Empirical Study of Failure Factors in Deploying Nuclear Power Plants in Newcomer Countries

Hanna Yasmine[1a], Philseo Kim[2a], Man-Sung Yim[1]
[1]Korea Advanced Institute of Science and Technology (KAIST),
[2]Texas A&M University
[a] These authors contributed equally.

hyasmine@kaist.ac.kr

Abstract

With the rising demand for electricity and the simultaneous urgency to reduce greenhouse gas emissions, nuclear energy is being revisited worldwide. As of 2022, 32 countries have operating nuclear power plants, and at least 30 countries have expressed an interest in deploying nuclear power programs. With or without nuclear power plants, some countries have postponed or canceled their peaceful nuclear power development programs. Few studies have discussed the failures of nuclear power programs. Therefore, this study aims to identify the critical factors that affect a country's decision to scrap or proceed with a peaceful nuclear power program. We collected over 80 countries' data on nuclear power development from 1960 to 2020. Thirty-two of those countries have operating nuclear power plants, and 50 countries had expressed an interest in nuclear power programs or had nuclear power plants under construction. Preliminary empirical analyses of the time-series datasets show that the occurrence of a nuclear accident (Three Mile Island, Chernobyl, or Fukushima) was one of the most significant factors in scrapping a nuclear power program.

I. Introduction

Since the Atoms for Peace Initiative in 1953, there were 60 countries that expressed an interest in nuclear power. However, between 1953 and 2022, only 32 countries deployed nuclear power plants. This raises questions about what factors lead a country to succeed in their nuclear power program, and what factors drive a country to stop pursuing a nuclear power program. This is important because in 2021, there are 28 countries expressed an interest in starting a nuclear program and learning from past experiences will be useful for their program to succeed. This study aims to discover the critical factors that affect a country's decision to cancel or proceed with their nuclear power program. This study will give a better understanding of the factors that impact the development of a nuclear power program, so countries can better assess their strengths and weaknesses when considering whether or not to embark on a nuclear power program.

II. Literature

There have been several studies that investigate the factors surrounding the nuclear power development, they can be categorized as quantitative and qualitative.

II.1. Qualitative Study

Sovacool and Valentine [1]in their studies on examining the history of nuclear program among 8 countries, argued that there are six factors that drive countries to have nuclear power plants despite the risks associated with nuclear power: (1) secrecy and national security; (2) technocratic ideology; (3) economic interventionism; (4) a centrally coordinated energy stakeholder network; (5) subordination of opposition to political authority; and (6) social peripheralization. Meanwhile, Jewell [2] examined 30 countries with nuclear power plants and compared them to 52 countries aspiring to have nuclear power plants. This study found that the shared drivers for nuclear energy among 30 nuclear countries are sizeable economic power and high demand for energy security. Macfarlane [3] used a different angle to determine the factors for nuclear power development: perspectives from the suppliers and buyers. Their study examined five prospective buyers: United Arab Emirates, Jordan, Turkey, Vietnam, and Indonesia; and five suppliers: France, Russia, South Korea, Japan, United States, Canada. The factors are as follows: gross domestic products (GDP), projected domestic electricity needs, energy security, carbon dioxide emissions reduction efforts, prestige and political power. Lester & Rosner [4] on their study about nuclear renaissance argued that the main driver for successful nuclear program in nuclear countries is energy security.

II.2. Quantitative Study

Nelson and Sprecher [5] examined 86 countries--with nuclear power plants and not--with 14 parameters using the stepwise regression model. They found that international openness, democratic institutions, and energy insecurity are the factors on the countries' reliance on nuclear energy for electricity production. Fuhrmann [6] used standard probit model to determine the factors on why countries built nuclear power plants, by examining 129 countries and tested 7 parameters. The significant factors are economic capacity, economic growth, energy imports. Similar to Jewell's study, but using quantitative means, Gourley & Stulberg [3] aim to identify characteristics shared among nuclear power countries. They examined 10 parameters of 150 countries using logistic regression analysis and found that economic power, energy security, and accidents are the correlates of nuclear energy. Csereklyei's [7] study aims to measure the impact of nuclear accidents towards countries' energy policies empirically. They used CIPS panel root test on 31 countries using 7 parameters. They found that energy imports and Chernobyl nuclear accident are the critical factors for the rise and decline of nuclear power. Gralla, et al [8] used a broader scope for identifying the factors related to the successful nuclear power program. They used generalized linear mixed model on 34 nuclear countries using 96 World Bank's development indicators. The results showed that 28 development indicators ranging from carbon dioxide emissions, electricity productions, military expenditure were found related to the success of nuclear program. Neumann, et al [9] used multinomial logistic regression to examine 7 parameters of 166 countries. They found that urbanization, electric power consumption, fossil fuel rents, energy imports (% of primary energy use), nuclear warhead possession, and lower level of democratic level tends to contribute to the successful nuclear program. Last, a study by Brutschin [10], et al, examined 79 countries using 18 parameters, with a logistic regression model to understand the diffusibility of nuclear technology in countries. They found that international relations, high electricity demand, and high dependence on energy imports are key factors for the easier nuclear technologies to be introduced to the countries.

III. Methodology

There are 82 countries examined in this study. Thirty-two countries with existing nuclear plants are in the "nuclear countries" category and fifty countries who expressed an interest to have nuclear plants are in the "newcomer countries". The list below shows the newcomer countries, taken from Brustchin [10]:

1. Algeria
2. Australia
3. Austria
4. Azerbaijan
5. Bahrain
6. Cuba
7. Chile
8. Denmark
9. Ecuador
10. Egypt
11. Georgia
12. Ghana
13. Greece
14. Indonesia
15. Iraq

16. Ireland
17. Israel
18. Jordan
19. Kazakhstan
20. Kenya
21. Kuwait
22. Laos
23. Libya
24. Malaysia
25. Morocco
26. Myanmar
27. Namibia
28. New Zealand
29. Nigeria
30. North Korea
31. Norway
32. Oman
33. Paraguay
34. Peru
35. Philippines
36. Poland
37. Portugal
38. Qatar
39. Saudi Arabia
40. Singapore
41. Sri Lanka
42. Sudan
43. Syria
44. Thailand
45. Tunisia
46. Uzbekistan
47. Venezuela
48. Vietnam
49. Bangladesh
50. Turkiye

Observation period on these newcomer countries starts at 1960 and ends at 2020. Meanwhile for the nuclear countries, the data point starts at the year when they expressed interest in nuclear power and after they have their first grid connection, the coding will always show grid connection until 2020. Table below lists the following details, taken from IAEA Power Reactor Information System [11]:

Table 1. Nuclear countries timeline period

Country	Year of expressing interest	Year of grid connection
Argentina	1967	1974
Belgium	1954	1962
Brazil	1961	1985
India	1954	1969
South Korea	1966	1977
Mexico	1970	1988
Pakistan	1956	1971
South Africa	1968	1984
Spain	1956	1968
Sweden	1955	1964
Finland	1965	1977

Country	Year of expressing interest	Year of grid connection
Switzerland	1961	1969
Japan	1956	1963
East Germany	1955	1964
West Germany	1955	1961
Bulgaria	1955	1974
Canada	1946	1967
China	1978	1991
Czechoslovakia	1955	1972
France	1952	1959
Hungary	1955	1968
Italy	1952	1963
Netherlands	1953	1968
Romania	1970	1996
Soviet Union	1949	1954
Yugoslavia	1966	1981
United Arab Emirates	2008	2020
United Kingdom	1947	1956
United States	1946	1957
Taiwan	1955	1982

III.1. Multinomial logistic regression

The multinomial logistic regression is used when the dependent variables are nominal. In this study, the dependent variables are the status of countries' nuclear power programs, which are classified into five categories: no nuclear power plants, expression of interest, construction and grid connection, and defer or scrap. The independent variables may or may not act as predictors for the dependent variables' outcome. They are being tested to determine if they affect a country's decision to express interest, construct and connect to the grid, or defer or scrap their nuclear power program.
Multinomial logistic regression needs a reference variable from the dependent variables. In this study, "no interest" is used as the reference.

Equation for Expression of Interest

$$\ln\left(\frac{\Pr(Y_i = Interest|x_i)}{\Pr(Y_i = No\ Interest|x_i)}\right) = \alpha_1 + \beta_1 \cdot x_i$$

Equation for Construction

$$\ln\left(\frac{\Pr(Y_i = Construction|x_i)}{\Pr(Y_i = No\ Interest|x_i)}\right) = \alpha_2 + \beta_2 \cdot x_i$$

Equation for Defer or Scrap

$$\ln\left(\frac{\Pr(Y_i = Defer\ or\ Scrap|x_i)}{\Pr(Y_i = No\ Interest|x_i)}\right) = \alpha_3 + \beta_3 \cdot x_i$$

Equation for Grid Connection

$$\ln\left(\frac{\Pr(Y_i = Grid\ Connection|x_i)}{\Pr(Y_i = No\ Interest|x_i)}\right) = \alpha_4 + \beta_4 \cdot x_i$$

III.2. Dependent Variables

Dependent variables are taken from the year in which historical events related to nuclear countries and newcomer nuclear countries' nuclear programs occurred. The following table lists the categorization of historical events to each respective dependent variable.

Table 2. Dependent variables

Dependent Variable Code	Description	Historical Events
0	No nuclear power plants	
1	Expression of Interest	• Nuclear cooperation regarding electricity generation • Public official statement on the nuclear power plant interest • Call for vendors/tenders for deploying nuclear power plants • Sites selection process initiation for deploying nuclear energy • Signed contract for construction • Government's projection of future electricity source from nuclear • Infrastructure review mission for large commercial power reactor by IAEA • Restarting nuclear program/construction of nuclear power plants • Listing nuclear power as a part of national development plan/energy mix
2	Construction	The year taken from IAEA's Power Reactor Information System

3	Defer or Scrap or Cancel	• Public statement of the country who scrapped or deferred the construction of nuclear power plant/planning of nuclear power deployment
		• Scientific literature stating that the decision to scrap or defer is attributed to following reasons:
		  ○ Nuclear accidents
		  ○ No investors or funding
		  ○ Change of administration/policy
		  ○ Bad project management
		  ○ Strong public opposition/public referendum who refused to have NPP

4	Grid Connection	The year taken from IAEA's Power Reactor Information System

III.3. Independent variables

Independent variables in this study are the factors combined that will yield the dependent variable outcome. Table below lists the independent variables employed in the equation.

Table 3. Independent variables

Category	Variables	Data References
Major nuclear accidents	The years when major nuclear accidents occurred	Three-Mile Island (1979), Chernobyl (1986), Fukushima (2011)
Oil Price	Oil price (contemporary $US per barrel)	[12]
Soviet Union dissolution	The year where Soviet Union officially dissolved	1991
Economy	Gross Domestic Product (GDP) per capita	[13]
Energy Security	Total electricity capacity installed (million kW)	[14]
Politics	Democracy level (Polity5)	[15]
Climate change drivers	Electricity from renewables (million kW)	[14]
International Cooperation	Defense pacts with major nuclear supplier countries (US, Russia, Canada, United Kingdom, France)	[16]

IV. Results & Discussion

Table 4. Results of Multinomial Logistic Regression

	Dependent variable:			
	Interest	Construction Start	Defer /Scrap	Grid Connection
	(1)	(2)	(3)	(4)
GDP per capita	1.957***	-1.382***	1.920***	-1.046***
	(0.196)	(0.383)	(0.422)	(0.289)
Total installed capacity	-0.140	1.627***	0.131	2.866***
	(0.082)	(0.244)	(0.184)	(0.178)
Electricity from renewables	-0.536**	0.386	-0.933*	-1.673***
	(0.175)	(0.383)	(0.367)	(0.205)
Democracy level	-0.828***	-14.292***	-0.247	1.465***
	(0.136)	(0.00002)	(0.274)	(0.164)
Defense pact with major nuclear suppliers	0.501***	-0.047	-0.067	0.519***
	(0.125)	(0.272)	(0.269)	(0.140)
Crude oil price	0.975***	-0.600**	0.365*	-0.120
	(0.095)	(0.212)	(0.181)	(0.111)
Major nuclear accidents	-0.101	0.789**	0.994***	0.542**
	(0.146)	(0.286)	(0.254)	(0.174)
Soviet Union dissolution	-0.073	-0.127	-0.125	0.059
	(0.243)	(0.428)	(0.546)	(0.249)
Constant	-25.435***	11.713**	-25.433***	3.927
	(2.096)	(3.884)	(4.479)	(2.900)
Akaike Inf. Crit.	4,856.969	4,856.969	4,856.969	4,856.969
Note:	*p**p***p<0.001			

The economic factor that is represented by GDP shows statistical significances in all categories. It has positive values in the category of interest and defer, and negative values in construction and grid connection. Putting GDP to represent economic power is based on the idea that nuclear power needs a high capital investment, thus, it is expected that countries with high GDP are likelier to succeed in their nuclear program. However, this result shows otherwise so interpreting the effect of GDP must be done in a careful manner. First, regardless of the countries, the value of GDP always keeps increasing from time to time. This affects all of the countries with all experiences in their nuclear program, from interest to grid connection. Therefore, it shows strong statistical significances in all categories. Second, majority of the samples is from countries with the experience of expressing interest and defer or scrap. Both newcomer and nuclear countries have the years of expressing interests. Out of 82 countries examined in this study, only 8 countries that never expressed defer or scrap, so it skews the results to favor the positive significance in defer or scrap category. As for the negative significances on the construction start and grid connection category, they stem from similar problems: among 50 newcomer countries, only 5 countries experienced construction category but eventually all of them scraped their nuclear programs. Further, grid connection category only applies to the 32 nuclear countries. Due to these following reasons, this study finds that GDP variable is difficult to isolate the economic factor in the nuclear programs among 82 countries.

As the representative for energy security, the independent variable to examine the demand of electricity is the grid size. Nuclear energy with their high base-load is attractive to the countries with high electricity demand and sizeable grid size. It shows strong positive significance in the construction and grid connection categories. This result adheres to the studies that argue energy security is the key driver for the successful nuclear program[2], [6].

The next variable is the amount of electricity produced from renewables. Generally, it shows negative significance in interest, defer or scrap, and grid connection. This result is interesting because it suggests that nuclear program is not harmonious with renewables development. With strong negative significance in the grid connection category, it suggests that the rise of electricity produced from renewables reduces the probability of successful grid connection category by a factor of 1.67. Similar result can be said with the interest category: countries with high shares of renewables may have no interest in nuclear power by a factor of 0.54. However, with the negative significance in the defer or scrap category, even with the rising interest of renewables, it can be inferred that countries may less likely to cancel or scrap their nuclear program. One of the possible explanations for this is countries with the rising shares of renewables, would retain their nuclear program rather than scrap them.

The political aspect represented by the democracy level has interesting results. It has strong negative significance in interest and construction categories, but has a strong positive significance in the grid connection category. Similar to GDP variable, this is caused by the pool of the countries. Coded as 0 for low-level democratic countries and coded as 1 for high-level democratic countries, the result infers that countries with low level democracy are more likely to show interest in nuclear program and some succeeded to reach the construction phase [9]. Due to the nature of coding the grid connection in nuclear countries to be continuous until 2020, nuclear countries who experienced low-level democracy years before, become fully democratic until the end year of observation, 2020. This explains why there is a strong positive significance in the grid connection category.

Moving on to the international cooperation aspect, it is interesting that military alliance in form of defense pacts with major nuclear suppliers, show strong positive significance in interest and grid connection. This is due to the nature of dataset that nuclear countries have the interest and grid connection variables, happen to have military alliances with the major nuclear suppliers.

The significance in crude oil price has double-sided effects in nuclear program. The rise of crude oil price did push some countries without nuclear power, to have interest in nuclear power. However, it affects the countries with the ongoing construction. When the crude oil price is high, it impedes the necessary economy to the construction process, hence the negative significance in the construction category. This also explains the positive coefficient in the defer or scrap category, with the rising crude oil price might lead the ongoing plan or construction into halt.

Nuclear accidents are interesting phenomena in this study. It shows strong significance in the construction, defer or scrap, and grid connection category. At a glance, this contradicts the nature of the category but it captures the countries' nuclear energy policies when an accident occurred. The strongest significance in the accident is given: majority of countries, especially newcomers, decided to halt or scrap their plans to have nuclear energy. However, this does not necessarily apply to the countries with existing nuclear plants, specifically the ones who were still under construction. Due to the nature of grid connection coding in nuclear countries, it shows positive significance in the grid connection. This result will not have major changes even if this study incorporates the number of plants shutting down after nuclear accidents among nuclear countries pool, as the majority of nuclear countries still retain their nuclear plants and their constructions despite the accidents.

For the last category, despite being one of the major suppliers of nuclear plants to its members, Soviet Union dissolution was not the end of everything for the nuclear program to some countries. One notable example with severe experience from Soviet Union dissolution was Cuba's failed construction in 1992 [17], but this does not apply to some ex-Soviet Union-affiliated members like Belarus [18] and Poland [19]. These countries still retain their interest in nuclear program even after the years of Soviet Union dissolution.

V. Conclusion

An empirical study assessing the nuclear energy policies among 82 countries was conducted. The result shows that energy security and international cooperation are the strong key drivers for countries to have successful nuclear program. Other aspects are more nuanced to the countries' situation. The big size of economy is not the silver bullet for countries to have successful nuclear program. Similarly, small size of economy will not always push the countries to scrap or defer their nuclear program. Some of the results might be closer to correlation rather than causation. First is interpreting the effect of level of democracy. Because of the nature of the dataset, the interest and construction category are apparent for non-democratic countries, but successful grid connection result is dominated by the democratic countries. This result can be inferred that political situations are fluid chronologically. Meaning that non-democratic countries are showing interest in nuclear program, but they will eventually turn to be democratic after they have their plants in operation. Similar observation can be said for the electricity shares from renewables, nuclear accident, and crude oil price. Nuclear energy policies from countries might respond differently to these categories. High shares of renewables might dampen countries' interest to pursue nuclear energy, but not to the extent to scrap their nuclear program. Accidents might cause some countries to scrap their program, but did not stop some countries to stop their construction and grid connection. High crude oil price might spark the interest to pursue nuclear program, but stalls the construction to the extent of scraping their nuclear program.

References

[1] B. K. Sovacool and S. V. Valentine, *The national politics of nuclear power economics, security, and governance*. London: Routledge, 2012.

[2] J. Jewell, "Ready for nuclear energy?: An assessment of capacities and motivations for launching new national nuclear power programs," *Energy Policy*, vol. 39, no. 3, pp. 1041–1055, Mar. 2011, doi: 10.1016/j.enpol.2010.10.041.

[3] A. N. Stulberg and M. Fuhrmann, Eds., *The nuclear renaissance and international security*. Stanford, California: Stanford Security Studies, an imprint of Stanford University Press, 2013.

[4] R. K. Lester and R. Rosner, “The growth of nuclear power: drivers & constraints,” *Daedalus*, vol. 138, no. 4, pp. 19–30, Sep. 2009, doi: 10.1162/daed.2009.138.4.19.
[5] P. Nelson and C. M. Sprecher, “WHAT DETERMINES THE EXTENT OF NATIONAL RELIANCE ON CIVIL NUCLEAR POWER?”.
[6] M. Fuhrmann, “Splitting Atoms: Why Do Countries Build Nuclear Power Plants?,” *Int. Interact.*, vol. 38, no. 1, pp. 29–57, Jan. 2012, doi: 10.1080/03050629.2012.640209.
[7] Z. Csereklyei, “Measuring the impact of nuclear accidents on energy policy,” *Ecol. Econ.*, vol. 99, pp. 121–129, Mar. 2014, doi: 10.1016/j.ecolecon.2014.01.010.
[8] F. Gralla, D. J. Abson, A. P. Møller, D. J. Lang, and H. von Wehrden, “Energy transitions and national development indicators: A global review of nuclear energy production,” *Renew. Sustain. Energy Rev.*, vol. 70, pp. 1251–1265, Apr. 2017, doi: 10.1016/j.rser.2016.12.026.
[9] A. Neumann, L. Sorge, C. von Hirschhausen, and B. Wealer, “Democratic quality and nuclear power: Reviewing the global determinants for the introduction of nuclear energy in 166 countries,” *Energy Res. Soc. Sci.*, vol. 63, p. 101389, May 2020, doi: 10.1016/j.erss.2019.101389.
[10] E. Brutschin, A. Cherp, and J. Jewell, “Failing the formative phase: The global diffusion of nuclear power is limited by national markets,” *Energy Res. Soc. Sci.*, vol. 80, p. 102221, Oct. 2021, doi: 10.1016/j.erss.2021.102221.
[11] International Atomic Energy Agency, “IAEA Power Reactor Information System.” [Online]. Available: https://pris.iaea.org/PRIS/WorldStatistics/OperationalReactorsByCountry.aspx
[12] Nasdaq, “Crude Oil Prices from 1861.” Dec. 22, 2022. [Online]. Available: https://data.nasdaq.com/data/BP/CRUDE_OIL_PRICES
[13] J. Bolt and J. L. van Zanden, “Maddison style estimates of the evolution of the world economy. A new 2020 update.” 2020.
[14] U.S. Energy Information Administration, “World Electricity Generation - International.” 2022. [Online]. Available: https://www.eia.gov/international/data/world/electricity/electricity-generation?pd=2&p=0000000000000000000000000000fvu&u=0&f=A&v=mapbubble&a=-&i=none&vo=value&t=C&g=00000000000000000000000000000000000000000000001&l=249-ruvvvvvfvtvnvv1vrvvvvfvvvvvvfvvvou20evvvvvvvvvvnvvvs0008&s=315532800000&e=1609459200000&
[15] Center for Systemic Peace, “The Polity Project.” 2018. [Online]. Available: https://www.systemicpeace.org/polityproject.html
[16] D. M. Gibler, “International military alliances, 1648-2008.” CQ Press, 2009. [Online]. Available: https://correlatesofwar.org/data-sets/formal-alliances/
[17] B. Khol, “Cuba: Nuclear Power Plant Construction Suspended; Report On Sugar Production & Sales,” 1992. [Online]. Available: https://digitalrepository.unm.edu/notisur/10229
[18] A. Stsiapanau, “Belarus - Short Country Report,” History of Nuclear Energy and Society, Jul. 2018. [Online]. Available: http://www.honest2020.eu/sites/default/files/deliverables_24/BY.pdf
[19] P. Potyrańska, “Opportunities and threats for the introduction of nuclear power in Poland,” *Energy Policy Stud.*, vol. 2, no. 4, pp. 36–48, 2019.