The Enigma of Resource-Rich Iran's Pursuit of Nuclear Energy

Prepared for the NPEC Title V Project

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I - Introduction

When Iran agreed to the Joint Comprehensive Plan of Action (JCPOA) in July 2015, it cleared a path for the Islamic Republic to achieve an ambition that predates that government's existence, at least for the non-military applications of nuclear energy. The terms of Iran's agreement with China, France, Germany, Russia, the United Kingdom, United States and European Union permit it to build civilian nuclear power plants while continuing to develop uranium enrichment under UN supervision.

However, the JCPOA left unaddressed the larger question of the appropriateness of nuclear power in a country with the world's second-largest reserves of natural gas, along with abundant, untapped renewable energy resources, all of which appear to be more economical in the Iranian context than the envisioned fleet of nuclear power plants.

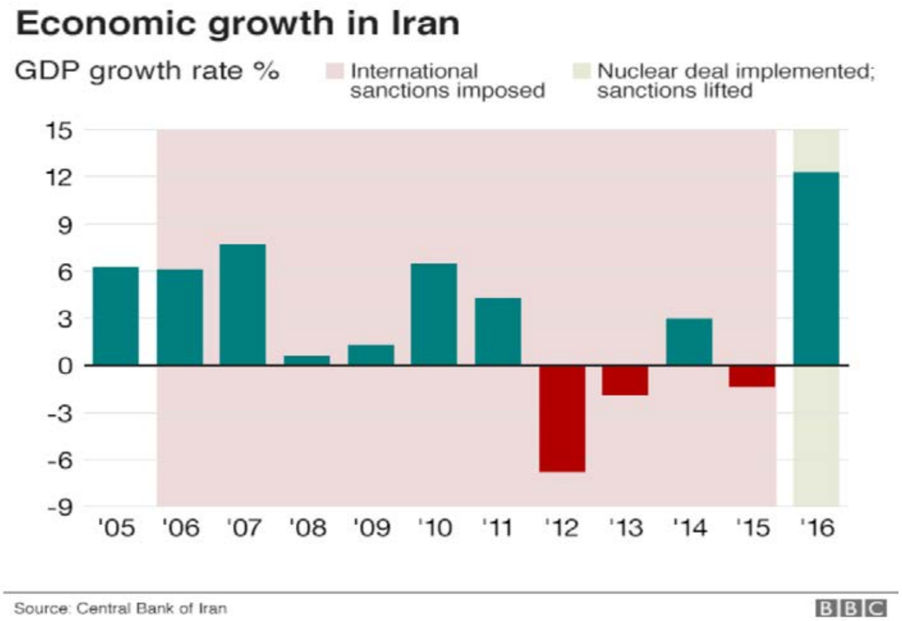
Iran has already paid a high price for its lengthy pursuit of nuclear energy. That price has included both direct costs in the form of foregone oil exports under international sanctions, along with substantial indirect costs resulting from reduced or restricted access to foreign direct investment, lending, and the settlement of dollar-denominated transactions.

The Iranian nuclear program attracted international scrutiny from its inception, particularly in light of Iran's decision to pursue not just the deployment of nuclear power plants, but of the nuclear fuel cycle starting with enrichment. Over many years, intelligence gathered by the US and other nations raised concerns that Iran's nuclear ambitions extended beyond civilian applications to include the development of a nuclear weapons capability. These suspicions were bolstered by periodic discoveries of undeclared nuclear facilities such as the Arak heavy water reactor and Natanz uranium enrichment plant in 2002 and the underground enrichment facility at Fordow in 2009.

The prospect of Iran becoming a nuclear weapons state alarmed the international community and prompted successive rounds of increasingly strict United Nations sanctions, beginning in 2006. At their most restrictive point, the sanctions targeted Iran's oil industry and oil exports, the country's principle source of foreign exchange and the engine of its economy. Other sectors and designated groups were also affected, including entities closely linked with the economic interests of Iran's leadership.

From late 2011 the combination of US and UN sanctions had a severe effect on Iran. As seen in Figure 1 below, the Iranian economy contracted in three of the four years the strictest sanctions were in place. During this period the country significantly underperformed the broader Middle East and North Africa region, which otherwise enjoyed steady, moderate growth.

Figure 1:



Considering only the impact on Iran's global sales of crude oil, its oil exports were cut by around 1.3 million barrels per day. An accurate estimate of total foregone oil profits on these volumes is impractical, since some of this oil was produced and stored for later sale, while other production was shut in, some of which may have been lost permanently. However, as reported by OPEC, the cumulative reduction in Iran's oil revenues in 2012-15, compared to 2011, came to $215 billion. Even after excluding the portion of that attributable to lower international oil prices in 2014 and 2015, the cost to Iran's economy still exceeded $175 billion, equivalent to around 5 months of current GDP.

Nor were sanctions the only pressure exerted on Iran in conjunction with its nuclear program. From the mid-2000s until 2013's "Joint Plan of Action", nuclear negotiations with Iran ebbed and flowed without a clear prospect of reaching resolution. The determination of the Iranian government not to give up or sharply constrain the activities in question fueled speculated that

Iran's nuclear ambitions could only be curbed through military strikes, whether by the US, an international coalition, or regional powers. This prospect appeared sufficiently likely to influence global oil markets by means of an "Iran risk premium" that helped to push oil prices above $100 per barrel on their way to an all-time high of $148 in 2008.

Iran's agreement in 2015 finally to limit its efforts, particularly with regard to enrichment, has been rewarded with the lifting of the nuclear-specific sanctions on the oil and gas industry along with many of those affecting other sectors. Some sanctions related to other aspects of Iran's policies and regional actions remain in place, but commercial ties, particularly with European countries and companies, have rebounded. Foreign Direct Investment increased to $12 billion in 2016, or roughly five times the average of 2003-2010. More than two-thirds of that investment was in oil and gas exploration, production and processing.

Meanwhile, Iran's single existing light-water reactor is in operation at Bushehr, with technical assistance from Russia. The facility is essentially a Russian modification of the previously uncompleted, pre-Iranian Revolution design and construction by Siemens of Germany, completed in 2011 by Russian contractors. Under the terms of Iran's nuclear power agreement with Russia, the latter is responsible for fueling this reactor and will receive all spent fuel from its operation. The second of as many as eight additional Russian reactors is reportedly under construction at the same site.

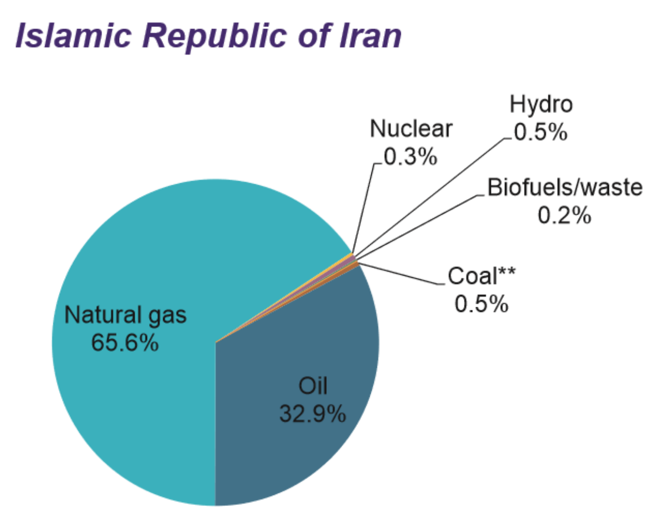
Iran's history of extraordinary costs incurred in pursuit of nuclear energy, along with its ongoing dependence on foreign nuclear expertise and fuel supplies, raises serious questions about the suitability of nuclear energy for the county. The county's economy has been built around its prodigious endowment of hydrocarbon resources, which meets the bulk of Iran's domestic energy needs and provides most of its income from international trade. At this point, nuclear power and even renewable energy still represent merely asterisks in its energy balances. Does Iran really need nuclear power plants to fuel its economic growth, or does it have better, more economical and less controversial options? That is the fundamental question this paper seeks to answer.

II - Energy demand

As indicated in the chart below (Figure 2) the energy mix of the Islamic Republic of Iran is dominated by two related fossil fuels: petroleum and natural gas. Together these meet 98% of the country's energy demand, supplemented by modest contributions from coal, hydropower and other renewables, and the output of country's only commercial nuclear power plant.

Figure 2:

Share of total primary energy supply* in 2015



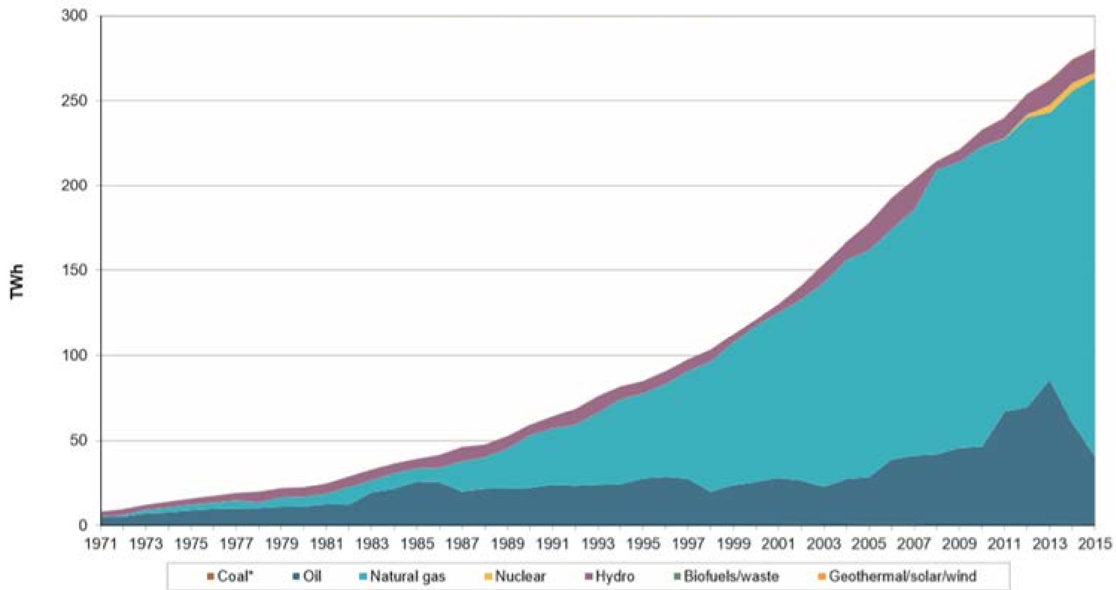
Source: International Energy Agency

As discussed in greater depth below, Iran has large reserves of both oil and natural gas. However, more than half of Iran's crude oil production is exported, while nearly all gas production is consumed internally. Gas is the mainstay of the domestic economy, with a 66% share of energy demand in 2015. It is used directly in the commercial and industrial, residential and transportation sectors. Iran is unusual among oil exporters in having nearly a quarter of its automobiles running on compressed natural gas (CNG). Gas also fueled the bulk of Iran's electricity supply in 2015.

In considering the current and potential future role of nuclear power in Iran's energy market, it is essential to examine where and how it competes with other energy sources. The main output of commercial nuclear power is electricity. In this respect nuclear power does not compete with the consumption of fossil fuels by motor vehicles or for process heat in industry. Space heating, transportation and other applications are amenable to electrification, but not to direct fuel substitution by nuclear energy.

Iran consumed 221,000 Gigawatt-hours (GWh) of electricity in 2015. As shown in Figure 3 below, facilities burning natural gas supplied 79% of that electricity. Another 14% was generated from oil—mainly seasonal use of petroleum products such as high-sulfur fuel oil—with all other sources contributing just over 6%. Within that, nuclear power stood at 1% of supply. Iran's record for seasonal peak electricity demand is approaching 56,000 Megawatts (MW), or 56 Gigawatts (GW) in summer.

Figure 3: Iran Electricity Generation by Fuel



Source: International Energy Agency

The chart above also indicates the remarkably rapid growth rate of electricity generation, and thus demand, in Iran prior to the imposition of the most restrictive UN oil sanctions. From 1995-2012 demand grew by a compound average rate of over 6.5% per year, while from 2012-15 growth slowed below 2% per year, based on data reported to the International Energy Agency (IEA). The growth of natural gas consumption other than for electricity generation during these periods, at 8% and 3.8% per year, respectively, is similar enough to the pace of electricity demand growth to suggest that Iran's economy was not electrifying more rapidly than the overall growth of domestic energy consumption in the economy in the last two decades. If anything, electrification may have slowed relative to total energy demand while the tightest sanctions were in place and the economy contracted.

(It is also evident that during the period of strongest sanctions, a pronounced shift toward oil-burning power plants occurred, and away from gas. This might be explained by depressed internal oil prices, relative to gas, if fuels were priced at market rates in Iran. However, Iran's fuels markets have been heavily distorted by subsidies of various kinds for many years. It seems equally plausible to conclude that a shift in the domestic energy mix was required to provide an outlet for oil—or its byproducts—that had to be produced due to reservoir integrity concerns or other factors, but could not practically be stored until sanctions would end at some future date.

The implementation of the JCPOA and the end of most nuclear-related sanctions, along with subsequent improvements in GDP growth, do not necessarily signify a return to the previous long-term trajectory of electricity growth. Post-JCPOA analysis of Iran's future energy supply and demand by the Stanford-Iran Project arrived at an implied rate of forecasted electricity demand growth of 2-2.5% through 2040. This was the based on a sector-by-sector buildup of demand, including much more rapid growth in the energy-intensive industrial sector. That is broadly consistent with an earlier forecast by BMI Research, which saw Iran expanding its power generation by 2.7% per year from 2016-23.

The Iran Project's report also found significant scope for efficiency improvements in Iran's existing gas-fired power plant fleet, through a combination of upgrading simple-cycle gas turbine plants to combined-cycle operation, and through replacement of gas-fired steam power plants by new combined-cycle plants. These upgrades would result in higher net generation of electricity, as well as significant fuel savings. When added to the expected increases in Iran's natural gas production over this period, the study found ample supplies of gas to sustain or even increase the high share of gas in power generation in Iran, depending on the level of future natural gas exports.

Recent reports indicate that Iran is continuing its legislated program of privatizing state-owned power generation assets. The Thermal Power Plants Holding Company will apparently sell another 11,570 MW of generation to private companies, in keeping with plans to reach private ownership of 80% of the power sector, by capacity.

III - Resource endowment and availability

Continued expansion of Iran's gas-fired power generation capacity from its already substantial installed base requires long-term access to reliable sources of natural gas on a commensurate scale. Unlike countries that must rely on imported gas from distant producers, transported either by pipeline or as liquefied natural gas (LNG) via ocean-going tankers, for Iran this consideration is reduced to a simple question of the size and accuracy of its domestic natural gas reserves.

Iran is a substantial net exporter of energy but most of that is in the form of crude oil and petroleum products. Although its state-owned energy industry aspires to become a significant exporter of LNG in the future, current gas exports are modest, consisting of pipeline deliveries to neighboring Turkey, Armenia and Azerbaijan. The latter volumes are largely offset by imported gas from Turkmenistan.

Despite low levels of gas trade, since 2013 Iran's reported "proved reserves" of natural gas have ranked as the largest in the world, following a substantial downward revision in Russian gas reserves. The new figures put Iran ahead of Russia and the US, even though both these countries produce a multiple of Iran's annual gas output.

As defined, proved gas reserves include only identified resources that are economic to produce at current prices, using current practices and technology. Changes in price or improvements in technology can result in large shifts in proved reserves, such as the 45% increase in US natural gas reserves from 2006 to 2106, resulting from improved capabilities to extract shale gas and other "tight" gas resources economically on a large scale. (*BP 2017 Statistical Energy Report*)

One measure of the sufficiency of a country's natural gas reserves is implied reserve life. This metric does not consider future field production rates or logistics, but simply divides reserves by annual production (R/P). Iran's gas reserve life stands at 166 years at current production. By comparison, Russia's reserve life equates to 56 years at current production, while that of the US, now the world's largest producer, is just under 12 years. (*BP 2017*)

That comparison suggests that, barring any obstacles to obtaining the necessary investment or access to technology, the scale of Iran's gas reserves should provide significant headroom to expand output without running into resource constraints. A 2015 forecast released by the National Iranian Gas Company indicated that with all economic constraints removed, and with large investments in new gas fields, Iran could increase its gas production to 450 billion cubic meters (BCM) per year by 2022, more than double reported 2016 production of 202 BCM. (*BP 2017*)

Iran's long-term gas potential ultimately hinges on the reliability of its published reserves. A 2005 study by the Society of Petroleum Engineers (SPE) found good agreement in the treatment of the three categories of resources traditionally included in "proved reserves"--"proved developed", "proved non-producing", and "proved undeveloped"—among the agencies responsible for reserves accounting standards in the US, Canada, UK, Norway, Russia and China. All three categories represent gas that is both economically and technically recoverable with additional investment. As long as Iran adheres to similar standards in its self-reported reserves, then those figures should be comparable to--and as reliable as--those of other major producers.

The largest area of potential uncertainty in this regard is in the category of "proved undeveloped" (PUD) reserves. In Iran's case, those account for at least 85% of stated gas reserves. In other words, most of Iran's future natural gas appears to reside in fields for which a discovery well has presumably been drilled, but that may not have been delineated through additional drilling, nor have they produced a cubic meter of commercial gas. That is not necessarily a serious cause for doubt, but it is indicative of the relative immaturity of Iran's gas sector, when compared to its oil industry, which has been producing since 1908 and is now rather mature.

If anything, Iran's reliance on PUD gas reserves suggests there may be further upside in its estimates, since reserves customarily grow as fields are developed through further drilling. Historical data on US natural gas provide a good example of how reserves and eventual production can multiply over time through development. Based on data from the US Energy Information Administration (EIA) cumulative US dry natural gas production (excluding gas liquids and reinjection) totaled 1,200 trillion cubic feet (TCF)—nearly 35 trillion cubic meters, or roughly Iran's current gas reserves—even though US proved natural gas reserves have never exceeded 368 TCF and were for many years estimated to be below 200 TCF. Improved technology and higher prices were also important factors in that reserve expansion, and both could play a role in the future growth of Iran's reserves.

Another indication that Iran has substantial gas reserves available to develop is that 47% of current reserves are attributable to the enormous offshore South Pars Field, which extends across Iran's maritime border with Qatar, where it is called the North Field. Together South Pars and the North Field form the world's largest non-associated natural gas field, i.e. gas not produced in conjunction with producing crude oil.

Qatar's production from this structure currently exceeds Iran's. In 2017 Qatar ended a self-imposed moratorium on further development of the field and is in the early stages of a significant expansion of output. For its part, Iran signed an agreement with French energy company Total, which will take a majority stake in the next stage of its South Pars development for an investment starting at $1 billion.

That announcement, the first such deal following the signing of the JCPOA, meets an important need. At this point the most important constraints on realizing future production growth from Iran's gas reserves are financial. Production technology, geology and geography all appear to be in hand.

Even without much foreign investment, Iran has managed to expand its gas production at a 6% compound average growth rate since 2006 (EIA data through 2014), in line with the rise of domestic demand for the product. That result has of necessity been achieved with local talent and technology, due to the direct and indirect impact of sanctions.

It is also worth noting that Iran's oil and gas production are still essentially all from conventional reservoirs. Shale gas and oil resources have been discovered in several parts of the country, but particularly for gas its development is likely to remain uneconomic for many years. The focus of the US oil and gas industry on shale gas in the previous decade, and on shale or "tight oil" in the current decade, was largely a function of the maturity and decline of most conventional US oil and gas fields. Iran still has a full menu of conventional gas discoveries to exploit at lower cost.

Finally, in addition to large hydrocarbon reserves, Iran's territory includes significant renewable energy resources. Their current contribution and future potential will be explored in the section below.

IV - Iran's Alternative Energy Options

At one time "alternative energy" encompassed a wide array of possible energy sources, including some that were far from commercial availability or competitive cost. And since "alternative" mainly conveyed choices to alleviate what was then regarded as an excessive reliance on expensive and presumably scarce oil and gas, even coal qualified in certain forms. Today, with coal under intense environmental pressure and nuclear power in either economic or regulatory retreat in much of the developed world, alternative energy and renewable energy have become more or less synonymous as the former term falls into disuse.

Hydropower still accounts for by far the largest renewable contribution to Iran's electricity generation. Dams and other hydroelectric installations made up roughly 17% of Iran's electric utility generating capacity in 2015. However, due to factors including persistent drought, hydro supplied only 5% of Iran's electricity that year.

These facilities exist at various scales, but more than 90% are larger than 10 MW. Their output has been highly variable over multi-year periods, but the trend has been generally downward, with hydropower in 2015 generating a quarter less annually than in 2007. For this reason, further meaningful expansion of hydropower in Iran appears unlikely.

By contrast, so-called non-hydro renewables, mainly wind and solar power, accounted for much less than 1% of both electrical capacity and generation in Iran as of the latest available statistics (2015), despite both potential and plans for substantial growth.

Iran's Sixth Five-Year Plan targets the addition of 5,000 MW of renewable energy by 2021 out of a total of 25 GW of generation of all types to be added. This appears to be based on previously announced targets from 2014, anticipating 5,000 MW of renewables by 2018. This appears to be focused mainly on wind and solar power with, with 500 MW of the latter as an initial target.

It is unclear whether any of these targets can be met within the planned timeframe. However, even if they were, this would very likely fall short of the goal of getting 10% of Iran's electricity from all renewable sources, including hydro, by 2021. If total generation grows from 2015 levels at the 2.7% per year rate cited above, the expected yield from another 5,000 MW of wind and solar installations might push renewables to 8% of all power generated, assuming no further deterioration of hydro output since 2015.

At least $3 billion of foreign investment has reportedly already been committed to renewable energy projects in Iran, equivalent to only around 1,500 MW of combined new wind and solar capacity. However, both that figure and the five times larger target set for 2030 represent just a small fraction of Iran's renewable energy potential, which has been estimated at 100,000 MW (100 GW) for wind alone, roughly equivalent to China's 2014 wind power capacity. In this respect the development of Iran's renewable energy resources other than flowing rivers is even less mature than its exploitation of its enormous natural gas reserves.

Iran's location and climate render it especially suitable for generating electricity from sunlight. Iran's renewable energy agency, SUNA, reports average annual solar intensity ranging from 4.5-5.5 peak-sun-hours per day (equivalent to 4.5-5.5 kWh/m2/d). This is an indication of excellent solar resources, with the high end of that range approaching some of the most attractive locations for solar power in the US southwest.

The higher the peak-sun-hours at a given location, the more electricity can be generated annually from the same quantity of solar photovoltaic (PV) panels or from a concentrating solar power (CSP) facility. Thus a solar installation in southern Iran might generate, on average, over 70% more electricity yearly than one in southern Germany, with much less monthly variability.

The latter point is especially important for integrating grid-connected renewables without stressing the existing power grid. Wind and solar energy are intermittent power sources, varying across daily, seasonal and annual scales. The lower the variation in peak sunlight, the more solar generation a power grid can integrate without requiring significant quantities of storage or other fast-reacting sources.

Intermittent renewables such as wind and solar power have useful synergies with natural gas, even as they compete for demand at the margin. Iran's current heavy reliance on natural gas for electricity generation is an advantage in this regard. Simple-cycle gas turbines in peak-power service can adjust quickly for fluctuations in supply due to changes in wind and cloud cover. The country's newer combined cycle power plants should have similar capabilities if they were designed to provide short "ramp" times, a measure of how quickly their output can increase or decrease.

Large-scale baseload generators, including nuclear power plants, typically cannot respond as quickly to such changes, if they can respond at all. This has become an important concern in markets with a high penetration of intermittent renewables, such as California, where the daily summer peak of solar generation is growing large enough to displace baseload generation, unless the renewable "overgeneration" is "curtailed", or taken off-line.

To put Iran's renewable energy targets and investments in perspective, its neighbor across the Persian Gulf, Saudi Arabia, has its own goal of achieving 10% of its generation from renewables by 2023, but starting from nearly zero without the equivalent of Iran's head-start in hydropower. The Kingdom plans to invest up to $7 billion in solar and wind installations in 2018 alone. Similarly aggressive developments are under way among the countries of the Gulf Cooperation Council. A single solar project in Dubai, the Mohammed bin Rashid Al Maktoum Solar Park, is intended to grow in phases from an initial scale of 13 MW, completed in 2013, to 5,000 MW by 2030—matching the ambition of Iran's entire renewable energy target.

A key driver of the wave of renewable energy installations across the Middle East and elsewhere is the rapidly falling cost of the associated technologies, particularly solar PV. This will be addressed in Section VII below.

V. Reducing Greenhouse Gas Emissions

Based on 2015 emissions of 630 million metric tons, Iran ranks eighth among countries for carbon dioxide (CO_2), the main greenhouse gas implicated in climate change, below Canada but above South Korea and Saudi Arabia. It ranks fifth on national emissions per unit of GDP, below China and Russia but above relatively carbon-intensive Canada and Australia.

Iran is a signatory to the Paris Agreement, joining most other countries of the world in the voluntary commitment to reduce its emissions of CO_2 and other greenhouse gases (GHGs). As of this writing, Iran has not yet ratified the agreement.

In preparation for the late-2015 Paris climate conference of the United Nations Framework Convention on Climate Change, Iran submitted its Intended Nationally Determined Commitment (INDC), spelling out its planned levels of emissions reduction and the conditions attached to them. In this document, Iran's government indicated it would reduce emissions unconditionally by 4% by 2030, relative to a "business-as-usual scenario." This relatively modest level of reductions would be achieved by reducing emissions from its electric utility sector, reducing natural gas flaring, improving energy efficiency, diversifying its economy, and participating in national and international "market-based mechanisms". That term usually refers to emissions trading and other means of shifting emissions reductions between companies, economic sectors, or governments.

Iran also committed to a higher level of emissions reductions, up to an additional 8% of baseline emissions, conditioned on receiving international assistance, including technology transfer and capacity building. The estimated cost of the promised 4-12% emissions reductions was $18-53 billion.

In the introduction of its INDC, the Islamic Republic referenced the country's need for continued hydrocarbon development to meet social and economic goals. Many of the specific technologies it identified as candidates for transfer relate to mitigating the greenhouse gas impact of oil and gas development, as well as in power generation, including natural gas combined cycle (NGCC) and combined-heat-and-power (CHP) generation, nuclear power and renewables.

Since the electricity sector is a primary contributor to the country's current emissions, its modernization should align with Iran's emission-reduction goals. In fact, all of the main strategies for updating generation in Iran—replacing gas-fired steam plants with NGCCs, deploying wind and solar power, and building nuclear power plants—contribute to meaningful emissions reductions. However, the extent and effective cost of the resulting emissions reductions varies significantly.

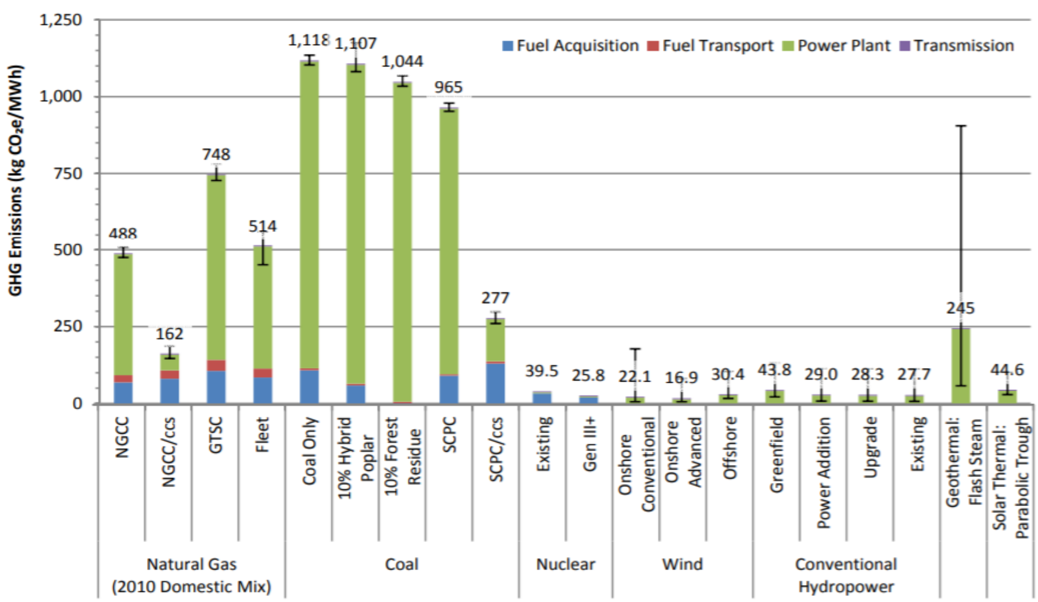
One particularly useful strategy not mentioned or implied in Iran's INDC is the displacement of oil from power generation. As noted in section II above, 14% of the electricity generated in Iran in 2015 was derived from oil, mainly high sulfur fuel oil and other petroleum products. Unlike in Saudi Arabia, little or none of the petroleum used by the power sector is in the form of crude oil. This is an important distinction when it comes to considering the alternate disposition of the petroleum that might be freed up by fuel switching or alternative generation.

The direct substitution of natural gas for residual fuel oil in even an inefficient steam power plant should result in a 29% drop in CO_2 emissions per Megawatt-hour (MWh), based on the relative emission factors of the two fuels when combusted. Replacing the steam plant with a modern NGCC could result in CO_2reductions of at least 46%, due to lower heat rate of the gas turbine, compared to a boiler-driven steam turbine, resulting in less fuel used for the same output.

This is analogous to the emissions reductions achieved in the US utility sector as lower-priced natural gas has displaced electricity generated from coal-fired power plants. US CO2 emissions from electricity generation have fallen by roughly one-fifth since 2008 as coal's share of the electricity market fell from 48% to 34% in 2015, while the share of generation from gas increased from 21% to 32%.

Figure 4 shows that even larger emission reductions can be achieved by displacing the output of steam generation, which has characteristics similar to coal, with renewables like wind and solar power. Iran's existing hydropower facilities also qualify as low-emission on this scale, as does Iran's sole nuclear power plant. However, nuclear power is hardly the only tool with which Iran could reduce its GHG emissions, nor, as we will see shortly, is it the least expensive.

Figure 4: Lifecycle GHG Emissions in Power Generation



Source: DOE National Energy Technology Laboratory

The chart also illustrates the emission-reduction potential of pairing gas power generation with carbon capture and sequestration, denoted as NGCC/ccs. CCS installations capture and concentrate CO2 from the power plant exhaust for injection into a long-term storage site, utilization in industrial processes, or for enhanced oil recovery as demonstrated by the PetraNova project in Texas. CCS on natural gas is a simpler proposition than for coal-fired power plants, with their inherent complexities of solids handling. Chevron's Gorgon liquefied natural gas (LNG) plant in Australia captures and stores over 3.4 million tonnes per year of CO2 from the natural gas feed to the plant, equivalent to the emissions from a 1,500 MW NGCC plant. Similar facilities have operated in the North Sea since 1996.

Iran's power sector consumed 11.6 million tonnes of fuel oil in 2015—equivalent to around 200,000 barrels per day—resulting in approximately 37 million tonnes per year of CO2 emissions. If that figure could be cut in half by shifting demand away from Iran's oil-burning steam plants and onto new, efficient NGCC power plants, it would go a long way to meeting the country's 4% emissions reduction pledge under the Paris Agreement. Eliminating oil power generation by substituting an equivalent capacity of wind or solar power would exceed that pledge.

Ending Iran's inefficient oil-based power generation would provide other significant benefits, especially in reducing local pollution. For Iran today, air quality is a more acute problem than climate change. Four of the 10 worst cities in the world for air pollution are in Iran, and despite clean-up efforts, Teheran's air is still labeled as "unhealthy" a third of the year. A 2004 paper published in the Iranian Journal of Health Science and Engineering found that merely substituting natural gas for fuel oil virtually eliminated the SOx emissions of four of the country's power plants, while reducing smog-forming NOx by 45-80%. New NGCC power plants have very low emissions of such local pollutants.

However, even if Iran were inclined to take this step, it must secure the additional gas supply, requiring additional upstream gas development, as well as an outlet for the displaced oil. As discussed in the next section, the latter concern is far from trivial, even for an oil-exporting nation like Iran.

VI. The Export Factor

Prior to the imposition of the UN sanctions that were lifted after the signing of the JCPOA, Iran had the second-highest oil exports within the Organization of Oil Exporting Countries (OPEC), shipping over 2.5 million barrels per day (MBD) as recently as 2010. Its recovery, post-sanctions, has been gradual, and conditions had changed in the interim. Iran's exports reached 2.1 MBD in 2017, but that would only rank fourth, at best, within OPEC, since the exports of both Iraq and the United Arab Emirates have grown in the meantime.

Moreover, when sanctions ended, global oil markets were experiencing a severe slump caused by the rapid growth of US shale oil production. Iran's resurgent exports compounded this situation until OPEC joined with Russia and other non-OPEC producing countries to restrain output and attempt to rebalance the global market and thereby shrink the significant bulge in global oil inventories that had accumulated. Following the lifting of a decades-old restriction limiting exports of all but a select few US oil grades, the US has become a significant oil exporter in its own right, adding another new factor to the global market.

With the oil market so delicately balanced, at least for the moment, and OPEC's members bound by their agreement with Russia, Iran would not necessarily be free to export additional oil liberated from power generation by a shift to other fuels or energy sources, even though the quantities are equivalent to roughly 10% of Iran's current oil exports. The fact that the fuel burned in Iran's steam plants is not crude oil, but rather a grade of residual fuel oil, complicates matters further.

Under a new regulation adopted in 2016, the International Maritime Organization (IMO) will restrict the global use in ocean-going vessels of high-sulfur fuel oil of the kind produced by Iran's refineries, starting on January 1, 2020. The regulation cuts allowable sulfur content of the fuel from the current 3.5% to 0.5%, requiring very significant changes in refinery operations in order to meet these new specifications or supply the marine market with other types of fuel that already conform.

Few other outlets exist for such high-sulfur fuels, beyond continuing to burn them domestically. As described in a 2016 report by Platts, the global refining industry has several options for complying with the IMO's new rule, including the diversion of higher-quality fuel from other markets, shifting refinery inputs to higher quality crude oil, and investment in new process equipment to substantially reduce the sulfur content of this material or convert it into other, more acceptable products. At this point the response appears to be a work in progress, with several of the above solutions having lead times that exceed the time remaining before implementation.

So in order for Iran to displace enough fuel oil from power generation to make a material difference in its CO_2 emissions, or to create a new high-value product stream for domestic consumption or export, its refineries would have to install sufficient upgrading capacity to process these volumes, at a cost of billions of dollars. The potential returns on such an investment might be attractive, at least initially, but it would compete with desired investments in oil and gas development and production facilities. The alternative would be to attempt to sell this material at distressed prices to refiners elsewhere that already have such capacity.

Thus, in Iran's case, the rationale for justifying investments in renewable energy or nuclear power on the basis of freeing-up oil currently used in power generation for export at a favorable economic uplift looks highly questionable. Under the circumstances, it appears that at least until significant investments have been made in Iran's oil refineries, new generation from either renewable or nuclear sources would instead compete directly with gas-fired power generation, and ultimately with the economics of future gas development and exports.

Iran is already a modest net exporter of gas. As noted in section III above, all of Iran's present gas exports occur via pipeline. Any significant increase in exports would likely have to be in the form of LNG, requiring investment in liquefaction facilities, in tandem with investment in additional production to provide the large, stable supply of natural gas necessary to support the multi-decade economics of LNG development.

Several LNG projects have been proposed for Iran but some have subsequently been withdrawn, including one with India's state oil and gas company, ONGC. Russian company Gazprom reportedly signed an agreement for LNG with Iran in late 2017. Other possibilities such as floating LNG facilities have also been raised, yet all of these potential projects face significant uncertainties as the global market absorbs the output of new LNG facilities in Australia and the onset of LNG exports backed by US shale gas. Significantly, French oil major Total's agreement to invest in the development of the South Pars gas field is intended to supply Iran's *domestic* market.

Fundamentally, Iran has gas to export, whether from reserves still in the ground or liberated from current power generation needs. For more than a decade the key to large-scale gas development—and hence exports—by Iran has been access to the necessary technology and finance, and by far the largest impediment to both has been Iran's nuclear program and the suspicions that have surrounded it. In principle, the JCPOA addressed those. However, doubts about the sustainability of the agreement, particularly with regard to continued US participation under the current administration, leave a cloud over the attractiveness of international investment in Iran's energy sector.

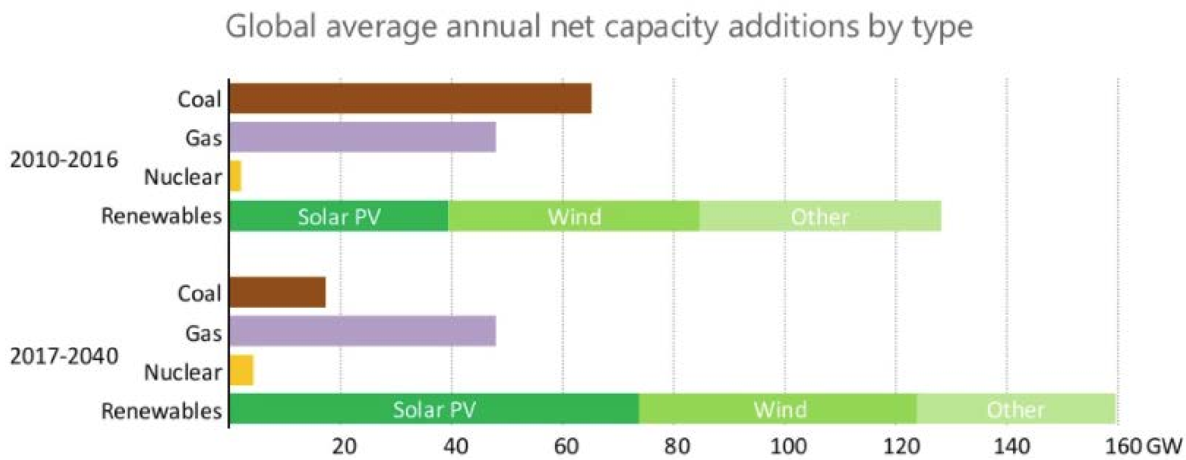
Nor are these investment needs small. In August 2017 Iran's oil minister Zanganeh cited a figure of $200 billion over five years to revitalize Iran's oil and gas industry and capitalize on its opportunities. Up to three-fourths of that should come from foreign investment. In this context recent deals with companies like Total represent only a down payment.

Gathering the required sums could prove challenging. The global oil and gas industry has more potential opportunities today than it appears to have the appetite to pursue. A bruising oil price slump from 2014-16 caused most international oil companies to reduce their capital budgets. The rapid post-slump recovery of US shale drilling is a factor, as well, moderating near-term prices while offering quicker returns on investment, compared to most large conventional oil and gas projects, such as those on offer in Iran. The result is something of a buyer's market in "upstream" opportunities. That may explain why BP, the 5th largest international oil company by market capitalization, has opted out of investment in Iran at this point.

VII. Comparing the Costs of Iran's Electricity Options

The global energy industry is experiencing change on an enormous scale, particularly when it comes to the shifting future mix of generation that will meet growing demand for electricity. The most recent forecasts from organizations like the International Energy Agency and US Energy Information Administration have increased the share likely to be taken by wind, solar and other renewable energy sources, along with slower but steady growth for natural gas, while moderating their view of the future market share of nuclear power. (See Figure 5.)

Figure 5: Renewables and Gas Lead World Electrical Capacity Growth



Source: IEA World Energy Outlook 2017

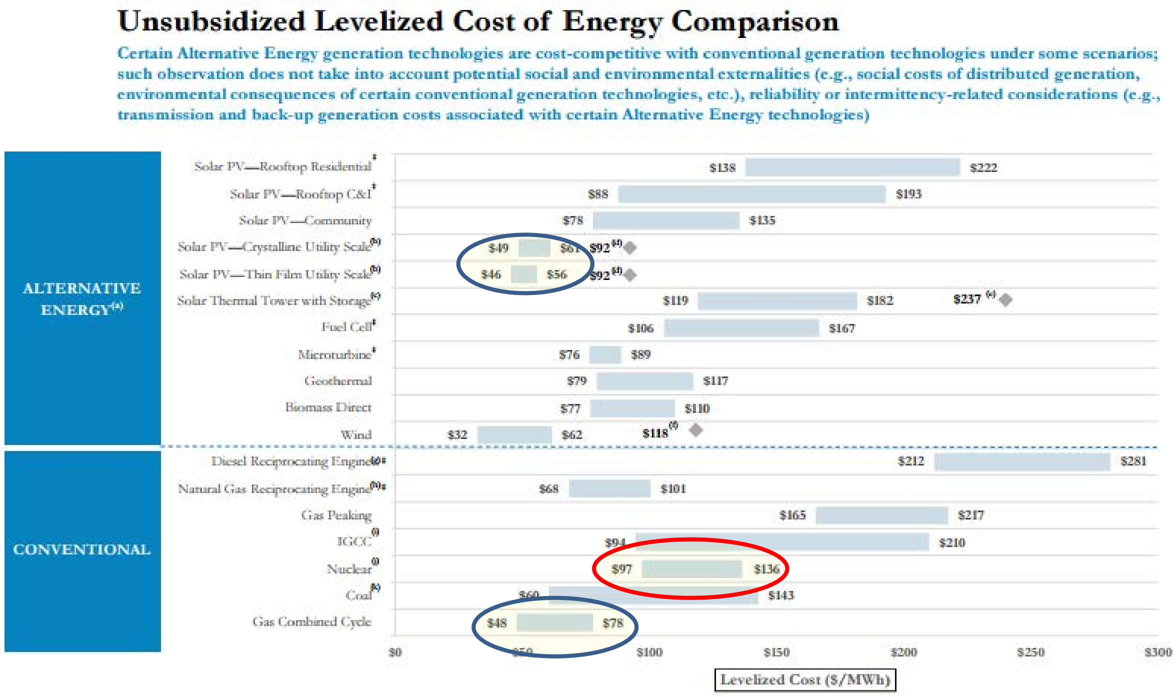
These shifts reflect sharp changes in conventional wisdom since the middle of the last decade. Notions of "peak oil" and its corollary , "peak gas", have wilted under a wave of production from conventional and non-conventional oil and gas resources, depressing prices and instilling a new sense of abundance. Meanwhile, renewables seemed likely to remain expensive well into the future have become competitive with conventional power plants, at least where the resources they tap are plentiful.

By contrast, after the recent cancellation of a flagship nuclear power project in South Caroline, the expected US "nuclear renaissance" has dwindled to a pair of reactors under construction in Georgia. Projects in France, Finland and the UK have experienced severe cost and schedule over-runs, while Germany is abandoning nuclear power even as its policy of "Energiewende"— literally "energy turn"— seeks to reduce GHG emissions by increasing the share of wind and solar power.

The result of these developments has been a surprising rearrangement of the relative cost of the main electric generation options. The "gold standard" for comparing the economics of these technologies is the "levelized cost of energy", or LCOE. It takes into account the differences among power sources with low capital but high lifetime fuel costs, and others with high capital costs but low or even essentially zero fuel expenses, along with differences in the timing of construction or installation.

Figure x below depicts ranges of LCOEs in US dollars per MWh for a broad array of generating technologies on a consistent set of assumptions concerning fuel prices, interest rates, and policies—in this case in the absence of technology-specific subsidies such as the tax credits or "feed-in tariffs" that renewables have enjoyed in a number of markets. The analysis was performed by Lazard in 2016. The range bars for solar PV, gas combined cycle, and nuclear power have been highlighted for clarity.

Figure 6:



Source: Lazard "Levelized Cost of Energy Analysis - Version 10.0"

As shown here both NGCC (gas combined cycle) and utility-scale solar power appear to be considerably cheaper than nuclear power in the absence of subsidies, even without considering local factors like Iran's abundant sunshine and effective natural gas prices much lower than the US prices on which this analysis was based.

The analysis is also sensitive to the cost of capital. With inflation as high as in Iran, and high interest rates, capital-intensive projects that require investment over a period of years, such as nuclear power plants, would see their LCOE shift to the right (higher). That would accentuate the economic advantage of solar arrays that are built in a factory and can be installed onsite fairly quickly.

Recent solar power bids in Saudi Arabia, coming in below the LCOE range at an effective price less than $20/MWh, suggest how much solar prices have fallen just in the last two years. It also highlights the advantage of regions with very high annual "insolation" or solar intensity

In addition to the helpful decline in the cost of solar power, the deployment of renewables in Iran benefits from policies instituted by the government to promote it, directly and indirectly. These include a five-year feed-in-tariff (FIT), paying solar developers an above-market rate for their electricity production, equivalent to $0.15 per kilowatt-hour (kWh).

Another policy advancing renewables less directly is the legislated privatization of Iran's state-owned generators. The government aims to increase private ownership of the power sector from the current 60% to 80%, while increasing annual renewable energy installation to 1,000 MW. With few of Iran's utility customer paying enough for electricity to cover the cost of generating it, renewables could become the most profitable generating assets, as long as the FIT remains in place.

VIII. Conclusions

Iran's energy economy is fueled by a few crucial inputs and driven to meet a relatively small set of needs. On the supply side of this ledger, the hydrocarbon resources within its territory are abundant and, in the case of natural gas, unsurpassed. On the demand side, the country's economy requires rising energy production to provide export revenue, sustain GDP growth, and meet the needs of consumers. Increasingly, the energy supplied within the country must be cleaner, both to reduce endemic urban air pollution and to meet the commitments Iran made under the Paris climate agreement.

However, when it comes to the other crucial input to the energy sector, the investment needed to develop Iran's resources and convert them into usable domestic energy or exportable goods, the industry is capital-constrained. That is not unusual when the government owns the oil and gas reserves, pipelines, refineries, and export facilities, as well as deciding how the significant cash flows generated by oil exports will be spent. Funds that in a publicly traded oil company would be reinvested in future production are often diverted to other purposes for which the government needs cash.

This explains why, despite external oil sales of around $36 billion in 2016, Iran must seek foreign investors to participate in the continued exploitation of its share of the massive South Pars gas field and the revitalization of its oil fields. It also explains why the sanctions imposed by the UN and US were effective in coercing Iran into the negotiations that led to the Joint Comprehensive Plan of Action on its nuclear program.

If the goal of Iran's energy sector is to produce as much energy as affordably possible for the growth of its domestic economy and energy exports, then the country's government appears to have better, more cost-effective options available than to spend scarce capital on a robust build-out of nuclear power plants and fuel enrichment.

There is every indication that renewable energy and modern gas-fired power plants can supply the foreseeable electricity needs of Iran's domestic economy, while reducing emissions of both local pollutants and greenhouse gases like CO_2. And because these technologies are cheaper in terms of both up-front investment and the levelized cost of their energy output, compared to nuclear power, this would leave more money to be invested in developing oil and gas fields for export purposes, compared to the convoluted and costly path of using nuclear power to displace for export some of the oil and gas currently burned there for electricity.

Iran has ample resources of natural gas and renewable energy—wind and sunlight—with which to grow its energy economy, while its nuclear ambitions have functioned as a large and sustained impediment to obtaining the foreign direct investment needed to undertake such growth. At least from an energy perspective, the continued pursuit of the government's nuclear program can only be described as an enigma.