THE ECONOMICS OF ENERGY INDEPENDENCE FOR IRAN

Thomas W. Wood, Matthew D. Milazzo, Barbara A. Reichmuth, and **Jeffrey Bedell**

Iran has pursued an ambitious nuclear program with the declared goal of long-term energy independence. While this is a worthwhile and generally accepted national planning objective, it is clear that Iran's nuclear program as now structured will not achieve this goal, and in fact may delay it by diverting capital and other resources from projects that would address pressing current energy sector problems and contribute to ultimate energy independence for Iran.

KEYWORDS: Iran; Uranium; Nuclear energy; Nuclear fuel cycle; Energy economics

In November 2003, the International Atomic Energy Agency (IAEA) issued a report that chronicled Iran's nearly two-decade history of undeclared nuclear activities and deception in dealing with the IAEA.[1] Iran maintains that its nuclear program is solely for peaceful energy development, while the United States, European leaders, and many in the international community say Iran's years of clandestine research and insistence on pursuing uranium enrichment suggest otherwise. Since its 2003 report, the IAEA has been closely evaluating the Iranian nuclear program in an attempt to confirm Iran's declaration that its nuclear program is strictly a peaceful one. By late July 2006, the UN Security Council (UNSC) adopted Resolution 1696, which called on Iran to suspend its uranium enrichment program by August 31, 2006, or face possible economic and/or diplomatic sanctions.[2] That deadline came and went with Iran declining to halt its uranium enrichment program, instead providing a counteroffer to participate in further negotiations. Iran's reluctance to accept the conditions of Resolution 1696 resulted in the unanimous adoption of Resolution 1737 by the Security Council on December 23, 2006. Blocking the import and export of sensitive nuclear material and equipment and freezing the financial assets of persons or entities supporting Iran's sensitive nuclear activities, Resolution 1737 stipulated that Iran suspend all enrichment-related and reprocessing activities, including research and development and work on all heavy water–related projects. The Security Council has requested a report from the IAEA director general within 60 days detailing Iran's compliance with the resolution. Given Iran's recent declaration that it intends to install 3,000 centrifuges at Natanz, it seems likely that a long and difficult diplomatic process lies ahead.

As a result of these recent events, Iran's nuclear program has been the focus of great interest in the international community and has been evaluated from different perspectives.[3] While much of the literature has focused on the status of Iran's program vis-à-vis international norms for nuclear projects under the Treaty on the Non-Proliferation

Nonproliferation Review, Vol. 14, No. 1, March 2007
ISSN 1073-6700 print/ISSN 1746-1766 online/07/010089-24

DOI: 10.1080/10736700601178572

of Nuclear Weapons (NPT), this article seeks to examine both Iran's nuclear program investments and alternative energy investments *strictly on their economic merits*. This perspective has nothing to say about formal compliance with international norms but can and does inform judgments on the *credibility* of the economic rationale that Iran often puts forward to justify its nuclear program. It also facilitates the evaluation of the nuclear program on a footing of investment comparability with other energy options.

When evaluated on the basis of its economic rationale, certain elements of Iran's nuclear program are highly questionable. In particular, we find that Iran's investment in front-end nuclear fuel cycle facilities is not consistent with the economics of nuclear power. The scale of facilities required to reach market competitiveness in these technologies is simply inconsistent with the scale of the country's uranium resources as estimated by the Iranian government. Further, the timetable for operational completion of these facilities promises to be an extended one, making recovery of a very substantial capital investment almost impossible at an economic rate of return.

Iran's Nuclear Program

Iran's nuclear program is extensive and expensive. Under way since 1975, it includes work in at least 22 facilities at nine sites.[4] With a declared scope that includes the development of six light water power reactors (in addition to the nearly completed Bushehr-1) over the next 15 years, Iran's nuclear program requires a pace of reactor development that has been equaled by few countries in the last 20 years.[5] In addition to these facilities, described in Iran's declaration to the IAEA, Iran's parliament passed a bill in March 2005 calling for an additional 13 nuclear reactors of 1,000-megawatts electric (MWe) each.[6] Mohammad Ghannadi-Maragheh, the research and technology deputy of the Atomic Energy Organization of Iran (AEOI), also mentioned this possibility in his 2005 address to the World Nuclear Association.[7]

The Iranian nuclear program includes several facilities on the "front-end" of the nuclear fuel cycle (such as uranium mining, conversion, enrichment, and fuel fabrication plants) that are expensive, technologically challenging, and for which sufficient uranium reserves have not been established in the country. These facilities are not scaled to support Iran's seven-reactor construction program and would require uranium imports to operate for more than a few years—and thus would not achieve energy independence.[8] Viewed as an economic venture, this program includes substantial technical risk, despite ongoing technical assistance from Russia. The planned start date for the first Iranian reactor at Bushehr has been delayed repeatedly and is several years behind schedule.

Iran's investments in front-end fuel cycle facilities have occurred at a time when obvious and pressing problems in its broader energy sphere go unaddressed. Iran burns a higher fraction of its natural gas at the wellhead (without capturing an energy benefit) than most other Organization of Petroleum Exporting Countries (OPEC) nations. Its refinery yield of gasoline per barrel of oil is less than one-half that achieved in the United States. Iran's gasoline consumption, based on an aging and energy-inefficient vehicle fleet, is growing rapidly and has caused its gasoline import bill to increase to almost $4 billion per year.[9] Energy waste is encouraged by a system of price subsidies for gasoline, natural gas, and electric power.

Any number of projects could address these problems based on readily available technology, at economic rates of return sufficient to attract foreign capital if needed. We examined both combined-cycle natural gas power plants and new refinery projects in some detail and found both to offer highly attractive returns. If Iran were to reduce its waste of natural gas at the wellhead to Middle Eastern rates, it could generate electrical power equal to more than two of its Bushehr-type reactors at a fraction of the cost. These are by no means the only types of projects that are suggested by Iran's energy circumstances. Other candidate projects could include upgrades to existing refineries, accelerated retirement and replacement of the transport fleet, energy efficiency measures in the electrical energy sector, market pricing to incentivize conservation, and utilization of abundant natural gas as a transport fuel.

There have been hopeful signs within the last several months that some of these projects, including refinery and energy efficiency, are now in the planning stages within the Iranian government and private sector. While this may presage a shift in government policy toward economic energy planning, two serious problems remain.

One problem is that Iran's continued investment in front-end nuclear technology projects will represent a significant drain on capital resources available for other projects. The extent of this effect is difficult to accurately estimate, but these projects compete for financial capital, brainpower, and political focus with the fossil energy and conservation projects described above. The 2005 proposal for an enrichment facility to be located in Russia, while a positive step from an economic perspective, would also demand Iranian capital to be realized. This problem of investment competition can only be addressed by abandoning the unproductive investment in indigenous front-end nuclear fuel cycle facilities and by negotiating a cost-sharing arrangement with Russia that reflects the true costs of Russian enrichment operations and equitably shares the economics associated with the technology.

The second, more subtle, economic problem is that continuation of front-end fuel cycle facility investments will sour the already shaky climate for foreign investment in Iran's energy economy and for international commerce with the country in general. Although this effect depends on perceptions and trust, it could be very important in the long run. The extent of international consensus evidenced in recent IAEA actions makes it clear that Iran's nuclear facilities are perceived as motivated by an intent to acquire weapons. It has been observed that this strong perception has "created an atmosphere of distrust in the region."[10] Pursuing even limited future nuclear research in these facilities would add to this atmosphere and clearly harm the prospects for productive economic collaboration and profitable projects. It is also likely to lead to additional economic sanctions, which would harm the national economy to an even greater degree and limit Iran's ability to address the kinds of inefficiencies in its energy and transportation sectors noted above.

Our conclusions apply to the front-end fuel cycle facilities developed to date by Iran, as well as to those contemplated for further investment, not to nuclear power in general. There may well be a civilian nuclear power program that makes economic sense for Iran, based on continued acquisition of foreign-supplied reactors such as the Russian VVER-1000 reactors under construction at Bushehr. A nuclear power program comprised of procured reactors with vendor-supplied fresh fuel and repatriation of spent fuel could prove economically viable and vital to an energy independence strategy for Iran.

Findings

Iran's estimated uranium reserves are not commensurate with its declared program of reactor development and would not in their most optimistic estimates allow for life-cycle operation of these reactors. Tehran's uranium reserves would likely be exhausted well before its seven-reactor construction program was even completed.

If energy independence is the goal, the logical strategy is conservation and stewardship of national oil and natural gas resources. Iran has, in proven (not speculative) reserves, roughly 90 years' worth of oil at its current production rates. The comparable statistic is 220 years for natural gas reserves. These figures substantially exceed world averages and contrast sharply with Iran's proven uranium reserves, which represent slightly more than one year's consumption for the declared reactor program.

Cost of Nuclear Program

Though sufficient data for a detailed and comprehensive estimate of the cost of Iran's nuclear program are unavailable, the seven reactors alone would cost between $7 billion and $10 billion, even at a very attractive cost per kilowatt (kW).[11] The costs of selected elements (front-end plus the heavy water reactor) of the program are at least in the vicinity of $600 million–$1 billion and could easily be more. If scaled up to provide sufficient fuel for the seven-reactor program, an additional investment of $700 million–$1 billion would be required. Given that Iran could easily and cheaply fuel its reactors with Russian-supplied fuel today, and that indigenous construction of the requisite facilities would take 5–10 years, any possible economic returns to these front-end fuel cycle facilities would not accrue for perhaps a decade, making the investment almost impossible to justify on economic grounds. Calculations also show that while the annual market cost of purchased fuel for a seven-reactor scenario would be approximately $350 million, the costs of indigenous fuel production in Iran's facilities could exceed that by nearly $125 million. This finding calls into question the economic logic of Tehran's program and suggests that other factors may be motivating its drive to acquire indigenous front-end nuclear capabilities.

Natural Gas Sector Investments

Iran's management of its natural gas sector is inconsistent with a serious program oriented toward energy independence. In 2003, it wasted 9.38 percent of its gross production—almost 430 billion cubic feet (ft^3).[12] The natural gas that is flared represents a total energy resource equivalent to more than four 1,000 MWe reactors. Even achieving the Middle Eastern average flaring efficiency would allow Iran to generate more than two 1,000-MWe reactors' worth of electrical power—using a resource that is now wasted.

We evaluated two gas sector projects that would allow for the capture, conditioning, transportation, and use of some of this wasted gas in electrical power production. These projects are more modest in scale than would be required to achieve Middle Eastern flaring rates and are well within the technical capability of Iran. Even at very conservative prices for the power produced, these projects would generate very attractive economic returns, paying their entire investment costs back far sooner than any of the nuclear program investments could *begin* to break even. While these projects were formulated only in notional or conceptual detail, we believe them to be representative of a large class of projects that could more efficiently exploit the country's huge gas reserves to achieve energy independence.

Refinery Sector Investments

Though it produces enough crude oil to be self-sufficient for all internal consumption, Iran imports 40 percent of its gasoline needs due to limited refinery capacity and low gasoline yield at its existing refineries. The market value of the gasoline imported in 2004 was roughly \$2 billion–\$3 billion and is expected to increase rapidly with both growth in gasoline demand (at around 9 percent per year) and price increases for gasoline.[13]

While the investment required to make Iran completely self-sufficient in terms of gasoline production would exceed the cost of the selected nuclear facilities we examined, it is roughly commensurate with the cost of an additional six 1,000 MWe reactors. Such an investment would be directly relevant to reducing the gasoline import bill and would represent a very attractive financial investment. A refinery costing \$10 billion and producing a gasoline yield typical of existing Iranian refineries or a smaller refinery producing a higher gasoline yield costing approximately \$5.6 billion would make the country self-sufficient with respect to its current gasoline imports and would produce very attractive financial returns.[14] All the costs of either of these facilities could be paid from a single year of Iran's net petroleum export revenues, and such facilities would also be attractive enough to attract foreign investment, should Iran choose to solicit it.

Despite simple solutions that would promote and probably achieve real energy independence, Iran's energy investments remain skewed in favor of a nuclear program that does not accord with its resource endowments or its near-term energy sector needs. In summary, Tehran's stated economic rationale for its nuclear program is inconsistent with both the facts of the program and its behavior in the broader energy investment sphere.

Approach

First, we examined the issue of Iran's indigenous resource endowments for nuclear and other energy resources. This perspective is the natural one for a program ostensibly targeted at energy self-sufficiency and reveals that Tehran's nuclear power program does not meet, prima facie, the announced goal of energy self-sufficiency.

Second, we examined the cost of selected elements of Iran's nuclear program. Because of the extensive nature of this program and the clandestine nature of some of the activities, it is difficult to say with any precision what the cost of the entire program has been. This difficulty motivated our analytical approach to focus on selected elements of the nuclear complex and to develop "parametric" cost estimates for these facilities. We selected a set of facilities for which we believe the economic rationale is questionable and then estimated capital costs for each. These are, in general, the front-end nuclear fuel cycle facilities: uranium mines and associated mills at Gchine and Saghand, the uranium conversion plant and fuel manufacturing plant at Esfahan, the heavy water reactor and associated facilities at Arak, and the enrichment facilities at Natanz.

Finally, we formulated (in summary form) some alternative energy projects that were financially commensurate with the elements of the nuclear program for which we prepared cost estimates. The nature of these projects was motivated by some obvious problems in Iran's energy economy—the waste of large volumes of natural gas and a growing bill for imported gasoline. We evaluated projects to address both of these problems and calculated the financial returns to these under conservative conditions.

Beyond the projects for which we performed pro forma financial analysis, there are clearly several other potentially attractive projects suggested by Iran's energy circumstances, including retrofitting existing refineries to enhance gasoline yield and market pricing to incentivize conservation.

Energy Resource Endowments

The underlying basis for a self-sufficient nuclear program is access to sufficient reserves of economically available uranium ore, which can be mined, converted, and enriched to manufacture the fuel required in power reactors. We evaluated Iran's uranium resources relative to its declared nuclear program based on IAEA data. The IAEA, in cooperation with the Nuclear Energy Agency (NEA) of the Organization for Economic Cooperation and Development (OECD), publishes *Uranium: Resources, Production, and Demand*.[15] This report, commonly known as the Red Book, is widely recognized in the international nuclear community as a primary reference document on world uranium supply. Based on self-reported data, the Red Book contains estimates of uranium resources in several categories of supply assurance based on existence and economic attractiveness, production capability, nuclear capacity, and related reactor requirements.

According to the 2005 Red Book, Iran possessed 1,927 metric tons (MT) of identified uranium resources and 14,550 MT of undiscovered uranium resources.[16] All 16,477 MT of Iran's uranium was indicated to cost between $80/kilogram (kg) and $130/kg to recover. However, due to low ore grades (approximately 0.05 percent) and fractional recovery of the mines, it is likely that the cost will be closer to the $130/kg estimate.[17]

The Russian-designed VVER-1000 in Bushehr was used as the design-basis reactor for forecasts of uranium requirements for future reactors. Per year, one VVER-1000 requires 25 metric tons (MT) of uranium dioxide (UO2) fuel, which is approximately 22 MT of 4.4 percent low-enriched uranium (LEU).[18] This 22 MT of LEU represents approximately 223 MT of natural uranium. At an ore content of 553 grams (g)/MT, this requires about 450,000 MT of ore. Based on these figures, Table 1 shows the operating time possible for a number of operating reactors given Iran's estimated natural uranium resources.

Table 1 assumes that all reactors would become operational at the same time. More realistically, a construction schedule consistent with the completion of seven reactors by 2020 results in the forecast given in Figure 1. The total uranium resource represents less than 25 percent of the life-cycle requirement of seven reactors, each with a nominal 40-year operating life.

TABLE 1
Reactor Years of Operation Based on Iran's Uranium Reserves

Number of Operational Reactors	Identified Resources Years of Operation	Total Resources Years of Operation
1	8.76	74.90
2	4.38	37.45
3	2.92	24.97
4	2.19	18.72
5	1.75	14.98
6	1.46	12.48
7	1.25	10.70

While the uranium reserves are subject to considerable uncertainty, and it is possible that additional reserves might be discovered and developed, the logic of a self-sufficient nuclear power program would require that this be undertaken *before* the investment of billions in fuel-cycle facilities whose useful operation depends on a uranium resource stream.

Hydrocarbons

Iran's hydrocarbon resources represent not only a large share of its indigenous energy supply, but also a large percentage of the world's energy resources. With 125.8 billion barrels of proven oil reserves, Iran possesses roughly 10 percent of the world's supply of oil.[19] In addition, Iran has the world's second largest supply of natural gas, with 940 trillion ft^3 of proven reserves, equivalent to 15.5 percent of the world's total.[20] Figures 2 and 3 summarize Iran's reserves of fossil fuels versus uranium in terms of both energy content and the reserve/production ratio.

FIGURE 1
Iran's Planned Reactor Construction and Uranium Resource Constraints

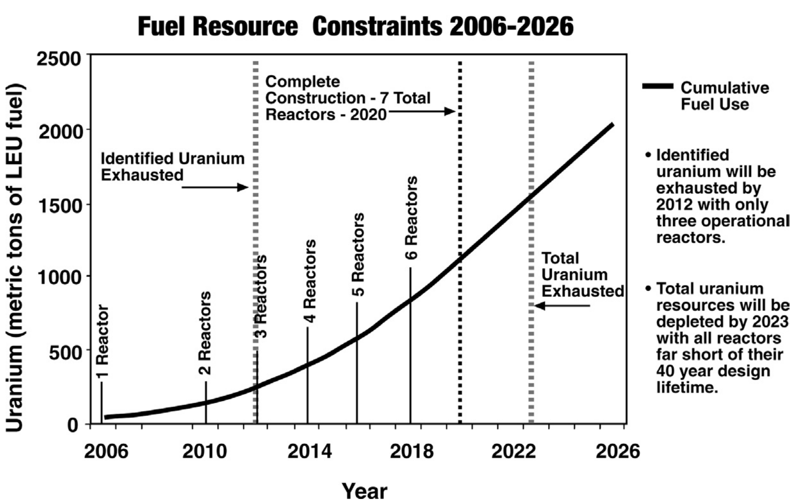
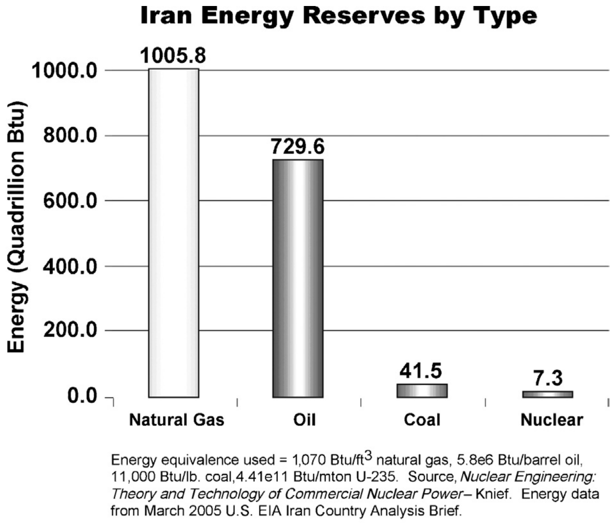


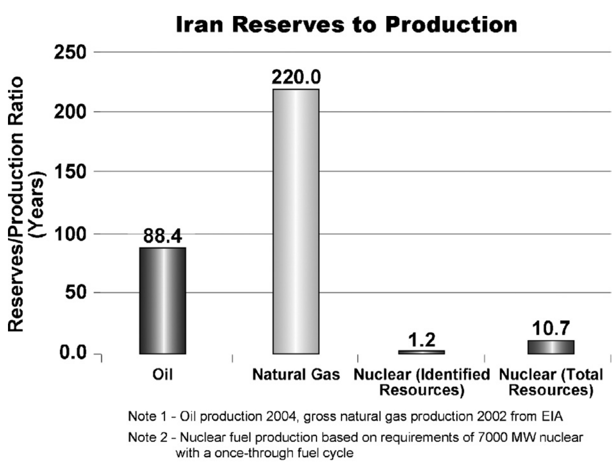
FIGURE 2
Iran's Energy Reserves (Quadrillion British thermal units, Btu)



Cost of Selected Nuclear Facilities

We do not present an estimate for the total expenditure on Iran's nuclear program over the last 30 years. Only the capital costs of key front-end nuclear facilities have been estimated. It is important to realize the inherent difficulty of determining the total cost of Iran's investment in a nuclear fuel cycle infrastructure due to years of clandestine construction and concealment efforts and the associated costs of a 30-year research and development (R&D) effort. Because the capital cost estimates of the Iranian facilities are

FIGURE 3
Iran's Energy Reserves (reserve/production ratio)



based on observations of comparable commercial facilities around the world for which financial data were available, and because we have not included the costs for either clandestine construction or R&D, our approach has realistically resulted in more conservative, minimized cost estimates for these facilities.

Uranium Mines

Iran has two primary uranium mines, each with an associated milling plant: Saghand and Gchine. The AEOI reports the Saghand mine is an underground mine with a 0.0553 percent uranium ore grade and a design capacity of 120,000 MT of ore, or approximately 50 metric tons of uranium (MTU) per year.[21] The Gchine mine is an open-pit mine that possesses a higher grade ore (approximately 0.2 percent uranium) and is reported to have a 21 MTU per year capacity.[22] Based on calculations from the OECD's *Economics of Uranium Ore Processing Operations*, the total capital investment in the mines is approximately $39 million for Saghand and $19 million for Gchine.[23] The total capacity of these mines (71 MTU/year) is not sufficient to make the fuel for one reactor for one year; a single VVER-1000 reactor requires the production of approximately 223 MT of natural uranium per year.[24]

Esfahan Uranium Conversion Facility

The design information Iran provided to the IAEA in July 2000 described the purpose of this facility as the conversion of uranium ore concentrate (UOC, yellowcake, or U3O8) into natural uranium hexafluoride (UF6) and subsequent conversion of low-enriched UF6 into UO2.[25] Sized to produce 200 tons of UF6 and 30 tons of UO2 per year, the conversion facility at Esfahan would support only one reactor per year. The cost estimate of the conversion facility is based on comparable Russian and Brazilian facilities. With five conversion lines, the uranium conversion facility at Esfahan is estimated to have a $30 million capital investment.

Natanz Enrichment Facility

Iran's Natanz facility is sized for approximately 54,000 centrifuges.[26] Our calculated price of construction varies for the types of centrifuge installed based on a separative work unit (SWU)/year basis.[27] Assuming a 3 SWU/year per centrifuge rate for a P1 design and a 5 SWU/year per centrifuge for a P2 design, the capital cost of the facility at Natanz could be between $180 million and $260 million.[28] Although a 54,000 P2 centrifuge plant could meet the nearly 270,000 SWU/year demand for two operating VVER-1000s, there would be little margin for error, meaning the centrifuge plant capacity factor would have to be near 100 percent. Because Iran's lack of operational experience will most likely prevent it from operating centrifuge cascades at such high capacity factors, whether Natanz can support the operation of two reactors in the near future is questionable.

Fuel Manufacturing Plant

The fuel manufacturing plant under construction at Esfahan (Isfahan) is scheduled for commissioning in 2007.[29] Designed for a preliminary annual throughput of 40 MT of UO2 fuel, enough for Bushehr (25 MT UO2 per year) and the 40 MW heavy water reactor (10 MT UO2 per year), the fuel manufacturing plant is designed to be scaled up to a total annual throughput of 140 MT of UO2.[30] Resende Unit 1, Brazil's 100 MTU/year fuel fabrication plant, was completed in 1985 with a total investment of approximately $17 million.[31] In 1998, a 400 MTU/year South Korean fuel fabrication plant was built for approximately $400 million.[32] An estimated investment of $30 million–$80 million is appropriate, depending on the total throughput of the plant.

Arak Nuclear Complex

The nuclear complex at Arak in west-central Iran is designed to include a 40 MW heavy water reactor (also known as the Iran Nuclear Research Reactor, or IR-40); a heavy water processing plant; and isotope separation facilities. Given the uncertainty and variations of reactor construction costs, and based on previous construction of test reactors in the United States, Canada, India, and Australia, the cost estimate of the IR-40 is approximately $70 million–$150 million.

The heavy water plant at Arak is designed to produce 16 MT of heavy water per year.[33] The initial heavy water requirement of the IR-40 is approximately 85,000 kg, which would cost approximately $25.5 million at an average separation price of $300/kg.[34] Based on the cost of heavy water plants listed in the IAEA's Nuclear Fuel Cycle Information System database, the Arak heavy water plant capital cost is estimated to be $10 million–$25 million. Arak's separation facilities are designed to consist of nine hot cells.[35] Assuming that a sealed, three-piece manipulator with three axes of motion costs between $60,000 and $100,000, hot cell facility construction (including the manipulators) could cost $25 million–$40 million.[36]

A conservative total approximate investment for the entire Arak Nuclear Complex is $200 million. Comparatively, a 1997 package project representing a 10 MW TRIGA reactor, isotope processing facility, and a low-level waste treatment and storage facility from General Atomics to Thailand was valued at $133 million.[37]

The total estimate for Iran's investment in the aforementioned nuclear fuel cycle facilities is conservatively $600 million. Including adjustments for error, this investment could be upward of $1 billion. These price estimates for capital investment have taken cost escalation into account and are given in 2004 dollars. Calculations for the cost estimates of the Saghand and Gchine uranium mines use the Marshall and Swift mining and milling cost index of 1232.7 for 2004.[38] Estimates for the construction costs for all other Iranian fuel cycle facilities of interest were escalated from their time of construction by the Chemical Engineering Plant Cost Index for 2004 of 444.2.[39]

This initial investment by Iran is not the total investment required for it to achieve its nuclear energy goals. The current infrastructure as designed is constrained particularly in the mining and milling sector such that it cannot support one reactor. If indeed Iran wants to maintain a totally independent nuclear fuel cycle for 7,000–20,000 MW of power, it will need to drastically increase the capacity of its current facilities, resulting in cost projections of nearly 7 to 20 times what it has already invested.

As a caveat to increased capital costs, it is difficult to project how and even if economies of scale will benefit increased Iranian investment. In the case of additional mining, it is assumed that Iran has already chosen the most economical sites for uranium mining, so additional mining in the country would more than likely result in diseconomies of scale. In addition, construction of clandestine facilities will continue to result in atypical expenditures (in comparison to commercial facilities) such as antiaircraft systems, dummy buildings, and hardened facilities.

Potential Alternative Energy Projects

Iran's energy posture suggests that investment in the fossil sector could be very productive. Better use of the natural gas resource, more efficient and higher-throughput refineries, and energy conservation measures generally all seem to be very attractive candidates as alternatives to a front-end nuclear fuel cycle for which uranium resources are constrained, and which will take many years to reach commercial productivity.

In assessing the question of intent for Iran's aggressive nuclear program, all collateral evidence relevant to a broad energy independence goal is material. This includes a broader sphere than electricity production per se, since Iran's energy economy is strongly based on petroleum production, conversion, and export. To the extent that investments and consumption behavior in this broader sphere confirm the primacy of energy independence objectives, they lend credence to Tehran's claim that it drives large expenditures in the nuclear sector. If, as it appears, this is not the case, then the claim for an energy independence rationale is weakened.

In this section, we examine the economic merits of some possible energy development projects that are roughly commensurate in financial scale with the investments in the nuclear program. These projects, and their potential returns on investment, provide a frame of economic reference within which the nuclear program should be considered. These projects are not formulated in detail, nor selected from a large set of candidates. We developed them by simple consideration of obvious and pressing needs in Iran's energy economy and briefly assessed them to permit conceptual cost and revenue estimates.

Optimization of an electric power program utilizing diverse generation resources is a complex programming problem under multiple sets of constraints. We did not seek to model the Iranian electrical generation mix in this fashion, since the principal degrees of freedom in this country's case can be simplified to the extent of nuclear and natural gas-fired generation. Hydroelectric is limited by site character and flow regimes, and oil-fired electrical generation is diminished by its value as an export commodity and transport fuel. Given this simplification, the problem becomes a simple unit-cost comparison between nuclear and gas-fired generation. To the extent that gas-fired generation utilizes free fuel (that is, otherwise flared gas), its unit cost is lower than base-load nuclear generation, even if it achieves very high capacity. Although a recent study shows the most likely nuclear and natural gas-fired generation costs for Iran are 3.65¢/kWh and 2.21¢/kWh, respectively, recent increases in market prices have impacted these estimates.[40] Over the last three years, the price of uranium has quadrupled and the price of natural gas has increased 42 percent, driving the electrical generation prices to approximately 5.28¢/kWh for nuclear and 2.83¢/kWh for natural gas.

Natural Gas Sector Projects

As noted in the section on energy resource endowments, Iran's natural gas resources are the second largest in the world. These resources have been exploited substantially to provide electric power, and Iran now provides more than 75 percent of its electricity production using natural gas.[41] While this pattern of natural gas use is atypical, the use of natural gas to fuel base-load electricity generation is an enviable circumstance for a country with plentiful gas supplies, since natural gas plants have low capital cost, are quickly built, offer high reliability, and present the most attractive carbon balance among fossil fuel options.[42]

In petroleum production, natural gas is often produced as a byproduct at the wellhead. It can be captured and exploited as an energy resource, re-injected into the well field to promote recovery of additional oil, or flared at the wellhead.[43] The quantity of natural gas flared at the wellhead is typically expressed as percentage of gross production, with the world average at approximately 8.1 percent. Figure 4 shows this percentage for several OPEC countries and reveals that Iran's percentage of natural gas flared at the wellhead ranks among the highest.

Given Iran's stature among the world's countries as the second largest holder of natural gas reserves (behind Russia) and the eighth largest producer of natural gas, it would appear reasonable to expect world-class technological sophistication in the development and utilization of this resource.[44] This would suggest that the world *average* for gas capture and utilization efficiency may in fact be a more conservative (less demanding) standard by which to judge the Iranian natural gas industry than is reasonably warranted. The fact that other Middle Eastern countries produce at much higher capture

FIGURE 4
Percentage of Natural Gas Production Flared at the Wellhead

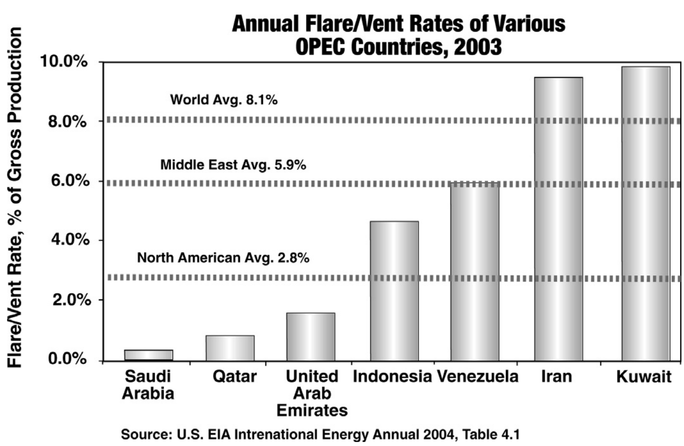
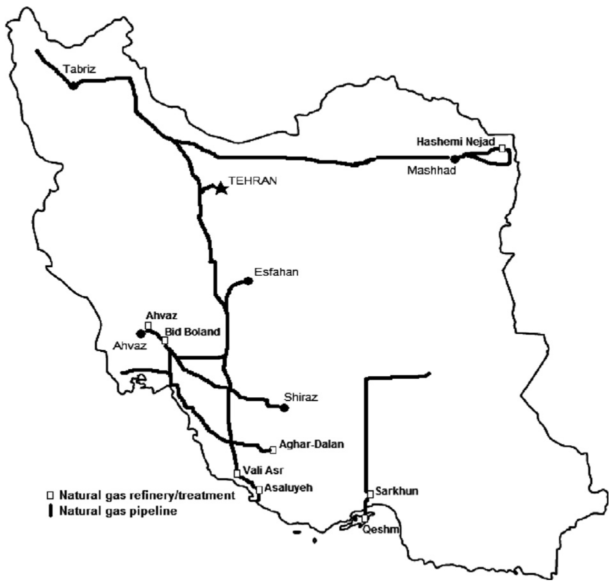


FIGURE 5

Major Elements of Iran's Natural Gas Infrastructure (adapted from University of Texas maps, Perry-Castaneda Library Map Collection)



efficiencies suggests that geological constraints are not a ready explanation for Iran's low capture efficiency.

Projects to utilize some of this flared gas in electrical energy production are clearly strong candidates for consideration, since the gas is available without the cost of additional exploration or well development. It is (at the wellhead) a free good that may be exploited. The investment necessary to do this would typically include some transportation, conditioning, possibly small storage facilities, and combined-cycle turbine electrical generation plants to burn the gas and produce electrical power.

In considering possible locations for such projects, the geography of petroleum fields, load centers, and natural gas infrastructure is relevant. Figure 5 displays major elements of Iran's natural gas infrastructure and some major load centers.[45]

One such project would capture 300 million ft^3/day (109.5 billion ft^3/year), process the gas near the wellheads, and pipe it to new generation facilities near load centers. We selected an option that would locate a 750 MWe generation facility in Esfahan and a 370 MWe facility in Ahvaz.[46] These are among the fastest growing electrical demand centers. A unit cost of \$500/kW was assumed for these plants. The total cost of this project was approximated at \$1 billion.

Without more detailed data, it is unclear if this gas could be transported in the existing gas pipeline infrastructure. We conservatively assumed that 200 miles of new pipeline would be required at a unit cost of \$1.7 million per mile.[47] An alternative, and slightly smaller, benchmark project was also formulated to correspond to the lower bound cost estimate for the selected nuclear facilities. This project would involve only a single 930

TABLE 2
Elements of Two Notional Gas-Sector Projects

	Principal Project Elements			
Project	**Conversion Capacity**	**Pipeline**	**Electrical Generation**	**Capital Investment**
1120 MWe Esfahan and Ahvaz	300 $Mmft^3$/day	200 miles	Esfahan – 750 MWe Ahvaz – 370 MWe	$1 billion
930 MWe Ahvaz	150 $Mmft^3$/day	50 miles	Ahvaz – 930 MWe	$617 million

MWe combined-cycle generation plant at Ahvaz, a 150 million ft^3/day (55 billion ft^3/year) processing plant, and 50 miles of pipeline. This smaller project is estimated to cost $617 million. Table 2 summarizes the main elements of both projects and their estimated costs.

The economic evaluation of these projects assumed use as base-load generation plants at a capacity factor of 85 percent. This performance is technically feasible for a modern combined-cycle plant and consistent with Iran's use of gas-fired plants to serve electrical base loads. We assumed a construction period of four years. This would be paced by the pipeline construction; combined-cycle power plants can be built in two to three years. The operating period for the power plant was assumed to be 30 years. The power generated was assumed to be sold at the standard (subsidized) average rate of 315 rials/kWh, equivalent to .036¢/kWh.[48] This is a conservative assumption, since the economic value of power should be greater than that reflected in a subsidized price. Also conservatively, the rate was not escalated over the life of plant.

These assumptions resulted in very favorable project economics for both of the benchmark gas sector projects. The larger project showed a payback period for the original investment of 4.6 years and an internal rate of return (IRR) of 18 percent.[49] The smaller project showed even better economics, with a payback period of only 3.2 years and an IRR of 23 percent. These returns are very high, even with the conservative assumptions on facility costs and electrical output prices.

These projects do not involve any new technology for Iran and would have extremely low technical risk when compared with a nuclear fuel cycle. Iran has built several combined-cycle plants in the past few years, including Rasht (1,290 MWe), Kerman (1,272 MWe), Montazer Qa'em (107 MWe), Fars (1,053 MWe), and Abadan (494 MWe).[50]

The costs of the projects we examined would allow for direct financing by the Iranian government out of oil export revenues, and the returns are high enough to attract foreign investment, should the government decide to solicit it. Iran has permitted foreign investment under a system of buyback contracts since 1987. In 2002, Iran approved a "law on the attraction and protection of foreign investments." This is the first clear step to encourage foreign investment since the revolution.[51]

Building both of the projects examined here would not bring Iran's gas sector into parity with the world in terms of efficiency in capturing and utilizing natural gas. Given the country's leading stature among the world's gas producers, such parity might be a reasonable target. If Iran captured and utilized all of its flared gas in excess of the Middle East's average flaring rate of 5.9 percent, this would amount to 160 billion ft^3/year. This quantity of gas would support electrical generation projects totaling 2,200 MWe, equivalent to two of the 1,000 MWe reactors that Tehran is projecting in its nuclear program. A more aggressive benchmark would be the North American average of less than 3 percent of production, resulting in the capture and utilization of 299 billion ft^3/year, which would support electrical generation capacity of approximately 4,100 MWe, equivalent to four Bushehr-type reactors. While we have not formulated specific projects of this scale, it is clear from the load growth and infrastructure factors that they would likely be very attractive and would replace much of the generation now slated for the nuclear program.

Beyond projects to exploit gas now flared at the wellhead by Iran, there are also many possible projects that would develop and exploit new gas fields. Projects could also be formulated to export natural gas directly rather than use it for electrical energy production. This could be accomplished via pipeline or liquefied natural gas (LNG) production and transport. Iran currently has plans to expand gas exports to Greece and Western Europe.[52] While we have not formulated specific projects for evaluation along these lines, there is every reason to believe they would offer very attractive returns, while building Iran's export earnings and hastening the ultimate objective of energy independence.

Refinery Sector Projects

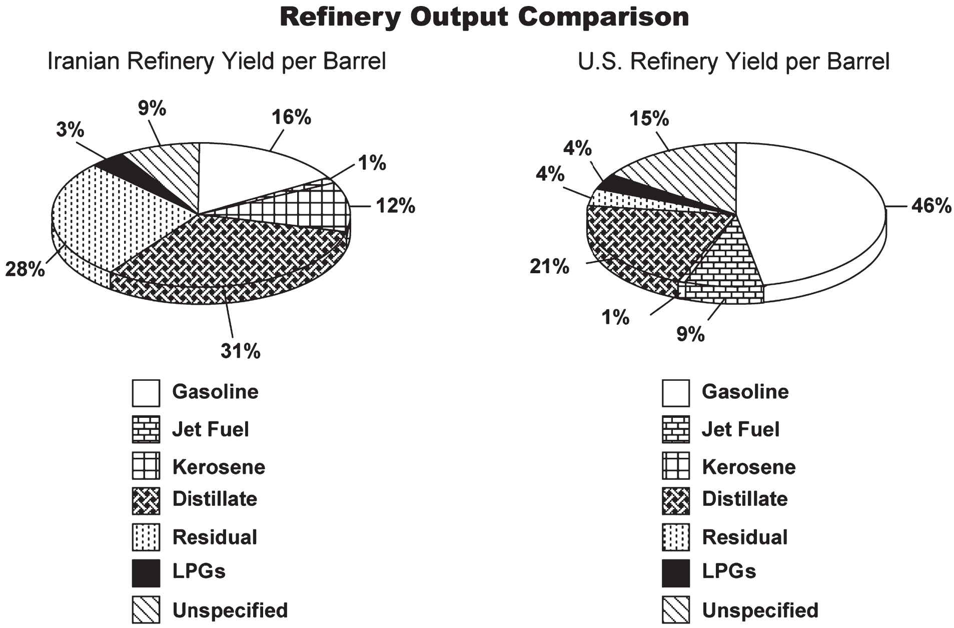
Despite being the second largest producer of crude oil in OPEC, Iran has recently begun to import substantial quantities of gasoline. In 2001, Iran was importing more than 53,000 barrels of gasoline per day.[53] By 2004, this had grown to nearly 140,000 barrels per day—40 percent of the country's consumption, costing up to $3 billion.[54] Forecasts predicted Tehran's gasoline import bill would hit $4.5 billion in 2005.[55]

Several factors have contributed to Iran's rapidly growing gasoline import bill. The country's transportation fleet is transitioning from predominantly diesel to more substantially gasoline-powered vehicles. Iranian refineries produce a much lower gasoline yield per barrel of oil than do U.S. refineries (see Figure 6). The Iranian government heavily subsidizes gasoline consumption, offering gasoline prices equivalent to 40 cents per gallon, even while importing gasoline at almost three times this cost.[56]

The growing problem with gasoline imports to Iran clearly points to additional refinery projects as important in any energy independence strategy. We evaluated the economics of two new refinery projects in order to explore potential returns.

Our evaluation of refinery economics requires accounting for the value of crude oil as a direct export product; its use as refinery feedstock represents a substantial opportunity cost in terms of export earnings.[57] This fact must be reflected in project evaluations, as must the volatility of oil and gasoline prices and the extent to which they are coupled or independent. It is generally acknowledged, however, that a strategy to export refined products will capture more value added in the petroleum economy.

FIGURE 6
Percentage Yields of Iranian and U.S. Refineries



Refinery Capacity

The scale of refinery construction or improvement projects requires eliminating Iran's gasoline imports and is much larger financially than the natural gas generation projects described above. The capacity required to eliminate gasoline imports is a function of the refinery yield assumed. As shown in Figure 7, refineries yielding the current average Iranian yield of gasoline per barrel of input would need to be substantially larger than those yielding a typical U.S. fraction of gasoline per barrel of oil for given gasoline yield.[58]

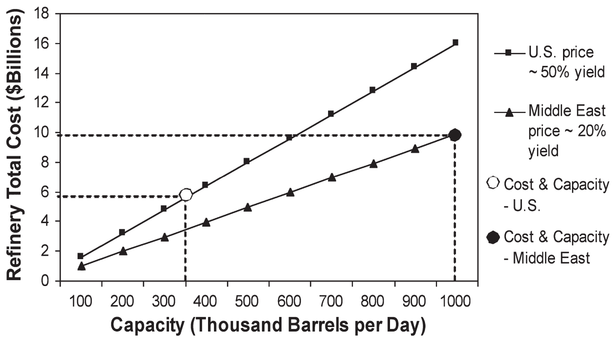
Because plant design features and costs are governed principally by the feedstock capacity, this means that adding refinery capacity to alleviate imports will cost substantially more under the Iranian yield model than under the U.S. model. This *does not mean* that such a project would be a less attractive investment, since it would benefit from increased economies of scale and would produce a substantially larger fraction of other refined products, which are also substantial generators of revenue.

We evaluated projects based on both the Iranian and U.S. refinery yield models. Based on the Iranian (low gasoline yield) model, a capacity of about 1 million barrels per day would be required. At the yield fractions typical of U.S. refineries, a much smaller refinery would be required for this gasoline yield—about 300,000 barrels per day.

We assumed a typical refinery construction cost of $10,000 per barrel per day capacity. Recent projects worldwide range from about $7,300/bbl/day (Basra, Iraq) to $16,000/bbl/day (United States). On this basis, the costs of two projects are estimated at $6 billion for the 300,000 bbl/day facility and $10 billion for the 1,000,000 bbl/day facility.

FIGURE 7

Refinery Costs as Function of Capacity for Iranian and U.S. Yield Plants



Oil and Refined Product Stochastic Revenue Model

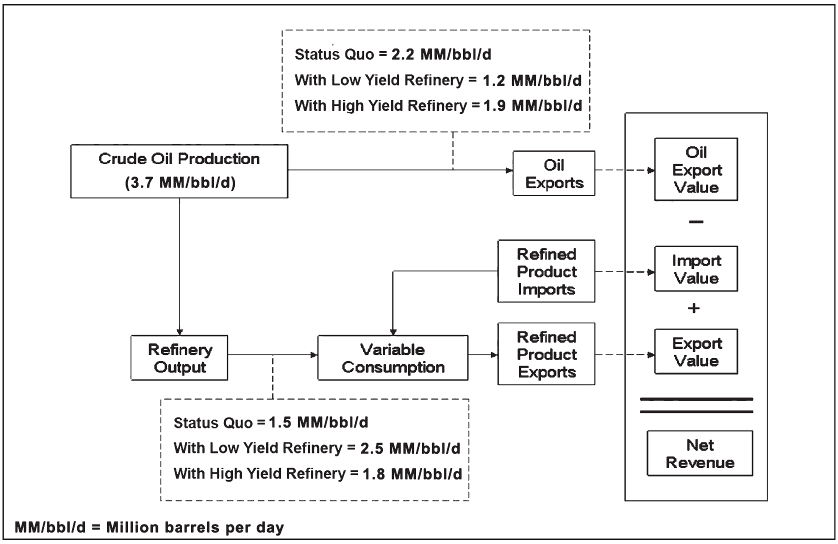
Estimating the economics for refinery projects required accounting for the net gains in revenues (less operating costs) for both the refinery outputs and the crude oil input. Because the gasoline and other refined products produced in these projects would be substituting for imports, we valued them at the import (world market) prices rather than the domestic prices. Because the opportunity cost of the crude oil used for input is (up to the production quota) export earnings foregone, we also value crude oil input at world market price.

These accounting conventions assure that the returns to these projects reflect their global market values rather than the (lower) subsidized prices in the Iranian economy. The economics of the refinery projects also depend on the future path of world oil prices and refined product prices. We incorporated three (exogenous) forecasts of world oil prices and a statistical model to calculate the relative prices of oil and refined products in our evaluation. A simple flow chart of this model is shown in Figure 8.

The model forecasts total revenue (Figure 9) between 2005 and 2035 for three refinery scenarios: (1) the current refining capacity of Iran (1,490,000 bbl/day), (2) an increase in oil refining capacity large enough to offset 2004 gasoline imports using Iranian refinery product yields (+1,000,000 bbl/day), and (3) an increase in oil refining capacity large enough to offset 2004 gasoline imports using U.S. refinery product yields (+300,000 bbl/day). Crude oil production is taken as exogenous at Iran's existing production level of 3.7 million bbl/day. The balance of crude oil exports and refined product exports is a function of the refinery scenario, and refineries are assumed to produce at capacity. Iran's *consumption* of refined products is forecast based on consumption trends over 10 years (1992–2002, with 2003 and 2004 estimated) of gasoline, jet fuel, kerosene, distillate oil, residual oil, and liquid petroleum gases (propane). If product consumption was trending negatively, it was held at the 2004 levels. Exports of refined products are modeled as production in excess of consumption at the forecast world price. (A more complete discussion of the model can be found in Appendix A.)

The *relative* price of oil and refined products is also a determinant of the returns to investments in refineries. Figure 10 illustrates the historical variability in this ratio using prices averaged on a daily basis. It is clear that this variability is around a reasonably stable

FIGURE 8
Diagram of Oil and Refined Product Stochastic Revenue Model



long-term average, and thus the expectation of relative prices tends to this value. There is risk associated with refinery investments, created by the chance that periods of high oil prices relative to refined products process could extend longer.[59]

Our economic model incorporated this risk by using statistical simulation. The resulting (total oil sector) net revenue forecasts for the Iranian yield case are shown in Figure 11. These forecasts reflect net revenues from all sources, including oil exports and net refined product sales (domestic production less domestic consumption). The model forecasts total revenue between 2005 and 2035 for three scenarios: (1) the current refining capacity of Iran, (2) an increase of oil refining capacity large enough to offset 2004 gasoline

FIGURE 9
Oil Price History and Forecasts

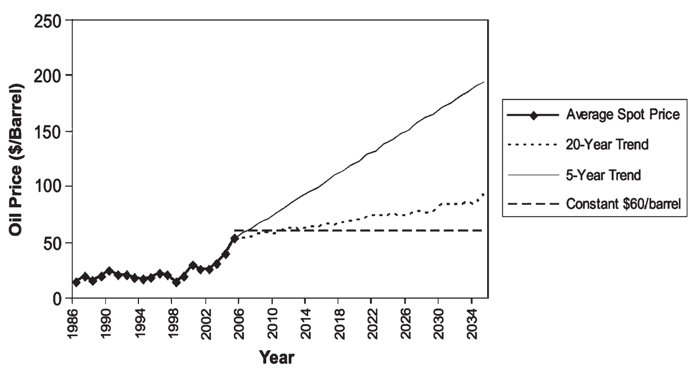
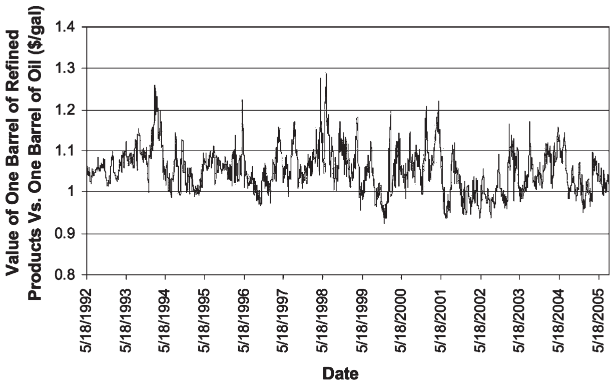


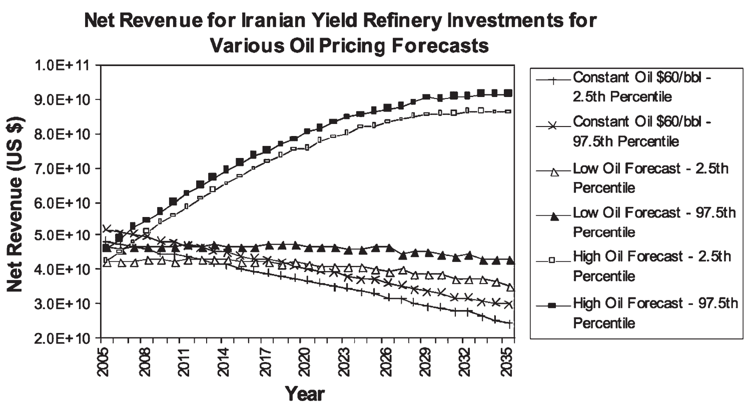
FIGURE 10
Historical Ratio of Refined Products to Crude Oil Prices



imports using Iranian refinery product yields, and (3) an increase of oil refining capacity large enough to offset 2004 gasoline imports using U.S. refinery product yields.

Utilizing this model, it appears that even with a modest increase in the price of oil, as shown in the low oil forecast case, Iran should maintain its export earnings even as its internal consumption of refined products increases. Each of the three production scenarios (status quo, new Iranian-technology refineries, and new U.S.-technology refineries) was calculated 1,000 times for each of the three price forecasts. The product yield of the refineries in these scenarios was considered static and not adapted to exploit current price variations in the model. Thus, refineries built on the Iranian-technology model were assumed to yield the product propositions shown in the left-hand panel in Figure 6, while those on the U.S.-technology model yielded products in the proportion shown in the right-hand panel of Figure 6. The forecast economic performance of these two refinery projects is comparable, with average IRRs of 12–13 percent. The higher gasoline-yield project has slightly better performance, but both projects give acceptable pro forma results.

FIGURE 11
Net Revenue Projects for Iranian Investment in Iranian-Type Refinery



Conclusions

One argument for nuclear power development in petroleum-exporting countries is that by incorporating nuclear power into the energy mix, petroleum that would otherwise be used domestically can then be exported, generating greater economic benefit. Russia has advanced this logic to support its recent aggressive plan for additional nuclear power development.[60]

While we did not incorporate this thinking in our economic modeling of the Iranian program, several comments are relevant. One, this argument is valid only to the extent that the export product and nuclear power are technologically substitutable, that is, the extent to which petroleum products are used for electrical energy generation. Because in Iran's case, crude oil is the principal petroleum export, this comes down to the extent to which oil is used for electrical energy generation. This represents only about 18 percent, or 5.6 GWe, of the installed electrical generation capacity in Iran. Thus, based on varying capacity factors for both oil and nuclear electrical generation plants, the first two to three 1,000 MWe reactors built would generate such a benefit (provided the corresponding oil-fired electrical capacity was in fact retired upon reactor start-up), but subsequent reactors would not, emphasizing that substitution of nuclear power for oil-fired power is not Iran's energy panacea. In Iran's case, the electrical energy generation mix suggests that the export maximization logic might apply more forcefully to the natural gas sector, *if in fact natural gas were exported to a significant degree*. In 2004, Iran exported only 15 percent of its natural gas.[61] It is clear from this that building exports of natural gas (through LNG terminals or pipeline construction) and developing nuclear power in Iran could be complementary. Export-earning arguments for nuclear power must also consider the imports required for a nuclear program. If, as we have shown, extensive nuclear development requires substantial nuclear fuel imports, much of the petroleum export benefit may be lost. Another point to consider is that if a country such as Iran has been found "incapable of maximizing profit, minimizing cost, or containing explosive demand in subsidized products" in an enterprise in which it has more than 50 years of operating experience utilizing technologies with low levels of sophistication, it is questionable how such a country could manage a highly technical nuclear-powered enterprise that requires a rigorous regulatory body, highly trained technical staff, and a pervasive culture of safety to operate successfully.[62] Additionally, we must question why a country would allow the production of its only major export and true source of world influence to precipitously decline into oblivion.[63] It is extremely doubtful that Iran would allow this to occur, and its apparent lack of urgency for resolving its domestic energy concerns is realistically either a temporary feint as it focuses national resources on a stronger bargaining chip, or a sign that there is indeed a serious platform from which diplomatic talks can secure successful agreements between it and the global community.

Does Iran really seek energy independence? On the basis of the economic evidence both within the nuclear program and in related energy industries, we conclude that Iran is not seriously pursuing energy independence, yet is attempting to justify a nuclear program motivated by a weapons objective under this rubric. This is not to argue that nuclear energy has no constructive role in a serious energy security program for Iran. An effective energy program would be built on Iran's very rich export petroleum resource, would invest in and incentivize efficient production and utilization of this resource, and would rely on a reliable world market for nuclear technology, uranium, and nuclear fuel services. The long-term goal for an Iranian nuclear sector in this vision could increase import substitution, as described, consistent with its indigenous resource base.

NOTES

1. International Atomic Energy Agency (IAEA), *Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, Report by the Director General, Nov. 10, 2003, GOV/2003/75, <www.iaea.org/Publications/Documents/Board/2003/gov2003-75.pdf>.
2. UN Security Council Resolution 1696, July 31, 2006.
3. Anthony Cordesman, *Iran's Developing Military Capabilities* (Washington, DC: Center for Strategic and International Studies, 2005); Peter Crail and Jean du Preez, ''IAEA Board Deplores Iran's Failure to Come into Full Compliance: Is Patience with Iran Running Out?'' Nuclear Threat Initiative (NTI), June 2004; Geoffrey Kemp, ed., *Iran's Bomb: American and Iranian Perspectives* (Washington, DC: Nixon Center, March 2004), <www.nixoncenter.org/publications/monographs/IransBomb.pdf>; Kamal Kharrazi, General Statement by Kamal Kharrazi, Minister of Foreign Affairs of the Islamic Republic of Iran to the 7th NPT Review Conference, May 3, 2005, <www.un.org/events/npt2005/statements/npt03iran.pdf>; George Perkovich, ''For Tehran, Nuclear Program is a Matter of National Pride,'' Carnegie Endowment for International Peace, March 21, 2005, <www.carnegieendowment.org/publications/index.cfm?fa=view&id=16694>; Sharon Squassoni, ''Iran's Nuclear Program: Recent Developments,'' Aug. 2, 2005, Congressional Research Service Report to Congress, <www.fas.org/sgp/crs/nuke/RS21592.pdf>; Steven C. Welsh, ''Iran's Nuclear Program and International Legal Instruments: IAEA Statute,'' Center for Defense Information, Nov. 24, 2004, <www.cdi.org/program/document.cfm?DocumentID=2685&StartRow=1&ListRows=10&appendURL=&Orderby=D.DateLastUpdated&ProgramID=82&from_page=index.cfm>; Ali-Asghar Kazemi, ''Iran: The Price of Going Nuclear,'' Middle East Academic Forum, Oct. 28, 2005, <http://aakazemi.blogspot.com/2005/10/iran-price-of-going-nuclear_28.html>; Ali-Asghar Kazemi, ''Strategic Implications of WMD Proliferation in the Middle East,'' Middle East Academic Forum, Jan. 14, 2006, <http://aakazemi.blogspot.com/2006/01/wmd-proliferation-in-middle-east.html>.
4. The start date of 1975 was selected because that is when Iran initiated the contract with Siemens to build the Bushehr reactor. On the number of facilities and sites, see: IAEA, *Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, GOV/2003/81, Nov. 26, 2003, <www.iaea.org/Publications/Documents/Board/2003/gov2003-81.pdf>.
5. *Nuclear News*, ''World List of Nuclear Power Plants,'' 7th Annual Reference Issue, March 2005, pp. 35–60, published by the American Nuclear Society.
6. This would result in a total of 20 Gigawatt-Electric (GWe) of electrical capacity by 2030. Energy Information Administration (EIA), Country Analysis Briefs: Iran—May 2005, Jan. 2006. Current briefs posted at <www.eia.doe.gov/emeu/cabs/Iran/pdf.pdf>.
7. Mohammad Ghannadi-Maragheh, ''Nuclear Fuel Cycle Activities in Iran,'' World Nuclear Association Annual Symposium 2005, <www.world-nuclear.org/sym/2005/ghannadi.htm>.
8. Imports would be the economic source of uranium—a worse case would be increasing uneconomic exploration and extraction of indigenous resources, and it is not clear this is physically possible.
9. All costs in this article are in 2004 dollars.
10. Kazemi, ''Strategic Implications.''
11. Industry literature on new reactor construction promotes competitiveness targets of $1,000/kW for overnight construction cost, although historical records, including those of the United States, indicate higher costs.
12. EIA, Country Analysis Briefs: Iran, May 2005 and Jan. 2006.
13. Ibid.
14. Analysis based on 2002 EIA data for Iranian total country energy balances and other price data from 2004.
15. Organization for Economic Cooperation and Development (OECD) Nuclear Energy Agency and the IAEA, *Uranium 2005: Resources, Production, and Demand* (Paris: OECD, 2006).

16. Ibid.
17. OECD, *Economics of Uranium Ore Processing Operations* (Paris: OECD, 1983).
18. Rosenergoatom, ''VVER-1000 Statistics,'' 2005.
19. EIA, Country Analysis Briefs: Iran, May 2005 and Jan. 2006.
20. Ibid.
21. Atomic Energy Organization of Iran, Saghand Mining Department website, 2005, <www.aeoi.org.ir/NewWeb/Recenter.asp?id =26 >.
22. IAEA, *Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, GOV/2004/90, Nov. 29, 2004, <http://www.iaea.org/Publications/Documents/Board/2004/gov2004-90.pdf>.
23. OECD, *Economics of Uranium Ore Processing Operations*.
24. Rosenergoatom, ''VVER-1000 Statistics.''
25. IAEA, *Report on the Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, GOV/2004/83, Nov. 15, 2004, <www.iaea.or.at/Publications/Documents/Board/2004/gov2004-83.pdf>; IAEA, ''Transcript of the Director General's Press Statement on Activities in Iran,'' Aug. 11, 2005, <www.iaea.org/NewsCenter/Transcripts/2005/transcr11082005.html>.
26. Mohammad Ghannadi-Maragheh, ''Nuclear Fuel Cycle Activities in Iran.''
27. IAEA, ''Transcript of the Director General's Press Statement on Activities in Iran,'' Aug. 11, 2005; IAEA, *Report on the Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, GOV/2004/11, Feb. 24, 2004, <www.iaea.or.at/Publications/Documents/Board/2004/gov2004-11.pdf>; IAEA, *Report on the Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, GOV/2004/34, June 1, 2004, <www.iaea.or.at/Publications/Documents/Board/2004/gov2004-34.pdf>; IAEA, *Report on the Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran*, GOV/2004/60, Sept. 1, 2004, <www.iaea.or.at/Publications/Documents/Board/2004/gov2004-60.pdf>; IAEA, ''Implementation of the NPT Safeguards Agreement in the Islamic Republic of Iran,'' GOV/2004/79, Sept. 18, 2004, <www.iaea.or.at/Publications/Documents/Board/2004/gov2004-79.pdf>.
28. David Albright and Corey Hinderstein, ''The Centrifuge Connection,'' *Bulletin of the Atomic Scientists*, 60 (March/April 2004), pp. 61–66; Alexander Montgomery, ''Ringing in Proliferation: How to Dismantle an Atomic Bomb Network,'' *International Security* 30 (Fall 2005), pp. 153–187.
29. IAEA, GOV/2004/90.
30. Mohammad Ghannadi-Maragheh, ''Iran Nuclear Fuel Cycle Experience,'' World Nuclear Association Annual Symposium 2003, <www.world-nuclear.org/sym/2003/ghannadi.htm>.
31. IAEA Integrated Nuclear Fuel Cycle Information Systems, iNFCIS database, </www-nfcis.iaea.org/NFCIS/NFCISMain.asp?Country=Brazil&Status=All&Scale=All&Type=CONV&Order=1&WhichFacility=784&RPage=1&Page=1&FacilityName=Fabrica%20de%20Combustivel%20Nuclear&RightP=Facility>.
32. Ibid.; NTI, ''Iran Profile: Nuclear Chronology,'' May 2006, <www.nti.org/e_research/profiles/Iran/1825_4968.html>.
33. IAEA, GOV/2003/81; NTI, ''Iran Profile: Nuclear Chronology''; IAEA, GOV/2003/75; OECD Nuclear Energy Agency and the IAEA, *Uranium 2005: Resources, Production, and Demand.*
34. IAEA, GOV/2003/75; GlobalSecurity.org, ''Weapons of Mass Destruction: Arak,'' Aug. 31, 2006, <www.globalsecurity.org/wmd/world/iran/arak.htm>.
35. IAEA, ''Transcript of the Director General's Press Statement on Activities in Iran,'' Aug. 11, 2005; IAEA, GOV/2004/11; IAEA, GOV/2004/34; IAEA, GOV/2004/60; Alistair Miller, ''Heavy Water: A Manufacturer's Guide for the Hydrogen Century,'' *Canadian Nuclear Society Bulletin* 22 (Feb. 2001), <www.cns-snc.ca/Bulletin/A_Miller_Heavy_Water.pdf>.
36. Central Research Laboratories, ''Mechanical Telemanipulators,'' 2005, <www.centres.com/nuclear/manip/mmanip.htm>.
37. General Atomics News, ''GA to Provide Nuclear Research Center in Thailand,'' June 26, 1997, <www.ga.com/news.php>.
38. ''Economic Indicators—Back Cover,'' *Chemical Engineering Journal* 13 (October 1, 2005).
39. Ibid.
40. Mojan Movassate, ''Iran's Energy Needs and Nuclear Power,'' Thesis Paper, Interschool Honors Program in International Security Studies Center for International Security and Cooperation Freeman-Spogli Institute for International Studies, Stanford University, March 2006.
41. EIA, Country Analysis Briefs: Iran, May 2005 and Jan. 2006.

42. Natural gas plants are typically used as peaking rather than base-load plants and typically have load factors of 20 percent–40 percent.
43. Failure to flare the gas results in accumulations that become explosive.
44. On natural gas reserves rank: EIA, *International Energy Outlook 2006*, Jan. 2006, <www.eia.doe.gov/oiaf/ieo/nat_gas.html>. On gas production rank: Geographic.org, <www.photius.com/rankings/economy/natural_gas_production_2006_0.html>.
45. University of Texas, 2004, Perry-Castaneda Library Map Collection, <www.lib.utexas.edu/maps/iran.html>.
46. Processing is needed to remove sulfur compounds prior to use in a power plant.
47. Massachusetts Institute of Technology, "The Future of Nuclear Power: An Interdisciplinary MIT Study," 2003, Table A-5.A.4, "Base Case Parameters," p. 135, <http://web.mit.edu/nuclearpower/>.
48. PetroleumIran.com, "Iran Overview," Feb. 2005, <www.petroleumiran.com/iran%20overview.html>.
49. The internal rate of return (IRR) is the discount rate at which the project cash-flow stream has zero value. This is the interest rate that would accrue to a 100 percent equity investor in the project, or the maximum rate at which a project owner could afford to incur debt to finance the project.
50. EIA, Country Analysis Briefs: Iran, May 2005; EIA, Country Analysis Briefs: Iran, Jan. 2006.
51. Ibid.
52. EIA, Country Analysis Briefs: Iran, May 2005 and Jan. 2006.
53. WorldEnergy.org, "Case Studies, The Case of Iran: Planning for the Future," March 2005, <www.worldenergy.org/wec-geis/publications/reports/pedc/cases/2_3_3.asp>.
54. EIA, Country Analysis Briefs: Iran, May 2005 and Jan. 2006.
55. EIA, May 2005, "Iran Country Energy Data Report 2001," <www.eia.doe.gov/emeu/world/country/cntry_IR.html>.
56. Data on price at which Iran sells subsidized gas is for spring 2005. On rate at which it imports gasoline: EIA, "Iran Country Energy Data Report 2001."
57. This is true even if a refinery is planned to utilize oil from sources beyond those produced for export, since the OPEC quota for Iran (as for all members) is a *production* quota rather than an *export* quota.
58. It is not clear to us why the Iranian gasoline yields are lower than those in the United States. Part of this difference may be intentional, as Iranian refineries have been optimized to produce a product mix favoring diesel fuel and distillate oil. The relatively heavy nature of Iranian crude is probably also a factor. The technology of the refineries may also be substantially less advanced; for example, Iran may have a lack of catalytic cracking stages.
59. The recent period of rapid escalation in oil prices is an example of short-run variability in this ratio. It was several weeks to a few months before the prices of refined products "caught up" those of crude oil.
60. International Energy Agency, "World Energy Outlook 2005: Middle East and North Africa Insights," 2005, <www.iea.org/Textbase/publications/free_new_Desc.asp?PUBS_ID=1540>; Rosenergoatom, "Strategy of Nuclear Power Development in Russia in the First Half of the 21st Century," 2000.
61. Baker Institute, "The Energy Dimension in Russian Global Strategy," James A. Baker III Institute for Public Policy, Rice University, 2005, <www.rice.edu/energy/publications/docs/PEC_summary_10_2004.pdf>.
62. Roger Stern, "The Iranian Petroleum Crisis and United States Security," *Proceedings of the National Academy of Sciences* 104 (Jan. 2, 2007), <www.pnas.org/cgi/content/abstract/104/1/377>.
63. Ibid. Stern predicts that Iranian oil exports will decline to zero by 2014–2015.

Appendix A: Stochastic Revenue Model Description

Oil export revenues are based on world oil prices, which were forecast by observing trends in the average of daily free on board (FOB) spot prices for Brent and Cushing from 1986 to 2006. Although it is unlikely that the recent rate of oil price increases can be sustained over the long term, further increases in real prices are almost certain to occur in the long run. Our three forecasts for oil prices (see Figure 9) are: 1) a constant oil price of $60 per barrel with no trend component, 2) a moderate rate of annual average increase (roughly 1.8 percent) based on the last 20 years of daily spot prices, and 3) a more substantial annual rate (4.2 percent) based on the last 5 years of daily spot prices as the upper bound.

Each of these scenarios was represented in the form of a linear trend equation (1).

$$P_{Oil} = \alpha + \beta(t) + e \tag{1}$$

Where the error term, e, is sampled from a distribution with a mean of zero and the standard error of regression residuals from the relevant time series (2).

$$S_e = \sqrt{\left[\left(\sum e_i^2\right) \Big/ (n-2)\right]} \tag{2}$$

This approach thus includes an assumption that global oil markets continue to function with about the same degree of random price behavior as observed in the historical record.

The *relative* price of oil and refined products is also a determinant of the returns to investments in refineries and is used to calculate refined product export values in our model. The historical variability (see Figure 10) is shown in this ratio using averaged daily FOB prices across several markets (New York, U.S.-Gulf Coast, Los Angeles, London, Rotterdam, and Singapore) from May 1992 to May 2005.

It is clear that this variability is around a reasonably stable long-term average, and thus the expectation of relative prices tends to this value. There is risk associated with refinery investments created by the chance that periods of high oil prices relative to refined products process could extend to longer durations. (The recent period of rapid escalation in oil prices is an example of short-run variability in this ratio. It was several weeks to a few months before the prices of refined products "caught up" to those of crude oil.)

Our economic model incorporated this risk by using statistical simulation. Using the historical averaged daily FOB prices for oil and refined products, the price of each refined product was expressed as a multiple of the oil price and a standard error calculated for these distributions. No temporal auto-correlation was incorporated in the model, meaning that each refined product price (P_{RPF}) forecast was chosen independently from the previous price. Thus each refined product price can be shown as in equation (3).

$$P_{RPF} = (\alpha + \beta(t) + e) \cdot \ \rho \tag{3}$$

Where ρ is equal to a ratio of refined product prices to oil prices.

As reflected in Figure 8, our model defines net revenue, REV_{Net}, as equal to the total export revenue, E_{Rev}, minus the cost of refined product imports, I_{Cost}.

$$REV_{Net} = E_{Revenue} - I_{Cost} \tag{4}$$

Equation (4) can be further broken down into:

$$REV_{Net} = (Q_{TOP} - \alpha_R) \cdot \ P_{OilF} + (\alpha R - Q_{Con}) \cdot \ P_{RPF} \tag{5}$$

Where Q_{TOP} is the total oil production of Iran, α_R is the country's total refinery capacity, and Q_{Con} is the quantity of refined products consumed.