NSSPI-08-014

Nuclear Security Science & Policy Institute

A Division of the Texas Engineering Experiment Station

WHAT DETERMINES THE EXTENT OF NATIONAL RELIANCE ON CIVIL NUCLEAR POWER?

Paul Nelson and Christopher M. Sprecher
Nuclear Security Science and Policy Institute; Department of Political Science
Texas A&M University
College Station, TX 77843-3473, 4348

October 24, 2008
(corrected December 14, 2008)

EXECUTIVE SUMMARY

In order to better understand, quantitatively and objectively, the factors that have been associated with the extent to which a given state relies on nuclear energy to generate electricity (termed as nuclear reliance*), regression analysis was applied to a set of fourteen hypothesized independent variables having associated measures constructed from a database assembled for this purpose. That process led to a basic linear model having five independent variables that collectively predict nuclear reliance with high confidence (*$p < .05$*, for all predictors) and acceptable goodness of fit, (*$R^2 = 0.53$*). This basic linear model was then employed as a tool to analyze several more-or-less current topics related to proliferation. These include: the historical effectiveness of the nonproliferation regime, as regards the spread of sensitive fuel-cycle technologies; the premise underlying (fuel) assurance programs, as intended to ensure access to (insensitive) nuclear materials and technology, in return for forgoing development of sensitive technologies; and the persistent lack of recipient states willing to accept the bargain underlying assurance programs.*

Table of Contents

TABLE OF FIGURES

LIST OF TABLES

I. INTRODUCTION

A recent article in the popular press[1] indicates that "at least 40 developing countries … have recently approached U.N. officials … to signal interest in starting nuclear power programs." Although the referenced article describes this as "a trend that concerned proliferation experts say could provide the building blocks of nuclear arsenals in some of those nations," in fact it is arguably in part corollary to several recent more-or-less multilateral approaches to *reducing* proliferation prospects by "ensuring fuel supply for nuclear power plants."[2] The idea underlying such "fuel assurance" programs, as they are commonly termed, seems to be to provide states the benefits of civil nuclear energy, without the necessity of pursuing sensitive dual-use technologies, such as reprocessing spent fuel for plutonium or enrichment of uranium. Within such programs, nuclear-weapon states (NWSs) presumably could meet their Nuclear Nonproliferation Treaty (NPT) Article IV obligation "to … co-operate … to the further development of the applications of nuclear energy for peaceful purposes, especially in the territories of non-nuclear-weapon States" without conflicting with their concomitant Article I obligation "not in any way to assist, encourage, or induce any non-nuclear-weapon State to manufacture or otherwise acquire nuclear weapons or other nuclear explosive devices."

At the same time there have appeared numerous cautions not to expect the perceived "renaissance" of the civil nuclear industry to proceed too rapidly, because of issues such as capital formation,[3] and the erosion of the infrastructure necessary to build various essential components - particularly reactor vessels - that has occurred during the past two decades of relatively few orders for new nuclear power plants (NPPs, e.g., Note 4). In view of this, Goldschmidt[5] has suggested a process of "laying out objective, well studied criteria to judge when and where nuclear energy makes sense or not," presumably especially in the relatively near term (next 10-15 years). *The first objective of this report is to provide a foundation for such future analyses by seeking an objective quantitative understanding of the national attributes that associate with the existing degree of reliance of various states upon nuclear energy to meet their electrical needs.* This purely empirical and descriptive approach is intended to contrast with and complement the somewhat prescriptive approach of Goldschmidt.[5] *The second objective is to employ that understanding (model) as a prism through which to view several issues topical to nonproliferation*: the degree of success of the nonproliferation regime in discouraging spread of sensitive fuel-cycle technologies; the premise underlying assurance programs; and the failure thus far of any of the several assurance programs offered to attract willing additional recipient states.

The methodology employed here is that of quantitative empirical analysis, specifically linear regression. The independent variables (predictors) include two distinct indicators intended to measure two somewhat different sources of confidence in supply of insensitive nuclear materials and technology (M&T). Quantitative empirical analysis is the cornerstone of modern political science, including international relations theory, at least as practiced in the US; however it seems to be less well known among nuclear technologists than the companion "literary" school of analysis that tends to be favored by international policy practitioners, and the game-theoretic approach that is known from applications to arms control and deterrence theory. See Note 6 for a somewhat whimsical discussion of these differing schools, as seen from within the field of international relations.

At issue here is the fact that there is a dearth of work aimed at delineating the causal factors underlying national choices to use nuclear reactors as a source of electrical power. By contrast, there is a significant body of literature (e.g., Thayer[7], Sagan[8], Jo and Gartzke[9], and Hymans[10]) analyzing the propensity of states to pursue nuclear weapons. Exceptions to this emphasis on nuclear weapons acquisition are Lidsky and Miller[11], Helm[12] and Yergin[13], who address in differing ways, but not that pursued here, the need for states to adapt nuclear power as a means of ensuring energy security.

The detailed research design is laid out in the following section. In it we discuss the selection of cases being analyzed and the conceptual bases of the dependent and independent variables. Section III then provides a description, and snapshots of the construction, of the basic linear model, with five independent variables, developed and employed in this report.[14] Section IV is devoted to a description of an important instance of the sensitivity analysis utilized to arrive at the basic linear model. In Section V we discuss the results as they relate to proliferation issues, especially the success of the current nonproliferation regime in limiting the spread of dual-use technologies.

II. RESEARCH DESIGN

In this section we develop a database to examine the reliance states have on nuclear power, and discuss how the relevant variables are measured. The remainder of this section is organized into three subsections. In the first section we discuss how we identified a suitable list of states to empirically examine.

The second subsection is devoted to a description of the attribute (Nuclear reliance) employed here as a dependent variable (y), and the details of how it is empirically measured. In the third subsection we generate a list of independent variables that are theoretically suitable candidates to be predictors of nuclear reliance and that have publicly available measures to provide the necessary observational data.

The NC86 Database

The first issue we address is determining the relevant states to be included in our regression model. We focus on states that have the potential to actually build nuclear power plants for energy production. Currently the NPPs that dominate both the current inventory and current marketing strategies of reactor vendors are relatively large, with typical generating capacities of ~ 1000 MWe[15]. This has historically been deemed necessary, in order to achieve capital costs per unit generating capacity that are economically competitive with alternative technologies for electrical generation.[16] The consequence is that an individual NPP tends to have a very large capital cost.[17] Because of this, not all of the 192 States[18] that currently are members of the United Nations are realistic candidates to support a NPP. For present purposes we rather arbitrarily designated a state as a *nuclear candidate* if it had, according to the most recently available data,[19] either a population of at least 20 million or a gross domestic product of at least $20 billion.

A total of 89 nuclear-candidate states meeting this criterion were identified. The source employed for evaluation of energy insecurity (one of the additional independent variables of the extended linear model of Appendix A) did not provide data for four of these (Afghanistan, Puerto Rico, Taiwan and Uganda), but an alternate source of energy-insecurity data was found for Taiwan.[20] The resulting set of 86 nuclear-candidate states is termed below the 86NC states; these comprised the data base supporting our effort to understand the circumstances that historically have led states to choose the civil-nuclear option. Only one (Armenia) of the 32 states[21] that in 2007 had civil NPPs did not qualify as a nuclear candidate.

The 86NC states are listed alphabetically in Table I, along with their respective nuclear reliances. The bar graph of Figure 1 displays the same information, but now in graphical form and ordered by decreasing nuclear reliances. The mean value of the nuclear reliances (.095 = 9.5%)[22] for the 86NC states is represented by the horizontal dotted line. The corresponding estimate $NR = .095$ provides the lowest order linear model of the form (1), with dependent variable NR and independent variables taken from among the set listed in the following subsection. It has, by definition, an associated value of $R^2 = 0$. This essentially means the linear model that sets the predicted value of the dependent variable equal to the mean of its observed values is taken as defining the zero point for explanatory value of a linear model. Our task in the following section is to explore the increased explanatory value obtained by systematically adding additional predictors from among the five identified in the following subsection. A similar exploration within a larger set of independent variables is described in Appendix A.

Having identified the set of cases we are examining, we now turn to the empirical specification of our model. The objective of the remainder of this section is to formulate the details necessary to fit, via *ordinary least-squares* (OLS) *regression* and to a linear model of the form

$$\hat{y} = \beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_n x_n + c, \quad (1)$$

a selected measure y of the extent to which states at this time rely on nuclear energy to meet their needs for civil energy. The resulting *basic linear model*, in five independent variables, will serve as the foundation for subsequent sections. See Appendix A for description of an extended linear model (fifteen independent variables), and discussion of the relationship between the two models.

Table I: The 86NC states, and their respective nuclear reliances

State	*NR*(%)	State	*NR*(%)	State	*NR*(%)	State	*NR*(%)
Algeria	0	Germany	27.6	Morocco	0	South Korea	40.2
Argentina	21	Ghana	0	Myanmar	0	Spain	26
Australia	0	Greece	0	Nepal	0	Sri Lanka	0
Austria	0	Guatemala	0	Netherlands	4	Sudan	0
Bangladesh	0	Hong Kong	0	New Zealand	0	Sweden	41
Belarus	0	Hungary	37	Nigeria	0	Switzerland	36
Belgium	54	India	3.6	North Korea	0	Syria	0
Brazil	4	Indonesia	0	Norway	0	Taiwan	22
Bulgaria	42	Iran	0	Pakistan	2.2	Tanzania	0
Canada	13	Iraq	0	Peru	0	Thailand	0
Chile	0	Ireland	0	Philippines	0	Tunisia	0
China	1.6	Israel	0	Poland	0	Turkey	0
Colombia	0	Italy	0	Portugal	0	UAE	0
Congo-Kinshasa	0	Japan	22	Qatar	0	UK	21
Croatia	0	Kazakhstan	0	Romania	10	Ukraine	44
Cuba	0	Kenya	0	Russia	16.4	USA	19.9
Czech Republic	19.8	Kuwait	0	Saudi Arabia	0	Uzbekistan	0
Denmark	0	Lebanon	0	Serbia	0	Venezuela	0
Egypt	0	Libya	0	Singapore	0	Vietnam	0
Ethiopia	0	Lithuania	79	Slovakia	57.4	Yemen	0
Finland	25.6	Malaysia	0	Slovenia	37		
France	79	Mexico	4	South Africa	6		

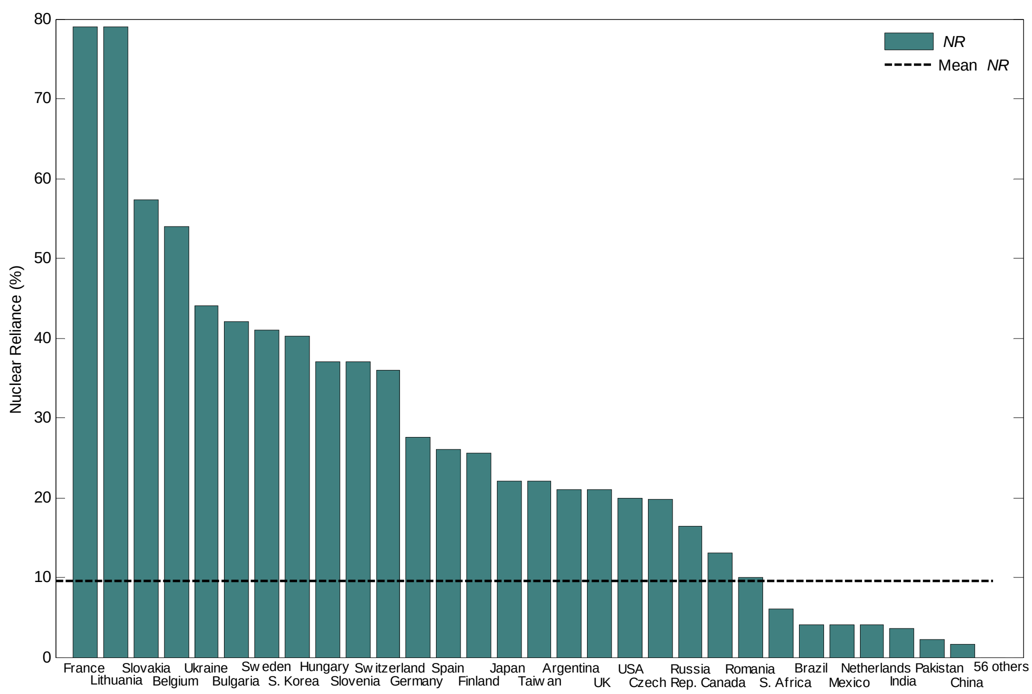

Figure 1 - Bar graph of nuclear reliances, for the 86NC states

Nuclear Reliance: The Dependent Variable

As variable for the linear models to be constructed in this report, we seek to identify an attribute that is both reasonably representative of the extent to which a given state relies on nuclear sources to meet its (civil) energy needs, and has a readily and publicly available measure. The U.S. Energy Information Administration[23] divides energy consumption into four different sectors: transportation, industrial, residential and commercial, and electric power. Within this framework civil nuclear energy is overwhelmingly used for electric power; in 2006 it was estimated[24] that approximately 16% of the world's electrical power was generated by nuclear energy.

For these reasons we use the fraction of the electric power generated within a state that comes from nuclear power plants (*NPPs*) as the attribute representing the commitment of that state to reliance on civil nuclear energy. This attribute shall be termed here as *nuclear reliance* (symbolically *NR*). The nuclear reliance of various states is reported annually by the International Atomic Energy Authority (IAEA). The valuation of *NR* used in this work was the most recent available from this source, at the time of writing (early 2008).[25] It should be noted that we can only measure NR for states with civil NPPs. Our data is not nuanced enough to allow us to determine what percentage of energy used by non-nuclear power states was originally generated from nuclear energy.

Note that, by its very definition, the nuclear reliance of a state can neither be less than zero nor greater than one. However, the minimum possible value of zero is attained, by many states, and the maximum possible value of one is nearly achieved, by two states.[26] We shall term a measure of some attribute as *unit standardized*[27] if its zero point is set at some natural value, often a theoretical minimum, that is nearly achieved for some observations (states), and similarly is scaled to have value one as a theoretical maximum that is nearly achieved, by some state or states. The attribute measures that will be used in the basic linear model (1) will always be unit standardized, in attribute-specific manners to be detailed in the following subsection (for the predictors of the basic linear model), or Appendix A (for the additional predictors of the extended linear model). The scaling required for unit standardization can always be achieved by dividing all values of the measure by the largest value of the measure that occurs within the states included in the observational sample.

Unit standardization is not necessary to carry out an OLS regression; however, it has the advantage of providing a ready interpretation of the resulting values of the predictors (β_i). Specifically they are the change in (predicted) nuclear reliance that would accompany a (hypothetical) change in the corresponding unit-standardized measure from the (natural) value of zero to value one. In particular, the use of unit standardization permits a cross comparison, of the hypothetical impact of the various attributes upon nuclear reliance, to be based upon a simple comparison of the values of the associated predictors. A similar cross comparison is not feasible for some alternate standardizations of variables that have been suggested.[28]

Independent Variables (Predictors)

The objective in this subsection is to compile a list of attributes (for the basic linear model), and associated measures, for use in the linear model (1) (with $y = NR$). The theoretical rationale for a correlation with nuclear reliance underlying each of these candidate independent variables is explained briefly. These attributes, and their associated valuations, have many deficiencies. In some cases there are no data available - perhaps even in principle - for a measure of the attribute we would like to represent. In those cases some surrogate attribute, for which data are available, is selected. In other cases only dichotomous[29] (yes/no, coded as 1/0) data are available, whereas one would like more nearly continuous information.

For all of these reasons, as well as the structural reason that state decisions regarding nuclear reliance depend nonlinearly upon more independent variables than we can hope to include, the linear models we ultimately construct are imperfect. There is some solace in awareness of this imperfection, through the associated value of R^2, and other statistics associated with the regression. These imperfections notwithstanding, to some extent various patterns emerge, as will be seen in Section V. Some of these suggest additional issues indicated in the concluding Section VI. Detailed discussion of these will be deferred to subsequent work.

ALGN? (*Historic alignment*): This attribute is intended as a surrogate for *secondary material and technology assurance*, by which is intended the degree of confidence a state, presumed unable to provide nuclear M&T domestically, has that the international market will work to provide it the M&T necessary for NPPs. The associated hypothesis is that confidence in *M&T assurance* will significantly impact the policy decisions of a state, or even a private electricity generator, regarding use of the nuclear option to meet pending needs for civil energy. Unfortunately, direct assessments of this level of confidence are difficult to come by, probably even in principal.[30] Here we therefore use as a surrogate for secondary fuel assurance the extent to which a state, assumed not to have the capability to provide itself nuclear M&T from domestic sources, has historically been aligned with one of the *de jure* nuclear-weapon states.[31] The associated measure is dichotomous, with values of one assigned to states that are neither fuel-cycle states (see below) nor *de jure* nuclear weapon states, but are successor states of the former Soviet Union or have at one time been members of NATO, SEATO or the Warsaw Pact, and also to Pakistan and Taiwan.[32] Otherwise a value of zero is assigned. This measure is intrinsically unit standardized, as are all dichotomous measures.

COAL (*Relative coal reserves*): The attribute we would like to include is ready and reliable availability of inexpensive alternative fuels for the generation of electricity. In the U.S. 49% of electricity generated in 2006 came from coal-fired plants, as compared to 19.4% from NPPs.[33] Worldwide nearly 66% (~ 10,900 TerraWatt-hours = TWhrs) of the electricity generated in 2004 (~ 16,650 TWhrs) came from "conventional thermal" sources,[34] which presumably were predominantly fuelled by either coal or natural gas. These data suggest coal is a major alternative to nuclear fuel for electrical production. The surrogate attribute thus actually used is "relative coal reserves," defined as the ratio of national coal reserves[35] to electricity generated within the state.[36] Valuations necessary to create a measure of this surrogate attribute were taken from the cited references. Unit normalization is accomplished through division by the maximum value, over all states in the database employed (cf. following subsection), as will be standard for continuous variables.

FCS? (*Fuel-cycle state*): Here the definition of a fuel-cycle state is 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 nuclear M&T assurance 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). The valuation of this attribute is somewhat subjective, as fuel-cycle technology may exist at stages varying from nascent, through pilot plants, to production plants. Our intent is to capture the latter. The value one is thus assigned to the *de facto* nuclear-weapon states that are not *de jure* nuclear-weapon states (i.e., India, Israel and Pakistan), plus Argentina,[37] Brazil,[38] Canada,[39] Japan[40] and the Netherlands.[41] The remaining 86NC states (cf. following subsection) are assigned the value zero.[42] This attribute is included to test the hypothesis that fuel-cycle states have greater difficulty attaining a high degree of nuclear reliance than do the *de jure* Nuclear weapons states, or perhaps even the states that have attained secondary fuel assurance through a historic alignment. This could happen, for example, if fuel-cycle states had more difficulty accessing international nuclear M&T. This dichotomous measure is of course inherently unit standardized.

IC? (*International commerce*): The attribute one would like to include here is some measure of the degree of incentive to the domestic nuclear reliance of a state that derives from its success in the international market for nuclear materials and technology. The underlying hypothesis is that while success in international commerce doubtless stems from a successful domestic nuclear program, there is also feedback in the opposite direction. The ideal measure to use to test this hypothesis would be some estimate of annual international sales of nuclear materials and technology. At least two difficulties arise in obtaining such sales data. First, most of this international commercial business is carried out by companies, private or national, that do not exactly tend to make this information freely available. Second, many of these companies are multinational in nature, so that even if the data were available for the individual companies it would be difficult to break it down into financial flows between states. Here we content ourselves with *IC* as a dichotomous measure of national effort to sell indigenously developed nuclear technology (not raw materials) or energy on the international market. The valuation of this attribute necessarily is somewhat subjective, as most states with a degree of capability in nuclear technology would market that capability internationally, subject to a suitable price and any treaty obligations. Specifically, the value one is assigned to the *de jure* nuclear-weapon states, except China, plus Argentina, Belgium, Canada, Japan, Kazakhstan, Lithuania, the

Netherlands, Slovakia, South Africa, South Korea and Sweden, based on a judgment that these states have significant activities in the international market for nuclear technology, including refined materials. A value of zero is assigned to the remaining 86NC states, as delineated in the following subsection.

PLTY (*Polity*): This is a standard political-science attribute measuring the degree to which a state has democratic tendencies. It is intended here as a surrogate for regime stability. The associated hypothesis is that regime stability tends to promote civil nuclear energy programs. The values used were taken from a standard political-science data base,[43] but with unit standardization attained by linearly mapping the [-10, 10] scale to the interval [0, 1].

III. THE BASIC LINEAR MODEL

The basic linear model was constructed by means of a version of the so-called stepwise regression class of algorithms. In this class of algorithms one begins with a response variable and some set of candidate independent variables. At the beginning of each step some subset of the candidate independent variables have been selected for inclusion in the model, based upon some statistical criterion, and the remaining independent variables are analyzed for possible inclusion, but only one is included in any given step. After inclusion of any independent variable, the previously included independent variables are scrutinized for possible exclusion. The process terminates at any step for which no previously excluded independent variable meets the criterion for inclusion.

In the version of stepwise regression employed here the variable selected for inclusion, at each step, was that having the highest confidence level of statistical significance, if appended to the prior model, provided that confidence level met some *a priori* selected threshold. Thus the process terminated when none of the independent variables currently excluded met that threshold inclusion confidence level. Likewise a previously included variable was excluded if its confidence level fell below some threshold expulsion level, upon inclusion of the new independent variable. The threshold expulsion level should, of course, be no higher than the threshold confidence level for inclusion. Confidence levels are commonly denominated in terms of the so-called *p*-statistic, where 1-*p* is interpreted as the probability that the associated independent variable has an effect in the direction indicated by the sign of the associated predictor.

The fundamental tool used for stepwise regression was the code STEPWISEFIT, in the MatLab[44] computational environment. The default threshold values of 97.5% confidence level (p=.05) for inclusion, and 95% confidence level (p=.10) for expulsion, were employed, not so much because they are customary as because they provided a very clean separation of confidence levels in the extended linear model (see Appendix A).

Application of STEPWISEFIT in this manner gives the following as the basic linear model:

$$\widehat{NR} = \underset{[8\times10^{-11}]}{(.30\pm.04)}IC\,?+\underset{[.004]}{(.097\pm.032)}ALGN\,?-\underset{[6\times10^{-4}]}{(.33\pm.09)}COAL-\underset{[.01]}{(.13\pm.05)}FCS\,?+\underset{[.015]}{(.11\pm.04)}PLTY-.034. \quad (2)$$

Here the estimated predictors are presented as (estimate ± standard deviation), and the values in brackets, below an estimated predictor value, are the *p*-statistics, after the final step, associated to these estimates. (Here the standard errors and *p*-statistics were obtained from STEPWISEFIT, as were all results presented in this section, except as specifically noted otherwise.) The various predictors are listed in the order in which they are added to the model by the stepwise regression process. This tends to correspond to order of increasing associated *p*-values; however, that is not absolutely necessary, because the *p*-statistics evolve across the various steps. For example, note the inversion of *p*-values between the *ALGN?* and *COAL* variables.

Some of the implications of this model are given in Section V below. The remainder of this section is given over to a discussion of the structure of this model, especially as it evolves through the steps in the stepwise regression process. This is intended to enhance understanding of the nature of the basic linear model, and thereby to promote an appreciation of the capabilities and limitations of the resulting model. Table II provides a summary of this evolution.

Table II: Stepwise evolution of the linear model

Step	Linear model	*p*-value(s)	Root mean-square error	R^2	Adjusted R^2	F	Outliers
1	$NR = (.27 \pm .04) IC ?+ .05$	1.0×10^{-8}	.15	.32	.32	40.4	Bulgaria, France, Hungary, Kazakhstan (-), Lithuania, Slovenia, Switzerland, Ukraine
2	$NR = (27 \pm .04) IC ?+ (.10 \pm 03) ALGN ?+ .02$	2.1×10^{-9}, .0034	.14	.39	.38	26.6	Bulgaria, France, Kazakhstan (-), Lithuania, Slovenia, Switzerland, Ukraine
3	$NR = (.31 \pm .04) IC ?+ (.13 \pm ?.03) ALGN ?- (.32 \pm .10) COAL + .02$	2.0×10^{-11}, 2.0×10^{-4}, .0012	.13	.46	.45	23.7	Bulgaria, France, Lithuania, Netherlands (-), Slovenia, Switzerland, Ukraine
4	$NR = (.33 \pm .04) IC ?+ (.12 \pm .03) ALGN ?- (.35 \pm .09) COAL - (.12 \pm .05) FCS ?+ .03$	2.1×10^{-12}, 2.9×10^{-4}, 4.2×10^{-4}, .025	.13	.50	.47	20.0	Australia, Bulgaria, France, Lithuania, Slovenia, Switzerland, Ukraine
5	$NR = (.30 \pm .04) IC ?+ (.10 \pm .03) ALGN ?- (.33 \pm .09) COAL - (.13 \pm .05) FCS ?+ (.11 \pm .04) PLTY - .03$	7.6×10^{-11}, 3.9×10^{-3}, 6.3×10^{-4}, 9.9×10^{-3}, .015	.13	.53	.50	18.3	Bulgaria, France, Lithuania, Slovenia, Switzerland, Ukraine
6	$NR = (.30 \pm .04) IC ?+ (.09 \pm .03) ALGN ?- (.31 \pm .09) COAL + (.13 \pm .05) FCS ?+ (.09 \pm .04) PLTY + (.011 \pm .010) EI - .02$	1.0×10^{-10}, 5.1×10^{-3}, 1.1×10^{-3}, 8.8×10^{-3}, .043, .25	.13	.54	.51	15.5	Bulgaria, France, Lithuania, Slovenia, Switzerland, Ukraine

The values of the coefficients of the various predictors change relatively little as additional predictors are added to the model (i.e., with subsequent steps). This stability is an indication there is a low degree of multicollinearity[45] among the five independent variables in the basic linear model. This stability continues through (at least) the sixth step that would be taken if the acceptance threshold for *p*-values were raised to .25, to permit inclusion of the energy insecurity variable appearing in the extended linear model (cf. Appendix A). Likewise, the *p*-values associated with the various predictors tend to change little, on an absolute scale, between successive steps.

The root mean-square error,[46] and R^2, and adjusted R^2 (see Note [47]) statistics are used here primarily to compare the relative explanatory power of the models emerging from the various steps. (The R^2 and adjusted R^2 statistics were obtained from the MatLab code REGSTATS.) For that purpose we shall principally focus upon the R^2; very naively, the value R^2=.32 found in the first step suggests that about a third of the global indigenous nuclear reliance can be associated to international commerce. But this conclusion must be used with considerable caution, because of both the crude nature of the measure employed here for international commerce (see the relevant discussion in Section II) and because of a very substantial scatter in the underlying data (see Appendix B, especially Figure B.1, for further details.

The value of R^2increases slowly through successive steps, but the value of .54 for the final basic linear model suggests that model predicts somewhat more than half of the tendency of states to rely on nuclear energy for electricity generation. Much the same holds for the trend in the values of the adjusted R^2 statistics, which adjusts for the inevitable increase of R^2 with an increasing number of predictors.

The outliers associated with a particular step are those states not having zero within the 95% confidence interval of the values of their respective residuals, as defined by the linear model resulting from that step. (The confidence intervals used were obtained by means of the MatLab code REGRESS.) Most have positive residuals (i.e., observed nuclear reliances excessively greater than the normative prediction); the few exceptions are indicated by a parenthetical dash. The outliers also are more-or-less stable, in that the six for the final model (Bulgaria, France, Lithuania, Slovenia, Switzerland and Ukraine) are outliers at all steps. (Note that all have positive residuals.) See Appendix A for a detailed discussion of the phenomenon of a few states (Hungary, Kazakhstan(-), Netherlands (-), Australia) appearing as outliers in the intermediate steps.

We conclude this section with a brief discussion of the two possible extremes predicted by the basic linear model (2), as regards nuclear reliance. This model predicts that the largest values of nuclear reliance (~ 48%) would tend to be seen among states that are historically aligned democracies engaged in international commerce of nuclear technology, but having little indigenous coal reserves and not being a fuel-cycle state. Cases of such states, with their respective nuclear reliances in parentheses, are: Belgium (54%); Lithuania (79%); Slovakia (57%); South Korea (40%) and Sweden (41%).

Similarly, the smallest value of nuclear reliance (~-49%) is predicted for a (hypothetical) state having diametrically opposing characteristics: an autocratically governed fuel-cycle state not engaged in international nuclear commerce, not historically aligned and having large domestic coal reserves. No state has all of these characteristics. Some instances of states having four of these five characteristics, again with their nuclear reliances in parentheses, are: India (3.6%); Iran (0) and Pakistan (2.2%).

IV. A Typical Step of the Stepwise Regression

It is useful to augment the stepwise statistical progressions summarized in Table II by a graphical presentation of the improvement needed and obtained in a given step. The objective of this section is to illustrate one perhaps useful way of obtaining such a graphical supplement. The example selected corresponds to the fourth step in Table II (i.e., the step in which the attribute *FCS?* is added to the predictors). This step is selected in part because the negative value of the coefficient of this attribute both is somewhat counterintuitive, and has some potentially important policy implications, as discussed further in the following section. Given these considerations, it is important to understand the basis for the value of this coefficient (-.13±.05 in the final version of the basic linear model).

See Appendix B for similar (but more abbreviated) graphical representations, and associated discussions, of the remaining steps represented in Table II.

The open black circles in Figure 2 represent a scatter plot of the residual nuclear reliance, as corrected for the linear model constructed in the preceding third step, against the value of the dichotomous variable (*FCS?*) added in the fourth step. There is substantial scatter along the "no" (zero) axis of the added attribute. By some contrast, there is a smaller degree of scatter among the (limited number of) fuel-cycle states, and they all have very small or negative residual nuclear reliances. The latter is what results, perhaps somewhat surprisingly, results in the negative value of the predictor associated to *FCS?*.

The tendency of the fuel-cycle states to have a negative residual nuclear reliance perhaps seems somewhat counterintuitive, as the fuel-cycle states include many commonly considered to be quite aggressive, in terms of development of civil nuclear energy. But recall that this does not (necessarily) imply the nuclear reliance of these states is small; rather it means that it tends, in aggregate, *to be smaller than predicted* by the linear model constructed with the three preceding independent variables (*IC?*, *ALGN?* and *COAL*).

Figure 2 - Observed and predicted (at fourth step) values of residual nuclear reliance, as corrected for *IC?*, *ALGN?* and *COAL*, versus status as a fuel cycle state.

The negative coefficient for fuel-cycle states is clearly seen in the values of residual nuclear reliance predicted from the linear model constructed in the fourth step, as represented by the solid (red) dots in Figure 2. The outliers in this regression are labeled by boxes in normal text. They are the persistent six outliers retained in the final version of the basic linear model, plus Australia.

The inclusion of Australia as an outlier (with excess *positive* nuclear reliance) is somewhat curious, because in the depiction of the successive regression given in Figure 2 it lies closer to the predicted value than any of Finland, Hungary or Belgium (labeled in boxes by italicized text), none of which are outliers for the simultaneous regression. This is presumably because the approximately 10% change in the *COAL* predictor, from the preceding step, affects the predicted value for Australia (*COAL* = 1) for the simultaneous regression significantly more than it does any of the latter three states (*COAL* values of respectively 0, .01 and 0).

In reference back to the fourth step in Table II, the estimated value of the coefficient associated to *FCS?* -.12, with a standard error of .05 and a confidence level of 98.75% (p=.025). This means that the attribute of being a fuel cycle state correlates significantly but negatively with nuclear reliance, with a relatively high level of confidence, but also with a significant degree of scatter. Addition of *FCS?* as an explanatory variable brings the associated value of R^2 up to .50, from its prior value of .46. It also results in small but noticeable changes in the predictors associated to the independent variables previously selected, especially in that for *COAL* (.32 to .35).[48] Overall these changes give an even higher level of confidence in the significance of these variables, except that the p-value for the historic alignment variable slightly increases by about 50%, but remains small in absolute terms.

V. IMPLICATIONS

The basic linear model (2) is simple to the point of arguably being simplistic. Yet it supports a discussion of some of the key issues facing the nonproliferation regime, as we seek to demonstrate in this section.

Impact of the Existing Nonproliferation Regime

The negative coefficient associated with the variable *FCS?* in the basic linear model (2) indicates that states not enjoying status as nuclear-weapon states under the NPT pay a penalty for electing nonetheless to pursue sensitive dual-use nuclear technologies. That penalty takes the form of an associated (aggregate) 13% (±5%) *reduction* in nuclear reliance. This is contrary to the expectation that states tend to pursue sensitive fuel-cycle technology in order to *increase* their nuclear reliance. (See the hypothesis associated with the variable *FCS?*, in Section II.)

The statistical methodology used here does not suggest the mechanisms underlying this apparent penalty. Indeed the list of the eight affected states (cf. the right-hand axis of Figure 2) suggests the possibility that different mechanisms are at work. Certainly India, and possibly Israel and Pakistan, have been impacted by various aspects of the nonproliferation regime, in light of their status as states not signatory to the NPT. In these three cases it seems clear also that increasing nuclear reliance was not the primary reason for pursuing status as a fuel-cycle state.

This clearly is not the case for the five remaining affected states. Nonetheless their nuclear reliance seems to have been adversely impacted by their status as fuel-cycle states.

Two conjectures come to mind as possible mechanisms underlying this phenomenon. One possibility is that the public distaste associated to nuclear weapons, which to some extent is associated to the strongly opposing international norms, attaches itself more strongly to civil nuclear energy in states that pursue avowedly dual-use technologies, and that adversely impacts public acceptance of NPPs.[49] Another is that the resource demands (e.g., scientifically and technologically educated or trained personnel) associated to establishing and maintaining status as a fuel-cycle state competes with the similar demands associated with NPPs, and thereby limits the ability to support the latter.[50]

Regardless of the underlying mechanisms, our basic linear model suggests that states seeking fuel-cycle status are likely to encumber a significant associated penalty. This takes the form of an approximately 13% reduction of their nuclear reliance, below what it otherwise would be. The obvious question for those seeking to minimize proliferation risks is whether that is sufficient to discourage states from pursuing fuel-cycle status.

If the true objective of a state is to position itself to have a small degree of nuclear latency, as measured say by the incremental time to achieve status as a *de facto* nuclear-weapon state, then the answer clearly is "no." But if the objective is to maximize nuclear reliance, then the answer depends upon the interplay between status as a fuel-cycle state and the remaining (four) attributes appearing in the basic linear model (2). We take this case as the starting point for our next subsection.

The Role of Assurance Programs

Consider the case of a hypothetical state that has little or no civil nuclear energy, but the desire to increase its nuclear reliance. The international community presumably has no objection to that objective, provided the state considered pursues it without seeking status as a fuel-cycle state, with the attendant risk of proliferation of nuclear weapons. What guidance does the basic linear model (2) provide the international community, in terms of actions it might take to encourage the desired line of development of nuclear reliance? That encouragement necessarily must involve one or more of the four attributes appearing in that model, other than *FCS?*.

Aside from *FCS?*, the attributes appearing in the model are *COAL*, *IC?*, *PLTY* and *ALGN?*, in order of decreasing magnitude of the estimated value of the associated coefficient. The international community has little ability to impact the coal reserves available to the state, which anyway must be relatively small in order for it to have significant motivation to increase its nuclear reliance. For the moment assume that, as the hypothetical state is assumed to have little nuclear reliance, it also has no aspirations of developing significant international commerce of its (necessarily limited) nuclear technology. (However, we shortly reconsider the possible impact of the *IC?* attribute.)

Somewhat similarly, whether the impact of polity is via actual democracy, or as a surrogate for stability, it seems primarily a matter for resolution by the state itself, not the international community. That leaves the historical alignment attribute. To the extent that this attribute is a surrogate for assurance of access to nuclear M&T, it presumably is capable of being affected by the international community. The hope that seems to underlie the various assurance programs under current consideration, as detailed in the Introduction, is that state will agree to forgo pursuit of sensitive fuel-cycle technologies, in return for such assurance.

Let us consider why any such assurance is necessary, or even advisable, given that in its absence our basic linear model predicts the subject hypothetical state will maximize its nuclear reliance by forgoing fuel-cycle status anyway. Without any such assurance, the values *COAL* = 0, *IC?* = 0 and *ALGN?* = 0 in effect are hypothesized. If *PLTY* is sufficiently large, certainly if it is one (a fully functioning democracy) then the predicted nuclear reliance is positive, for *FCS?* = 0, but negative for *FCS?* = 1. Thus a state that is sufficiently stable (or democratic) would be predicted to best achieve a modicum (~8%) of nuclear reliance by forgoing fuel-cycle status.

Suppose however that *PLTY* is small, so that the state is autocratic (or unstable, if one accepts polity as a surrogate for stability), and the state is unwilling (or unable) to change that. In that case the predicted value of nuclear reliance is negative (≤-3.4%), regardless of the value of the attribute *FCS?*. In that case the state might opt to pursue fuel-cycle status, for either of two reasons. First, it might simply hope, against the apparent odds, that its pursuit of an independent fuel-cycle capability would in fact increase its nuclear reliance. (The cases of India and Brazil, in Figure 2, suggest this possibility.) Second, the state might pin some hopes on its pursuit of this option opening up the possibility of engaging in international nuclear commerce, thereby - in the long run - even further increasing its nuclear reliance. (This potential synergism between international commerce and fuel-cycle status will be revisited in the following subsection.)

But suppose now that some program exists to provide assurance of access to nuclear M&T, in return for forgoing status as a fuel-cycle state. In that case the predicted nuclear reliance of the hypothetical democratic or autocratic states, without fuel-cycle status, increase respectively to 18% and 7%. If such states rationally acted to maximize their nuclear reliance, then they would accept the assurance program. This is, in effect, the rationale for assurance programs, as viewed through the prism of the basic linear model (2).

Sensitive Fuel-cycle Technology as an Entrée to International Commerce

The conclusion stemming from the preceding subsection is that if a state having low nuclear reliance and coal reserves, no aspirations to engage in international commerce in nuclear M&T, and lack of assured access to (insensitive) nuclear M&T acts rationally to maximize its nuclear reliance, then it will accept the (often implicit) bargain inherent in most currently proposed assurance programs: forgo aspirations to sensitive fuel-cycle technologies, in return for assured access to (insensitive) nuclear M&T. But in fact no state has yet agreed to accept such status as a "consumer" state in an assurance program. Can this apparently irrational behavior of states be explained, within the framework of our basic linear model?

One possible explanation is that states tend to perceive acceptance of consumer status, and consequent status as not a fuel-cycle state, to exact a corollary inability to ever engage in international commerce in nuclear M&T. In effect that would, according to the basic linear model, place a ceiling of ~18% (~7%) on a democratic (respectively, autocratic) state accepting consumer status. By contrast, these estimated nuclear reliances would increase, by ~7% and even absent benefit of assurance (*ALGN?*), if the state calculates that fuel-cycle status enables international commerce

In effect we have just argued that the assumption (preceding subsection) that states having a small nuclear reliance would tend to be willing to forgo international commerce in nuclear M&T is questionable. If true, why might it be true?

The most obvious possibility is that the potential of international commerce really is important to some states that might otherwise be candidates to become consumer states within some assurance program. There is certainly anecdotal evidence in that respect. For one example, recently it was reported that Spain is seeking to become a nuclear supplier to India, even though "Spain has a moratorium on building more nuclear plants at home and plans to shut down the eight existing plants after their operating licences expire."[51] There is some belief that assurance programs have even encouraged some states to solidify plans to achieve fuel-cycle status, in order to avoid forgoing that option.[52]

The other possibility is that the international commerce attribute might well serve as a surrogate for other attributes not achieving significance in the basic linear model, but not directly associated to *IC?*. For example, it is a reasonable hypothesis that either of the attributes energy insecurity or *per capita* GDP could provide the initial impetus to develop a high level of nuclear reliance, and then that having success in developing a high nuclear reliance could promote national development of international commerce in nuclear M&T. In such an event, the motivational contribution of *EI* or *GDP_ppp* to development of nuclear reliance in that state would factually be very real, but statistically it would tend to be masked by the subsuming contribution of international commerce. In Appendix A (last subsection) it is shown that the attributes energy insecurity and *de jure* NWS (perhaps surprisingly) tend to come to the fore when international commerce is suppressed.

VI. CONCLUSION

Stepwise regression applied to a set of fourteen candidate predictors of nuclear reliance (fraction of national electrical energy generated by nuclear power plants) leads to a basic linear model in five predictors, each of which is significant at more than 99% confidence level ($p < .02$). The associated value of R^2 is .53, which suggests ample opportunity for additional predictors. Some possibilities in this regard are briefly discussed in the second and final subsection of this concluding section. The first subsection is a brief summary of the implications of our basic linear model for the international effort to control the proliferation of nuclear weapons, especially via programs intended to assure states access to (insensitive) nuclear materials and technology, in return for forgoing development of sensitive (dual-use) technologies.

Conclusions for Nonproliferation

- There is empirical evidence that the existing nonproliferation regime provides significant motivations not to pursue sensitive technologies, in the form of an estimated penalty of 13% in nuclear reliance (nearly equal to the global nuclear reliance of 16%) for states that have developed such technologies, but are not nuclear weapons states under the NPT.
- There is also evidence of the potential leverage for programs offering assured access to insensitive nuclear materials and technology, in return for forgoing development of sensitive technologies. This evidence takes the form of an estimated aggregate enhancement oby10% (more than half of the global nuclear reliance) in nuclear reliance, for states that have historically been aligned with one of the nuclear weapons states under the NPT.
- Even given this respective "stick" and "carrot" approach, it can be a difficult decision for a state to forgo development of sensitive fuel-cycle technology, because that could be concomitant to forgoing the (33%) benefit to nuclear reliance stemming from the different enablers of a high nuclear reliance that in the present work are subsumed here under the attribute "international commerce."

The last of these conclusions raises the question of the wisdom of seeking to control the proliferation of nuclear weapons solely through actions related to civil nuclear energy. This doubt persists, regardless of whether one seeks this control via penalties ("sticks") on the civil side, per the Nuclear Nonproliferation Act of 1978, or rewards ("carrots"), as envisioned by assurance programs. Even the aggregate leverage deriving from these two approaches may not be sufficient to dissuade states from seeking sensitive technologies.

Put another way: In order to control the spread of dual-use technologies it certainly is necessary to provide alternative pathways for the development of civil nuclear energy, but it may not be sufficient. Tools beyond those relating to civil nuclear energy may be imperative.

Possible Future Related Work

In addition to their potential benefit for controlling proliferation of sensitive technologies, some perceive assurance programs as having benefits to meeting the NPT Article IV obligations of the nuclear weapon states.[53] The sheer proliferation of states expressing interest in that regard mandates some effort to sort out the NPP initiatives that might lead to action in the short term (next 10-15 years) from those likely to bear fruit over a somewhat longer term. It would be of potential interest to explore the potential application of our basic linear model to predicting the national initiatives most likely to bear fruit.

The approach used here is inherently inconsistent, in that it regresses the current nuclear reliances of various states, which evolved from decisions made over several decades, against present-day snapshots of various attributes. It would be desirable to develop a more consistently dynamic approach.

It would be of some interest to carry out case studies of the persistent outliers of the basic linear model of Section III. In particular we note that none of these six outliers were considered as historically aligned through NATO. This suggests there might be additional explanatory value in separating the attribute *ALGN?* into two (or more) distinct attributes.

Perhaps the most surprising aspect of the basic linear model (2) is the failure of the stepwise regression process to identify any statistically significant predictor of nuclear reliance that in some way represent the wealth or standard of living of a state. There is some indication in the data of a nonlinear (quadratic) dependence on per capita GDP, which could mask a wealth dependence. We hope to explore that further elsewhere.

Appendix A: The Extended Linear Model

This appendix is devoted to the extended linear model that was mentioned several times in the body of the report. It consists of three subsections. The first ("Additional Predictors") contains the details of the nine additional independent variables of the extended model. The second subsection is "An Overview of the Stepwise Regression." The third and final of the three subsections ("The Full Regression") provides the results of regressing nuclear reliance against all fourteen of the independent variables.

The Additional Predictors

The independent variables of the basic linear model (2), as listed in Section II of the report, were selected, via stepwise regression (as described in the next subsection of this appendix) applied to a larger list of candidate independent variables. The additional independent variables, and their associated theories and measures, are listed following, in alphabetical order:

***EI* (Energy Insecurity):** This attribute is intended to represent the need a state might perceive for nuclear energy, in order to restrict its dependence on imports. The theoretical basis for including such an attribute is the fact that nuclear fuel is a very compact energy source, to the extent that it is relatively easy to store supplies adequate for multiple years. For example, when a modern light-water reactor is refueled, it typically is supplied with fuel for 2-3 years of operation. Assured fuel adequate for such long periods can practically be stored for few, if any, alternate sources of energy that are suited to base-load electrical generation. Thus nuclear energy provides a degree of immunity to short-term market or political fluctuations that is not provided by other sources of energy. This suggests the hypothesis that states that import more of their energy will tend to have a greater preference for nuclear energy, other things being equal. The measure adopted for energy insecurity is the percentage of energy used that is imported, as publicly reported.[54] Unit standardization is attained for this measure simply by converting the percentages from the cited source to the equivalent fraction. Note that the zero point of *meas*(*EI*) does not occur at the minimum value over all 86NC states,[55] but rather at the "natural" point of zero net imports of energy.

***EGEN* (Electricity generated)**: This attribute is intended as a surrogate for the demand within a state for generation of electricity. The theory associated with including this demand as a causal attribute for nuclear reliance is embodied in the hypothesis that the more electricity a state needs, the more it needs to generate via

NPPs, other things being equal. Electricity actually generated is used here as a surrogate for demand. Data providing annual electricity generation of various states are available.[56] These data are denominated in terms of TWhrs. The unit standardization required here is attained in the standard manner, division by the largest *EGEN* among the states included in the 86NC data base that will be described in the following section.

GAS **(Relative reserves of natural gas)**: The rationale for including this as a candidate independent variable is virtually identical to that given for *COAL*, in Section II above.. In the United States, 20% of electricity generated in 2006 came from gas-fired plants, as compared to 19.4% from nuclear energy.[57] The measure of the attractiveness of natural gas as an alternative to nuclear fuel that is employed is "relative reserves of natural gas," defined as the ratio of national reserves of natural gas[58] to electricity generated within the state.[59] Valuations necessary to create a measure of this surrogate attribute were taken from the cited references, and unit normalization was accomplished in the standard fashion.

GDP **(Gross domestic product)**: This attribute is intended as a surrogate for the ability of a state to raise capital domestically. The theory for including such an attribute as a candidate independent variable is that the modern NPPs that dominate both current inventory and current marketing strategies of reactor vendors are relatively large (typically generating capacities of ~ 1000 MWe). This has historically been deemed necessary, in order to achieve capital costs per unit generating capacity that are economically competitive with alternative technologies for electrical generation.[60] Nonetheless, the consequence is that an individual NPP tends to be costly. Therefore one can hypothesize that the availability of capital to a state will have a significant impact upon the possibility of it building a NPP. Capital availability for a state presumably is somewhat linked to its aggregate wealth. The gross domestic product of a state is the generally accepted measure of its aggregate wealth. [61]

GDP_ppp **(per capita Gross Domestic Product)**: This attribute is included among the candidate independent variables as a putative surrogate for two different attributes that presumably would have a positive correlation with nuclear reliance. First, the larger the per capita GDP, presumably the larger the portion of the population that achieves the advanced technological education and training needed to staff NPPs and their associated support industry. Second, a larger per capita GDP presumably correlates with increased demand for electricity,[62] some of which might be produced by NPPs. Per capita GDP, for the year 2006 and on the basis of purchasing power parity denominated in dollars,[63] were employed as the specific measure. Unit standardization was accomplished by the usual device of dividing by the maximum over the 86NC states.

NWs? **(de facto Nuclear Weapon State)**: This attribute has a dichotomous measure, with value 1 if a *de facto* nuclear-weapon state, 0 otherwise. The *de facto* weapons states were taken as the five *de jure* nuclear-weapon states under the NPT, plus India, Israel and Pakistan. This attribute is included as a candidate independent variable to provide for consideration of the hypothesis that there is a historic synergism between civil and military nuclear power.

NWS? **(de jure Nuclear Weapon State)**: This is a dichotomous measure, with value one assigned to the five recognized nuclear-weapon states under the Nuclear Nonproliferation treaty, and zero to the remaining states. This attribute is intended to provide for assessment of the hypothesis that recognition as a *de jure* nuclear weapon state has beneficial effects to a state's civil nuclear program.

PFPS **(Primary fuel production state)** is a dichotomous measure of the ability of a state to produce sensitive nuclear materials indigenously. It is included to permit testing of the hypothesis that this ability will enhance the domestic civil nuclear program of a state. The value one is assigned to the *de facto* nuclear-weapon states (see below), plus Argentina, Brazil, Canada, Japan and the Netherlands, and only those states. The rationale for these assignments is exactly the same as in the preceding discussion of fuel cycle states, except that now the *de jure* nuclear weapon states are included. In fact the three variables *FCS?, NWS?* and

PFPS? are linearly dependent (*PFPS?* = *FCS?* + *NWS?*), so that the expectation is that at most two of these will ultimately be selected as independent variables for the basic linear model, or for any linear model.

POP **(Population)** is included as a candidate independent variable, to test the hypothesis that it somehow correlates with nuclear reliance, although the reason why it should is unclear, at least for states of the minimum population to reasonably utilize the electricity output from a single NPP. Valuation used was as reported in Note [64]. Unit standardization was attained in the usual manner.

On an excluded attribute: Globally hydropower appears to generate approximately as much electricity as does nuclear power. This suggests inclusion of untapped hydropower as a candidate independent variable, to test the hypothesis that states having such potential tend to prefer it to nuclear power. Unfortunately there does not appear to be a source of data for global untapped hydropower, or any reasonable surrogate.

Overview of the Stepwise Regression

The MatLab code STEPWISEFIT was employed, with the default inclusion and expulsion thresholds ($p \leq .05$ or $\geq .10$, respectively), to regress the five independent variables of Section II, plus the additional nine candidate independent variables described in the preceding subsection, against nuclear reliance. The result was that the variables were selected in the order *IC?* (1.0×10^{-8}), *ALGN?* (.0034), *COAL* (.0012), *FCS?* (.025) and *PLTY* (.015), where the parenthetical numbers indicate the *p*-statistics for the predictor of the newly selected independent variable at the step of its selection. At the sixth step none of the additional candidate independent variables met the inclusion threshold. At this time the *p*-statistics for the estimates of the various predictors associated with the remaining independent variables were as indicated in Table A.I. Thus energy insecurity, indicated in bold (red) was the leading candidate for further inclusion, if the inclusion criterion were further relaxed. The independent variables selected for inclusion, with the default threshold values, are indicated by (green) italicized values of the corresponding *p*-statistics.

Table A.I: The *p*-statistics for the estimates of the various predictors, after final step (default values for the thresholds)

Attribute	Final *p*-statistic	Attribute	Final *p*-statistic	Attribute	Final *p*-statistic
ALGN?	*.0039*	*GAS*	.85	*NWS?*	.86
COAL	*6.2×10^{-4}*	*GDP*	.54	*PFPS?*	.86
EI	**.25**	*GDP_ppp*	.78	*PLTY*	*.015*
EGEN	.63	*IC?*	*7.6×10^{-11}*	*POP*	.59
FCS?	*.010*	*NWs?*	.38		

The Full Regression

The code STEPWISEFIT of MatLab was again the fundamental tool used for the regression underlying the extended linear model. Now however the threshold values were modified to p=.9999 for inclusion, p=.99999 for expulsion, with the intent that the only predictors to be excluded were those perfectly linearly dependent on others (e.g., *PFPS?*; cf. above).

Application of STEPWISEFIT in this manner gives the following as the extended linear model, as presented in a manner similar to that of Eq. (2):

$$\widehat{NR} = \underset{[2.6\times10^{-8}]}{(.32\pm.05)}IC? + \underset{[.014]}{(.087\pm.035)}ALGN? - \underset{[.002]}{(.31\pm.10)}COAL - \underset{[.011]}{(.19\pm.07)}FCS? + \underset{[.12]}{(.083\pm.052)}PLTY +$$

$$\underset{[.24]}{(.013\pm.011)}EI + \underset{[.31]}{(.11\pm.11)}NWs? - \underset{[.61]}{(.23\pm.46)}EGEN + \underset{[.41]}{(.053\pm.064)}GDP\_ppp + \underset{[.51]}{(.13\pm.19)}POP - \qquad (3)$$

$$\underset{[.58]}{(.089\pm.16)}NWS? + \underset{[.79]}{(.038\pm.14)}GAS + \underset{[.93]}{(.036\pm.39)}GDP - .033.$$

The associated statistics are root-mean square error = .13, R^2 = .56, adjusted R^2 = .48 and F = 7.1. As compared to the (final) basic linear model of Section III (cf. Table II) these statistics display (marginal) improvement. The same model is displayed in Table A.II, in a manner more traditional to political science, with the independent variables listed in order of their selection by the stepwise regression algorithm.

Table A.II: The extended linear model, in tabular form

Response variable: Nuclear reliance	Coefficient	S.E.	Significance†
Independent variables			
International commerce?	.32	.05	****
Historic alignment?	.087	.035	**
Relative coal reserves	-.31	.10	***
Fuel-cycle state?	-.19	.07	**
Polity	.083	.052	*
Energy insecurity	.013	.011	
de facto NWS?	.11	.11	
Electricity generated	-.23	.46	
per capita GDP	.053	.064	
Population	.13	.19	
de jure NWS	-.089	.16	
Relative natural gas reserves	.038	.14	
Gross domestic product	.036	.39	

†Significantly significant predictor estimates are indicated by:
* (p<.2); ** (p<.05); *** (p<.01); and **** (p<.001)

The coefficients of the predictors appearing in the earlier basic liner model tend to change relatively little in this extended linear model. An exception is the coefficient of *FCS?*, which decreases (algebraically) by about 50%.

A couple of matters in this extended linear model warrant at least a passing comment. One is that the coefficient of *EGEN* is negative, which seems counterintuitive. A hint as to a possible reason for that is that the p-statistic associated to *EGEN* changes significantly (from .25 to .61) between the time it is added to the model and the final model. Both of these could be due to the trend initially captured by including this independent variable ultimately being captured better through an independent variable added subsequently. A likely candidate to be the subsequent variable that has the effect is population. This conjecture will not be explored further here.

The second item worth mention is that the coefficients of *GDP_ppp* and (especially) *EI* are surprisingly small. We conjecture that this is because the bulk of the effect of these predictors already is captured in the international-commerce variable. We explore that conjecture further here, because of its relevance to the rationale for the consideration in the last subsection of Section V of the possibility that states will be reluctant to forgo the possibility of engaging in international commerce in nuclear M&T. As regards policy implications of that possibility it is important to know whether that is international commerce per se, or possibly international commerce as a more comprehensive surrogate for domestic needs.

Toward that end we carried out a similar regression, except with international commerce not included among the independent variables. The corresponding modified extended linear model is described in Table A.III, in a manner similar to that employed in Table A.II. There are now only four significant predictors (p < .2), as compared to five for the extended linear model of Table A.II. Polity and historic alignment are the two significant predictors the two models have in common, while the significant predictors *IC?*, *COAL* and *FCS?* of the extended linear model (Table A.II) are replaced by *NWS?* and *EI* in the modified extended model, with the former having (much) the larger coefficient and also a higher level of confidence. In effect this says that, in the presence of the attributes of polity and historic alignment, the attributes *de jure* NWS and energy insecurity better capture the combined ability of international commerce, relative coal reserves and fuel-cycle state to predict nuclear reliance than do the latter two attributes alone. Thus the international commerce attribute appears to mask aspects of the significance of masks aspects *de jure* NWS and energy insecurity. Note however that *IC?* seems to have aspects not captured by *NWS?* and *EI*, as the modified extended model has significantly poorer statistics (root-mean square error = .16, R^2 = .33, adjusted R^2 = .19 and F = 2.9) than the extended model.

Table A.III: The modified extended linear model, in tabular form

Response variable: Nuclear reliance	Coefficient	S.E.	Significance
Independent variables			
Polity	.12	.06	*
de jure NWS	.36	.18	**
Historic alignment?	.084	.043	*
Population	-.071	.23	
Relative coal reserves	-.12	.11	
Energy insecurity	.019	.013	*
per capita GDP	.083	.079	
Electricity generated	-.28	.56	
de facto NWS	-.076	.13	
Fuel-cycle state?	.026	.080	
Relative natural gas reserves	.042	.17	
Gross domestic product	.098	.48	

Appendix B: Details of the Stepwise Regression

The objective of this appendix is to provide a step-by-step description of the addition of the independent variables to the basic linear model. The approach for each step is similar to that already appearing in section IV, for the fourth step (addition of the predictor *FCS?*).

Step 1: International Commerce

The results from this initial step are summarized in the first row of Table II (Section III). In this initial step of the model construction the variable *IC?* is significant at a high confidence level ($p = 1.0\times10^{-8}$). The root mean-square error, R^2, adjusted R^2, and F statistics are used here primarily to compare the relative explanatory power of the models emerging from the various steps. (The R^2 and adjusted R^2 statistics were obtained from the MatLab code REGSTATS.) For that purpose we shall principally focus upon the R^2; very naively, the value R^2=.32 found in the first step suggests that about a third of the global indigenous nuclear reliance can be associated to the attribute international commerce. But this conclusion must be used with considerable caution, because of both the crude nature of the measure employed here for international commerce (see the relevant discussion in Section II) and because of a very substantial scatter in the underlying data.

The latter is illustrated by Figure B., which is a graphical representation of observed nuclear reliances against international commerce, and of the prediction from the linear model in the first step (the solid dots). Briefly, the states having zero international commerce appear visually to consist of two clusters, one of (a large number of) states having nuclear reliances of 5% (the predicted value) or less, and the other of ten states having nuclear reliances from 10% to over 30% (five states). Likewise the predicted value for states involved in international commerce separates the observations into two clusters, one consisting of eight states having nuclear reliances below about 20%, and a second consisting of six states having nuclear reliances of more than 40%. Thus while the linear model emerging at the first step captures correctly a graphically clear tendency for nuclear reliances to increase with international commerce, it also leaves a great deal of scatter in the observed data that is not explained by international commerce.

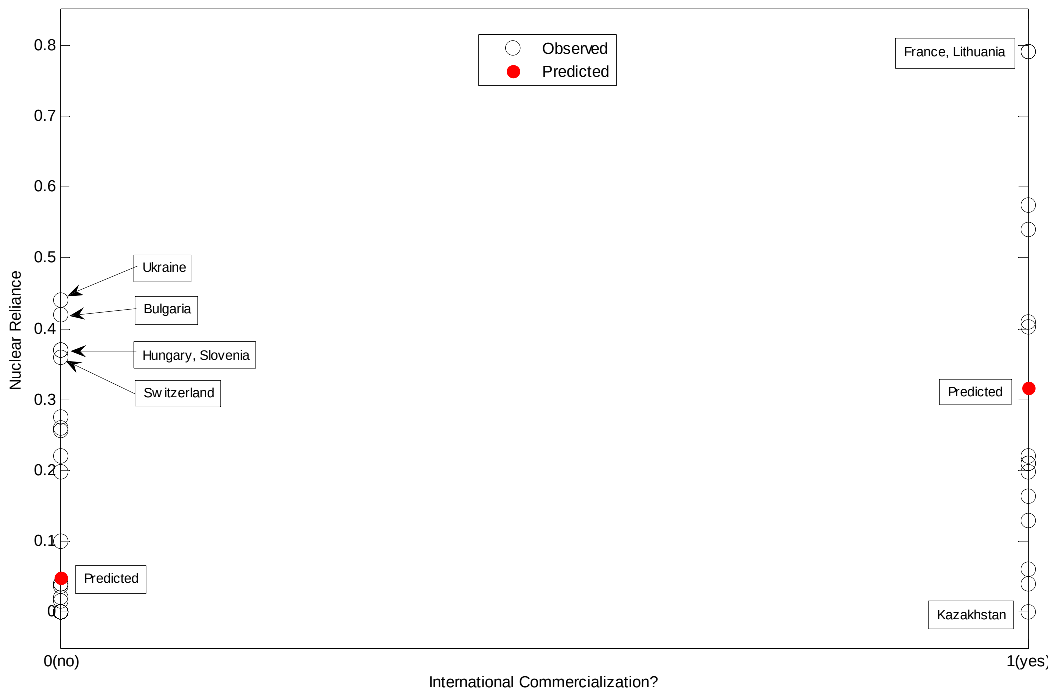

Figure B.1 - Observed and predicted (at first step) values of nuclear reliance, versus international commerce

The extent of this scatter is clearly illustrated by the (eight) states labeled as "outliers" in the last column of the first row of Table II. These were identified as those states not having zero within the 95% confidence interval of the values of their respective residuals. (These confidence intervals were obtained by means of the MatLab code REGRESS.) All except Kazakhstan, as identified by the parenthetical dash, have positive residuals (i.e., observed nuclear reliances excessively greater than the normative prediction). As shown by the labels in Figure B.1, not surprisingly the seven states having unexpectedly large nuclear reliances comprise the states having the largest nuclear reliances within their respective groupings according to engagement in international commerce or not.

Step 2: Historic Alignment

The independent variable added in the second step of the stepwise regression process is historic alignment. The characteristics of the resulting linear model are summarized in the second row of Table II Briefly, there is a very high confidence level in the significance of the estimated value of the predictor (p=.0034), but the standard deviation of .03 is approximately a third of that estimated value, which indicates a substantial variation within the data. (The confidence level for the *IC?* predictor is even higher for this second-step model, but it was already very high.) The statistics indicate some improvement in the predictive power; in particular the value of R^2 suggests a predictive power of 39%, as compared to 32% of the first-step model. The outlier states are the same as in the preceding step, except that now Hungary (a historically aligned state) is not included among the outliers.

Figure B.2 - Observed and predicted (at second step) values of residual nuclear reliance, as corrected for *IC?*, versus historic alignment.

This situation is illustrated graphically in Figure B.2, which is a plot of two things, both against the dichotomous variable historic alignment. First, the open circles represent the values of the residuals of the observed nuclear reliances, as corrected against the prediction provide by the linear model of the preceding step (i.e., with inclusion of only international commerce as an independent variable). Second, the solid disks are predicted values, as obtained by regressing the previously described residual against historic alignment.[65] This is intended to give a sense of the extent to which historic alignment has any explanatory value for this residual, and the predicted values provided by the regression can capture that value. The figure essentially displays graphically both the overall upward trend of nuclear reliance with historic alignment and the substantial scatter in the underlying data, both of which are foreshadowed in the discussion of the preceding paragraph. The italicized label now indicating Hungary represents its status as no longer an outlier, but clearly it has only slightly evaded that status.

Step 3: Relative Coal Reserves

The variable added at the third step is relative coal reserves. The results, as shown in the third row of Table II, include the following: a predictor that is large in magnitude (.32) but negative in sign, indicating (as might be expected) a tendency for nuclear reliance to decrease significantly with increasing (relative) coal reserves; a standard error in the predictor of .10, again about 1/3 the value of the estimated (magnitude) of the predictor, again suggesting data with significant scatter; and a confidence level of 99.88% (p=.0012) , suggesting that the tendency for nuclear reliance to decrease with increasing coal reserves is quite clear, although subject (from the standard deviation previously noted) to substantial scatter. The already high level of confidence in the significance of the two previously added variables is only further increased by the addition of *COAL* to the model. The value of R^2 increases notably from the model of step 2, .39 to .46, for an explanatory power of 46%.

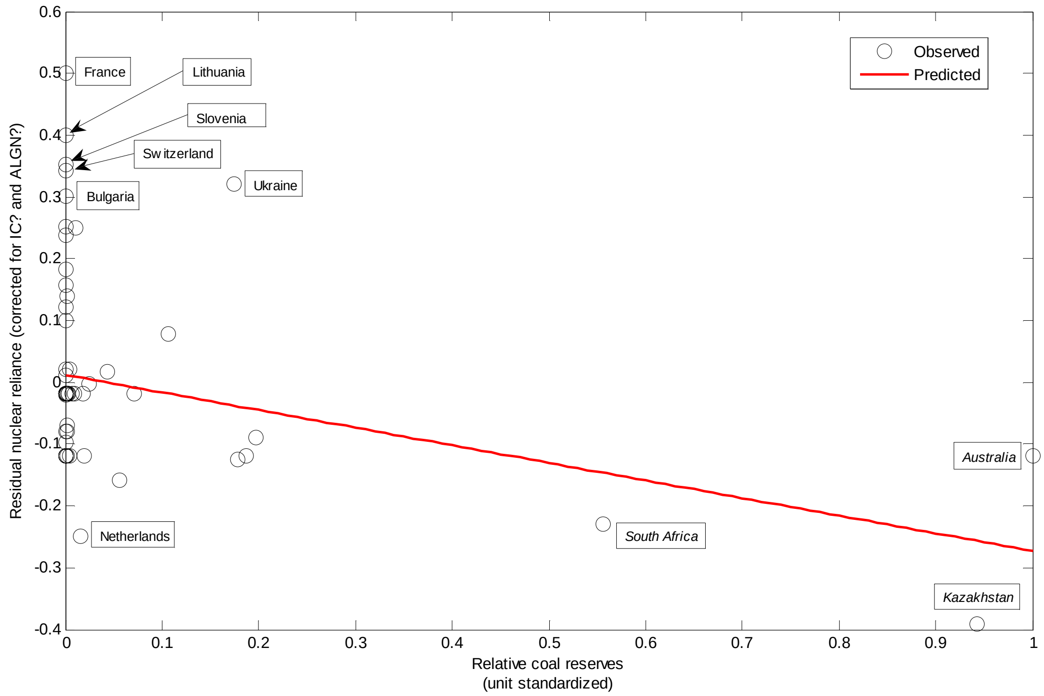

Figure B.3 - Observed and predicted (at third step) values of residual nuclear reliance, as corrected for *IC?* and *ALGN?*, versus relative coal reserves.

These tendencies are clear in Figure B.3, which is similar to the preceding Figure B.2, except that now the residual reliance is corrected for the results of the model found in the preceding step (i.e., for both *IC?* and *ALGN?*). Now all of the states for which this residual is positive are found at the left side of this figure; i.e., small values of relative coal reserves. With the possible exception of Ukraine, all of the states having any significant residual nuclear reliance (i.e., *NR* inadequately explained by the variables previously added) are also states having insignificant coal reserves, relative to their use of energy for production of electricity. Nonetheless, there remains a substantial scatter in the nuclear reliances, among the many states having small relative coal reserves. Addition of the *COAL* variable removes Kazakhstan, which has rather large coal reserves, from the list of outliers. It is replaced by the Netherlands, as the sole outlier having a lower nuclear reliance than predicted. Other states having notably large coal reserves, relative to their current needs for production of electricity, are indicated by italicized labels.[66]

Step 5: Polity

The fourth step is already discussed in Section IV of the text. In the fifth and final step the fifth and final variable, polity, is included in the model. The resulting linear model, as summarized in the fifth row of Table II, the estimated value of the predictor associated with *PLTY* is .11, with a standard error of .04, and a 99.25% confidence level of significance (p=.015). Again the polity attribute seems significant, to a very high level of confidence, but the relative magnitude of the standard deviation suggests significant scatter in the associated data. Addition of *PLTY* as an explanatory variable brings the associated value of R^2 up to a respectable value of .53, signifying that more than half of the tendency of a state to rely on nuclear energy for generation of electricity. It also results in small but noticeable decreases in the magnitude of the predictors associated to all of the previously selected attributes. The levels of confidence for these prior predictors also decrease, except for a slight increase in that for *COAL*, but all have a very high confidence level (≥ 98.5%). There is no change in the list of outliers, except that Australia (*PLTY* = 1) no longer is deemed to have an excessively high nuclear reliance.

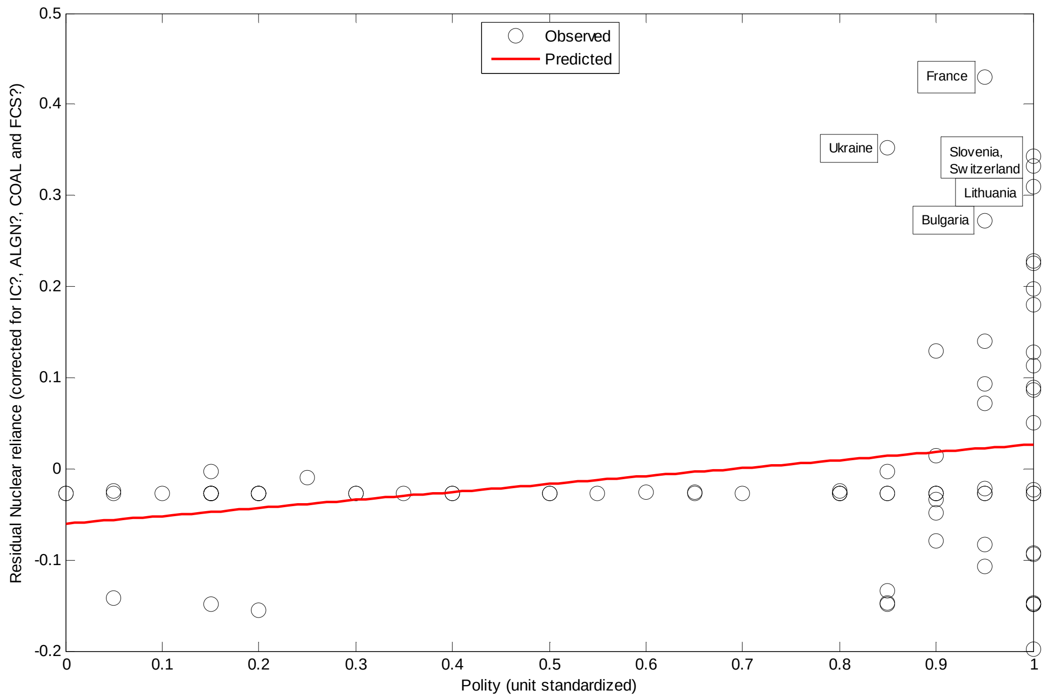

Figure B.4 - Observed and predicted (at fifth step) values of residual nuclear reliance, as corrected for *IC?*, *ALGN?*, *COAL* and *FCS?*, versus polity (unit standardized)

The situation at this fifth step is represented graphically, in the customary fashion, in Figure B.4. The most striking feature of this presentation perhaps is that all outliers rate at 0.85 or greater on the *PLTY* scale; in fact no state having a PLTY value less than 0.85 has a residual nuclear reliance, after correction for the variables previously included, that can be graphically discerned to lie above zero. Nonetheless, there is a very substantial scatter in the nuclear reliances at the higher levels of polity. It is as if being a democracy is necessary to attain a higher level of nuclear reliance than indicated by the preceding variables, but by no means is sufficient.

Step 6: Energy Insecurity

The linear model listed in the last row of Table II resulted from carrying out the same procedure, except with the inclusion and exclusion thresholds for STEPWISEFIT changed to .30 and .40, respectively. This now sixth step resulted in inclusion of energy insecurity as an additional independent variable, as expected. The estimated value of the associated predictor is .011, which at first blush seems small; however remember that the zero point of *EI* is set at zero net imports. If it were set instead at the minimum value, then this predictor would be approximately a factor of ten higher. More significant is the fact that the standard error is nearly as large as the estimated value of the predictor. This obviously is associated to the low level of confidence (87.5%). Addition of energy security very slightly improves R^2, and likewise only slightly changes the prior values of the other predictors. s well as the other statistics. resulted in inclusion. There is no change in the list of outliers.

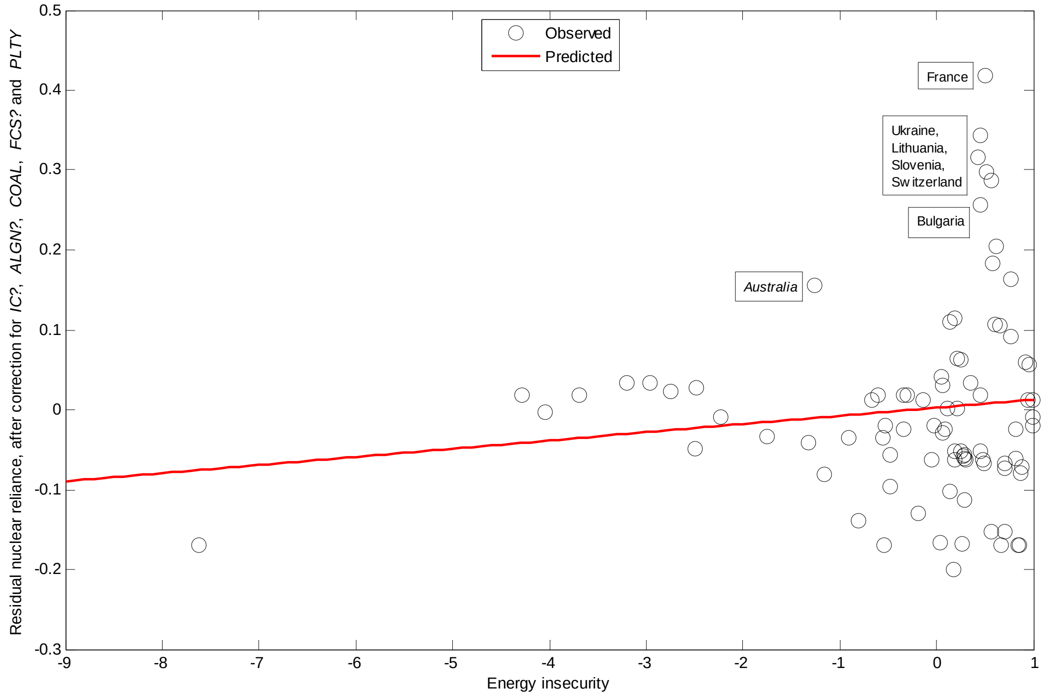

Figure B.5 - Observed and predicted (at sixth step) values of residual nuclear reliance, as corrected for *IC?*, *ALGN?*, *COAL*, *FCS?* and *PLTY*, versus energy insecurity (unit standardized)

Figure B.5 depicts graphically the regression underlying this linear model, in the fashion now familiar from Section. There are two noteworthy features of this figure. First, all outliers of the underlying (simultaneous) linear model, as in dictated by the labels in normal type, have energy insecurities very near 0.5. (They range from .46 to .47.) Second, almost no state that is a net producer of energy has a residual nuclear reliance significantly greater than zero; Australia, as indicated by the italicized label, is the sole exception, and that appears to be more another instance of the aberration already mentioned in regard to Figure 2 than a real phenomenon.

This result does not necessarily, in itself, imply that energy insecurity is a poor predictor of nuclear reliance. It could, rather, be that it is slightly inferior in that regard to some combination of the previously included independent variables that collectively capture the majority of its ability to predict nuclear reliance. This possibility can be explored to some extent by using STEPWISEFIT to regress *EI* against those variables. The result of that process is the linear model

$$\widehat{EI} = (1.39 \pm .42) PLTY - 1.20,$$
$$[.0013]$$

in the notation introduced relative to Eq. (2). The remaining independent variables are rejected, at the default threshold for inclusion, with projected *p*-statistics for the next step of respectively .85 (*IC?*), .73 (*ALGN?*), .33 (*COAL*) and .68 (*FCS?*). Thus in this case it appears more likely that energy insecurity has little explanatory power. To test this hypothesis we used STEPWISEFIT to regress nuclear reliance against the pool of 14 total independent variables thus far discussed, less *PLTY* and *COAL* (which is the next variable that would be added in the preceding regression of *EI*). Energy insecurity still was not included in the resulting linear model. The conclusion is that energy insecurity does not appear to be a reliable (linear) indicator of nuclear reliance.

NOTES

[1] Joby Warrick, "Spread of Nuclear Capability is Feared: Global Interest in Energy May Presage a New Arms Race," *Washington Post*, May 12, 2008, <http://www.washingtonpost.com/wp-dyn/content/article/2008/05/11/AR2008051102212.html>, accessed May 18, 2008.

[2] "IAEA would have authority over enrichment facility," *Nuclear News*, April 2008, p. 64.

[3] Glenn R. George, "Financing New Nuclear Capacity: Will the 'Nuclear Renaissance' Be a Self-Sustaining Reaction?," *Electricity Journal* 20/3 (2007), pp. 12-20.

[4] Tyler Hamilton, "Nuclear revival bumps against atrophy: Possible shortage of super-forged parts threatens to delay renaissance," Toronto Star, May 3, 2008, <http://www.thestar.com/Business/article/420941>, accessed May 3, 2008.

[5] Pierre Goldschmidt, "Nuclear Renaissance and Non-Proliferation," Lecture at the 24th Conference of the Nuclear Societies, February 18-21, 2008, <http://www.carnegieendowment.org/files/nuclearsocieties_2-19-081.pdf>, accessed May 3, 2008.

[6] Anonymous, "A Medieval Sociology of International Relations," <http://www.gotterdammerung.org/humor/medieval-ir.html>, accessed May 3, 2008.

[7] Bradley A. Thayer, "The Causes of Nuclear Proliferation and the Utility of the Nuclear Nonproliferation Regime," *Security Studies* 4 (1995), pp. 463-519.

[8] Scott D. Sagan, "Why do States Build Nuclear Weapons? Three Models in Search of a Bomb," *International Security* 21 (1996-97), pp. 54-86.

[9] Dong-Joon Jo and Erik Gartzke, "Determinants of Nuclear Weapons Proliferation," *Journal of Conflict Resolution* 51/1 (2007), pp. 167-194.

[10] Jacques Hymans, *The Psychology of Nuclear Proliferation* (Cambridge, Cambridge University Press, 2006).

[11] Lawrence M. Lidsky and Marvin M. Miller. "Nuclear Power and Energy Security: A Revised Strategy for Japan," *Science and Global Security* 10 (2002), pp. 127-150.

[12] Dieter Helm, "Energy Policy: Security of Supply, Sustainability and Competition," *Energy Policy* 30 (2002), pp. 173-184.

[13] Daniel Yergin, "Ensuring Energy Security", *Foreign Affairs* 85 (2006), pp. 69-82.

[14] Appendix A contains a description of an extended version of this linear model (fourteen independent variables).

[15] MWe = MegaWatt electrical, which is the commonly used unit for denominating the capacity of a plant for generating electricity.

[16] See Nuclear Power Technology Development Section, IAEA, "International Project on Innovative Nuclear Reactors and Fuel Cycles (INPRO)," < http://www.iaea.org/OurWork/ST/NE/NENP/NPTDS/Projects/INPRO/index.html>, accessed September 23, 2008, for an international program directed in substantial part toward small to medium scale reactors. The Westinghouse IRIS (International Reactor Innovative and Secure) is a medium-scale (335 MWe) commercially offered PWR; cf. Mario D. Carelli *et al.*, "The Design and Safety Features of the IRIS Reactor," *Nuclear Engineering and Design* 230 (2004), pp. 151-167.

[17] Anecdotal reports currently circulating put the capital cost of a 1000 MWe NPP in the vicinity of $5 billion. However, it is difficult to pin down exact numbers, in the absence of any firm orders, with concomitant risk-sharing agreement among the participating organizations.

[18] United Nations Member States, http://www.un.org/members/list.shtml, accessed December 16, 2007.

[19] The Economist Newspaper Ltd., *Pocket World in Figures* (London, Profile Books Ltd. , 2007).

[20] World Nuclear Association, "Taiwan," <http://www.world-nuclear.org/info/inf115_taiwan.html>, accessed December 16, 2007.

[21] "World List of Nuclear Power Plants," *Nuclear News* (March 2007). This includes Iran, in anticipation of its long-awaited Bushehr plant going into operation; however, in the absence of any operating experience, and to be consistent with the source used for nuclear reliance for other countries, the nuclear reliance of Iran is here reckoned as zero.

[22] This differs from the 16% global average quoted previously, because the 9.5% figure is an unweighted average of nuclear reliances over the 86NC states only, whereas the 16% is the percentage of electricity generated globally that come from nuclear energy. If electrical generation from other than the 86NC states were negligible, then presumably the mean nuclear reliance of the 86NC states, as weighted by their respective values of electricity generated, would approximate 16%.

[23] Energy Information Administration, "Energy 101," <http://www.eia.doe.gov/basics/energybasics101.html>, accessed December 15, 2007.

[24] Ian Hore-Lacy, *Nuclear Energy in the 21st Century* (London, World Nuclear University Press, London, 2006) p. 28.

[25] Department of Nuclear Energy, Division of Nuclear Power, Nuclear Power Engineering Section, IAEA, "Country Nuclear Power Profiles," <http://www-pub.iaea.org/MTCD/publications/PDF/cnpp2004/CNPP_Webpage/pages/countryprofiles.htm>, accessed December 15, 2007.

[26] France and Lithuania both have a nuclear reliance, per the indicated metric, of .79 = 79%.

[27] The term "standardized" is widely employed in the social sciences, to denote some type of transformation of a variable into "natural" units. Two examples are P standardization, in which each observation of a variable is assigned a number corresponding to the percentage of observations below it, and F standardization, in which the zero point of the associated measure is taken as the mean of the observed values, and the scale is determined by assigning the value one to the standard deviation of the observations (i.e., the square root of the sum of the squares of the differences between the observations and the means). In the physical sciences the process of converting to some such "natural" units is often termed as "normalization."

[28] For example, a value of 0.25 for the purchasing power parity of the per capita GDP corresponds to a state in which per capita wealth, on the basis of purchasing power, is 25% that of the wealthiest state (the US, followed very closely by Ireland and Norway), which has some intuitive interpretation. Under an F standardization, and a sample corresponding to the 86NC database to be developed below, that would correspond to 25% of the standard deviation ($11,700 annually) above the mean GDP_ppp ($14,100 annually). In order to arrive at that one would need to remember these two latter numbers, and it is not altogether clear even that evokes such an intuitive picture as does "25% as wealthy as the wealthiest state." It works out to ~ $17,025 annually, or about 43% as wealthy per capita as the US, for a unit standardized value of .43

[29] Symbols for dichotomous variables will end with "?," which suggests their values represent answers to yes/no questions. (For example: "Does this state engage in international commerce in nuclear technology or refined nuclear materials?.")

[30] Interviews of decision makers are one traditional way to ascertain such information. Unfortunately it is tempting for such leaders to mask, perhaps subconsciously, mistakes made in domestic calculation by casting blame on external influences. The issue of nuclear assurance is well-suited to such misdirection.

[31] The nuclear weapon states recognized under the NPT are China, France, Russia, the UK and the US.

[32] Successor states to the former Yugoslavia are considered *not* to have been historically aligned.

[33] Energy Information Administration, "Electricity Basic Statistics, 2006," November 2007, http://www.eia.doe.gov/basics/quickelectric.html," accessed June 29, 2008.

[34] 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, 2008.

[35] Coal reserve data employed in this measure were "recoverable anthracite and bituminous," in millions of short tons, from Energy Information Administration, "World Estimated Recoverable Coal," Table 8.2,

<http://www.eia.doe.gov/fuelcoal.html> -> International data -> Coal -> Reserves, accessed June 18, 2008.

[36] Energy Information Administration, “International Energy Annual, 2005,” Table 6.3, “World Total Net Electricity Generation, 1980-2005,” <http://www.eia.doe.gov/pub/international/iealf/table63.xls>, accessed May 16, 2008.

[37] “In August 2006, Buenos Aires announced a major nuclear initiative worth $3.5 billion to finish its third nuclear reactor plant (Atucha II), restart a heavy water production plant in Neuquen Province, and conduct feasibility studies for construction of a fourth reactor at Embalse. It also plans to resume nuclear enrichment activities at the Pilcaniyeu complex using a gaseous diffusion based enrichment technology known as SIGMA, which is purported to be more economic and more proliferation resistant than alternative methods of enrichment.” From Nuclear Threat Initiative, “Argentina Profile,” <http://www.nti.org/e_research/profiles/Argentina/index.html>, accessed June 29, 2008.

[38] “As part of its nuclear propulsion programme, the Brazilian Navy installed in Iperó a demonstration enrichment centrifuge pilot plant. Recently the Brazilian Government decided to start the industrial implementation of the ultracentrifuge process developed by CTMSP in the Resende Industrial Plant in the state of Rio de Janeiro. It is expected the first unit to start operation by end-2003. The complete set of units is intended to be operating in eight years, to attend the ANGRA 1 needs and partially the needs of ANGRA 2 and 3 (~300,000 SWU/year). A future increase of this capacity will depend on technical evaluation and resources availability.” From IAEA, “Country Nuclear Power Profiles: Brazil (2003),” <http://www-pub.iaea.org/MTCD/publications/PDF/cnpp2004/CNPP_Webpage/countryprofiles/Brazil/Brazil2003.htm>, accessed June 29, 2008.

[39] “The Bruce Heavy Water Plant in Ontario was the world's largest heavy water production plant with a capacity of 700 tonnes per year. … Improved efficiency in the use and recycling of heavy water plus the over-production at Bruce left Canada with far more heavy water than it needed for its future needs. Also, the Girdler process (employed at that plant) released large amounts of hydrogen sulfide as a byproduct, raising environmental concerns. The Bruce plant was shut down in 1997. In 2003, the new owners of the site asked for permission to decommission and disassemble the plant. Atomic Energy of Canada Limited (AECL) is currently researching other more efficient and environmentally benign processes for creating heavy water. This is essential for the future of the CANDU reactors since heavy water represents about 20% of the capital cost of each reactor.” From “Heavy Water,” http://neohumanism.org/h/he/heavy_water.html#Canada, accessed June 29, 2008. The upshot is that while Canada seems currently to have no production facilities for D_2O, AECL has considerable technological experience in this area. It also has, as the world’s only commercial purveyor of heavy-water reactors, considerable interest in maintaining and improving that technology.

[40] “Fuel cycle activities in Japan comprise *enrichment*, conversion, fuel fabrication, zircaloy cladding, *reprocessing* and radioactive waste activities.” From IAEA, “Country Nuclear Power Profiles: Japan (2004),” <http://www-pub.iaea.org/MTCD/publications/PDF/cnpp2004/CNPP_Webpage/countryprofiles/Japan/Japan2004.htm>, accessed June 29, 2008.

[41] “Uranium enrichment in the Netherlands is carried out by Urenco Nederland B.V. … Uranium enrichment is the most important part of the fuel cycle for the Netherlands and it is very successful. Urenco Nederland BV has a licence for a capacity of 2 500 t SW/a (tonnes of separative work per year).” From IAEA, “Country Nuclear Power Profiles: The Netherlands (2002),” <http://www-pub.iaea.org/MTCD/publications/PDF/cnpp2004/CNPP_Webpage/countryprofiles/Netherlands/Netherlands2003.htm>, accessed June 29, 2008.

[42] One reasonably could include Iran as a fuel-cycle state, but here we elect not.

[43] Values used for polity were the "polity2" variable from the Polity IVe database (Monty G. Marshall *et al.*, “Polity IV Project,” < http://www.systemicpeace.org/inscr/inscr.htm>, accessed September 23, 2008), for year 2002.

[44] MatLab is a registered trademark of The MathWorks.
[45] For an accessible introduction to the topic of multicollinearity, see Michael S. Lewis-Beck, *Applied Regression: An Introduction*, Sage University Paper 22, Sage Publications, Newbury Park, CA, 1980.
[46] The root mean-square error is forum by dividing the sum of the squares of the residuals by the number of observations, and taking the square root of the result. It is primarily used here as a relative measure of the explanatory capability of the models emerging at the various steps, with smaller root mean-square error implying a higher degree of explanation.
[47] Adjusted R-square := 1-(sum-square of residuals/(n-p-1))/(sum-square of observations/(n-1)), where n is the number of observations and p is the number of predictors in the linear model.
[48] The Pearson correlation coefficients between *FCS?*, on the one hand, and *IC?*, *ALGN?* and *COAL*, on the other hand, are respectively .27, -.12 and -.06.
[49] The authors are indebted to Dr. Jon Phillips, of the Pacific Northwest National Laboratory, for pointing out this possible mechanism. We conjecture this was a significant factor in the cases of Canada, Japan and the Netherlands.
[50] This perhaps was a dominant factor for Argentina and Brazil, although it could have been a factor, to varying degrees, in all six of the remaining fuel-cycle states.
[51] Shuchi Yadav, "Spain eyes India's lucrative nuclear market," CNN-IBN, Sept. 20, 2008, http://www.ibnlive.com/news/spain-eyes-indias-lucrative-nuclear-energy-market/73967-3.html, accessed September 20, 2008.
[52] It has been reported that "countries that don't currently enrich uranium or reprocess such as South Africa, Argentina, Canada, and South Korea have all declared their interest in acquiring sensitive nuclear technologies since GNEP was announced." See Leonor Tomero, "The future of GNEP," *Bulletin of the Atomic Scientists* 9July 31, 20080 <http://www.thebulletin.org/web-edition/reports/the-future-of-gnep/the-future-of-gnep-the-international-partners>, accessed September 20, 2008. Note that in the present work Argentina and Canada are already considered as fuel-cycle states, and South Africa and South Korea are considered as engaged in international commerce in nuclear M&T.
[53] The nonproliferation and Article IV benefits are not altogether distinct. That is, certainly one might argue that were the Article IV obligation taken more seriously, especially by the U.S., it could increase the rationally estimated value of assurance programs, and thereby have a tangible, if indirect, benefit to the cause of nonproliferation.
[54] The values of energy insecurity used in the present study were obtained conveniently from the NationMaster.com web site (<http://www.nationmaster.com/graph/ene_imp_net_of_ene_use-energy-imports-net-of-use>, accessed December 16, 2007), which cites the World Development Indicators database (<http://devdata.worldbank.org/query/default.htm>), accessed December 16, 2007) as its source. The NationMaster site clarifies the definition of what we are terming energy insecurity as follows: "Net energy imports are estimated as energy use less production, both measured in oil equivalents. A negative value indicates that the country is a net exporter. Energy use refers to use of primary energy before transformation to other end-use fuels, which is equal to indigenous production plus imports and stock changes, minus exports and fuels supplied to ships and aircraft engaged in international transport."
[55] That minimum occurs for Norway, and is approximately -760%.
[56] EIA "International Energy Annual, 2005," Table 6.3.
[57] EIA "Electricity Basic Statistics, 2006."
[58] Natural gas reserve data employed in this measure were "proved natural gas reserves," in trillions of cubic feet, as estimated on January 1, 2008, from Energy Information Administration, "Annual Energy Outlook 2008: International Natural Gas Reserves and Resources Tables and Reports:," <http://www.eia.doe.gov/oil_gas/natural_gas/info_glance/natural_gas.html> -> International data -> Reserves & Resources, accessed June 30, 2008.
[59] EIA, "International Energy Annual, 2005," Table 6.3.
[60] The effort to develop economically competitive small to medium sized reactors, referred to earlier (Note 16), is essentially an attempt to reverse this historic trend.

[61] The precise valuation we use here is that taken from *Pocket World in Figures*, 2007. It is reported there in dollars; the unit standardization required here is attained by dividing by the largest *GDP* among the states included in the 86NC data base described in Section II.
[62] Electricity demand also was previously hypothesized to correlate with electricity generated. To the extent that it is also correlated with *GDP_ppp*, it should then also be true that *GDP_ppp* and *EGEN* are correlated.
[63] GDP_ppp data from "Pocket World in Figures," 2007.
[64] Population data from "Pocket World in Figures," 2007
[65] This can be thought of in terms of generating a linear model by adding the regression line connecting the solid disks in Figure B.2 to the linear model represented in the preceding step. The linear model generated by such a sequential regression process generally will be inferior, by most measures, to the linear model generated by a simultaneous regression process, as are the linear models in Table 2. In this particular instance the sequential and simultaneous models seem very close. This is presumably because the independent variables *IC?* and *ALGN?* are substantially independent (Pearson correlation coefficient = -.024, which is much less than one in magnitude.
[66] It is perhaps also noteworthy that the predictors associated with the variables *IC?* and *ALGN?* change noticeably between the second-step and third-step linear models. This suggests a certain degree of statistical dependence between *COAL* and one or both of these previously included variables. The values of the Pearson correlation coefficients between COAL, on the one hand, and *IC?* and *ALGN* on the other, are respectively .25 and .22. This indicates this dependence is shared roughly equally between the two prior variables, and perhaps even more strongly between the two taken collectively.