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Analysis of Load Factors at Nuclear Power Plants

Michael T. Maloney, *Clemson University*

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Introduction

One of the important factors in forecasting levelized cost at nuclear power plants (NPPs) is load factor.[1] In our earlier work, we assumed a best-case scenario for load factors in Russia of 79 percent. However, nuclear power plants world wide have not historically enjoyed load factors this high, nor has Russia. Since levelized cost is directly proportional to load factor, this is a significant factor in determining the true cost effectiveness of nuclear power. A 10 percent decrease in load factor, say, from 79 percent to 71 percent, increases cost by 10 percent.

The world wide historical experience in load factor is 69.4 percent for reactors currently operating and 68.3 percent for all commercial reactors over all time.[2] These numbers are capacity weighted averages by machine by year. The following two tables show the world wide experience by year and by country. By year, load factors have been improving. Load factors were 50 to 60 percent in the early 1970s. They have increased to around 80 percent today. Even so, there is still a wide range of operating performance across countries. Even looking at the most recent experience, countries such as Finland, Belgium and Switzerland that operate in the high 80s and low 90s of load factor are offset by countries like India which is in the 50s.

Load Factor Effects

Many things can affect load factor for an electric generator. For nuclear plants in particular, age is important. Because of the complexity of the machinery and controls is it common for nuclear plants to operate at less than full power when they first come on line. Indeed, on average it takes NPPs 9 months from first powering the reactor until commercial operation, and 10 percent of the time it takes more than a year. Even in the first year of operation, the reactor is will not run at full power or be synchronized to the gird all the time. Age also works against reactors. On average, the older they get, the lower their load factors.

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[1] Load factor is the amount of power produced by a generator divided by the engineering capacity of the unit. Usually load factors are stated for a year. The calculation, then, is the total kilowatt hours of power generated by the unit divided by the capacity of the unit in kilowatts times the number of hours in the year.

[2] Data on design, construction, and operating characteristics of nuclear power plants world wide is available from the International Atomic Energy Agency (IAEA) through its Power Reactor Information System (PRIS).

Table 1. Load Factors for Nuclear Power Plants— World Wide Experience by Year

Year	*All Reators*	*Currently Operating*
1970	0.53	0.53
1971	0.56	0.56
1972	0.54	0.52
1973	0.55	0.53
1974	0.54	0.51
1975	0.58	0.56
1976	0.60	0.58
1977	0.59	0.58
1978	0.61	0.62
1979	0.58	0.59
1980	0.57	0.57
1981	0.59	0.59
1982	0.59	0.59
1983	0.61	0.62
1984	0.62	0.63
1985	0.66	0.66
1986	0.65	0.66
1987	0.64	0.67
1988	0.65	0.66
1989	0.65	0.67
1990	0.66	0.69
1991	0.68	0.70
1992	0.68	0.70
1993	0.70	0.71
1994	0.70	0.71
1995	0.71	0.73
1996	0.72	0.73
1997	0.71	0.73
1998	0.74	0.75
1999	0.77	0.77
2000	0.78	0.78
2001	0.80	0.80
2002	0.85	0.85

Table 2. Load Factors for Nuclear Power Plants—By Country

Country	*All Reators*	*Currently Operating*	*Since*1996
Armenia	0.52	0.54	0.53
Argentina	0.74	0.74	0.81
Belgium	0.82	0.82	0.89
Bulgaria	0.53	0.53	0.53
Brazil	0.35	0.35	0.55
Canada	0.70	0.76	0.77
Switzerland	0.84	0.84	0.88
China	0.73	0.73	0.76
Czech Republic	0.79	0.79	0.84
Germany	0.73	0.76	0.86
Spain	0.77	0.78	0.88
Finland	0.86	0.86	0.93
France	0.65	0.67	0.72
United Kingdom	0.67	0.66	0.74
Hungary	0.83	0.83	0.87
India	0.45	0.45	0.56
Italy	0.37		
Japan	0.72	0.72	0.80
South Korea	0.82	0.82	0.86
Kazakhstan	0.20		
Lithuania	0.48	0.48	0.43
Mexico	0.69	0.69	0.75
Netherland	0.79	0.79	0.92
Pakistan	0.29	0.29	0.34
Romania	0.75	0.75	0.75
Russia	0.64	0.64	0.62
Sweeden	0.71	0.71	0.76
Slovenia	0.72	0.72	0.83
Slovak Republic	0.71	0.71	0.69
Taiwan	0.79	0.79	0.83
Ukraine	0.62	0.63	0.68
United States	0.67	0.68	0.82
South Africa	0.62	0.62	0.78

We capture these many factors in the following statistical analysis. We use multiple regression to model the load factor at each plant as a function of the characteristics of that plant. Plant characteristics include the age of the plant and the length of the construction period. We use {0,1} dummy variables to take account of the period from the reactor startup and the first year of commercial operation, the first year of commercial operation, and the last year of commercial operation for reactors that have been shut down. In addition, we include dummy variables for each country and year pair.

As noted above, we expect operation before the plant enters its commercial phase to be characterized by relatively low load factors. This same phenomenon is likely to be true in the first and last years of commercial operation because the plant does not operate for the whole year. Age in and of itself is likely to be negatively related to load factors at least after some point. We allow for a varying age effect by including a squared term. We also test to see if there is a size effect; that is, we check to see if big plants are generally more efficient than small ones. We include the length of the construction period on the hypothesis that plants delayed in construction are not likely to run as well as ones that are finished in a timely fashion.[3] Finally, a dummy variable for plants that have been shut down gives a differential in operating efficiency between operating and closed facilities.

Table 3. Regression of Load Factor on Plant Characteristics

Independent Variables:	*Coefficient*	*t-stat*
Age of the Power Plant	-0.004	-8.31
Length of Construction Period	-0.009	-9.86
Prior to Commercial Operation*	-0.351	-24.33
First Year of Commercial Operation*	-0.200	-21.22
Plant has been Shut Down*	-0.070	-10.36
Last Year of Operation*	-0.255	-10.91
	F-stat	*d.f.*
Classification Variables for Country and Year	22.81	(776, 9330)
R-squared	.491	
No. of Observations	9331	

Notes: (*) denotes {0,1} dummy variable. Age in years from time of commercial operation. "Prior to Commercial Operation" is a dummy variable for years from reactor startup and time of commercial operation.

The estimates shown in Table 3 conform to our expectations. Age, holding constant for the first and last years of commercial operation is everywhere negative. The quadratic term proved to be statistically insignificant; the estimated effect is everywhere negative. Operating efficiency declines at nearly one-half of a percent per year. Prior to commercial operation, plants operate at load factors 35 percent lower than after they begin commercial production. Also, load factors are 20 percent lower in the first year and 25 percent lower in the last year of commercial operation. Finally, shutdown plants were 7 percent less efficient in each year of the their commercial lives compared to plants that are still running.

The effects associated with these variables hold constant general effects associated with nuclear power plant operation in each year in each countries. In other words, we estimate a country and time specific factor of performance which essentially averages operating efficiency for each country for each year. We assume that the startup, shutdown, age, and construction experiences are common across countries and time. However, we imagine that on top of these, there are country-specific factors. We allow these to vary by time as well. In essence what we have is a yearly average of operating efficiencies across all of the nuclear power plants in service in each country.

[3] There are several reasons why this might be true. Regulatory delay could have resulted in mandated changes in design. Construction delays could have resulted from design flaws. Economic delays could lead to redesign difficulties. Our estimate is the average over all of these.

Country Rankings

Table 4 shows the estimated country effects derived from the regression analysis presented in Table 3. These estimated effects are load factors for the average reactor in each country over its commercial life under the assumption of best-case construction and startup. They represent the relative operating efficiencies across countries. Table 4 shows the effects averaged over the years 1996 through 2002.[4]

Table 4. Average Load Factor Experience by Country

Country	*Load Factor*	*Country*	*Load Factor*
Armenia	0.53	Japan	0.79
Argentina	0.81	Korea, South	0.85
Belgium	0.90	Kazakhstan	0.26
Bulgaria	0.54	Lithuania	0.44
Brazil	0.69	Mexico	0.81
Canada	0.77	Netherlands	0.85
Switzerland	0.91	Pakistan	0.34
China	0.72	Romania	0.81
Czech Republic	0.84	Russia	0.62
Germany	0.87	Sweden	0.77
Spain	0.90	Slovenia	0.85
Finland	0.95	Slovak Republic	0.72
France	0.75	Taiwan	0.84
United Kingdom	0.80	Ukraine	0.69
Hungary	0.89	United States	0.89
India	0.62	South Africa	0.80

Notes: Load factor is based on regression analysis in Table 3, and averaged for years 1996 on. Estimates are the average experience in each country under the assumption of a 30 commercial life and best-case construction record .

Again we see a wide range of operating efficiencies. For the most part, the relative rankings between countries change little from the raw data, though there are a few interesting differences. Brazil, which seemed pathetic in the raw data, looks a little better in these estimates. But, India and the eastern European countries including Russia still bring up the rear, while Finland, Belgium, and Switzerland are at the top.

An important question involving these operating efficiencies is, How much can be attributed to the design and operation of the plants themselves and how much is due to the overall electricity system of the country itself? This question is important in an analysis of the cost of nuclear power because design and operational inadequacies are potentially resolved if and when new plants are constructed, whereas inefficiencies systemic to the country-wide electricity system are much less likely to be remedied. We approach this question by examining the operating efficiency of the electricity system in each country.

Line Losses

The best measure of the operating efficiency of a country's electricity system available to us is line losses. Line losses represent electricity that is generated but lost in

[4] Data for most countries goes only through 2001.

the movement of the power from the generator to the ultimate consumer. It is energy that is dissipated in the transmission and distribution system.

More electric power is lost when power moves across low voltage lines than it does at high voltage. For instance, in the United States, most of the large generation units and especially the nuclear power plants tied into the electrical system or grid through 500,000 volt lines. This power moves throughout the system to substations where the voltage is reduced and reduced until it reaches households at 220 volts. Obviously, the further power moves along higher voltage lines in its path from generator to home, the lower will be the line losses.

Country by country data on electricity generation, consumption, and line losses from transmission and distribution were obtained from the World Bank.[5] The data include generation by type of fuel as well as total generation. The data are annual from 1992 through 2000. The average line loss percentage is shown in Table 5 for the countries for which data are available.

[5] The Energy Information Administration of the U.S. Department of Energy reports international data from which line losses can be calculated. However, for more than half of the observations, the line loss percentage is exactly 7. EIA cautions on the accuracy of these data.

Table 5. Electricity Line Losses in Transmission and Distribution by Country

Country	*Line Loss Percent*	*Country*	*Line Loss Percent*	*Country*	*Line Loss Percent*
Albania	48.7	Germany	4.0	Pakistan	24.4
Algeria	17.2	Ghana	0.8	Panama	21.2
Angola	21.8	Greece	7.5	Paraguay	1.8
Argentina	17.0	Guatemala	16.3	Peru	16
Armenia	32.2	Haiti	47.4	Philippines	15.5
Australia	6.8	Honduras	23.9	Poland	11.8
Austria	6.3	Hong Kong, China	13.1	Portugal	9.9
Azerbaijan	15.6	Hungary	12.9	Qatar	6.6
Bahrain	4.7	Iceland	6.6	Romania	11.3
Bangladesh	17.7	India	20.7	Russian Federation	10.2
Belarus	13.7	Indonesia	12.2	Saudi Arabia	8.5
Belgium	5.0	Iran, Islamic Rep.	12.5	Senegal	13.6
Benin	71.5	Ireland	8.7	Singapore	4.4
Bolivia	21.1	Israel	4.2	Slovak Republic	7.2
Bosnia & Herzegovina	18.2	Italy	7.4	Slovenia	5.4
Brazil	16.7	Jamaica	10.4	South Africa	7.6
Brunei	2.6	Japan	3.6	Spain	9.2
Bulgaria	14.0	Jordan	9.8	Sri Lanka	18.2
Cameroon	18.8	Kazakhstan	14.9	Sudan	25.5
Canada	7.2	Kenya	18.4	Sweden	7
Chile	9.0	Korea, Rep.	4.7	Switzerland	5.9
China	7.0	Kyrgyz Republic	24.4	Syrian Arab Republic	26.3
Colombia	22.2	Latvia	29.4	Taiwan, China	5.2
Congo, Dem. Rep.	4.2	Lebanon	15.1	Tajikistan	12.3
Congo, Rep.	38.6	Lithuania	14.0	Tanzania	18.5
Costa Rica	7.6	Luxembourg	25.4	Thailand	8.7
Croatia	18.3	Malaysia	8.4	Trinidad And Tobago	9.1
Cuba	18.0	Malta	10.8	Tunisia	10.3
Cyprus	5.6	Mexico	14.1	Turkey	16.6
Czech Republic	7.6	Moldova	25.0	Turkmenistan	11.2
Denmark	5.7	Morocco	4.3	Ukraine	13.6
Dominican Republic	27.1	Mozambique	29.9	United Arab Emirates	9
Ecuador	22.9	Myanmar	34.2	United Kingdom	8.3
Egypt, Arab Rep.	12.1	Nepal	21.4	United States	6.7
El Salvador	13.9	Netherlands	4.3	Uruguay	17
Estonia	16.7	Netherlands Antilles	12.4	Uzbekistan	8.9
Ethiopia	10.0	New Zealand	11.3	Venezuela	21
Finland	4.0	Nicaragua	26.4	Vietnam	19.1
France	5.9	Nigeria	32.4	Yemen, Rep.	22.1
Gabon	10.3	Norway	7.3	Zambia	2.8
Georgia	19.8	Oman	14.5	Zimbabwe	11.6

Notes: Data from the World Bank. Means of annual observations, 1992 through 2001.

The line loss data seem reasonable in the large. Developed countries typically have lower line losses than underdeveloped ones. Even so, there are some outliers. One way of examining these data is to relate the line losses to other characteristics of the electrical system. We do this by estimating a regression of line losses on various characteristics of the electricity system. Specifically, we regress line losses on the percentage of exports, electricity consumption per capita, electricity consumption divided by the area of the country, and area itself.

Exports are expected to be associated with lower line losses because exports are almost always accomplished over high voltage transmission lines. Also, it seems reasonable to believe that the transmission system will be of higher quality in countries that have more exports. Across our sample the average export percentage is 5 with a standard deviation of 10.[6] Electricity consumption per capita and per square mile are likely associated with lower line losses simply because they are indicators of more intense electricity use.

Table 6. Regression of the Percentage Line Losses on Country-Wide Electricity System Characteristics

Independent Variables:	*Coefficient*	*t-stat*
Percentage of Exports	-0.12	-5.19
Electricity Consumption Per Capita*	-0.03	-11.31
Electricity Consumption Per Square Mile*	-3.75E-3	-1.83
Intercept	.41	27.93
R-squared	.31	
No. of Observations	1074	

Notes: (*) denotes logs.

The results of this regression are shown in Table 6. The equation explains 30 percent of the variation in line losses across time and places. All variable behave as expected. The coefficient on the percentage of exports can be interpreted to say that a 10 percentage point increase in exports decreases line losses by 1.2 percentage points, so the effect is not huge. The effect of electricity consumption per capita is statistically significant, but also quite modest in its impact. The coefficient says that a 10 percent increase in consumption per capita decreases line losses by .3 percent. Finally, electricity consumption per square mile is trivial. The main point of this regression is simply to show that line losses are systematically related to the electricity system, which gives us some confidence about the quality of the data.

Our main goal is to relate the quality of the electricity system to load factors for nuclear generators. The results of this analysis are presented in Table 7. Here we regress our estimated load factors on the line loss percentage. Several specifications are given.

[6] Export percentage is kilowatt hours of electricity exports divided by generation plus imports. These data come from EIA-DOE.

Table 7. Regressions of the Estimated Load Factors for Nuclear Generators on Country-Wide Line Losses

	Coefficient / (t-stat)		
Independent Variables:	(a)	(b)	(c)
Line Loss Percentage	-1.69	-1.40	-1.66
	(-11.49)	(-6.20)	(-5.07)
Percentage of Exports		-0.18	
		(-1.83)	
Electricity Consumption Per Capita*		0.03	
		(1.85)	
Intercept	0.90	0.66	0.90
	(52.29)	(4.83)	(22.36)
R-squared	.33	.34	.46
No. of Observations	275	273	32

Notes: (*) denotes logs. Specification (c) is country averages over the years for which line loss data are available. Specifications (a) and (b) are based on pooled time series and cross sectional observations. The number of observations differs because of data availability on electricity exports.

The results shown in Table 7 demonstrate with a reasonable degree of precision that load factors at nuclear power plants are significantly related to the overall quality of the electricity system as measured by the percentage line losses. The estimated coefficient says that a 1 percentage point increase in line losses is associated with a 1.5 percentage point decrease in load factor. The estimated coefficient varies by a statistically insignificant amount based on specification. The specification based on the average of the annual observations for each country assures us that the statistical significance of the effect is not spuriously inflated by autocorrelation. Inclusion of the other variables in the regression does not affect the result, nor are they significant predictors of nuclear generator load factors.

Application of the Results

Given our estimated relation between nuclear power plant operating efficiency and the overall efficiency of the electric system, it remains only to predict the values for countries of interest. Table 8 shows the actual and predicted values of load factor for all countries currently operating nuclear power plants and for three countries that are considering nuclear generation, Egypt, Iran, and Turkey.

In comparing the predicted values for countries with NPPs in operation, notice that there is some variation between the actual and predicted values. The model does not explain all variation (as shown by the R-squared statistic), but it is correct on average. It is interesting to note that two countries of interest, China and India, both have predicted values that are very similar to the actual ones. For India, the predicted and observed operating efficiencies are below par.

For the three countries that are considering nuclear power, our forecast of operation efficiencies are all also below par. By our estimates, both Egypt and Iran can both expect nuclear power to be around 15 percent more expensive than the best-case scenario estimate. Turkey can expect nuclear power to be 27 percent more expensive.

Table 8. Predicted Nuclear Power Plant Load Factors Based on Country-wide Line Losses

Country	*Load Factor Experience*	*Line Loss Percent*	*Predicted Load Factor*
Argentina	0.85	0.17	0.61
Armenia	0.53	0.32	0.36
Belgium	0.87	0.05	0.81
Brazil	0.47	0.17	0.62
Bulgaria	0.53	0.14	0.66
Canada	0.74	0.07	0.78
China	0.77	0.07	**0.78**
Czech Republic	0.82	0.08	0.77
Finland	0.93	0.04	0.83
France	0.71	0.06	0.80
Germany	0.84	0.04	0.83
Hungary	0.89	0.13	0.68
India	0.53	0.21	**0.55**
Japan	0.77	0.04	0.84
Kazakhstan	0.35	0.15	0.65
Korea, South	0.84	0.05	0.82
Lithuania	0.42	0.14	0.66
Mexico	0.79	0.14	0.66
Netherlands	0.85	0.04	0.82
Pakistan	0.37	0.24	0.49
Romania	0.79	0.11	0.71
Russia	0.61	0.10	0.73
Slovakia	0.74	0.07	0.78
Slovenia	0.80	0.05	0.81
South Africa	0.72	0.08	0.77
Spain	0.86	0.09	0.74
Sweden	0.75	0.07	0.78
Switzerland	0.90	0.06	0.80
Taiwan	0.81	0.05	0.81
Ukraine	0.67	0.14	0.67
United Kingdom	0.80	0.08	0.76
United States	0.83	0.07	0.78
Selected Countries			
Egypt		0.12	**0.69**
Iran		0.13	**0.69**
Turkey		0.17	**0.62**

Notes: Load factor experience is our measure of the operational performance on average in each country for nuclear power plants over thirty years of commercial life assuming a best-case construction record. These numbers differ slightly from the earlier table because they are averaged over the years for which line loss data is available.