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AN EMPIRICAL ASSESSMENT OF ELEMENTS OF THE FUTURE OF CIVIL NUCLEAR ENERGY

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EXECUTIVE SUMMARY

A methodology is described that combines an earlier empirical model of nuclear reliance (fraction of the electricity of a state that is produced by nuclear energy) with US Energy Information Administration projections of worldwide regional electricity demand to yield state-by-state projections of future electrical generation from nuclear energy. The following conclusions are drawn from comparisons of the resulting projections for year 2030 to World Nuclear Association estimates of nuclear intent at about that time.

i) For a group of 23 states that have been mentioned as new aspirants to civil nuclear energy, there is good agreement between the methodological projections and the WNA estimates for all except six states. The nature of the difference between intent and projection depends upon whether the projections of aspirant behavior assume these aspirants plan as if assured of future access to nuclear materials and technology to the extent historically associated to states aligned with one of the Nuclear-Weapon States. If that assurance is not assumed, then most of the significant differences occur in the direction of intent significantly greater than projection. On the other hand, if assurance is assumed, then the significant differences tend toward intent significantly smaller than projection.

ii) The projections tend to support existence of a significant potential market for small and medium reactors, as compared to the now more-or-less standard reactors having capacities of 1000 Megawatts-electric or greater.

iii) Currently scheduled closures of nuclear power plants in a number of states tend to run counter to projections.

iv) For the 86 states in the data base underlying the empirical model, six display an extremely weak intent as compared to projections with assurance, and five show an extremely strong intent on the same comparison. The six states having an extremely weak intent have a mean per capita gross domestic product (based on purchasing power parity) nearly four times that of the five states having an extremely strong intent.

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1. INTRODUCTION

Estimates of the number of states not currently hosting nuclear power plants (NPPs) but having expressed some interest in doing so range from 40 to upward of 50. Notwithstanding this particular manifestation of the oft-noted nuclear renaissance, as of December 2009 the World Nuclear Association data assessed there were only 14 such aspirant states that had developed nuclear intent to the point of having "future reactors envisaged in specific plans and proposals and expected to be operating by 2030."[1] The author has used a recent empirical model[2] to generate various projections of the nuclear-energy capacity in 2030 of the 86 states comprising the database underlying this model. Alongside the aforementioned WNA data on intent, these projections suggest the following notable points:

1. The nuclear intent of the various states hinges, perhaps crucially in some cases, upon their assessment of the likelihood nuclear-developed states will not hinder access to nuclear materials and technology for nominally civil purposes, in consonance with the interpretation of Article IV of the Nuclear Non-Proliferation Treaty that seems to exist among many developing states.
2. Economically viable small-to-medium reactors might be quite attractive to many aspirant states.
3. Currently scheduled shutdowns of reactors in a number of states tend to run counter to projections.
4. The data suggest a complex dependence upon national wealth of the intent to use NPPs to meet electrical generation needs.

Each of these points is further discussed below, in sections respectively devoted to them. There intervenes a section devoted to the methodology underlying the data that provides the basis for these discussions.

2. METHODOLOGY

2.1. The empirical model

The model underlying the projections presented here was developed by using stepwise regression. The dependent variable was selected as *nuclear reliance* = fraction of national electricity generated from nuclear energy. The underlying dataset consisted of 86 states that in 2006 had either a population greater than 20 million or a GDP greater than $20 billion.[3] The initial pool of candidate dependent variables consisted of fourteen different attributes anticipated to be correlated with nuclear reliance, and for which valuations either were readily available or could readily be constructed.

These attributes were, with parenthetical explanations as necessary, the following: historic alignment (with one of the P5); coal reserves; fuel-cycle state (a state that is not a Nuclear-Weapon State, under the provisions of the Nuclear Nonproliferation Treaty, but nonetheless attempts to attain some level of assurance of access to nuclear materials and technology through maintaining some indigenous capability for the relatively difficult technologies required to produce material that can help to sustain a chain reaction - i.e., enriched uranium, recycled plutonium or heavy water); international commerce (in the sense of a national effort to sell indigenously developed nuclear technology - not raw materials - or energy on the international market); polity; energy insecurity (fraction of energy imported); electricity generated; gas reserves; GDP; per capita GDP based on purchasing power parity; *de facto nuclear-weapon state*; *de jure Nuclear Weapon State*; *primary fuel production state* (states having the ability to produce sensitive nuclear materials indigenously); and population. The italicized attributes were coded as dichotomous (dummy) variables.

The stepwise regression process revealed the first five of these as statistically significant.[4] The attributes "coal reserves" and "fuel-cycle state" were negatively correlated with nuclear reliance, and the others were positively correlated. Presumably the (fairly strong) negative correlation for "coal reserves" is because coal historically been the primary competitor to nuclear as a source of energy for generating electricity. The underlying reason for the negative correlation of "fuel-cycle state" is less clear. Possibilities that have been suggested are that fuel-cycle facilities compete with NPPs for scarce resources (e.g., trained and educated personnel), or that the close association of fuel-cycle facilities with potential weapons programs creates an overarching negative public attitude toward all nuclear enterprises, including NPPs.

2.2. 2030 projections

The 2030 projections of the nuclear capacities of the various states were generated as follows. Nuclear reliances were generated using two variants of the regression model generated in the preceding subsection. One was the base model itself, with the attributes of the various states assumed to have that same value used in generating the model. The second was the same, except that the value of the dependent variable "historic alignment" was taken as one for *all* states. This was intended as a simulation of what might happen - or at least what the various states might intend to happen - if in the future all states received the same benefits (whatever they might be) regarding development of civil nuclear energy as the model seems to suggest has in the past been bestowed upon states aligned with one of the P5.

These nuclear reliances were then converted to annual capacities for generating electricity from nuclear energy by multiplying by the estimated 2030 annual electricity (energy) generation for the corresponding state. The estimated annual electricity generations were obtained by starting from published 2005 generations,[5] then compounding based on EIA estimates of growth rates for various states or regions.[6]

Finally, these projected annual electricity generations were converted to "nominal nuclear power plants" (NNPPs), where one NNPP = 7 terawatt-hours per year. This is very close to the electrical energy produced per year by a 1000 Megawatt-electric (MWe) nuclear power plant at 80% capacity factor. Thus the NNPP is a convenient way of reporting an annual electricity generation in terms that provides an immediate conversion into an equivalent number of NPPs of as close to a standard capacity for NPPs as exists.

2.3. Estimation of net 2030 intents

Estimates of the net nuclear intent of states for 2030 were generated as follows. The baseline was taken as current (2008) data for nuclear electricity generation, denominated in NNPPs. WNA data for plants under construction, planned and proposed were then similarly converted into NNPPs, by applying an assumed 80% capacity factor to the reported capacities. The corresponding sums for a given state were then added to the 2008 baseline. Finally, anticipated plant closures by 2030 were similarly converted to an equivalent in NNPPs, and subtracted. The result, in NNPPs, was taken as the estimated net nuclear intent of the corresponding state for 2030.[7]

The basis for aligning this estimate with year 2030 is the following source description of the categories of civil-nuclear intent indicated above:

- Building/Construction = first concrete for reactor poured, or major refurbishment under way.
- Planned = Approvals, funding or major commitment in place, mostly expected in operation within 8 years, or construction well advanced but suspended indefinitely;
- Proposed = Specific program or site proposals, expected operation within 20 years.

The latter supports a 2029 date for completion of the majority of the NNPPs included in the estimate derived above. An additional year for conservatism is perhaps not too amiss.

3. PROJECTIONS OF ASPIRANT INTENT

Table I lists the various projections and estimated intents, for the 14 newly aspirant states mentioned above and nine additional states that have sometimes been indicated to have considerable aspirations to become a nuclear-energy state.[8] Here projections in *italics* (**bold**) indicate instances of states which the estimate of intent is significantly smaller (larger)[9] than that projection. For about 2/3 of the listed states neither holds, which indicates a degree of agreement between the projection and estimated intent.

Table I: Projections and estimates, for several aspirant states

States	NNPPs projected by 2030	NNPPs projected by 2030, with assurance	estimated 2030 intent, in NNPPs
Algeria	0	0.9	0
Australia	0	0	0
Bangladesh	0.3	1.1	2.0
Belarus	0.5	0.5	2.0
Chile	0.6	1.7	0
Egypt	**0**	2.5	2.0
Indonesia	**1.8**	5.2	6.0
Iran	1.5	*6.4*	3.1
Israel	0	0.3	1.2
Italy	9.6	9.6	17.0
Kazakhstan	1.4	1.4	2.4
Libya	0	0.4	0
Malaysia	0.8	*3.1*	0
Nigeria	0.2	0.8	0
North Korea	0	0.5	1.0
Philippines	*2.4*	*2.4*	0
Poland	3.1	3.1	6.0
Thailand	**2.2**	5.8	6.0
Turkey	5.1	5.1	3.6
UAE	**0**	**1.0**	20
Vietnam	**0**	**1.2**	10
Venezuela	0.9	*2.9*	0
Yemen	0	0.1	0

On the other hand, in five instances the estimated 2030 intent significantly exceeds the basic projection (strong intent), while in only one instance is it significantly smaller (weak intent). Of the former (Egypt, Indonesia, Thailand, UAE and Vietnam) all seem to be judged by Gourley and Stulberg[10] as likely successful in standing up a civil nuclear program, although their case-study approach does not lend itself to estimates of degree of success in achieving stated intent. The basic projection suggests some reason to doubt that such success will be fully forthcoming, perhaps especially so in the case of UAE and Vietnam. As for the state having weak intent (Philippines), Gourley and Stulberg assess it as an "attractive candidate for a nuclear energy program." However public support seems highly questionable, perhaps in part owing to disastrous experience with an attempt from the early 70's to the mid 80's to build a (Westinghouse) light-water reactor. This failed attempt (Bataan Nuclear Power Plant) ultimately became a major national obligation, but it has been recently considered for rehabilitation.

By contrast, in comparison to the projection with assurance, only two (UAE and Vietnam) of these 23 states continue to display strong intent, while four now show the weak intent that might signal either innate conservatism or uncertainty in the support that might be forthcoming from the nuclear-developed states. The reader likely can discern instances of both possibilities among these four states (Iran, Malaysia, Philippines and Venezuela). The case of Iran needs no discussion here, and that of the Philippines already has been discussed. Although Malaysia has as of yet no official proposals for NPPs, it has started moves toward a nuclear-energy program and is to complete a comprehensive energy policy study including consideration of nuclear power before 2010.[11] It has been reported[12] that Venezuela is "seeking Russia's help to develop nuclear energy."

It is also possible to view the predictors of Table I as estimates of the 2030 nuclear intent of the various states. From that viewpoint the results in that table suggest the basic projection significantly misestimates in about one-third of the cases, and most of those are underestimates. Similarly, the projection with assurance appears to misestimate in about one-third of the states, with most of those being overestimates. Over the larger set of 86 states the significant misestimates occur somewhat less frequently, primarily because the majority of those states have as yet no nuclear intent at the level of proposed NPPs, and the projections do rather well at capturing that. Further, while over this larger set the two projectors have about the same overall accuracy (viewed as estimators of 2030 intent), the basic projector tends to err in the direction of underestimation, while the errors for projection with assurance tend to be better balanced.

4. SMALL-TO-MEDIUM REACTORS AND CONSORTIA

The number of instances (13 of 46) of fractional projections (greater than zero, less than one) in Table I emphasizes that there could be a viable market for NPPs having smaller capacity that the 1000+ MWe capacity that has become standard in the nuclear industry. This illustrates the basis for the IAEA position that "there is continuing interest in Member States in the development and application of small and medium sized reactors."[13]

There are significant challenges in providing small and medium reactors (SMRs) to meet this apparent need. The first is overcoming the "economy of scale" (lower capital cost per unit capacity for plants of larger capacity) consideration that has historically provided the motivation for the evolution toward NPPs of larger capacity. From the viewpoint of SMRs this becomes the "diseconomy of downscaling" that is counterindicative to SMRs. A number of innovative designs and approaches have been suggested, but it remains to be verified that any of these provide economically competitive downscaling.[14]

Of course SMRs were constructed during the evolution of nuclear energy, and versions of some of those designs are commercially offered and even under construction today.[15] But it is unclear how many of those under construction are proceeding on the unsubsidized basis necessary to establish proof of economic downscaling.[16] In addition a significant fraction of the SMR designs for which there currently exists some experience are pressurized heavy-water reactors; these reactor designs occasion some concerns regarding proliferation risks.[17]

In some instances the need for fractions of NPPs conceivably could be met through standard-sized plants owned and operated by regional consortia, such as Gourley and Stulberg[18] indicate for Albania, Jordan and Lithuania. It is conceivable that such considerations could be underneath the significant nuclear aspirations of the UAE and Vietnam. The projections above do not reflect such consortia, but the methodology could be modified to do so, by appropriately aggregating the attributes of the component states.

5. PLANT CLOSURES

Table II is a listing of the six states within the 86 database states that display an "extremely weak"[19] estimated 2030 intent, as compared to the projection with assurance. In addition to the two projections of 2030 capacity and the estimated 2030 intent, there is now a fifth column listing the corresponding 2008 nuclear capacities.

Table II: Data for states exhibiting extremely weak estimated 2030 intent

States	NNPPs projected by 2030	NNPPs projected by 2030, with assurance	estimated 2030 intent, in NNPPs	2008 NNPPs
Belgium	7.4	7.4	0	6.2
Germany	19.8	19.8	0	20.1
Malaysia	0.8	3.1	0	0
Netherlands	4.0	4.0	0.6	0.6
Norway	4.6	4.6	0	0
Spain	9.3	9.3	1.7	8.1

Three of these six states had little (Netherlands) or no (Malaysia, Norway) nuclear capacity in 2008. In any event Malaysia has already been discussed, and there is little or nothing to add here. In both the Netherlands and Norway there seems to be, for whatever reason, little or no public support for nuclear energy. One possible contributing factor to that will be discussed in the following section, but here the focal point is the three remaining states (Belgium, Germany and Spain).

What these states have in common is a significant current nuclear capacity, and present (as of August 2009) plans to reduce that capacity significantly, even to zero, except in the instance of Spain. These plans are contrary to those in many states, including the US, where at least larger existing NPPs are being considered for extension of a decade or more beyond their originally envisioned lifetimes. If such extensions were to occur in Belgium, Germany and Spain, thereby keeping their 2030 nuclear capacities equal to their current capacities, then those 2030 nuclear capacities would be quite close to the 2030 projections - much closer than current (August 2009) intents. This suggests these states might at some point encounter considerable internal resistance in executing their current (as of August 2009) plans to shut down the bulk of their currently operating NPPs.

There have long been anecdotal reports that plant-life extension remained a possibility in both Belgium and Germany. As of this writing (December 2009) the situation in Belgium seems to be that "this October, finally, a commission recommended a 10-year life extension for three of the oldest nuclear power reactors, to 2025, and a 20-year life extension for the other four."[20] Somewhat similarly, "following the election of Germany's center-right government this September, that country abandoned a commitment to setting a time limit of 2021 for phasing out nuclear power."[21] Even in Spain there is a recent report of government willingness "to talk on extending the life span of nuclear power plants beyond 40 years." Perhaps these reports indicate that the pressures suggested by the model are having some effect.

6. WEALTH EFFECTS

For reasons nicely detailed by Gourley and Stulberg,[22] one could reasonably expect some measure of financial resources to be significantly correlated to nuclear reliance. Two such measures were included among the initial pool of candidate independent variables: GDP, and per capita GDP based on purchasing power parity (GDP_ppp). It is perhaps at least mildly surprising that the stepwise regression process selected neither as among the most significant correlates to nuclear reliances, from among the selected initial pool.

Nonetheless, Table III shows there appears to be some type of significant dependence on GDP_ppp. Specifically, it shows that states having extremely weak estimated 2030 nuclear intent, relative to NNPPs projected by 2030, with assurance, (i.e., the six states already featured in Table II) tend to be relatively wealthy, in terms of this measure of wealth. (Among the 86 nuclear candidate states the largest GDP_ppp in the data year 2006 was the US, at $39,680 and the third quartile was $24,882.). By contrast, states having an extremely strong estimated 2030 nuclear intent tended toward being relatively poor. (Among the 86 nuclear candidates states in 2006 the median, first quartile and smallest GDP_ppp were respectively $9140, $4235 and $670 (Tanzania).)

Table III: GDPs, based on purchasing power parity, for states displaying extremely weak or extremely strong estimated 2030 nuclear intent

Extremely weak estimated 2030 nuclear intent		Extremely strong estimated 2030 nuclear intent	
State	GDP_ppp (2006)	State	GDP_ppp (2006)
Belgium	$31,100	India	$3140
Germany	28,300	Pakistan	2230
Malaysia	10,280	UAE	24,060
Netherlands	31,750	Ukraine	6390
Norway	38,450	Vietnam	2250
Spain	25,050		
MEAN	$27,488		$7614

Indeed, except for the case of Malaysia - an anomaly previously discussed - all states displaying extremely weak intent have estimated 2030 nuclear intents in the upper quartile. Similarly, except for the UAE all states displaying extremely strong intent[23] have a GDP_ppp below the median value, and with the additional exception of Ukraine all are in the lower quartile. As Table I has already shown, the estimated nuclear intent of the UAE shows by any calculation the largest excess relative to the corresponding projected value.[24] Ukraine perhaps has an exceptionally strong motivation to pursue nuclear energy because of its current dependence on natural gas of Russian origin, for both energy and income.[25]

These data suggest the conjecture that nuclear reliance perhaps depends upon per capita wealth in a nonlinear fashion, in which very poor state cannot afford nuclear energy, and very wealthy states tend to employ some of that wealth to avoid relying on nuclear energy, while less wealthy (but not extremely poor) states choose nuclear energy, perhaps in an effort to effect a quantum improvement in the situation of their populace. This conjecture will be studied further in future work.

7. Concluding remarks

It may be useful to have an alternative view, to that provided by the proclaimed intention of various states, of the likely course of the nuclear renaissance. If so, then the projection methodology used here, which is based upon historical trends, may provide a useful alternative.

It would be a mistake to think of this projection methodology as an effort to predict the future. At most it will be as accurate as the fit of the underlying model to the historic data, which suggests the model captures about half of the ultimate basis for nuclear reliance ($R^2 = 0.53$). The remaining basis must reside in systemic or unit attributes not currently captured in the underlying model.

Perhaps a better way to think of the projection methodology, either in its current form or some future improved version, is as a way to identify those individual states whose stated future nuclear intent warrants closer inspection. If the nuclear renaissance is a race, it may yet be that some of the current hares will falter and tortoises will emerge.

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NOTES

[1] WNA (2009), *World Nuclear Power Reactors and Uranium Requirements*; World Nuclear Association; December 1, 2009; http://www.world-nuclear.org/info/reactors.html; accessed December 17, 2009. The 14 newly aspirant states included in this WNA table are Bangladesh, Belarus, Egypt, Indonesia, Iran, Israel, Italy, Kazakhstan, North Korea, Poland, Thailand, Turkey, UAE and Vietnam.

[2] P. Nelson and C. Sprecher, "Are sensitive technologies enablers of civil nuclear power? An empirical study," *Atoms for Peace*, in press.

[3] Three additional states, Afghanistan, Puerto Rico and Uganda, qualifying under this criterion were omitted because some of the required data were not readily available.

[4] For details of the stepwise regression see Appendix B of P. Nelson and C. Sprecher, What Determines the Extent of National Reliance on Civil Nuclear Power?, Report No. NSSPI-08-014, Nuclear Security Science and Policy Institute, Texas A&M University, December 14, 2008. The work reported here employed a slightly different model from that in the cited references, because of correction of some relatively minor errors subsequently identified in the underlying database.

[5] EIA (2006), Energy Information Administration, "International Energy Annual, 2005," Table 6.3, "World Total Net Electricity Generation, 1980-2005," September 17, 2007, <http://www.eia.doe.gov/pub/international/iealf/table63.xls>, " accessed June 29, 2009.

[6] EIA (2009), "International Energy Outlook 2009," Table H10, "World Total Net Electricity Generation from Central Producers by Region and Country, 2006-2030," May 2009, http://www.eia.doe.gov/oiaf/ieo/index.html, accessed June 3, 2009.

[7] Most of the data so employed were from the August 2009 issue of WNA (2009), *op cit.* Plant closure data were taken from the various WNA country reports that are accessible from this page. Between August 2009 and this writing (December 2009) some of these data have changed. The more striking of these changes will be briefly discussed below, in order to illustrate the rapidly evolving situation regarding the issues considered here.

[8] Several states of some interest (e.g., Albania, Armenia, Jordan, Mongolia and Namibia) are omitted because they did not satisfy the criterion of either $20B GDP or 20M population, 2006 data, that was used as a cutoff criterion for inclusion in the database underlying the model, so the relevant data for them was not readily available.

[9] "Significantly smaller" means smaller by both two or more NNPPS and 50% or more of the projection. "Significantly larger" means larger by both two or more NNPPS and 50% or more of the estimated intent.

[10] Bernard Gourley and Adam N. Stulberg, "Nuclear energy development: Assessing aspirant countries," *Bulletin of the Atomic Scientists*, November/December 2009, vol. 65, no. 6, pp. 20–29.

[11] "Preventing Nuclear Dangers in Southeast Asia and Australasia," IISS Strategic Dossier, International Institute for Strategic Studies, September 2009, http://www.iiss.org/publications/strategic-dossiers/preventing-nuclear-dangers-in-southeast-asia-and-australasia/read-the-dossier/, accessed December 18, 2009. Cf. esp. the section of Chapter 6 entitled "Official Interest."

[12] Tim Padgett, "Chávez to Iran: How About Some Uranium?," Time, October 8, 2009, http://www.time.com/time/world/article/0,8599,1929256,00.html, accessed December 18, 2009.

[13] "Common Technologies and Issues for Small and Medium Sized Reactors," IAEA, http://www.iaea.org/NuclearPower/SMR/, accessed December 18, 2009. The IAEA classifies as "small" a NPP having capacity less than 300 MWe, and as "medium" one having capacity between 300 MWe and 700 MWe.

[14] For details underlying much of this discussion see Vladimir Kuznetsov, "Small and Medium Sized Reactors: Development Status and Deployment Potential/ IAEA Activities in support of SMR Development and Deployment," September 2008, http://www.iaea.org/OurWork/ST/NE/Downloads/files/SMRs_GC52Briefing.pdf, accessed December 18, 2009.

[15] Most of the SMRs currently under construction seem to be evolved versions of older reactor designs. Several of the NPPs currently indicated by the WNA as planned or proposed appear to be SMRs. (Iran- 1 small reactor (SR) planned; Kazakhstan- 2 SRs planned, 2 SRs proposed; Pakistan- 2 SRs planned; Romania, 2 medium reactors planned, 1 proposed; South Africa, 24 SRs proposed.)

[16] Perhaps the most market-oriented arrangement associated with the SMRs presently under construction is the 650 MWe CANDU-6 currently under construction by AECL at Chernavoda, Romania.

[17] "Heavy water in itself isn't dangerous at all, you don't make weapons with it, but it does enable you to operate a nuclear reactor that is optimal for producing plutonium, which could be used for bombs." George R. Perkovich, as quoted in Bernard Gwertzman, "Nuclear Quagmire with Iran," Council on Foreign Relations, September 24, 2008, http://www.cfr.org/publication/20831/nuclear_quagmire_with_iran.html?breadcrumb=%2Fpublication%2Fpublication_list%3Ftype%3Dinterview, accessed December 18, 2008.

[18] *Op cit.*

[19] In this context "extremely weak intent" means smaller by both three or more NNPPS and 75% or more of the projection under the assumption assurance will prevail.

[20] Sonal Patel, "Belgium, Germany Edge toward Nuclear Future," Power Magazine, December 1, 2009, http://www.powermag.com/issues/departments/global_monitor/Belgium-Germany-Edge-Toward-Nuclear-Future_2326.html, accessed December 18, 2009.

[21] *Ibid.*

[22] *Op cit.*

[23] Here "extremely strong intent" means greater by both three or more NNPPS and 75% or more of the intent under the assumption assurance will prevail.

[24] For a broader view of the UAE's ambitious energy program see Christopher M. Davidson, *Abu Dhabi*, Columbia University Press, New York, 2009, especially Chapter 4.

[25] Don Wolcott and Michael J. Economides, "Gazprom – Gas Company or Russia's Battering Ram?," Global Politician, December 19, 2009, http://globalpolitician.com/26108-russia, accessed December 21, 2009.