ESTIMATING COSTS OF GEN IV SYSTEMS

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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 which he wrote the Terms of Reference 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, Lawrence Livermore, Oak Ridge, 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 (Hanford), and received his PhD in economics from the University of California, Berkeley.

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OUTLINE

Good Morning, I will be discussing the following items but will not be covering everything on every slide. This is an **introduction** to nuclear power plant cost estimation. Please ask questions if you don't understand something!

1. Economic Modeling Working Group (GIF-EMWG)
2. *Cost Estimating Guidelines and G4ECONS*
3. Levelised Unit Energy Cost (LUEC) (= Levelized Cost of Electricity, LCOE)
4. GIF-EMWG Code of Accounts (COA)
5. Overnight Costs + Contingency + Interest During Construction = Total Capital Investment Cost (TCIC = "Capital at Risk" at the time of plant start up)
6. Annual Fuel and O&M Costs, including Decommissioning funds
7. LUEC (Levelized Cost of Electricity, LCOE): a Generation IV example
8. Benchmarking G4ECONS with IAEA's NEST

CREATING THE GENERATION IV ROADMAP (2001-2003)

The early Gen IV Roadmap Committee was composed of policy committees, a cross-cutting Evaluation Methodology Group (EMG) and a number of technical working groups, each focused on a different reactor technology (water, gas, metal and other):

the gas-cooled fast reactor (GFR),

the lead-cooled fast reactor (LFR),

the molten salt reactor (MSR),

the sodium-cooled fast reactor (SFR),

the super-critical water reactor (SCWR), and

the very high temperature gas reactor (VHTR).

EVALUATION METHODOLOGY GROUP, EMG (2001-2003)

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

ECONOMIC CROSS-CUT GROUP (2002-2003)

The EMG created the Economic Cross-Cut Group to define the economic criteria for selecting “Generation IV Forum supported technologies” within a multi-criteria decision analysis framework.

After much debate two economic criteria were selected:

- EC−1 – low total capital investment cost, TCIC, equal to the overnight construction cost + contingency + interest during construction (IDC) (See EMG, *Generation IV Roadmap: Viability and Performance Evaluation Methodology Report*, 2002, p. 68) and

- EC−2 – low average cost, as measured by levelised unit energy costs (LUEC), following the NEA/IEA’s *Projected Cost of Generating Electricity* (1998, and later editions in 2005, 2010, and 2015). If only electricity is generated, then LUEC = the Levelized Cost of Electricity, LCOE

GIF/EMWG/2007/004

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

Printed by the OECD Nuclear Energy Agency
for the Generation IV International Forum

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.

https://www.gen-4.org/gif/upload/docs/application/pdf/2013-09/emwg_guidelines.pdf

GIF/EMWG/2007/005

User's Manual for G4-ECONS Version 2.0
A Generic EXCEL-based Model for Computation of the Projected Levelized Unit Electricity Cost (LUEC) and/or Levelized non-Electricity Unit Product Cost (LUPC) from Generation IV Systems

October 25, 2007

Prepared by

Kent Williams, Oak Ridge National Laboratory, United States, and
Keith Miller, NexiaSolutions, United Kingdom

For
The Economic Modeling Working Group
of the Generation IV International Forum

Based on the "*Cost Estimating Guidelines*" a transparent cost estimating tool was developed: G4ECONS ("Generation 4 Estimator of the Cost of Nuclear Systems"). There were 4 goals:

1. Simplicity: Minimize data requirements
2. Universality: Be applicable to all GIF member countries
3. Transparency: Visible formulas
4. Adaptability: To allow incorporation of other modules, e.g., to evaluate different fuel cycles

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

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

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

← **Step 2**: Calculate O&M and FUEL

the sum of which is divided by the annual energy output

E 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

The GIF Code of Accounts (COA):

Account 10 – Capitalized Pre-Construction Costs
\+ Accounts 20– Capitalized Direct Costs

= Direct Cost

\+ Accounts 31-34 Field Indirect Costs

= Total Field Cost

\+ Accounts 35-39 Capitalized Field Management Costs

= Base Construction Cost

+Accounts 40 – Capitalized Owner Operations
+Accounts 50 – Capitalized Supplementary Costs

= Overnight Construction Cost

\+ Accounts 60 – Capitalized Financial Costs

= Total Capital Investment Cost (TCIC)

Annualized Costs:

\+ Accounts 70 – Annualized O&M Costs
\+ Accounts 80 – Annualized Fuel Costs
\+ Accounts 90 – Annualized Capital Costs
Annual MWh

= Levelized Unit Energy Costs (LUEC)

The GIF Code of Accounts (COA):

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
Direct Cost	
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
	89 Contingency on Annualized Fuel Costs
90	Annualized Financial Costs
	92 Fees
	93 Cost of Capital
	99 Contingency on Annualized Financial Costs

OVERNIGHT COST: AN EXAMPLE

To estimate the cost of an Molten Salt Reactor (MSR), Oak Ridge National Laboratory (ORNL) used the "*Cost Estimating Guidelines*" and G4ECONS to write *Advanced High Temperature Reactor Systems and Economic Analysis* (ORNL/TM-2011/364) taking off from a generic two-unit PWR-12 (similar to Watts Bar 1&2) at about 3,400 MW, where the cost for Watts Bar 2 was about $4.5B/1,168MWe = $3,850 as reported at http://www.world-nuclear-news.org/NN-Watts-Bar-2-final-completion-cost-approved-0402167.html (values here in 2011 and 2016 USD)

GIF COA	General Description		Cost in $1000 of 2011 USD	% ages	Cost in $1000 of 2016 USD
20	Capitalized Direct Costs		$2,232,386	58%	$2,559,858
21	Structures and improvements		$543,188	14%	$622,869
22	Reactor plant equipment		$727,316	19%	$834,007
23	Turbine plant equipment		$537,068	14%	$615,851
24	Electric plant equipment		$195,175	5%	$223,806
25	Heat rejection sys.		$117,554	3%	$134,798
26	Miscellaneous plant equipment		$112,085	3%	$128,527
30	Capitalized Indirect Costs		$1,322,537	34%	$1,516,542
	Base Construction Costs		$3,554,923	92%	$4,076,400
40	Capitalized Owner's Cost	assumed to be	$300,000	8%	$300,000
50	Capitalized Supplemental Costs	assumed to be	$0	0%	$0
	Overnight Construction Cost	for 1,147 MWe	$3,854,923	100%	$4,376,401
	Overnight Construction Cost/kWe		$3,360		$3,820

http://info.ornl.gov/sites/publications/files/Pub32466.pdf

ADD THE APPROPRIATE "INTEREST DURING CONSTRUCTION" (IDC) RATE: "THE TIME VALUE OF MONEY"

$$IDC = \Sigma_t \, (cx_t \cdot OC) \cdot [(1 + \mathrm{m})^t - 1] \quad (t = lt, \ldots, 0),$$

OC are Overnight Construction expenditures,
cx_t are construction expenditures as a percent of OC in month t,
m is the monthly cost of capital during construction, $(1 + \mathrm{m}) = (1 + \mathrm{r})^{1/12}$,
–1 subtracts monthly expenditures in t, $cx_t \cdot OC$, from the summation,
lt is the months of construction (from 'pouring first concrete' to operation)
0 is the start of commercial operation

In G4ECONS this is approximated with end of quarter payments and an "S-curve" cumulative expenditure distribution.

WEIGHTED AVERAGE COST OF CAPITAL IN THE INTEREST DURING CONSTRUCTION:

The weighted average cost of capital (WACC), r, is

WACC = r = [d · debt/(debt + equity)] + [e · equity/(debt + equity)]

where

d is the real rate of return on debt,
e is the real rate of return on equity (Note: tax effects are ignored for simplicity)

In general, the nominal cost of debt, $\underline{d}$, is equal to the real cost of debt, d, plus the inflation rate, **i**:

$(1 + \underline{d}) = (1 + d) \cdot (1 + \mathbf{i}) \approx (1 + d + \mathbf{i})$ For example,

$(1 + \underline{d}) = (1 + 3\%) \cdot (1 + \mathbf{2\%}) = (1 + 5.06\%) \approx (1 + 5\%)$

Instead of parameterizing the cost of capital, we use 3%, 5%, 7.5%, 10%, etc.

INFLATION VERSUS COST ESCALATION:

- **Inflation refers to the change in the value of a currency (e.g., $, €, £, ¥) over time. It is measured through surveys of "baskets" of identical goods and services for households (Consumer Price Index, CPI) or for firms (Producer Price Index, PPI).**

- **Cost Escalation (nominal) refers to the changes in prices for inputs in specific industries, such as the construction industry, not adjusted for currency inflation.**

- **Real cost escalation subtracts the currency inflation.**

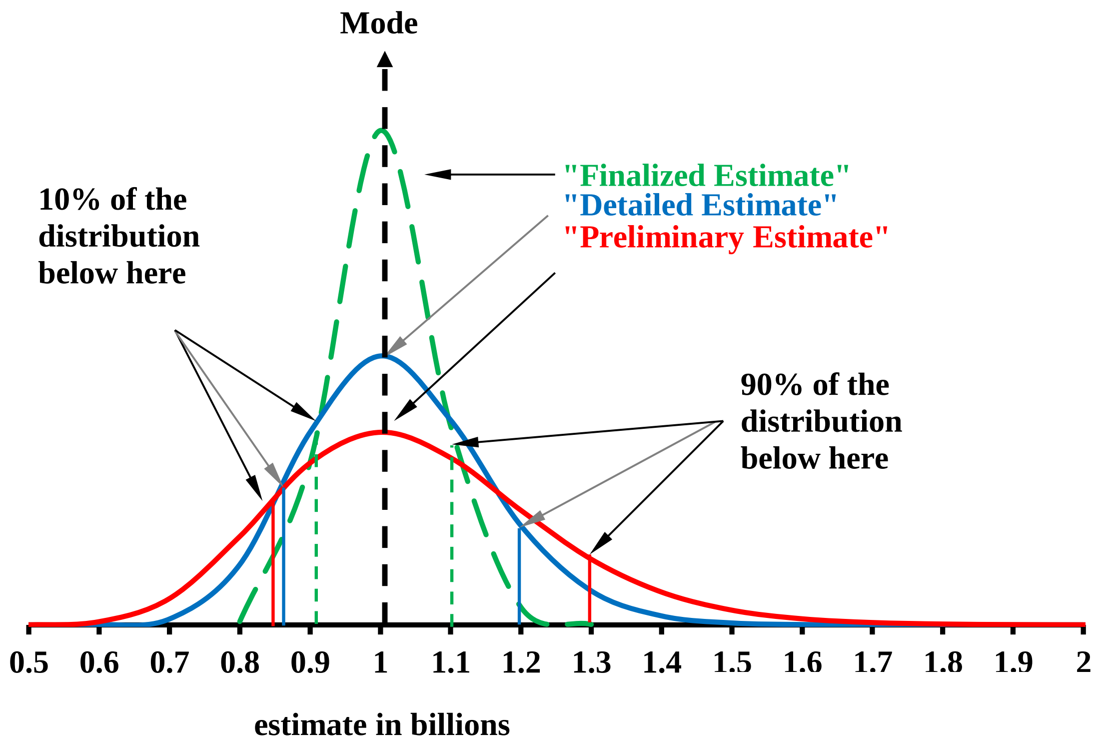
- **Cost Escalators should not be used to deflate prices in nominal currency!**

ADD THE APPROPRIATE CONTINGENCY RATE; IT DEPENDS ON THE LEVEL OF PROJECT DEFINITION!

AACE End Usage	AACE Expected Accuracy Range	AACE Contingency	EPRI Designation	EPRI Contingency
Concept Screening Level of Project Definition: 0-2%	Low: -20% to -50% High: +30% to +100%	50%	NA	NA
Feasibility Study Level of Project Definition:1-5%	Low: -15% to -30% High: +20% to +50%	30%	Simplified Estimate	30% to 50%
Authorization or Control Level of Project Definition: 10-40%	Low: -10% to -20% High: +10% to +30%	20%	Preliminary Estimate	15% to 30%
Control or Bid/Tender Level of Project Definition: 30-70%	Low: -5% to -15% High: +5% to +20%	15%	Detailed Estimate	10% to 20%
Check Estimate or Bid/Tender Level of Project Definition: 50-100%	Low: -3% to -10% High: +3% to +15%	5%	Finalised Estimate	5% to 10%

Sources: From Rothwell (2005: Table 1) with permission from AAEC International; originally from AACE (1997), updated in AACE (2011) and EPRI (1993) (the last publicly available version of EPRI's Technology Assessment Guide, later versions being proprietary, but having similar contingencies)

LEVELS OF PROJECT DEFINITION:



	Mode	Median	Mean	Standard Deviation	80% Confidence
Preliminary Estimate	1.000	1.033	1.049	18.30%	-18% to +31%
Detailed Estimate	1.000	1.017	1.025	13.10%	-14% to +20%
Finalised Estimate	1.000	1.005	1.008	7.00%	-8% to +10%

Source: Rothwell, Economics of Nuclear Power (2016, p. 114). London: Routledge.
https://www.routledge.com/Economics-of-Nuclear-Power/Rothwell/p/book/9781138858411

TOTAL CAPITAL INVESTMENT COST

GEN IV International Forum[SM]

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	PWR12	AHTR	AHTR
(enrichment)	3%	19.75%	9.00%
Capitalized preconstruction costs (accounts 11–19)	$6	$6	$6
Capitalized direct costs (accounts 21–29)	$2,171	$2,391	$2,391
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

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	$M/yr
73	Pensions and Benefits	6.29	$M/yr
74+76	Consumables	18.64	$M/yr
75	Repair costs including spare parts and services	10.93	$M/yr
77	Capital replacements/upgrades (levelized)	0.00	$M/yr
78	Insurance premiums & taxes & fees	11.12	$M/yr
79	Contingency on O&M	0.00	$M/yr
70	Total O&M	78.47	$M/yr
	Annualized D&D cost per MWh	0.27	$/MWh
	Total O&M + D&D	8.61	$/MWh

58	Decontamination & Dismantling (D&D)	300	$M
	Sinking fund interest	5%	/yr
	Sinking fund factor	0.83%	/yr
		40	yrs
	Annualized D&D	2.48	$M/yr

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:

$$A = D\&D \cdot \{r / [(1 + r)^N - 1] \} ,$$

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

$$F = \{ [FC / (24 \cdot B \cdot eff)] + WASTE \} \cdot E$$

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

ANNUAL FUEL COSTS IN ORNL (2011)
TABLE 56. FUEL CYCLE COST (2011$):

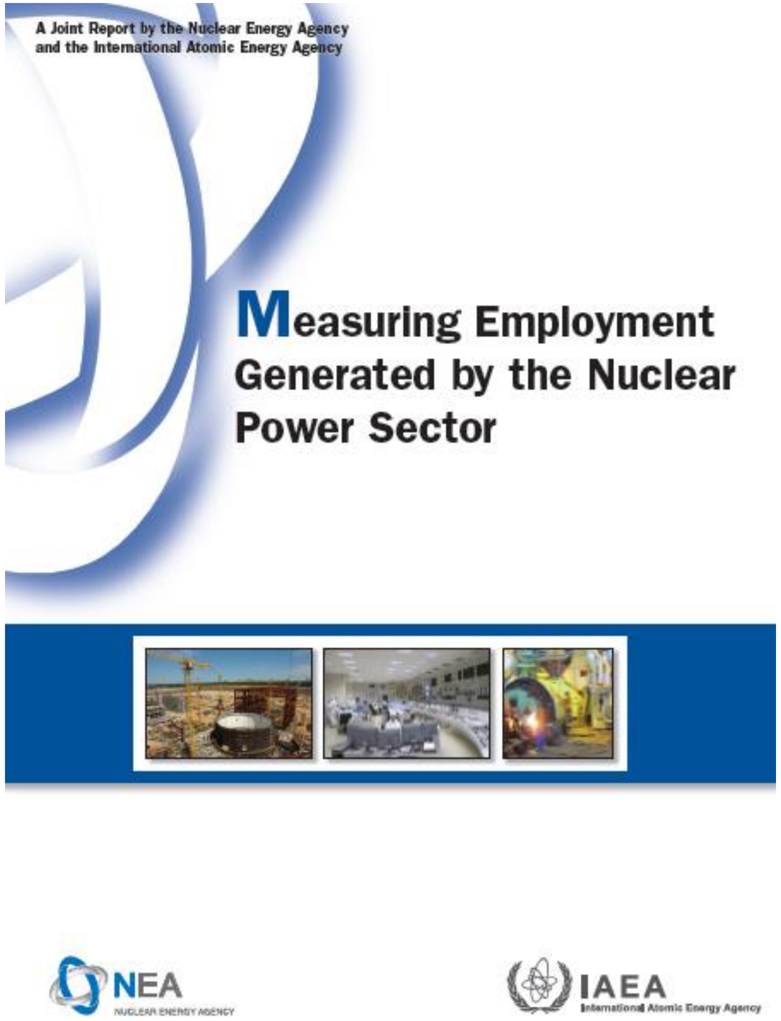
	2011 dollars	PWR12 BE (millions)	AHTR 19.75% (millions)	AHTR 9% (millions)	PWR12 BE $/MWh	AHTR 19.75% $/MWh	AHTR 9% $/MWh	
$NU \cdot P_{UF6} = \{$	Annual average ore cost	$20.20	$95.74	$45.13	$2.24	$7.76	$3.66	
	Annual average conversion cost	$1.55	$7.36	$3.47	$0.17	$0.60	$0.28	
$SWU \cdot P_{SWU} =$	Annual average enrichment cost	$10.93	$79.37	$33.71	$1.21	$6.44	$2.73	
$P_{FEB} =$	Annual average fuel fabrication cost	$5.67	$12.10	$25.27	$0.63	$0.98	$2.05	
	Annual average enrichment tails disposal cost	$0.79	$4.33	$1.98	$0.09	$0.35	$0.16	
	Total front end fuel cycle cost	**$39.15**	**$198.90**	**$109.57**	**$4.34**	**$16.13**	**$8.89**	
	SNFstorage (including packaging)	$2.36	$5.04	$10.53	$0.26	$0.41	$0.85	
	Payment to Nuclear Waste Fund	$9.02	$12.33	$12.33	$1.00	$1.00	$1.00	
	Total back end fuel cycle cost	**$11.38**	**$17.37**	**$22.86**	**$1.26**	**$1.41**	**$1.85**	
	Total fuel cycle cost $FC =$	**$50.53**	**$216.27**	**$132.43**	**$5.60**	**$17.54**	**$10.74**	$= F$

NEA/IAEA (FORTHCOMING). *MEASURING EMPLOYMENT GENERATED BY THE NUCLEAR POWER SECTOR*. PARIS: OECD

This NEA/IAEA study's aim is to establish standards by which to measure employment generated by standard-sized facilities of each electricity technology.

This work was overseen by the NEA's Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC).

The work was done in collaboration with employees at Areva, Center for Advanced Energy Studies (Idaho, US), Generation IV International Forum Secretariat, Korean Atomic Energy Research Institute (KAERI), Nuclear Energy Institute (US), PriceWaterHouseCoopers Strategy Group, Rosatom Central Institute, and University of Stuttgart's Institutes für Energiewirtschaft und Rationelle Energieanwendung.



NEA/IAEA (FORTHCOMING). *MEASURING EMPLOYMENT GENERATED BY THE NUCLEAR POWER SECTOR*. PARIS: OECD

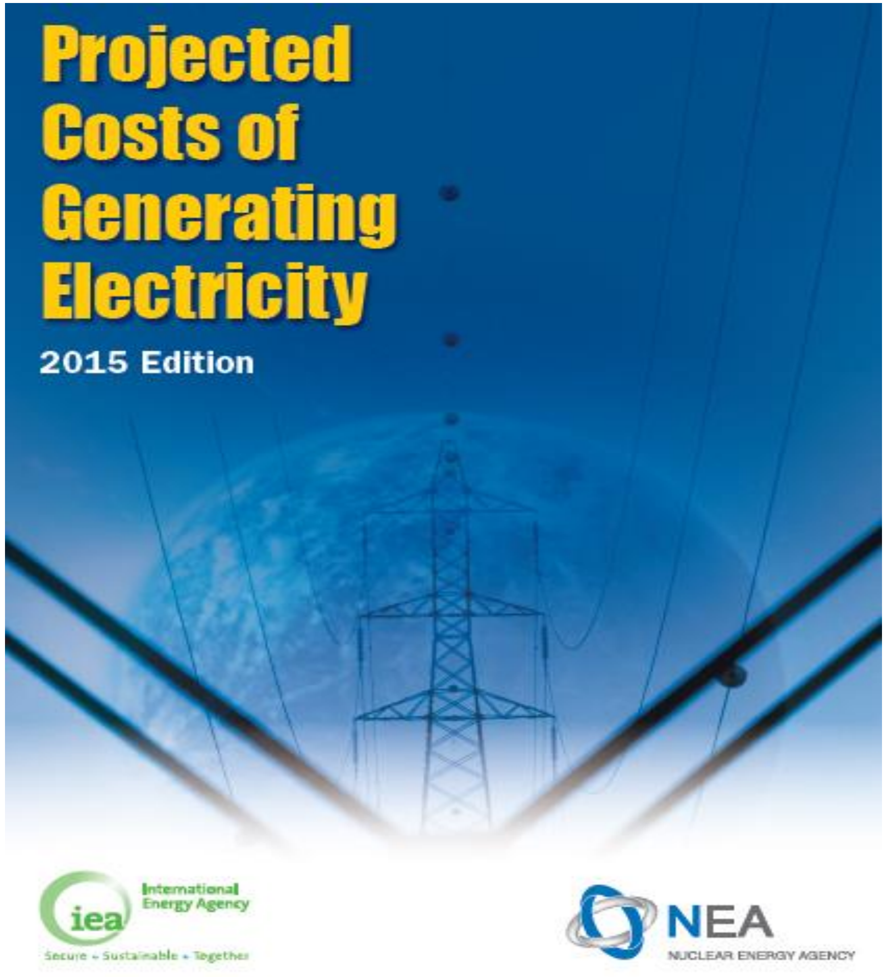
Descriptor	NAICS	1,000s
Labour	Labour	$68,900
Taxes	Taxes	$20,300
Other basic inorganic chemical manufacturing	325180	$18,300
Architectural and engineering services	541330	$15,100
Other Federal Government enterprises	926130	$14,000
Other nonmetallic mineral mining	212399	$12,000
Maintenance and repair of nonresidential buildings	811310	$8,800
Support activities for other mining	213115	$7,000
All other miscellaneous professional and technical	5413	$5,300
Misc. electrical equip. and component manufac.	335999	$4,300
Other State and local government enterprises	923130	$3,600
Investigation and security services	561612	$3,400
Scientific research and development services	541712	$2,700
Environmental & other technical consulting services	541620	$2,700
Power, distribution, and transformer manufac.	335311	$2,000
Waste management and remediation services	562211	$1,900
Business support services	561499	$1,700
Professional and similar organizations	813910	$1,600
Facilities support services	561210	$1,300
Valve and fittings other than plumbing	332919	$1,200
Securities- commodity contracts- investments	523999	$1,100
Insurance carriers	524126	$1,100
Employment services	5613	$1,000
Other (less than $1,00,000)		$15,600
Total		$215,000
Total Fuel (= Inorganic Chemicals+Minearl and Other Mining)	325180	$37,300

Levelised fuel cost parameters	Advanced LWR
Size (gross MWe, net = 1 000 MWe)	1050
Natural uranium, tU	185.4
Cost of uranium, USD thousands/year	$16,690
Cost of conversion, USD thousands/year	$1,850
Cost of SWU, USD thousands/year	$13,280
Enriched uranium, tU	19.723
Cost of fuel fabrication, USD thousands/year	$5,920
Fuel cost, USD thousands/year	$37,740

Source: Adapted from Rothwell (2016, p. 158)

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

Year of estimate/dollars	System 80+ 2001	PWR12 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/

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

Country	Tech	Size	Over night	Investment cost			Refurbish and D&D			Fuel/ waste	O&M costs	LCOE			
				3%	7%	10%	3%	7%	10%			3%	5%	7%	10%
		MWe	$/kWe	USD/MWh			USD/MWh			USD/ MWh	USD/ MWh	USD/MWh			
Belgium	Gen III	XXX	5 081	26.99	60.09	92.79	0.46	0.08	0.02	10.46	13.55	51.45	66.13	84.17	116.81
Finland	EPR	1 600	5 250	27.89	62.09	95.87	0.44	0.06	0.01	5.09	14.59	48.01	66.52	81.83	115.57
France	PWR-EPR	1 630	5 067	26.91	59.92	92.53	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	0.26	0.06	9.60	10.40	53.90	70.08	89.94	124.95
Japan	ALWR	1 152	3 883	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	8.58	9.65	28.63	34.05	40.42	51.37
Slovakia	VVER 440	535	4 986	26.65	59.85	93.05	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	100.75	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	77.71	101.76
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	1 080	1 807	9.60	21.37	32.99	0.16	0.03	0.01	9.33	6.50	25.59	33.05	37.23	48.83

APPLICATION: A SUPER CRITICAL WATER-COOLED REACTOR (SCWR) AND TWO FAST REACTORS

GEN IV International Forum℠

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Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Benchmarking of nuclear economics tools

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BENCHMARKING G4ECONS & NEST

ABSTRACT: Benchmarking of the economics methodologies developed by the Generation IV International Forum (GIF) and the International Atomic Energy Agency's (IAEA) International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO) was performed for three Generation IV nuclear energy systems. GIF's Economic Modeling Working Group (EMWG) developed an EXCEL-based spreadsheet package, G4ECONS to calculate the total capital investment cost (TCIC) and the levelised unit energy cost (LUEC). G4ECONS can accept the types of projected input, performance and cost data that are expected to become available for Generation IV systems through various development phases; it can model both open and closed fuel cycles.

The Nuclear Energy System Assessment (NESA) Economic Support Tool (NEST) was developed to enable an economic analysis using the INPRO methodology to easily calculated outputs including the TCIC, LUEC and other financial figures of merit. NEST is also EXCEL-based and can be used to evaluate nuclear reactor systems using the open fuel cycle, MOX (mixed oxide) fuel recycling, and closed cycles. A Super Critical Waster-cooled Reactor (SCWR) system with an open fuel cycle and two Fast Reactor systems, one with a break-even fuel cycle and another with a burner fuel cycle, were selected for the benchmarking exercise. Published data on capital and operating costs were used for benchmarking of the two spreadsheet models. Both G4ECONS and NEST calculated comparable TCICs and LUECs; with some variation in fuel cycle costs. This exercise was also useful in understanding the differences in the two models.

FOUR NEST VERSIONS

- Version 1 (basic version) as described in INPRO methodology manual (TECDOC1575, 2008). This is the simplest version of NEST using traditional equations for engineering cost calculations for once-through fuel cycles in comparison with a non-nuclear power plant.
- Version 2 (advanced version) is based on a model developed by Bunn, Fetter, Holdren, and van der Zwaan, The Economics of Reprocessing vs. Direct Disposal of Spent Nuclear Fuel (2003).
- Version 3 (advanced version) is based on the cash flow model used in MIT, The Future of Nuclear Power: An Interdisciplinary Study (2003).
- Version 4 is an extension of V.1 (including some aspects of V.2), designed for break-even closed fuel cycle system calculations and NPPs operating with conversion rates other than 1 (breeders and burners).

COMPARING G4ECONS & NEST

- Thermal Spectrum Reactor:
  - High Performance Light Water Reactor Phase 2 (HPLWR Phase 2) Project. Sixth Framework Programme, Assessment of the HPLWR Concept from Karlsruhe Institute of Technology: High Performance Light Water Reactor Design and Analyses
  - Reactor characteristics (base case, nth-of-a kind): Capacity: 1,000 MWe, Overnight cost: $2,430/kWe, Fixed O&M: $96.53/kWe

- Two fast reactor systems from the Final Report of INPRO Collaborative Project GAINS
  - SFR – BN800 type Break-Even Reactor, 870 MWe, ~12% Pu fuel, no MA recycle
  - Generic metallic-fuelled Burner Fast Reactor, 1,000 MWe,~20% Pu fuel, MA recycle

    Overnight costs $4,600/kWe (2009),

    Fuel costs: based on INL's *Advanced Fuel Cycle Cost Basis* report

(Benchmarking results for these two nuclear energy systems show little difference between the G4ECONS and the NEST versions; see the paper pp. 126-128)

ADJUSTED HPLWR RESULTS

Fig. 1: Levelized Unit Fuel Costs

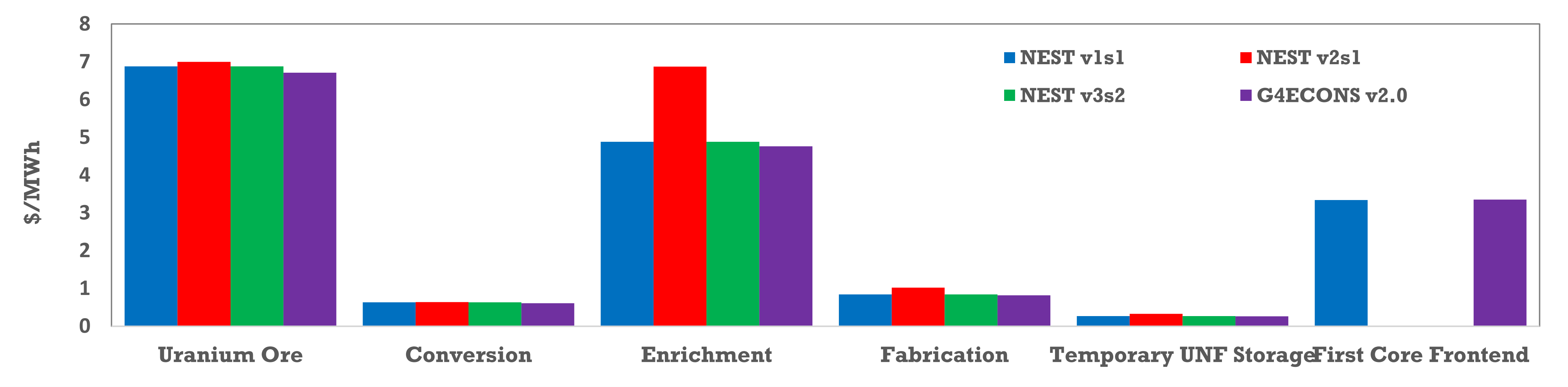
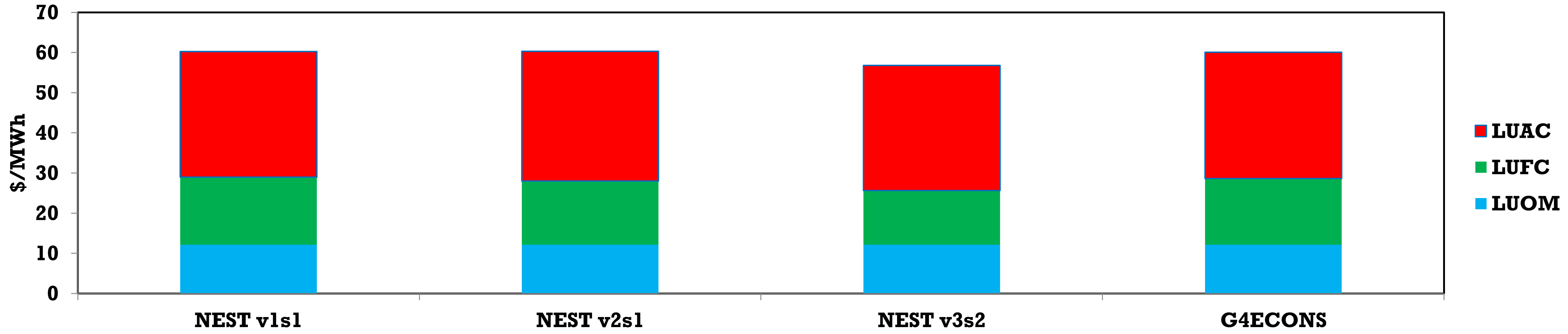


Fig. 2: Levelized Unit Energy Costs



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 Burner 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.

Upcoming Webinars

29 November 2017	Feedback of Phenix and SuperPhenix	Dr. Joel Guidez, CEA, France
14 December 2017	The sustainability: a Relevant Framework for Addressing GEN IV Nuclear Fuel Cycles	Dr. Christophe Poinssot, CEA, France
24 January 2018	Design, Safety Features and Progress of the HTR-PM	Prof. Yujie Dong, INET, Tsinghua University, China