

Estimating Costs of Generation IV Systems

Summary / Objectives:

This webinar will provide an overview of the Economic Modelling Working Group's Cost Estimating Guidelines for Generation IV Nuclear Energy Systems (GIF, 2007). Topics include an overview of the Guidelines, a comparison of the Guidelines with other nuclear power plant cost estimating models, and a discussion of benchmarking activities by the EMWG with INPRO.

Meet the Presenter:

Dr. Geoffrey Rothwell since 2013 has been the Principal Economist of the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD, Paris, France), where he acts as the Secretariat for the Economic Modelling Working Group (EMWG). For EMWG he wrote the TOR in 2003 as the Chair of the Economics Cross-cut Group of the Generation IV Roadmap Committee. He was active in writing the Cost Estimating Guidelines for Generation



IV Nuclear Energy Systems (GIF, 2007). While teaching at Stanford University from 1986-2013, he consulted to Idaho, Oak Ridge, and Pacific Northwest, and Argonne National Laboratories, for whom he updated the University of Chicago's 2004 report, The Economic Future of Nuclear Power, published as The Economics of Nuclear Power, Routledge, London, 2016. Dr. Rothwell grew up in Richland, Washington, and received his PhD in economics from the University of California, Berkeley.

Looking back over the startup phase of the GIF-EMWG:

Economic Modeling Working Group (EMWG) created to define the economic criteria for selecting GIF supported technologies (GIF systems) by the cross-cutting Evaluation Methodology Group (EMG) composing the early Gen-IV Roadmap Committee which selects GIF systems. Two economic criteria: EC-1 low total capital investment cost, and EC-2 low average cost, leveled unit energy costs, LUEC were selected, “Cost Estimating Guideline” and a transparent cost estimating tool, G4-ECONS, were developed by EMWG in 2007.

EVALUATION METHODOLOGY GROUP, EMG (2001-2003) GENIV International ForumSM

The EMG was tasked with developing a multi-criteria evaluation to be applied by the technical working groups to some 80 variants of nuclear energy systems for the selection of the most promising technologies.

The EMG developed four sets of criteria:

- (1) safety
- (2) economic
- (3) sustainability
- (4) non-proliferation and physical protection

The economic goals were

- (1) To have a clear life-cycle cost advantage over other energy sources, and
- (2) To have a level of financial risk comparable with other energy projects

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GIF EMWG-2007/004 GENIV International ForumSM

COST ESTIMATING GUIDELINES FOR GENERATION IV NUCLEAR ENERGY SYSTEMS
Revision 4.2
September 26, 2007

Prepared by
The Economic Modeling Working Group
Of the Generation IV International Forum

GENIV International ForumSM

Printed by the OECD Nuclear Energy Agency
for the Generation IV International Forum
https://www.gen-4.org/gif/upload/docs/application/pdf/2013-09/emwg_guidelines.pdf

The EMG defined the Terms of Reference for the GIF Methodology Working Groups, one of which was the Economic Modeling Working Group (EMWG), which prepared the *Cost Estimating Guidelines for Generation IV Nuclear Energy Systems* (2007).

The “*Cost Estimating Guidelines*” defined a *Code of Accounts (COA)* with which the *TCIC* and *LUEC* are defined.

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Code of Accounts and LUEC:

GIF Code of Account (COA) developed for estimated LUEC. COA is bottom-up approach to accumulate the total capital investment cost (TCIC). LUEC composed by annualized TCIC, Operation and Maintenance (O&M), and Fuel costs.

LEVELISED UNIT ENERGY COST (LUEC) in dollars, euros, etc. per megawatt-hour = GENIV International ForumSM

KC Capital Cost is equal to the payments each year to the banks and investors, like a annual mortgage payment, to pay down the **Total Capital Investment Cost** ← **Step 1: Calculate KC from TCIC**

O&M is the annual Operations and Maintenance (O&M) expense and Capital Additions, CAPEX ← **Step 2: Calculate O&M and FUEL**

FUEL is the annual fuel payment, a function of the amount and price of fuel

E the sum of which is divided by the annual energy output in megawatt-hours (MWh) equal to the product of MW, the size of the generator in megawatts, TT, the total number of hours in a year, and CF, the Capacity Factor ← **Step 3: Divide by E and calculate LUEC**

Source: Rothwell, Economics of Nuclear Power (2016, p. 154). London: Routledge.
<https://www.routledge.com/Economics-of-Nuclear-Power/Rothwell/p/book/9781138858411>

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The GIF Code of Accounts (COA): GENIV International ForumSM

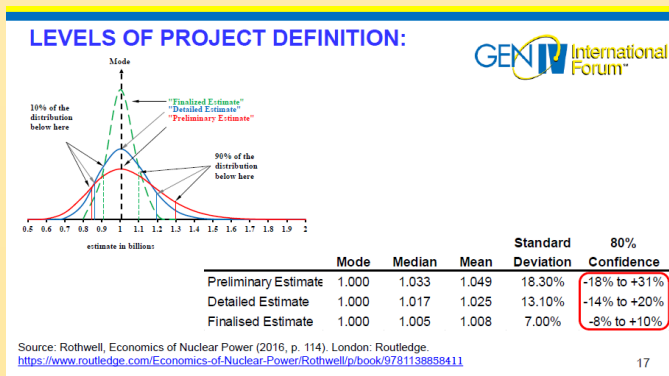
Account Number	Account Title
10	Capitalized Pre-Construction Costs
20	Capitalized Direct Costs
21	Structures and Improvements
22	Reactor Equipment
23	Turbine Generator Equipment
24	Electrical Equipment
25	Heat Rejection System
26	Miscellaneous Equipment
27	Special Materials
30	Capitalized Indirect Services Costs
35	Design Services Offsite
36	PM/CM Services Offsite
37	Design Services Onsite
38	PM/CM Services Onsite
-	Base Construction Cost
+ 40	Capitalized Owner's Costs
+ 50	Capitalized Supplementary Costs
+ 55	Initial Fuel Core Load
-	Overnight Construction Cost
+ 60	Capitalized Financial Costs
+ 63	Interest During Construction
+ 19+29+39+49+59+69	Contingencies
=	Total Capital Investment Cost

Account Number	Account Title
70	Annualized O&M Costs
71	O&M Staff
72	Management Staff
73	Salary-Related Costs
74	Operations Chemicals and Lubricants
75	Spare Parts
76	Utilities, Supplies, and Consumables
77	Capital Plant Upgrades
78	Taxes and Insurance
79	Contingency on Annualized O&M Costs
80	Annualized Fuel Cost
81	Refueling Operations
84	Nuclear Fuel
86	Fuel reprocessing Charges
87	Special Nuclear Materials
88	Contingency on Annualized Fuel Costs
90	Annualized Financial Costs
92	Fees
93	Cost of Capital
99	Contingency on Annualized Financial Costs

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TCIC:

TCIC composed by Direct cost, Indirect Services Costs, Owner's Costs, financial cost, interest during construction (IDC) and contingencies. TCIC except financial, interest and contingency costs is called as overnight cost. Some case consider Initial Fuel Core Load cost as fuel cost but this case consider this as TCIC because this cost is significant as initial cost. The overnight cost of Molten Salt Reactor (MSR) estimated by Oak Ridge National Laboratory (ORNL) was \$3350/kWe (2011USD) for example. IDC estimated depend on construction period. Estimation of appropriate contingency is needed. The rate of contingency could be decrease in stage of project definition. TCIC was estimated by ORNL in 2011 as \$3149/kWe for the Advanced High Temperature Reactor (AHTR) System with 9% enriched uranium compare with \$4012 of PWR12 for example.



TOTAL CAPITAL INVESTMENT COST

Advanced High Temperature Reactor Systems and Economic Analysis calculates the TCIC for a "Better Experience" BE ("Nth-of-a-Kind") version of the PWR-12 and compares it with 19.75% and 9% enriched uranium for the AHTR. However, these estimates do not include contingency, which would "increase the cost estimate by at least 25%" (p. 88)

Capital cost, in millions of 2011 dollars (enrichment)	PWR12 3%	AHTR 19.75%	AHTR 9.00%
Capitalized preconstruction costs (accounts 11-19)	\$6	\$6	\$6
Capitalized direct costs (accounts 21-29)	\$2,171	\$2,301	\$2,301
Capitalized support services (accounts 31-39)	\$1,323	\$1,323	\$1,323
Capitalized operations costs (accounts 41-49)	\$300	\$300	\$300
Overnight cost without initial fuel load	\$3,800	\$4,019	\$4,019
Initial fuel load	\$135	\$419	\$111
Total overnight cost with initial fuel load	\$3,935	\$4,438	\$4,130
Interest during construction (calculated)	\$655	\$739	\$688
Total Capitalized Investment Cost (TCIC)	\$4,590	\$5,177	\$4,818
Reactor net electrical capacity (MW)	1,144	1,530	1,530
Specific TCIC (\$/kWe)	\$4,012	\$3,384	\$3,149

O&M and Fuel Costs:

Such kind of staffing cost and repair cost are estimated as O&M cost. Decontamination & Dismantling (D&D) cost are estimated as contributions to a sinking fund. Fuel cost includes front end and backend cost. Fuel cost was estimated as \$10.74/MWh for AHTR System with 9% enriched uranium compare with \$5.60 of PWR12 for example.

ANNUAL O&M COSTS IN G4ECONS

System 80+ (PWR that became the APR1400)	
70 OPERATIONS COST CATEGORY	
71+72 On-site Staffing Cost (71: non-mgt 72: mgt)	31.50 \$/Myr
73 Pensions and Benefits	8.29 \$/Myr
74+76 Consumables	18.84 \$/Myr
75 Repair costs including spare parts and services	10.93 \$/Myr
77 Capital replacements/upgrades (levelized)	0.00 \$/Myr
78 Insurance premiums & taxes & fees	11.12 \$/Myr
79 Contingency on O&M	0.00 \$/Myr
70 Total O&M	78.47 \$/Myr
Annualized D&D cost per MWh	0.27 \$/MWh
Total O&M + D&D	8.61 \$/MWh
58 Decontamination & Dismantling (D&D)	
Sinking fund interest	5% Yr
Sinking fund factor	0.83% Yr
40 yrs	
Annualized D&D	2.48 \$/Myr

Annual D&D costs are calculated as contributions to a sinking fund, earning the same rate of return as the weighted average cost of capital, r :

$$A = D \cdot D \cdot \left(\frac{r}{1 - (1 + r)^{-N}} \right)$$

where D&D is a fraction of Direct Cost (Account 20), e.g., 33%

ANNUAL FUEL COSTS

$$FC = NU \cdot P_{UF6} + SWU \cdot P_{SWU} + P_{FAB}$$

NU is the ratio of natural uranium input to enriched uranium output,
 P_{UF6} is the price of natural uranium input plus its conversion to UF₆,
 SWU is the number of Separative Work Units (SWU) required in enrichment,
 P_{SWU} is the price of enriching uranium hexafluoride, UF₆,
 P_{FAB} is the price of fabricating UO₂ fuel from enriched UF₆, and

$$F = \left\{ \frac{FC}{24 \cdot B \cdot \text{eff}} + \text{WASTE} \right\} \cdot E$$

FC is the cost of nuclear fuel in US dollars per kilogram of uranium (US\$/kgU),
 24 is the number of thermal MWh in a thermal megawatt-day,
 B is the burnup rate measured in thermal megawatt-days per kgU,
 eff is the thermal efficiency of converting MW-thermal into MW-electric,
 WASTE is the interim storage cost per MWh

Source: Rothwell, Economics of Nuclear Power (2016, p. 156). London: Routledge.
<https://www.routledge.com/Economics-of-Nuclear-Power/Rothwell/p/book/9781138858411>

Cost estimation of LUEC by ORNL and NEA:

ORNL estimated as \$30.56 /MWh for System 80+, \$48.18/MWh, \$43.05/MWh for AHTR System with 9% enriched uranium. NEA is regularly reporting the estimated levelized cost of each countries. Relatively low overnight cost was estimated for AR1400 in Korea and AP1000/CPR1000 in China.

LEVELISED COSTS IN ORNL (2011)
TABLE 54: LUEC IN \$/MWH (p. 85):

Year of estimate/dollars	System	PWR12 2001	AHTR BE 2011	AHTR 19.75% 2011	AHTR 9% 2011
Capital cost recovery		\$17.40	\$29.66	\$24.47	\$22.77
Operation and maintenance		\$8.61	\$12.60	\$9.31	\$9.31
Fuel cycle costs		\$4.28	\$5.60	\$17.54	\$10.74
Decommissioning fund		\$0.27	\$0.32	\$0.23	\$0.23
Levelized unit cost of electricity		\$30.56	\$48.18	\$51.55	\$43.05
Total capital investment cost, \$/kW(e)		\$2,092	\$4,012	\$3,384	\$3,149

COMPARE WITH LEVELISED COSTS IN NEA/IEA (2015)
<http://www.oecd-nea.org/ndd/egc/2015/>

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LEVELISED COSTS IN NEA/IEA (2015)
TABLE 3.4: LCOE IN \$/MWH (p. 41):

Country	Tech	Site MWe	Over night \$/MWe	Investment cost			Refurbish and D&D			Fuel/ waste \$/MWh	O&M \$/MWh	LCOE			
				3%	7%	10%	3%	7%	10%			3%	7%	10%	
				USD\$/MWh	USD\$/MWh	USD\$/MWh	USD\$/MWh	USD\$/MWh	USD\$/MWh			USD\$/MWh	USD\$/MWh	USD\$/MWh	
Belgium	Gen III	XXXX	9 061	26.99	60.09	82.29	0.46	0.08	0.02	10.46	13.58	11.45	66.13	64.17	116.81
Finland	EPR	1 600	9 250	27.89	62.09	85.87	0.44	0.06	0.01	5.09	14.59	48.01	66.52	81.83	115.57
France	FWR-EPR	1 630	9 067	26.91	59.92	82.53	0.40	0.06	0.01	9.33	13.33	49.98	64.63	82.64	115.21
Hungary	AES-2006	1 180	6 215	32.30	69.68	104.89	1.59	0.28	0.06	9.60	10.40	53.90	70.66	89.94	124.95
Japan	ALWR	1 152	3 083	20.62	45.92	70.90	0.42	0.07	0.02	14.15	27.43	62.63	73.80	87.57	112.50
Korea	APR 1400	1 343	2 021	10.41	22.20	33.15	0.00	0.00	0.00	8.98	9.86	28.63	34.05	40.42	51.37
Slovakia	YYR 440	535	4 986	26.65	59.85	83.05	4.65	1.50	0.83	12.43	10.17	53.90	66.68	83.95	116.48
UK	2-3 PWRs	3 300	6 070	31.59	68.42	103.46	0.54	0.09	0.02	11.31	20.93	64.38	80.88	100.25	135.72
US	ABWR	1 400	4 100	30.75	54.86	79.16	1.26	0.52	0.26	11.33	11.00	54.34	64.81	72.21	101.26
Non-OECD member countries															
China	AP 1000	1 250	2 615	13.89	30.92	47.75	0.23	0.04	0.01	9.33	7.32	30.77	34.57	47.61	64.40
	CPR 1000	1 000	1 807	9.60	21.37	32.99	0.16	0.03	0.01	9.33	6.50	29.59	33.05	42.23	48.83

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Benchmarking G4-ECONS and NEST developed by IAEA:

NEST was developed in 4 phases by IAEA, and it was extended to treat designs of break-even closed fuel cycle and multiple conversion rates in Version 4. The benchmark study between G4-ECONS and NEST was carried out with selected thermal reactor (high performance LWR by KIT) and fast reactor (BN-800 by Rosatom) and identified little deference but not

ADJUSTED HPLWR RESULTS

Fig. 1: Levelized Unit Fuel Costs

Fig. 2: Levelized Unit Energy Costs

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BENCHMARKING CONCLUSIONS:

There were three key differences in the fuel cycle assumptions between NEST and G4ECONS: how the initial core is financed, how UNF is disposed of, and the cost of recycled material (Pu) for the initial core. The G4ECONS LUEC results were adjusted to better align with NEST assumptions.

- For the HPLWR, the difference between NEST and G4-ECONS LUEC results were negligible (<0.5%), except for NEST v3s2 which underestimates the cost of the initial core resulting in a difference of 6%.
- For the Break-Even Fast Reactor, the differences between NEST and G4-ECONS LUEC results were within 1% and less than the differences between the NEST systems.
- For the Bumer Fast Reactor, the NEST and G4-ECONS LUEC results were found to be within 0.5%.

Future versions of G4ECONS will consider revising their fuel cycle assumptions to improve harmonization across the tools.

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