

Nuclear Power
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About the 'Breaking the Climate Deadlock' Initiative

'Breaking the Climate Deadlock' is an initiative of former UK Prime Minister Tony Blair and independent not-for-profit organisation, The Climate Group. Its objective is to build decisive political support for a post-2012 international climate change agreement in the lead up to the 2009 UN Climate Change Conference in Copenhagen. Its particular focus is on the political and business leaders from the world's largest economies, particularly the G8 and the major developing countries. The initiative builds on Mr Blair's international leadership and advocacy of climate change action while in office, and The Climate Group's expertise in building climate action programmes amongst business and political communities.

This briefing paper and its companions were commissioned by the Office of Tony Blair and The Climate Group to support the first Breaking the Climate Deadlock Report – 'A Global Deal for Our Low Carbon Future' – launched in Tokyo on June 27th 2008. Written by renowned international experts and widely reviewed, the papers' purpose is to inform the ongoing initiative itself and provide detailed but accessible overviews of the main issues and themes underpinning negotiations towards a comprehensive post-2012 international climate change agreement. They are an important and accessible resource for political and business leaders, climate change professionals, and anyone wanting to understand more fully, the key issues shaping the international climate change debate today.

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Executive Summary

- Nuclear energy can play an important role in climate change mitigation. It could provide up to 35 percent of global electricity production by 2050. This would however be equal to an 8-fold increase in capacity, and is likely to be close to the technically maximum construction capacity.
- Nuclear waste, safety and proliferation are issues not satisfactorily resolved at the moment, and could benefit from international cooperation.
- Generation IV reactors are expected to have the potential for substantially improved performance with regard to nuclear waste, proliferation, safety and economics compared to current commercial Generation III reactors, but will not be available before 2030.
- Public perception, high investment cost and environmental impact of mining are other barriers for nuclear energy.
- Nuclear energy accounts for approximately 40 percent of total energy-related public research and development (R&D) expenditures.
- Economics and carbon dioxide abatement cost of nuclear are favourable compared to other electricity production technologies. In addition, compared to fossil fuel power production options, nuclear provides benefits for air quality and energy supply security.
- Construction of large-scale nuclear power plants worldwide will reveal existing bottlenecks in materials supply chains, components and assembly manufacturing capacities and in regard to the sufficiency of high-skilled personnel.

Recommendations

- Sharing of technologies, experience and knowledge could speed up the process for determining the most promising reactor designs. When more is known about the prospects of these designs, sharing of technologies is even more important in order to move towards commercialisation of Gen IV reactors.
- Enhance international cooperation on addressing the proliferation issue.
- Enhance the international dialogue on long-term waste disposal issues, with the aim to develop international guidelines.
- Continue dialogue with all stakeholders about pros and cons of nuclear energy.
- Initiate discussions on eligibility of nuclear energy under the Clean Development Mechanism in the Ad Hoc Working Group on further commitments under the Kyoto Protocol (AWG KP).

Nuclear Power

This paper explores the role of nuclear energy, the research and development and initial steps desirable to secure the viability of its full potential. It covers:

- The potential of nuclear power
- Benefits and barriers in connection with nuclear energy
- Costs of nuclear energy
- Prospects for supporting new generation technologies
- The role of international initiatives and of governments

Generations of nuclear power plants

In a nuclear power plant, heavy atom nuclei are split, thereby converting matter into energy. Most nuclear reactors use enriched uranium as fuel, which is generated by processing natural uranium ore. The nuclear fission process generates heat, which is carried by steam or hot gas to a generator to produce electricity.

There is no clear-cut classification for types of reactors, but the following distinction by generation (Gen) can be made¹:

- Gen I: Early prototypes;
- Gen II: First designs of Light Water Reactors (LWR) (e.g. Pressurised Water Reactor, Boiling Water Reactor, Russian Water Power Reactor, etc), Heavy Water Reactors (HWR) and Gas Cooled Reactors;
- Gen III: Evolutionary changes compared to Gen II, including passive safety features (e.g. European Pressurised Water Reactor, and several reactors developed in the US, Japan, Russia)
- Gen III+: Revolutionary 'Inherently safe' reactor designs (e.g. Improved designs of Gen III technologies, AP1000 (Advanced Pressurised Water Reactor), Economic Simplified Boiling Water Reactor)
- Gen IV: New reactor concepts that further improve performance regarding nuclear safety, fuel efficiency, economics, etc.

As of 2007, there were 438, mostly Gen II nuclear power plants world-wide, with a total installed capacity of 372 Giga Watts electrical (GWe). These plants generate approximately 16 percent of global electricity, with 60 percent of capacity in the US, France and Japan². Almost all plants are of the Gen II type, although several currently under construction are of the Gen III type. China, India, Russia, Japan, South Korea and Ukraine are planning 116 GWe of additional nuclear capacity by 2020. The first commercial Gen III+ reactors are expected between 2015 and 2020, with Gen IV reactors expected to become available from 2030 onwards.

The potential of nuclear power

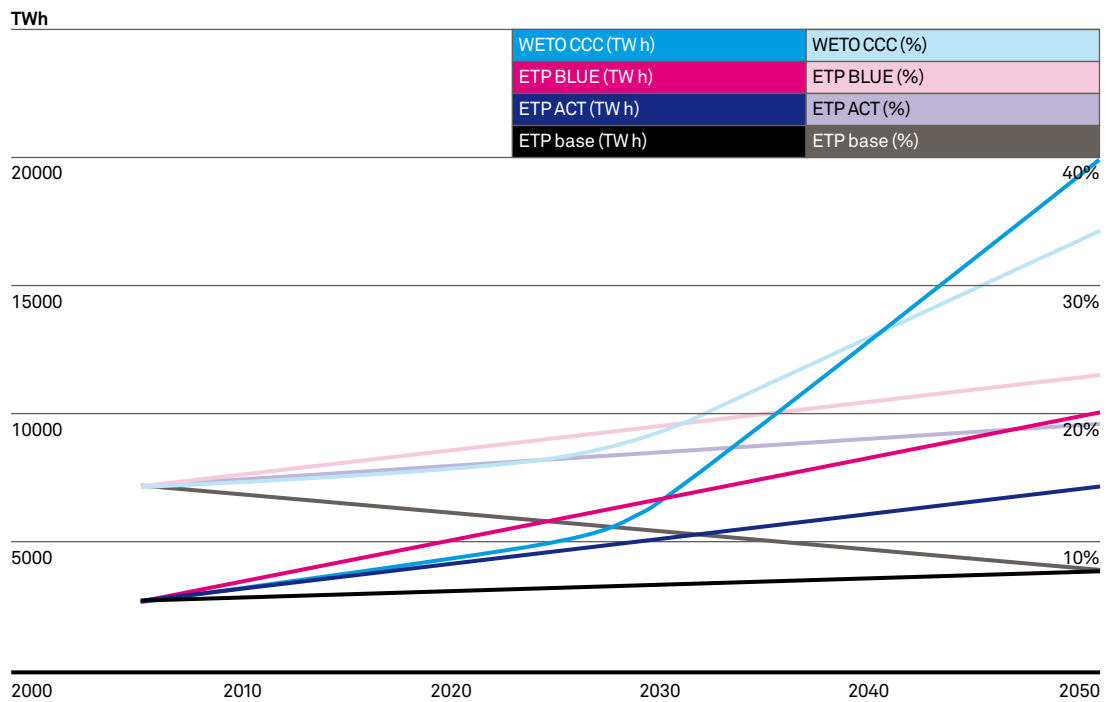
Nuclear energy is a typical base-load power technology and as such it competes with other base-load power generation (e.g. coal). Small (<300 Megawatt electric – MWe) and medium (300–700 MWe) size reactors type could be a niche market for nuclear energy. These smaller Gen III+ (e.g. High Temperature Gas cooled reactors) and Gen IV reactors, could provide electricity for small regional systems, desalinisation plants, as well as hydrogen and process heat.³

In mitigation scenarios based on economic modelling, nuclear is projected to play an important role

There is considerable disparity between estimates on the scale at which nuclear energy will play a role in the future. This is true both to the extent to which nuclear is likely to form part of the energy mix, and the degree to which it will play a role in reducing greenhouse gases (GHGs) by displacing fossil fuels. Figures are not easy to compare because they are based on different criteria, such as whether one assumes coal-fired power with or without carbon capture and storage. However, several estimates show there is large potential for nuclear energy to reduce GHGs. Exhibit 1 gives projections for global production of nuclear energy (in TeraWatt-hours, or 10^{12} Watt-hours) and its share in the electricity mix for a number of energy scenarios up to 2050.

Exhibit 1

Role of nuclear energy in scenario studies



Note

For the ETP scenarios figures have been linearly interpolated between 2050 and 2005

The IPCC⁴ projects a decreasing share of nuclear in the global electricity mix in its baseline and low-growth scenarios until 2030. The latter refers to few new-build plants and partial replacement of current capacity. In the baseline scenario of the Energy Technology Perspectives (ETP Base) model⁵, global nuclear power production increases slightly but its share in the electricity mix decreases to 8 percent. In the ETP ACT 'Map' scenario⁶, which brings 2050 CO₂ emission back to current levels, the share of nuclear increases to 19 percent. In the ETP BLUE 'Map' scenario⁷, where CO₂ emissions are reduced 50 percent below current levels in 2050, (consistent with 550 ppmv GHG concentration levels), nuclear production increases four-fold and its share to 23 percent.

The World Energy Technology Outlook (WETO-H₂), in its Carbon Constraint Case (CCC), projects a more rapid increase in nuclear power particularly after 2030. In 2050, 34 percent of electricity would come from nuclear, with a fair share coming from 'new designs'. Asia could quadruple its nuclear generation between 2030 and 2050 to 39 percent, while Europe could go up to 41 percent (EC, 2006). This scenario is close to the 'High Nuclear' variant of the ETP BLUE scenario, which requires an average of 50 GWe capacity increase per year – more than twice the historical rate of increase⁸.

In 2030, it may be possible to abate 1.88 Gigatonnes (Gt) of carbon dioxide equivalent (CO₂e) per year, equal to approximately 3.8 percent of global GHG emissions in 2004 (49 GtCO₂e). For OECD and non-OECD countries the potential is 0.9 and 0.7 Gt respectively. In the ETP BLUE Map scenario the CO₂ reduction by nuclear compared to the baseline in 2050 is 2.8 GtCO₂/yr, or 6 percent of the total reduction by all technologies. However, to achieve this more than 30 GW nuclear capacity would need to be added on average each year between now and 2050, which is again higher than historical rates of increase. Supply chain and skilled labour constraints could be limiting factors to achieve these capacity increases.

Fuel availability not a limiting factor

The availability of fuel for the nuclear reactor is generally not seen as a limiting factor. Even if we assume a 2 percent growth rate in nuclear electricity production, there are sufficient uranium resources until 2100 up to a price of \$130/kilogram (kg)¹¹. This price is higher than current prices of \$40–50/kg but would result in only slightly higher cost of electricity. In case the depletion rate of the resources would be deemed too high, the utilisation rate could be decreased by using other reactor technologies such as fast-breeder reactors or making more use of reprocessing rather than the once-through process.

Benefits and barriers

Nuclear energy is controversial for a variety of reasons, which relate to cost, disposal of waste and risk issues. However, it has the advantages of local air quality during operation, and can play a role in security of supply issues. The economics are a matter of some debate, but what is certain is that the capital costs are high. There are several ways in which obstacles are being addressed, and certain opportunities could be enhanced.

Nuclear energy benefits air quality and energy supply security compared to fossil-based power

Apart from producing low-carbon electricity, nuclear energy provides two other important benefits compared to fossil-based electricity:

- **No health-affecting air pollutants** such as particulate matter (PM), mercury, nitrogen oxides and sulphur dioxide are emitted during operation of the power plant (in the mining phase of the nuclear fuel cycle PM emissions are significant). This contrasts to coal-fired power, where air pollution in the operation phase is a significant problem¹².
- **Energy security of supply (SoS)** is another key concern for policymakers, which relates to ensuring reliable and affordable energy to end-users. Natural gas is generally seen as risky in this regard, due to the market concentration of suppliers, price fluctuations and the relatively low reserves compared to current extraction rates. Nuclear fuel, i.e. uranium, is regarded as less risky due to the better global spread of reserves, as well as the volume of proven reserves. If reserves were to decline faster than expected, it is also possible to use the uranium more efficiently in the nuclear fuel cycle. Unlike natural gas-based electricity production, which is very price sensitive, changes in uranium prices only have a small impact on the overall electricity generation cost¹³. Nuclear energy therefore has an advantage for SoS compared to gas-based electricity. Compared to coal the advantages are less apparent (apart from the uranium's greater ease of storage).

Nuclear waste, proliferation and safety are key problems that have not been resolved satisfactorily

- **Nuclear waste:** spent fuel will stay above the radioactive level of natural uranium for more than 100,000 years. After reprocessing the lifetime is approximately 10,000 years. Repositories for such high-level waste do not exist at the moment. Deep geological storage is being studied, and projects to realise such storage are ongoing and projected to be used in Sweden and Finland after 2015-2020. Research into reducing the waste lifetime to less than 2000 years (called partitioning and transmutation) is ongoing but not expected to be commercial within the next decades. For low- and medium-level radioactive wastes (which degrade to non-radioactive waste within 100 years) repositories exist in several countries.
- **Proliferation of nuclear technology for non-peaceful purposes:** uranium enrichment and reprocessing of spent fuel are critical steps that can be used to produce nuclear weapons. International treaties to monitor and curtail the trade in nuclear material and technologies include the Treaty on Non-Proliferation of Nuclear Weapons (ratified by 190 countries) and the Additional Protocol, monitored by the IAEA (International Atomic Energy Agency); and the Proliferation Security Initiative taken by 60 countries. Moreover, in 2006 the IAEA initiated the implementation of a system in which Member States obtain nuclear fuel from an international nuclear fuel bank. The nuclear fuel is returned after use. In the long term this should lead to a situation in which all enrichment and reprocessing plants are placed under international supervision.
- **Terrorism:** attacks on transport and storage of radioactive materials are possible. National and international bodies are tracking the transport of nuclear fuels and waste continuously. Newly constructed nuclear facilities and storage sites are built with strong safety measures (including deactivation of the reactor in case of an attack) and protection against an aeroplane crash. A 'dirty bomb', i.e. an explosive combined with radioactive material, can also be made from material found outside of the nuclear fuel cycle.
- **Accident risk:** public exposure to radiation is possible due to accidents during operations of the nuclear reactor or other phases in the nuclear fuel cycle. Risk is minimised by improved reactor designs (passive safety features, or inherently safe design) and certification by international standards. Occupational health risks

during uranium mining are comparable to other types of mining. The operators of nuclear plants are generally liable for any damage to third parties up to a certain limit, above which public funds cover additional compensation.

- **Uranium mining may have a significant impact on the local environment.** The most important impacts are radon emission to the air and heavy metals to the groundwater and soil. The ‘tailings’ (waste product of the ore processing) remain radioactive for thousands of years and these should be stored in a safe and closed environment.
- **High capital cost:** as shown below, upfront investment costs for nuclear are significantly higher than for other power generation technologies. A 1,000 MW electrical reactor may cost up to €3 billion, and even more when interest during construction is taken into account. Competing technologies are both less expensive, per unit of capacity installed, and can be built in smaller units of capacity and are therefore much less capital-intensive. Small- and medium-size nuclear reactors may address this issue to some extent.
- **The construction time** of new nuclear power plants is 4.5-7 years, which is longer than competing technologies. In addition, licensing to start new construction can take more than 5 years. The uncertainty regarding final storage of nuclear waste adds to uncertainty for investors. In the future, more global safety and licensing standards and regulations would decrease this uncertainty and increase transparency.
- **Public perception** of nuclear energy is not very positive in many countries. A recent study found that on average in the EU, 61 percent of people think that the share of nuclear energy should be decreased (as it poses safety problems) compared with 30 percent who think it should be increased (as it does not contribute to climate change)¹⁴. On the global level, 59 percent of citizens in 18 countries were not in favour of building new nuclear power plants¹⁵.
- **Cost of decommissioning:** this includes all costs from shutdown until the site is in accordance with local policy, which can take several decades. Total decommissioning cost (undiscounted) is expected to be lower than \$500/kilowatt (kW)¹⁶ for water reactors. A decommissioning fund is often set up over the lifetime of the plant, and due to interest revenues the discounted cost in the cost of nuclear electricity is approximately €1/Megawatt hour (MWh).

Cost of nuclear electricity

The total nuclear cost of electricity (COE) is made up of:

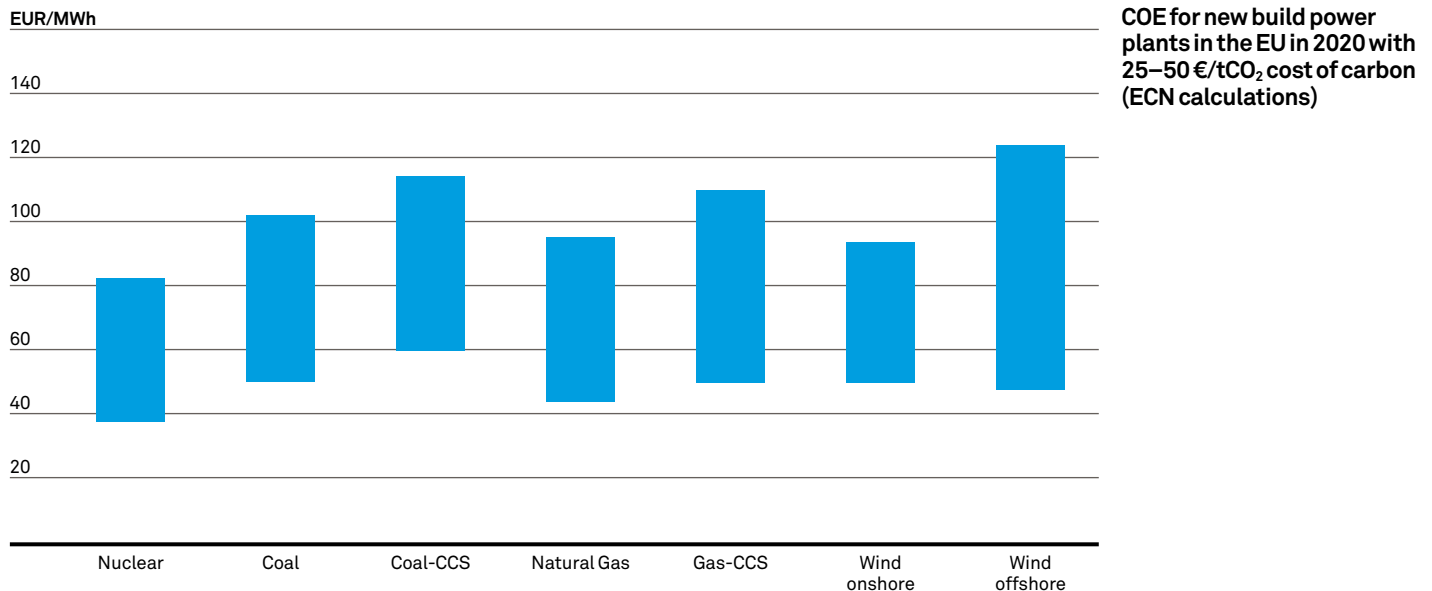
- Capital cost (upfront investment plus additional investments)
- Decommissioning cost
- Nuclear fuel cycle (mining, separation, conversion, fabrication, reprocessing if applicable, and waste disposal)
- Variable operation & maintenance cost
- Fixed operation & maintenance cost

Costs comparable to fossil-based options, cheaper when carbon cost included

Recent literature has shown a considerable range in estimates for nuclear COE. One study¹⁷ carried out a survey of six literature sources and reports a nuclear COE of between 31-80 €₂₀₀₆/MWh. This large range can be attributed to differences in assumptions and calculation methodologies including capital costs, discount rate during operation and construction, and fuel cycle cost.

Recent (unpublished) calculations by the Energy research Centre of the Netherlands (ECN) for COE of nuclear took into account these studies and uncertainties. Key assumptions include overnight investment cost (i.e. not taking interest during construction into account) of €₂₀₀₇ 2000-3000/kW, CO₂ price of 25-50 €/tCO₂ and construction time of 5-7 years with interest at 10-16 percent.

Using these assumptions, Exhibit 2 shows the resulting COE for new nuclear plants and competing technologies for 2020 in the EU. It should be noted that the assumed CO₂ prices have a strong impact on coal (i.e. it is the most sensitive parameter): if the default value was 0 €/tCO₂, the default COE for coal decreases to €50/MWh.



Broadly speaking COE for nuclear from an investor's perspective is in the same range as for coal and gas-based power (if the CO₂ price is excluded). The same observation is true of the CO₂ abatement cost, which refers to the difference in COE for a carbon-intensive electricity source (e.g. coal) and a less carbon-intensive source (e.g. nuclear). For nuclear compared to coal the CO₂ abatement cost would therefore be close to zero. However due to uncertainties in the COEs generally a range of abatement cost is reported. According to the IPCC¹⁸ this abatement cost for nuclear compared to fossil-based electricity lies between -24 and 25 \$₂₀₀₆/tCO₂ and mainly depends on fossil fuel price developments (notably gas), and the capital costs for nuclear.

Considering this range in abatement cost no meaningful estimates of the total additional cost by applying nuclear as a CO₂ reduction measure in climate mitigation scenarios can be given. On the other hand, what can be said is the required capital investment is large. In order to achieve a 50 percent CO₂ reduction in 2050 in the ETP BLUE Map scenario \$45 trillion of investment is estimated to be required in the energy sector. Of this, \$650-750 billion (or 1.4-1.6 percent) could be needed for nuclear R&D, demonstration plants and further deployment until 2035. From 2035 to 2050 the total investment for commercial development is an estimated \$1-1.5 trillion. The regional spread would be OECD North America 26 percent, China and India 26 percent, OECD Europe 18 percent, OECD Pacific 14 percent and other 16 percent¹⁹.

Prospects for supporting new generation technologies

Future technologies could improve performance of nuclear energy with regard to safety, waste generation and operation, particularly by Gen IV reactors. Commercialisation of these reactors by 2030 requires large R&D funds and international cooperation. Nuclear fusion does not pose the problems attached to nuclear fission, but commercialisation is not expected before 2050.

A large share of nuclear electricity produced today is generated by Generation II reactors, while power plants being constructed are mostly from Generation III. Technology development towards better performance with respect to safety, waste generation and improved operations is ongoing, as summarised in Exhibit 3. Substantial public budget is spent on research and development (R&D) for nuclear technologies. Over the past 10 years this has been constant at approximately \$4 billion per year or 40 percent of total public support for energy-related R&D²⁰. For the private sector R&D spending data is more limited but estimates are in the range of \$40-60 billion for the energy sector as a whole.

Development of new nuclear technologies

| Type | Development stage | Improvements | Remarks |
|----------------|--|---|---|
| Gen III | Commercial | | |
| Gen III+ | Prototypes after 2012; commercial 2015–20 | Improved safety principles | Prototypes being designed in China and South-Africa |
| Gen IV | Research; expected to be commercial after 2030 | Improved efficiency Reduced costs Radioactive waste reduction Reduced proliferation risk Improved reliability More possibilities for H ₂ production | Many different designs under development; several international partnerships have been initiated, but international cooperation is also segmented |
| Nuclear fusion | Research aiming to demonstrate technical feasibility; commercialisation not expected before 2050 | (Nearly) inexhaustible, pollution-free and safe source of energy | R&D carried out in the International Thermonuclear Experimental Reactor (ITER) project |

The role of international initiatives and of governments

To further enhance the development of the Generation IV nuclear fission technologies, a variety of international initiatives have been set up²¹. The long-term goals of these initiatives include the development of economical, safe and environmentally sound reactor designs, based on technology that excludes severe accidents, is proliferation-resistant, and that minimises high-level waste. Achieving these objectives would require additional R&D, and a substantial coordinated public effort and resources. Sharing of expensive R&D facilities could be an area of international collaboration.²²

The Clean Development Mechanism (CDM) offers the opportunity to developed countries to comply with their Kyoto Protocol emission reduction targets by buying credits from emission reduction projects in developing countries. However, nuclear energy projects are currently not eligible under the CDM. In the current UN climate change negotiations²³ discussion is ongoing about whether or not to include nuclear in the CDM after 2012²⁴. Inclusion could help deployment of nuclear energy in developing countries through the transfer of finance and technology from industrialised countries.

In addition, national governments and international initiatives could improve conditions for nuclear energy by:

- Developing conditions and criteria for the implementation of nuclear power plants;
- Investing in new manufacturing capacities to remove the bottleneck caused by existing insufficient capacities in case of growing demand for nuclear;
- Increasing transparency in procedures for licensing;
- Developing a roadmap for long-term storage of nuclear waste; and
- Maintaining a dialogue about the pros and cons of nuclear energy with the public.

These steps are desirable to secure the viability for the ongoing development of the potential of nuclear energy.

Glossary of Terms

| | |
|-----------------------------|--|
| IAEA: | International Atomic Energy Agency |
| AWG KP: | Ad Hoc Working Group on further commitments under the Kyoto Protocol |
| CCC: | Carbon Constraint Case |
| CCS: | Carbon capture and storage |
| CO₂: | Carbon dioxide |
| COE: | Cost of Electricity |
| ECN: | Energy research of the Netherlands |
| Gen: | Generation |
| Gt: | Gigatonnes |
| GWe: | Gigawatts electric |
| IAEA: | International Atomic Energy Agency |
| IEA: | International Energy Agency |
| ITER: | International Thermonuclear Experimental Reactor |
| kg: | kilogram |
| kWe: | kilowatt electric |
| kWh: | kilowatt hours |
| MWe: | Megawatt electric |
| LWR: | Light Water Reactors |
| PM: | Particulate matter |
| SoS: | Security of Supply |
| tCO₂e/yr: | tonnes CO ₂ (equivalent) per year |

Endnotes

- ¹ Scheepers, M.J.J., A.J. Seebregts, A.J.; P. Lako, F.J. Blom, F. van Gemert (2007) *Fact finding kernenergie* (in Dutch). ECN-B-07-015, Petten, October 2007.
- IEA/OECD (2008) *Energy Technology Perspectives. Scenarios & strategies to 2050, in support of the G8 Plan of Action*. ISBN 92-64-04142-4. OECD/IEA, Paris
- ² IEA/OECD (2008) *op. cit.*
- ³ *Ibid*
- ⁴ IPCC (2007) *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. AR4 mitigation.
- ⁵ IEA/OECD (2008) *op. cit.*
- ⁶ There are a number of variants to the IEA's ACT scenario. 'ACT Map' is the reference scenario.
- ⁷ There are a number of variants to the IEA's BLUE scenario. 'BLUE Map' is the reference scenario.
- ⁸ IEA/OECD (2008) *op. cit.*
- ⁹ IPCC (2007) *op. cit.*
- ¹⁰ *Ibid*
- ¹¹ Van der Zwaan, B. (2008) *Prospects for nuclear energy in Europe*. Forthcoming in *Int. J. Global Energy Issues*.
- ¹² In this regard, the ExternE study of the European Commission estimated the environmental external cost of electricity to be €2.5-7 per MWh for nuclear, as compared to €20-150 for coal (without CCS) and €10-40 for gas.
- ¹³ However, in liberalised energy markets the electricity price in a country or region is set by the marginal production method, which is very often gas or coal, and nuclear generation therefore only has a limited impact on the wholesale electricity price.
- ¹⁴ Eurobarometer cited in Scheepers et al (2007) *op. cit.*
- ¹⁵ Van der Zwaan (2008) *op. cit.*
- ¹⁶ IPCC, (2007) *op. cit.*
- ¹⁷ Scheepers et al (2007) *op. cit.*
- ¹⁸ IPCC, (2007) *op. cit.*
- ¹⁹ IEA/OECD (2008) *op. cit.*
- ²⁰ IEA/OECD (2008) *op. cit.*
- ²¹ International initiatives set up to enhance Gen IV fission technologies include:
- Generation IV International Forum (GIF), a group of ten countries and the EU, coordinated by the US Department of Energy;
 - The International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), coordinated by the IAEA (IPCC, 2007, *op. cit.*); and
 - The Global Nuclear Energy Partnership initiated by the US and currently comprising 21 countries and three observer organisations (GNEP (2008). *Global Nuclear Energy Partnership*, website <http://gneppartnership.org/> (viewed May 22, 2008)).
- ²² EA/OECD (2008) *op. cit.*
- ²³ UNFCCC, 2008. *Emissions trading and the project-based mechanisms. Draft conclusions proposed by the Chair*. FCCC/KP/AWG/2008/L.8, 12 June 2008, Bonn, Germany.
- ²⁴ More specifically the discussion takes place in the Ad Hoc Working Group on further commitments under the Kyoto Protocol (AWG KP)

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