Green Growth and Nuclear Energy

Holger Rogner*

Introduction

The issue

Since the 1986 Chernobyl accident, the sustainability of nuclear energy technologies and fuel cycles has understandably sparked intense debate at gatherings addressing climate change mitigation, sustainable development, and more recently, green economy and green growth. Topical disputes include: concerns about operational plant safety; the lack of a demonstrated solution to the disposal of high-level nuclear waste; doubtful economics; public acceptance; and the technology's potential contribution to nuclear weapons proliferation.

At the international level, energy and its role in sustainable development was first addressed at the ninth session of the Commission on Sustainable Development[1] in 2009 (CSD-9), where nuclear power was also intensely debated. The international community agreed to disagree on the role of nuclear power in sustainable development. CSD-9's final text observed that some countries view nuclear power as an important contributor to sustainable development while others do not, and summarized briefly the logic of each perspective (UN 2001). The community agreed that, "the choice of nuclear energy rests with countries" (UN 2001).

Ten years later, as the CSD process geared up for the Rio+20 Earth Summit in 2012, the notions of green economy and green growth were increasingly used to emphasize socio-economic development aspects (as the prime objective of developing countries), rather than environmental protection (the prime objective of industrialized countries).

This article outlines nuclear energy's potential contribution as part of a green energy portfolio, as well as its role in a green economy towards green growth.

Green economy and green growth

Green economy

A unique and universally accepted definition of the "green economy" has yet to be developed. The term itself underscores the significance of the economic and social dimensions of sustainability. The United Nations Environment Programme (UNEP) defines the green economy as one that results in "improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities" (UNEP 2010). Specifically, a green economy is characterized by socially inclusive development (including aspects of quality of life beyond income), environmentally benign production and consumption patterns and the efficient use of natural resources.

Green growth

Green growth builds upon the green economy principle by adding the explicit objective of advancing economic growth and development towards the criteria defined for a green economy, in the sense that growth should reduce social inequity, mitigate climate change, and prevent environmental degradation and the unsustainable use of natural resources. It represents a fundamental adjustment to the classical growth paradigm by recognizing the environment as a factor in the production function. "Green growth means fostering economic growth and development, while ensuring that natural assets continue to provide the resources and environmental services on which our well-being relies" (OECD 2011).

Green growth and energy

"Green growth requires a green engine. Improving the environmental performance of energy transformation and consumption is a cornerstone of any attempt towards green growth" (OECD 2011). Typical criteria for green energy include, inter alia:

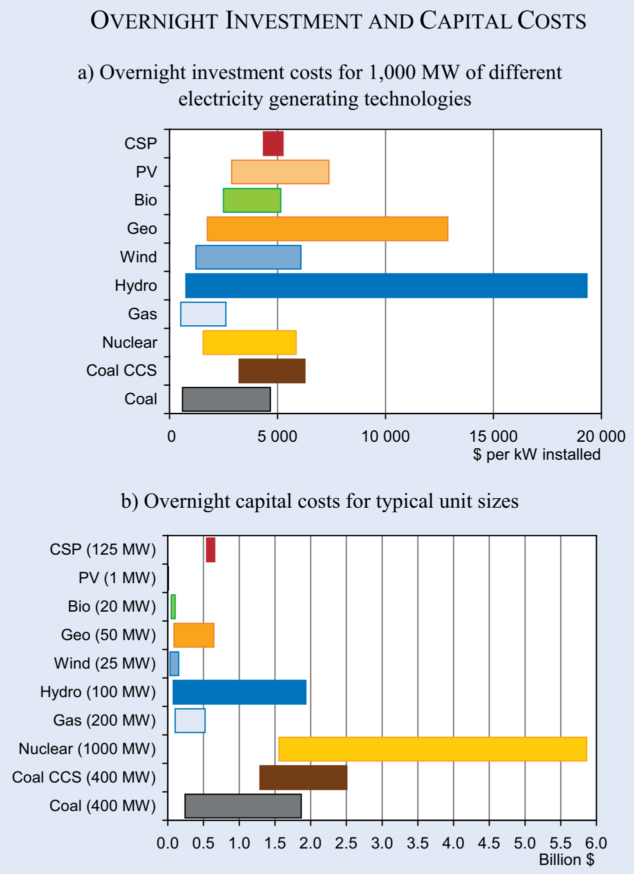
* IIASA Austria / KTH Sweden.

[1] The UN Commission on Sustainable Development (CSD) was established to oversee the implementation of Agenda 21, the principal outcome document and action plan of the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro, 1992.

- High security of energy supply
- Low local/regional air pollution
- Low greenhouse gas (GHG) emissions
- Low threat to biodiversity & human health/security
- Competitive generating costs
- Low material intensity (3R= reduce, reuse, recycle)
- Low resource depletion
- Low waste volumes
- Low noise/ visual pollution
- Low land requirements
- High innovation potential

According to these criteria, nuclear energy could well qualify as a green energy technology. However, many oppose nuclear energy because of its long-lived radioactive waste, the risk of severe accidents with long-term impacts, weapons proliferation concerns, and its lack of public acceptance. Table 1 summarizes the principal arguments that have been brought forward in past and on-going debates.

Figure 1



Source: IEA/NEA (2010).

Economics

The economics of nuclear power are characterised by large up-front capital costs, but low and stable fuel and operating costs. The investment in a nuclear power plant can amount to several billion dollars (USD two – eight billion depending on its design, location, finance, etc.) for a typical 1,000 MW

Table 1

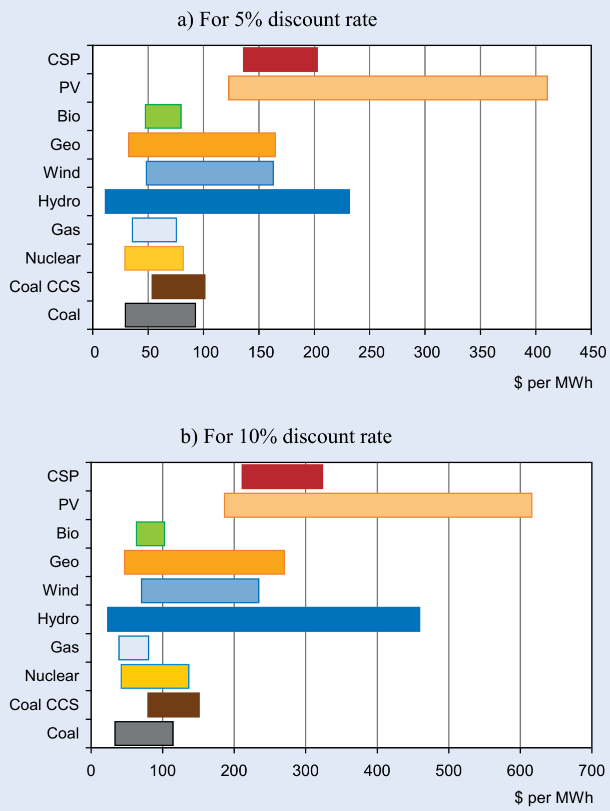
Pros and cons of nuclear power as a technology to support green growth

Arguments against nuclear power	Arguments in favour of nuclear power
Nuclear power is unsafe and its risks are excessive – it can never be made safe enough	Nuclear power on a life cycle basis has an excellent safety record compared with the alternatives
Diverts attention from energy efficiency and renewables	Expands electricity supplies ("connecting the unconnected")
No solution for climate change mitigation, especially in the short run	Reduces harmful emissions, including greenhouse gases
Trans-boundary consequences and issues related to transport of spent fuel	Enhances energy security
Lacks economic basis – too expensive and always depends on subsidies	Competitive supplier of base-load electricity at stable and predictable generating cost
Nuclear weapons proliferation	Increases human and technological capital
High externalities	Ahead in internalising externalities
Uranium resources last only a few decades	Nuclear power decoupled from any resources constraints – no alternative uses for uranium
No long-term solution to high level nuclear waste	Wastes are manageable
Lacks public acceptance	Keeps options open for future generations

Source: The author.

Figure 2

LCOE of Different Generation Options



Source: IEA/NEA (2010).

nuclear power plant, which accounts for some 60–75 percent of total generation costs.

Figure 1 summarizes the overnight investment cost (OC) data, i.e., without interest during construction (IDC), of the OECD study "Projected Costs of Generating Electricity – 2010 Update" (IEA/NEA 2010).

Figure 1a shows a large overlap and spread of specific investment costs for different energy supply technologies, typically explained by varying local conditions, technology designs, as well as regulatory and environmental constraints. The lower boundary represents the conditions in large developing countries such as China and India, while higher prices reflect particularly challenging site conditions in OECD countries.

On a per unit size, nuclear power investment exceeds that in its alternatives considerably. Smaller unit projects are easier to finance, especially for utilities with low capitalization. Small grid sizes in developing countries limit the integration of presently commercially available designs of 1,000 MW or more per unit. In the future, the commercialization of small and medium sized nuclear power plants of 100 to 600 MW per unit might ease financing and their integration into national power grids.

Long-run marginal generating costs accounting for OC, interest during construction (IDC), fuel, operating and maintenance costs, as well as waste management and decommissioning costs are often used to rank investment alternatives. Figure 2 shows the ranges of the levelized costs of electricity (LCOE) generation for real discount rates of five and ten percent per year.[2]

The LCOE range for nuclear power coincides with that of most competing technologies. Furthermore, any greenhouse gas emission policy, e.g., carbon taxes or emissions caps, further improves the competitiveness of nuclear power. Nuclear power offers stable and predictable generating costs. Uranium accounts for about five percent[3] of nuclear generating costs (Figure 3), and unlike coal and natural gas fired electricity generation, a doubling of resource prices hardly affects the total generating costs of nuclear power (Rogner 2010). The decommissioning costs in Figure 3 are not discernible either because they are very low in actual terms (as in the case of wind), or are incurred so far in the future (e.g., 80 or more years for nuclear power) that discounting makes them quasi invisible.

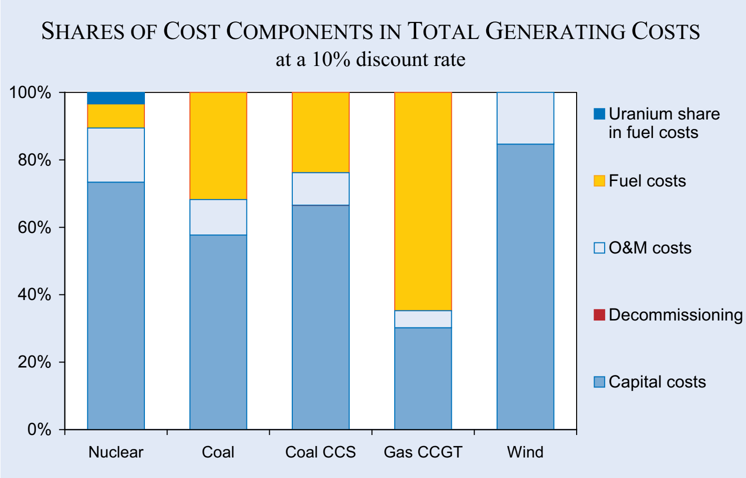
Energy security

Nuclear energy enhances energy security. Its low fuel volumes allow for easy stock-piling, i.e., the on-site storage of uranium for the entire life time of the plant. Long-refuelling cycles of 18 to 24 months plus the practice of on-site storage of fuel elements for one refuelling event provides sufficient time to seek alternate suppliers in case the original supplier defaults on contractual arrangements.

[2] The OECD study uses harmonized technology performance assumptions and boundaries, as well as clearly specified fuel prices, decommissioning and waste management costs for the LCOE calculations.

[3] The full nuclear fuel cycle costs include enrichment, fuel element fabrication and spent fuel management (in addition to the uranium costs).

Figure 3



Source: Adapted from IEA/NEA 2010 and NEA 2003.

Uranium reserves and resources are abundant and available. Figure 4 shows the recent development of identified uranium resources and the geographical distribution for 2011. Present uranium resources are sufficient to fuel existing reactors for more than 90 years, and if all conventional uranium occurrences are considered, for almost 200 years. The reprocessing of spent fuel and the recycling of unspent uranium and plutonium doubles the reach of each category (see next section on 'Making nuclear energy even more compatible with green growth'). Fast breeder reactor technology can further increase uranium utilization 50-fold or even more.

In addition to conventional uranium occurrences, enormous low and lowest concentration (unconventional) occurrences also exist. Phosphates, carbonite, non-ferrous ores, lignite and black schists contain an estimated 17 million tonnes uranium (tU). Low concentration occurrences are widespread in many rocks and in seawater. The total mass of uranium in seawater is enormous and amounts to about 4,500 million tU.

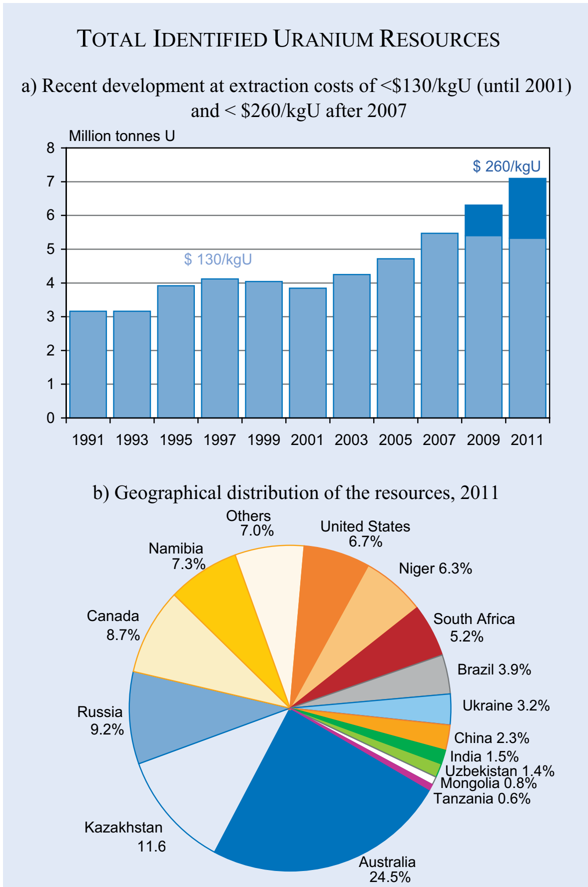
Nuclear operating safety

The essence of nuclear operating safety is the protection of the population, workforce and the environment from ionized radiation. Operating safety is thus the highest priority for nuclear power plant design and operation. As a result, the radiation from normal operation of nuclear power plants are insignificant compared with the average radiation exposure from natural and other anthropogenic sources (UNSCEAR 2010).

Nuclear power and fuel cycle facilities contribute an estimated two µSv per person per year to the average global radiation exposure of 2,420 µSv per year – between 1,000 and 13,000 µSv depending on location (UNSCEAR 2010; WHO 2012). Diagnostic medical examinations (X-rays) contribute some 400 µSv per year.

In the event of a severe nuclear accident, however, surface radioactive concentrations in the plant vicinity can be high and can last for years or decades. In areas further away, agricultural production and fishing may need to be temporarily suspended. However, non-radiation impacts can be significantly larger than radiation impacts. For example, the severest consequences of the Chernobyl accident were social in nature and are not directly radiation related (Gerasimova 2008). Most of the 335,000 evacuees from villages around Chernobyl

Figure 4



Source: NEA/IAEA (2010, 2012).

Table 2

Total life cycle material requirements for selected materials

	Iron kg per GWh	Copper kg per GWh	Bauxite kg per GWh	Concrete m^3 per GWh
Hard coal	2,700	8	30	22.8
Lignite	2,314	8	19	na
Gas combined cycle	1,239	1	2	3.9
Nuclear (PWR)	457	6	27	17.2
Wood CHP	934	4	18	na
PV 5 kW poly	4,969	281	2,189	
Wind 1.5 MW at 5.5 m/s	2,066	52	35	99.3
Wind 1.5 MW at 4.5 m/s	4,471	75	51	na
Hydro 3 MW	2,700	8	30	na

Source: Peterson, Zhao and Petroski (2005); Voss (2009).

did not return to their original homes and suffered from depression and stress related difficulties (Simmons 2012).

The Three Mile Island accident resulted in the release of minute amounts of radioactive gases with inconsequential health and environmental impacts (UNSCEAR 2011). In contrast, the Chernobyl and Fukushima Daiichi accidents released large amounts radioactive materials with significant social, economic and environmental consequences. However, there have been no radiation related fatalities in the Fukushima Daiichi accident (UNSCEAR 2012). The latest analyses estimate the long-term fatalities associated with the Chernobyl accident at cumulative 4,000 to 10,000 late life cancer deaths.[4] More fatalities per year are recorded in other industries like, mining, coal, oil and hydro power (Burgherr, Eckle and Hirschberg 2011).

Nuclear energy and the environment

Resource utilization

The rational use of resources is closely related to the 3R (reduce, reuse, recycle) principles. An important aspect of resource utilization is the high energy density of uranium relative to fossil fuels. High density means low resources and waste volumes. Resource utilization can be maximized (and volumes of high level radioactive waste minimized) through the reprocessing of spent nuclear fuel – a first step towards a 3R compatible resource utilization strategy. Unlike the once through fuel cycle (OTC) where all of the spent fuel is eventually disposed of in a geological repository, the reprocessing fuel cycle (RFC) extracts the plutonium generated during operation and unused uranium from the spent fuel. The reprocessed fissile material is recycled into new fuel, which reduces fresh uranium requirements. RFC reduces the volume of high level radioactive waste (HLW) requiring geological disposal drastically (i.e., by > 90 percent) compared to the OTC and improves the rate of resource utilization by a factor of two to over 60 depending on the reactor technologies involved (see next section).

Materials requirement

Power plant construction is material intensive and the evaluation of construction material inputs is central to the lifecycle assessments of nuclear and other non-fossil energy systems. Table 2 shows the total life cycle requirements for selected materials. The material quantities per technology are location dependent, especially for concrete requirements. Except for natural gas combined cycle plants, nuclear power has the lowest material intensity.

Interaction with the environment

Greenhouse gas emissions

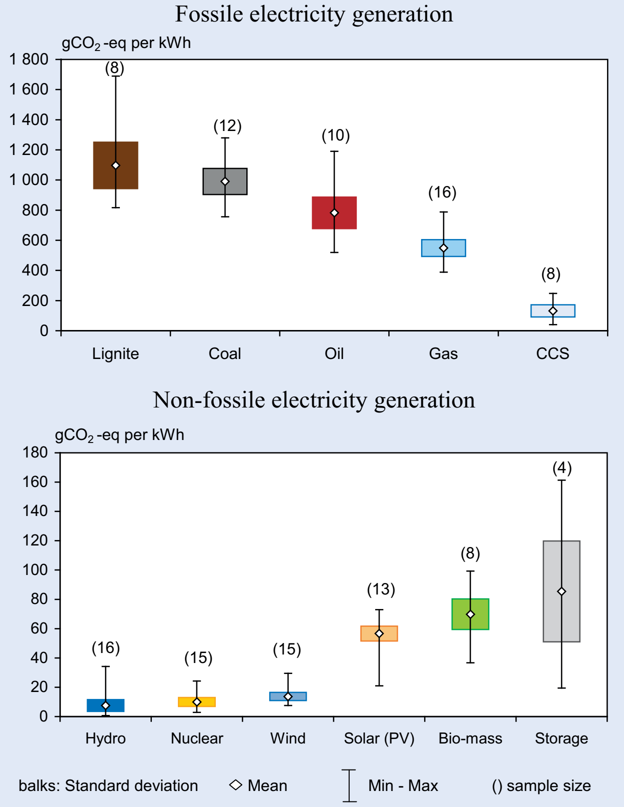
The full technology chain for nuclear energy includes uranium mining (open pit or underground), milling, conversion, enrichment (diffusion or centrifuge),

[4] Today, uncertainty remains about future mortalities due to the long latency periods for many cancers; however cancer deaths in Chernobyl affected regions are expected to be similar to non-Chernobyl controls (Simmons 2012).

fuel fabrication, power plant construction and operation, reprocessing, conditioning of spent fuel, interim storage of radioactive waste, and construction of the final repositories. On a life cycle basis, the nuclear chain emits between 2.8 and 24g CO_2-equivalent/kWh (Weisser 2007). The bulk of greenhouse gas emissions arise from plant construction (emissions from cement and material production and component manufacturing). Figure 5 shows that nuclear power, together with hydropower and wind based electricity, is one of the lowest emitters of GHGs in terms of g CO_2-eq. per unit of electricity generated on a life cycle basis (IPCC 2007, 2011)

Figure 5

LIFE CYCLE GHG EMISSIONS OF DIFFERENT ELECTRICITY GENERATION OPTIONS



balks: Standard deviation ◇ Mean Min - Max () sample size

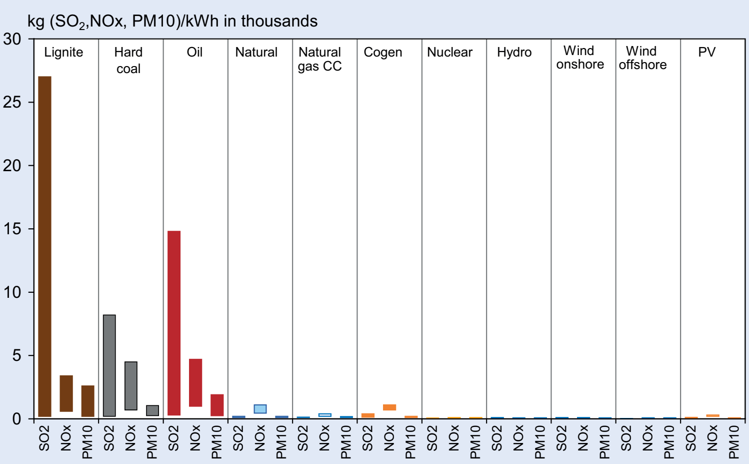
Source: Weisser (2007).

Other pollutant emissions

Nuclear power plants can also avoid emissions of other non-GHG air pollutants associated with negative health and environmental impacts on local and regional scales. Nuclear power plants (as well as renewable technologies) emit virtually no air pollutants like nitrogen oxides (NO_x), sulphur dioxide (SO_2) or particulate (PM10) emissions during operation (Figure 6). By contrast, fossil-based power plants are major contributors to air pollution, and result in local poor air quality, haze, limited visibility and reduced sunlight. The World Health Organization (WHO) has estimated that air pollution causes approximately two million premature deaths worldwide each year (WHO 2008).

Figure 6

AIR POLLUTANTS FROM SELECTED ENERGY CHAINS



Source: Adapted from NEA (2007).

Solid waste

All electricity generation technologies generate waste – fuel and material extraction, fuel preparation, equipment manufacturing, plant construction, plant operation and decommissioning in one way or another generate by-products and wastes. These wastes can vary widely for different electricity chains in terms of volumes per kWh, toxicity and longevity.

The nuclear chain produces waste of varying levels of radiotoxicity. Low (LLW) and intermediate level wastes (ILW) account for some 97–98 percent of the total volume, but only approximately eight percent of total radioactivity. LLW and ILW arise mainly from routine facility maintenance and operations, as well as fuel cycle activities and range from just above nature's background level to slightly elevated levels. Disposal of LLW and ILW has been practiced safely for decades in many countries using engineered surface facilities, shallow and intermediate depth facilities (IAEA 2009a).

It is the high level waste (HLW) that is the topic of debate. HLW is either spent nuclear fuel or separated waste from reprocessing spent fuel. Globally, nuclear power plants combined produce approximately 10,000 m^3 HLW per year. This would cover the size of a soccer field to a depth of 1.5 meters (Commonwealth of Australia 2006). HLW accounts for two to three percent of total nuclear radioactive waste, but presents particular challenges due to its radiotoxicity and longevity (IAEA 2004).

Although to date no repository accepting civilian nuclear HLW is in operation, the nuclear industry has practiced the safe temporary surface storage of spent fuel for more than half a century. Over the last two decades, however, major advances towards the first operating disposal facility have been accomplished. Sweden and Finland have the most advanced spent fuel management programmes with sites selected with full participation of the surrounding communities. Other countries (e.g. France, Canada) have set out timetables for developing geological disposal facilities.

It should be noted that long-lived toxicity is not unique to radioactive waste; other forms of hazardous waste, such as mercury, will retain their toxicity forever and will thus require indefinite isolation. Although small in comparisons to its total waste, PV cell manufacturing generates some amounts of toxic and hazardous wastes with necessary confinement of thousands of years (ENEF 2010).

Internalizing external costs

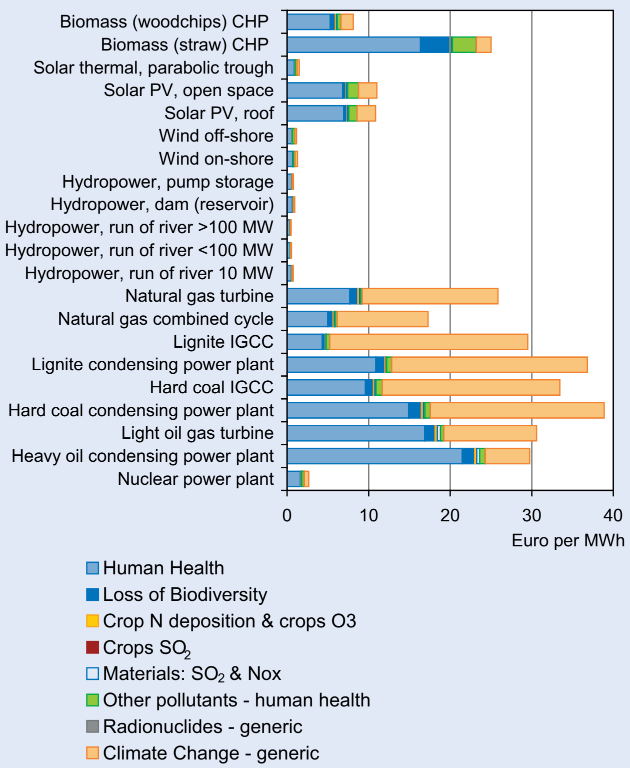
Externalities arise when an economic agent enjoys benefits or imposes costs without having to make a payment for doing so. The adverse health and environmental damages (hidden costs) caused by fossil sourced electricity generation or damage costs by severe nuclear accidents and that are not compensated by the producer are negative externalities. Factoring external costs into the market price of electricity (“internalization”) would necessarily result in higher prices (imposing a carbon tax per tonne of CO_2 emitted as a proxy for damages caused by climate change would, for example, reduce the attractiveness of fossil-fuelled generating technologies). It would send correct pricing signals to the market place, thus changing the merit order of investment and operating decisions, as well as reducing demand and emissions with subsequent lower externalities.

Several studies have attempted to quantify externalities, most of which focus on electricity generation (EU 2003; NRC 2009; Ricci 2010). The latest systematic analysis of external costs of various electricity supply technologies and their associated chains is available from European Commission’s CASES[5] project (Markandya, Bigano and Porchia 2011). The CASES project estimated monetized externalities due to: (1) climate change; (2) human health impacts, biodiversity loss, crops, and materials of familiar air pollutants; (3) health impacts of heavy metals; and (4) health impacts of radionuclides.

[5] Cost Assessment for Sustainable Energy System (CASES).

Figure 7

AVERAGE EXTERNAL COSTS FOR THE EUROPEAN UNION (EU27)



Source: EU CASES Project (Markandya et al. 2011).

Figure 7 shows the estimated average monetized external costs (on a life-cycle basis) in the EU over the period 2005–2010 for a range of electricity generation technologies.

Human health impacts due to classic air pollutant emissions and the adverse consequences from greenhouse gas emissions dominate the external costs across all technologies. Through safety and environmental regulations, the nuclear industry is ahead in internalizing costs and thus compares well with its alternatives.

Making nuclear energy even more compatible with green growth

The future development of new generation nuclear energy systems is influenced by economics, safety, proliferation resistance and environmental protection, including improved resource utilization and reduced waste generation (while drastically shortening the time span until radiation levels reach natural background levels).

Increased safety

Enhancing by design the defence-in-depth of future nuclear reactors through a combination of active and passive safety systems mitigates the risk of severe accidents by at least an order of magnitude as compared to existing designs. The ultimate target is to limit relocation or evacuation measures to within the plant perimeter in the case of a severe accident.

Addressing 3R principles in long-term reactor and fuel cycle strategies

Currently, nuclear reactors use some 67,000 tU annually and generate some 11,000 t of heavy metal as spent fuel. It is the six percent of non-uranium constituents that constitutes HLW and requires long-term isolation from the biosphere. HLW accounts for over 90 percent of the radiotoxicity of spent fuel. It also needs cooling because fission products generate a significant amount of heat during the initial several hundred years. Short-term risks are due to the mobility of spent fuel in the geosphere and the possibility of it entering the biosphere, while the long-term hazard of spent fuel and HLW is the longevity of actinides (IAEA 2004).

Great progress has been made in terms of understanding and delineating suitable underground repositories. These engineered or natural barriers provide for the isolation and containment of radioactive waste, allowing time for radioactive decay such that any eventual release of radioactivity back to the surface environment will be comparable to releases from natural rock formations and insignificant to adverse effects on health and the environment (NEA 2008). However, the total confinement of radiotoxic materials in human-made structures beyond 10,000 years cannot be guaranteed (IAEA 2004). Reducing or eliminating long lived radionuclides, therefore, has been an area of intensive R&D, especially as waste management remains one of the biggest challenges to public acceptance.

Reprocessing spent fuel is a first step towards a 3R waste management strategy. Unlike once through fuel cycles (OTC), where all spent fuel is eventually disposed of in a geological repository, the reprocessing fuel cycle (RFC) extracts plutonium and unused uranium from spent fuel. RFC reduces the volume of HLW requiring geological disposal drastically by > 90 percent compared to OTC[6]. 99.9 percent of the uranium and plutonium is recovered. The HLW then contains only fission products and minor actinides, including a very minor fraction of the unrecovered major actinides. When plutonium and uranium are removed, the radiotoxicity falls below that of natural uranium ore within approximately 9,000 years (Figure 8).

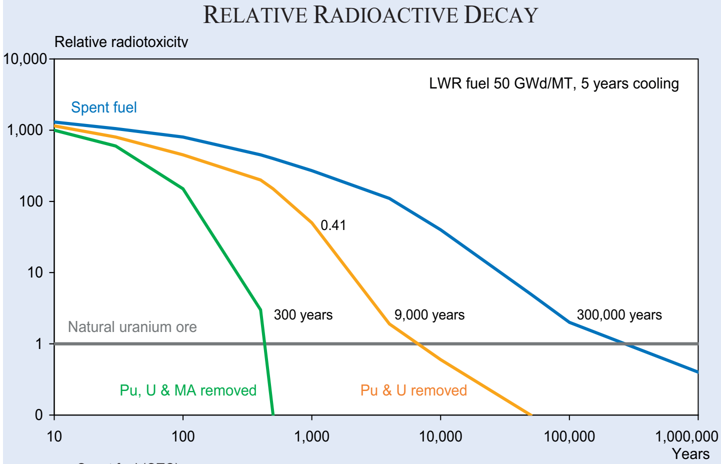
Recovered uranium and plutonium can be fabricated into new reactor fuel (e.g., mixed oxide fuel (MOX) – fuel consisting of recycled uranium and plutonium, as well as of fresh uranium) for use in conventional light water reactors. As a co-benefit, the 3R waste management strategy would reduce fresh uranium requirements, further reducing mining and its associated impacts. The use of MOX fuel in thermal reactors doubles increases the uranium utilization efficiency by a factor of two (IAEA 2009b).

Compared with OTC, reprocessing in combination with advanced breeder technology and closed

[6] Reprocessing increases the amounts of low level wastes (LLW) and intermediate level wastes (ILW). LLW and ILW have been stored safely for more than half a century in many countries around the world. Usually LLW is packaged in steel drums and stored in near surface facilities. ILW is typically packaged for disposal by encapsulation in highly-engineered steel or concrete containers and deposited in intermediate depth facilities such as abandoned mines or intentionally excavated facilities.

nuclear fuel cycles (CNFC) would boost overall resource utilization by a factor of 60–70 with corresponding reductions in HLW generation (and disposal requirements). The fast breeder reactor (FBR) generates more fissile material by converting the non-fissile isotope U238 of natural uranium into fissile plutonium, which can be reprocessed to make more fuel. Non-fissile U238 is 140 times more abundant than fissionable isotope U235, effectively decoupling FBRs from fuel resource constraints.

Figure 8



Source: Royal Society (2011).

Nuclear waste management and safeguards would be further simplified if fissile material and actinides could not only be removed from spent fuel (as in CNFC), but also destroyed through 'partition and transmutation' (P&T) technologies (Royal Society 2011), i.e., by separating the long lived elements plutonium, uranium, minor actinides and long-lived fission products from the spent fuel (partitioning) and converting (transmutation) them into shorter-lived or stable and harmless isotopes. In essence, partitioning is an extension to other radionuclides of the current reprocessing techniques, a kind of 'super reprocessing' or individual isotopic separation.

Transmutation is the conversion of one chemical element or isotope to another. Natural transmutation occurs when radioactive elements decay over a period of time, transforming into eventually stable elements. Artificial transmutation involves irradiating actinides in nuclear reactors with fast neutrons, which decreases their intrinsic radiotoxicity by a factor of 100–1,000 (IAEA 2004). The radiotoxicity of the remaining waste then declines substantially over only a few hundred years (Figure 8), almost allaying concerns about radioactive leaching into the biosphere. P&T is at a very early stage of development and not expected to be deployable on an industrial scale for several decades.

Nevertheless, even with integrated P&T, some radioactive isotopes will always accompany the bulk of the fission products. Whichever strategy is followed, a repository for radioactive waste will need to be established, whether through direct disposal, reprocessing or P&T (Widder 2010; IAEA 2009a).

Concluding remarks

Energy is an essential component of green growth – there is no growth without energy, green or otherwise. Energy in the context of green growth must satisfy several criteria including but not limited to: the efficient use of natural resources, affordability, access, the prevention of environmental degradation, low health impacts and high energy security. Although nuclear energy appears to be largely compatible with most criteria for green energy, perceptions differ widely concerning its benefits and risks for green growth.

Nuclear power can be competitive in some markets and existing nuclear plants are often the lowest cost base-load generators on the grid. Its long-run marginal competiveness depends on investors' time horizons and risk averseness. Liberalized markets characterized by short-run shareholder value maximization are less likely to adopt a technology with high upfront capital costs and long amortization periods than in markets where investors take a longer-term perspective; where energy security concerns allow for an insurance premium; where investors value predictable and stable generating costs; or where nuclear energy's climate and environmental benefits are visible to investors.

[7] Development that "meets the needs of the present without compromising the ability of future generations to meet their own needs" (UN 1987).

Nuclear power expands the supply options for present and future generations and is consistent with the Brundtland definition of sustainable development[7]. Future generations should have the right to decide for themselves about the suitability of the technology to meet their needs. From a resource perspective, nuclear power holds the potential to decouple itself from long-term resource limitations. On a life cycle basis, nuclear power has low externalities, lower than those of fossil fuel chains, and comparable with the electricity chains of many renewables.

Today's technology is not tomorrow's. As with all technologies, innovation and R&D in the nuclear field will lead to progressively higher safety margins and improved economics in new reactors. However, absolute safety is a myth – accidents will happen, which is one profound lesson learned from the Fukushima Daiichi accident. While the social, psychological and economic damages of the accidents are enormous, not a single person has died from radiation caused by the Fukushima Daiichi plant and long-term radiation-related health effects from the accident will not be statistically notable.

If the Chernobyl accident is any indication, the Fukushima Daiichi accident will certainly lead to the further strengthening of stringent safety measures and regulatory schemes. It can also be expected that probabilistic safety assessments will increasingly be complemented by beyond-design based deterministic approaches.

When judging nuclear power on its green growth merits, one should be aware that there is no technology without risks and interaction with the environment. Fossil fuel chains cause tens of thousands of deaths every year and contribute to climate change. While wind, solar and nuclear energy have quasi no interaction with the environment at the point of electricity generation, there are emissions and wastes associated with material extraction, manufacturing and construction and, in the case of nuclear, with the front and back-end of the fuel cycle. It is therefore imperative to compare all options on a level playing field. Some societies may well view the risks as excessive and shy away from nuclear energy. Other societies will continue to adopt or expand its use as an integral part of their national green growth strategies.

References

Burgherr, P., P. Eckle and S. Hirschberg (2011), *Final Report on Severe Accident Risk including Key Indicators,* SECURE Deliverable no. 5.7.2a, Security of Energy Considering its Uncertainty, Risk and Economic Considerations (SECURE), Brussels.

ENEF (2010), *Strengths, Weaknesses, Opportunities, Threats (SWOT) Analysis,* Part 1: Strengths & Weaknesses, Document by the Working Group Opportunities, Subgroup on Competitiveness of Nuclear Power, European Nuclear Energy Forum, Luxembourg.

EU (2003), *External Costs – Research Results on Socio-Environmental Damages Due to Electricity and Transport,* EUR 20198, Brussels.

Gerasimova, N. (2008), "Long Term Consequences of the Chernobyl Catastrophe and Remediation Programs in the Russian Federation", proceedings of the *International Conference on Chernobyl: Looking Back to Go Forward* organized by the International Atomic Energy Agency, Vienna.

Commonwealth of Australia (2006), "Australia's Uranium ¬ Greenhouse Friendly Fuel for an Energy Hungry World. A Case Study into the Strategic Importance of Australia's Uranium Resources for the Inquiry into Developing Australia's Non-Fossil Fuel Energy Industry", House of Representatives, Standing Committee on Industry and Resources, Canberra.

IAEA (2004), "Implications of Partitioning and Transmutation in Radioactive Waste Management", *Technical Reports Series* no. 435, International Atomic Energy Agency, Vienna.

IAEA (2009a), "Classification of Radioactive Waste – General Safety Guide", *IAEA Safety Standards Series* no. GSG-1, International Atomic Energy Agency, Vienna.

IAEA (2009b), *Status and Trends of Nuclear Technologies*, Report of the International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO), International Atomic Energy Agency, Vienna.

IEA/NEA (2010), *Projected Costs of Generating Electricity 2010,* OECD Publishing, Paris.

IPCC (2007), *Climate Change 2007: Mitigation, Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge and New York.

IPCC (2011), *Special Report on Renewable Energy Systems and Climate Change*, IPCC Working Group III - Climate Mitigation, Cambridge University Press, Cambridge and New York.

Markandya A., A. Bigano and R. Porchia, eds. (2011), *The Social Cost of Electricity: Scenarios and Policy Implications - Private and External Costs Assessment, Policy Implication and Scenarios for the EU and Selected Non-EU Countries*, Edward Elgar Publishing, Cheltenham. Associated data files available on the CASES project web-site: http://www.feem-project.net/cases/downloads_presentation.php.

NEA (2003), *Nuclear Energy Today, Nuclear Development*, OECD Publishing, Paris.

NEA (2007), *Risks and Benefits of Nuclear Energy, Nuclear Development*, OECD Publishing, Paris.

NEA (2008), *Nuclear Energy Outlook 2008*, OECD Publishing, Paris.

NEA/IAEA (2010), *Uranium 2009: Resources, Production and Demand*, Joint Report prepared by the OECD Nuclear Energy Agency and the International Atomic Energy Agency, OECD Publishing, Paris.

NEA/IAEA (2012), *Uranium 2011: Resources, Production and Demand*, Joint Report prepared by the OECD Nuclear Energy Agency and the International Atomic Energy Agency, OECD Publishing, Paris.

NRC (2009), *Hidden Costs of Energy: Unpriced Consequences of Energy Production and Use*, National Academy of Sciences, Washington, D.C.

OECD (2011), *Towards Green Growth*, OECD Publishing, Paris.

Peterson, P. F., H. Zhao and R. Petroski (2005), *Metal and Concrete Inputs for Several Nuclear Power Plants*, Report UCBTH-05-001, University of California, Berkeley.

Rogner, H.-H. (2010), "Nuclear Power and Sustainable Development", *Journal of International Affairs* 64 (1), 137–63.

Ricci, A. (2010), *Policy Use of the NEEDS Report*, Final integrated report Deliverable no 5.3 – RS In New Energy Externalities Developments for Sustainability (NEEDS).

Royal Society (2011), *Fuel Cycle Stewardship in a Nuclear Renaissance*, The Royal Society Science Policy Centre Report 10/11, London.

Simmons, P. (2012), "The 25th Anniversary of the Chernobyl Accident", *Business, Economics and Public Policy Working Papers* no 2012-1, University of New England, Armidale.

UN (1987), *Report of the World Commission on Environment and Development: Our Common Future,* Transmitted to the General Assembly as an Annex to Document A/42/427, New York.

UN (2001), *Report on the Ninth Session (5 May 2000 and 16–27 April 2001)*, Economic and Social Council Official Records, 2001, Commission on Sustainable Development, New York.

UNEP (2010), *Green Economy: Developing Countries Success Stories*, United Nations Environmental Programme, Economics and Trade Branch, Geneva.

UNSCEAR (2010), "Sources and Effects of Ionizing Radiation", *UNSCEAR 2008 Report* (1), United Nations, New York, http://www.unscear.org/unscear/en/publications/2008_1.html (accessed 7 October 2010).

UNSCEAR (2011), "Sources and Effects of Ionized Radiation", *UNSCEAR 2008 Report* (2), Annexes C, D and E, United Nations, New York.

UNSCEAR (2012), UNSCEAR Assessment of the Fukushima-Daiichi Accident, Background Information for Journalists, 23 May 2012, http://www.unis.unvienna.org/pdf/2012/UNSCEAR_Back grounder.pdf (accessed 29 October 2012).

Voss, A. (2009), "Life Cycle Analysis for Different Energy Sources", paper presented at the Symposium *Energy 2050*, Stockholm, October.

Weisser, D. (2007) "A Guide to Life-Cycle Greenhouse Gas (GHG) Emissions from Electric Supply Technologies", *Energy* 32 (9), 1543–59.

WHO (2008), Air Quality and Health, Fact Sheet No. 313, Geneva, http://www.who.int/mediacentre/factsheets/fs313/en/index.html.

WHO (2012), *Preliminary Dose Estimation from the Nuclear Accident after the 2011 Great East Japan Earthquake and Tsunami,* Geneva, http://www.who.int/ionizing_radiation/pub_meet/ fukushima_dose_assessment/en/index.html (accessed 2 August 2012).

Widder, S. (2010), "Benefits and Concerns of a Closed Nuclear Fuel Cycle", *Journal of Renewable and Sustainable Energy* 2 (6).