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Knowledge Gaps in Economic Analyses of Advanced Reactor Concepts

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Abstract

The development of next generation nuclear systems is predicated on improvement in sustainability, safety, proliferation resistance and economics. The economic assessment of the reactor concept is required as early as in the concept development stage. The Generation IV International Forum (GIF) has developed a methodology for economic assessment of the Generation IV (GEN-IV) nuclear energy systems. The GIF economics methodology was used for the assessment of one of the reactor concepts for the Super-Critical Water-cooled Reactors (SCWR), namely the European pressure-vessel type concept referred to as the High Performance Light Water Reactor (HPLWR). The economic analysis involved studying the sensitivity of two main economic indicators, namely, the Levelized Unit Electricity Cost (LUEC) and the Total Capital Investment Cost (TCIC). The knowledge gaps in estimating the capital costs and fuel costs, as well as the uncertainties in other cost parameters affecting the economic assessment of the nuclear energy system in the concept development stage are presented.

1. Introduction

Economics is an important consideration in the development of next generation nuclear energy systems. The Generation IV International Forum (GIF) considers the economic enhancement as one of the four main goals for the development of the Generation-IV (GEN-IV) reactor systems. The GIF economics-enhancement goal requires the GEN-IV systems to have a life cycle cost advantage over the other energy systems, and comparable financial risks to other energy projects [1]. These requirements should be applied throughout all phases of the nuclear energy system development, starting with the concept development.

The Super-Critical Water-cooled Reactor (SCWR) is one of six concepts selected for collaborative research and development (R&D) in the GIF [1]. It is the only water-cooled reactor among the six selected concepts. Evolving from the current fleet of power reactors, two SCWR concepts (the pressure vessel and pressure-tube types) are being developed through GIF collaborations. The Canadian SCWR concept is the pressure-tube type. The concept development is focused on achieving the four GIF goals, including enhancements in economics, safety, sustainability, and proliferation resistance [2].

The economic benefit of the Canadian SCWR concept is being assessed using the GIF methodology [3] and the analytical tool (G4-ECONS) [4]. Prior to applying the tool to the Canadian SCWR concept, a benchmarking exercise of the G4-ECONS tool was performed against the economic analysis result of another SCWR concept, the High Performance Light Water Reactor (HPLWR) concept [5**Erreur ! Source du renvoi introuvable.**]. The cost-analysis results using the G4-ECONS are shown to be close to that published for the HPLWR.

Significant challenges in analysing the economics of GEN-IV reactor concepts were identified; some of these challenges are attributed to knowledge gaps related to the inputs for economic analyses.

The objective of this paper is to describe the knowledge gaps in economic analyses of the advanced reactor concepts. Assumptions can be made in filling these gaps for the analyses and appropriate sensitivity analyses can be performed to account for the uncertainties.

2. Economic Analysis Methodology and Knowledge Gaps

Two important indicators of economics of nuclear energy systems, in the concept development stage are:

- the Levelized Unit Energy Cost (LUEC), expressed as $/MWh, and
- the Total Capital Investment Cost (TCIC) expressed as $/kWe installed capacity.

The other economic indicators, such as return on investment and internal rate of return, may become important to potential investors and decision makers in later stages of system development. The GIF cost-estimation guidelines [3] provide a basis for the economic analysis and the G4-ECONS analytical tool [4] calculates the LUEC and TCIC based on the inputs. The LUEC includes all costs incurred at different times over the life of the plant expressed at a single point in time (reference year) using the time value of money (discount rate). The LUEC has three main components, namely, the capital costs, fuel costs, and operation and maintenance costs. The confidence level in the calculated LUEC depends on the accuracy of the input data used in the analysis. The GEN-IV nuclear systems that are in the concept development phase have limited design information, but have sufficient information on reactor concept, balance of plant, and fuel cycle to perform economic analysis using appropriate assumptions.

For most Generation-IV concepts (excluding small modular reactor designs), it is too early in the concept development stage to suggest non-fuel operational cost improvements. Therefore, non-fuel annual operational costs, such as salaries, pensions, consumables, regulatory fees etc., are assumed to be equal to the non-fuel annual operational costs of a Generation-III reactor in the same operating environment. Knowledge gaps and challenges in estimating capital and fuel cycle costs for the SCWR concept are discussed below. The uncertainties in the costs are addressed through sensitivity analyses over an appropriate range of costs for the purpose of the economic analyses.

The GEN-IV costing guidelines refers to the Advanced Fuel Cycle Cost Basis report published by Idaho National Laboratory (INL) as the source of most fuel cycle costs, and associated accuracy ranges [6]. For costs excluded in that report, the GEN-IV estimating guidelines suggest using another authoritative source, or performing a fuel cycle facility cost analysis.

2.1 Capital Costs

Capital costs are the single largest component of the LUEC for new-built nuclear plants and are the most challenging to estimate for new reactor concepts. Capital costs include the overnight cost, financing costs, cost of start-up and commissioning, and owner’s costs (licensing and administrative costs) during construction. The cost of decommissioning and decontamination (D&D) at the end of the operating life also needs to be taken into account in the capital costs. The three factors with the largest effect on the capital costs are overnight costs, financing costs and the construction time [7].

2.1.1 Overnight Costs

Comprehensive guidelines exist for estimation of the cost of nuclear systems [3]. The guideline describes the top-down cost estimation method which is suitable for the systems that are at the concept development stage. It involves breaking down the system into major components that have similarities with other components where costs are available in the published literature, and then applying suitable scaling factors to estimate the cost of the respective components. All costs are normalized to a reference calendar year using appropriate escalation rates. Examples of main cost components include reactor vessel, steam turbine, reactor building, etc. The SCWR system has many similarities with the GEN-III water-cooled reactors. However, the component costs are not readily available in the literature, as the utilities and the contractors seldom publish such data. The overall tender prices, or the overnight costs estimates, are often published and are reported in terms of $/kWe installed capacity. There is also significant variation of capital costs by country, particularly between the emerging industrial economies of East Asia and the mature markets of Europe and North America. There are several explanations for the variation, including differential labour costs, more experience in the recent building of reactors, economies of scale from building multiple units and streamlined licensing and project management within large civil engineering projects [8]. With few new orders, the data set for new build costs is lacking. Historical cost data from the reactors built since 1970s are of little use, and the cost projections for the new reactors show significant variations. Some recently published overnight costs for GEN-III reactors vary from $1,600/kWe to $4,700/kWe [8].

For the GEN-IV systems that are in the early stages of development, appropriate contingencies should be applied. The GIF cost estimating guidelines give the basis for establishing contingency rates to achieve a desired confidence level [3]. The contingency rates decrease as the system development progresses from the R&D stage to the project stage. In this study, a sensitivity analysis was performed to account for the uncertainty in the overnight costs in the range of –15% to +50%. The costs are for N^{th} of a kind (NOAK) project expressed in 2007 constant United States dollars. According to GIF guidelines, NOAK costs are achieved when 8 GWe of capacity has been constructed for a particular nuclear energy system [3].

2.1.2 Financing Costs

The time value of money is an important factor because of the large investment required for nuclear power plants. The interest paid on the capital during the construction period is accrued until commercial operation, and impacts the total capital investment in the nuclear power plant. The finance cost depends on the finance structure (equity and loans) and the corporate structure (private or public). The IAEA economics methodology gives a rough rule of thumb for discount rates; 3% to 5% for government owned utility in a regulated market, 5% to 10% for private sector utility in a regulated market, and 10% to 15% for private utility operating in a de-regulated market [9]. The discount rate should be selected based on careful evaluation of the capital market for the proposed nuclear power plant. The total capital investment is amortized over the plant operating life using the discount rate. For the purpose of this study, a sensitivity analysis was performed over a range of discount rates from 5% to 10%.

2.1.3 Construction Time

Construction time also has a significant impact on the capital costs, as the interest during the construction period accumulates. Experience with GEN-III new-build projects shows significant cost overruns because of construction delays. Construction schedule improves with experience, as similar units are replicated starting with the first commercial plant. To account for this uncertainty, a sensitivity analysis was performed over a range of construction times from 4.5 years to 6 years. The cash flow during the construction period follows an S-shaped distribution in the G4-ECONS model [4].

There is also a significant uncertainty in the D&D costs at the end of the operating life due to a lack of data and regional variability in labour rates. The D&D costs in this analysis are assumed to be a fixed percentage (33%) of the overnight cost.

2.2 Fuel Cycle

The development of advanced nuclear fuel cycles for GEN-IV nuclear energy systems may be required for substantive improvements in overall safety, sustainability, economics, and proliferation resistance. The Canadian SCWR concept is based on the once-through thorium fuel cycle and the European HPLWR is based on the once-through enriched uranium fuel cycle.

Economic factors related to the use of advanced fuels will depend on aspects of all stages of the fuel cycle: source material, reprocessing, fabrication, irradiation fuel cycle, short term storage, and waste disposal. The particular details of the economics of each stage in the fuel cycle depend on the type of fuel cycle and fuel type.

2.2.1 Source Material

To date, fresh uranium has been the source material for ~90% of the world's commercial nuclear power reactors. Uranium resources are well documented and the historic costs are well known, however there is uncertainty in the future cost of uranium ore.

Thorium fuel is of interest as an alternative to uranium because of the abundant reserve (3-4 times more than uranium), relatively wide distribution in the world (particularly in China, India, and Turkey), and potential reductions in the decay heat and radiotoxicity of spent fuel. The irradiation of thorium produces fissile uranium but virtually no transuranics[1], which are the source of much of the long term decay heat and radiotoxicitiy in used nuclear fuel (UNF). Because thorium has no fissile component, the use of thorium-based fuels relies on fissile components derived from uranium or UNF. Use of plutonium from UNF, either alone or in combination with other transuranics, has the added advantages of reducing plutonium inventory, and reducing (through in-reactor transmutation) the transuranics inventory, which improves non-proliferation and environmental factors. Thorium based fuel is being considered for the Canadian SCWR concept because of these advantages.

[1] Transuranics are elements with atomic mass higher than uranium, including plutonium, americium and curium.

However, the cost of thorium and plutonium as source fuels is largely unknown as no commercial market exists. In many cases, the technology required to support such fuel cycles is still under development. Therefore, the uncertainty in the cost of advanced thorium fuel cycles must be taken into account when performing an economic analysis of the Canadian SCWR concept.

2.2.2 Reprocessing

If the source material is extracted from UNF, the UNF must first be reprocessed before it can be fabricated into fuel assembles to be inserted into the reactor. Currently, of the 435 reactors in operation worldwide, 30 reactors in Europe and several in Japan use reprocessed UNF [10].

The existing reprocessing plants use the Plutonium Uranium Redox EXtraction (PUREX) method; an aqueous chemical-based method for plutonium and uranium extraction from UNF. Pyroprocessing methods are high temperature-based alternatives to more conventional aqueous-based reprocessing methods. In lieu of aqueous or organic solvents, molten salts or metals are used in the separation process. There appears to be some advantages in the use of pyroprocessing methods over the PUREX process [11], but pyroprocessing methods have never been performed at an industrial scale.

The costs, per kg of UNF reprocessed, for the current PUREX method are well known. However, the content of fissionable material (e.g., uranium and plutonium) in the UNF varies with the type of reactor, original fuel type, burn-up and age of the UNF. Therefore, there is uncertainty in the amount of UNF that must be reprocessed to create sufficient source material. This translates to uncertainty in the costs associated with reprocessing.

2.2.3 Fabrication

The steps required to manufacture nuclear fuel are dependent on the selected fuel type. Uranium-based fuels require conversion, enrichment and fabrication. All of which are well defined with known costs. The fabrication costs of other fuel types, however, are less certain. For example, it is not clear what safety features the regulators will require to operate a commercial fabrication facility for fuels with a high concentration (>10%) of plutonium. Estimates of the mixed-oxide fuel costs and UNF reprocessing for thermal and fast reactors are available in the literature [12].

2.2.4 Short Term Storage and Waste Disposal

When removed from the reactor, all UNF must remain in storage until it is safe to handle. If the UNF is part of a partially closed or closed fuel cycle, it will remain in storage until reprocessing is required. Costs of short term storage are well known and can be calculated with minimal uncertainty. However, if the UNF is part of an open fuel cycle, the UNF may eventually be placed in a permanent waste disposal site; likely a deep geological repository (DGR). Although much research has been done on DGR's, commercial development has just begun. Costs are still evolving as new techniques are developed. The DGR cost is further impacted by the addition of advanced fuels, which have different long term decay heat and radiotoxicity in their UNF. More research is required to determine how this will affect the DGR. This uncertainty must be considered in the economic analysis of GEN-IV reactors.

3. HPLWR Economic Uncertainty Analysis

The HPLWR concept is a pressure-vessel type SCWR being designed by ten partners from eight European countries. This 1,000-MWe reactor concept evolves from the GEN-III European Pressurized Reactor (EPR).

An economic analysis of the HPLWR design was published in 2009, and it forecasted a 20% lower capital costs compared to the reference case of an Advanced Boiling Water Reactor (ABWR)[5**Erreur ! Source du renvoi introuvable.**]. The fuel cycle costs are expected to be slightly higher, but this increase is considered of minor importance due to the historically small influence of fuel cycle costs on the LUEC. In principle, the HPLWR economic analysis shows that savings are expected over conventional GEN-III designs. However, the report identifies that limited data are available restricting their confidence in the estimate.

Using the GEN-IV cost estimating guidelines, base estimates were established for the cost inputs. A sensitivity analysis was then preformed to quantify the effect each variable has on the TCIC ($/kWe), levelized unit fuel cost (LUFC, $/MWh), and LUEC ($/MWh).

3.1 Input Parameters

The HPLWR economic uncertainty analysis was based on the uncertainty of nine key cost estimation parameters. Table 1 below provides these parameters as well as the low, base and high cost estimates used in the uncertainty analysis.

Table 1: HPLWR Cost Estimation Parameters

Parameter	Units	Low	Base Estimate	High
Capitalized Costs[2]	$ Million	2,300	2,700	4,050
Real Discount Rate	%	5	8	10
Years to Construct	Years	4.5	5	6
Uranium Ore	$/lb U_3O_8	11.5	29	100
Enrichment Cost	Cost	80	110	135
% Enrichment	% U-235	7	8	9
Operational Life	Years	35	40	60
Non-Fuel Operating Costs	$ Million	85.5	95	104.5
Decommissioning(D&D) Costs	$ Million	680	800	1,200

[2] Total capital costs include: direct capital costs ($1,530 M), indirect capital costs ($700 M) and owners costs ($200 M). They are individually defined in the G4-ECONS model, but assumed to share a common uncertainty.

3.2 Individual Sensitivities

3.2.1 Individual Uncertainty in TCIC

The TCIC is all-inclusive of capital cost required to build the reactor per kilowatt electric installed, and includes interest during construction, which is dependent on both the real discount rate and the construction period. The effect of various cost inputs on the TCIC was analysed and displayed using a tornado diagram, which is a graphical method to view the results of a deterministic sensitivity analysis. It was found that the TCIC for the HPLWR is strongly affected by the uncertainty related to the capitalized costs and the real discount rate (Figure 1). There is less uncertainty associated with the years to construct the HPLWR; thus the effect of this uncertainty on TCIC is limited.

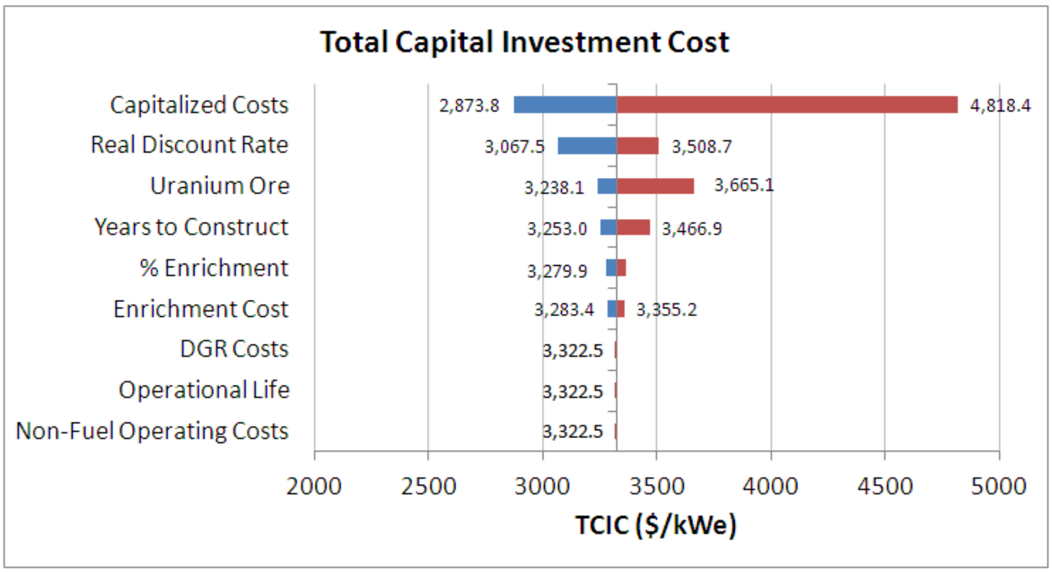

Figure 1: Total Capital Investment Cost Tornado Diagram

In addition, fuel cycle costs, such as the cost of uranium ore, the enrichment percentage and the enrichment cost, have some affect on the TCIC, as the first fuel core required to start the reactor is classified as a capital cost in the G4-ECONS model.

3.2.2 Individual Uncertainty in LUFC

The LUFC is an indicator of the front end (materials, enrichment and fabrication) and the back end (on-site storage and deep geological repository) costs per MWh. The tornado diagram of the LUFC sensitivity, Figure 2, shows that the uncertainty surrounding future uranium prices dominates the uncertainty in the LUFC estimate for the HPLWR. This uncertainty is followed by the % of enrichment, enrichment cost and a small sensitivity to the operational lifetime of the HPLWR.

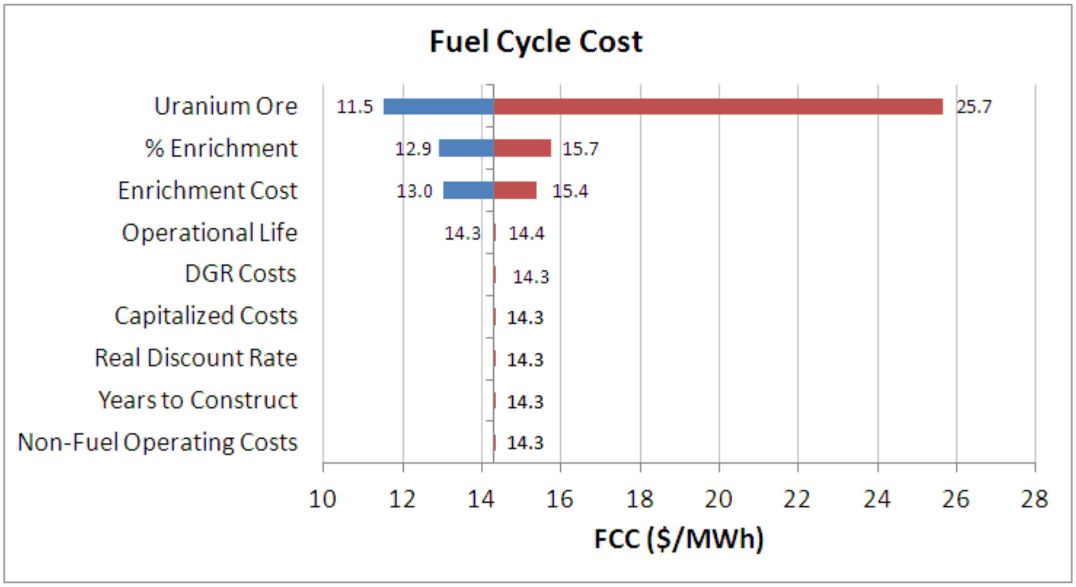

Figure 2: Fuel Cycle Cost (FCC) Tornado Diagram

3.2.3 Individual Uncertainty in LUEC

The LUEC measures the total cost of the reactor (i.e., capital, operations and fuel cycle costs), per MWh. As the tornado diagram in Figure 3 below shows, the LUEC for the HPLWR is most sensitive to the uncertainties in the real discount rate, capital costs and the future costs of uranium ore.

As evident from Figures 1 to 3, the D&D costs have insignificant impact on TCIC, LUFC and LUEC.

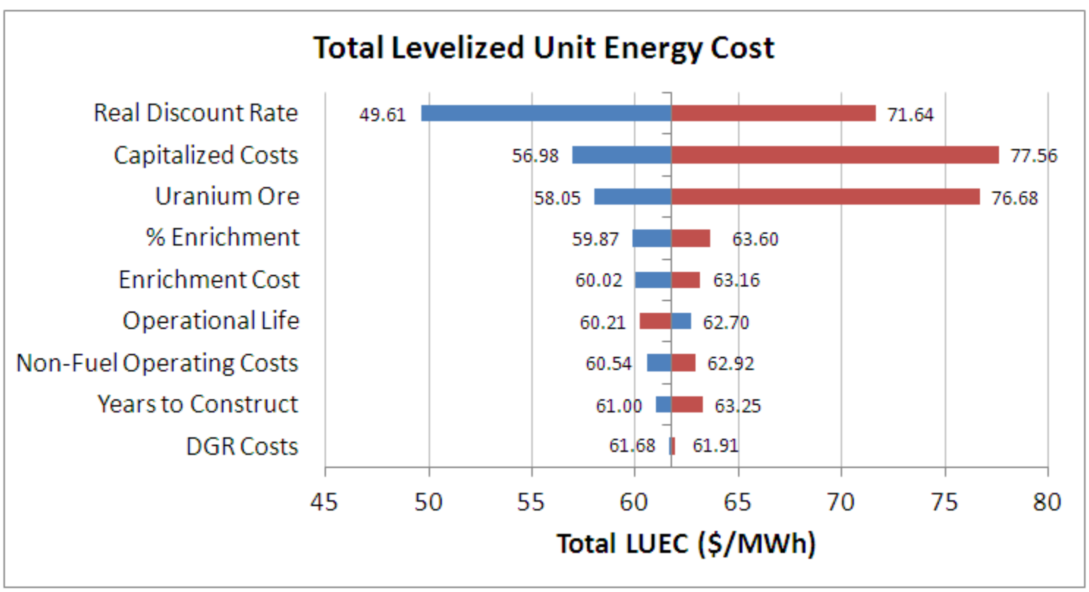

Figure 3: Total Levelized Unit Energy Cost (LUEC) Tornado Diagram

3.3 Economic Viability Estimates

The analysis that is depicted above in the tornado diagrams identifies key variables, which have the largest potential impact to the economic viability of the HPLWR. To determine the full range of potential outcomes, these impacts must be considered concurrently. As such, a cumulative probability analysis was performed, but restricted to the most influential seven variables[3]. Since each variable has three scenarios (low, base, high), there are 3^7 = 2,187 possible outcomes to consider. By assuming that each possible outcome has an equal probability of occurring, an 80% confidence interval is developed for the TCIC, LUFC and LUEC.

3.3.1 Impact of Uncertainty in TCIC

The TCIC estimates are calculated for the NOAK, focusing on the long term economic viability of the HPLWR concept. At its current state of development, uncertainties in the reactor concept still exist; this is reflected in the cumulative distribution in Figure 4 below. There is a 50% probability that the TCIC will be less than $3,405/kWe, with the 80% confidence interval ranging from $2,798/kWe to $5,047/kWe. In 2010, the Nuclear Energy Agency (NEA) estimated the overnight capital costs for a GEN-III 1,400-MWe nuclear reactor to be $4,101/kWe [13], and the World Nuclear Association website [8] shows a range of $1,600/kWe to $4,700/kWe in the published cost of recently proposed GEN-III reactor projects. Therefore, with the existing uncertainty, although cost reductions are possible, the economic viability of the HPLWR is inconclusive in terms of the TCIC.

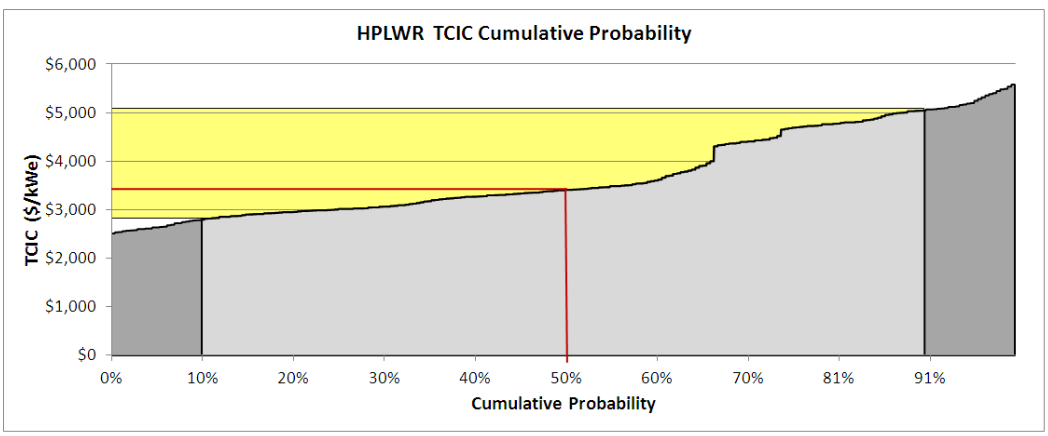

Figure 4: TCIC Cumulative Probability Curve

3.3.2 Impact of Uncertainty in LUFC

The cumulative probability curve for the LUFC of the HPLWR is shown in Figure 5 below. The median cost is $14.23/MWh, with the 80% confidence interval ranging from $10.48 to $26.99/MWh. The NEA estimated the LUFC for Generation-III reactors as $9.33/MWh [13]. As indicated in the HPLWR report, the fuel costs are slightly elevated over the average GEN-III

[3] The uncertainty in the D&D cost and in the years to construct were shown to have little effect on the TCIC, LUFC and LUEC measures (see section 3.1). Therefore, they were removed for the cumulative probability analysis.

reactor; primarily due to the higher enrichment compensating the neutron absorption of the stainless-steel cladding required for the super-critical operating conditions.

The cumulative probability curve for the LUFC of the HPLWR shows that LUFC could reach as high as $26.99/MWh. However, as discussed above (Figure 2), the uncertainty in the LUFC is primarily a result of uncertainty in future cost of uranium ore; this would also affect all GEN-III uranium fuelled reactors. Therefore, this large uncertainty is less likely to affect the economic viability of the HPLWR compared to GEN-III reactor designs.

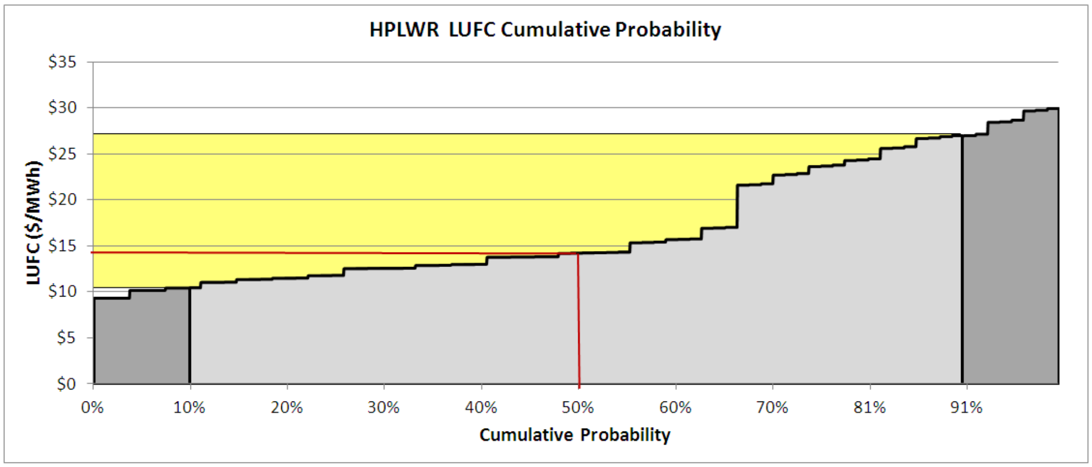

Figure 5: LUFC Cumulative Probability Curve

3.3.3 Impact of Uncertainty in LUEC

Based on the cumulative probability curve, Figure 6, there is a 50% probability that the LUEC of the HPLWR is at most $65.57/MWh. Furthermore, there is an 80% confidence that the LUEC is between $47.52/MWh and $90.52/MWh.

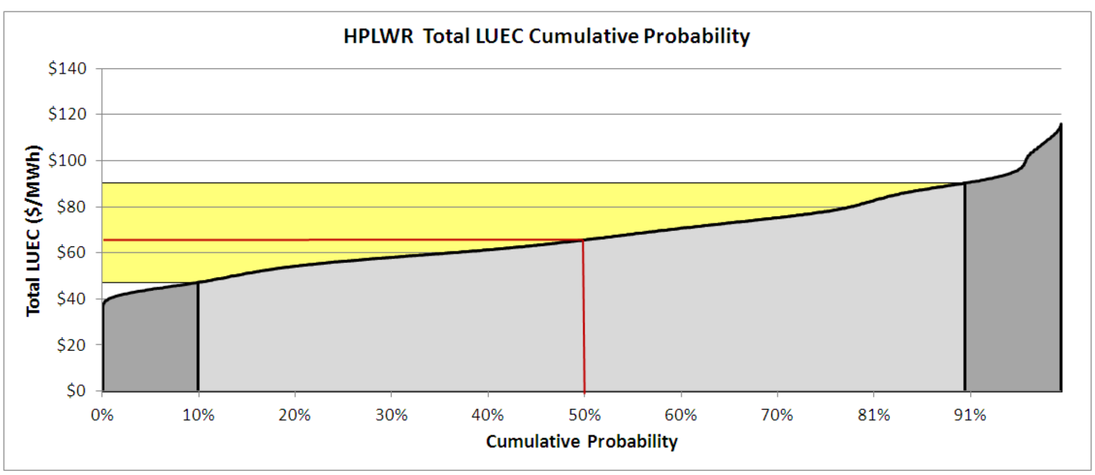

Figure 6: LUEC Cumulative Probability Curve

The NEA estimated the LUEC, for GEN-III reactors, at $58.53/MWh with a 5% discount rate and $98.75 with a 10% discount rate [13]. In comparison to the NEA estimate, a reduction in LUEC could be achieved with the HPLWR. The HPLWR report**Erreur ! Source du renvoi introuvable.** [5] also contains a sensitivity analysis with a narrow range of capital cost (-20% to 0% with respect to the reference case) and reported a range of LUEC between $24/MWh to $62/MWh. With the high uncertainties assumed for the capital costs and broad range of uranium ore costs assumed in this study, the 80% confidence interval is too broad and overlaps the LUEC ranges reported for GEN-III reactors.

4. Conclusions

Although the decision makers would like to know the LUEC for the next generation nuclear systems in the early stages of their development, there is a high level of uncertainty in the cost estimates and the sensitivity analyses must be performed over a sufficiently broad range of cost parameter values. The two main components of the LUEC, with relatively large uncertainties are the capital costs and the fuel costs.

Capital costs are the largest contributor to the LUEC, yet the cost estimates are based on limited design information available at the concept development stage, and therefore, larger rates of contingencies (e.g., -15% to +50% assumed in this study) must be considered. Novel fuel cycles being considered for the next generation nuclear energy systems further complicate the analysis as some of the fuel reprocessing and fabrication technologies have not yet been deployed. For example, for the Canadian pressure-tube type SCWR concept, using once through thorium cycle, the thorium ore is not yet commercially mined, resulting in the uncertainty in the cost of the ore and fuel fabrication.

The other parameters that might have some uncertainties, but only minor influence on the LUEC include the construction time, operational life, and non-fuel operating and maintenance costs. The future cost of ore also has a strong influence on the economics, but it is not unique to the GEN-IV systems. An increase in the cost of uranium ore would not affect the economics of GEN-IV systems that do not utilize freshly mined uranium, while negatively impacting comparable uranium-fuelled GEN-III designs. This could result in a greater economic advantage for the GEN-IV fast-reactor systems employing closed fuel cycles. The same may not be the case for uranium-fuelled GEN-IV concepts.

Finally, the economic environment strongly influences the economics of the GEN-IV nuclear reactors. The capital costs are highly sensitive to the location where the reactor is built. For some countries, where a new reactor has not been built in the last two decades, a reference reactor may not exist for the current construction environment. The financing cost is directly related to the operating environment (ex. public or private), and has a major influence on both the LUEC and the TCIC. Therefore, the discount rate must be carefully selected considering the capital market.

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