COST ESTIMATION WITH G4-ECONS FOR GENERATION IV REACTOR DESIGNS

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I. INTRODUCTION

The Economic Modeling Working Group (EMWG) was created by Generation IV International Forum (GIF) early in the Generation IV process. The Group was charged with developing a methodology to assess the progress of the Generation IV systems in achieving the economic goals established by the GIF Policy Group. The objective was to establish a simplified cost estimating methodology appropriate for Generation IV systems in various stages of development.

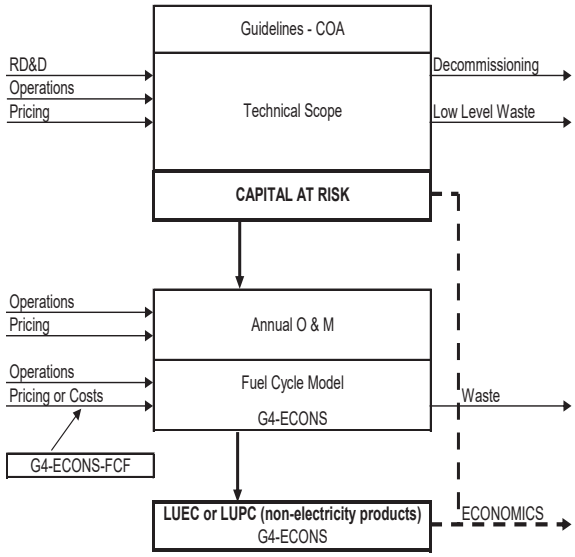
The GIF Cost Estimating Methodology has been developed and tested by the EMWG. It consists of 1) The Generation IV Cost Estimating Guidelines and 2) a software package, G4-ECONS, to facilitate the implementation of the Guidelines.

In this paper, the results of an application of G4-ECONS on the Generation IV systems is presented. The study was part of an independent determination and assessment of plant design characteristics of future nuclear reactor designs and their associated fuel cycles. All six Generation IV designs have been assessed and compared to a reference Generation III design.

II. GIF COST ESTIMATING GUIDELINES AND G4-ECONS

The GIF Cost Estimating Guidelines provide a comprehensive approach for assessing the performance of Generation IV systems in achieving the established economic goals [1, 2]. The methodology may be used to assess the cost structure of the Generation IV systems in comparison with Generation III systems, identify cost drivers and possibilities for design improvement in this regard. The Guidelines provide detailed processes for developing the total capital investment and calculating the levelized unit electric cost. The overall structure of the cost estimating methodology is shown in Figure 1.

Figure 1: Structure of the GIF cost estimating methodology [2]



The central feature of the methodology is the comprehensive Code of Accounts. The Code of Accounts (COA) provides a disciplined structure for capturing and categorizing all appropriate costs in the development of a consistent system cost estimate.

Because the Generation IV systems will for some time be in varied states of development and maturity, a "top down" approach with scaling factors is considered for the cost estimation.

To facilitate implementation of the Cost Estimating Guidelines, the EMWG developed

an EXCEL based spreadsheet package, G4-ECONS. For this study, G4-ECONS version 2.0 was used [3, 4]. Levelized unit electric cost is calculated, as well as its components capital, O&M and fuel cycle costs.

III. SELECTED GENERATION IV REACTOR DESIGNS AND FUEL CYCLES

Reactor design was not part of the study, therefore existing design data have been used from other studies. For each Generation IV system [5], a design basis has been selected. Also, as most data were available for near term application of the system, an HTR design has been selected instead of a "real" VHTR (with outlet temperatures above 1 000°C), and the fast reactor fuels have been selected as MOX based, instead of the more advanced nitride, carbide or metal fuels.

The following reactor designs have been selected to represent the six Generation IV concepts in this study:

- HTR: HTR-PM. This is a twin pebble bed high temperature reactor, based on the German HTR Modul design [6]. It is currently under construction in China. The fuel is enriched uranium oxide in the form of coated particles in pebble fuel.
- SFR: European SFR. This is a sodium cooled fast reactor based on design of European Commission R&D project ESFR [7], Phénix, Superphénix, and EFR design experience. The fuel is fast reactor MOX fuel.
- LFR: European LFR. This is a lead cooled fast reactor based on the European Commission R&D projects ELSY [8] and its follow-up project LEADER. The fuel is fast reactor MOX fuel.
- GFR: European GFR. This is a gas cooled fast reactor based on the European Commission R&D projects GCFR [9] and its follow-up project GoFastR. The fuel is fast reactor MOX fuel.
- SCWR: European SCWR. This is a super-critical water reactor based on the European Commission R&D projects HPLWR1 and its follow-up project HPLWR2 [10], and the Japanese design JSCWR. It was largely based on the German Gundremmingen BWR. The fuel is LWR MOX fuel.
- MSR: US American MSBR. This is a thermal molten salt breeder reactor, designed by Oak Ridge National Laboratory around 1970 [11]. The fuel is thorium molten salt.

These reactor designs are being compared with a reference Generation III design, in order to allow intercomparison of the Generation IV designs. The reference Generation III design selected is the EPR as under construction in Finland, France and China, by the French vendor Areva.

The selected designs have very much different power levels, as illustrated by Figure 2. In addition, the thermal conversion efficiency figures used in this study have been collected from the available literature, and shown in Figure 3.

Figure 2: Power levels of the six selected Generation IV designs and the reference Generation III design

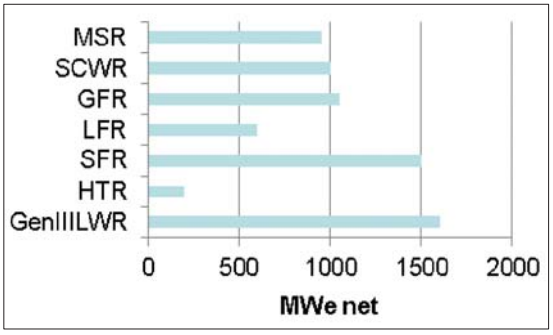
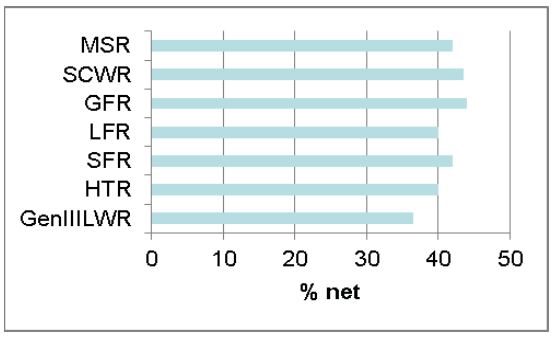


Figure 3: Efficiency figures of the six selected Generation IV designs and the reference Generation III design



IV. COST ESTIMATE RESULTS

Construction costs have been estimated by scaling from known cost distributions and adaptation by expert judgement. This methodology is elaborately described in [12].

First, the relative distributions of the costs for different reactor types are collected from literature sources for the construction cost accounts 2 to 4. Then, following the GIF EMWG COA [1], the overnight construction cost components of the different reactor types are estimated relative to the construction costs of a reference plant which are put to 100%.

One of the main considerations for each code of account is to scale reactor data to the reference plant data with the net electric (or thermal) power. The scaling relationship in the equation below has been employed, using different scaling factors for reactors employing a small (up to 20%) and a large difference in net electric (or thermal) power [13].

$$Cost_{new} = Cost_{ref} \left(\frac{Power_{new}}{Power_{ref}} \right)^{a}$$

in which "$Cost_{new}$" and "$Cost_{ref}$" are the costs of the considered plant and the reference plant respectively, "$Power_{new}$" and "$Power_{ref}$" are the power levels of the considered plant and the reference plant respectively, and "a" is the scaling factor.

Besides scaling to power level, other considerations may lead to increase or decrease certain accounts with respect to the accounts of the reference design. For example, the reactor vessel and other reactor plant equipment may be expected to pay a larger contribution to the overnight construction costs for Generation IV reactors than for Generation III reactors because of the application of more expensive materials which can withstand elevated temperatures and more demanding coolants. Also the vessel size, related to power density, and pressure may be different. Other considerations include:

- Space requirements.
- Containment size.
- Application of passive safety systems.
- Need for an intermediate circuit.
- Complex fuel handling in HTR, the FR and MSR.
- Use of chemically highly reactive sodium as coolant in SFR.
- Use of Rankine vs. Brayton cycle.

In this way, construction costs and their distribution have been determined for the six systems in relation with the reference Generation III design as indicated in Figures 4 and 5. The ranges indicated in Figure 4 are derived from the contingency figures from INL [13], increased by a factor 1.5 because of these figures come from an older (1995) study on the ALMR, a relatively proven SFR design compared to most other Generation IV concepts.

Figure 4: Overnight construction cost ranges

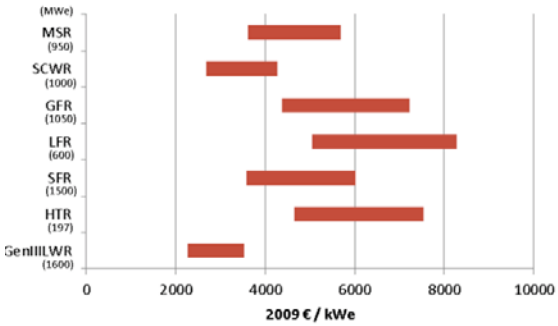
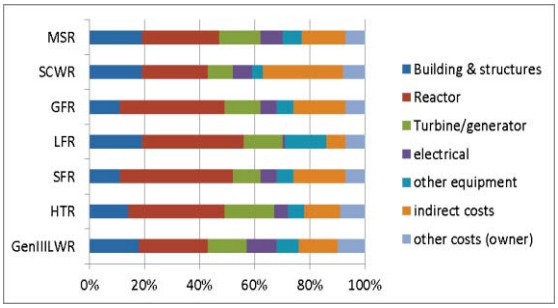


Figure 5: Distribution of the costs over the main cost components



The relatively high costs of the LFR can be attributed to the small power level compared to the SFR while in the current assessment the benefits of small reactor designs allowing for modular construction and increasing the learning curves are not considered. For the MSR, it should be known that the fuel processing plant equipment costs are included in the construction costs.

Also cost ranges have been determined for the Operation and Maintenance costs, as shown in Figure 6. They are based on various literature sources.

The Fuel cycle costs are shown in Figures 7 and 8, divided into front-end and back-end costs. When estimating costs for Generation IV reactor fuel cycles, accounting for non-

conventional fuels is needed. Compared to the reference Generation III LWR, the pebble bed HTR has a large number of fuel assemblies, a small amount of heavy metal mass per fuel assembly, a small amount of elements per reload and a short time between refuellings (simulating continuous on-line reloading). A similar definition has been used for the MSR, with continuously reloaded liquid fuel simulated by "very small fuel assemblies". A workaround simulation thorium fuel had to be introduced, as the thorium fuel cycle was not included yet in this version of G4-ECONS. In the model, thorium has been taken for uranium, and uranium for plutonium.

Figure 6: Operation and maintenance cost ranges

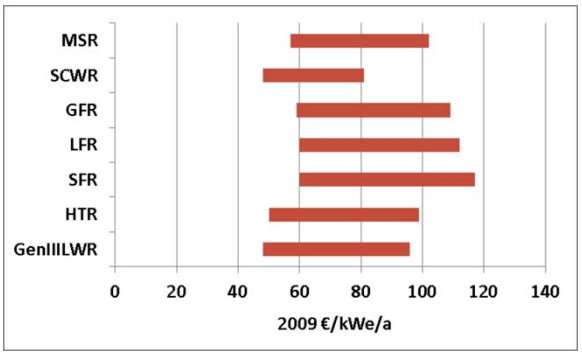
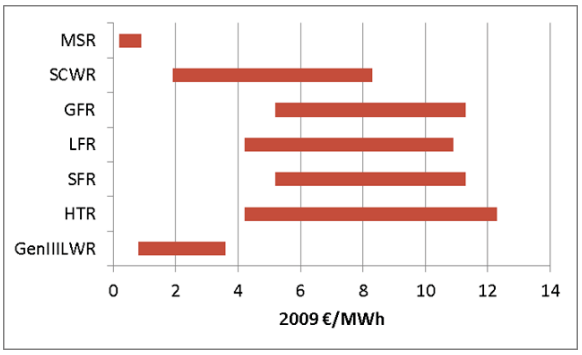
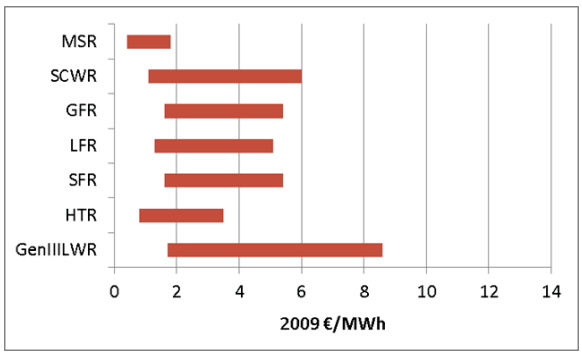


Figure 7: Front-end fuel cycle cost ranges



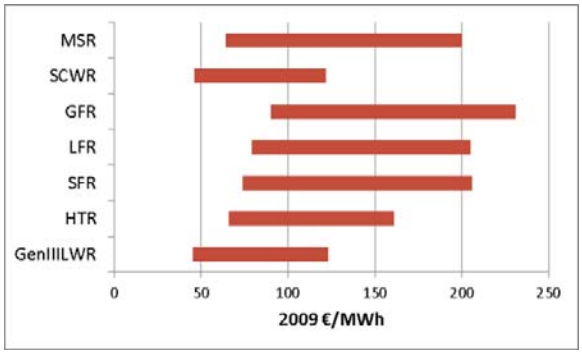
It can be observed that all Generation IV designs except the MSR show increased front-end costs due to more costly fuel fabrication. The MSR costs are low because of the absence of fuel element fabrication and dismantling. Also, the MSR fuel processing costs are in the investment costs, not in the fuel cycle costs. On the other hand, the back-end costs for all Generation IV designs are low compared to the Generation III reference design.

Figure 8: Back-end fuel cycle cost ranges



Taking construction costs, O&M and fuel cycle costs together, the levelized electricity generating cost (LUEC) ranges have been calculated, as shown in Figure 9. The discount rate has been set on 10%.

Figure 9: Levelized electricity generating cost ranges



It can be observed from Figure 9 that only the SCWR has electricity generating costs comparable to the reference Generation III LWR; all other designs have higher generating costs. On the other hand, the ranges are wide, and are overlapping for all systems. Also, special cost-influencing features for specific reactor systems, like cogeneration for the HTR, or invulnerability against very high uranium prices for the fast reactor systems, have not been investigated.

V. CONCLUSIONS

The Generation IV Cost Estimating Methodology appeared to be very suitable to produce a consistent cost evaluation of the six Generation IV Systems. All selected Generation IV reactor systems have higher specific construction costs, compared to the reference Generation III LWR design. Also the front-end fuel cycle costs are mostly higher, a price being

paid to decrease the back-end fuel costs. When regarding electricity as the only product, and within the current circumstances like uranium price and discount rate, only the SCWR equals the electricity generating cost range of the reference Generation III LWR, all other systems have higher generating costs. However in general, the cost results still come with large uncertainties, and should be regarded as preliminary. The economic assessments can then be improved and uncertainties reduced as the designs mature.

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