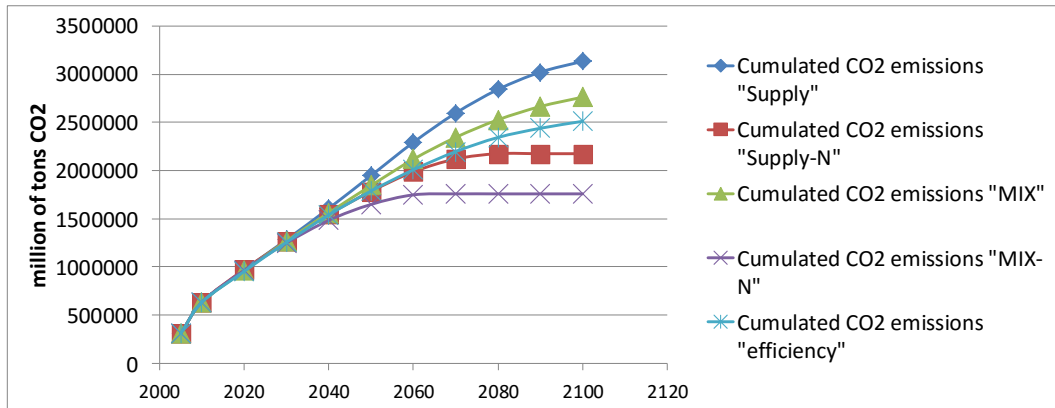


Figure 13

Evolution of integrated CO₂ emissions for scenarios Supply, Mix, and Efficiency between 2010 and 2100, with and without acceleration of nuclear production. No CCS was assumed. CO₂ reabsorption by oceans and biomass is not included.

Without CCS the Supply-N and MIX-N scenarios, although they have much better performances than the original ones, are not able to fulfill the 1000 Gt limit required by IPCC RCP 2.6. Figure 14 shows that adding CCS only to biomass energy sources, as proposed by the original MESSAGE scenarios, allows the RCP 2.6 criterion to be achieved.

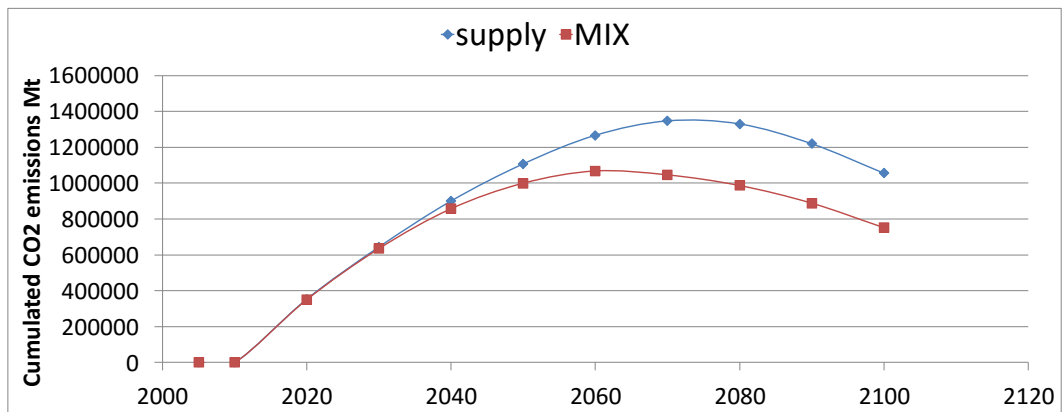


Figure 14

Evolution of integrated CO₂ emissions between 2010 and 2100 for scenarios Supply-N and Mix-N with CSS applied to biomass combustion.

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 a RCP 2.6 path owing to reduced energy consumption, as shown on Figure 15.

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

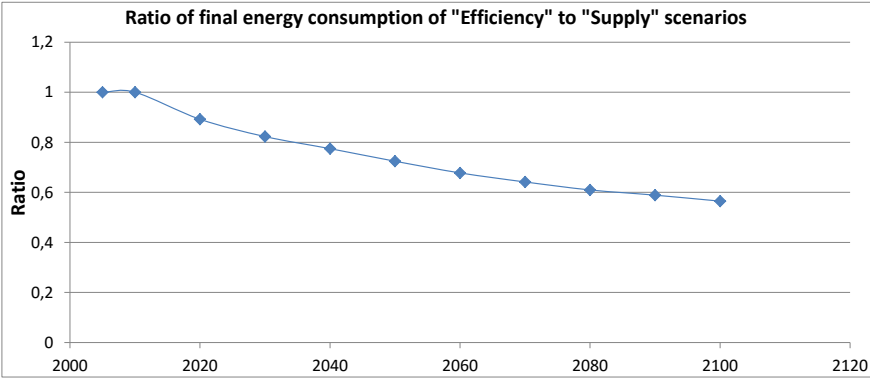


Figure 15

Ratio of final energy consumption of the “Efficiency” scenario to that of the ‘Supply’ scenario

Figure 16 shows a comparison of annual gross CO₂ 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 CO₂ 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.

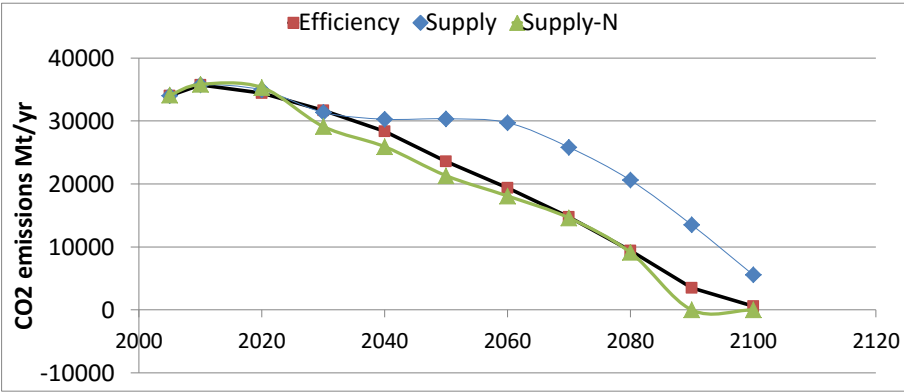


Figure16

Comparison of CO₂ 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 RCP 2.6 criterion without extensive use of CCS, except for biomass.

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

Table 9

Values of RCPs and global temperature increases for various scenarios. Correspondences between CO₂ atmospheric concentrations, RCP and temperature increases are given in the IPCC report AR4 (IPCC AR4)¹².

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 \$2,000/kW for mass-producible metal-fueled 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)¹³. 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 10000 billion \$/y 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 on 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.

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 CO₂.

Techniques	OECD	China
	US \$/MWh	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

Table 10

Levelized kWh costs of electricity for OECD and China (NEA costs)¹⁴. A 5% discount rate was assumed.

6. Workforce and industrial resources

The possibility to reach an annual rate of building of a 100 GWe/y nuclear power between 2020 and 2040, and 300 GWe/y 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, 4 in 1974 and 9 in 1975. France has a population of 60 million. Countries which already have a nuclear program and 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 23000 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 9 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 20000 GWe of FBR power consumes 20000 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 60000 tons/y 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 20000 GWe FBR fleet will not need new mining.

Coal plants with equivalent energy output would require extraction of 80 Gt/y. As an example of surface mining we take the German Hambach opencast mine with a surface of 40 km² 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 km² (and 2 times more for hard coal).

7.2 Surface footprint and biodiversity

Nuclear plants have a surface footprint around 2 km²/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 km² (Footprint)¹⁵, that for wind turbines 300 km² and that of biomass, 2500 km². 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.

	Nuclear	Fossil	PV	Wind	Biomass
Footprint km ²	40 000	100 000	2 000 000	12 000 000	50 000 000

Table 11

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

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

7.3 Raw material needs

As an example, the EPR (European Pressurized Reactor, 1650 MWe) requires 500 000 m³ of concrete and 110 000 tons of steel. CO₂ emissions due to the EPR construction are calculated to amount to approximately 1 million tons (Materials EPR)¹⁶. Over a lifetime of 60 years the EPR will produce 720 TWh. This leads to a CO₂ emission from construction materials of 0.5 gCO₂/kWh. With present technologies wind turbines require 8 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 CO₂ emitted by kWh produced, for example 100 g CO₂ per 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. CO₂ emissions/kWh for a few examples are given on Table 12.

Technique	Coal	Gas CCG	Hydro	Wind	Solar PV	Nuclear
Emission gCO ₂ /kWh	1024	491	6	15	45	16

Table 12

CO₂ emissions in gCO₂/kWh for different electricity production techniques (Hirshberg)¹⁷

With a standard of 100g CO₂/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 CO₂-free electricity production could, thus, be obtained after 30 years.

2. Introduce an Emission Trading Scheme or a Carbon Fee & Dividend, as described by James Hansen et al. (Hansen Tax)¹⁸

9. Safety issues

9.1 Reactor accidents

With 20000 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 correspond 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 atmosphereⁱ. This means that one might expect 2 nuclear accidents with significant radioactivity release per century for the entire fleet.

ⁱ 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.

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.

Along the same line P.A.Kharecha and J.E. Hansen (Kharechea mortality)¹⁹ 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.

Technique	Deaths per 1000 TWh
Coal (world)	170000
Coal (China)	280000
Coal (US)	15000
Oil	36000
Natural gas	4000
Biomass	24000
Solar PV	440
Wind	150
Hydroelectricity	1400
Nuclear	90

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. Data from ExternE (Forbes).

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 risk)²⁰ written by one of us. As an example, living in a background radiation of 20 mSv/y, a maximum limit for return in the Fukushima neighborhood, is equivalent, as far as cancer development is concerned, to smoking 3 cigarettes per day. The number of years of life lost in a background of 100 mSv/y 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 a FBR produces only 1 ton (essentially fission products) since uranium, plutonium and minor actinides are recycled.

Therefore, 20000 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 IAEAⁱ, contrary to the massive gas diffusion plants previously used. Furthermore, ²³⁵U explosive devices are rather straightforward to build, while, due to the presence of the non-fissile ²⁴⁰Pu isotope, plutonium devices require the delicate use of timed chemical implosion before the atomic explosion can take place. In order to minimize the presence of ²⁴⁰Pu isotope the irradiation of ²³⁸U necessary for production of ²³⁹Pu 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. Fueling 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

ⁱ International Atomic Energy Agency

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 an immense panic. This is an illustration that the main risk of nuclear is not that associated to the reality of radiation, but that associated to 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, the 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/y. 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 in 2020, would significantly alleviate the constraints required to stabilize global temperatures before 2100. The CO₂ volume to be stored would be divided by at least by a factor 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 20000 GWe in 2100 is possible if the world relies on breeding with improved reprocessing techniques, deploying thorium-fueled 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)²¹.

Following a study published in Forbes Magazine (Forbes)²², when compared to those related to global warming, the risks associated with nuclear electricity production are small. Including 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.

Appendix 1

Energy Conventions

Final energy : Energy bought by the final user. For example: natural gas or electricity.

Secondary energy : energy output from the production plant. For example: electricity, hydrogen, gasoline... 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 2

Regional developments in the MESSAGE scenarios

A.2.1 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 Yugoslav Rep. 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, United States of America, 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, United Kingdom

A.2.2 Regional development of nuclear energy following the MESSAGE Supply scenario.

Figure 17 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), United States (NAM), Korea and other East and Southeast Asian States (Taiwan, Thailand, Indonesia).

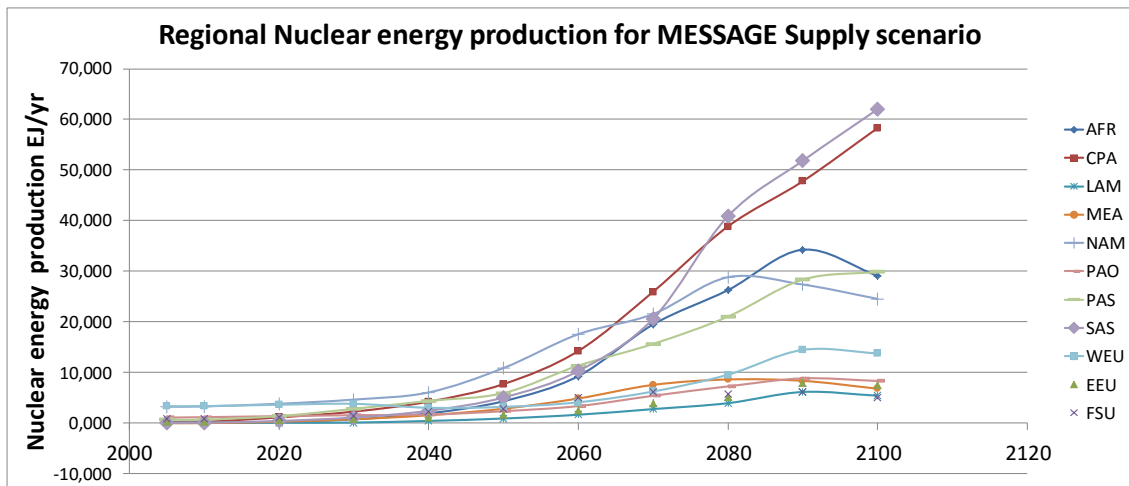


Figure 17

Evolution of nuclear electricity production in various geographic regions according to the MESSAGE « Supply » scenario. The definition of regions is given in A.2.1

A.2.3 Regional evolution of the final energies per million capita in the Supply scenario

Figure 18 shows that, even in the Supply scenario a tendency towards equity of the final energy consumption per capita is present

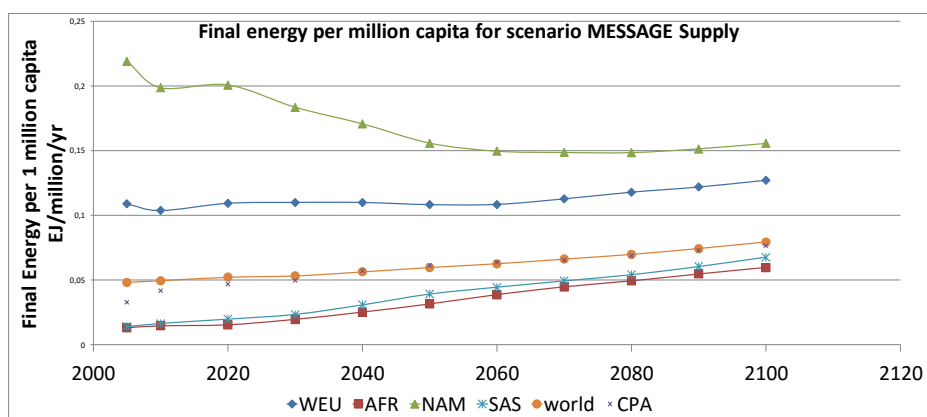


Figure 18

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

A.2.4 Regional evolution of the final energies per million capita in the Efficiency scenario

Figure 19 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.

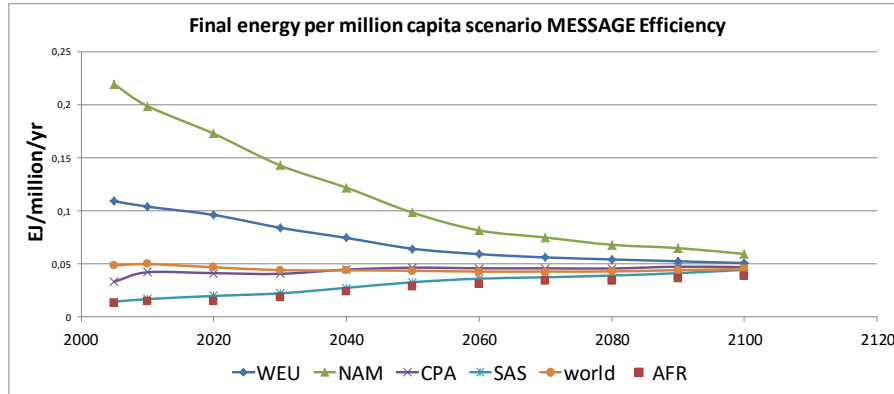


Figure 19

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

Appendix 3

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.

A.3.1 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, GEN 3ⁱ reactors are supposed to have 36% thermo-dynamical efficiency and FBR up to 45% due to higher outlet temperatures.

ⁱ GEN 3 : Generation 3 reactors like advanced PWR and PHWR

A.3.2 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 2/3 correspond to fission of ^{235}U and the remaining to fast fission of ^{238}U and fission of $^{239,241}\text{Pu}$ 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 per GWe PWR. This has to be compounded by enrichment tails on one hand, re-enrichment of these tails and of reprocessed depleted Uranium, on the other hand. 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 one 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.

A.3.3 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. Due to their superior neutron utilization PHWR reactors produce 2.4 times more plutonium than PWR (Guillemin)²³.

A.3.4 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)²⁴ 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 a 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. 11400 FBR after 40 more years.

Figure 20 compares the plutonium production of a 2325 GWe PWR fleet to that of the same PHWR power. Life time of the reactors was assumed to be 50 years.

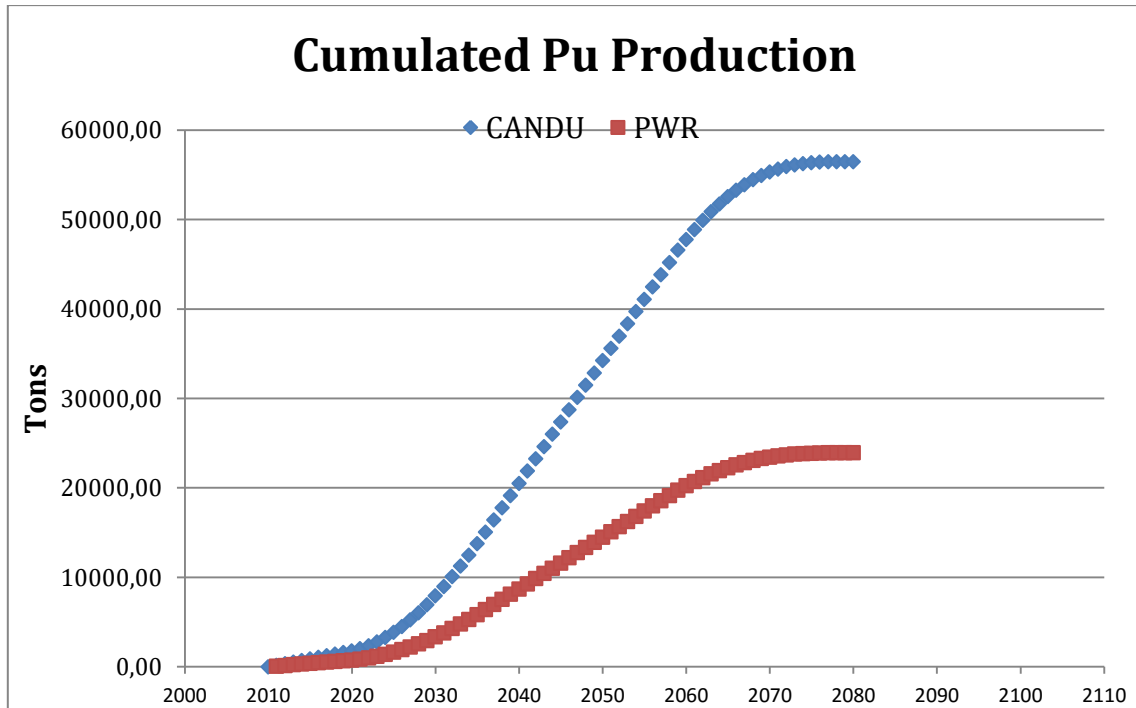


Figure 20

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 optimizing 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.

Total Pu inventory /GWe tons	Proportion of PHWR in the thermal fleet %
8	50
7	37
6	14
5,5	0

Table 14

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

A.3.5 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/y. The Pu production of PWR is chosen to be 0,25 tons/y, that of PHWRs to be 0,59 tons/y and the net production of Pu by FBR to be 0,2 tons/y.

The core inventory of FBR is assumed to be 4 tons of Plutonium. The fuel is supposed to stay 4 years in 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, in the other 5,5 tons.

Starting at year 0 we assume a constant building rate of 135/y until 20 years after the starting year ; at that time the building rate increases to 300/y. The number of thermal reactors (PWR or PHWRs) being built is 135/y at the beginning and starts leveling off 10 years after year 0 to vanish in year 20. The complement to 135/y before year 40 and to 300 after is made of FBR. After 80 years the number of FBR (the only ones left) reaches 15000 for an energy production of 430 EJ, as seen on 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/y, that of PHWRs around 80 tons/GWe/y. In our calculation we have used an average value of 100 tons/GWe/y. 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 19000 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/y. For an inventory of 8 ton/GWe, the total inventory for 19000 FBR amounts to 150000 tons. With a 0,2 ton/y 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 27000 tons. For PWR the cumulated Plutonium production is only 12000 tons. For PHWRs it reaches 34000 tons.

If the inventory is reduced to 5,5 tons/GWe the total inventory for 19000 FBR amounts to 105000 tons with a need of 19000 tons in 2050.

Figure 21 is an example of the evolution of the available Plutonium stock for various choices of the percentage of PHWRs in the thermal neutrons reactors fleet with two different values of the Plutonium inventory of the FBRs. We note that the combination of a 100% PWR fleet and a FBR Plutonium inventory of 8 tons/y leads to a negative stock, which means an impossibility to reach the objective of 19000 FBR reactors.

An important part of the stock rests in the used fuels since, after the rate of FBR construction is stabilized at 300/y the yearly processing rates are 2400 tons of Plutonium with a 8 tons inventory and 1650 tons for a 5.5 tons 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 19000 reactors would be 3800 t/y, allowing the construction of 475 reactors with 8 t/GWe inventory and of 690 FBR with 5,5 t/GWe inventory. This means that the FBR fleet will be easily at equilibrium. Some natural Uranium will still be necessary at a rate of 19000 tons per year.

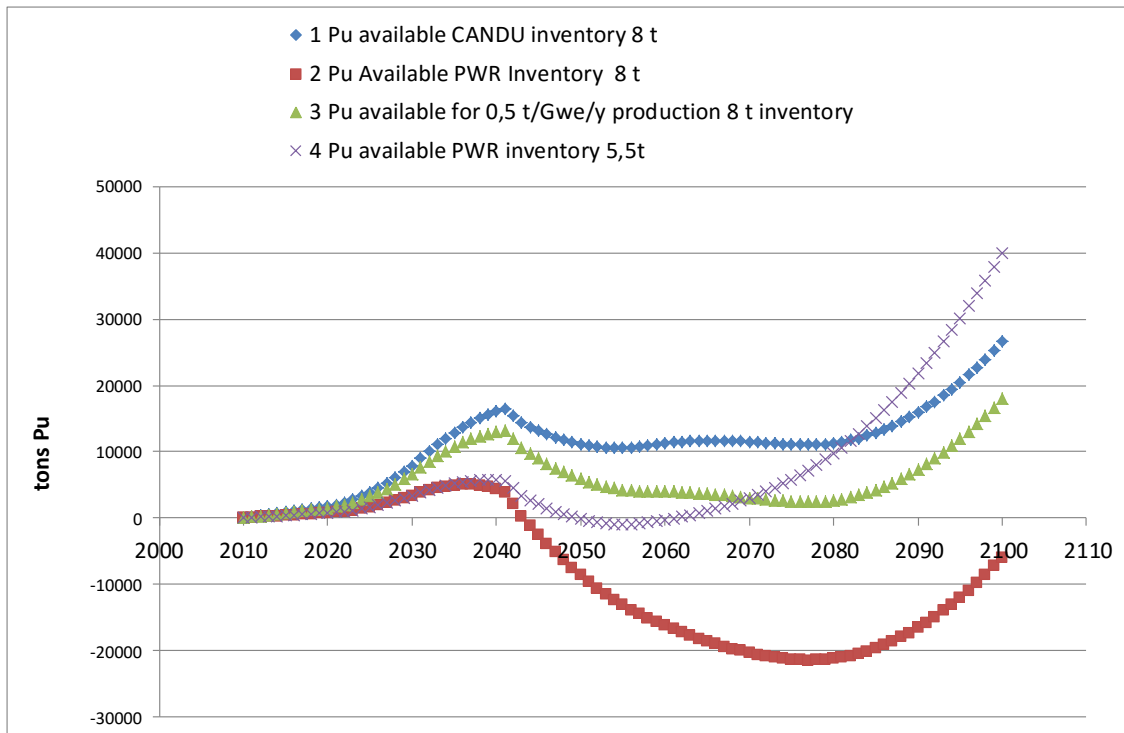


Figure 21

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 a FBR plutonium inventory of 8 tons/GWe.

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

3 assumed a mixed Thermal reactors fleet with 73% PHWRs and a FBR plutonium inventory of 8 tons/GWe.

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

References

¹ (IPCC AR5 2014) <https://www.ipcc.ch/report/ar5/>

² (IIASA_WEB_site)

<http://www.iiasa.ac.at/webapps/ene/geadb/dsd?Action=htmlpage&page=regions>

GEA Scenario database (Version 2.0.2)

³ (GEA, 2012): *Global Energy Assessment - Toward a Sustainable Future*, Cambridge University Press, Cambridge, UK and New York, NY, USA and the International Institute for Applied Systems Analysis, Laxenburg, Austria. Chapter 7, Table 7.1

⁴ (Supply nuclear) <http://www.iiasa.ac.at/web-apps/ene/geadb/dsd?Action=htmlpage&page=regions>

⁵ (Supply fossil) <http://www.iiasa.ac.at/web-apps/ene/geadb/dsd?Action=htmlpage&page=regions>

⁶ (Super Phenix Wikipedia)

https://fr.wikipedia.org/wiki/Superph%C3%A9nix#Bilan_neutronique_de_Superph.C3.A9nix

⁷ (Purex Wikipedia)

<https://fr.wikipedia.org/wiki/PUREX>

⁸ (OECD NEA 2009) <http://www.oecd-nea.org/ndd/pubs/2010/6891-uranium-2009.pdf>

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.

⁹ (Nifenecker 2011) Future electricity production methods. Part 1: Nuclear energy Hervé Nifenecker Published 14 January 2011, IOP Publishing Ltd , [Reports on Progress in Physics, Volume 74, Number 2](#)

¹⁰ (Nifenecker 2003) [Scenarios with an intensive contribution of nuclear energy to the world energy supply](#) H.Nifenecker, D. Heuer, J.M. Loiseaux, O. Meplan, A. Nuttin, S. David, J.M. Martin

[Int. J. of Global Energy Issues](#) > [2003 Vol.19, No.1](#) > pp.63-77

<http://www.inderscience.com/info/inarticletoc.php?jcode=ijgei&year=2003&vol=19&issue=1>

¹¹ (Nifenecker 2011)Future electricity production methods. Part 1: Nuclear energy Hervé Nifenecker Published 14 January 2011, IOP Publishing Ltd , [Reports on Progress in Physics, Volume 74, Number 2](#)

¹² (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

¹³ (EFR cost) <http://bibliothek.fzk.de/zb/kfk-berichte/KFK5255.pdf>

¹⁴ (NEA costs) OECD/IEA-NEA 2010, Projected costs of Generating Electricity, Table 3.7

¹⁵ (Footprint) <http://www.nei.org/News-Media/News/News-Archives/Nuclear-Power-Plants-Are-Compact,-Efficient-and-Re>

¹⁶ (Materials EPR) <http://quille-industrie.com/metiers/nucleaire/centrale-electronucleaire-epr-flamanville>

¹⁷ ((Hirshberg) <http://www.sfen.org/fr/nuclear-for-climate> and http://www.sauvonsleclimat.org/images/articles/pdf_files/ec_2008/Hirschberg.pdf slide 12

¹⁸ (Hansen Tax) See, for example <http://www.worldwatch.org/node/5962>

¹⁹ (Kharecha mortality) [Pushker A. Kharecha*](#) and [James E. Hansen](#), Prevented Mortality and Greenhouse Gas Emissions from Historical and Projected Nuclear Power, *Environ. Sci. Technol.*, 2013, 47 (9), pp 4889–4895

²⁰(Nifenecker risk)Hervé Nifenecker , A review of post-nuclear-catastrophe management , *Reports on Progress in Physics*, Volume 78, Number 7

²¹(Brook)Brook, B.W. & Bradshaw, C.J.A. (2015) Key role for nuclear energy in global biodiversity conservation. *Conservation Biology*, 29, 702-712. doi: 10.1111/cobi.12433

²² (Forbes) <http://www.forbes.com/sites/jamesconca/2012/06/10/energys-deathprint-a-price-always-paid/>

²³ (Guillemin) Thesis Perrine Guillemin : Recherche de la haute conversion en cycle Thorium dans les réacteurs PHWR et REP, Tab.2.7

²⁴ (IFR) https://en.wikipedia.org/wiki/Integral_fast_reactor