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by

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Abstract

In early 2005 the government of Bulgaria commissioned the construction of a new nuclear power plant (NPP) near the town of Belene on the Danube border with Romania. The € 4 billion project will be executed by a consortium appointed in October 2006 by the National Electric Company led by the Russian Atomstroyexport. The work will be overseen by the architect-engineer of the plant, the American company WorleyParsons. The endeavor received a "green light" in December 2006 when the Nuclear Regulatory Agency of Bulgaria approved the Belene site for the construction of a new nuclear power plant.

The need for a new electricity-producing facility in Bulgaria after the shutdown of Units 1-4 of Kozloduy is clear. It is not clear, however, what dictated the choice of nuclear technology. Why didn't Bulgaria decide to build another coal-fired plant, since it has always been the case that coal plants provide the largest percentage of total electricity production in the country? Was the decision based upon the economic advantage of nuclear versus other technologies, in particular coal? To address these questions, I will perform a comparative analysis between the Belene NPP and a plausible alternative such as a coal-fired Thermal Electric Power Plant (TEPP). The basis of the analysis is comparing the marginal cost (MC) of both generating technologies. The lower MC technology is deemed economically superior. I identify the input price (P_I) of both the nuclear plant and the coal plant with their respective levelized discounted cost of electricity (LDCE), which I develop based on a literature review. I estimate a Cobb-Douglas production function with multiplicative energy terms. The estimated output elasticity of nuclear and coal is their respective marginal product (MP). Combining information on the relative P_I and MP of both technologies I gauge the relative magnitude of their MC.

I. Introduction:

The transition from communism and a planned economy to democracy and a market economy which took place at the end of 1989 in Bulgaria has not been easy on its citizens. There has been much political instability in the decades of this process: it was not until Kostov's government of 1997 that a cabinet lasted its full mandate. The tottering executive power was unable to restrain the organized crime which grew out of proportion in that early period. The situation for the average citizen was much aggravated by the accompanying economic crisis. In January 1997, inflation was allowed to spiral out of control, leading to several months of hyperinflation finally subdued with the involvement of the International Monetary Fund which established a currency board in June 1997.

Throughout this tumultuous period there were a few industries which in the public eye were pillars of what little economic muscle Bulgaria had to exhibit. One of these was, and still is, the power industry. In the heart of it lay the six-unit Kozloduy Nuclear Power Plant (NPP). Producing little less than half the total electricity of the country, Kozloduy was clearly an integral asset in the Bulgarian energy portfolio. The facility has had an even greater value as a symbol of Bulgaria's technologic prowess.

The latter explains in large part the social unrest that met the European Union's (EU) demand that Bulgaria shut down Units 1-4 of Kozloduy prematurely. The EU's rationale for this demand was that those older units of the NPP were not up to international safety standards. There is mixed evidence whether there might have been room for improvement in that respect for Units 1 and 2. However, there is conclusive evidence to the contrary for Units 3 and 4: after thoroughly examining these reactors on site in Kozloduy for two weeks, 18 inspectors of the World Association of Nuclear Operators concluded "the units met all necessary international standards for safe operation" (WNA[1] 2007). Yet the EU's demand was not something the government could dismiss since accession to the EU has been the number one national priority of Bulgaria since the beginning of the changes in 1989. The four reactors were shut down prior to January 1, 2007, when Bulgaria became a full member of the EU. The decommissioning of Units 1-4 of Kozloduy was a blow on the Bulgarian power sector. Although it posed no threat to the stability of the country's own electricity balance, it cut severely into its exporting capabilities upon which much of the entire South-Eastern Europe region depended to various degrees.

To regain its competitive edge in the regional power market, Bulgaria began making plans to build a second nuclear facility: the Belene NPP, some 50 miles East of Kozloduy, also on the Danube river. The site and project of Belene were not new. It was something started under communist rule in 1987 but terminated in 1991 due to lack of funds. By the end of the 1990s Bulgaria's attractiveness to foreign investors had much improved. In 2003 the Bulgarian Energy Ministry was approached by five reactor vendors interested in the completion of the Belene project (WNA 2007). Encouraged by these offers, in early 2005 the Bulgarian government commissioned the construction of the Belene NPP. In October 2006, after an official bidding process, a consortium led by the Russian Atomstroyexport (ASE) was chosen over a Skoda-led conglomeration, to execute the € 4 billion project. The work will be overseen by the architect-engineer of the plant, the American company WorleyParsons. The endeavor received a "green light" in December 2006 when the Nuclear Regulatory Agency of Bulgaria approved the Belene site for the construction of a new NPP (WNA 2007).

Bulgaria's decision to build a new nuclear facility seems to be part of a global nuclear revival. The September 8th, 2007 issue of *The Economist* magazine devotes two articles to the

[1] WNA stands for World Nuclear Association.

international nuclear awakening and another one in *The Economist Technology Quarterly* from the same date.

The use of nuclear energy for power generation was undertaken after President Eisenhower's speech in front of the UN General Assembly in which he called for the application of nuclear energy for peaceful purposes. In 1954 Lewis Strauss declared in front of the Atomic Energy Commission of the United States that one day electricity generated by nuclear power would be "too cheap to meter" (as quoted in "Nuclear Dawn", *The Economist Technology Quarterly*, September 8, 2007). This statement succinctly expresses the optimism many shared about this new source of energy. From the onset, nuclear power generation's comparative advantage has been its low operating costs, relative to fossil-fuel power generation. This is in large part due to the high energy-density of uranium, the fuel for the fission process that is the heart of a NPP. Many nuclear facilities were built in America, Russia and Europe throughout the 1960s, and 1970s. Currently, there are 439 reactors operating around the world, producing 15% of its electricity ("Nuclear dawn", *The Economist Technology Quarterly*, September 8, 2007).

The euphoria ended abruptly, however. With the rise of environmental awareness in the 1970s, the public became fearful of an eventual meltdown and its consequences. Added to that was the growing concern over radioactive waste disposal[2]. Social concern translated into a more convoluted regulatory process. This added to the huge capital investments necessary to build a NPP, which have always been the main disadvantage nuclear has had over coal, gas or oil. In the US, high interest rates and the leveling of electricity demand exacerbated the problem of justifying the huge construction costs of nuclear facilities. In 1979 the first major accident in the industry occurred at the Three Mile Island NPP near Harrisburg, Pennsylvania. A combination of

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[2] It is noteworthy that to date no country has a permanent repository for the toxic waste to which nuclear fuel is turned after about 3 years in the reactor.

equipment malfunction and operator error led to the partial meltdown of the reactor core. The situation was contained and there were no people harmed and no significant leakage of radiation. A true catastrophe took place in April 1986 at the Chernobyl NPP in Ukraine. A series of operator failures and design flaws caused the discharge of a huge amount of power in the reactor core of Unit 4, leading to an explosion which released large amounts of radioactive material into the atmosphere. Thirty emergency workers met their death immediately after the incident. Most of Europe was contaminated by the fallout for many years to come. The UN estimates about 4,000 casualties resulted from the Chernobyl meltdown ("Nuclear power's new age", *The Economist*, September 8, 2007). These two accidents were all that was needed to finally seal the fate of the nuclear industry for more than two decades: from "too cheap to meter", it became "too expensive to matter" ("Atomic renaissance", *The Economist*, September 8, 2007).

By the end of this year the US Nuclear Regulatory Commission expects to receive 12 full applications for the construction of new NPPs. These will be the first full applications in America for thirty years ("Atomic renaissance", *The Economist*, September 8, 2007). Meanwhile, Finland is building the first European NPP in 15 years. In all, there are 31 reactors underway around the globe ("Nuclear dawn", *The Economist Technology Quarterly*, September 8, 2007). India and China are looking at expanding significantly their existing nuclear programs. Vietnam and Turkey are looking at starting their own. Clearly, nuclear power's position has changed.

There is a substantial change in the technology. Existing reactors are now on-line 90% of the time versus 50% in the 1970s ("Nuclear power's new age", *The Economist*, September 8, 2007). New reactors can burn uranium at a higher efficiency than older ones, making the marginal cost of operation even smaller, as well as decreasing the amount of waste generated. New reactors are being designed which can use some of the highly active material in the waste from conventional reactors as fuel, thereby minimizing the amount of toxic waste even further.

Vendors predict smaller construction periods due to learning-by-doing from old plants. New designs include “passive safety” systems in which no human intervention is necessary to shutdown the reactor and prevent a meltdown in the event of a runaway chain reaction.

There is some anecdotal evidence the public’s outlook on nuclear is already changing. In Britain 30% of the population is against nuclear power, versus 60% three years ago. Similarly 50% of Americans versus 41% in 2001 favor the expansion of nuclear power (“Nuclear power’s new age”, *The Economist,* September 8, 2007). An improved social attitude is a necessary and sufficient condition for streamlining of the regulatory process. This in turn means lower construction costs. Overall, improving the technology has translated into improving the economics of nuclear power.

More importantly, there are external benefits associated with nuclear power generation which have been amplified by current events. The recent hikes in the price of oil and gas improve nuclear’s position relative to these energy sources. The world’s fossil fuel supply is quickly shrinking and is in the hands of hostile or shaky governments. In contrast, uranium is thought to be relatively abundant and there are large deposits of it in friendly places such as Canada and Australia. In this way, nuclear power is able to uniquely address the issue of energy security in Western countries. Concern over climate change has put a premium on low greenhouse emission technologies. Like wind and solar power, nuclear does not generate any such emissions. Unlike wind and solar, nuclear power generation is consistently stable and offers the ability to produce large amounts of base-load electricity. NPPs are thus the only viable alternative to fossil-fuel generation as global demand for electricity doubles in the next few decades.

The need for a new electricity-producing facility in Bulgaria after the shutdown of Units 1-4 of Kozloduy is clear. It is not clear, however, what dictated the choice of nuclear technology. Why didn’t Bulgaria decide to build another coal-fired plant, since it has always been the case that coal plants provide the largest percentage of total electricity production in the country? That question has never been disputed widely in the Bulgarian media, the reason being the Belene project was met with an overall positive attitude from the public which saw it as a way of recovering whatever pride in its eyes the country lost by conceding to EU demands of shutting down Kozloduy. Was the choice of technology that is to replace Kozloduy dictated by an irrational desire to get back at the EU, or was it instead a rational decision based upon the economic advantage of nuclear versus other technologies, in particular coal?

The basis of the analysis is comparing the marginal cost (MC) of both generating technologies. Microeconomic theory tells us that the MC of an input (usually labor or capital; in this case power-generating technology) is equal to the ratio of that input's price (P_I) to its marginal product (MP):

$$MC = \frac{P_I}{MP} \tag{1}$$

I identify P_I of both the nuclear plant and the coal plant with their respective levelized discounted cost of electricity (LDCE), which I develop based on a literature review. I estimate a Cobb-Douglas production function augmented with multiplicative energy terms. The estimated output elasticity of nuclear and coal is their respective MP. Combining information on the relative P_I and MP of both technologies I gauge the relative magnitude of their MC. The preferred option is, of course, the one with the lower MC.

Although this paper does not aim at making any recommendations, its conclusions will be useful in determining whether the optimal mix in Bulgaria's energy portfolio consists of more or less nuclear-generated power. This has obvious policy implications in terms of incentives or disincentives for investment in nuclear power generation. The present study adds to the literature quantifying the new economics of nuclear power.

The remainder of the paper is organized as follows. Section II studies the LDCE of nuclear power generation relative to some viable alternatives, in particular coal fired TEPPs. Section III presents and justifies the estimated econometric model and the results from the estimation. Section IV concludes.

II. The Levelized Discounted Cost of Electricity

I use the Levelized Discounted Cost of Electricity (LDCE) as the input price for both technologies. The LDCE is a constant price which if received by the plant owner for each unit of electricity generated over its lifetime will provide a flow of revenues just sufficient to cover all of the costs incurred in building and operating the plant throughout its life (Deutch and Lester, 2004, 57). Mathematically, if NCF_t stands for the net cash flow of the plant in year t, n is the lifetime of the plant, i is the prevailing discount rate, then the LDCE solves the present value equation:

$$\sum_{t=1}^{n} \frac{NCF_t}{(1+i)^t} = LDCE \sum_{t=1}^{n} \frac{1}{(1+i)^t} \qquad (2)$$

The above equation reveals much of the appeal of using the LDCE as the input price for both options. Since NCF_t can be vastly different for different technologies, the above approach allows you to treat on an equal footing very dissimilar cost structures. This makes the LDCE approach especially advantageous in comparing nuclear and coal power-generating technologies. NPPs have always been characterized by high upfront costs and long construction periods, while coal plants take much less time and money to complete. In the same time, once online, NPPs are cheap to run, relative to coal-fired TEPPs, because uranium is such a high energy-density source. Coal plants are much more sensitive to the fuel component and are subject to constant shocks in the price of coal.

The changing economic position of nuclear power relative to fossil fuel based generation in recent years which has lead to the possibility of a nuclear renaissance discussed above has led to a parallel renaissance in the literature of nuclear economics. There have been several major studies dedicated to comparing costs from different modes of power generation. All of these studies are similar in that they employ the levelized cost methodology.

The International Energy Agency (IEA) and the Organization for Economic Co-operation and Development's Nuclear Energy Agency (OECD-NEA) published in 2005 their conclusions from the sixth in a series of studies *Projected Costs of Generating Electricity*. They estimate the cost of generating electricity across different power plants and across ten different countries.

The possible revival of nuclear power generation in the United States has led a team from MIT to conduct their own study into this technology's economic merits. The main criterion of economic competitiveness is low levelized cost of electricity production. *The Future of Nuclear Power* (MIT 2003) compares this cost between nuclear, coal and gas plants. Unlike the IEA/OECD-NEA study reviewed above, MIT's analysis shows nuclear power generation to be an unattractive option.

Another study that examines the cost of producing electricity from different technologies is the *Reference Costs for Power Generation* (2003), conducted by the General Directorate for Energy and Raw Materials (DGEMP) of the French Ministry of the Economy, Finance and Industry, in collaboration with industry experts. The study is slightly different than the preceding examples in that it is mainly concerned with the investor's point of view: standard discount rates are taken to discount future costs to the present and investment costs such as interest during the construction period are included in the calculations of levelized costs. By performing a full analysis at 3%, 5%, 8% and 11% discount rates the study gives a measure of the sensitivity of project costs on discount rates. Unlike the previous studies, this one includes explicitly the costs of greenhouse emissions in the coal and gas cases.

In *Competitiveness Comparison of the Electricity Production Alternatives* (2003), Tarjanne and Luostarinen compare the costs of electricity generation from different plant types in Finland. The alternatives discussed are not limited to nuclear, coal and gas-fired plants, but also include some renewable energy source such as a wind turbine. The study aims at providing the most accurate information on costs of generating electricity in Finland and thus costs are based on the March 2003 price level in Finland. Similarly to the DGEMP report, emission trading is considered. The study assumes an unusually high load factor[3] of 91.3%. In contrast, the other studies discussed limit themselves to an 85% load factor.

The Cost of Generating Electricity (Royal Academy of Engineering, 2004) is another study of comparative electricity-generation costs across different available technologies. It is similar to the Finnish report discussed previously in that it takes on the question from a very country-specific perspective. In particular it aims at answering the question what is the best mix of technologies for power generation in the United Kingdom. The choice is between the usual nuclear, coal and gas as well as some renewable-source technologies such as wind turbines and biomass.

The U.S. Department of Energy assigned the University of Chicago to carry out an authoritative study into the competitiveness of NPPs against the main alternatives, coal and gas-fired plants. The findings of this study came out in *The Economic Future of Nuclear Power* (University of Chicago, 2004). What is interesting about this study is that it emphasizes the cost of implementation of some of the new technologies recently developed in the nuclear sector that were discussed in the introduction. This is done through the introduction of first-of-a-kind engineering (FOAKE) costs for NPPs. To counter-balance these, the report also includes a

[3] The load factor, or capacity factor, of a power plant is the ratio of the actual amount of energy it produces divided over the theoretical maximum.

parameter for the possible impact of learning-by-doing, which would cut these at 3% annually. As a result of the FOAKE costs, this study finds the first couple of units in a new NPP to be more expensive than later ones. These conclusions suggest some assistance from the government may be necessary to make a new NPP attractive to investors.

Levelized Unit Electricity Cost of Comparison of Alternative Technologies for Baseload Generation in Ontario (CERI 2004) is an independent study performed by the Canadian Nuclear Association which aims at choosing among nuclear, combined cycle gas turbines and coal plants as the most appropriate for power generation in Ontario.

The results of each of the above studies are summarized in Table 1. Some fundamental assumptions have to be made in each of these studies that are dictated by their common methodology, regardless of their scope and perspective. Among these, there is a subset of key assumptions which drive the disparity in results evident in Table 1. The difference in the assumed overnight costs of construction[4] is a major source of result variability. So are dissimilar assumptions of fuel prices, especially those of gas. Variations in technical assumptions, such as the load factor, introduce another degree of freedom in the results. Some of the aforementioned studies explicitly assign a cost of emissions from coal and gas plants, others do not, further affecting the results. Finally, the most obvious source of variation in the results is the diversity of discount factors utilized in this panel of analyses.

The World Nuclear Association (WNA) is a private organization which serves as a round-table for the people and institutions that comprise the global nuclear power industry. In 2005 it came out with a report titled *The New Economics of Nuclear Power*. The report strives to provide "definitive analysis of the costs of constructing and operating a nuclear power plans in the 21st

[4] Overnight construction costs are the costs incurred during the building of a power plant, including equipment, engineering and labor expenditures, quoted without the interest accrued during the construction period (hence the term "overnight" – no interest would be accumulated if construction was literary done overnight).

century” (WNA 2005). It does so by distilling the conclusions of many recent studies on the subject, including the ones mentioned above. The principal conclusion of the report is that nuclear power is the cheapest way to generate electricity in most industrialized countries today, even without consideration of its geopolitical and environmental advantages, which are becoming increasingly recognized today. The study attributes this improved economic competitiveness to decreased costs. Standardized designs and shorter construction times have brought construction costs down. Streamlined licensing procedures have been made possible due to the technological advances and the safety record of the industry. These translate into reduced regulatory costs and associated uncertainty by allowing predictable timetables to be drawn. As a result, financing NPPs has become cheaper. Operating costs have been subject to the same downward trend: in the US alone they have decreased by 44% from 1990 to 2003. Increased capacity factors are largely responsible for that phenomenon. Increased investment in refurbishment and capacity upgrades as well as a rise in the number of applications for license extensions serve as a testament to the marked ascend in the profitability of existing plants. Based on these observations and recent studies, the report advocates nuclear power’s long-term competitiveness.

Both in the introduction and its conclusion the WNA report (2005) stresses the sensitivity of its finding and the findings of similar studies to their specific assumptions and “local conditions”. This is why, in reviewing the recent literature of comparative electricity cost studies, I put the greatest emphasis on this last report prepared by the architect-engineer of the Belene project, WorleyParsons. In *Feasibility Study Report of Belene Nuclear Power Plant Section 5 Annex* from 2005, a WorleyParsons team lead by economist Lynn Rubow compares the cost of electricity from the Belene NPP and three alternatives: a lignite-fired TEPP, and imported coal TEPP and a natural gas fueled TEPP. These alternatives are chosen so that they deliver the same quantity of electric energy as the Belene NPP.

The Parsons study develops in some detail external costs associated with fossil and nuclear technologies. This portion of the analysis is based on the authoritative ExternE study carried out by the EU. The ExternE treatment is “technology neutral” (Rubow, 2005, 3), meaning external costs are not biased toward any particular technology.

The external costs of nuclear power are separated in two categories: financial costs and the effects of ionizing radiation on health and the environment.

External financial liabilities can be further broken down into decommissioning costs, costs associated with spent fuel disposal and storage and catastrophic accident costs. The financial costs of decommissioning and spent fuel management can be accurately estimated and internalized by creating dedicated accrual accounts in which resources are allocated for those purposes throughout plant operation. Financial liabilities arising from accidents are internalized by insurance. The Parsons study estimates the external costs of severe accidents to be below 5% of the external costs of routine operation of an NPP, or alternatively, less than 1% of the nuclear fuel costs excluding externalities, thus having a very minimal effect on the overall cost structure of a nuclear plant.

The external impacts on health and the environment in routine operation of a reactor are developed by the Parsons study again in concordance with the ExternE methodology. First, the physical impact of constructing, operating and decommissioning an NPP on the environment and human activity, such as diseases, fatalities, effects on water and food, etc., are described. These effects are then quantified and monetized[5]. The results are extremely sensitive on the choice of a discount factor: the external costs at a 0% discount rate are 50 times greater than at a 10%

[5] The question arises as to the appropriate discount factor. This is a sensitive issue, since some by-products of fission have ostensible environmental effects many years into the future. A low discount factor means people now bear most of the costs and in this way it favors future generations. Conversely, a high discount factor favors present generations. This choice is clearly outside of the realm of positive economics and has been called “political” and even “meta-ethical” (Rubow, 2005, 8).

discount rate (Rubow, 2005, 9). However, even in the upper limit the overall external costs of a nuclear fuel cycle in normal operation do not exceed 10% of the direct costs.

In developing the external costs for the fossil options some of the same considerations are taken into account. One important distinction is the introduction of direct emissions costs. Since nuclear power generation does not produce any emissions these costs are relevant solely for the fossil options. In the Parsons study fossil-fuel plants are charged the full amount of their emissions, since any emission represents the foregone opportunity of selling an amount of emissions permits on the European emissions trading market. In this treatment, the external costs associated with fossil fuel power generation far exceed, both in absolute terms and as a percentage of direct costs, the external costs associated with NPPs.

The Parsons study considers the social impact of all options. The choice of technology, whether domestic or imported fuel, and domestic or foreign equipment and services will be used is likely to have a substantial effect on the overall Bulgarian economy. Job creation under any economic conditions, other than full employment, is a positive stimulus to every economy. There are indirect benefits to the government, which gains a tax payer while shedding an unemployed person. There is a multiplier effect from each job created, which can be intuitively understood as additional employment necessary to satisfy the needs of the newly employed. With these considerations in mind, the Parsons study discusses the differential contribution ot employment the four alternatives present. The natural gas option has a low contribution to short-term and permanent employment as it requires few people (relative to the other options) for construction and operation. Also, it is highly depended on imported fuel and components. In this perspective, it is inferior in its impact on the local economy than both coal options and the nuclear option. These have a high contribution to both short-term and permanent employment as they require a large number of laborers for construction and similarly large highly skilled personnel to operate them. Since lignite coal is abundant in Bulgaria, the lignite option has the added advantage of being able to use domestic resources.

Rubow's group develops an economic model which incorporates all of the above considerations as well as development of fuel, capital and operating costs and uses that to compare the nuclear option with the three fossil fuel options in terms of their LDCE. Figure 1 presents a flow chart of the model. Figure 2 presents the results of the economic analysis. The Belene NPP has comparative economic benefits relative to the three fossil options, which are much more pronounced upon consideration of externalities.

The studies reviewed above, with an emphasis on the Parsons study, provide evidence in support of the fact that nuclear power generation has a lower LDCE than coal power generation. The nuclear option is superior to the coal option in terms of input price. To complete the analysis I now turn to the marginal product of each technology.

III. Estimated Output Elasticity of Nuclear and Coal Energy:

The output elasticity estimates are based on a Cobb-Douglas production function. This traditional form is augmented to include multiplicative energy terms. In double-log, the estimation equation assumes the form:

$$\ln Y_t = \beta_0 + \beta_1 \ln(K/L)_t + \beta_2 \ln E_t^N + \beta_3 \ln E_t^C + \beta_4 \ln E_t^{Other} + \beta_5 Y\_gap_t + \beta_6 Year_t + \varepsilon_t \qquad (3)$$

Output growth is a function of the capital-labor ratio. The coefficients of interest are β_2 and β_3, the output elasticity of energy from nuclear- and coal-based generation, respectively, both of which should be positive. These output elasticity estimates reflect the respective marginal products. The third energy term is featured in the regression to account for the remainder of the energy input to the economy. Eqn. (3) is estimated using annual U.S. data in the period 1965-2006. A key assumption is that the same qualitative relationship between the productivity of the two technologies holds in Bulgaria. This is arguably a bold assumption, but it is necessary. One of the classical assumptions under which ordinary least squares estimation is permitted requires variability in the regressors. As discussed in the Introduction, Bulgaria has thus far only had one NPP and therefore it has insufficient variability in the energy delivered from this source[6].

An important difference between a traditional Cobb-Douglas and eqn. (3) is the use of the capital-labor ratio instead of both variables separately. The reason for doing so is the extremely high in-sample multicollinearity between these variables. Although (imperfect) multicollinearity does not violate any of the Classical Assumptions, it could lead to perverse results, especially in small samples such as this one[7]. The use of the capital-labor ratio, or even the omission of either capital or labor is actually a common technique in endogenous growth literature[8]. In this specification, β_1 is the output elasticity of capital per worker, which can be interpreted as the percentage point change in output per 1% increase in the capital-labor ratio, holding all else constant. I expect this to be positive.

It is not clear empirically how to best measure labor and capital services. Many specifications were attempted using different variables. Some scholars argue an index of hours worked may be used for labor services in lieu of total non-farm payrolls. The argument is that total non-farm payrolls is a measure insensitive to economic turning points, as companies are hesitant to lay off workers due to the costs of recruitment. Instead laborers get assigned less work, a phenomenon which can clearly be observed in an index of hours worked. Although such

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[6] Ideally, eqn. (3) should be estimated on a cross-section of countries with varied energy-generation portfolios. Unfortunately, capital stock data is generally not provided by statistical agencies even in Western European countries, precluding such an analysis.

[7] Here is one way to understand this. If two variables are highly mutlicollinear, the computer randomly attributes the explanatory power they posses to only one of them. The other usually falls out of significance. Also, its coefficient estimate might have the wrong sign, as the estimation will be largely driven by the few instances in the sample when the two variables differ, which are usually due to random shocks driving those variables in opposite directions for no systematic reasons.

[8] See for example Abel, Bernanke and Croushore (2008), pp. 238-240.

“labor hoarding” is a well-established macroeconomic phenomenon, it is not pertinent to eqn. (3). Capital is utilized and made productive by worker’s skills. It is much more intuitively appealing, therefore, to use total non-farm payrolls in constructing the capital-labor ratio featured in the model. When considering the productive stock of capital care must be taken not to include measures of fixed assets which are essentially idle, as for example residential private fixed assets (housing). While such a measure of the capital stock reflects a major source of wealth for households, it does not accurately capture the productive stock of capital. Therefore, I choose the net stock of private fixed nonresidential assets.

Eqn. (3) controls for variability in output exogenous to labor, capital and energy services. In a time-series of output, one has to control for the underlying trend in output growth, due to technological progress, as well as the cyclical variations in output around this trend. These two effects are captured by Year and Y_gap. The Year coefficient (β_6) captures the average annual growth-rate of output independent of other factors, i.e. the average annual growth-rate of technological progress. It is expected to be positive. A 1% increase in the output gap leads to a β_5 *100 percentage points change in GDP. When the economy is above potential (Y_gap is positive), the growth of output is generally positive; when the economy is below potential (Y_gap is negative) growth of output is usually negative. Thus, β_5 is also expected to be positive.

One final consideration is the Three Mile Island Accident. The Introduction noted how this accident resulted in a permanent shift away from nuclear energy. One might think it is appropriate to somehow, via a dummy variable, splitting the sample, or otherwise, account for this structural change. Figure 3, however, reveals it is hard to detect a shift in trend due to the accident. It is evident from the graph that the dip in energy consumption from NPPs is modest and short-lived. Indeed, there have been no new constriction permits for NPPs issued in the U.S.

since 1979, but there have been many issued right before the accident leading to many new plants coming online after the partial meltdown. This circumstance masked the effects of the Three Mile Island accident on the industry.

Table 2 provides definitions, sources and descriptive statistics for the data used. A few figures are worth pointing out. The mean value of Y_gap over the sample period, -0.318, is indistinguishable from zero within one standard deviation (2.433). The U.S. economy has done a good job at keeping in line with its potential in the past four decades. A substantially higher amount of energy derived from oil and gas (548.9 Mtoe and 397.4 Mtoe) was used relative to coal-generated energy (291.8 Mtoe). This is explained by the significant proportion of energy that goes for transportation and household heating instead of electricity generation. Lastly note the minimum amount of nuclear energy is close to zero, reflecting the relative novelty of this technology – as mentioned in the introduction the prospect of using nuclear power for peaceful purposes was not envisioned until 1954.

Table 3 summarizes the estimation results. As is common with time-series, the regression exhibits a very high R-square of 0.99, suggesting that 99% of the variability in the U.S. GDP data is explained by the model. The control parameters β_1, β_4, β_5 and β_6 are all significant at the 1% level and of the expected sign. The magnitude of some estimates is reassuring. For example, β_6 suggests that the average annual growth-rate of technological progress has been around 2.4%, which is in line with the growth indicated by empirical macroeconomic literature. As revealed by β_2 , all else equal, a 1% increase in the consumption of energy delivered from nuclear sources, has lead to a 0.012% increase in U.S. GDP in the period 1965-2006, significant at the 1% level. In the same time, β_3 implies that a 1% increase in the consumption of energy delivered from coal sources has lead to a 0.046% increase in U.S. GDP. Although this last result is insignificant, it does provide some evidence that coal power-generating technology has exhibited higher productivity than nuclear power-generating technology in the period 1965-2006 in the U.S.

IV. Conclusion:

An investigation into the marginal cost of coal power-generating technology versus the marginal cost of nuclear power-generating technology was performed through the perspective of the Belene NPP project underway in Bulgaria. Studies provide some evidence that the Belene NPP has a lower LDCE than coal alternatives. A Cobb-Douglas production function augmented with multiplicative energy terms estimated with U.S. data suggests, however, that the nuclear option is less productive. Combining these findings in eqn. (1) reveals the relative position of the marginal cost of the Belene project relative to a coal alternative is ambiguous, depending on the relative magnitude of the price and productivity effects which push it in opposite directions. As it stands, the question of whether the Belene NPP is superior to a coal alternative cannot be answered with certainty.

This paper leaves ample room for further investigation in several directions. While the Cobb-Douglas production function is an appropriate first step, other functional forms such as Constant Elasticity of Substitution (CES) production functions might provide an alternative environment for introducing energy as an input in production. More importantly, repeating the above analysis with an extended data set should provide more robust results. Ideally, one would want to use a panel of countries which have used nuclear power over many years to introduce fixed-effect type of variation in energy-generating portfolios. Obtaining data on the productive stock of capital across different countries is a prerequisite to such an analysis, however. Unfortunately, measures of the net stock of capital are not readily available for most countries, even for developed European countries. Finally, this study begs the question is there an a priori reason that the there should be a differential in the output elasticity of energy derived from different sources, or is this result simply an artifact of the sample used. One possible reason why this might be a real effect is the different physical efficiencies of different power-generating technologies. It has been suggested these should be translated completely into the input price differential. While I do not find a convincing explanation as to why the differential result should be expected, I find the rebuttal of the physical efficiencies hypothesis equally unconvincing. Perhaps energy generation markets are inefficient at translating the physical efficiency differentials into price differentials. Still, this question remains very much open and potentially a fertile ground for further research.

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Appendix – Tables and Figures

Table 1.

Studies of Comparative Costs of New Generating Plants: Electricity Price per MWh

	IEA/OECD-NEA (2005)		MIT (2003)	DGEMP (2003)	T&L (2003)	RAE (2004)	UofC (2004)	CERI (2004)
	$	$	$	€	€	£	$	Can$
	5%	*10%*		*8%*	*5%*	*7.50%*		
Nuclear	21-31	30-50	67	28	24	23	51	53
Coal	25-50	35-60	42	34	28	25	35	48
Gas	37-60	40-63	38	35	32	22	33	72

Figure 1. Rubow's Economic Model Flow Chart

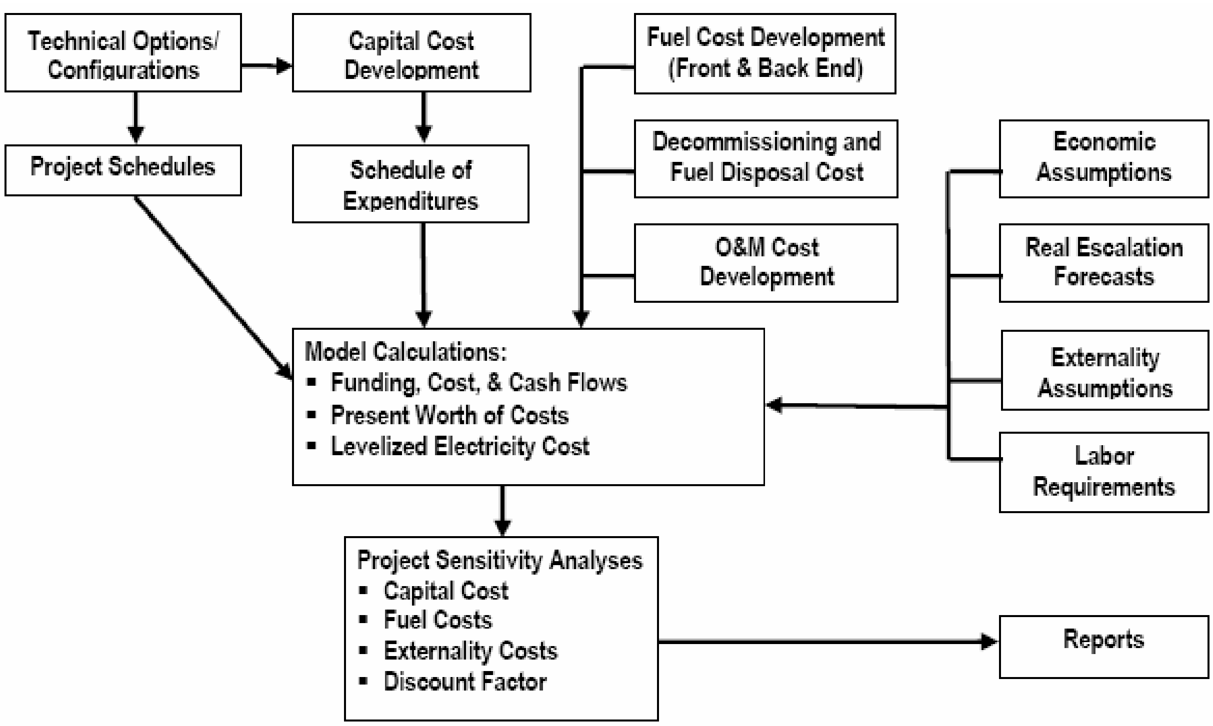


Figure 2. Rubow's LDCE Results

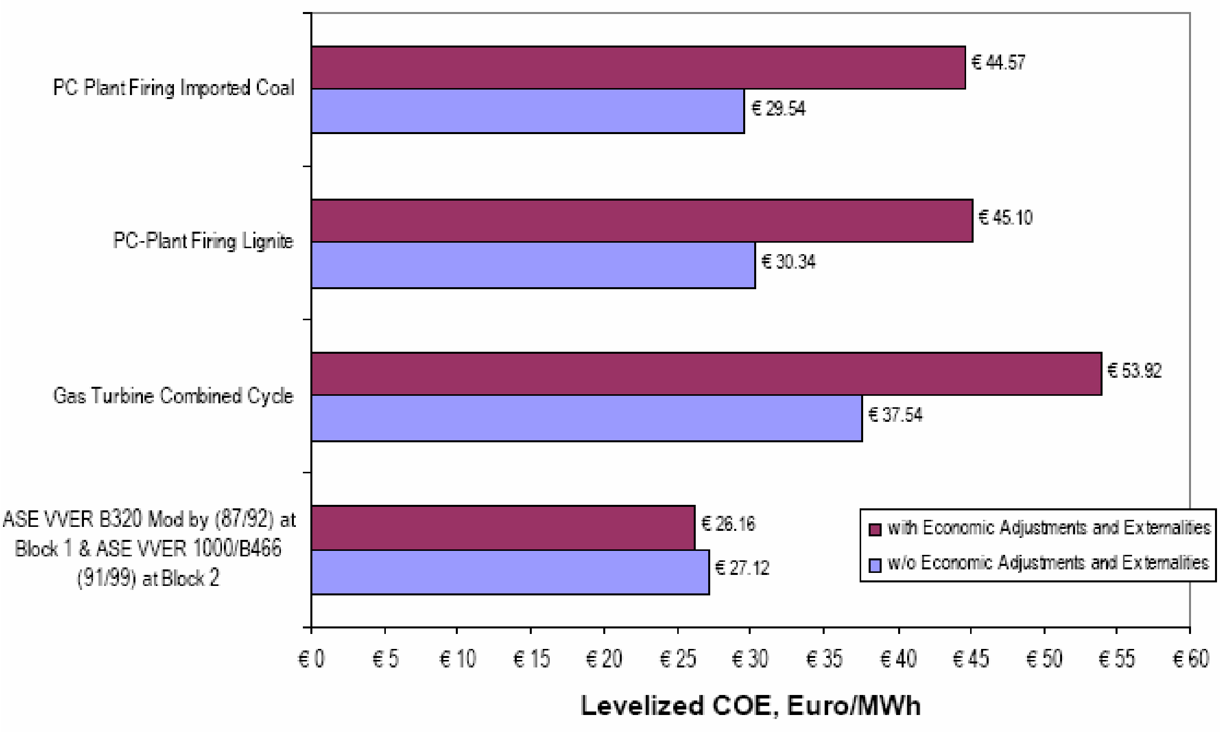
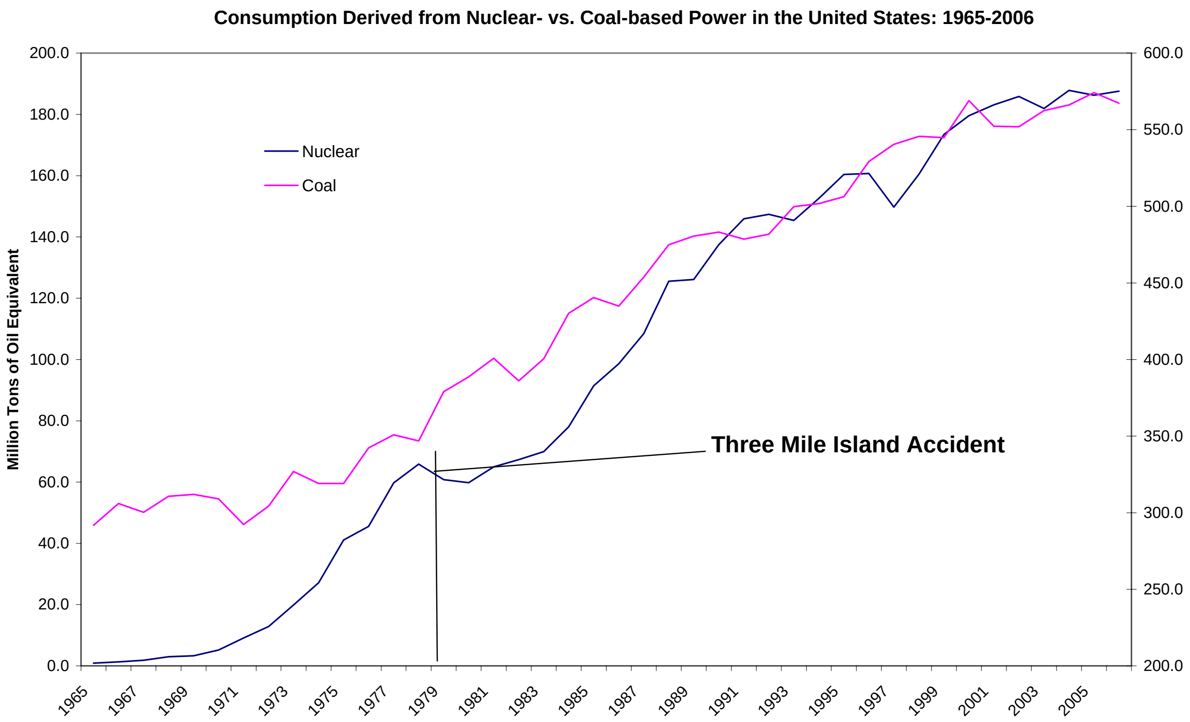


Table 2.

variable name	definition (source)	Mean	Std. Dev.	Min.	Max.
Y	real GDP in billions of chained 2000 dollars (FRED)	6,540	2,409	3,191	11,319
Y*	potential real GDP in billions of chained 2000 dollars (FRED)	6,572	2,426	3,085	11,372
Y_gap	percentage point departure from potential: =(Y/Y*-1)*100	-0.318	2.433	-6.726	5.413
L	total nonfarm payrolls in thousands; annual average of monthly data (FRED)	99,452	23,050	60,878	136,091
K	chain-type quantity index (2000=100) for net stock of private fixed nonresidential assets (BEA)	67.9	24.2	31	111
E^N	consumption of energy derived from nuclear power generation, in million tonnes of oil equivalent (mtoe) (BP Statistical Review of Energy)	96.9	66.5	0.8	187.8
E^C	consumption of energy derived from coal power generation, in mtoe (BP Statistical Review of Energy)	432.3	98.1	291.8	574.2
E^O	consumption of energy derived from oil power generation, in millions of tonnes (BP Statistical Review of Energy)	789	97.7	548.9	951.4
E^G	consumption of energy derived from gas power generation, in mtoe (BP Statistical Review of Energy)	521.3	54.9	397.4	602.7
E^H	consumption of energy derived from hydroelectric power generation, in mtoe (BP Statistical Review of Energy)	63.1	8.4	45.0	81.5

NOTE: Number of observations = 42 for all variables

Figure 3.



Consumption Derived from Nuclear- vs. Coal-based Power in the United States: 1965-2006
Million Tons of Oil Equivalent
Nuclear
Coal
Three Mile Island Accident
200.0
180.0
160.0
140.0
120.0
100.0
80.0
60.0
40.0
20.0
0.0
600.0
550.0
500.0
450.0
400.0
350.0
300.0
250.0
200.0
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
2003
2005

Table 3.

Variable:	$H_{A:}$		Preferred Model:
K/L	>0	Coeff. St. Err. p-value	0.286*** 0.077 <0.001
Year	>0	Coeff. St. Err. p-value	0.024*** 0.001 <0.001
Ygap	>0	Coeff. St. Err. p-value	0.01*** <0.001 <0.001
lnE^N	>0	Coeff. St. Err. p-value	0.012*** 0.003 <0.001
lnE^C	>0	Coeff. St. Err. p-value	0.046 0.039 0.121
lnE^{Other}	>0	Coeff. St. Err. p-value	0.128*** 0.035 <0.001
R-sqr.	0.99		
Adj. R-sqr.	0.99		

Note: *** labels significance at the 1% level