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EPRG Working Paper 1217

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Abstract The potential for countries which currently have a nominal nuclear energy infrastructure to adopt thorium-uranium-fuelled nuclear energy systems, using a once-through “open” nuclear fuel cycle, has been presented by the International Atomic Energy Agency. This paper highlights Generation III and III+ nuclear energy technologies that could potentially adopt an open thorium-uranium fuel cycle and qualitatively highlights the main differences between the open thorium-uranium and open uranium fuel cycles. Furthermore, 28 indicators (and corresponding metrics) have been identified that could elucidate the advantages and disadvantages of nuclear energy systems which utilise thorium-uranium fuels in an open cycle. Such systems will be compared to an AREVA EPR operating with a once-through uranium fuel cycle. The indicators determined in this work have been drawn by grouping 270 indicators from eight previous studies of indicators associated with holistic and specific appraisals of the various life-cycle stages associated with the nuclear fuel cycle. The 28 indicators cover techno-economic, environmental, waste, social, and proliferation-resistance themes and can be determined quantitatively, either by explicit determination or from an appropriate sensitivity analysis.

Keywords Nuclear, Thorium, Sustainable Development, Indicators

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1. Introduction

The world faces two unprecedented challenges: the first is the threat arising from anthropogenic climate change and the second is the need to underpin economic growth with continued availability of affordable energy. The global population continues to grow and there is a most remarkable process occurring under which millions of people in developing countries are emerging from poverty. This emergence from poverty comes with an increased demand in energy services (such as heat, light, transport and information exchange). As a consequence, energy demand in 2035 is expected to increase by one-third compared to energy demand in 2010 (IEA2011a) and this demand can, in part, be met through a greater use of nuclear energy. Such energy would have the beneficial attribute that it has very low associated green-house gas emissions (SPRIng2011a), although the downsides of such technologies would involve the management of radioactive waste, namely from the spent fuel, and also the possibility of added potential for nuclear weapons proliferation. It has been suggested that open-cycle thorium-fuelled nuclear reactors, as defined in Section 4 of this paper, are a possible solution for developing countries with no existing nuclear infrastructures and current low per-capita electricity consumption that will have growing future electricity demands (IAEA2011a).

The question remains as to the advantages and disadvantages of this type of technology, compared to existing uranium-fuelled reactors. This could be answered by a suitable sustainability appraisal, covering the most pertinent aspects of the whole life-cycle of a nuclear reactor operating with such an open fuel cycle. This appraisal can then be used to compare existing and novel thorium-uranium-fuelled nuclear energy systems to a benchmark conventional uranium-fuelled system to determine which technology is the most holistically desirable.

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The aim of this paper is to present a series of indicators that will elucidate the relative advantages and disadvantages of thorium-fuelled nuclear energy systems, which will be of particular pertinence to a developing country, compared to the most recent Gen III+ uranium-fuelled reactors. In this work, no candidate countries will be explicitly named but such a territory will be generically referred to as "Country X". Section 2 reviews the trends in current nuclear energy production and the impact on resources. Section 3 outlines previous attempts to use thorium-based fuels in commercial and prototype reactors. This discussion will lead to potential commercial reactors (up to and including Gen III+) which can adopt thorium-uranium fuels and could feasibly be commissioned. Section 4 outlines the "once-through" open cycle for thorium-uranium fuels. Section 5 reviews the similarities and differences between thorium-uranium and uranium fuels over the complete open cycle. Section 6 details the limitations and boundary conditions associated with such a study. Section 7 provides an overview of indicators that have been previously used in analyses of nuclear energy systems and the indicators deemed most purposeful from mapping these sets.

2. Current Nuclear Energy Production and Impact on Resources

In 2009, global electricity production totalled 20,055 TWh, of which nuclear power contributed 13.4% (IEA2011b). Estimates from 2011 suggest there are 434 nuclear power reactors operating with a total capacity of 370.4 GWe (WNA2012a, WNA2012b). The majority of these installations are light water reactors (LWRs), such as pressurised water reactors (PWRs) (266/434) and boiling water reactors (BWRs) (85/434) which use enriched uranium fuel, typically containing 3–5% ^{235}U, and light water to serve as coolant and to moderate the fission neutrons. The remaining reactor types include pressurised heavy water reactors (inclusive of CANDU reactors), graphite-moderated gas-cooled reactors (e.g. AGR) and graphite-moderated boiling-water-cooled (RBMK) reactors. The trend in using pressurised water reactors continues in the near term, as these form 82 of the 100 nuclear new build power reactors scheduled to begin operation from 2010 to 2017 (WNA2011a). The expected annual consumption of uranium for the 434 reactors amounts to 62,552 tonnes, which corresponds to 73,708 tonnes of U_3O_8 (WNA2012a). From the most recent OECD report on uranium resources, production and demand, it is estimated that there are 5.4 million tonnes of uranium from identified resources that can be extracted for under US$130 per kgU (OECD2010a). Furthermore, an estimate of all identified, speculative and unconventional resources, including the recovery of uranium from phosphate rocks and rare-earth element processing, provides a current total of 19.2 million tonnes (IAEA2012a, IAEA2009a, Tulsidas2009a). These estimates yield a supply lifetime of 86.3 years and 307 years, respectively, at 2011 consumption rates.

Another source of fuel that could be used in nuclear energy systems is thorium. Unlike natural uranium which contains 0.72% fissile ^{235}U, natural thorium (~ 100% ^{232}Th[*]) does not contain a fissile component and therefore needs to be converted into fissile ^{233}U by neutron capture and subsequent beta-decay. Current estimates of reasonably-assured thorium reserves range from 6.4 million tonnes to 7.5 million tonnes (Tulsidas2011a). Although, due to its longer half-life, ^{232}Th ($T_{1/2} = 1.4 \times 10^{10}$ years) would be expected to be three times more abundant than ^{235}U ($T_{1/2} = 7.04 \times 10^{8}$ years) and ^{238}U ($T_{1/2} = 4.468 \times 10^{9}$ years). Therefore, the current estimated reserves for thorium appear to be surprisingly low, although it should be noted that current estimates form only a partial picture, as information is still lacking for numerous countries, most notably China. Due to its mineralogy, thorium is typically collocated with other valuable elements in various minerals, namely those bearing rare-earth elements, e.g. see Table 3 in Reference (USGS2010a) which notes at least 22 possible thorium-bearing mineral forms. As thorium is typically a by-product of rare-earth-element processing, it is commonly treated as a radioactive waste. Thorium currently is used in few commercial applications, with small amounts of thorium oxide being used in alloys and catalysts and even smaller amounts of thorium nitride being used in gas-mantles. Currently, thorium itself is not treated as a commodity, although there is a strong chance this would change if thorium could be successfully utilised in nuclear energy systems.

3. Application of Thorium to Prototype and Commercial Reactors

Previous attempts to use thorium-based fuels in commercial and prototype reactors have been undertaken and some future reactor designs and concepts are based on thorium. The Shippingport Light Water Breeder Reactor, fuelled with binary ceramic thorium-uranium fuel containing 1–5% uranium, enriched to 98% ^{233}U, successfully operated for 29,000 effective full power hours between 1977 and 1982 (Olson2002a). Further work on developing LWR cores that can maximize in-situ breeding of thorium has been undertaken by A. Radkowsky (Radkowsky1998a). In addition, work has been performed on optimizing a “proliferation-resistant” thorium-uranium fuel design for existing LWR cores (Todosow2004a). Successful experimental High-Temperature Gas-cooled Reactors (HTGRs) have been developed at the former AEA Winfrith site in the UK (Dragon Reactor Experiment) and at Jülich, Germany (AVR), the latter operating from 1967 to 1988. However, prototypical power stations built at Fort St Vrain, Colorado USA, and the Thorium High Temperature Reactor in North-Rhine Westphalia, Germany, proved to be rather unsuccessful due to engineering and fundamental design problems in the former and licensing and funding problems in the latter. For a review of HTGRs, see

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[*] It should be noted that ^{230}Th is also present in the Earth’s crust due to the decay of ^{238}U. Assuming a maximal uranium reserve of 19.2 million tonnes, that ^{230}Th in the Earth’s crust comes only from the decay of ^{238}U and that all ^{238}U was generated 4.54×10^{9} years ago, a rough calculation would estimate ~3 tonnes of ^{230}Th in the Earth’s crust.

Chapter 6 of Reference (Nuttall2005a) and references therein. Currently, an experimental high-temperature reactor is operating at Tsinghua University in China, and there is a plan for a modular prototype HTR power station to be built in Shandong Shidaowan, China.

In terms of future potential reactors, development of Molten-Salt Breeder Reactors is underway in the USA, China and Japan building upon the work of A. Weinberg and the Molten Salt Reactor Experiment that was operated at Oak Ridge from 1965-1969 (USAEC1972a). Although there are ambitious research programs in development for such reactors, various technical challenges still need to be overcome (Forsberg2006a). Research and development of Accelerator Driven Sub-critical Reactors is also on-going in the United Kingdom, USA, China and India, e.g. see (ThorEA2010a), but significant improvements in the reliability of current accelerator technology will be required (Steer2011a).

Concerning the commissioning of new thorium-uranium-fuelled nuclear reactors based on existing technologies up to and including Gen III+, it is envisaged that there will be three technologies where this fuel can be used: 1) Existing LWR technology, such as PWRs and BWRs; 2) the "Advanced Heavy Water Reactor" (Sinha2006a, Thakur2011a), a prototype of which is expected to be commissioned by 2015; 3) a High-Temperature Pebble-Bed Gas-Cooled Reactor, similar to the prototype being developed in Shandong Shidaowan, China (Zhang2009a) or the Prismatic Gas-Turbine Modular Helium Reactor (GT-MHR) being developed by General Atomics (GA2002a). These reactors should be compared to most recent uranium-based Gen III+ technology and, as an example, we select the European Pressurized Reactor being developed by AREVA (Areva2011a).

4. Open Cycle for Thorium-Fuelled Nuclear Energy Systems

Schematic diagrams of the "open" (once-through) and the closed nuclear fuel cycles are presented in Figure 1.

The central tenet of the "open" nuclear fuel cycle, shown in upper part of Figure 1, is that all fuel is used only once and is directly disposed of thereafter. Therefore, no reprocessing steps are included, as might otherwise be used in a closed fuel cycle to recover the unused nuclear fuel ultimately to be re-used in the reactor, as shown in lower part of Figure 1.

This study will be centred round the "open" fuel cycle. As mentioned in Reference (IAEA2011a), open-cycle thorium-fuelled nuclear energy appears to be the most deployable solution of all potential near-term thorium-fuelled systems in countries which currently have no substantial nuclear infrastructures. This is partly due to the reprocessing stages in a closed cycle adding a significant cost to the overall fuel cycle[**], e.g. for a uranium-fuelled LWR, an estimate that reprocessing would only become cost-effective when uranium prices reach US$340/kgU (Bunn2003a). Furthermore, a current estimate of the cost of thorium from India is US$78/kgTh (DAE2008a) and the availability of low-cost thorium nuclear fuel has the potential to put downward pressure on uranium prices. Also, the open fuel cycle is viewed as being more proliferation-resistant than closed fuel cycles. This is mainly due to the fact that in an open cycle desirable "specific" and "alternative" nuclear materials, see Table 2.1 in Reference (IAEA2001a), such as ^{235}U and ^{239}Pu, remain in the spent nuclear fuel are not separated/isolated and are also denatured with ^{238}U. This sentiment is echoed in proliferation-resistance assessment methodologies, such as Bathke's Figure of Merit approach (Bathke2009a) and Texas A&M University's Multi-Attribute Utility Assessment (Charlton2007a). Nevertheless, ^{233}U is also a specific nuclear material which would be bred and burned in thorium-uranium-fuelled nuclear reactors and such fuel would typically require a higher ^{235}U enrichment. Therefore, the properties of ^{233}U would need to be appropriately included in a proliferation-resistance assessment.

[**] A hypothetical reprocessing-based fuel cycle which could apply to candidate countries is the "Global Nuclear Energy Partnership" (see Larry Brown's report in Reference (IAEA2006a)). This fuel cycle involves the spent nuclear fuel being shipped back to the country which manufactured the fuel which, after reprocessing the spent nuclear fuel, would provide fresh mixed-oxide-based fuel back to the country where the reactor is located. The country performing the reprocessing would dispose of the resultant waste. This particular fuel cycle is not studied in this work given the added complexities associated with the transport of spent nuclear fuel and the fact that closed fuel cycles such as this are outside the scope of the funding for this particular work.

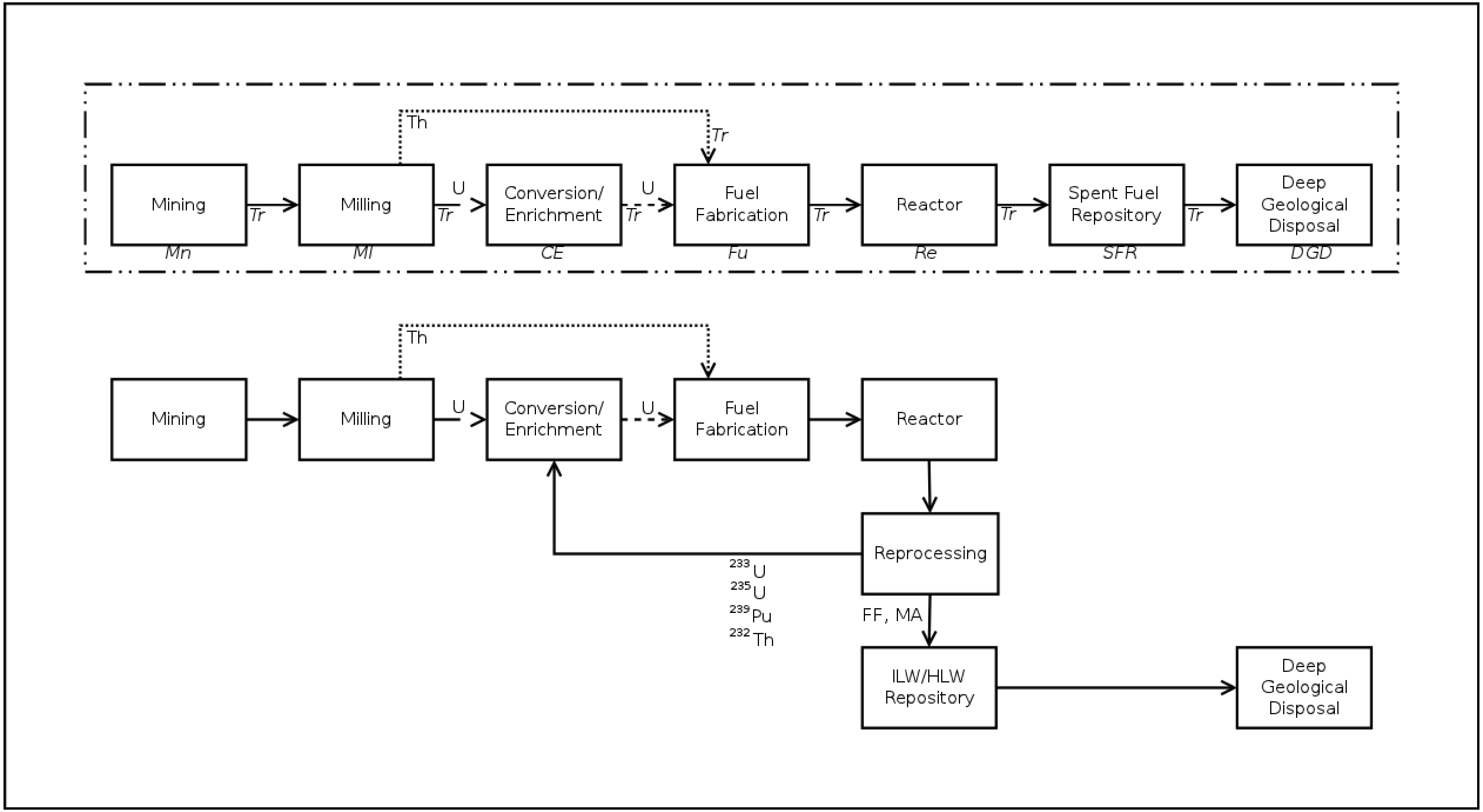

Figure 1: Upper: Schematic diagram of the open nuclear fuel cycle for thorium-fuelled nuclear energy systems. The double dot-dash line denotes the life-cycle boundary in this work. Lower: Schematic diagram of the closed nuclear fuel cycle for thorium-fuelled nuclear energy systems.

5. Similarities and Differences between the Process Stages of the Open Cycle for Uranium and Thorium Fuels

Differences between thorium and uranium and the various reactor technologies outlined in Section 3 (i.e. EPRs, AHWRs and HTGRs), can significantly affect the life-cycle stages associated with the open nuclear fuel cycle, shown in the upper portion of Figure 1. A qualitative appraisal of the potential impacts is presented below.

Mining and Milling: uranium is typically sourced in one of four ways: open-pit mining, underground mining, recovery from in-situ leaching and recovery from heap leaching. Although recent estimates of current thorium reserves suggest that ~67% could be mined using traditional open-pit and underground mining techniques (37% from carbonatite rocks, 20% from vein deposits and 10% from peralkaline rocks), ~30% could be excavated from placer deposits (e.g. recovery of monazite from beach sands in Kerala and Tamil Nadu, India) (Barthel2011a). This excavation process from placer deposits significantly differs from traditional mining techniques and could have a noticeable impact on the front-end of the fuel cycle. Furthermore, thorium is mined in combination with currently more valuable resources, such as rare-earth-elements, and the thorium is typically treated as radioactive waste by-product.

Conversion and Enrichment: the majority of current nuclear power plants operate with enriched uranium. The process of enrichment is electricity intensive and requires the conversion of U_3O_8 to UF_6 (and subsequent conversion of UF_6 to UO_2). The thorium in nuclear fuel cannot be enriched and the only possible chemical conversion which may be required is that of $Th(C_2O_4)_2$, and possibly $Th(NO_3)_4.xH_2O$, to ThO_2. Given that ^{232}Th is fertile, initial ^{235}U (or another fissile isotope from an open-cycle source) enrichments of 10–20% would be needed to sustain a nuclear chain-reaction whilst fissile ^{233}U is being bred.

Fuel Fabrication: for most conventional nuclear reactors, ThO_2 and UO_2 are typically sintered into ceramic pellets that are housed in zircaloy clad fuel pins. There are potential proliferation-resistance benefits with using blended ThO_2-UO_2 ceramics. However, blended fuels are expected to cost more to fabricate. Furthermore, in both "prismatic" and "pebble-bed" HTGRs, graphite-based "TRISO" fuel is used, and is fabricated by powder agglomeration which is markedly different to typical sintering of ceramic fuels.

Reactors, Spent Fuel Storage and Deep Geological Disposal Facility: the different fuel compositions, discharge burn-ups and potential differences in neutron spectra would lead to significant variations in the isotopics of the spent-fuel. This could impact the intrinsic proliferation-resistance of the reactor, the radiation fields which workers would be exposed to and also the length of time for which the spent nuclear fuel would need to be cooled. Furthermore, the differences in physical properties of ThO_2 and UO_2 fuel forms could affect the migration of radionuclides to the environment.

6. Limitations and Boundary Conditions of the Study

Although it has been mentioned that this study will only focus on the open nuclear fuel cycle for reactors which could be commissioned by 2020, there are other limitations which will affect the metrics that will be adopted for this study.

As this project will only be looking at comparing thorium-fuelled nuclear energy systems to existing nuclear energy systems. Metrics that are specifically geared for inter-comparison between nuclear and non-nuclear energy technologies will not be considered here. Given that the target country of implementation is unspecified, metrics detailing the state's capabilities and responsibilities are deemed to be outside the scope of this particular work.

It is expected that basic construction materials (concrete, steel, etc.) would be produced in the developing country where the reactor will operate and bespoke components would be manufactured externally in developed countries. Furthermore, it will be assumed that the fuel will be imported, within the framework of the nuclear suppliers group, and would not be fuelled from indigenous uranium and thorium.

As there are no commercial thorium-fuelled reactors currently in operation, certain economic/techno-economic indicators must be assumed (for example, the plant availability factor). For these indicators, a sensitivity analysis, using upper and lower bounds, will be performed and the impact of these bounds on other indicators, such as the levelised cost of electricity, will be reported.

The boundary conditions for our study will comprise of the following:

- Construction, operation and decommissioning of the nuclear reactor with construction, operation and decommissioning of ancillary facilities associated with the once-through cycle shown by the double dot-dash line in the upper portion of Figure 1 (e.g. uranium mine, spent-fuel repository, etc.). Construction, operation and decommissioning of ancillary facilities (e.g. copper refinery) will only be accounted for in the life-cycle impact of producing a unit quantity of that material.
- The indicators chosen in this study will cover all of the impacts of producing thorium and uranium at each stage of the life-cycle. For ancillary materials (e.g. copper, zircon, concrete, etc.), only the environmental emissions that can be accounted for in producing these materials will be included.

- Spatially, only the construction of the reactor, spent-fuel repository and deep-geological disposal facility will be performed within Country X. The construction of other facilities in the front-end of the fuel cycle will be performed in countries where existing capabilities exist (e.g. Canada, Kazakhstan, and Australia for uranium mining and milling, USA, France, UK, and Russia for conversion and fuel fabrication). This boundary reflects the current trend in how nuclear power plants are fuelled and potential mechanisms for supplying fuel to current non-nuclear states.
- Temporally, the whole-life of each facility within the life-cycle will be taken into account. For the nuclear power reactor, no life extensions will be accounted for. For the deep-geological disposal, a life-time of 100,000 years will be assumed. This means that radioactive waste should be accounted for in three time steps to cover the immediate hazard, the intermediate hazard of a number of generations and the very long-term hazard.
- A discount rate of 0% will be assumed for this work. The real discount rate for electricity generation can typically vary in the range of 5–10% (IEA2010a). However, the rationale for choosing a 0% discount rate in this work is two-fold. First, external factors which affect the discount rate include the capital cost of construction, construction time, operational lifetime of the plant, the geographical location of the plant and how the plant is financed. Therefore, it would be incorrect to ascribe a blanket discount rate given the variation in reactor technologies being studied. Second, future uncertainties, in terms of public/government acceptance of nuclear power and competition from alternative energy generation technologies, may make discount methodologies intractable. These notions are informed by the inter-temporal equity section of Nicholas Stern's "Economics of Climate Change" (Stern2007a). One problem of choosing a 0% discount rate is that protracted costs in the future, for instance those associated with long-term waste storage, could dominate the overall cost appraisal. This may be remedied by setting an appropriate boundary condition on the life-span of the spent fuel repository.

7. Sustainability Indicators

Given the amount of pre-existing literature on Sustainable Development Indicators, the following is a concise summary that will highlight salient aspects of this previous work directly relevant to the comparative study of open-cycle thorium-fuelled nuclear energy systems with existing uranium-fuelled LWRs.

The application of Sustainable Development Indicators spans national, international, systems-level (as exemplified by the UN Indicators of Sustainable Development (UN2007a)) and sector-specific appraisals (e.g. in the case of indicators in the energy sector, see (IAEA2005a) which lists 30 environmental, economic and social indicators). It should be noted that in the recent OECD report on "Trends towards Sustainability in the Nuclear Fuel Cycle" (OECD2011a), it is mentioned that there is no current consensus on quantitative methodologies that would be easily applicable for determining the sustainability aspects of the nuclear fuel cycle. Furthermore, there are many schema for sustainability indicators in the nuclear fuel cycle at present, but no scheme has yet come to dominate. Given that there is no established set of indicators which allows a comparison of nuclear technologies from a wide sustainability perspective, it is appropriate to identify those indicators fit for this purpose. This is achieved below by an inter-comparison of previous studies from which the most appropriate indicators have been selected, whilst also considering any gaps relating to sustainability concerns not thus far represented in previously recommended metrics.

Concerning sustainability indicators for nuclear energy systems, we highlight seven specific works which are of particular pertinence. These are described in Table 1.

From the seven studies listed in Table 1, a combined total of 270 separate indicators are produced. A complete list of these indicators is presented in Table A in Appendix 1. We have grouped these indicators into seven categories: Environmental, Techno-Economic, Social, Safety, Proliferation Resistance, Physical Protection, and Waste. It should be noted that the infrastructure metrics quoted in INPRO have been separated into the Safety, Waste and Techno-Economic indicators as appropriate. To look for correlations between the indicators, they have been mapped as sets with an attempt to observe trends in the number of times they are reported and the deviations in how similar metrics are reported. Figure 2 shows a complete representation of all 270 indicators in an affinity diagram, with overlaid labels highlighting the general features that will be the focus of this particular work. A list off all the indicators is presented in Table A in the Appendix. The individual indicators which will be reported in the comparison of thorium-fuelled nuclear energy systems are presented in Tables 2–6. Given that there is a large deviation in the electrical power output of the nuclear energy systems listed in Section 3, two separate quantities should be reported for each indicator. First, an absolute value for the indicator (assuming the total impact for one nuclear energy system and associated infrastructure) and, second, the same value normalised to one unit of electricity produced by the nuclear energy system, i.e. a functional unit of one kWh_e. It should be noted that Physical Protection metrics are not included in this study as these are wholly dependent on a particular state's capabilities and infrastructure. Furthermore, given the associated overlap, the Social and Safety metrics are jointly reported in Table 6.

The indicators presented in Tables 2–6 are intended to provide a complete appraisal of the impacts of each stage of the nuclear fuel cycle. It is expected that the indicators reported can also be included as part of an inter-comparison of non-nuclear energy generation technologies, though more work would be needed in creating a complete set for such a comparison.

Table 1: Summary of Previous Reports on Sustainability Indicators for Nuclear Energy Systems.

Source Reference	Number of Indicators	Comments
Stamford2011a	43	Focus on nuclear energy generation in the United Kingdom, i.e. considers closed fuel cycle. Cradle-to-grave approach broadly spanning economic, environmental and social factors.
Wilson2011a	29	Focus on existing US nuclear energy policy. Covering cost, safety, resource utilisation, sustainability and non-proliferation. Analysis techniques discussed.
DOE2002a	24	Focus on future nuclear energy systems. Both thermal and fast systems considered. Main focus on reactor technology and safety.
Jülich2007a	36	Table 2.1 from RED-IMPACT report listing idealised indicators for nuclear energy. "RED-IMPACT §2"
Jülich2007a	31	Table 8.1 from RED-IMPACT report listing specific quantifiable indicators centred round the impact of waste disposal and minimisation. "RED-IMPACT §8"
OECD2001a	36	Indicators spanning economic, environmental and social indicators over closed-fuel cycle. Levelised costs and radioactive waste are sub-divided for each stage of the fuel cycle.
IAEA2008a	125	Expansive work centred mainly on the impact of a nuclear energy system in a country-specific scenario. Spans economics, environmental, safety, proliferation resistance, physical protection, waste management and infrastructure.
Lamego2002a	16	Indicators listed apply to whole life-cycle of nuclear power but with specific background towards the mining and milling sectors.

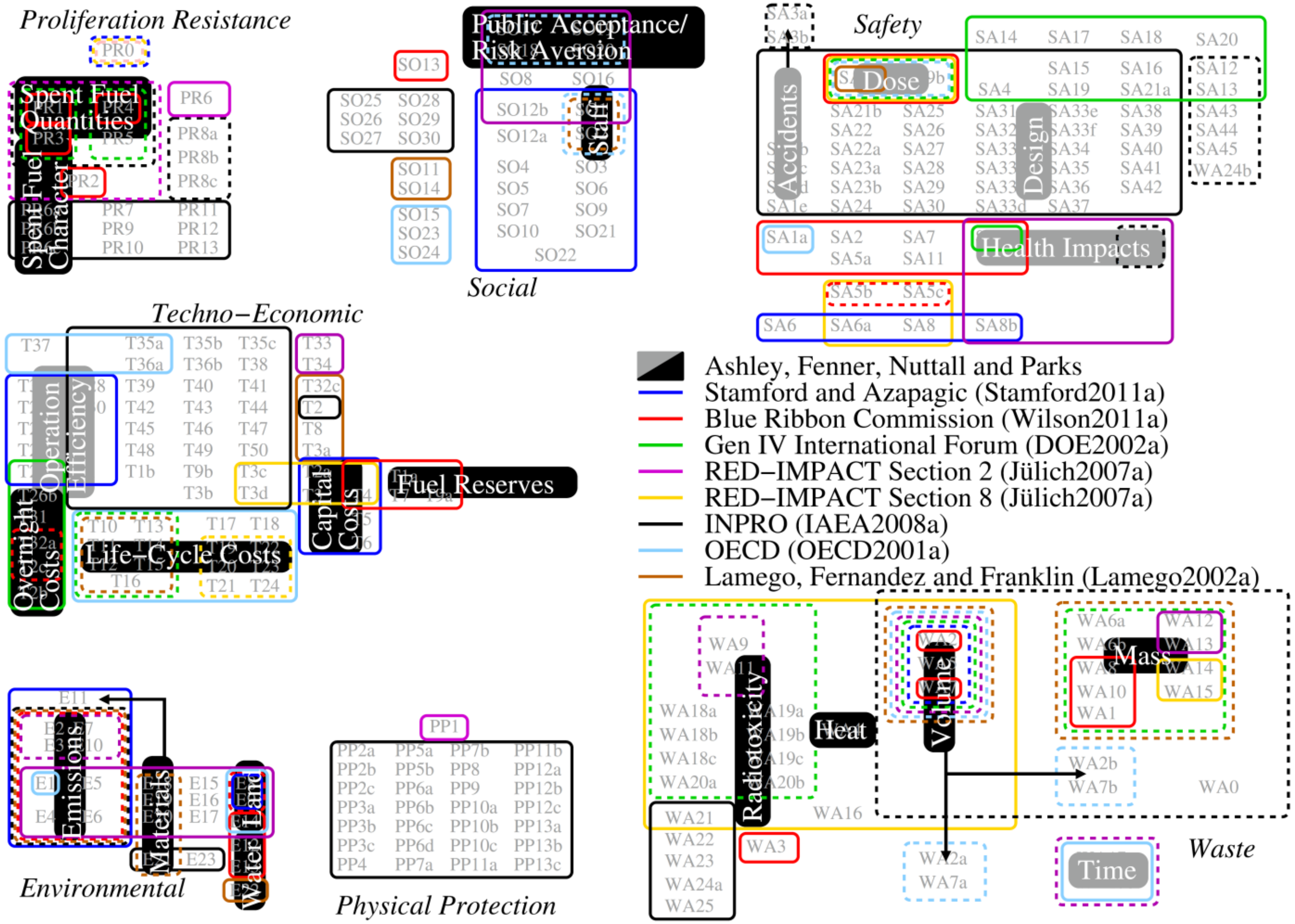

Figure 2: Affinity diagram of 270 nuclear energy indicators mapped into seven themes. Each individual indicator label is detailed in the Appendix. Solid lines denote explicit mention of the indicator; dashed lines denote individual or groups of indicators that comprise an inferred indicator. Solid colour boxes denote the general themes which will be covered in this work. Individual indicators used in this study are reported in Tables 2–6. Indicator sets denoted in black will be quantitatively determined. Indicators sets denoted in grey will be quantitatively determined from an appropriate set of sensitivity analyses.

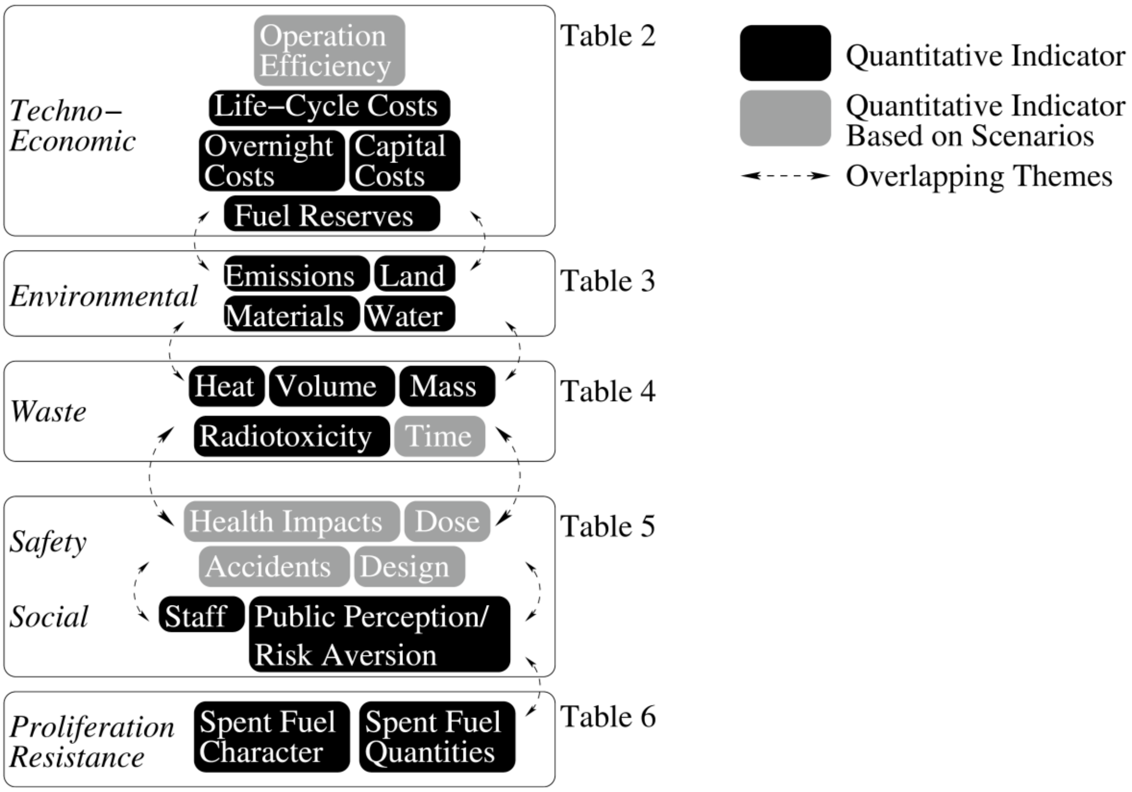

Figure 3: Thematic indicator sets for appraising open-cycle thorium-uranium-fuelled nuclear energy systems. Individual indicators for each theme (shown in italics) are correspondingly reported in Tables 2–6. Indicator sets denoted in black will be quantitatively determined from an appropriate set of sensitivity analyses. Dashed arrows denote overlaps in the indicator sets.

Table 2: Techno-Economic Indicators.

Category	Indicator	Units	Life-Cycle Stage (Fig. 1)
Fuel Reserves	Lifetime of Global Uranium Reserves at Current Extraction Rates	Years	Reactor (*Re*): Operation
Operation Efficiency	Time Between Start of Construction and Start of Operation	Years	Reactor (*Re*): Construction
Cost	Capital Cost	Pence	Reactor (*Re*): Construction & Decommissioning
	Levelised Cost of Electricity	Pence	*Mn, Ml, CE, Fu, Re, SFR, DGD*

Table 3: Environmental Indicators.

Category	Indicator	CML characterisation factor	Units	Life-Cycle Stage (Fig. 1)
Emissions	Freshwater Aquatic Eco-Toxicity Potential	$FAETP_{\infty}$	kg 1,4-DCB(eq)	*Mn, Ml, CE, Fu, Re, SFR, DGD*
	Marine Aquatic Eco-Toxicity Potential	$MAETP_{\infty}$	kg 1,4-DCB(eq)	*Mn, Ml, CE, Fu, Re, SFR, DGD*
	Global Warming Potential	GWP_{100}	kg CO_2(eq)	*Mn, Ml, CE, Fu, Re, SFR, DGD*
	Ozone Depletion Potential	$ODP_{\text{steady state}}$	kg CFC-114(eq)	*Mn, Ml, CE, Fu, Re, SFR, DGD*
	Acidification Potential	AP	kg SO_2(eq)	*Mn, Ml, CE, Fu, Re, SFR, DGD*
	Eutrophication Potential	EP	kg PO_4^{3-} (eq)	*Mn, Ml, CE, Fu, Re, SFR, DGD*
	Photochemical Smog Potential	POPC	kg C_2H_4 (eq)	*Mn, Ml, CE, Fu, Re, SFR, DGD*
	Terrestrial Eco-Toxicity Potential	$TETP_{\infty}$	kg 1,4-DCB(eq)	*Mn, Ml, CE, Fu, Re, SFR, DGD*
Land Use	Land Area Required		m^2yr	*Mn, Ml, CE, Fu, Re, SFR, DGD*
Materials	Fresh-water Consumption		Litres	*Mn, Ml, CE, Fu, Re, SFR, DGD*
	Construction and Non-Renewable Materials		kg	*Mn, Ml, CE, Fu, Re, SFR, DGD*

Table 4: Waste Indicators

Category	Indicator	Units	Life-Cycle Stage (Fig. 1)
Volume	Volume of LLW, ILW and HLW to be Stored	m^3	*Re, SFR*
Mass/ Radiotoxicity	Activity of LLW, ILW and HLW after 300 years	Bq	*Re, SFR, DGD*
	Activity of LLW, ILW and HLW after 100,000 years	Bq	*DGD*
Time/Heat	Minimum Time Required in Wet Storage	Years	*Re, SFR*

Table 5: Social and Safety Indicators

Category	Indicator	CML characterisation factor	Units	Life-Cycle Stage (Fig. 1)
Accidents	Worker Fatalities (with and without large accident)		Number	*Mn, Ml, CE, Fu, Re, SFR, DGD*
	Public Fatalities (with and without large accident)		Number	*Mn, Ml, CE, Fu, Re, SFR, DGD*
Safety	Core Damage Frequency		Number per year	*Re*
Health Impacts	Human Toxicity Potential (excluding radiation)	HTP_∞	kg 1,4-DCB(eq)	*Mn, Ml, CE, Fu, Re, SFR, DGD*
Health Impacts and Dose	Health Impact on Workers (including radiation)		DALY	*Mn, Ml, CE, Fu, Re, SFR, DGD*
	Health Impact on Public (including radiation)		DALY	*Mn, Ml, CE, Fu, Re, SFR, DGD*
Staff	Employment Opportunities		Person-yrs	*Mn, Ml, CE, Fu, Re, SFR, DGD*
Public Acceptance and Risk Aversion	Public Acceptance and Risk Aversion		Score	*Mn, Ml, CE, Fu, Re, SFR, DGD*

Table 6: Proliferation Resistance Indicator.

Category	Indicator	Unit	Life-Cycle Stage (Fig. 1)
General	Proliferation-Resistance Index	Score	Mn, Ml, CE, Fu, Re, SFR, DGD

Techno-Economic Indicators

The techno-economic indicators are focussed on fuel reserves, operational efficiency and cost. Given that this is an intra-comparison of nuclear energy technologies, the impact on uranium fuel reserves will be reported parametrically to that of the benchmark EPR system. The fuel reserve indicator will be calculated using a material-flow analysis and will account for the variations in enrichment in each of the studied systems. This parameter, coupled with the expected energy production from nuclear energy technologies, will then allow for intra-comparison of other nuclear energy generation technologies.

Nuclear energy systems have long lead times between the start of construction and the start of energy production, typically 5–7 years (BERR2008a, IEA2010a)). In an intra-comparison of technologies, significant deviations can occur in the construction times for first-of-a-kind and next-of-a-kind reactors. Construction of the first EPR reactors in Olkiluoto, Finland and Flamanville, France has experienced significant delays (Thomas2010a) although the new reactors being built in Taishan, China are expected to be completed on schedule. Furthermore, licensing agreements for a reactor can take different periods of times dependent on the country in which it is being built, e.g. the US Nuclear Regulatory Commission adopts a "prescriptive" approach whereas the UK Office of Nuclear Regulation adopts a "goal-setting" methodology. Ideally, these factors would be taken into account for the AHWR and HTR-PM/GT-MHR but could potentially be too complex to analyse in such a comparison.

Nuclear power plants are typically capital-intensive with low operation and maintenance and fuel costs compared to other electricity generation technologies (e.g. see (OECD2009a, IEA2010a)). The capital cost is of particular pertinence to developing countries, as in many cases they lack the credit worthiness needed for such large projects. In comparing nuclear energy technologies, consideration will need to be taken for the amount of bulk material required to construct the required facilities and also the complexity of the plant design. The levelised cost of electricity should also be reported depending on the potential fuel price scenarios for both uranium and thorium.

Environmental Indicators

The environmental indicators listed are centred round the themes of emissions and materials. To gauge the emissions and impacts over the whole life-cycle, Life Cycle Analysis, (e.g. see (Guinée2002a) and references therein) can be performed for each stage of the open cycle. Each of the emissions indicators quoted relates to CML characterisation factors (vanOers2001a) which provide a weighting factor for each individual emission. The general form of each characterisation factor is given in Equation (1),

$$CML_{label} = \sum_{i}^{I} CML_{weighting} \left(\;\right) \times Q \left(\;\right) \qquad (1)$$

where CML_{label} is the weighted total emission per kWh, $CML_{weighting}$ is the individual weighting factor for each emitted material i in units of (kg(eq)/kg) and $Q(i)$ is the amount of material i emitted per kWh.

Material and land-use indicators will also be calculated in a Material Flow Analysis, although these will be reported in terms of absolute amounts and amounts normalised per kWh, given that there may be limitations on the bulk quantities of materials needed for Country X. For the different nuclear reactor technologies, it is expected that large quantities of concrete, steel, reinforcing steel, and water will be required. For the EPR and AHWR technologies, zircaloy production for the cladding of the fuel needs to be accounted for. For the AHWR, the production of heavy water and its impacts need to be ascertained. For the HTGR, the cladding of the fuel is silicon carbide and helium gas will act as the coolant. As there are a number of future electricity generating technologies which will require helium, questions over the supply and price of helium remain (Nuttall2012a). In addition, as thorium-uranium nuclear fuels are intended to prolong the current uranium reserves, the lifetime of global uranium reserves at current extraction rates will be presented.

Waste Indicators

The waste indicators are separated into the general categories of volume, radiotoxicity and minimum time which spent fuel has to remain in wet storage. For volume and radiotoxicity metrics, it would be desirable to report values for High Level Waste (HLW), Intermediate Level Waste (ILW) and Low Level Waste (LLW) given that these types of waste require separate facilities. The current internationally accepted radioactive classification scheme (IAEA2009b) does not prescriptively specify boundaries between these classes of waste. Therefore, for this work, HLW is defined as having a thermal output greater than 2 kW/m^3 (IAEA1994a). ILW has a thermal output less than 2 kW/m^3 (IAEA1994a) but has an alpha activity greater than 4 MBq/kg and/or a beta/gamma activity greater than 12 MBq/kg (DECC2008a). LLW is assumed to have a contact dose less than 2 mSv/h. Furthermore, given that the isotopic composition of the spent fuel from thorium-uranium systems is expected to be quite different from typical isotopic compositions from spent fuel assemblies from uranium-fuelled systems, reporting of specific actinide and fission-fragment concentrations may also be required.

Social and Safety Indicators

The social and safety indicators are based on core damage frequencies, the human health impacts, both inclusive and exclusive of radiation dose, the employment required, and public acceptance and risk aversion at each stage of the life-cycle.

Nuclear incidents and accidents are typically reported on the seven-point International Nuclear and Radiological Event Scale (IAEA2009c). Therefore, in comparing thorium-uranium-fuelled nuclear energy systems, the consequences of the range of accidents should ideally be weighted for the different input fuel feeds and for the isotopic composition of the fuel in the reactor and of the spent nuclear fuel. However, the (Level 3) Probabilistic Safety Assessment (PSA) associated with such a study would very much be site dependent and so determining absolute quantities for this metric would be difficult. A similar problem exists for determining the public health risks given that data is still being obtained for both Chernobyl and Fukushima Daiichi. Therefore, there is a strong chance that the results of this study for major accidents may have to be parametric and not absolute.

As mentioned earlier, the safety of the nuclear power plant is partly dependent on the fuel composition but also on the fundamental design principles of the reactor. A qualitative safety assessment, such as the UK Office of Nuclear Regulations "Safety Assessment Principles" (HSE2006a), for each reactor type may yield a parametric comparison to the EPR which has been granted provisional licensing agreement in the UK (Areva2012a). However, a quantitative appraisal would be possible from a Level 1 PSA, which yields core damage frequencies and would provide more insight into the differences between these nuclear energy systems. An overview of the information which can be garnered from these PSAs can be found in (Fullwood1999a).

The staff required to build and operate each of the facilities within the open cycle will need to be accounted for. Of particular relevance to nuclear energy in developing countries will be the level of education of the workers and whether such skilled workers could be indigenously trained.

Finally, the public acceptability and risk aversion not only to the nuclear energy systems, but also to the mining procedures which are employed, to the impact of transportation systems and to the treatment of spent nuclear fuel need to be represented over the whole life cycle supply chain. Such metrics may be complex to ascertain given the wide range of externalities which affects people's perception of nuclear power, nuclear waste and mining, together with regional variations in opinion. Therefore, a qualitative appraisal, with an appropriate scoring system, would need to be formulated to address these gaps.

Proliferation Resistance Indicator

The proliferation resistance indicator will be based on an independent analysis relating to the spent-fuel compositions of the waste fuel and also the quantities of specific nuclear materials which enter the system. Various methodologies to obtain this indicator (e.g. as seen in References (Bathke2009a, Charlton2007a, Hesketh2010a, Hesketh2011a)), could be used, although minor modifications to these methodologies to account for the differences between ^{232,234}U and ^{238,240}Pu must be included.

8. Conclusions and Outlook

The potential for thorium-uranium-fuelled nuclear energy systems, operating in an open fuel cycle, to be used in developing countries has been introduced. Nuclear energy systems, up to and including Generation III/III+ systems, which could adopt thorium-uranium fuels have been discussed with the most suitable possibilities being: LWRs (e.g. the EPR), heavy water reactors (e.g. the AHWR), and high temperature reactors (e.g. the HTR-PM or GT-MHR). This work highlights the differences between the thorium-uranium and uranium open fuel cycles and also presents a set of indicators which have been developed to highlight the relative advantages and disadvantages of thorium-uranium-fuelled nuclear reactor compared to the benchmark example of a uranium-fuelled EPR. The 28 indicators chosen have come from an endeavour to map the most pertinent indicators for nuclear energy systems. This mapping includes 270 indicators from seven previous works on indicators relating to nuclear energy systems and the nuclear fuel cycle. The boundary conditions and possible limitations of such a study have been introduced.

As there is no specific target country which is being assumed to adopt this technology, it is not possible for stakeholder opinions which would influence the weighting of the chosen indicators in a multi-criteria decision assessment to be included. Therefore, this work is designed to provide a general template that could be used as the basis for a policy tool for a generic country.

To further develop this work, information relevant to the indicators identified in this work for the facilities at each stage of the life-cycle needs to be compiled. Such a compilation will also include details pertinent to the modelling of the nuclear reactor technology, including core configuration, discharge burn-ups and refuelling schemes. Thereafter, once quantitative indicators have been determined from the aforementioned data, an appropriate multi-criteria decision analysis methodology for open-cycle thorium-fuelled nuclear power, pertinent to the constraints that would be faced in developing countries, needs to be formulated.

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Appendix: List of All Sustainability Indicators

Table A: Nuclear Energy Indicators used in Previous Sustainability Reports. In the Reference column, capitalised letters denote indicators which are explicitly mentioned. Lower-case letters denote indicators which are inferred either individually or as part of a group.
A, a: denotes Reference (Stamford2011a).
B, b: denotes Reference (Wilson2011a).
C, c: denotes Reference (DOE2002a).
D, d: denotes Section 8 of Reference (Jülich2007a).
E, e: denotes Section 2 of Reference (Jülich2007a).
F, f: denotes Reference (OECD2001a).
G, g: denotes Reference (Lamego2002a).
H, h: denotes Reference (IAEA2008a).

Indicator Label	Indicator	Reference
E1	Global Warming Potential [kg(CO_2)eq/kWh]	A, b, E, F, g, h
E2	Freshwater Eco-toxicity Potential [kg(1-,4-DCB)eq/kWh]	A, b, e, g, h
E3	Marine Eco-toxicity Potential [kg(1-,4-DCB)eq/kWh]	A, b, e, g, h
E4	Ozone Depletion Potential [kg(CFC-11)eq/kWh]	A, b, E, g, h
E5	Acidification Potential [kg(SO_2)eq/kWh]	A, b, E, g, h
E6	Eutrophication Potential [kg(PO_4^{3-})eq/kWh]	A, b, E, g, h
E7	Photochemical Smog Potential [kg(C_2H_4)eq/kWh]	A, b, e, g, h
E8	Land Occupation [m^2yr/kWh]	A, b, e, f
E9	Greenfield Land Use [%]	A, b, e, f
E10	Terrestrial Eco-toxicity Potential [kg(1,4-DCB)eq/kWh]	A, b, e, g, h
E11	Recyclability of Input Materials [%]	A
E12	Freshwater Consumption [l]	B
E13	Freshwater Withdrawals [l]	B
E14	Disposal Space [m^2/yr] or [ha/GWh]	B, e, f
E15	Noise Pollution	E
E16	Change of Landscape	E
E17	Bio-Diversity/Species "Eco-system"	E
E18	Use of Aluminium	E, g
E19	Use of Iron	E, g
E20	Use of Copper	E, g
E21	Use of Other Non-Renewable Natural Resources	g, H
E22	Use of Other Renewable Natural Resources	G
E23	Application of ALARP to Limit Environmental Effects	H
T1	Total Levelised Cost of Electricity [£/kWh]	A, H
T1a	Total Cost of Electricity [£/kWh]	B

T2	Capital Cost [£]	f, G, H
T2a	Capital Cost (Reactor) [£]	A, D
T2b	Overnight Construction Costs (LCC) [£]	C
T2c	Overnight Construction Costs (Risk to Capital) [£]	b, C
T3	Operation and Maintenance Cost [£/kWh]	A, D
T3a	Marginal Cost [£/kWh]	G
T3b	Waste Operational Costs (Interim Storage to DGD) [£/kWh]	H
T3c	Decontamination and Decommissioning Costs (Reactor) [£/kWh]	D, f, H
T3d	Total Repository Cost [£]	D, f, H
T4	Levelised Fuel Cycle Cost [£/kWh]	A, B, D, f
T5	Fuel Price Sensitivities [£/kWh]	A
T6	Financial Incentives [£/kWh]	A
T7	Disposal Costs [£/kWh]	B
T8	Discount Rate [%]	G
T9a	U_3O_8 Consumption [kg/kWh]	B, G, H
T9b	ThO_2 Consumption [kg/kWh]	H
T10	Cost of Raw Materials [£/U_3O_8]	c, F, g
T11	Cost of Separation Work [£/SWU]	c, F, g
T12	Cost of Conversion [£/UO_2]	c, F, g
T13	Cost of Fabrication [£/Fuel Form]	c, F, g
T14	Cost of Storage [£/Fuel Form]	c, F, g
T15	Cost of Reprocessing [£/UO_2_Rep]	c, F, g
T16	Cost of Transport [£.kg/km]	c, F, g
T17	Cost of Encapsulation and Condition [£/kg(SF)]	F
T18	Cost of Disposal [£/kg(SF)]	F
T19	Cost of Governmental Research [£]	d, F
T20	Cost of Non-Governmental Development [£]	d, F
T21	Cost of Basic R&D [£]	d, F
T22	Cost of Laboratory/Process [£]	d, F
T23	Cost of Pre-Industrial [£]	d, F
T24	Cost of Industrial [£]	d, F
T25	Capacity Factor [%]	A
T26a	Availability Factor [%]	A
T26b	Forced Outage Rate	C
T27	Technical Dispatchability [Rank]	A, H
T28	Economic Dispatchability [#]	A, H
T29	Lifetime of Global Fuel Reserves [kgU]	A, C
T30	Plant Flexibility [yr^{-1}]	A, H
T31	Construction Duration (LCC) [£/yr]	C
T32a	Construction Duration (Risk to Capital) [£/yr]	b, C
T32b	Time Between Plant Start-Up and Start of Construction [yr]	A
T32c	Technological Innovation/Improvements [Patents/kWh]	G
T33	Added Value "Income Generation"	E
T34	R/P Ratio	E
T35a	Energy Recovered per kgU	F, H
T35b	Energy Recovered per kgTh	H
T35c	Energy Recovered per kg of Limited Non-Renewable Resource Consumed	H

T36a	Ratio of Necessary Energy Input to Obtained Output	F, H
T36b	Power Available for Use in the Innovative Nuclear System	H
T37	Range of Ton-Kilometres Energy Intensity Ratio	F
T38	Cost of Incorporating Intrinsic and Extrinsic Measures to Improve PR	H
T39	Availability of Waste Management Technology	H
T40	Time Required to Industrialise Waste Management Technology	H
T41	Availability of Resources to Meet Radioactive Waste Demand	H
T42	Financial Figures of Merit	H
T43	Licensing Status	H
T44	Financial Robustness Index of Innovative Nuclear System	H
T45	Status of Legal Frameworks	H
T46	Status of States Capability for the Nuclear Fuel Cycle	H
T47	Availability of Credit Lines	H
T48	Size of Installation	H
T49	Availability of Infrastructure to Support Owner/Operator	H
T50	Availability of Human Resources	H
SO1	Direct Employment [person-yrs/kWh]	A, E, f, g
SO2	Indirect Employment [person-yrs/kWh]	A, f, g
SO3	Proportion of Staff from Locality [%]	A
SO4	Spending on Local Suppliers [%]	A
SO5	Direct Investment in Local Community [%]	A
SO6	Corruption from Supplier Countries [Score]	A
SO7	Imported Fossil Fuel Avoided [toe/kWh]	A
SO8	Fuel Import Dependency	E
SO9	Diversity of Fuel Supply Mix [Score]	A
SO10	Fuel Storage Capabilities [GJ/m^3]	A
SO11	Education [# of Courses]	G
SO12a	Use of Abiotic Resources (Elements) [kg Sb(eq)/kWh]	A
SO12b	Use of Abiotic Resources (Fossil Fuels) [MJ/kWh]	A, E
SO13	Mass of Depleted U [kg/kWh]	B
SO14	Public Health [£/kWh]	G
SO15	Change in Work Opportunity	F
SO16	Resettlement Necessities	E
SO17	"Public Acceptance" NIMBY/BANANA	E, f, H
SO18	"Risk Aversion" Kind of Risk Constraints	E, f
SO19	"Risk Aversion" Nature of Risk Source	E, f
SO20	"Risk Aversion" Dimensions of Risk Consequence	E, f
SO21	Human Toxicity Potential [kg (1,4-DCB)eq/kWh]	A
SO22	Volume of Liquid CO_2 to be Stored [m^3/kWh]	A
SO23	Autonomy of Resources	F
SO24	Induced Industrial Production	F
SO25	Long Term Commitment to Nuclear Option	H
SO26	Demand For and Price of Energy Products	H
SO27	Information Provided to the Public	H
SO28	Participation of the Public in Decision Making	H
SO29	Government Policy	H

SO30	Attitude to Safety and Security	H
SA1a	Operational Accidents [#/yr]	B, F
SA1b	Calculated Frequency of Occurrence of Design Basis Accidents	H
SA1c	Calculated Frequency of Major Release of Radioactive Materials into the Environment	H
SA1d	Expected Frequency of Abnormal Operation and Accidents	H
SA1e	Expected Frequency of Failures of Disturbances	H
SA2	Core Damage Frequency [#/yr]	B
SA3	Potential Damage of Severe Accidents (Range) [m]	E
SA3a	Consequence of Abnormal Operation	h
SA3b	Consequence of Accidents	h
SA4	Accident Exposures	C, H
SA4a	Health Impact of Accidents on Workers	E, h
SA4b	Health Impact of Accidents on Public	E, h
SA5a	Estimated Peak Dose Rate [mrem/yr]	B
SA5b	Maximum Individual Dose to Public	b, D
SA5c	Maximum Individual Dose to Workers	b, D
SA6	Fatalities Due to Large Accidents [# Fatalities/GWh]	A
SA6a	Worker Fatalities [# Fatalities/GWh]	A, D
SA7	Number of Latent Cancer Fatalities [#]	B
SA8	Total Human Health Impacts from Radiation [DALY/GWh]	A, D
SA8a	Public Human Health Impacts from Radiation [DALY/GWh]	E
SA8b	Worker Human Health Impacts from Radiation [DALY/GWh]	A, E
SA9a	Collective Dose to Public [mrem/yr]	B, c, D, f, G, H
SA9b	Collective Dose to Workers [mrem/yr]	B, c, D, f, H
SA10	Discharged Waste Heat	B, C, E
SA11	Transports of Radioactive Waste[#]	B
SA12	Reliable Reactivity Control	C, h
SA13	Reliable Decay Heat Removal	C, h
SA14	Dominant Phenomena Uncertainty	C
SA15	Long Fuel Thermal Response Time	C, H
SA16	Integral Experiments Scalability	C, H
SA17	Source Term	C
SA18	Mechanisms for Energy Release	C
SA19	Long System Time Constraints	C, H
SA20	Long and Effective Holdup	C
SA21a	Passive Safety Features	C, H
SA21b	Active Safety Features	H
SA22	Robustness of Design	H
SA22a	Sub-Criticality Margins	H
SA23a	High Quality of Operation	H
SA23b	Capability to Inspect	H
SA24	Reliability of Engineered Safety Features	H
SA25	Number of Confinement Barriers Maintained	H
SA26	Capability of Engineered Safety Features to Restore Innovative Nuclear System to a Controlled State	H

SA27	Calculated Frequency of Major Release of Radioactive Materials into Containment/Confinement	H
SA28	Ability to Control Relative System Parameters and Activity Levels in Containment	H
SA29	In-Plant Severe Accident Management	H
SA30	Independence of Different Levels of DID	H
SA31	Evidence that Human Factors are Addressed Systematically in the Plant Life Cycle	H
SA32	Application of Formal Human Response Models from Other Industries or Development of Nuclear	H
SA33a	Stored Energy	H
SA33b	Flammability	H
SA33c	Criticality	H
SA33d	Inventory of Radioactive Materials	H
SA33e	Available Excess Reactivity	H
SA33f	Reactivity Feedback	H
SA34	Confidence in Innovative Components and Approaches	H
SA35	Safety Concept Defined	H
SA36	Clear Process for Addressing Safety Issues	H
SA37	RD&D Defined and Performed and Database Developed	H
SA38	Computer Codes or Analytical Methods Developed and Validated	H
SA39	Scaling Understood and/or Full Scale Tests Performed	H
SA40	Degree of Novelty of the Process	H
SA41	Use of Risk Informed Approach	H
SA42	Uncertainties and Sensitivities Identified and Appropriately Dealt With	H
SA43	Long Term Safety from Radioactive Waste	h
SA44	Radioactive Emission Control Measures from Waste Management Facility	h
SA45	Waste Forms	h
WA0	Total Activity [Bq/GWh]	h
WA1	HLW Disposal Mass [kg/GWh]	B, c, g, h
WA2	HLW Disposal Volume [m^3/GWh]	a, B, c, D, e, f, g, h
WA2a	Volume of Alpha-emitters from HLW	f
WA2b	Volume of Gamma-emitters from HLW	f, h
WA3	HLW Radiological Hazard Potential	B
WA4	Thermal Output of HLW after 50 years	D
WA5	Volume of ILW	a, c, D, e, f, g, h
WA6a	Mass of ILW	c, g, h
WA6b	Mass of LLW	c, g, h
WA7	LLW Solid Waste (Volume) [m^3/GWh]	a, B, c, D, e, f, g, h
WA7a	Volume of Alpha-Emitters from LLW	f
WA7b	Volume of Gamma-Emitters from LLW	f, h
WA8	LLW Gaseous Releases [kg/GWh]	B, c, g, h

WA9	Radiotoxicity of Gaseous Releases	c, D, e
WA10	LLW Liquid Releases [m^3/GWh]	B, c, g, h
WA11	Radiotoxicity of Liquid Releases	c, D, e
WA12	Non-Radioactive Toxic Waste	c, E, g, h
WA13	Non-Radioactive Non-Toxic waste	c, E, g, h
WA14	Operational Waste	c, D, g, h
WA15	Decommissioning Waste	c, D, g, h
WA16	Length of Repository Gallery Required for Waste	D
WA17a	Time of Confined Alpha-Emitters	e, F
WA17b	Time of Confined Gamma-Emitters	e, F
WA18a	Radiotoxicity at 500 years	c, D
WA18b	Radiotoxicity at 10,000 years	c, D
WA18c	Radiotoxicity at 1,000,000 years	c, D
WA19a	Radiotoxicity Flux Released into the Biosphere (0-10,000 y)	c, D
WA19b	Radiotoxicity Flux Released into the Biosphere (10,000-100,000 y)	c, D
WA19c	Radiotoxicity Flux Released into the Biosphere (100,000-1,000,000 y)	c, D
WA20a	Dose to Human Intrusion at 300 years	c, D
WA20b	Dose to Human Intrusion at 10,000 years	c, D
WA21	Required Isolation Time (To Reach 10 mSv Intervention Level)	D, H
WA22	Appropriate Waste Classification Scheme	H
WA23	Time to Produce the Waste Form Specified for End State	H
WA24a	Waste Minimization Study	H
WA24b	Volume and Activity Reduction Measures	h
WA25	Process Descriptions that Encompass the Entire Waste Cycle	H
PR0	Proliferation Resistance	A, D, F
PR1	Mass of SNM [kg/GWh]	B, c, e, h
PR2	Required Enrichment Capacity [kgSWU/GWh]	B, e
PR3	Attractiveness of SNM	B, c, e, h
PR4	Mass of Separated Plutonium [kg/GWh]	B, c, e, h
PR5	Mass of Other Separated SNM/ANM [kg/GWh]	c, e, h
PR6	Extrinsic Proliferation Resistance	E
PR6a	Accountability of Nuclear Materials	H
PR6b	Amenability of Nuclear Materials	H
PR6c	Detectability of Nuclear Materials	H
PR7	Attractiveness of Nuclear Technology	H
PR8a	Difficulty to Modify Process	h
PR8b	Difficulty to Modify Facility Design	h
PR8c	Difficulty to Misuse Technology or Facilities	h
PR9	Redundancy of Intrinsic and Extrinsic PR Measures	H
PR10	Robustness of Barriers Covering Each Acquisition Path	H
PR11	PR Taken into Account Early as Possible in Design of INS	H
PR12	States Commitment, Policies and Obligations to Non-Proliferation	H
PR13	Verification of Extrinsic Measures by State and IAEA	H
PP1	"Public Security" Measures Against Terrorist Attacks	E

PP2a	Competent PP Authorities Designated, Empowered (with Responsibilities)	H
PP2b	Legislative and Regulatory PP Framework Development	H
PP2c	Responsibilities of PP Between Authorities and Facility Operator Defined	H
PP3a	Addressing of Synergies Between PR, PP, Safety and Operations	H
PP3b	Accounting of PP in All INPRO Areas	H
PP3c	Evidence of PP when Innovative Nuclear System is Shut-Down/Decommissioned	H
PP4	Is There a Trustworthiness Program (with Established Criteria)	H
PP5a	Has There Been Development of a Confidentiality Program	H
PP5b	Has the Confidentiality Program Been Implemented Over All Levels	H
PP6a	Is There Evidence of a DBT or Other Appropriate Threat Statement Which Has Been Developed	H
PP6b	Are There Provisions for Periodic Review of Threat by the State	H
PP6c	Is There Evidence that the Concept of DBT (or Other) Been Used to Establish the PP System	H
PP6d	Has the Designer Introduced Flexibility in PPS Design to Cope with the Dynamic Nature of Threat	H
PP7a	Judicial Consequences Defined For Malicious Acts Against Nuclear Materials and Facilities	H
PP7b	Application of "Graded" Approach to PP Requirements	H
PP8	Definition and Implementation of Quality Assurance Policies to PP	H
PP9	Security Culture Developed and Implemented for All Organisations and Persons In Innovative Nuclear Systems	H
PP10a	Assessment of Potential Benefits of Terrain, Topography and Geography to Adversaries	H
PP10b	Assessment of Transportation and Off-Site Response Routes	H
PP10c	Consideration of Future Development and Encroachment by Public	H
PP11a	Consideration of PP to Design of Innovative Nuclear System Components	H
PP11b	Consideration of PP to Layout of Innovative Nuclear System Components	H
PP12a	Integration of DDAD, and Response to Achieve Timely Interruption	H
PP12b	PPS Designed to Account for Insider Adversaries	H
PP12c	Redundancy of PPS	H
PP13a	Assignment of Responsibilities for Executing Emergency Plans	H
PP13b	Established Capabilities of PP to Prevent/Mitigate Radiological Consequences of Sabotage	H
PP13c	Established Capabilities of PP to Recover Stolen Nuclear Materials or Recapture Nuclear Facility	H