Nuclear Energy & Environmental Sustainability

Assessing the Sustainability of Nuclear Energy

Final Master Thesis
Nathalie I.V. Gross
ID: 240117

Supervisor: Professor Wim Passchier

December 2008
University of Maastricht, Maastricht Graduate School of Governance
Abstract

The occurrence of anthropogenic climate change is becoming increasingly evident. As a result, a third wave of nuclear energy utilization is being promoted as a substantial solution for the mitigation of CO2 emissions. Simultaneously, there is an almost global acceptance for integration of sustainable development, especially in relation to the current global energy system, which has emerged as unsustainable. Consequently, it is imperative to investigate if nuclear energy can be a solution for the apparent environmental crisis from an environmental sustainability perspective. Contrary to advocate claims that nuclear energy emits negligent amounts of CO2 emissions, there are indirect processes, which are carbon intense. In addition, nuclear energy falls short of satisfying the sustainability criteria. Significantly, pursuing a nuclear energy path supports a business-as-usual energy economy, inhibiting the necessary transition towards the realization of sustainability. An alternative option to nuclear energy is the utilization of Renewable energy technologies. By means of the development an implementation of appropriate policies, technological innovations and social change, renewables posses the ability to provide a sustainable energy future.
# Table of Contents

Executive Summary………………………………………………………………pp. 5

1. Introduction………………………………………………………………….pp. 6
   1.1 Motivation…………………………………………………………………pp. 9
   1.2 Scope, Approach, and Perspective……………………………………pp. 9
   1.3 Contribution………………………………………………………………pp. 10
   1.4 Content……………………………………………………………………pp. 10

2. Nuclear Energy Process……………………………………………………..pp. 11
   2.1 Global Development……………………………………………………pp. 11
   2.2 The Nuclear Cycle………………………………………………………pp. 11
       2.2.1 Construction………………………………………………………..pp. 13
       2.2.2 Mining and Milling………………………………………………pp. 13
       2.2.3 Preparing Fuel (Conversion & Enrichment)………………pp. 14
       2.2.4 Generation and Waste……………………………………………pp. 14
       2.2.5 Fuel Reprocessing………………………………………………pp. 16
       2.2.6 The Reactor…………………………………………………………pp. 16

3. Nuclear Energy and Sustainability…………………………………………..pp. 18
   3.1 Emissions and Environmental Impacts………………………………pp. 18
       3.1.1 Construction……………………………………………………….pp. 19
       3.1.2 Mining and Milling………………………………………………pp. 21
           Mining………………………………………………………………pp. 21
           Milling………………………………………………………………pp. 23
       3.1.3 Fuel Preparation (Conversion & Enrichment)………………pp. 24
           Conversion…………………………………………………………pp. 24
           Enrichment…………………………………………………………pp. 24
           Fuel Fabrication………………………………………………pp. 25
       3.1.4 Operation and Maintenance……………………………………pp. 26
3.1.5 Spent Fuel and Reprocessing........................................................ pp. 26
3.1.6 Dismantling and Decommissioning................................................ pp. 27
   Deep Geological Repository.............................................................. pp. 29
3.1.7 Additional Impacts and Concerns................................................ pp. 29
   Routine Release of Small Amounts Radioactive Isotopes............. pp. 29
3.2 Sustainability...................................................................................... pp. 30
   3.2.1 Sustainable Backstop Supply Criteria (Nuclear)........................ pp. 31
       Uranium Availability................................................................. pp. 32
       Reactor Capacity........................................................................ pp. 35
       Generation, Energy Debt, and Environmental Justice.......... pp. 36
       Energy Debt.............................................................................. pp. 37
       Environmental Justice............................................................... pp. 38

4. If not nuclear, then what?........................................................................ pp. 40
   4.1 Renewable Energy........................................................................ pp. 40
   4.2 Sustainable Backstop Supply Criteria (Renewables).................... pp. 41
   4.3 Renewables: Can they deliver?...................................................... pp. 44

5. Conclusion............................................................................................ pp. 47
   5.1 Summary of main findings.......................................................... pp. 47
   5.2 Limitations and future research ideas......................................... pp. 48

Acknowledgements................................................................................. pp. 50
References.............................................................................................. pp. 51
Appendix................................................................................................. pp. 57
   A 1 World Nuclear Power Reactors 2007-08 and Uranium Requirement.... pp. 57
   A 2 Material Requirements for Nuclear Power Plant Construction........ pp. 59
   A 3 Decommissioning & Clean up...................................................... pp. 62
   A 4 Definitions of uranium resource classification categories............. pp. 65
Executive Summary

Nuclear energy is experiencing a third wave as salvation for climate change. Advocates frame nuclear energy as a viable solution to mitigate CO2 emissions because of its low carbon intensity. Concurrently, global consensus is growing over the need for sustainability. Thus, it is necessary to explore the viability of nuclear energy from an environmental sustainability perspective.

Nuclear energy is not environmentally benign. The various phases of the nuclear process comprise high energy costs and are carbon intensive. As well, the nuclear energy process generates ecological impacts via radioactive releases and waste. From a sustainability perspective, nuclear energy falls short of all criteria. There are serious concerns associated with the availability of uranium, which is a finite resource. Additional limitations from a sustainability perspective are crucial aspects of the social-environmental interface. The utilization of nuclear energy imposes on intra- and inter-generational equity and environmental justice. Particularly, the transition towards sustainability requires a paradigmatic change in how energy is exploited. The further development of nuclear energy supports a business-as-usual energy economy, inhibiting the transition towards sustainability.

A viable alternative to the utilization of nuclear energy is the deployment of renewable energy technologies. The environmental impacts generated by renewable energy technologies are habitually negligent (except large-scale hydro and to some extent wind farm). From a sustainability perspective, renewable energies are more accessible, available, distributable, and considerate of the social-environmental interface. Significantly, the utilization of renewable energy technologies espouses the transition towards a sustainable (energy) future. The technological potential of renewable energy technologies can be realized by the implementation of effective and consistent policies, technological innovation, and changes in societal behavior patterns. Consequently, the deployment of renewable energy technologies is an effective and sustainable alternative to the utilization of nuclear energy.
1. Introduction

During the late 1940’s and 50’s, the development of nuclear fission for electricity production was a scientific breakthrough, which posed a promising future for the supply of economic energy. Although there were several risks accompanying this development in the form of nuclear proliferation\(^1\), these were controlled by keeping nuclear energy strictly classified by the government. From the 70’s onwards, opposition to nuclear energy steadily increased as the risks of nuclear accidents, radiation, waste and nuclear proliferation became more evident. In particular, a certain amount of unrest towards nuclear power emerged as a consequence of the accident at Three Mile Island in the United States and the catastrophe in Chernobyl. Consequently, nuclear power experienced some decline and stagnation. A number of countries announced their nuclear power phase-out, fewer reactors were ordered while many orders for reactors were even cancelled (World Nuclear Association, 2005). Although, the global supply of electricity from nuclear power remained constant, the industry experienced a brown-out.

After years of being on the political backburner, the nuclear energy debate is making a comeback. However, this instance is not entirely consumed with security, cheap energy, proliferation or radiation, but all in the name of climate change. The first wave of nuclear energy was based on cheap and abundant energy, the second wave claimed nuclear to be the solution for the oil crisis and the currently emerging third wave, as salvation against climate change (Verbruggen, 2008). Over the past decade it has become increasingly evident that anthropogenic climate change is taking place. Changes in atmospheric concentrations of greenhouse gases like CO2 as well as aerosols, land-cover depletion, and solar radiation due to the exponential growth in fossil fuel use as well as land clearing alter the energy balance of the climate system. “Global GHG emissions due to human activities have grown since pre-industrial times, with an increase of 70% between 1970 and 2004” (IPCC, 2007). The fourth assessment of the IPCC in 2007 as well as the

\(^1\) Nuclear proliferation is the dissemination of nuclear weapons, fissile material, and technology and information applicable for nuclear weapon development and/or use to nations, which are not recognized by the Treaty of Nonproliferation of Nuclear Weapons as “nuclear weapon states” (World Nuclear Association, 2008).
Stern review in 2006 hardened that climate change is a reality and is developing into a critical threat to the essential life-support systems of our world and of our way of life (Verbruggen, 2008). It is thus, necessary to mitigate the rising concentration of greenhouse gases in the atmosphere to avoid the consequences of climate change. While some see this as an obligation to take measures for reducing emissions by promoting the exploration of renewable and sustainable energy technologies others see that a world powered by renewable energies is far from being realizable.

Advocates of nuclear energy have recently emerged framing nuclear as being a substantial solution for the battle against climate change. The Nuclear Energy Institute (2007) emphasizes the importance of utilizing emission-free energy sources such as nuclear, claiming that it is a “carbon-free” energy source. Some believe that nuclear energy utilization can act as a bridge until renewable technologies are developed far enough to make sufficient contributions to the global energy mix. A proponent of this view is James Lovelock, an environmentalist, who in 2006 published The Revenge of Gaia, expressing that through greenhouse gas emissions and other forms of environmental degradation the world is at the brink of a crisis, which should be mitigated by a large-scale transition to nuclear power if electricity supplies are to remain reliable and carbon dioxide emissions are to be decreased (Lovelock, 2006).

Opponents of nuclear power as a solution for climate change emphasize that nuclear power is not a sustainable solution and that there are better energy options in the form of renewable energy technologies. Despite nuclear energy not producing any greenhouse gas emissions during its heat and electricity stages, it is not a zero emission energy source. There are always additional energy requirements, which need to be accounted for when considering the implementation of any energy technology. For example, energy is consumed with the construction of necessary structures. Nuclear power requires substantial amounts of energy inputs, usually provided by fossil fuels, to be developed. Consequently, accounting for a substantial amount of greenhouse gas emissions. In addition, certain phases of the nuclear process cause environmental impacts, by means of, for example, radioactive waste in various forms.
Notably, when exploring the impacts of nuclear energy there is a certain magnitude, which must be considered. The “nuclear option” implies a large-scale utilization of nuclear energy. If nuclear energy is accepted as a viable energy path in mitigating climate change its utilization must and will be intensified on a global scale. This would result in a significant expansion of nuclear installations around the world and consequently, an amplification of any externalities associated with nuclear power, such as risks, energy costs, and waste.

Since the almost worldwide political consensus on the urgent need for sustainability, questions on defining and developing sustainable development into an executable task has been none short of a challenge. Questions on what sustainability is and should be as well as what the implications are is still debatable. In considering the complexity of incorporating the three pillars of environmental, social and economic concerns, defining sustainability has, amongst its many attempts to be defined, resulted in rather ambiguous terms. This ambiguity has been celebrated and criticized.

The position of this paper regarding sustainability adopts a one-pillar model, which regards the environment to be prioritized before social and economic pillars. This however, does not imply that environmental sustainability is mutually exclusive from social and economic concerns. “Although ES is needed by humans and originated because of social concerns, ES itself seeks to improve human welfare by protecting the sources of raw materials used for human needs and ensuring that the sinks for human wastes are not exceeded, in order to prevent harm to humans” (Goodland, 2005, p.3). Environmental sustainability also means the management and maintenance of natural capital by keeping human economic activity within the overall limits of the biophysical environment. It is necessary that sustainable practices be incorporated into production processes and consumption patterns.
1.1 Motivation
There is an undeniable need for a global transition towards sustainability and sustainable energy technologies, especially in reference to the environment. Energy is a basic necessity of modern mankind and requires accessibility, reliability, affordability, and increasingly important, needs to be clean (ECN, 2007). The fossil fuel economy has emerged as being unsustainable as resources are diminishing rapidly and the environmental impacts become more evident. Nuclear energy has been proposed as a promising solution for reducing CO2 emissions and securing energy availability. Transitioning towards a sustainable world requires the incorporation of sustainable practices, which also applies to developing a global energy system. It is imperative to make decisions regarding energy with the long-term in mind to consequently, avoid engaging in unsustainable technical fixes that will later lead us into the next crisis.

1.2 Scope, Approach, and Perspective
Although there are a multitude of other issues regarding nuclear energy, the approach of this paper will focus on an environmental sustainability perspective. Environmental sustainability implies the ability to maintain human life, the proper functioning of natural systems, the stable working of society, and a general quality of existence for all living organisms. Resulting from the growing claims that nuclear energy is the solution to our environmental plight, it is hereby intended to explore in how far the nuclear process imposes on the environment. Specifically, is nuclear energy a solution to the emergent environmental crisis from an environmental sustainability perspective? Noteworthy, nuclear energy will be assessed according to the “nuclear option,” meaning nuclear power becoming the dominant global energy provider and is limited to electricity generation. Furthermore, the environmental sustainability perspective is by no means mutually exclusive from other problems present in this matter. However, this paper intends to focus on the purely ecological impacts in the form of CO2 emissions, ecological disruptions and radioactive waste generation in respects to nuclear energy.
1.3 Contribution
This paper aspires to contribute to academic literature by providing an environmental perspective of the nuclear energy debate. Most literature and information sources at present, compare nuclear with unsustainable energy sources, such as coal, focus on aspects, such as proliferation, terrorism, and amongst other, public opinion. Although these aspects are important, if nuclear energy is claimed as a solution to climate change it must be critically examined from an environmental perspective. Due to this new wave of nuclear deliberation, according studies and literature must be developed. It is imperative to understand what the environmental impacts are when considering the nuclear option. Additionally, this paper seeks to contribute to the public understanding of what role nuclear energy can play in mitigating climate change whilst incorporating the concept of sustainability. The importance in the public having exhaustive information to their disposal lies in their influence on politics. The citizens are the voters and require detailed information before deciding on such important issues.

1.4 Content
This paper begins by providing relevant background information about nuclear energy by giving an overview of the nuclear process. Chapter three is divided into two parts: the first, will explore energy costs, ecological impacts, and waste production along the entire nuclear process; the second part will analyze nuclear energy from a sustainability perspective. Subsequently, chapter four will explore the potential of renewable energy technologies as an alternative to the nuclear option. Consequently, chapter five will summarize the main findings of this paper, including limitations and ideas for further research.
2. Nuclear energy process

2.1 Global Development
In 2007, the contribution of nuclear energy to the global electricity generation amounted to approximately 15 percent (BP, 2007). Worldwide, there are 439 nuclear reactors for electricity generation in 30 countries of which 16 countries satisfy at least one quarter of their demands by nuclear energy (Nuclear Energy Institute, 2008). Since 2007, some 30 additional power reactors are under construction and approximately 70 reactors are planned to be constructed (World Nuclear Association, 2008). For a global overview of nuclear power reactors refer to appendix 1.

2.2 The Nuclear cycle
The nuclear cycle is categorized into two parts: the front-end and back-end fuel cycle. At the front-end of the nuclear cycle, the portion involving fuel before it is delivered to a power plant, includes the mining of uranium ore at mines, the milling process where uranium is extracted, conversion where uranium is transformed into a gaseous form, the enrichment of uranium to the desired form, and finally, the solidification of the enriched uranium and its fabrication into fuel (Tester, Drake, Driscoll, Golay & Peters, 2005). The back-end of the fuel cycle entails the storage of spent fuel, the re-processing of spent fuel and generated waste, the management of low-, intermediate-, and high-level waste, the decommissioning and decommissioning phase of a nuclear power plant and the restoration of closed mines (Tester et al., 2005).
Figure 1: Full Nuclear Process Chain

Source: Adopted from Storm van Leeuwen (2006)
Energy won from nuclear energy is through the nuclear fission of certain uranium-isotopes and fissionable isotopes produced from uranium. Uranium is an element that generally occurs naturally in low concentration and can be found in soil, rock and water. There are various isotopes of uranium but only certain ones, mainly uranium-235, are fissile and suitable for nuclear use.

2.2.1 Construction
The construction phase of a nuclear power plant involves the fabrication, transportation, and use of materials to build generators, turbines, cooling towers, control rooms, and other infrastructure developments (Sovacool, 2008). The construction of a nuclear power plant requires certain amounts of steel and concrete, amongst other materials, which are energy and carbon intensive. Commonly, discussions regarding the construction of nuclear power plants are consumed with the economic viability of such construction projects and the potential in energy production. Nevertheless, the materials used for construction have a strong link with CO2 emissions and must be critically explored in the context of environmental impacts.

2.2.2 Mining and Milling
Uranium mining is the process of extracting uranium ore from the ground. Uranium is a metal that has to be chemically extracted from uranium ore and subsequently, treated and converted to be used for nuclear energy. There are various mining methods, which can be utilized to extract uranium and because it is generally present in minute quantities the extraction process is very volume intensive. Although, there are exceptions to where there are higher concentrations of uranium, such as in Australia and Canada. Uranium can be extracted in general by using two methods: open-pit mining or underground mining. Open-pit mining entails the removing of the top layer of burden allowing for extraction to occur in a large open air pit and underground mining entails the digging of tunnels allowing for the ore to be extracted underground (Dreicer, Ton & Manen, 1995). An additional method sometimes applied to uranium extraction is in-situ leaching (ISL). This method involves retaining the ore in the ground and recovering uranium from it by dissolving it. This is done by pumping particular chemicals into the underground ore
body and consequently, after a time period ranging from 3-25 years, extracting the uranium-bearing liquid (Storm van Leeuwen & Smith, 2005). “Uranium ISL uses the native groundwater in the ore body which is fortified with a complexing agent and in most cases an oxidant” (World Nuclear Association, 2008). Subsequent to the uranium solution being extracted from the ground the uranium is recovered by milling.

Once the uranium has been mined it must be milled to extract the uranium oxide from the ore. To avoid having to transport large amounts of material, the milling process is commonly carried out near the mining site (Dreicer et al., 1995). Milling entails grinding large amounts of rock into fine slurry, which is then leached in sulfuric acid to extract what is called “yellowcake.” Yellowcake is a uranium ore concentrate containing above 80 percent uranium (Lenzen, 2008, p. 2181). A byproduct of the mining and milling process are tailings. Tailings are solid waste products comprised of most of the original ore processed to extract uranium, including radioactivity (World Nuclear Association, 2008).

2.2.3 Preparing Fuel (Conversion & Enrichment)

The preparation process of nuclear fuel depends on the source technology. For light water-reactors, which are most common, for the uranium to be usable it requires conversion into a gaseous form known as hexafluoride to subsequently, be enriched to prepare nuclear fuel. Thus, the yellowcake substance is transported to a conversion plant and later to an enrichment facility. The uranium, to be useful in light water-reactors, must have a uranium-235 concentration of at least 3.5 percent, in comparison with the 0.7 percent in which it is present in natural uranium (Fleming, 2007). The enrichment process entails removing approximately 85 percent of uranium-238 from uranium hexafluoride known as “enrichment tails” (World Nuclear Association, 2008). Once U-238 has been removed, the uranium, which is left, mainly uranium-235, is enriched and passes on to the next stage of the cycle. The 15 percent of enriched uranium are then converted into ceramic pellets of uranium dioxide, packed in zirconium alloy tubes and finally, are bundled together to form fuel elements for reactors (Fleming, 2007). The enrichment tails retain diminutive amounts of uranium-235 and are therefore, not used for energy.
However, such depleted uranium can sometimes be used by being converted into metals for a variety of purposes, such as munitions or ballast in airplanes, because it is denser than lead (World Nuclear Association, 2008). However, most enrichment tails remain in their gaseous form and are stored.

2.2.4 Generation and Waste
Once the fuel has been prepared it can be used to generate heat for steam and consequently, to produce energy. Along the phases of the nuclear cycle, significant amounts of waste are generated. Due to the various levels of radioactive contamination of materials, a long-term and safe containment of waste is necessary to prevent exposure to the environment, as well as the public. The radioactive elements in the waste are present in different concentrations and have different half-lives therefore, requiring different ways in dealing with different waste, especially for material with radioactive contamination that last for long periods of time. The International Atomic Energy Agency has established a classification system for radioactive waste. Radioactive waste is placed within three categories: Low-level waste (LLW), Intermediate-level Waste (ILW), and High-level waste (HLW). Low-level waste, because of its low radionuclide content allows for normal handling and transportation and does not require any shielding. Intermediate-level waste does require shielding because of its radionuclide content but no provision for heat dissipation. High-level waste consists of highly radioactive liquid, containing mainly fission products, as well as some actinides, which is separated during chemical reprocessing of irradiated fuel (aqueous waste from the first solvent extraction cycle and those waste streams combined with it); any other waste with radioactivity levels intense enough to generate significant quantities of heat by the radioactive decay process; spent fuel, if it is declared a waste (IAEA, 1994, p. 8). In addition, the IAEA (1994) classification makes a differentiation within ILW and LLW between short and long-lived waste and alpha bearing waste. Short- and long-lived waste refers to the decay of radioactive waste based on an acceptable or not acceptable activity level from a radiological viewpoint. “Alpha bearing waste is radioactive waste containing one or more alpha emitting radionuclides, usually actinides, in quantities above acceptable limits established by the national regulatory body” (IAEA, 1994, p. 9).
ILW and LLW are generally stored in near-surface waste disposal sites to isolate the waste from the human environment and allow for the natural decay of radioactivity (Dreicer et al., 1995). In regards to the management of HLW only hypothetical concepts exist past basic storage, until now, high-level waste is disposed of by storage. (Tester et al., 2005). Current consideration propose deep ecological disposal. The sources of waste range from spent fuel elements, emissions and catastrophic releases through accident, plutonium and dismantling of the reactor itself. Notably, no effective disposal method for nuclear waste has yet been adopted.

2.2.5 Fuel re-processing
The nuclear fuel cycle can be classified into two types: a once-through and closed fuel cycle. Some reactors operate on a once-through cycle that disposes of spent fuel directly where other reactors operate on a closed fuel cycle, separating waste products from unused fissionable material so that it can be reused as fuel. (Sovacool, 2008) Once the concentration of the used uranium decreases to below 1 percent it can be re-processed to recover uranium for reuse. The re-processing process is highly complex and requires a higher degree of enrichment and is not always incorporated in the cycle for security concerns. Re-processing is also used for recovering plutonium from spent fuel, raising concerns about potential proliferation. Consequently, to avoid its diversion and theft certain safeguard methods would have to be put in place (Tester et al., 2005, p. 394). In addition, “reprocessing is widely recognized to be uneconomical and is likely to remain so in the foreseeable future” (Tester et al., 2005, p. 393).

2.2.6 The Reactor
The type of reactor defines the lifetime of a nuclear reactor. However, at present the average lifetime of a nuclear reactor can be approximated between 30-40 years, whereas it runs at full capacity for approximately 24 years (Fleming, 2007). Throughout the lifetime of a nuclear reactor, maintenance and refurbishing is necessary until, eventually corrosion and radioactivity make maintenance not viable.
Ultimately, a nuclear reactor must be dismantled. The first step in doing so is dealing with the storage of fuel elements and the cleaning of the cooling system to reduce radioactive corrosion residuals and unidentifiable deposits (Fleming, 2007). Used fuel assemblies are highly radioactive and project a lot of heat therefore, they are generally stored in special ponds that act as a barrier for the radiation and heat from the spent fuel (World Nuclear Association, 2005). Nevertheless, storage of these spent fuel elements are only intended as a provisional phase before it can be reprocessed or finally disposed. In addition, the longer the storage times the higher the decay of radioactivity. Once a cooling-off period, which can last as long as 50-100 years, the reactor can be dismantled, which entails it being broken into small pieces that can be put in containers and disposed of (Proops, Gay, Speck & Schroder, 1996).
3. Nuclear Energy and Sustainability

3.1 Emissions and Environmental Impacts

Differences in conclusions of lifecycle studies of greenhouse gas emissions and ecological impacts associated with nuclear energy are due to discrepancies in the framing and defining of the system. For example, some studies do not include factors, such as costs and impacts of building the appropriate structures according to the particular technology. It is difficult but nonetheless, important to develop a comprehensive scope of any energy technology to avoid discrepancies in assessing the associated costs and impacts.

The claim that nuclear energy is CO2 emission free is implausible because energy costs are unavoidable and necessary for the development and management of any energy technology. However, it is vital to explore how energy intensive the nuclear process is and if in fact it can be utilized as a viable option to dealing with global warming. Additionally, it is imperative to investigate ecological impacts not only in the form of emission but waste generation. Therefore, to attain an accurate overview of ecological impacts through greenhouse gas emissions and waste generated by the nuclear process, it is imperative to account for the entire life cycle from primary energy extraction to the energy output, as for any energy process. “To do so, one has to follow all relevant steps along the life-cycles of energy technologies, tracking all activities, which directly or indirectly emit greenhouse gases” (Fritsche, 2006, p. 2).

This section aims at identifying energy costs, waste generation, and ecological impacts throughout the nuclear process by looking at construction, mining, milling, conversion and enrichment, fuel fabrication, generation, spent fuel and reprocessing, decommissioning and dismantling phases. The term energy costs implies energy inputs, which up to date, predominantly are supplied by fossil fuels and consequently, contribute to greenhouse gas emissions. Studies of greenhouse gas emissions associated with nuclear energy are scarce in the open literature. One phase that has been omitted is the excavation for uranium ore and the related energy costs and ecological impacts because
of the time limitations of this paper. Also, this paper omits the further reflection of ecological impacts on human health. However, notwithstanding, any influences on the environment are not mutually exclusive from impacts on humans. Noteworthy, discrepancies in the information provided can occur according to a particular nuclear technology. For example, certain technologies do not require the enrichment of uranium. Consequently, the energy costs, waste generation, and ecological impacts differ accordingly.

3.1.1 Construction
The energy costs needed for the construction of a nuclear power plant is influenced by what type of technology is used, as well as the size and regulatory system. Reliable data on the amounts of construction material needed for a nuclear power plant are scarce in the open literature. “The energy requirements for construction of a nuclear power plant cannot be measured directly, due to the complexity, scale and diversity of materials, activities and equipment involved” (Storm van Leeuwen & Smith, 2007, p. 20). However, it is possible to make estimations by indirectly measuring inputs and outputs. According to White (1995), based on the estimates of materials needed for an older 1000MW pressurized water reactor an approximation for a typical nuclear power plant can be made resulting in 170,000 tons of concrete, 32,000 tons of steel, 1363 tons of copper, and a 205,464 of other materials for the construction of a nuclear plant (White, 1995). Much of the construction material, such as steel and concrete, are carbon intense requiring significant amounts of energy to be produced. Some data on material requirements for the construction of an 1 GW(e) LWR, in Mg according to a variety of studies can be found in Appendix 2.

Any industrial process, including the nuclear system, involves direct energy inputs and outputs. Direct energy inputs, such as fuel and electricity, are necessary for services, processing of materials, capital goods (machines, transport), and also raw materials (Storm van Leeuwen & Smith, 2007). The output is comprised of product demand, material wastes (gaseous and liquid effluents and solid waste), and low temperature waste heat, released into the biosphere (Storm van Leeuwen & Smith, 2007).
Figure 2: Simplified outline of the process analysis of the construction of the nuclear system

Source: Adopted from Storm van Leeuwen and Smith (2007)

The energy inputs of the construction of a nuclear power plant comprise energy consumed at the construction site (i.e. transportation); energy embodied in services, such as craft labor but also research laboratories and institutional services; the energy embodied in the construction materials, chemical, and auxiliary materials; the energy embodies in the manufacturing and construction of components and capital goods; and the energy necessary for the construction and maintenance of capital goods (Storm van Leeuwen & Smith, 2007).

A variety of materials required for the construction of a nuclear power plant are energy intense to produce. Additionally, many materials required for construction must be of a certain quality. Just as for any industrial plant, the materials used during construction significantly determine the safety and operational lifetime. To attain this high quality in materials, it is necessary to use very pure materials and fabrication processes under tightly controlled conditions (Storm van Leeuwen & Smith, 2007).
3.1.2 Mining and Milling

The sources of environmental impacts from mining and milling are the energy costs, which result in CO2 emissions, ecological impacts, and the production of radioactive waste, especially radon. According to Hu, Weng & Wang (2008), uranium mining (ore extraction) and milling (physical and chemical extraction of U from the ore) have generated the largest volume of radioactive waste.

Mining

The process of recovering uranium from the earth's crust is energy intensive, requiring mechanical and chemical processes, which consequently emit gases, such as CO2 and other hazardous wastes (Storm van Leeuwen & Smith, 2007). Energy costs of mining are determined by direct energy inputs comprised of, for example, fuel for trucks. Indirect energy inputs take the form of chemicals, as well as human labor and other services. The most significant determinants are the grade of the ore and the mining method employed. Ore grade refers to the concentration of uranium in the ore. “Most of the published calculations of the net energy production of a nuclear power plant—and hence the CO2 emissions produced by the whole nuclear chain— are based on a single fixed value the energy use of the production of uranium ore” (Storm van Leeuwen & Smith, 2007, p. 2). Using a fixed value can lead to discrepancies in evaluating energy costs since the mining of lower grades are more energy intensive than of higher ore grades, thus, producing diverse values. For the production of uranium oxide from a low ore grade, a larger amount of ore mass is processed compared to a higher-grade ore. Consequently, the extraction yield declines the lower the ore grade.

The energy requirements for mining are also influenced according to which type of method is employed. As briefly explained in section 2.2.2, the two most common mining methods are open-pit mining and underground mining. Open-pit mining entails the removing of the top layer of burden, allowing for extraction to occur in a large open air pit and underground mining entails the digging of tunnels allowing for the ore to be extracted underground (Dreicer et al, 1995).
Both methods raise concerns for potential radiological exposure including: discharging mine water that contains radioactive contaminants, releasing radon and dust in the exhaust air from underground mines, and releasing radon and dust from open pit mines (Chambers, Cassaday & Lowe, 1989). Significantly, the mining process produces piles of so-called waste rock consisting of overburden and ore, which has too low a grade to be processed (Diehl, 2004). Accordingly, waste rock contains certain amounts of radioactivity. In addition, uranium ore contains radium, which as it decays forms radon, an inert radioactive gas that can escape from solid materials such as waste rock (Chamber, 1989). The weathering and erosion of waste rock leads to the contained radioactive materials to be released into the environment and consequently, beyond the boundaries in which they can be controlled. Consequently, contamination of soil and nearby water bodies can occur.

An additional method for the extraction of uranium is via in-situ leaching, a process requiring the use of various chemicals, which are determined by the groundwater, geology, and compilation of the ore body. As briefly explained in section 2.2.2, this method recovers uranium by dissolving uranium bodies underground and then extracting the uranium-bearing liquid. The energy costs for this process can be determined according to which chemicals are used as well as drilling injections and production wells, pumping and the extraction of the uranium from the uranium bearing liquid (Storm van Leeuwen & Smith, 2005). Additionally, energy requirements depend on the ore grade but also on the environment. Nevertheless, average values are limited because data regarding actual mines are deficient in the open literature (Storm van Leeuwen & Smith, 2005). One of the most critical concerns related to this method is the large-scale contamination of aquifers. This contamination is, however, not only caused by the chemicals used but also by radioactive and toxic elements including radium, heavy metals, and arsenic (Storm van Leeuwen & Smith, 2005).

The type of mining method employed reflects different levels and types of emissions. For example, open-pit mining often produces higher levels of gaseous radon and methane (a greenhouse gas) than underground mines (Andseta, Thompson, Jarrell & Pendergast,
An additional factor in energy demands according to mining method is determined by the location of mining operations and energy availability. Mining locations closer to industrial centers receive more efficient and centrally generated power where in contrast remote mining locations are dependent on less efficient energy sources that increase fossil fuel use and consequently, generate increased levels of carbon dioxide (Andseta et al., 1998).

**Milling**

The milling process involves the grinding of uranium ore into a fine powder, which is then subjected to a leaching process where highly acidic or alkaline solutions cause the uranium to dissolve and separate it from solid rock particles. The uranium is then concentrated and converted into a relatively pure product called yellowcake, which for a large part consist of uranium oxides. (Chambers et al., 1989). As is the case during the mining stage, energy costs of milling are influenced by the different properties of the ore. “In the cases where ores have a concentration of 0.1% the milling must grind 1000 ton of rock to extract 1 ton of yellowcake” (Sovacool, 2008, p. 2951).

Waste materials produced by the milling process are called tailings, which consist of ground rock particles, water and various amounts of chemicals (Chambers et al., 1989). Tailings contain most of the original ore and contain substantial amounts of radioactivity, in the form of remaining uranium and radium and other uranium and radium decay products in amounts as present in the original ore (World Nuclear Association, 2008). Additionally, similar to the risks of waste rock from mining, mill tailings are exposed to the atmosphere and pose a threat by being chemically mobile. The radioactive material of tailings, especially radon, can spread past controllable boundaries causing significant long-term risk for the environment (Storm van Leeuwen & Smith, 2005). Radioactive effluents from uranium mines can be dispersed via gas, wind blown dust and water through run-off or seepage into the ground water table. In addition, because tailings are in a geochemical disequilibrium various additional reactions, dependent on the environment, can occur which increases hazardousness (Diehl, 2004).
Uranium mill tailings require to be managed to avoid environmental hazards. During the 1950’s in the Northern territory of Australia, tailings and liquid wastes were generally dealt with by discharging them onto adjacent lowlands, which formed creek lines and rivers, allowing for the radioactive materials to be spread by weathering (Mudd, 2008). In other regions of Australia, mills constructed dams to retain tailings and liquid wastes. Uranium mill tailings are commonly dispersed as sludge in special ponds and on completion of mining operations these tailings ponds are covered with clay and topsoil to reduce radiation (World Nuclear Association, 2008). Over time it has become increasingly important to properly manage mill tailings to avoid ecological contamination and exposure to hazardous levels of radon.

3.1.3 Fuel Preparation (Conversion & Enrichment)

The phase subsequent to the production of yellowcake is towards the preparation of the nuclear fuel. This requires the refinement of the yellowcake into a concentrated and gaseous form known as uranium hexafluoride, necessary for enrichment.

Conversion

The conversion process takes place at a conversion plant and thus, requires the uranium material to be transported. At a conversion facility uranium is first refined into uranium dioxide that is needed for the types of reactors, which do not require enriched uranium, where the rest is then converted into uranium hexafluoride before being shipped to the enrichment plant (World Nuclear Association, 2008).

Enrichment

After the conversion process, the hexafluoride is transferred to an enrichment plant to increase the ratio of uranium-235 to uranium-238. The enrichment process can be executed using two different technologies, namely gaseous diffusion or centrifuge enrichment. Although enrichment via gaseous diffusion amounts to 40 percent of world enrichment capacity, the technology is old and inefficient and most plants of this type are being phased out (World Nuclear Association, 2008). The enrichment process utilizes significant amounts of energy according to the technology employed. The contribution
from centrifuge enrichment to total greenhouse gas emissions is low due to its lower energy intensity compared to a diffusion plant, which is more energy intense. (Dones, Heck, Emmenegger & Jungbluth, 2005, p. 15). Nonetheless, the common utilization of both technologies, dependent on the way the necessary electricity is produced, rely on certain amounts of fossil fuels, contributing to CO2 emissions. The energy requirements for enrichment varies according to the method used, where gaseous centrifuge enrichment ranges from 40 to 100 kWh/SWU and gaseous diffusion requires 2400 to 3000 kWh/SWU (Fthenakis and Kim, 2007, p. 2553). “The Separative Work Unit or SWU is a measure of the work expended during an enrichment process” (FAS, 2008).

The operations at an enrichment plant results in atmospheric releases and liquid releases of uranium and other chemicals. The ExternE project assessed atmospheric and liquid releases of a gaseous diffusion enrichment plant in France. Results have shown that annual releases of gas contain approximately 5kg of uranium with an assumed fraction of uranium-235 of 1.5 percent as well as small amounts of chemical releases (Dreicer et al., 1995). Annually produced liquid effluents contain approximately 1kg of uranium and are discharged at a nearly located river (Dreicer et al., 1995).

The enrichment process produces depleted uranium as its main waste byproduct. After enrichment, about 85 percent of the oxide comes out as waste in the form of depleted uranium hexafluoride, known as enrichment tails, which must be stored (Sovacool, 2008). Most of the depleted uranium is stored in metal containers still as hexafluoride and some has been converted into metal. This metal has been used for ballast in airplanes and in armor-penetrating munitions (Storm van Leeuwen & Smith, 2005).

**Fuel Fabrication**

For the enriched uranium hexafluoride to be used as reactor fuel it must, as briefly explained in section 2.2.3, be converted into a solid form. It is then packed into zircalloy tubes (fuel pins), of which a number are then bundled together to form fuel elements, which are then placed into the reactor (Storm van Leeuwen & Smith, 2005). Although contentious, according to Storm van Leeuwen & Smith (2005), probably the most energy
intensive aspect of this process is the actual production of the zircalloy, which is energy intense to produce.

Additional energy costs endured by the nuclear process up to this point, include the before mentioned transportation of uranium material from mines to processing and enrichment facilities. The IEA (2002) reports that just in Europe, most uranium is transported 150-805 km by railway, 1250 km by boat, or 378 by truck (International Energy Agency, 2002). Additional energy costs materialize in the construction, maintenance, decommissioning and dismantling of these facilities. Processing and enrichment facilities generate indirect energy costs that are part of the nuclear process.

3.1.4 Operation and Maintenance
Electricity generation from nuclear power does not directly emit greenhouse gases but does so from indirect lifecycle phases and energy inputs (Sovacool, 2008). Estimations of energy requirements for the operation of a nuclear power plant are difficult to assess (Lenzen, 2008). Nonetheless, the operation phase of the nuclear process requires energy necessary for the functioning of the plant. Energy is needed for cooling and fuel cycles, as well as maintenance and back up systems. The efficient and safe functioning of a nuclear power plant requires maintenance and refurbishments. Indirect energy inputs comprise provisions of power during outages, repairs and shutdowns (Sovacool, 2008).

3.1.5 Spent Fuel and Reprocessing
After a few years, used fuel elements must be removed and replaced by new fuel rods. To maintain efficient energy production, about one third of the fuel assemblies are replaced each year, which consequently results in spent fuel assemblies (Dreicer et al, 1995). As explained in section 2.2.5, spent fuel can be discharged or reprocessed. A once-through cycle stores the spent fuel, often done in nearby reactor sites, in water pools to allow for radioactive decay and physical protection. Reprocessing of spent fuel is done to extract fissile material (i.e. plutonium) and is employed in countries like France, the United Kingdom, and Japan, where the United States does not reprocess spent fuel and only stores it. Reprocessing produces highly radioactive waste products which are
consequently stored and require final disposal. Subsequently, the sequestration of nuclear waste is necessary to avoid biosphere and human exposure to dangerous levels of radiation (Sovacool, 2008). Spent fuel and reprocessed spent fuel are highly radioactive waste products, which require storage and final disposal. “The half-life of uranium-238, one of the largest components of spent fuel, is about the same as the age of the earth: 4.5 billion years” (Sovacool, 2008, p. 2953).

The energy costs of managing spent fuel consist of the operational costs of maintaining the spent fuel, the reprocessing phase if undertaken, interim and final storage. Spent fuel must be packaged and stored in special facilities thus, consuming energy for the storage of spent fuel and maintenance of the storage facility, as well as consequent dismantling of the facility.

3.1.6 Dismantling and Decommissioning
The final stage of the nuclear process is the decommissioning and dismantling of the reactor. The average operational lifetime for a nuclear energy facility is 30-40 years, although some reactors have closed earlier and others have applied for an extension. Nonetheless, a nuclear energy facility is ultimately subjected to dismantling, decommissioning, and the disposal of radioactive material. Subsequent to a cooling period of approximately 50-100 years, a reactor vessel requires dismantling and cutting into small divisions that are packed in containers for final disposal (Proops et al., 1996).

Notably, the time span of how long a nuclear power plant can operate is determined by its technology. Newer technologies promise longer operation spans for nuclear power plants. Values for this phase, dismantling and decommissioning, differ according to type of nuclear technology.

The International Atomic Energy Agency has defined three options for the decommissioning of a nuclear energy facility: Immediate dismantling, safe enclosure, and entombment. Immediate dismantling allows for the nuclear facility to be removed from regulatory control soon after shutdown. The final dismantling and decommissioning can then take place with a few months or years. Safe enclosure postpones the final removal
from regulatory control for 40-60 years during, which the facility is placed into a safe storage configuration until dismantling and decommissioning eventually takes place. The entombment option entails placing the facility into a condition that will allow the remaining on-site radioactive material to remain on-site without necessity to remove it completely (World Nuclear Association, 2007).

According to the World Nuclear Association Database, 115 power and research reactors, 5 reprocessing facilities, 14 fuel fabrication plants, and 60 mines are currently awaiting or undergoing decommissioning (McKeown, 2003). As reported by the International Atomic Energy Agency, at the end of 2005, eight power plants had been completely decommissioned and dismantled, and the sites were released for unconditional use (World Nuclear Association, 2007). The releasing of prior nuclear power sites for unconditional use may be contested considering the persistent nature of certain radioactive materials and the routine release of radioactive isotopes during the regular operation of a nuclear power plant.

The Nuclear Decommissioning Authority (NDA) in the UK has developed a strategy for complete dismantling and decommissioning of a nuclear power plant, which is thus far the most detailed published information. This is done in four phases: 1) Cleaning up higher-hazard legacy facilities, 2) site closure, environmental restoration and site end states, 3) management of contaminated lands, 4) management of radioactive particles and contaminated sediments (Nuclear Decommissioning Authority, 2006). Detailed information on each phase is present in Appendix 3. At the end of its life, a typical nuclear reactor poses the task of disposing of about 10,00 tons of medium to high level radioactive waste, some 10,00 tons of low to medium level radioactive waste and some 100,000 tons of non-active material (Thierfeldt, 1995). Consequently, an extensive decommissioning and dismantling process, which accounts for all the waste generated during the process of nuclear operations requires substantial energy to execute.
Deep Geological Repository

All countries in which nuclear power plants operate will have to deal with the management of low-, intermediate- and high-level and long-lived radioactive waste. This aspect of nuclear power production is one for which no accepted solution has been found. However, finding a solution for the management of nuclear waste is a key issue that is important for environmental protection and the future of the nuclear industry where current plans consider the deep geological repository. Deep geological repository is a concept for the isolation of nuclear waste to be stored in underground storage facilities. Radioactive waste is packaged into special containers to secure the possibility of radionuclides escaping into the biosphere before natural decay has reduced radioactivity to acceptable levels.

The utilization of deep geological repository for radioactive waste management raises the need for exploring related energy costs, waste generation and environmental impacts. In respects to this concept being rather juvenile in its development significant research is essential. Nonetheless, the before mentioned factors are relatively certain because these hold true for operations for any intricate establishment. Energy costs are necessary for the construction of such a structure, consisting of direct and indirect energy inputs. Environmental impacts become evident in respects to the magnitude of a deep geological repository and possible ecological disruptions, although uncertain.

3.1.7 Additional Impacts and Concerns

Routine releases of small amounts of radioactive isotopes

During the operation of a typical nuclear reactor, over 200 radionuclides are produced, many of which are short-lived and decay to low levels within a few decades (Crowly, 1997). Some of these radionuclides are emitted during the normal operations of a nuclear power plant. Hu et al. (2008) provide data for the gaseous discharge of 14C into the atmosphere from pressurized water reactors in Germany resulting in 280±20GBq/GWe in 1999, where, on average 30% is thought to have been emitted in the form of CO2, and the rest in organic form (Hu et al., 2008, p. 5).
3.2 Sustainability

Sustainability is a complex concept, thus making it difficult to put into operation. The global ecosystem provides raw materials, sometimes in large quantities but nevertheless, they are finite and require their maintenance rather than being run down. The overexploitation of these sources impairs the provision of life-supporting systems. The aim of this section is to explore the sustainability of nuclear energy. This will be done by exploring by utilizing the sustainable backstop supply criteria presented by Verbruggen (2008).

“The idea of sustainability suggests that goals of economic growth can be effectively combined with goals of social welfare and environmental quality” (Bruggink, 2001, p.11). Energy is the driver of economic growth and development but also simultaneously the major source of emissions, which have significant effects on the environment. Thus, energy requires significant consideration and plays an important role in the discussion over sustainability. An energy system that can be viewed as sustainable must, amongst other, consider inter- and intra-generational equity, environmental justice, and most important, the environment.

The current global energy regime is dominated by fossil fuels, which provide more than 85 percent of global commercial energy and more than 68 percent of commercial electricity (BP, 2005). Fossil fuels are an unsustainable energy source because they are finite in all forms and generate substantial amounts of greenhouse gas emissions. In actuality, the only sustainable energy source accessible on earth is from the sun. Any other energy obtained from earths sources are finite and will result in eventual exhaustion. In addition, all processes, which take place in a closed system increase entropy (Storm van Leeuwen & Smith, 2005). To offset this function energy should be taken from outside the system (i.e. the sun). Based on these factors nuclear energy can be categorized as an unsustainable energy source.
3.2.1 Sustainable Backstop Supply Criteria

First coined in 1973, the concept of a “backstop” supply technology by definition is a technology that can deliver an unlimited amount of energy at a given (high or very high) cost (Verbruggen, 2008). Nonetheless, during this time, energy concerns focused on exhaustibility not inclusive of the sustainability factor. Verbruggen (2008) points out towards the necessary inclusion of sustainable development in contemporary discussions over energy exhaustibility. As a result, the criteria developed by Verbruggen (2008) represents the four essential dimensions of sustainable development, in accordance with the IPCC: “1) Political (participation, inclusion, democratic institutions, governance), 2) People (redistribution of global opportunities, access to development and welfare), 3) Planet (ecological resilient and sustainable, avoiding irreversible risks), 4) Prosperity (rather than profit, i.e. the costs must be reasonable and not wasting valuable economic resources)” (Verbruggen, 2008, p. 4039).

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Nuclear power performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unlimited</td>
<td>Nuclear power can only be considered an unlimited source if fusion and/or breeder technology become technically, economically and safely achievable. These are technologies, which have not yet been realized. Notably, promises made by the nuclear industry regarding the future of nuclear energy are based on advanced technologies not yet fully developed.</td>
</tr>
<tr>
<td>Democratically decided</td>
<td>Nuclear technology and the nuclear fuel cycle require protection to avoid access by intruders because certain materials can be abused for terrorism. Additionally, decision-making on nuclear projects often does not involve the public until decisions have been made because citizens lack the knowledge of such complex technologies.</td>
</tr>
<tr>
<td>Globally accessible</td>
<td>The huge monetary and technological capital of nuclear energy makes it inaccessible for developing countries. In addition, the expansion of nuclear know-how increases the risk of proliferation consequently, leading to necessary containment and phasing out of nuclear technology.</td>
</tr>
<tr>
<td>Environmentally benign</td>
<td>Nuclear fission is a carbon free process. Other emissions (inert gases) in the air are not as massive and diverse as emissions from fossil fuel combustion. Release of radioactive isotopes is the most significant source of contamination; massive releases happen in case of accidents.</td>
</tr>
<tr>
<td>Low risk</td>
<td>Given the probability of accidents, and given the – from a human perspective – eternal lifetime of radioactive waste, nuclear power is</td>
</tr>
</tbody>
</table>
not without risks. Therefore one could call upon societal risk processing institutions and procedures, i.e. the insurance sector. However, given that the risks of nuclear accidents and the eternal horizon of nuclear waste fall out of the range accepted by experienced professional underwriters, it is false to argue that the societal risks of nuclear power are minor, and should be accepted by the lay people of present and future generations.

Affordable

“Safe” nuclear power is too costly to build and operate. When societies accept particular kinds and levels of risks and the wheel of fortune is benevolent, large amounts of nuclear power can be generated at affordable monetary spending. The presented accounts however neglect the externality costs of major accidents and of the eternal concern for the high-level waste. Our instruments to gauge and assess such externality costs fall short. Up to now this is used as a validation that the costs are low, but in fact is an extra argument to adopt a precautionary attitude and policy.

Source: Adopted and modified from Verbruggen, 2008, p. 4040

_Uranium Availability_

Verbruggen (2008) explains that nuclear energy as an unlimited energy source is based on technologies that have not yet been realized. According to the MIT study _The Future of Nuclear Power_ (2003), based on current knowledge, do not believe it is realistic to expect that there are new reactor and fuel cycle technologies that simultaneously overcome the problems of cost, safety, waste, and proliferation. Consequently, it is necessary to investigate current technologies dependent on uranium, which is not an unlimited source. When considering a possible future where electrical energy will be produced by nuclear energy it is necessary to investigate for how long this energy source can deliver thus, uranium availability must be explored. As explained in section 3.1, uranium, to efficiently produce energy without offsetting the energy balance, requires a grade that is high enough. In other words, if the nuclear system consumes as much energy as it generates, known as the energy cliff (Storm van Leuween, 2006). This additionally limits the amount of usable uranium, which can be used to produce nuclear fuel. The development of nuclear energy over the next 25 years has to focus on two aspects: the supply of uranium and the addition of new reactor capacity (Energy Watch Group, 2006).
Different classification systems have been developed to categorize uranium sources. The source terminology applied will be that of the International Atomic Energy Agency and Nuclear Energy Agency. This classification scheme divides resource estimates into separate categories reflecting different levels of confidence in the quantities reported and then, further separates estimated resources within each category based on cost of production (OECD, 2007). Definitions of uranium resource classification categories are found in Appendix 4.

**Figure 3: NEA/IAEA Classification Scheme for Uranium Resources**

<table>
<thead>
<tr>
<th>Recoverable at costs</th>
<th>IDENTIFIED RESOURCES</th>
<th>UNDISCOVERED RESOURCES</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;USD 40/kgU</td>
<td>REASONABLY ASSURED RESOURCES</td>
<td>INFERRED RESOURCES</td>
</tr>
<tr>
<td>USD 40-80/kgU</td>
<td>REASONABLY ASSURED RESOURCES</td>
<td>INFERRED RESOURCES</td>
</tr>
<tr>
<td>USD 80-130/kgU</td>
<td>REASONABLY ASSURED RESOURCES</td>
<td>PROGNASTICATED RESOURCES</td>
</tr>
</tbody>
</table>

Decreasing confidence in estimates

Source: Adopted from OECD (2007)

It has become evident that 11 countries have exhausted their uranium resources and it is highly probable that resources are left in Australia with the majority of ores containing
less than 0.06% uranium, Kazakhstan with ores containing concentrations below 0.1%, and Canada, of which has ores with uranium content of more than 1 percent (Energy Watch Group, 2006). “Discovered available reasonable assured resources are somewhere between 1.9 and 3.3 million tons, depending on the cost class with an estimation of additional resources (with lower data quality) being between 0.8 and 1.4 million tons” (Energy Watch Group, 2006, p. 7).

![Figure 4: Uranium Resources (NEA 2006)](image)

<table>
<thead>
<tr>
<th>Resource Category</th>
<th>Cost Range</th>
<th>Resource [kt]</th>
<th>Data reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reasonably Assured Resources (RAR)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;40 $/kgU</td>
<td>1,947</td>
<td>1,947</td>
<td>High</td>
</tr>
<tr>
<td>40–80 $/kgU</td>
<td>696</td>
<td>2,643</td>
<td></td>
</tr>
<tr>
<td>80–130 $/kgU</td>
<td>654</td>
<td>3,297</td>
<td></td>
</tr>
<tr>
<td>Reasonably Assured (IR) - former EAR I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;40 $/kgU</td>
<td>799</td>
<td>4,096</td>
<td>Low</td>
</tr>
<tr>
<td>40–80 $/kgU</td>
<td>362</td>
<td>4,458</td>
<td></td>
</tr>
<tr>
<td>80–130 $/kgU</td>
<td>285</td>
<td>4,743</td>
<td></td>
</tr>
<tr>
<td>Undiscovered Resources</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prognosticated</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;80 $/kgU</td>
<td>1,700</td>
<td>6,443</td>
<td></td>
</tr>
<tr>
<td>80–130 $/kgU</td>
<td>819</td>
<td>7,262</td>
<td></td>
</tr>
<tr>
<td>Speculative</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;130 $/kgU</td>
<td>4,557</td>
<td>11,819</td>
<td></td>
</tr>
<tr>
<td>unassigned</td>
<td>2,979</td>
<td>14,798</td>
<td></td>
</tr>
</tbody>
</table>

Source: Adopted from Energy Watch Group (2006)

According to the Energy Watch Group (2006) proved reserves and stocks will be exhausted within the next 30 years. If the estimates of possible reserves, made by the Nuclear Energy Agency, are converted into production volumes, a shortage could be
delayed until 2050 (Energy Watch Group, 2006). However, because possible reserves are very speculative, they do not provide an adequate basis for planning over the next 20-30 years (Energy Watch Group, 2006).

Future prospects for finding uranium sources are rather uncertain. Deffeyes and MacGregor (1980) explain that the distribution of uranium in the earth’s crust is not well investigated. It is in their view not possible to establish estimations about the chances of finding uranium ores with a given grade within the accessible part of the lithosphere (Deffeyes & MacGregor, 1980). Notably, the probability of discovering new uranium sources that are rich and in abundance is uncertain and based on the scarcity of reports over the last few decades, most unlikely. However, propositions have been made for the extraction of uranium from sources such as seawater. Nevertheless, due to the low concentration of uranium in other sources the extraction process would, dependent on the technology, be very energy intensive and would most likely offset the energy balance. Propositions for the processing of such sources for uranium are, in addition, not fully studied, as well as developed.

Reactor Capacity
Concerns for the satisfaction of energy demands are not limited to the present. The world is still growing and future energy paths must consider the satisfaction of future demands, which will grow extensively. Prosperity, poverty alleviation, and the environment strongly depend on safe and sustainable energy. Exploring the nuclear energy option must additionally, be done in terms which take growing demand into account. In other words, it is not if nuclear energy can satisfy current capacity and demands but if it can provide and satisfy the demands of the future. According to Barnaby and Kemp (2007), with a source capacity of 1,000 MWe, between 2,000 and 2,500 reactors will be needed globally by 2075, meaning approximately three new reactors would have to go online every month till then. However, in line with the Energy Watch Group (2006) the necessary increase in reactor capacity will be deferred by the maintenance of current global nuclear capacity.
Approximately 45 percent of reactors worldwide are more than 25 years old of which 90 percent have been operating for more than 15 years (Energy Watch Group, 2006). To retain the current capacity and to allow for the increase in capacity, these reactors will have to be substituted by the end of their lifetime, which will require the completion of 15-20 new reactors per year in comparison to the 3-4 completed a year, at present (Energy Watch Group, 2006). The number of reactors under construction and those, which will soon be decommissioned, indicates that nuclear capacity cannot be increased before, 2011, at the earliest (Energy Watch Group, 2006). Conclusively, by the time nuclear capacity can be increased there will be severe uranium supply shortages, ultimately, inhibiting further developments. Thus, the nuclear capacity needed to offset greenhouse gas emissions is not achievable.

Notably, according to the WEO 2006 report, nuclear energy is considered to be the least efficient measure in combating greenhouse warming. In line with the “Alternative Policy Scenario”, the projected reduction in greenhouse gas emissions is primarily attributed to improved energy efficiency, 13 percent by fuel switching, 12 percent by the enhanced use of renewable energies and only 10 percent by the enhanced use of nuclear energy. Based on this scenario, enhanced use of nuclear energy attributes less than renewable energy technologies (WEO, 2006).

Generations, Energy Debt, and Environmental Justice

An important aspect of the social-environmental interface is the link between environmental impacts and social equity. Verbruggen (2008) explains that nuclear energy is procedurally unfair by not including society in the decision-making process, technological accessibility is unevenly distributed, safe utilization is too costly, and presents high societal risks for current and future generations. However, Verbruggen (2008) fails to emphasize the distribution of impacts. Sustainability includes the regard for future generations (intergenerational equity) and how current actions will affect them. As expressed by the Brundtland Commission emphasizing that sustainable development is a matter of equity both between and within generations: “Even the narrow notion of physical sustainability implies a concern for social equity between generations, a
concern that must logically be extended to equity between generations” (Dresner, 2004, p. 34). Future generations are likely to bear the burdens of actions taken now. Some define this as the most important component of sustainability.

**Energy Debt**

Verbruggen (2008) points to the risks, which will be incurred by future generations but fails to emphasize that besides risks and the costs of these risks they will have to endure the general costs of waste produced during current generations. Thus, it can be said that a significant amount of the energy costs of employing nuclear energy now will have to be paid by future generations who will not profit from nuclear-produced energy. “These are thus energy debts: debts incurred during its productive lifetime, which our descendant will have to pay” (Storm van Leeuwen & Smith, 2005, p. 3). Future generations will not only have to deal with the costs and effects of currently induced environmental impacts from currently generated CO2 emissions but they will be forced to deal with the waste produced by current generations. The energy debts generated by nuclear power can be put into three categories: energy costs until actual operation of a nuclear power plant, energy costs during the actual operation of a nuclear power plant and the costs occurring after shut-down. The construction of a nuclear power plant, the mining, milling and refining of uranium ores, the enrichment and fabrication of nuclear fuel, and the operation and maintenance of a nuclear power plant result in CO2 emissions. The second category includes the sequestration of highly radioactive spent fuel elements and depleted uranium, the rehabilitation of mining and milling areas after operations, the costs of dismantling and decommissioning of plants at the end of their life-cycle, as well as the waste generated (Storm van Leeuwen & Smith, 2007). Although the social, cultural and technological achievements provided by the energy in the present day are of benefit for future generations, they should not be outweighed negative impacts. The extent of these impacts is uncertain and difficult to assess thus, making it challenging to determine the acceptability of transferring them to future generations. Hence, developments that increase benefits and decrease costs are preferable and should be pursued.
Environmental Justice

Environmental justice focuses on questions of distribution, inequality and injustice, in particular, for people and social groups that are already marginalized and disadvantaged. The historical exploitation of fossil fuels has undoubtedly been a key element in rapid technological, social, economic and cultural changes with evident benefits but also widely distributed burdens unequally disseminated within and amongst nations. The utilization of nuclear energy implies a variety of impacts according to the concept of environmental justice. Firstly, environmental impacts are not bound to the borders in which they are generated and tend to experience a spillover effect. The risks of a nuclear plant in one country, is a risk for surrounding countries. Secondly, the waste issue generated by the nuclear fuel cycle provides the immense unequal distribution of negative impacts.

The utilization of nuclear energy in one country imposes the related risks on countries around them. In the case of an accident it can be presumed that the impacts, immense or negligible, will have a spillover effect. The disaster at Chernobyl presents an illustration of how the effects of a nuclear power plant accident can impose impacts on other nations. The nuclear meltdown produced a radioactive cloud that not only spread across soviet states, but also reached as far as western European states, such as the United Kingdom. Views on nuclear energy are different across nations, just as in the discussions between Austria and Slovakia. Austria, a small non-nuclear country is surrounded by nations with nuclear power plants, including Slovakia, which runs several nuclear power plants not far from the Austrian boarder. “Given the controversy surrounding the safety of nuclear power plants in central and eastern Europe post-Chernobyl, it is understandable that the Austrian government is concerned about the further increase in nuclear power plants in this area” (Loefstedt, 2008, p. 2227). Austria, although nuclear-free, would be significantly impacted if anything were to occur at Slovakia’s nuclear plants and thus, share the nuclear risks involved although they have chosen not to utilize this type of energy technology.
The town of Mailuu-Suu in Kyrgyzstan was once an elite soviet industrial town engaged in uranium mining and milling. Since mining operations ended in the 1960’s the radioactive waste, to this day, remains. People still live in Mailuu Suu, where sometimes, impoverished inhabitants steal the concrete posts and barbed wire fences that confine radioactive material dumps to retrieve scrap metal to re-sell (Watson, 2008). People living in Mailuu Suu are exposed to different forms of risks. Radioactive waste materials, such as tailings, low-grade ore and waste rocks were placed in moderate mountain terrain and gently sloping alluvial areas, frequently near waterways, such as the Mailuu-Suu river and its tributaries (Vandenhove, Sweeck, Mallants, Vanmarcke, Aitkulov, Sadyrov, Savosin, Tolongutov, Mirzachev, Clerc, Quarch, & Aitaliev, 2006). In addition, the region is a tectonically active area where there are concerns about earthquakes, floods and landslides, which can consequently lead to the escaping of radioactive materials by leaking and plunging into the river that runs across the boarder into the Fergana valley, known as the food basket of Uzbekistan. Major landslides potentially affect, directly or indirectly, the tailing deposits along the valley where in some instances have already led to the damage or destruction of the tailings dregs (Vandenhove et al., 2006). The radioactive pollution of the Mailuu Suu river in case of a disaster will on the one hand be problematic on a local scale but on the other hand be problematic on a regional scale, impacting a major agricultural area in Uzbekistan, which uses the river for irrigation (Vandenhove et al, 2006).

Several cases in the United States additionally illustrate how the nuclear industry can impose on environmental justice. Due to most U.S. uranium deposits being located directly in or near native lands, American Indian communities have been displaced or left to deal with the environmental impacts left behind from completed mine operations (Hoffman, 2001). In most cases, the nuclear industry left without properly dealing with generated wastes, which consequently, damaged groundwater and allowed for the weathering of radioactive material (Hoffman, 2001).
4. If not nuclear, then what?

Studies comparing emissions and environmental impacts of nuclear energy with other conventional energy sources, such as coal, ascertain that nuclear energy is the better option. However, throughout the previous chapters it has become apparent that nuclear energy, nonetheless, is not a viable energy option from an environmental sustainability perspective. Therefore, the aim of this section is to assess renewable energy technologies from an environmental sustainability perspective and in how far they are a better alternative to nuclear energy.

4.1 Renewable Energy

Mankind’s exploitation of renewable energy sources is far from being a novel concept. On the contrary, it has been the main source of energy for conceivably over hundreds of years until the emergence of the fossil fuel powered economy. “Renewable energy technologies rely on the use of natural resources such as solar radiation, the winds, waves and tides, which are continuously replenished and will therefore not run out “(Elliot, 2000, p. 261). These renewable energy sources, in their modern form, cover a wide range of technologies including hydro (dams, run-of-the-river), wind (aero, wave), solar (photovoltaic, thermal), tidal, biomass, and geothermal (Johansson & Turkenburg, 2004). Generally speaking, renewable energy technologies lack the production of environmentally damaging emissions. Nonetheless, the implementation of any energy system requires certain amounts of energy costs in, for example, the building of needed structures for the functioning of the system. Notwithstanding, considerations become significant in view of technologies, such as wind farms or dams, and how these influence the ecological equilibrium in which they function. For example, large-scale hydro projects have caused substantial ecological disruptions.

In light of renewable energy sources in their abundance and negligent interference with the environment they, nevertheless, have not evolved into a dominant energy provider and only provide a small fraction of the world’s energy supply. “Although renewable energy has real environmental benefits that could provide some insurance for stabilizing our planet’s health, the short-term economics of renewable systems have not been
universally competitive” (Tester et al., 2005, p. 409). The contemporary mood towards renewable energy technologies is favorable but the realization of these is strongly inclined by energy policies on domestic and international levels. The main barriers to the extensive development of renewable energy technologies are high capital costs, high interest rates, lack of supportive legislation on the national and international level, lack of knowledge on a regional level and a shortage, as well as difficulty in demonstrations of the technology. (Twidell & Brice, 1992) However, these are all limitations that can be conquered.

4.2 Renewables and Sustainable Backstop Criteria

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Renewable electricity sources performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unlimited</td>
<td>Renewable energy supplies are globally accessible and interminable when obtained from available natural flows, such as solar radiation, light, wind, and water currents. Other technologies supplied by sources, which are in competition with other ends, such as food, water, and preservation are limited in their prospective. Because renewable energy can be deployed economically only in an energy economy that is a few times more efficient than the present one, the unlimited character is strengthened.</td>
</tr>
<tr>
<td>Democratically decided</td>
<td>More than half of renewable electricity generation is to be developed in a distributed way. There is a large aptitude for end-user or end-user cooperatives investment and ownership. The power of centralized units will decrease, and so will the nuclear secrecy.</td>
</tr>
<tr>
<td>Globally accessible</td>
<td>Renewable energy supplies are globally dispersed but not evenly distributed. Some regions have an abundance of some sources and other regions of other sources. The scale, complexity, diversity, security, safety, of renewable energy technologies allow for larger accessibility, including the opportunity for poorer areas of the world to utilize their vast renewable energy supplies and develop an independent electricity sector once the industrialized sector of the world also convert toward the efficient use of renewables and develop the necessary technologies.</td>
</tr>
<tr>
<td>Environmentally benign</td>
<td>Apart from large-scale hydro and non-sustainable biomass, which compete with other ends, the impacts of renewable energy technologies are minor. Associated impacts are none or negligible if integrated into human activities, e.g. rooftop solar, wind turbines in industrial areas.</td>
</tr>
<tr>
<td>Low risk</td>
<td>Aside from large-scale hydro and non-sustainable biomass, risks posed by renewable energy technologies are low and manageable.</td>
</tr>
<tr>
<td>------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Affordable</td>
<td>Although wealthy societies retain the necessary capital to develop an fully implement renewable energy sources, are reluctant to transition because of low priced fossil fuels and nuclear power. Transition is crucial for the progress of sustainable development, where this transition is realizable and more economical than business-as-usual. However, the according to current values the availability and costs of a full transition is subject to concern.</td>
</tr>
</tbody>
</table>

Source: Adopted and modified from Verbruggen, 2008, p. 4041

Based on the criteria presented by Verbruggen (2008), renewable energy satisfies most aspects, although affordability is under debate. For renewable energies to become an affordable option energy efficiency must be maximized, which is determined by investments in R&D, as well as putting the appropriate policies in place to further development and implementation. Thus, proper allocation of funds towards renewable energy technologies will allow for faster advancements in technologies, which are not only more affordable but also more efficient and consequently, allow for wider deployment. For instance, photovoltaic power requires exposure to sunlight resulting in concerns for storage, which is expensive to collect, convert and utilize to bridge intermittent supplies (Verbruggen, 2008). Technological advancements and government subsidies have allowed for photovoltaics to be utilized in countries like Germany, which are not as solar intense as other regions in the world. In addition, as technologies progress, storage costs will also decrease. Also, countries with extensive renewable energy development programs have allowed for significant growth in the deployment of renewables and the commencement of a competitive market. Although there is a considerable indolence, economically and politically, present in today’s energy supply system, these can be overcome.

The domination of the global energy system by nuclear energy is unsustainable and appears to be unachievable according to the information presented in section 3.2. Apart from the view that nuclear energy is the solution, other nuclear advocates frame nuclear energy as part of the solution, soliciting a marriage with renewable energy technologies.
or professing nuclear energy as a bridge until renewable energy technologies are further developed. According to Verbruggen (2008), nuclear and renewable power is opposites, unable to be deployed concurrently to address the energy and climate change challenge. The reasons for this are multifold. Nuclear energy supports a “business-as-usual” energy economy, it is bulky and expansive, the infrastructure necessary is different from other interconnected power sources, risks and externalities limit development perspectives, its resource and capacity sucking from other technologies, such as renewables, will intensify (Verbruggen, 2008). Whereas renewable energy technologies are compatible with the sustainability, they are distributed, flexible, risks and externalities are low, but will remain in a struggle for R&D resources and production capacities (Verbruggen, 2008).

Engaging in the nuclear option or an option that considers the deployment of renewables in chorus with nuclear energy will constrain the development of renewables and impede the path towards a sustainable energy future. Priorities in research funding and production capacities that will have to be decided on cannot be neglected. The funding for renewable energy remains small compared with much more speculative technologies, such as nuclear fusion (Grubb, 1990). In addition, both energy paths require different infrastructure, such as grid-connection. However, most significant is the compatibility with sustainable development. Whilst the expansion of renewable energy has been identified as a necessary part of the transition towards sustainable development, nuclear energy maintains the business-as-usual status quo. The current global energy regime, which is dominated by the over-use of commercial energy sources and by the utilization of non-sustainable energy production and consumption is endangering the earth’s life-supporting systems. As a result, a paradigm shift in global energy exploitation is needed for the mitigation of environmental impacts from the current “business-as-usual” system. The endorsement of nuclear energy does not comply with a new paradigm. “Climate change is now exploited by nuclear power advocates for organizing a third wave, however, falling back on the same promises— once again— of better technologies and of final solutions to unsolvable problems” (Verbruggen, 2008, p. 4042). Based on the comparison of renewable and nuclear energy from a sustainability perspective, renewable energies are the better candidate. Consequently, it is crucial that further development,
utilization, and expansion of renewable energy technologies are supported by economic and political policies.

4.3 Renewables: Can they Deliver?

Albeit the satisfaction of the sustainability criteria renewable energy technologies must be proficient in providing power if they are to become a viable energy solution for the future. Nuclear energy possesses the ability to produce vast amounts of energy, thus it is necessary to explore if renewable energies can deliver adequate amounts of energy to satisfy current demands and in the future from a technological perspective.

The vision *A Sustainable Energy System in 2050: Promise or Possibility* developed by the Energy Research Institute of the Netherlands (ECN) and the Nuclear Research & Consultancy Group (NRG) (2007) defines a path towards a sustainable energy system in Europe for the year 2050. This vision outlines the policies necessary to manifest the technological development of renewable energy technologies, such as affordable solar cells, according to realistic judgments concerning the time span for commercialization. The outcome according to this vision is a 35 percent contribution of total energy supply by renewable energy sources. Whilst energy conservation receives considerable attention, nuclear energy will have only a limited role and the utilization of coal with CO2 carbon capture will intensify for the production of electricity and hydrogen. Ultimately, the developed energy path will lead to a 60 percent CO2 emission reduction below 1990 levels in Europe.

Electricity generation and distribution will retain a 40 percent contribution by fossil fuels, mainly through coal with CO2 capture. Nonetheless, renewable energy sources will account for approximately the same amount, whilst nuclear energy contributes only around 20 percent, only a small increase from current nuclear contribution. The drastic reduction in CO2 is ultimately on account of the utilization of renewable energy sources. Wind energy, photovoltaic solar energy, as well as solar thermal systems for electricity generation will supply the largest part of the electricity provided by renewable energy
technologies. Nuclear energy will be supported by approximately half of European member states, assuming an EU wide solution is decided upon for the safe disposal of nuclear waste.

The arrival at a sustainable energy system by 2050 according to this guide is attributed to technological advancements and significantly, societal change and appropriate policy implementation. Presented is an approach called ROBUST, from the Dutch acronym “realization of a coordinated strategy to reduce greenhouse gas emissions” (ENC, 2007, p. 24). The main components of the ROBUST approach include:

- The establishment of long-term objectives for greenhouse gas emissions and security of supply, coupled with their operationalization in the medium term. These objectives must be approved and supported by all stakeholders, and they also need to be harmonized with other areas of policy: agriculture, the internal market, the environment and foreign relations.
- The formulation of a clear vision on the portfolio of technologies needed to achieve the objectives set, as well as the establishment of an RD&D roadmap to bring about the necessary innovation, and provision of the tools and resources required for that process.
- The development of a consistent set of policy instruments to help technologies through their development phases, although without distorting the market, including incentives to phase out less efficient technologies.
- The establishment of limits and standards: strict ceilings for greenhouse gas emissions and clear standards for energy consumption and the use of sustainable energy – all tightened up on a regular basis.
- Cooperation and communication between governments, businesses and the public with respect to RD&D, the market introduction of new technologies, the construction of new infrastructure. This should overcome resistance and lead to a stable investment climate.
- Regular monitoring, evaluation and reflection, in order to review the results achieved and adjust the ROBUST approach accordingly.
- The international dimension: involving other parts of the world (ENC, 2007, p. 25)

Accordingly, concrete objectives can be devised for distinct elements, which are essential for the realization of the ultimate sustainable vision. Emphasized is the imperative role of policy development and implementation as a prerequisite for the transition towards a sustainable energy future. Notwithstanding, to attain these changes there must be a combination of organizational transformations and changes in behavioral patterns.
Notably, the promise to mitigate climate change according to both nuclear and renewable energies is based on technological advancements. Nonetheless, it is evident that a new sustainable energy system is necessary, not only for the satisfaction of growing energy demands, but also for the mitigation of climate change. Although a transition towards the deployment of new energy technologies, new resources and a new energy infrastructure are important. The urgency for transition, however, lies in social innovations, such as new behavioral patterns and decision-making processes on a global scale. According to the vision, the energy system will not be entirely sustainable by 2050 and there will be more opportunity and necessity for energy saving and further development of renewable energy sources. However, the most crucial problems associated with the contemporary energy system will have been overcome.

The creation of a future with a sustainable energy system consumed with renewable energy technologies, energy conservation, and an overall paradigmatic shift in how the world exploits energy is possible. The technological potential of renewable energies has been established, leaving it up to governments and citizens to make the according decisions at the appropriate times to arrive at sustainable future. While assessments for when it will be possible to arrive at such a future differ, a drastic transformation through a global cooperative mobilization of sustainable towards a necessary sustainable future should, however, not be underestimated.
5. Conclusion

This section summarizes the main findings of this research followed by its limitations and suggestions for future research.

5.1 Summary of Main Findings

The aim of the research at hand was to explore nuclear energy from an environmental sustainability perspective. This was done by exploring the various phases of the nuclear process and applying a sustainability criterion.

The contemporary support for nuclear energy is based on the argument that it is a substantial solution for battling climate change because of its low carbon intensity. However, there are a variety of production phases necessary for the utilization of nuclear energy, which produce significant amounts of CO2 emissions. The nuclear process requires mining, milling, processing, enrichment, and fuel fabrication, as well as transportation, common energy demands necessary for the generation of electricity in a power plant. Additionally, post electricity activities such as decommissioning, dismantling, and processing and storing of waste require significant amounts of energy. Furthermore, energy intensive materials such as steel and concrete are necessary for construction of power plants and necessary facilities along the entire nuclear process. “The energy used for these purposes is partly produced by fossil energy (which causes greenhouse-gas emissions), and some additional greenhouse-gas emissions result directly from chemical reactions during material processing (e.g. cement production)” (Fritsche, 2006, p.2).

The nuclear process causes additional ecological disruptions through the release of radioactive material. During various phases, especially during mining and milling, radioactive substances attain chemical mobility and are released into the environment. Additionally, each phase of the nuclear process generates substantial amounts of radioactive waste for which no concrete solution has yet been developed and implemented. Consequently, increasing the risk of radioactive material escaping into the atmosphere. Uncertainty and risk are perceptible factors associated with nuclear energy
and its possible ecological impacts. In particular, decommissioning and dismantling of a nuclear power plant, the management of waste via deep geological repository, routine releases of radioactive isotopes, and the impacts of a nuclear power plant accident.

According to the sustainability criteria utilized in this study, nuclear energy falls short in all aspects. Nuclear energy is a limited energy source. Uranium resources are finite and it is uncertain if the necessary reactor capacity for growing demands is realizable. The distribution and availability of nuclear energy technology is unevenly distributed. Nuclear technology requires to be handled with high security to avoid misuse, thus, it is not available to everyone. Nuclear technology is also very expensive and cannot be equally utilized. Nuclear energy is not environmentally benign by generating substantial greenhouse gas emissions, radioactive releases and radioactive waste. Finally, nuclear energy is unsustainable from an inter- and intra-generational perspective. The costs and impacts of utilizing nuclear energy are unevenly distributed across current generations and will be forced upon future generations.

Ultimately, an alternative option to nuclear energy is the utilization of renewable energy technologies. Renewables are more sustainable according to the criteria applied in this paper. The natural energy flows required for renewable energy technologies are more accessible and available. Renewables can be better distributed and made available to a wider range of users. Renewable energy technologies have minor effects on the environment. Renewable energy technologies positively impact the inter- and intra-generational perspective. Evidently, by making the appropriate social changes and policy decisions a sustainable energy system substantially supplied by renewable energy technologies can be accomplished.

5.2 Limitations and Future Research
A limitation experienced while conducting research was resource constraints. In the past, assessments of nuclear energy focused on, amongst other, economic viability, safety, and proliferation. Assessments in the context of global warming is relatively novel. Studies that comprehensively investigated the ecological impacts of nuclear energy are scarce. It
is therefore, necessary that the ecological impacts require further research. In addition, a great deal of information was inaccessible. The nuclear process requires discretion for safety reasons thus, classifying and concealing of information, which can lead to the exploitation of radioactive materials. Nevertheless, this is a factor, which is necessary to implement for safety reasons.

Another limitation, which became evident during research was inconsistencies in values. The gap between different positions on the potential of nuclear energy as a solution for global warming and a sustainable energy source are strongly influenced by differences in outcomes of various studies. A review of nuclear lifecycle studies done by Sovacool (2008) assesses the disparity in lifecycle estimates. “Studies primarily differ in terms of their scope; assumptions regarding the quality of uranium ore; assumptions regarding type of mining; assumptions concerning method of enrichment; whether they assessed emissions for a single reactor or a fleet of reactors; whether they measured historical or marginal/future emissions; assumptions regarding reactor type, site selection, and operational lifetime, and type of lifecycle analysis” (Sovacool, 2008, p. 2954). Such differences in studies make it difficult to accurately assess the potential, as well as externalities of nuclear energy. The omission of certain relevant variables tends to bias results. Although difficult, it is necessary for studies to address the entire fuel cycle and become more accurate, transparent, accountable, and comprehensive. In addition, nuclear energy is currently being framed in an environmental context in a time where sustainability is a global interest. It is, therefore, necessary that nuclear energy is studied in accordance with its charge and generation.
Acknowledgements

This master thesis represents the culmination of my Master in Public Policy and Human Development (MPP) with a concentration in sustainable development at the University of Maastricht.

There are numerous people who, throughout this time, have provided me with incredible support. Therefore, I would like to show my utmost appreciation at this point.

Firstly, I would like to extend my utmost gratitude to my parents, who with their emotional and financial support have allowed me to come as far as I have.

I would like to thank my advisor Professor Wim Passchier for his support and guidance. Without his time and effort I would not have been able to accomplish this endeavor, consequently, contributing to my academic development.

Last, but not least, I would like to express my appreciation to my family and friends who motivated and encouraged me during my writing process.

In general, I would like to thank everyone who supported me and contributed to my master thesis.
References


## Appendix

### A 1 World Nuclear Power Reactors 2007-08 and Uranium Requirement

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>billion kWh</td>
<td>% e</td>
<td>No.</td>
<td>MWe</td>
<td>No.</td>
<td>MWe</td>
</tr>
<tr>
<td>Argentina</td>
<td>6.7</td>
<td>6.2</td>
<td>2</td>
<td>935</td>
<td>1</td>
<td>692</td>
</tr>
<tr>
<td>Armenia</td>
<td>2.35</td>
<td>43.5</td>
<td>1</td>
<td>376</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bangladesh</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Belarus</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Belgium</td>
<td>46</td>
<td>54</td>
<td>7</td>
<td>5728</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Brazil</td>
<td>11.7</td>
<td>2.8</td>
<td>2</td>
<td>1901</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bulgaria</td>
<td>13.7</td>
<td>32</td>
<td>2</td>
<td>1906</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Canada*</td>
<td>88.2</td>
<td>14.7</td>
<td>18</td>
<td>12652</td>
<td>2</td>
<td>1500</td>
</tr>
<tr>
<td>China</td>
<td>59.3</td>
<td>1.9</td>
<td>11</td>
<td>8587</td>
<td>7</td>
<td>6700</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>24.6</td>
<td>30.3</td>
<td>6</td>
<td>3472</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Egypt</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Finland</td>
<td>22.5</td>
<td>29</td>
<td>4</td>
<td>2696</td>
<td>1</td>
<td>1600</td>
</tr>
<tr>
<td>France</td>
<td>420.1</td>
<td>77</td>
<td>59</td>
<td>63473</td>
<td>1</td>
<td>1630</td>
</tr>
<tr>
<td>Germany</td>
<td>133.2</td>
<td>26</td>
<td>17</td>
<td>20339</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Hungary</td>
<td>13.9</td>
<td>37</td>
<td>4</td>
<td>1826</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>India</td>
<td>15.8</td>
<td>2.5</td>
<td>17</td>
<td>3779</td>
<td>6</td>
<td>2976</td>
</tr>
<tr>
<td>Indonesia</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Iran</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>915</td>
</tr>
<tr>
<td>Israel</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Japan</td>
<td>267</td>
<td>27.5</td>
<td>55</td>
<td>47577</td>
<td>2</td>
<td>2285</td>
</tr>
<tr>
<td>Kazakhstan</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Korea DPR (North)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Korea RO (South)</td>
<td>136.6</td>
<td>35.3</td>
<td>20</td>
<td>17533</td>
<td>3</td>
<td>3000</td>
</tr>
<tr>
<td>Lithuania</td>
<td>9.1</td>
<td>64.4</td>
<td>1</td>
<td>1185</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Mexico</td>
<td>9.95</td>
<td>4.6</td>
<td>2</td>
<td>1310</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Netherlands</td>
<td>4.0</td>
<td>4.1</td>
<td>1</td>
<td>485</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Pakistan</td>
<td>2.3</td>
<td>2.34</td>
<td>2</td>
<td>400</td>
<td>1</td>
<td>300</td>
</tr>
<tr>
<td>Romania</td>
<td>7.1</td>
<td>13</td>
<td>2</td>
<td>1310</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Country</td>
<td>Billion kWh</td>
<td>% e</td>
<td>No.</td>
<td>MWe</td>
<td>No.</td>
<td>MWe</td>
</tr>
<tr>
<td>-------------</td>
<td>-------------</td>
<td>-----</td>
<td>-----</td>
<td>------</td>
<td>-----</td>
<td>------</td>
</tr>
<tr>
<td>Russia</td>
<td>148</td>
<td>16</td>
<td>31</td>
<td>21743</td>
<td>7</td>
<td>4920</td>
</tr>
<tr>
<td>Slovakia</td>
<td>14.2</td>
<td>54</td>
<td>5</td>
<td>2064</td>
<td>2</td>
<td>840</td>
</tr>
<tr>
<td>Slovenia</td>
<td>5.4</td>
<td>42</td>
<td>1</td>
<td>696</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>South Africa</td>
<td>12.6</td>
<td>5.5</td>
<td>2</td>
<td>1842</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Spain</td>
<td>52.7</td>
<td>17.4</td>
<td>8</td>
<td>7442</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Sweden</td>
<td>64.3</td>
<td>46</td>
<td>10</td>
<td>9016</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Switzerland</td>
<td>26.5</td>
<td>43</td>
<td>5</td>
<td>3220</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Thailand</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Turkey</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ukraine</td>
<td>87.2</td>
<td>48</td>
<td>15</td>
<td>13168</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>57.5</td>
<td>15</td>
<td>19</td>
<td>11035</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>USA</td>
<td>806.6</td>
<td>19.4</td>
<td>104</td>
<td>99049</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Vietnam</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>WORLD**</td>
<td>2608</td>
<td>16</td>
<td>439</td>
<td>371,989</td>
<td>36</td>
<td>29,958</td>
</tr>
</tbody>
</table>

### Material Requirements for Nuclear Power Plant Construction

Some data material requirements for construction of an 1 GW(e) LWR, in Mg.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>steel</td>
<td></td>
<td></td>
<td>40 000</td>
<td>33 000</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Other Steel</td>
<td></td>
<td></td>
<td>25 000</td>
<td>No</td>
<td>10 000</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>distinction made between rebar and other steel</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Carbon steel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>32 731</td>
</tr>
<tr>
<td></td>
<td>Iron</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>34 662</td>
</tr>
<tr>
<td></td>
<td>Stainless steel</td>
<td>May be included in “other steel”</td>
<td>2100</td>
<td>Probably constituents separately listed</td>
<td>2080</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Galvanized iron</td>
<td></td>
<td>-</td>
<td>1300</td>
<td>-</td>
<td>1257</td>
</tr>
<tr>
<td></td>
<td>Copper/ Copper alloy</td>
<td>1200</td>
<td>740</td>
<td>2000</td>
<td>694</td>
<td>726</td>
</tr>
<tr>
<td></td>
<td>Brass + Bronze</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Aluminum</td>
<td></td>
<td>200</td>
<td>20</td>
<td>45</td>
<td>18</td>
</tr>
<tr>
<td></td>
<td>Chromium</td>
<td></td>
<td>-</td>
<td>-</td>
<td>150</td>
<td>415</td>
</tr>
<tr>
<td></td>
<td>Inconel</td>
<td></td>
<td>-</td>
<td>100</td>
<td>-</td>
<td>124</td>
</tr>
<tr>
<td></td>
<td>Lead</td>
<td></td>
<td>-</td>
<td>50</td>
<td>8</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td>Nickel</td>
<td></td>
<td>-</td>
<td>1</td>
<td>100</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Manganese</td>
<td></td>
<td>-</td>
<td>-</td>
<td>400</td>
<td>467</td>
</tr>
<tr>
<td></td>
<td>Molybdenum</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>164</td>
</tr>
<tr>
<td></td>
<td>Tin</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Zinc</td>
<td></td>
<td>-</td>
<td>-</td>
<td>100</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>Other materials</td>
<td></td>
<td>-</td>
<td>-</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sum metals</td>
<td></td>
<td>66 400</td>
<td>37 311</td>
<td>12 809</td>
<td>36 986</td>
</tr>
<tr>
<td></td>
<td>Insolation</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>922</td>
</tr>
<tr>
<td></td>
<td>Asbestos</td>
<td></td>
<td>-</td>
<td>-</td>
<td>45</td>
<td>138</td>
</tr>
<tr>
<td></td>
<td>Magnesia</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>783</td>
</tr>
<tr>
<td></td>
<td>Paint</td>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>730</td>
</tr>
<tr>
<td>Material</td>
<td>Mass (kg)</td>
<td>Density (kg/m³)</td>
<td>Notes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------</td>
<td>-----------</td>
<td>-----------------</td>
<td>-------</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wood</td>
<td>5600</td>
<td>0.5</td>
<td>[reported: 4.8 · 10^6 bd ft =&gt; 11330 m³ =&gt; ~5600 Mg (assumed density 0.5 Mg/m³)]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete</td>
<td>180 000</td>
<td>2.4</td>
<td>[reported: 98130 yd³ =&gt; 75025 m³ =&gt; 180000 Mg (assumed density 2.4 Mg/m³)]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cement</td>
<td>30 133</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aggregate (course)</td>
<td>90 361</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aggregate (fine)</td>
<td>45 855</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total Mass</td>
<td>217 311</td>
<td></td>
<td>217 908 (excluding paint and wood) 224 238 (including paint and wood)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Adopted and modified from Storm van Leeuwen and Smith (2007)

In Storm van Leeuwen and Smith (2007):


A 3 Decommissioning & Clean-up

Site end states
The assumption used to be that decommissioned nuclear sites would ultimately be returned as ‘green field’ sites, ready for a new use without any restrictions. However, following the Government’s decommissioning policy review in 2004, it is now envisaged that there could be a variety of site end states, ranging from indefinite institutional control (remaining within the nuclear licensing regime) to the release of sites for any further use. Each of these options will have advantages and disadvantages, depending on the nature of specific sites, the nature of any contaminated land present and their potential for alternative uses. By definition, then, end states can only be defined on a site-by-site basis and we, therefore, propose to review site end states and end dates with stakeholders as part of a separate consultation.

Higher-hazard legacy facilities
We feel that in accelerating the remediation of high-hazard facilities, the benefits of long-term hazard reduction will outweigh any short-term potential penalties of increased handling and discharges. However, any increases in discharges will need to be robustly assessed to ensure they represent BPEO and are consistent with the UK National discharge Strategy. We do not consider there to be any alternative to the reduction of hazards posed by these facilities, which is our top clean-up priority.

Climate and coastal change
Looking at the longer-term, we need to be mindful of the possible challenges that both potential climate change and coastal erosion could pose to our proposed plans for decommissioning and clean-up and waste management, as well as for site end states and end dates. If these challenges look likely to increase, we need to be ready with effective measures that have been designed on a site-by-site basis and which do not have unacceptable environmental consequences. We therefore propose to gain a national understanding of the potential threats from climate and coastal change. We will continue to work with our contractors, the environment agencies and other relevant organisations
to make sure we have robust coastal and flood defences for as long as we need them.

**Contaminated land**

There are varying degrees of radiological and chemical contamination at all of our sites which, in some cases, extend beyond the site boundary. In collecting baseline data, we obtained estimates of the quantities of land which has been contaminated at each of our sites but not a complete understanding of the nature and extent of the contamination on our sites. There are a number of options for the management of this contaminated land which will need to be evaluated by our management & operations contractors for each site in developing long-term optimised management plans. We are therefore seeking further information, as a first step to accelerating the evaluation of contaminated land and the development of these long-term management plans.

**Radioactive particles**

The contamination of the seabed near Dounreay with radioactive fuel fragments is a key local issue. For this reason, it is discussed in our Strategy, although the Scottish Environmental Protection Agency (SEPA) and UKAEA are undertaking a major study to examine the options for addressing this issue. We will work closely with UKAEA to ensure that monitoring continues to the satisfaction of the environmental regulator (SEPA) and to implement the selected Best Practicable Environmental Option (BPEO) for managing this issue following a separate consultation on the potential management options. We expect this to begin in 2006.

**Reactor decommissioning**

When reactors have ceased generating, the baseline plan is to take them into ‘Safestore’. This means removing all of the nuclear fuel, and much of the ancillary equipment, but leaving the bulk of the reactor and any Intermediate Level Waste (ILW) in two or three storage buildings on the site. The Safestore strategy is then to leave the radioactive contents for 80 to 125 years to take advantage of radioactive decay. However, there are realistic alternatives to this approach:
1. **An accelerated programme to care and maintenance.**
   - as little as five years to reach the care and maintenance phase;
   - up to 100 years in care and maintenance.
2. **Prompt decommissioning and clean-up:**
   - defuelling, decommissioning and closure of the site in 25 years or less.

Certainly, prompt decommissioning presents a number of challenges in terms of waste management, differing discharge profiles and the non-negotiable priority of worker safety. However, we feel that the potential benefits are worth exploring: it would use the existing, highly skilled workforce and bring socio-economic benefits for the local area and it would free the site earlier for other uses. We therefore believe that the argument for prompt reactor decommissioning within 25 years warrants serious evaluation and we propose to work with the industry and regulators to progress it.

Source: Adopted from Nuclear Decommissioning Authority 2006, p. 130-131
A 4 Definitions of uranium resource classification categories

**Reasonably Assured Resources (RAR)** refers to uranium that occurs in known mineral deposits of delineated size, grade and configuration such that the quantities which could be recovered within the given production cost ranges with currently proven mining and processing technology, can be specified. Estimates of tonnage and grade are based on specific sample data and measurements of the deposits and on knowledge of deposit characteristics. Reasonably Assured Resources have a high assurance of existence. Unless otherwise noted, RAR are expressed in terms of quantities of uranium recoverable from mineable ore (see Recoverable Resources).

**Inferred Resources** refers to uranium, in addition to RAR, that is inferred to occur based on direct geological evidence, in extensions of well-explored deposits, or in deposits in which geological continuity has been established but where specific data, including measurements of the deposits, and knowledge of the deposit’s characteristics, are considered to be inadequate to classify the resource as RAR. Estimates of tonnage, grade and cost of further delineation and recovery are based on such sampling as is available and on knowledge of the deposit characteristics as determined in the best known parts of the deposit or in similar deposits. Less reliance can be placed on the estimates in this category than on those for RAR. Unless otherwise noted, Inferred Resources are expressed in terms of quantities of uranium recoverable from mineable ore (see Recoverable Resources).

**Prognosticated Resources** refers to uranium, in addition to Inferred Resources, that is expected to occur in deposits for which the evidence is mainly indirect and which are believed to exist in well-defined geological trends or areas of mineralisation with known deposits. Estimates of tonnage, grade and cost of discovery, delineation and recovery are based primarily on knowledge of deposit characteristics in known deposits within the respective trends or areas and on such sampling, geological, geophysical or geochemical evidence as may be available. Less reliance can be placed on the estimates in this category than on those for Inferred Resources. Prognosticated Resources are normally
expressed in terms of uranium contained in mineable ore, i.e., in situ quantities.

**Speculative Resources (SR)** refers to uranium, in addition to Prognosticated Resources, that is thought to exist, mostly on the basis of indirect evidence and geological extrapolations, in deposits discoverable with existing exploration techniques. The location of deposits envisaged in this category could generally be specified only as being somewhere within a given region or geological trend. As the term implies, the existence and size of such resources are speculative. SR are normally expressed in terms of uranium contained in mineable ore, i.e., in situ quantities.

**Cost categories**, in United States dollars (USD), used in this report are defined as: <USD 40/kgU, <USD 80/kgU, and <USD 130/kgU. All resource categories are defined in terms of costs of uranium recovered at the ore processing plant.

Source: Adopted from OECD (2007)