Defining Plant-level Costs

The Full Costs of Electricity Provision

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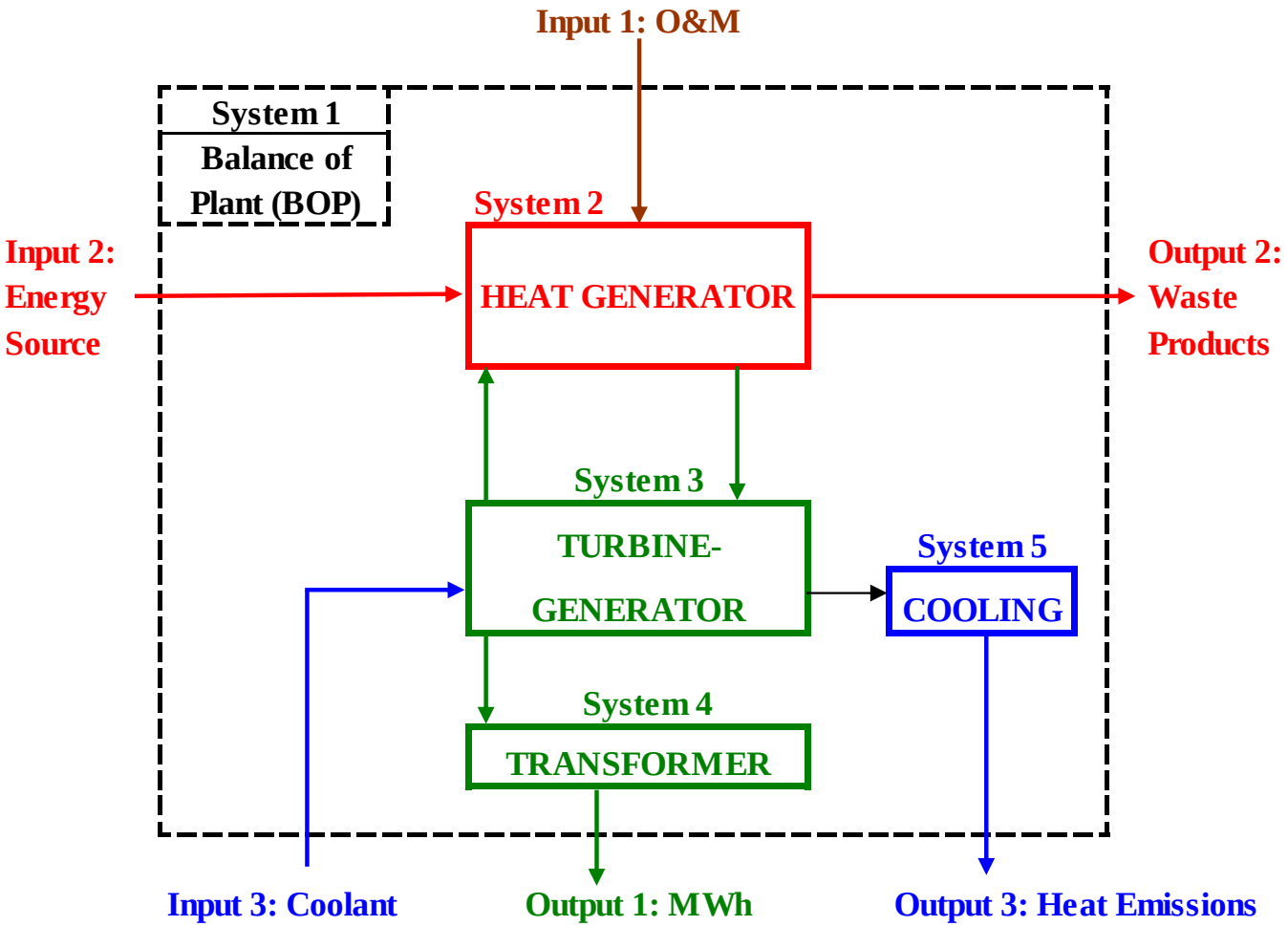
A Generic Power Plant



Long-Run Average Levelized Cost

$$LC = [CAPITAL(OC, r, lt) + FUEL + O\&M] / E$$

(variables in red, parameters in black)

CAPITAL is the product of Fixed Charge Rate and Total Capital Construction Costs, which depends on the Overnight costs, OC, cost of capital, **r**, and the lead time, lt

FUEL (*F*) is the *annual* fuel payment and a function of the amount of fuel and price of fuel

O&M (*L*) is the *annual* Operations and Maintenance expense and Capital Additions, CAPEX

E is *annual* energy output equal to **MW** · **TT** · *CF*, i.e., the size of the generator in megawatts, **MW**, the total number of hours in a year, **TT**, and the Capacity Factor, *CF*

CAPITAL (OC, r, lt)

OC	Overnight Cost Components
DIR	Direct Construction Costs
INDIR	Indirect Construction Costs (which cannot be assigned to a specific Direct Construction Cost Account
OWN	Owners' Costs incurred by the electric utility/owner-operator
SUPP	Other costs, such as spare parts, etc.
C_{ON}	Contingency, appropriate to the risk of final cost
IDC	Interest During Construction, a function of the cost of capital, **r**, and construction lead time, *lt*
KC	Total Capital Investment Costs, TCIC in GIF-EMWG Code of Accounts

$$BASE = (DIR + INDIR + OWN + SUPP)$$ **[OC without contingency]**

$$OC = BASE \cdot (1 + C_{ON}) = (DIR + INDIR + OWN + SUPP) \cdot (1 + C_{ON})$$

$$KC = OC \cdot (1 + idc) = (DIR + INDIR + OWN + SUPP) \cdot (1 + C_{ON}) \cdot (1 + idc)$$

Contingency = C_{ON}

Comparison of AACE and EPRI cost estimate stages

AACE End Usage	AACE Expected Accuracy Range	AACE Contingency	EPRI Designation	EPRI Contingen
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)

Interest During Construction = idc (**r**, *lt*)

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

where

cx_t	are construction expenditures as a percent of *OC* in month *t*,
m	is the monthly cost of capital during construction, $(1 + \mathbf{m}) = (1 + \mathbf{r})^{1/12}$,
–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) and
0	is the start of commercial operation with the generation of electricity and revenues.

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

$$IDC \cong \{[(lt - 1) \cdot (\mathbf{m} / 2)] + [(lt - 1) \cdot (lt - 2) \cdot (\mathbf{m}^2 / 6)]\} \cdot OC$$

$$IDC \cong \{[(\mathbf{m} / 2) \cdot lt] + [(\mathbf{m}^2 / 6) \cdot lt^2]\} \cdot OC$$

and

$$\mathbf{idc} \cong [(\mathbf{m} / 2) \cdot lt] + [(\mathbf{m}^2 / 6) \cdot lt^2]$$

KC (*OC*, r, *lt*)

$$KC = OC \cdot (1 + idc) = (DIR + INDIR + OWN + SUPP) \cdot (1 + C_{ON}) \cdot (1 + idc)$$

ABWR Cost Estimates from Nuclear Energy Agency (2000) and Tennessee Valley Authority (2005) Series and Title	NEA (2000) $/kW 1999$	TVA (2005) $/kW 2004$	TVA (2005) %	NEA (2000) $/kW 2013$	TVA (2005) $/kW 2013$	Cost Increase $/kW 2013$
10 Capitalized Pre-Construction	$0	$0	0%	$0	$0	$0
21 Structures & Improvements	$293	$300	11%	$460	$403	($57)
22 Reactor Equipment	$366	$540	20%	$575	$726	$150
23 Turbine Generator Eqp.	$183	$360	13%	$288	$484	$196
24 Electrical Equipment	$110	$150	6%	$173	$202	$29
25+26 Cooling System & Misc.Eqp.	$73	$70	3%	$115	$94	($21)
20 Total Direct, *DIR*	$1,026	$1,419	53%	$1,611	$1,906	$296
30 Capitalized Indirect costs , *INDIR*	$293	$192	7%	$460	$258	($202)
40 Capitalized Owner's cost, *OWN*	$0	$240	9%	$0	$322	$322
50 Supplementary costs, *SUPP*	$0	$0	0%	$0	$0	$0
Base Overnight Cost, *BASE*	$1,319	$1,851	69%	$2,071	$2,487	$581
Contingency Rate, C_{ON}	9%	16%	16%	9%	16%	6%
Overnight Cost, *OC*	$1,440	$2,140	80%	$2,261	$2,875	$614
IDC Factor (for Series 60), **idc**	14%	25%	25%	14%	25%	11%
Total Construction Cost, *KC*	**$1,641**	**$2,680**	**100%**	**$2,577**	**$3,601**	**$1,023**

Mapping the Direct Cost Supply Chain

Source: SCANA (2011), Analyst Day Presentation, p. 6.

Overview of the Direct Cost Supply Chain

Component	Location	Continent	Component	Location	Continent
Condenser	Sacheon, ROK	Asia	Instrumentation Valves	Solon, OH, USA	NAmerica
Containment Vessel	Yokohoma, JPN	Asia	Integrated Head Package	Blackfoot, ID, USA	NAmerica
Demineralizer	Ansan City, KOR	Asia	Liquid Ring Vacuum Pump	Pittsburgh, PA, USA	NAmerica
Heat Exchangers	Ansan City, KOR	Asia	Pumps	Brea, CA, USA	NAmerica
Reactor Vessel	Changwon, KOR	Asia	Reactor Coolant Pumps	Cheswick, PA, USA	NAmerica
Steam Generators	Changwon, KOR	Asia	Reactor Vessel RV Flowskirt	York, PA, USA	NAmerica
Transformers	Tokyo, JPN	Asia	Recirculation Heaters	Pittsburgh, PA, USA	NAmerica
Turbine Generator	Tokyo, JPN	Asia	Selonoid Values	Pittsburgh, PA, USA	NAmerica
Valves	Cheonan, KOR	Asia	Seperators	Neenah, WI, USA	NAmerica
Accumulators	San Giorgo, ITA	Europe	SG Recirc and Drain Pumps	Colchester, VT, USA	NAmerica
Containment Recicr Screens	Winterthur, CHE	Europe	Spent Resin Tank	Neenah, WI, USA	NAmerica
Core Make-up Tanks	San Giorgo, ITA	Europe	Squib Valves	McKean, PA, USA	NAmerica
IR Water Storage Tank IRWST	Winterthur, CHE	Europe	Tank Demineralizers	Detroit, MI, USA	NAmerica
Pressurizer	San Giorgo, ITA	Europe	Valves	Bolingbrook, IL, USA	NAmerica
PRHR Hx Heater Exchanger	San Giorgo, ITA	Europe	Valves	Rancho, St. Marg., CA, USA	NAmerica
Reactor Coolant Loop RCL Piping	Milan, ITA	Europe	Valves	Ipswich, MA, USA	NAmerica
AP1000 Modules	Lake Charles, LA, USA	NAmerica	Valves	Winchester, MA, USA	NAmerica
Air Operated Pump	Mansfield, OH, USA	NAmerica	Valves	Raleigh, NC, USA	NAmerica
Aux. Relief Values	Brantford, ON, CAN	NAmerica	Valves	Springville, NC, USA	NAmerica
Control Rod Drive Mech. CRDM	Newington, NH, USA	NAmerica	Variable Freq. Drives	New Kensington, OA, USA	NAmerica
Cranes	Shoreview, MN, USA	NAmerica	Cooling Tower Fans	Sao Paulo, BRA	SAmerica
Degasifiers	Neenah, WI, USA	NAmerica			

Source: NEA, *Nuclear New Build: Insights into Financing and Project Management* (2015), p. 223

Calculating Total Nuclear Fuel Costs

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

where

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 (costs to manage used fuel from Rothwell, 2015) plus geologic disposal costs (set equal to US$1/MWh real – that is, implicitly increasing with inflation, unlike contributions to the Nuclear Waste Trust Fund).

$$FC = [NU \cdot P_{UF6} \cdot (1 + \mathbf{r})^{ltU}] + [SWU \cdot P_{SWU} \cdot (1 + \mathbf{r})^{ltS}] + [P_{FAB} \cdot (1 + \mathbf{r})^{ltF}]$$

where

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* UF_6,
lt_U is the carrying time from uranium purchase to reactor loading, for example 1.0 years,
SWU is the number of separative work units required in enrichment,
P_{SWU} is the price of enriching uranium hexafluoride, UF_6,
lt_S is the carrying time from conversion to reactor loading, for example 0.5 years,
P_{FAB} is the price of fabricating UO_2 fuel from enriched UF_6, and
lt_F is the carrying time from fabrication to reactor loading, for example 0.25 years

Calculating Fossil Fuel Costs

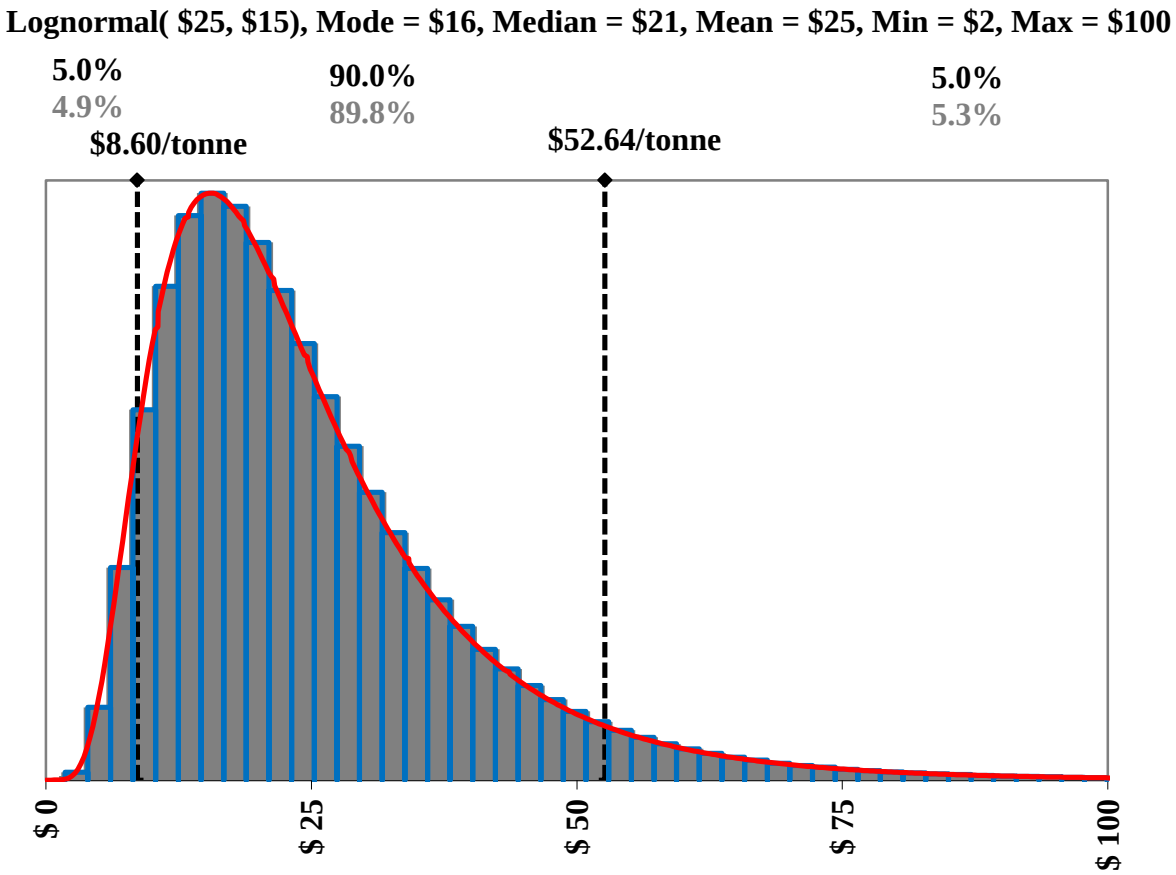
$$F_{CCGT/MWh} = [(P_{NGAS} \cdot HR_{CCGT}) / 1{,}000] + (P_{CO2} \cdot CO_{2CCGT})$$

where

F_{CCGT}	is the total natural gas expense,
$F_{CCGT/MWh}$	is the cost of natural gas per MWh,
P_{NGAS}	is the price of natural gas,
HR_{CCGT}	is the heat rate (in BTU/kWh) for CCGTs from Table 5.1,
P_{CO2}	is the price of tCO_2 ($F_{CCGT/MWh}$ is calculated with and without the price of CO_2),
and	
CO_{2CCGT}	is the tonnage of CO_2 produced by the CCGT unit per MWh, known as the 'carbon intensity factor'.

Carbon Dioxide Cost (Price?)

Cost of CO_2 in US$/tonne, simulated with lognormal density



Source: Mean from MIT (2009), fitted to a lognormal density with SD = $15

Nuclear Annual O&M Costs (U.S.)

Category	Changes		new 2010 $ in thousands
IMPLAN Descriptor	IMPLAN	NAISC	2010$K
Labour	Labour	Labour	$62,041
Taxes	Taxes	Taxes	$18,260
Other basic inorganic chemical manufacturing	125	325188	$16,476
Architectural and engineering services	369	5413	$13,568
Other Federal Government enterprises	429	NA	$12,623
Other nonmetallic mineral mining	27	21239	$10,823
Maintenance and repair of nonresidential buildings	40	23*	$7,920
Support activities for other mining	30	213113-5	$6,300
All other miscellaneous professional and technical	380	54191, 54193, 54199	$4,763
Misc. electrical equipment and component manufacturing	275	335999	$3,872
Other State and local government enterprises	432	NA	$3,275
Investigation and security services	387	5616	$3,088
Scientific research and development services	376	5417	$2,459
Environmental and other technical consulting servi	375	54162, 54169	$2,407
Power, distribution, and specialty transformer manufacturing	266	335311	$1,766
Waste management and remediation services	390	562	$1,746
Business support services	386	5614	$1,525
Civic- social- professional and similar organizati	425	8134, 8139	$1,436
Facilities support services	385	5612	$1,138
Valve and fittings other than plumbing	198	332911-2, 332919	$1,072
Securities- commodity contracts- investments	356	523	$1,011
Insurance carriers	357	5241	$975
Employment services	382	5613*	$900
Pump and pumping equipment manufacturing	226	333911, 333913	$851
Power generation and supply	31	2211	$812
Management of companies and enterprises	381	55	$786
Warehousing and storage	340	493	$623
Construction of other new structures	36	23*	$554
Other (less than $500,000)			$10,441
Total			$193,510

CCGT Variable and Fixed O&M Costs (U.S.)

CCGT, Source: EIA, "Assumptions for the …"	Year Dollars	Size MW	LT y	OC $/ kW	OC 2013$/ kW	Variable 2013$/ MWh	Fixed 2013$/ kW/y	Heat Rate BTU/kWh
AEO 1995, Table 29	1987	400	4	$476	$853	$4.66	$48.38	7,369
AEO 1996, page 54	1987	400	4	$332	$595	$0.72	$48.38	7,300
AEO 1997, Table 33	1995	400	4	$620	$979	$0.79	$42.65	6,985
AEO 1998, Table 37	1996	400	3	$572	$883	$3.09	$21.30	6,985
AEO 1999, Table 37	1997	400	3	$575	$889	$0.79	$21.99	6,985
AEO 2000, Table 37	1998	400	3	$576	$912	$0.81	$22.55	6,985
AEO 2001, Table 43	1999	400	3	$576	$904	$0.80	$22.17	6,927
AEO 2002, Table 38	2000	400	3	$590	$875	$0.77	$21.45	6,870
AEO 2003, Table 40	2001	400	3	$608	$893	$3.00	$15.01	7,000
AEO 2004, Table 38	2002	400	3	$615	$924	$3.11	$15.55	6,928
AEO 2005, Table 38	2003	400	3	$558	$797	$2.52	$14.76	6,732
AEO 2006, Table 38	2004	400	3	$575	$772	$2.45	$14.31	6,732
AEO 2007, Table 38	2005	400	3	$594	$743	$2.35	$13.78	6,717
AEO 2008, Table 38	2006	400	3	$706	$845	$2.33	$13.61	6,752
AEO 2009, Table 8.2	2007	400	3	$947	$1,079	$2.28	$13.33	6,752
AEO 2010, Table 8.2	2008	400	3	$968	$1,059	$2.23	$13.09	6,752
AEO 2011, Table 8.2	2009	400	3	$917	$972	$3.26	$15.31	6,333
AEO 2012, Table 8.2	2010	400	3	$1,003	$1,055	$3.27	$15.37	6,430
AEO 2013, Table 8.2	2011	400	3	$1,006	$1,037	$3.31	$15.55	6,333
AEO 2014, Table 8.2	2012	400	3	$1,021	$1,031	$3.30	$15.52	6,333
MIT (2009, p. 18-22)	2007	1,000	2	$850	$968	$0.47	$26.20	6,800

$$OM_{CCGT/MWh} = VOM_{CCGT} + [(1{,}000 \cdot FOM_{CCGT}) / (CF_{CCGT} \cdot 8{,}766)]$$

where

VOM_{CCGT} is variable O&M from Table and

FOM_{CCGT} is fixed O&M from Table

Projected Costs of NPP Investment

Country	Technology	Net capacity	Overnight cost	Investment cost (with		
				3%	7%	10%
		MWe	USD/kWe	USD/kWe		
Belgium	Gen III	1 000-1 600	5 081	5 645	6 498	7 222
Finland	EPR	1 600	5 250	5 832	6 714	7 463
France	PWR-EPR	1 630	5 067	5 629	6 479	7 202
Hungary	AES-2006	1 180	6 215	6 756	7 535	8 164
Japan	ALWR	1 152	3 883	4 313	4 965	5 519
Korea	APR 1400	1 343	2 021	2 177	2 400	2 580
Slovak Republic	VVER 440	535	4 986	5 573	6 472	7 243
United Kingdom	Mulitple PWRs	3 300	6 070	6 608	7 399	8 053
United States	ABWR	1 400	4 100	4 555	5 243	5 828
Non-OECD member countries						
China	AP 1000	1 250	2 615	2 905	3 344	3 717
	CPR 1000	1 080	1 807	2 007	2 310	2 568

Projected Costs of Nuclear LCOEs

Country	Technology with 60 year life times	Size	Refurbishment and D&D costs			Fuel and waste costs	O&M costs	LCOE			
			3%	7%	10%			3%	5%	7%	10%
		MWe	USD/MWh			$/MWh	$/MWh	USD/MWh			
Belgium	Gen III	1 000-1 600	0.46	0.08	0.02	10.46	13.55	51.45	66.13	84.17	116.81
Finland	EPR	1 600	0.44	0.06	0.01	5.09	14.59	48.01	66.52	81.83	115.57
France	EPR (2030)	1 630	0.40	0.06	0.01	9.33	13.33	49.98	64.63	82.64	115.21
Hungary	AES-2006	1 180	1.59	0.26	0.06	9.60	10.40	53.90	70.08	89.94	124.95
Japan	ALWR	1 152	0.42	0.07	0.02	14.15	27.43	62.63	73.80	87.57	112.50
Korea	APR 1400	1 343	0.00	0.00	0.00	8.58	9.65	28.63	34.05	40.42	51.37
Slovakia	VVER 440	535	4.65	1.50	0.83	12.43	10.17	53.90	66.68	83.95	116.48
UK	Multiple PWRs	3 300	0.54	0.09	0.02	11.31	20.93	64.38	80.88	100.75	135.72
US	ABWR	1 400	1.26	0.52	0.26	11.33	11.00	54.34	64.81	77.71	101.76
Non-OECD members											
China	AP 1000	1 250	0.23	0.04	0.01	9.33	7.32	30.77	34.57	47.61	64.40
	CPR 1000	1 080	0.16	0.03	0.01	9.33	6.50	25.59	33.05	37.23	48.83