DPRK ENERGY SECTOR: CURRENT STATUS AND SCENARIOS FOR 2000 AND 2005

<u>Prepared for the Conference:</u>

"Economic Integration of the Korean Peninsula"

Washington D.C, September 5 and 6, 1997

<u>Conference Organizers:</u>

The Institute for International Economics

<u>Prepared By:</u>

David F. Von Hippel
Peter Hayes

Nautilus Institute for Security and Sustainable Development
1831 Second Street, Berkeley, California 94710 USA
Telephone: 510-204-9296 Telefax: 510-204-9298
E-mail: phayes@nautilus.org
World Wide Web: www.nautilus.org

Oregon Office:
910 E 23rd Avenue, Eugene, Oregon 97405-3075 USA
Telephone/Telefax: 541-687-9275
E-mail: dvonhip@igc.apc.org

TABLE OF CONTENTS

1. INTRODUCTION AND BACKGROUND..1

1.1. THE DPRK SOCIAL AND POLITICAL SYSTEM, AND ITS INFLUENCE ON THE ENERGY SECTOR 1
1.2. THE "AGREED FRAMEWORK" AND KEDO..2
1.3. PLAN OF THIS PAPER 3

2. THE RECENT AND CURRENT STATUS OF THE DPRK ENERGY SECTOR...........................3

2.1. ENERGY RESOURCES IN THE DPRK...4
2.1.1. Fuels for thermal power generation...4
2.1.2. Hydroelectric resources 5
2.1.3. Nuclear options...5
2.1.4. Other renewable generating options...6
2.2. DPRK ELECTRICITY GENERATING FACILITIES 6
2.3. ESTIMATED ELECTRICITY GENERATION AND DEMAND IN THE DPRK 7
2.4. THE DISPOSITION OF HFO SUPPLIED BY KEDO IN 1996 9

3. RECENT AND CURRENT ENERGY-SECTOR PROBLEMS IN THE DPRK............................10

3.1. PROBLEMS WITH FUEL SUPPLY 10
3.2. DAMAGE TO HYDROELECTRIC PLANTS...10
3.3. EQUIPMENT PROBLEMS AT THERMAL POWER PLANTS AND LOAD CENTERS 11
3.4. THE STATUS OF THE DPRK TRANSMISSION AND DISTRIBUTION GRID 11
3.5. INSTITUTIONAL PROBLEMS..12
3.6. THE KEDO-SUPPLIED PWRS IN THE DPRK GRID 12

4. TWO SCENARIOS OF DPRK ENERGY-SECTOR DEVELOPMENT.......................................14

4.1. DESCRIPTION OF SCENARIOS: "RECOVERY" AND "DECLINE"..14
4.2. SCENARIO RESULTS: ELECTRICITY SUPPLY AND DEMAND..16
4.3. SCENARIO RESULTS: DISPOSITION OF KEDO-SUPPLIED HFO 17
4.4. ESTIMATE OF DPRK PRODUCTION OF PLUTONIUM AND OTHER RADIOACTIVE WASTES....................19

5. IMPLICATIONS OF RESULTS, AND STRATEGIES FOR COOPERATION............................21

5.1. SUMMARY OF CURRENT SITUATION, AND IMPACT OF KEDO ACTIVITIES..21
5.2. STRATEGIES FOR COOPERATION AND ENGAGEMENT 22

6. ENDNOTES 26

ANNEX: SUMMARY DPRK ENERGY BALANCES FOR 1990 AND 1996, WITH SCENARIOS FOR 2000 AND 2005

THE ROLE OF KEDO AND NUCLEAR POWER IN THE DPRK ENERGY SECTOR: CURRENT STATUS AND SCENARIOS FOR 2000 AND 2005

1. Introduction and Background

The actions, postures, and circumstances of the Democratic People's Republic of Korea (the DPRK or North Korea) have been the focus of significant world attention over the past four years. The much-publicized problems regarding North Korea include concerns about nuclear proliferation, economic decline, ever-present security issues, energy shortages, floods, and most recently, food shortages. All of these problems have their roots in both recent and more distant Korean and world history--roots that are both deep and tangled. Various bilateral and multilateral approaches have been fashioned or proposed over the last few years to attempt to address the problems of the DPRK. The Korean Peninsula Development Organization (KEDO), for example, was created to address the politically-linked problems of nuclear proliferation, electricity-sector development, and more broadly, engagement of the DPRK in cooperative projects of concern to the nations of Northeast Asia.

The goal of this paper is to provide a brief overview of the recent and current status of the DPRK energy sector, as well as some of the factors that will influence the development (or continued decline) of the sector over the next eight years and beyond. The energy sector in the DPRK has been a particular focus of the authors' research and analytical work over the past several years[1].

1.1. The DPRK Social and Political System, and Its Influence on the Energy Sector

The "Chuche" or autarchic philosophy of the DPRK government has shaped the electricity and energy sectors in the DPRK. Development of indigenous resources—notably coal—has taken precedence, as has "reverse engineering[a]" and other techniques of developing technologies that can be produced domestically. The focus on domestically-produced energy technologies, and the corresponding lack of technology imports (especially recently) has resulted in an energy sector that is notably inefficient. Another major factor in shaping the DPRK's electricity and energy-consuming infrastructure has been the influence of Russian advisors and aid. The former Soviet Union was intimately involved in designing, and in many case providing equipment for, constructing, and even operating thermal power plants, industrial plants, and many other elements of the DPRK economy. As a consequence, Russian design criteria and operating practices are widely used in the DPRK. In many cases, the Russian-designed plants provided to the DPRK operate much less efficiently comparable processes in other countries, contributing to the overall inefficiency of the DPRK economy[b].

The North Korean workforce is literate, disciplined, and hard-working; these attributes have been key in allowing the DPRK to make the economic strides that it did during the phase of heavy

[a] In "reverse engineering", a device or technology is acquired from outside the country, disassembled, and evaluated to figure out how it works and how it was made. A domestic process for production of the item is then designed.

[b] In some cases, reportedly, the infrastructure exported to the DPRK from the former Soviet Union was built to extra-rugged specifications for longevity under DPRK conditions. Often, this involved a tradeoff that resulted in reduced energy-efficiency.

industrialization in the two decades following the Korean War. The DPRK workforce, however, suffers from a lack of technological training as a result of North Korea's political isolation. In addition, the relatively low rate of growth of the population means that the workforce is aging. This trend may cause average workforce productivity to decline over the long term (all else being equal, as the ratio of active workers to retirees declines), and may present problems in retraining workers for new, higher-technology jobs (for example, to make goods that would be competitive in the export market). Academics and engineers involved in the basic sciences and in applied research and development probably also suffer lower productivity due to limited and tightly-controlled contact with their peers in other countries.

The DPRK government has shown a preference for massive construction projects. This predilection, plus the ability to muster large work forces rapidly, is helpful when constructing hydroelectric impoundments, barrages (sea-walls), and other large public works such as recovering from the floods, but is less helpful in constructing smaller, more specialized, and more efficient equipment. The large outlays (reportedly $890 million per year[2]) by the government for massive monuments honoring the Kim regime have siphoned off money and labor that could have been used for energy-sector projects or other (arguably more useful) social infrastructure projects.

Another workforce issue is that a significant fraction (probably on the order of 17 percent) of the potentially economically-active males are in the armed forces of the DPRK. Although soldiers apparently participate in public works projects and in some other civilian economic activities (such as harvesting of crops), the proportion of workers in the active armed forces (and the time spent by the 5 million reservists in military training) undoubtedly acts as a drain on the overall DPRK economy[c], including its energy economy.

1.2. The “Agreed Framework” and KEDO

As a condition of the October, 1994 Agreed Framework signed by the governments of the United States and the Democratic People’s Republic of Korea (the DPRK), the DPRK is to be supplied two pressurized-water-type light-water nuclear reactors for electricity generation (referred to as PWRs) in exchange for abandoning its existing graphite-moderated nuclear research reactors and taking further steps to comply with nuclear safeguards . Until the reactors are completed, the Korean Peninsula Energy Development Organization (KEDO) has an obligation under the Framework to supply 500,000 metric tonnes (te) of heavy fuel oil (HFO) to the DPRK annually. KEDO oil deliveries started in 1995, and deliveries in the year ending October 31, 1996 were scheduled to total 500,000 tonnes[3]. The oil delivered by KEDO is intended to be used to fuel electricity generation facilities, and, nominally, is intended to help the DPRK maintain electricity supplies while the PWRs are under construction.

This proposed transfer of PWR technology is sought by the DPRK as a means to maintaining both a civilian nuclear program and the threat of a military nuclear program. At the same time, it is attractive to other nations (led by the United States) as a means to start the thawing of relations with the DPRK, as a way to lessen the probability of nuclear weapons proliferation, and as a means to exert better international control over the DPRK nuclear program. Funding for the PWR transfer is likely to come from the recently formed Korean Peninsula Energy Development Organization (KEDO), which obtains its financing mostly from the ROK, with some additional inputs from the United States and

[c] This in addition to the direct financial outlays for maintenance of the armed forces.

Japan[d]. Although energy efficiency and renewable energy measures could conceivably provide the same energy services to the DPRK economy as would the PWR, and could do so on at least a similar time scale and for lower cost[4], energy efficiency measures are not politically substitutable for the PWR transfer. The PWR transfer—or some similar arrangement—is, however, a necessary first step to a political opening by North Korea, an opening that could lead to investments—such as investments in energy efficiency—that will serve to start to integrate the economy of DPRK with the other economies of the region. This integration would enhance stability and security in the region in the medium and long-term, and is the underlying logic implicit in the hopes of US and ROK policy-makers to achieve a "soft landing" for the DPRK economy and polity.

Although the oil transfers and PWR construction carried out under the Agreed Framework are not likely to have major direct impacts on the quality of life in the DPRK, the Framework contains major confidence building measures, and--if adhered to by all parties—should have important indirect positive impacts on the DPRK economy. In particular, if cooperation on HFO transfers and PWR issues between the DPRK, the ROK, the United States, and other parties proceeds smoothly, it should open the door to further external collaborations on topics like transfer of advanced (and less polluting) energy and industrial technologies, cooperation on regional environmental issues, and general development (or re-development) assistance to the DPRK.

1.3. Plan of this Paper

The remainder of this paper is organized as follows:

- In **Section 2** we outline the current status of the DPRK energy sector, focusing on the status of supplies of and demand for electricity;
- In **Section 3** we describe some of the current problems in the electricity sector, including the implications of those problems for the measures undertaken as part of the Agreed Framework;
- In **Section 4**, we present the major assumptions and results of two scenarios for the future of the energy sector in the DPRK; and
- In **Section 5**, we supply our summary as to the current and future efficacy of measures undertaken under the Agreed Framework, as well as suggestions in regard to cooperative ventures to help address energy-sector and related issues in the DPRK.

2. The Recent and Current Status of the DPRK Energy Sector

The status of the DPRK energy sector in general, and the electricity sector in particular, provides the underlying motivation—at least the stated motivation—for the DPRK's interest in nuclear power. In this section, we provide a thumbnail portrait of the DPRK energy sector—focusing on electricity supply and demand—as it was in 1990 and as it reportedly is today.

[d] Though funding for KEDO has come from the countries indicated, the DPRK will be obliged to repay the funds loaned to build the PWRs. As of late June, 1997, KEDO and the DPRK were to sign an agreement specifying penalties to the DPRK if the DPRK fails to repay the loan (Chosun Ilbo, "DPRK TO SIGN PROTOCOL ON REPAYMENT LIABILITY FOR LIGHT WATER REACTOR PROJECT," 06/20/97).

Overall energy use per capita in the DPRK is relatively high, primarily due to inefficient use of fuels and reliance on coal. Coal is more difficult to use with high efficiency than oil products or gas. Based on our estimates, primary commercial energy[e] use in the DPRK in 1990 was approximately 67 GJ per capita, approximately 3 times the per capita commercial energy use in China in 1990, and about 50 percent of the 1990 per capita energy consumption in Japan (in which 1990 GDP per-capita some ten to twenty times higher than the DPRK).

The industrial sector is the largest consumer of all commercial fuels—particularly coal—in the DPRK. The transport sector consumes a substantial fraction of the oil products used in the country. Most transport energy use is for freight transport; the use of personal transport in the DPRK is very limited. The residential sector is a large user of coal and (in rural areas) biomass fuels. The military sector (by our estimates) consumes an important share of the refined oil products used in the country. The public/commercial and services sectors in the DPRK consume a much smaller share of the fuels supplies in the DPRK than they do in industrialized countries, due primarily to the minimal development of the commercial sector in North Korea. Wood and crop wastes are used as fuels in the agricultural sector, and probably in some industrial subsectors as well.

The Annex to this paper provides our estimated Summary Energy Balances for the DPRK for 1990 and 1996, as well as the provisional results of our scenarios (as described in Section 4 of this paper) for the years 2000 and 2005.

2.1. Energy Resources in the DPRK

The key fuel/energy resources for generation of electric power in the DPRK are fuels for thermal power plants—principally coal—and hydraulic resources to power hydroelectric plants. Resources for nuclear and renewable generation are also available, but their use is currently very limited.

2.1.1. Fuels for thermal power generation

North Korea's major energy resource is coal. The DPRK has substantial reserves of both anthracite and brown coal, though the quality of its coal reserves varies substantially from area to area. Overall reserves of coal in the DPRK have been estimated (variously) at 600 million tonnes[f], 1.8 billion tonnes[5], 7.8 billion tonnes (including both proved and probable reserves)[6], 2.5 to 6.6 billion tonnes of coal equivalent[7], and 10 billion tonnes[8]. These estimates amount to approximately 10 to 100 years of reserves at current consumption. Other sources place reserves even higher levels—up to 70 - 90 billion tonnes, about one thousand times greater than 1990 annual coal production[9]. There is little, if any, coal cleaning practiced in the DPRK[g].

[e] Primary energy counts all fuel use, including conversion and transmission/distribution losses. Commercial energy excludes, for the most part, use of biomass fuels such as firewood and crop wastes.

[f] "Recoverable" coal reserves; US Department of Energy Information Administration (USDOE EIA, 1996), North Korea. From USDOE EIA World-wide web site, http://www.eia.doe.gov/emeu/cabs/nkorea.html.

[g] Coal preparation involves pulverizing and washing coal to reduce impurities such as ash and sulfur. Power plant and industrial boilers, and even the smaller boilers in residential and public/commercial buildings, would be more efficient and easily operated and maintained if they were fueled with prepared coal.

There are no operating oil wells in North Korea. Oil resources reportedly have been located offshore in DPRK waters[h], although there is substantial uncertainty on this count. All crude oil and some petroleum products were imported (as of 1990) from Russia, China, and Iran, with some additional DPRK oil purchases reported on the Hong Kong spot market. Since 1990, crude oil imports have been restricted by a number of economic and political factors. Two operating oil refineries produced (as of 1990) the bulk of refined products used in the country. As of 1996, only one of the two refineries was apparently operating, and imports of refined products had not expanded sufficiently to replace the lost production. We have heard no reports of gas use for electricity generation, and the DPRK lacks facilities for gas production or LNG (liquefied natural gas) imports[i].

There are various types of biomass wastes generated in the DPRK that could conceivably be used (to a limited extent) to fuel electricity generation. These including municipal solid wastes, wastes from crop production, food products preparation, wood products wastes, and wastes from the paper and pulp industries. Some of these wastes may currently be used for industrial cogeneration (of heat and power) or solely to raise steam for industrial processes. We do not know to what extent these wastes may be available for power generation, but would guess that other demands for the wastes (for example, as feedstocks, as fuels for "biomass trucks", or for rural cooking and heating) would probably consume the bulk of available supply. Given the condition of the DPRK forests (especially in the light of the recent floods and food shortages), the use of dedicated wood plantations to fuel electricity generation would not seem to be a short- or medium-term option.

2.1.2. Hydroelectric resources

The mountainous terrain in North Korea, and the relatively wet climate, make for hydraulic resources suitable for hydroelectric development. Hydroelectric resources in North Korea were developed extensively during the Japanese colonial period, when the Northern part of the Korean peninsula supplied much of the peninsula's power, primarily from hydroelectric sources. At present, a total of roughly 4,500 MW of hydroelectric capacity is installed, and estimates of total hydroelectric potential in the DPRK range from about 10,000[10] to 14,000 electric MW[11,12].

2.1.3. Nuclear options

The DPRK, like the Republic of Korea[13], possesses "considerable" resources of uranium[14]. Starting in the mid-1960s, and with technology and technological assistance from the Soviet Union, the DPRK built a research reactor (initially 2 kWt, later upgraded to 8 kWt) at Yongbyon. In the 1980s the DPRK constructed its 30 MW[j] gas-cooled reactor, which is graphite-moderated and capable of using natural uranium[15]. In this way, the DPRK was able to avoid relying on foreign suppliers for uranium enrichment technologies. The DPRK constructed a reprocessing facility at Yongbyon, apparently to produce weapons-grade plutonium from the spent fuel from the gas-cooled reactor. The DPRK has

---

[h] North Korean sources tout oil reservoirs amounting to 6 to 10 billion tonnes of crude offshore of the DPRK in both the East and West Sea. Other sources we have contacted on this topic indicate that reserves do exist, but the oil that is there is presently uneconomic for extraction. Still other, likely more reliable, sources have indicated that little or no oil is present in DPRK offshore area.

[i] There may be use of refinery, coke oven, or blast-furnaces gases for cogeneration of heat and electricity in industrial settings, but we have no direct evidence of such use.

[j] The output of this plant is given as 25 MW, 30 MW, and 5 MW (the latter as electric capacity) by different sources.

agreed to shut down and dismantle its nuclear facilities as part of the provisions of the Agreed Framework.

In order to use its uranium resources in the PWRs to be supplied by KEDO as part of the Agreed Framework, the DPRK either will have to construct enrichment facilities, or, more likely, will reach an agreement with a supplier who will process and enrich natural uranium mined in the DPRK and provide finished reactor fuel.

2.1.4. Other renewable generating options

Apart from hydroelectric resources, the DPRK's potential renewable resources for electricity generation include tidal, wind, and solar power. The tidal power potential of the DPRK has been estimated at 4,700 MW[16]. The Nampo lock gate project (also sometimes referred to as the West Sea Barrage) reportedly was to have had a tidal power component, but apparently the power-generation aspect of the project was discontinued due to "expected" high capital costs[17]. We do not know at what stage the project was canceled, or what the generation capacity was to have been.

Various sources, and the prevailing topography and wind patterns on the Korean peninsula, suggest that there may be a substantial wind resource in the DPRK. There have been reports of experiments with small wind turbines, but we do not know where or how large the wind machines installed (if any) were. Official publications have expressed interest in developing wind power, particularly in isolated areas such as offshore islands[k]. The areas bordering China are mentioned as having a particularly good wind resource. As a temperate country with both cloudy and sunny weather periods, and flat land at a premium, the DPRK's suitability for either solar thermal-electric or solar photovoltaic power is probably only fair to just average[l].

2.2. DPRK Electricity Generating Facilities

There are reportedly over 500 electricity generation facilities in the DPRK. Of these, however, only 62 major power plants reportedly operated as part of the interconnected transmission and distribution grid as of 1990, with the remaining plants being primarily small, isolated hydroelectric facilities and/or facilities associated with industrial installations. These 62 plants include 42 hydroelectric plants and 20 thermal plants. Eighteen of the thermal plants are fired primarily with coal[18, m]. The power generation system in general suffers from a lack of spare parts in many instances, as well as testing equipment for use in maintenance activities.

[k] This would seem to indicate that DPRK energy decision-makers and researchers do not tend to think of wind power as a resource suitable for connection to the grid. Why this would be is unclear.

[l] In terms of surface insolation (sunlight reaching the surface), the Korean peninsula receives a score of 150 to 175 (units unspecified) on a map where global insolation varies between 75 to 100 (high latitude and polar regions) and 250 to 275 (arid and desert regions). Source: Sellers W.D. (1965), Physical Climatology. University of Chicago Press, Chicago, IL, USA. As reproduced in http://www.arts.ouc.bc.ca/geog/G111/6ginsolation.html.

[m] One estimate suggests that 85 percent of total national generation takes place in the 62 major power plants. Another reliable source has told us that virtually all generation in the DPRK takes place at about 30 major generating stations, and that all of the other plants, to the extent that they actually exist, are very small, inoperable, or both.

Although there are discrepancies between the various estimates of the installed capacity of thermal electricity generating capacity in the DPRK[n], we have assumed that the total installed thermal generating capacity as of 1990 was approximately 3,400 megawatts. Of the major thermal power plants that are connected to the national transmission and distribution (T&D) grid, only two are reported to be oil-fired. Of these, by far the largest[o] is the 200 MW plant at Sonbong (referred to in various transliterations as “Oungi”, “Oung gi” and “Unggi”) where many of the KEDO heavy fuel oil (HFO) deliveries have been made. Since 1990, the only reported major addition to the roster of thermal power plants has been the completion in the early 1990s, with Russian assistance, of one 50 MW unit of the (reportedly) 150 MW East Pyongyang plant.

As noted above, North Korea has a fairly extensive total potential for hydroelectric development. The DPRK's ability to mobilize massive work forces for public works projects such as dams has helped the country to tap this potential, and as of 1990 approximately 4,500 of an estimated 10,000 to 14,000 MW of hydroelectric potential had been developed. Twenty major hydroelectric plants account for approximately 90 percent of the 4,500 MW of hydroelectric capacity reportedly in service as of 1990. Electricity from several plants (including the output of turbines totaling roughly 700 MW of capacity) is exported to China.

Much of the DPRK’s generation capacity was installed in the 1970s and 1980s, with extensive Soviet aid, although a significant portion of generation facilities—particularly hydroelectric facilities—date back to the Japanese occupation[p].

As of the early 1990s nearly 3,000 MW of hydroelectric facilities were reportedly under construction in the DPRK. We have little or no information about how construction on these projects (if any) has progressed, or what effect the floods of 1995 and 1996 might have had on ongoing hydro projects. The only exception is the Kumgang Mountain plant, a first phase of which (about 125 MW) was opened in 1996. This modest addition, however, is overwhelmed by the reported loss in hydroelectric capacity caused by the impacts of the 1995 and 1996 floods (see section 3.2, below).

2.3. Estimated Electricity Generation and Demand in the DPRK

Our best estimate is a total of 46 TWh (terawatt-hours) of electricity was generated in the DPRK in 1990. This estimate is roughly mid-way between official DPRK estimates (of 60 TWh and greater) and estimates by ROK sources (27.7 TWh[19]), published Russian sources (35 TWh[20]), and more informal estimates of 31-32 TWh[21], but the latter may be a consumption rather than a production figure. The estimated per-capita electricity demand in the DPRK in 1990 (subtracting electricity losses, exports to China, and use within power plants) was somewhat over 1400 kWh per capita. By way of comparison, overall 1990 electricity demand in South Korea was about 2200 kWh per capita[22]. Based on our estimates, electricity generation in the DPRK had fallen to less than 24 TWh (625 kWh per capita demand) by 1996.

---

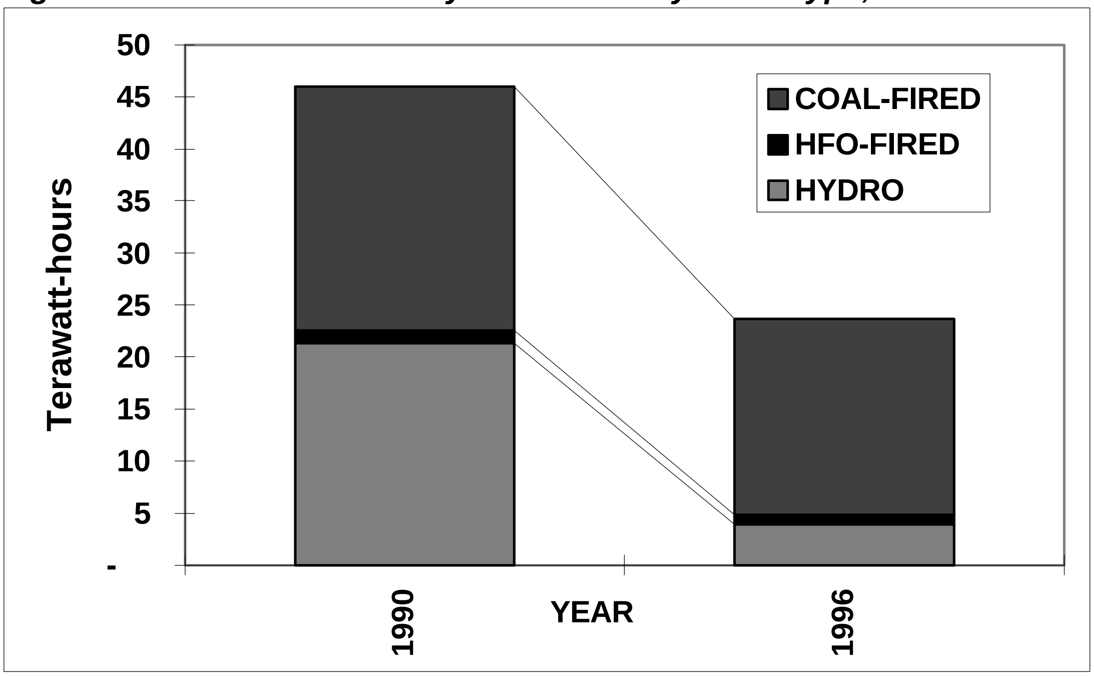
[n] Choi (1993), for example, cites a total capacity for coal-fired generating stations of 2,850 MW in 1991, while the United Nations lists 4,500 MW of thermal capacity for 1989 though 1992. Other documents in our files list a total of 2,900 MW of capacity as of 1990 in the largest seven thermal plants alone, and still others list “official figures” of up 6,000 MW of thermal capacity in 1990.

[o] If, indeed, a second oil-fired plant exists, it must be quite small.

[p] Most of the thermal power plants in the DPRK (and a large portion of the DPRK’s industrial capacity as well) were built with substantial technical and financial assistance from the Soviet Union. The USSR also assisted the DPRK in rebuilding most of the major hydroelectric facilities.

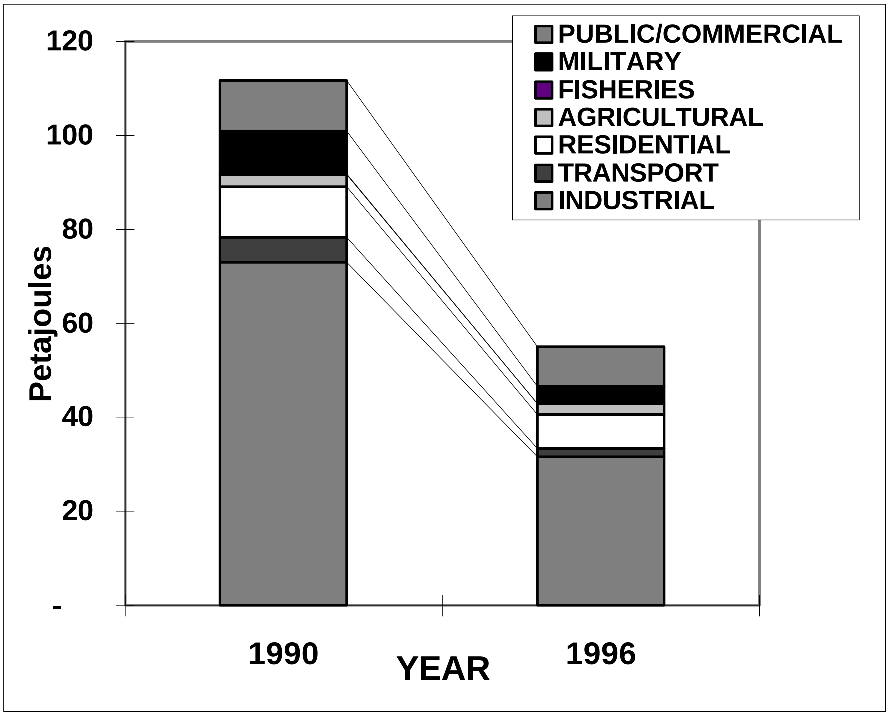
Electricity generation as of 1990 was primarily hydroelectric and coal-fired, in approximately equal proportions, with a small amount of oil-fired electricity generation taking place at the 200 MW plant associated with the oil refinery at Sonbong. By 1996, as a result of damage to hydroelectric facilities, a much greater proportion of electricity was generated at thermal plants. Estimated DPRK electricity generation by plant type in 1990 and 1996 are shown in Figure1.

Figure 1: Estimated Electricity Generation by Plant Type, 1990 and 1996



As with coal, the bulk of the electricity demand in the DPRK is in the industrial sector, with the residential and military sectors (by our estimates) also accounting for significant fractions of electricity consumption. The patterns of electricity demand by sector in 1990 and 1996 are shown in Figure 2.

Figure 2: Estimated Electricity Consumption by Sector, 1990 and 1996[q]



2.4. The Disposition of HFO Supplied by KEDO in 1996

The heavy fuel oil supplied to the DPRK by KEDO was and is intended for use as a fuel for electricity generation. HFO supplied by KEDO during late 1995 and 1996 has been burned at the oil-fired power plant at Sonbong, and used to improve the quality of coal used at several other thermal power plants[r]. As the absorptive capacity of the DPRK for both heavy fuel oil and electricity has been limited by the poor state of the DPRK economy, a substantial amount of HFO has had to be placed in storage. Of the approximately 1,060,000 tonnes of HFO that constituted the DPRK's supply in 1996 (about 500,000 tonnes of which were supplied by KEDO), we estimate that 27 percent was used by industry, 27 percent was used in the oil-fired plant at Sonbong, 31 percent was used in (nominally) coal-fired power plants, and the remaining 15 percent (over 150,000 tonnes, or nearly a third of KEDO supplies) was placed in storage. Broadening the ways in which KEDO HFO can be used under the terms of the Agreed Framework to include key industrial activities—notably production of the mineral magnesite, for which oil-fired equipment apparently already exists in the DPRK—would help to relieve pressure on DPRK oil storage facilities.

[q] Note that the "Fisheries" consumption of electricity is too small to be seen on this graph.

[r] This use of HFO has been in excess of the fraction of oil fuel usually used as a "starter" fuel in coal-fired power plants. Nominally, this added oil fuel would constitute an uneconomic use of HFO, as coal is available as a less-expensive fuel. However, because the quality of coal available in the DPRK has been deteriorating, HFO has likely become more important as an additive to raise the heating value of power plant fuels.

3. Recent and Current Energy-Sector Problems in the DPRK

3.1. Problems with Fuel Supply

There have been many reports of problems with fuel supply in the DPRK over the last several years. Although it is often difficult for outsiders (and probably for most DPRK residents as well) to discern the ultimate cause and extent of these problems, fuel supply difficulties certainly include:

- *A lack of oil products*, particularly motor fuels, caused by a lack of foreign currency (or will) to pay for imports of crude oil and refined products, and the withdrawal of Russian oil supplies formerly available on a "soft-money" basis.
- *Maintenance* (and possibly fuel supply) problems on railroad lines and equipment that cause bottlenecks in coal shipments.
- *Equipment and flooding problems in coal mines*, including lack of investment in new infrastructure or spare parts.
- *Problems with electricity plants and with the electricity transmission and distribution system* (as described below)

Lack of fuels in many sectors of the DPRK economy has apparently caused demand for energy services to go unmet. Electricity outages are one obvious source of unmet demand, but there are also reports, for example, that portions of the North Korean fishing fleet have been idled for lack of diesel fuel. Residential heating is reportedly restricted in the winter to conserve fuel, resulting in uncomfortably cool inside temperatures. The problem posed by suppressed and latent demand for energy services is that when and if supply constraints are removed there is likely to be a surge in energy (probably particularly electricity) use, as residents, industries, and other consumers of fuels increase their use of energy services toward desired levels.

3.2. Damage to Hydroelectric Plants

We have recently learned that a significant portion—perhaps as high as 85 percent—of the DPRK's hydroelectric generating capacity has been rendered unusable by the floods of 1995 and 1996. This seems believable, based on the location of some major hydroelectric facilities in the areas where some of the worst flooding occurs, and anecdotal reports of the amount of silt and other debris that was washed down-river by the floods. Other reports have indicated that relatively little damage to hydro facilities had occurred[s] as a result of flooding, but the remoteness of major hydro facilities and the non-obvious nature of damage might make such problems hard to detect for many visitors. We assume that the majority of the damage done by the floods has been to fill impoundments with silt, reducing the capacity of dams and clogging spillways and channels. It is possible that damage to gates, turbines, and other mechanical equipment has also occurred[t]. Of these problems, the siltation of reservoirs may be

[s] Several sources who have been to the DPRK recently said they had no knowledge of major damage to large hydroelectric facilities. Another source had heard of damage to "one or two" "small to medium-sized" (less than 10 MW) plants.

[t] At one point during the 1996 floods, the water levels in one chain of hydro facilities along a river in the North of the country were reportedly such that the turbines actually spun backwards. One would expect this type of circumstance to cause at least some equipment damage.

the most difficult for the DPRK to reverse, as it requires 1) heavy equipment (and fuel) that the DPRK does not have to spare, and 2) considerable time to accomplish.

3.3. Equipment Problems at Thermal Power Plants and Load Centers

Power generation facilities are reported to be in generally poor condition--and often (because they are based on technologies adopted from former Soviet Union, China, or elsewhere) not well adapted to the coal types with which they are fired. The downturn in the DPRK economy of 1989 through the present, coupled with a sharp reduction in the amount of concessional aid available from Russia, has left the DPRK unable to afford key spare parts (including boiler tubes for thermal power plants). As a consequence, the generation efficiency of the thermal power stations in the DPRK is reportedly low, and breakdowns are frequent. Thermal power plants generally lack all but the most rudimentary pollution control equipment, and also, in almost all cases, lack any kind of computerized combustion control facilities. In-station use of power is reportedly fairly high, and “emergency losses” of power have been reported at major stations.

Much of the energy-using infrastructure in the DPRK is reportedly antiquated and/or poorly maintained. Buildings apparently lack insulation, and the heating circuits in residential and other buildings apparently cannot be controlled by residents. Industrial facilities are likewise either aging or based on outdated technology, and often (particularly in recent years) are operated at less-than-optimal capacities (from an energy-efficiency point of view).

3.4. The Status of the DPRK Transmission and Distribution Grid

The unified electrical grid in the DPRK apparently dates back to 1958[23]. The DPRK T&D system must manage a fairly complex grid of 62 power plants, 58 substations, and 11 regional transmission and dispatching centers. The T&D system is supposed to be controlled by the Electric Power Production and Dispatching and Control Centre (EPPDCC) in Pyongyang.

The system of electricity dispatching is inefficient, minimally or not at all automated, and prone to failure. Estimates of transmission and distribution (T&D) losses vary from an official 16 percent up to more than 50 percent, but any estimates of T&D losses are difficult to confirm, as there is minimal end-use metering in the DPRK[u]. Connections between the elements of the T&D system were, as of the early 1990s, reportedly operated literally by telephone and telex, without the aid of automation or computer systems. This system results in poor frequency control, poor power factors, and power outages[v]. Outages on the grid are reportedly frequent, and the process of reacting to outages and isolating areas where the outages occur is cumbersome and slow, often resulting in a cascading series of outages (and further delays in restoring power). Poor frequency control and low power factors can damage end-use equipment, and can shorten the life of T&D components[24]. In addition, outages result in significant economic losses as a result of lost industrial production and services. As of 1990, the EPPDCC lacked direct access to even the most rudimentary data from power plants and substations, having direct readout of neither <u>measurements</u> such as voltage, current, active power, frequency, nor <u>status indicators</u> such open/close conditions of circuit breaker or switch positions. The only exception

[u] That is, generally, power is reportedly simply provided to consumers without metering, so “sales records” as such, do not exist.
[v] A nearly-completed UNDP-funded project, "Electric Power Management System" was only designed to address control systems at four critical power plants and four substations around Pyongyang.

to this lack of access as of 1990 were links to three power plants, but even these links were reportedly "slow and outdated".

When a transmission fault or power plant failure disrupts the system, or when voltages or frequencies at load centers fall below permissible levels, the EPPDCC staff must guide remote operators in restoring the system through the aforementioned system of telephones and telexes, and without access to complete system information on which to base their instructions.

The T&D system also reportedly suffers from poorly-maintained transmission lines and substations, including inadequate or missing insulators on power poles and insulation on power lines, inadequate wire tension, and other problems[w]. In addition to the lack of proper equipment noted above

3.5. Institutional Problems

A thorough description of the institutional problems that must be grappled with during any attempt to improve the DPRK's energy situation is beyond the scope of this paper. Two major categories of problems are:

- The *fragmentation of institutional responsibility* in the energy sector inhibits efforts to upgrade the DPRK's energy systems in general, and the electricity generation and T&D systems in particular. More than a dozen agencies are involved in the electricity sector, but there is no single institution in North Korea that is fully responsible for electricity systems operations, energy analysis related to electricity production and consumption, integrated planning, and management.
- *Lack of energy product markets*: Confounding attempts to improve efficiencies of energy supply and consumption in the DPRK, and compounding the risk of a surge in the use of energy services if supply constraints are removed, is the virtual lack of energy product markets in the DPRK. Without fuel pricing reforms, there will be few incentives for households and other energy users to adopt energy efficiency measures or otherwise control their fuels consumption. Energy consumers are also unlikely, without a massive and well-coordinated program of education about energy use and energy efficiency, to have the technical know-how to choose and make good use of energy efficiency technologies.

3.6. The KEDO-Supplied PWRs in the DPRK Grid

The power grid in the DPRK operates at a nominal frequency of 60 Hz (Hertz, or cycles per second). Frequency control is poor, however, and the actual frequency on the system often reportedly falls to 57 to 59 Hz, and sometimes as low as 54 to 55 Hz.

Of the neighboring countries, both China and Russia have electricity systems that operate at 50 Hz, while the grid in the Republic of Korea operates at 60 Hz. This difference means that in order to interconnect the DPRK grid with the Chinese and/or Russian grid, as has been contemplated under the Tumen River Area Development Programme (TRADP), it will either be necessary to convert from 60

[w] Some of these problems are apparently institutional: those work units charged with maintaining power lines are different from those responsible for generating power, and are not supplied by central authorities in the DPRK with the funds or equipment to provide proper T&D maintenance.

Hz to 50 Hz or from 50 Hz to 60 Hz at the intersection of the power grids. Such interconnections are costly: the cost for an interchange to convert 1,000 MW of power has been estimated at $460 million[25]. Interchange costs can be offset, however, by reductions in required reserve capacity in one or both of the interconnected systems. That is, the interconnected systems (in aggregate) need not build as many power plants, thus there is significant capital cost savings.

Although the ROK power grid operates at nominally the same frequency as the DPRK grid[x] we suspect that interconnection of the grids, in their present form, will require some power conditioning at the point of interconnection to assure that the power entering South Korea meets ROK standards for frequency and other attributes. The best way to achieve this outcome is probably to add a station near the DPRK/ROK border that converts the AC (alternating current) power from the DPRK to DC (direct current) power, then back to AC power synchronized with the ROK system for export to the south. This conversion process would be carried out using a series of solid-state devices. Power losses through these types of AC-DC-AC system are minimal, typically much less than one percent. The cost of AC-DC-AC a systems of the size that would be required is on the order of US $125 million per GW of capacity[y], or on the order of 5 percent of the costs of the PWRs to be transferred by KEDO.

This information about the types and costs of technologies required for power inter-conversion costs suggests (to us) two interesting questions related to the ordering of ROK assistance (if forthcoming) in revamping the DPRK grid:

- Should the first step in assistance be to interconnect the two grids, so that power can be sold (for example) from the KEDO-provided PWRs to South Korea; or would the ROK (and, ultimately, a unified Korea) be better served by revamping the DPRK system first to make it suitable to synchronize with the ROK grid (effectively creating one Korea-wide system), thus avoiding (at least some) power conditioning costs?
- Would it be less expensive and technically less risky (again, assuming that the power from the PWRs is to be substantially sold to South Korea) to simply connect the PWRs to the ROK grid, but <u>not</u> (at least initially) to the DPRK grid? Doing so, of course, could face political difficulties quite apart from its practicality, and might raise additional political questions about the PWR transfer. In this case, it might be necessary to build a new transmission line from the reactor site to the ROK border.

Apart from any issues of interconnection of the DPRK grid with Russia, China, or the ROK, the DPRK grid in its current configuration is likely not stable enough to allow safe operation of the PWRs to be supplied by KEDO. First, the size of the grid (at about 8,000 MW) is only marginally large enough to support 2 GW of generation capacity at one site. Crudely, no generating unit should exceed more than about 10-20 percent of the total system capability—or the available system reserve—or the operation of the whole system may be threatened due to unexpected outages[26]. Since the DPRK grid at present often reportedly operates as a set of isolated (or semi-isolated) grids rather than as a single unified grid, the issue of grid size relative to the size of the PWRs becomes even more important. There

---

[x] The fact that the power grids in the Koreas operate at a different frequency than most of the rest of continental Asia (and virtually all of Europe) is probably a legacy of the Japanese. Japan uses both 50- and 60-cycle grids ("Listing of Countries with their Frequency and Voltage", provided on ZZZAP Power World-wide Web site http://azap.com/countries.html).

[y] Order-of-magnitude cost estimate obtained in conversation (1997) with G. Jutte of Siemens Power Transmission and Distribution, Limited. There are a number of technical issues that will have to be considered when and if AC-DC-AC converters are to be used in Korea, including the line voltage on the DPRK side, the distance over which the power must be transferred, and many others. The AC-DC-AC systems could also be used to interconvert 50 Hz and 60 Hz power at the borders of the DPRK with China and Russia, suggesting that the $460 million interconnection cost listed above may be somewhat high (or may include different hardware).

are also technical issues associated with the operation of nuclear reactors under conditions where frequency fluctuations requiring reactor shut-down are frequent[z]. Further, a nuclear power plant is usually operated as a baseload plant and cannot be quickly powered up and down to follow peak demand cycles. Ascertaining whether a nuclear power plant would be technically appropriate in relation to demand patterns would require access to data either as yet uncollected, or not released by the DPRK Government. Finally, it remains an open question as to whether a nuclear power plant could be operated safely and its output dispatched, given the parlous nature of the current power operating infrastructure described earlier in this section. Admittedly, it would take 5 to 7 years (if South Korea were to be the supplier and architect-engineers) before the PWRs can be completed, which would provide some time to train power system and nuclear plant operators. Nonetheless, the status of the current power system does not inspire confidence that safety and operational objectives would be achieved in a DPRK nuclear power program.

In any case, it is clear that—unless the KEDO-supplied reactors are to be isolated, and their power sold exclusively out of the country—the DPRK grid will have to be substantially refurbished before the PWRs are brought on-line.

4. Two Scenarios of DPRK Energy-sector Development

Continuing a thread of research into the present and future of the DPRK energy sector that we have pursued since 1994[27], the authors are currently preparing a study of two scenarios of energy-sector development in the DPRK through the year 2005[28]. Some of the key assumptions and results of these scenarios are presented below. The results presented here should be considered preliminary, as we are still (as of this writing) in the process of revising our analysis.

4.1. Description of Scenarios: “Recovery” and “Decline”

Briefly, the general assumptions in the two scenarios are as follows:

1. A combination of external aid and internal transition results in a Recovery of the DPRK economy to levels slightly below those reported for 1990 by the year 2000, surpassing 1990 performance in most sectors by 2005. We have explored variants of the Recovery scenario for 2005 that include A) export of most of the power generated by the KEDO-supplied PWRs to the ROK[aa], and B) the DPRK mostly retaining the electricity from the PWRs for domestic use.
2. Internal transitions are not carried out, external aid is not forthcoming in substantial quantities, and the DPRK economy continues, albeit at a reduced rate, its overall Decline of 1990 to 1996

[z] When a reactor must be taken off-line quickly (as when frequency varies too greatly from design parameters), control rods must be rapidly inserted into the reactor core to “quench” the nuclear chain reaction. If a combination of several of these control rod fail to be inserted properly—and the more frequently reactors must be shut down, the more probable this event becomes—the chain reaction can continue, with the possible result being overheating of the reactor core.

[aa] Our assumption that the ROK would be the most likely importer of electricity generated by the PWRs is based on the ROK’s status as the supplier of the PWR technology, its rapidly growing need for generating capacity, and recent informal proposals floated by observers from ROK and the DPRK. If political and technical obstacles can be overcome, however, there is no particular reason why electricity generated by the PWRs could not be exported to China or, when the economy in the Russian Far East improves, to Russia.

through the year 2000. After 2000, the economy stabilizes and even recovers slightly (in part as a result of cooperation forced by the PWR transfer) through the year 2005.

Both cases assume that the DPRK and other parties comply with the terms of the Agreed Framework, and that the reactors supplied by KEDO can be constructed and brought on line by or before 2005—the latter is arguably a somewhat optimistic assumption.

Specific assumptions in the Recovery Scenario include:

- Re-starting the Sonbong refinery by 2000, and expanding it to 2.5 times its current capacity by 2005[bb]. The oil-fired power plant associated with the refinery undergoes a similar expansion.
- Rehabilitation (by 2000) of roughly half of the hydroelectric capacity affected by the floods, with rehabilitation of the remaining capacity by 2005.
- An improvement in generation efficiency at existing coal-fired power plants by 2005 (if power from the PWRs is exported).
- Use of HFO in coal-fired plants at a rate of 9.5 percent (2000) and 3.5 percent (2005) of fuel input.
- Industrial production (physical output) at 70 percent (2000) and 120 percent (2005) of 1990 values for most subsectors.
- Substantially increased use of passenger transport relative to 1990, and increases in freight transport consistent with increases in industrial output.
- Substantial increases in commercial/public sector electricity use.
- Substantial increases in residential use of electricity.
- Modest increases in military activity—back to 1990 levels by 2000, and above 1990 levels by 2005.

For the Decline scenario, specific assumptions include:

- Only limited changes in oil imports relative to the situation in 1996, and the Sonbong refinery remains off-line.
- Repair/rehabilitation of about one-quarter of damaged hydroelectric capacity by 2000, with an additional quarter brought back on-line by 2005.
- Use of HFO in coal-fired plants at a rate of 10.6 percent (2000) and 5 percent (2005) of fuel input.
- Industrial production at 25 to 30 percent (2000) and 33 to 40 percent (2005) of 1990 levels for most subsectors.
- Continued reduction in passenger and freight transport through 2000, with a modest increase in transport use from 2000 to 2005.
- Continued slow reductions in residential electricity use through 2000, increasing slightly from 2000 to 2005.

[bb] Russian assistance would be a strong possibility in this endeavor, particularly given that the plant is Russian built and is near the border of the DPRK with the Russian Far East.

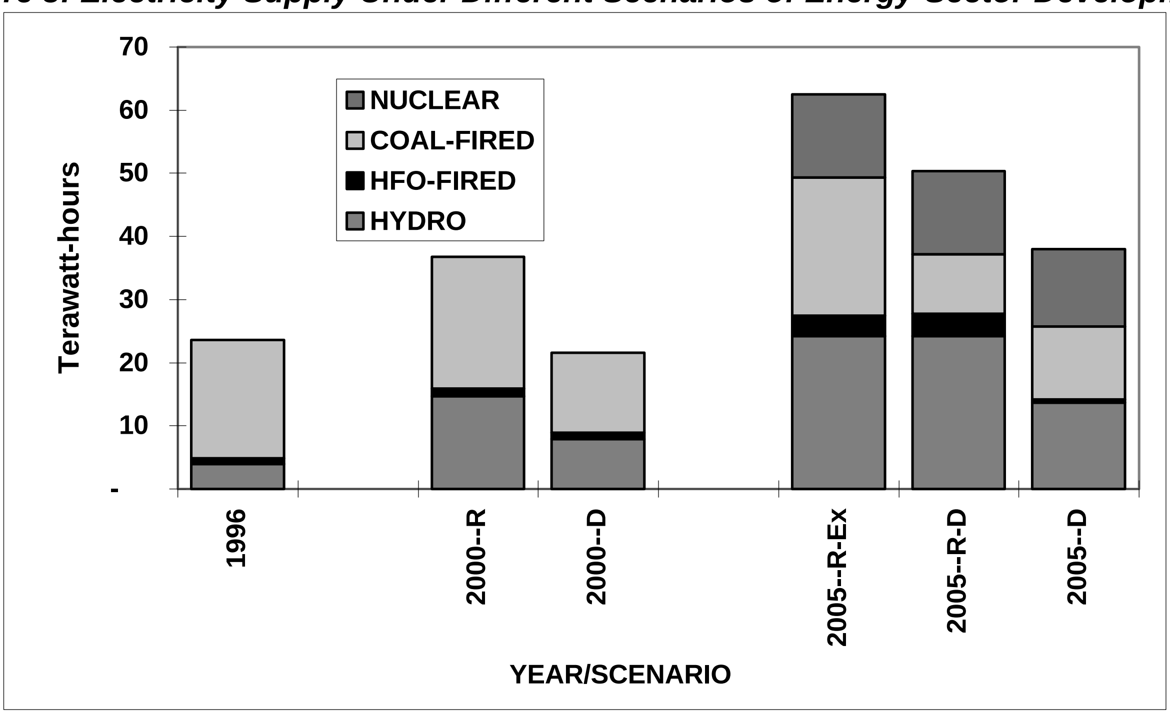
- Military activity continues to decrease slowly through 2000, recovering to 1996 levels by 2005.

4.2. Scenario Results: Electricity Supply and Demand

An overview of the results of our Recovery and Decline scenarios with regard to future electricity supply and demand is provided in Figures 3 and 4 (respectively). In the Recovery scenarios, the proportion of electricity provided by hydroelectric plants increases from 17 percent in 1996 to 40 percent in 2000. In the variant of the Recovery scenario where power from the KEDO-supplied PWRs is largely exported ("2005-R-Ex" in Figure 3), hydroelectric plants provide 38 percent of generation in 2005; in the Recovery variant where PWR generation is retained for domestic use ("2005-R-D" in Figure 3), hydroelectric facilities provide just under half of all generation. Overall generation in 2005 is higher in the Export variant of the Recovery scenario The use of thermal plants (coal- and oil-fired) drops to 26 percent of total generation in the Domestic-use variant of the Recovery scenario, as coal-fired generation is displaced by nuclear generation.

In the Decline scenario, overall electricity generation falls to just over 23 TWh by 2000, recovering to about 38 TWh in 2005. The latter figure, however, includes 12 TWh of nuclear generation, most of which is assumed to be exported. Hydroelectric production—which is assumed to be impaired due to flood-related damage, makes up a somewhat smaller portion of total electricity generation in the Decline scenario than in either of the Recovery scenario variants—even though total generation is much lower.

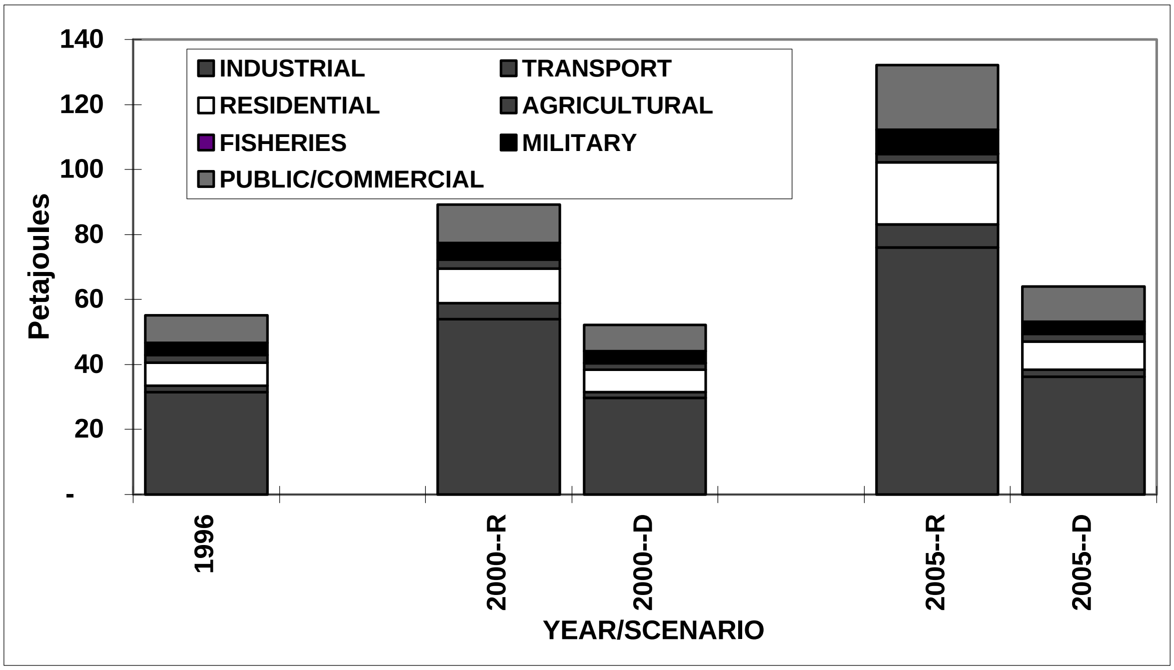
Figure 3: Electricity Supply Under Different Scenarios of Energy-Sector Development



As shown in Figure 4, the overall consumption of electricity is markedly different in the Recovery and Decline scenarios, but the general pattern of electricity demand does not change much. The fraction of electricity demand accounted for by the industrial sector is somewhat higher in the

Recovery scenarios, but not markedly so. Overall, electricity demand increases at a rate of nearly 13 percent per year through 2000 (and 8 percent per year during 2000 - 2005) in the Recovery scenario, while falling at about 1.5 percent per year through 2000 in the Decline scenario. After 2000, electricity demand in the Decline scenario increases at about 4 percent per year. Though a growth rate in electricity consumption of 13 percent per year seems high for a developing economy, two factors should be considered when assessing the merits of this scenario. First, such growth rates in electricity demand are not unprecedented in Asia, and the ROK provides a local case-in-point[29]. Second, the electricity-using infrastructure in the DPRK exists and is reportedly largely intact[cc]. As a consequence, that infrastructure does not, as in a true developing country, need to be built from the ground up[dd].

Figure 4: Electricity Demand Under Two Scenarios of Energy-Sector Development



4.3. Scenario Results: Disposition of KEDO-supplied HFO

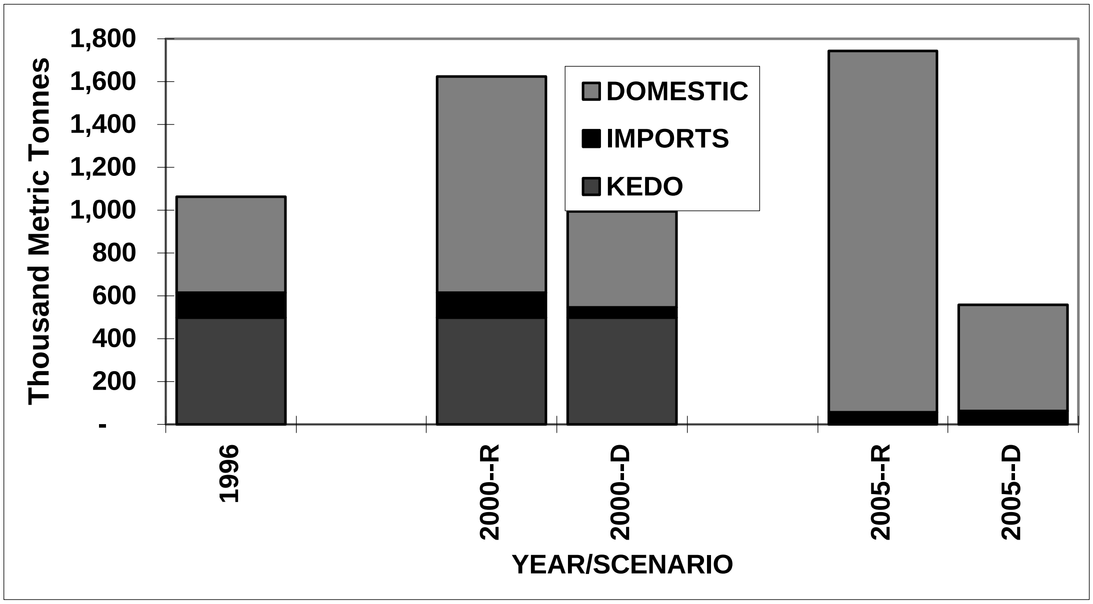
In the interim period before start-up of the PWRs to be supplied by KEDO, how might the 500,000 annual tonnes of heavy fuel oil shipped to the DPRK by KEDO be used? Figures 5 and 6 show, respectively, our scenario results for the contribution of the KEDO-supplied HFO to the total heavy fuel oil supplies in the DPRK, and the pattern of HFO use under each scenario (and in 1996). The KEDO-supplied HFO constitutes a much larger fraction of total HFO supplies in 1996 and in the Decline scenario in 2000 than in the Recovery scenario (in 2000). In 2005, refinery expansion and crude oil imports allow the DPRK to maintain and even increase supplies of HFO even in the absence of KEDO deliveries (after the PWRs are built). In the Recovery scenarios the expansion of the refinery at Sonbong provides the capacity to more than make up for the cessation of the KEDO deliveries. In the

[cc] Many of the DPRK industrial plants, though recently operating at low capacity factors or completely inactive, have apparently been kept in good enough condition (thanks in part to maintenance procedures established by the Russians) that the they can be re-started rapidly given fuel, key spare parts, and demand for goods.

[dd] Although some new infrastructure will doubtless have to be built when and if the DPRK undergoes the structural adjustments necessary for participation in the regional and global economy.

Decline scenario, 2005 HFO supplies decrease to about half of their 1996 levels as KEDO deliveries cease.

Figure 5: Supply of Heavy Fuel Oil in the DPRK Under Two Scenarios

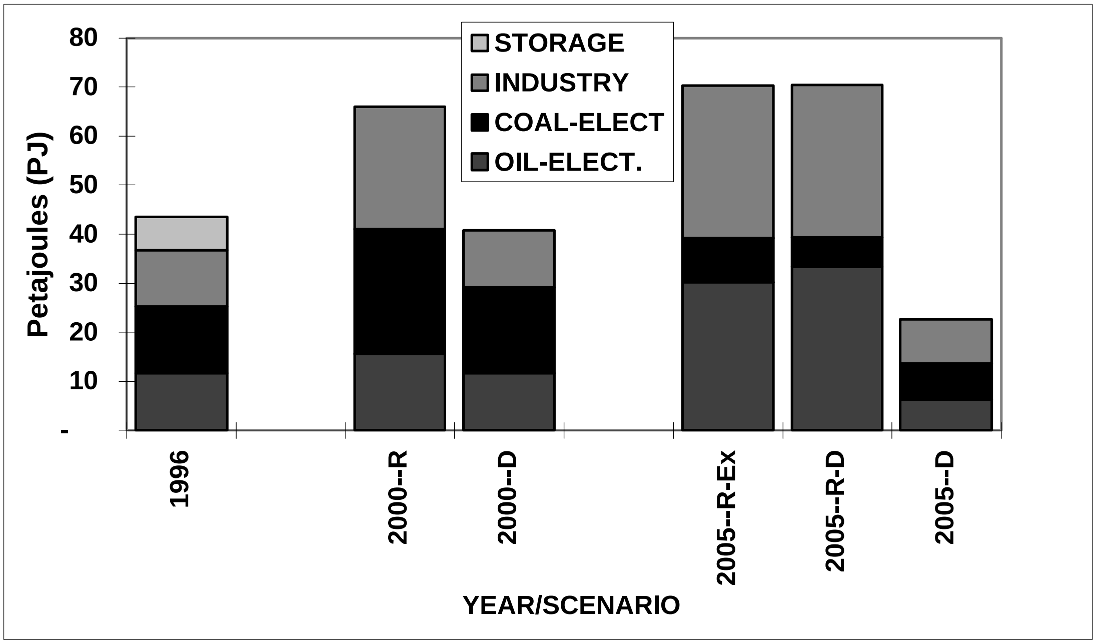


Substantially more HFO is consumed in the industrial sector in the Recovery scenarios than in the Decline scenario (see Figure 6), principally due to increased production of the mineral magnesite for export[ee]. Relative to the Recovery scenario in which PWR power is exported, more HFO is used for generation at the oil-fired plant at Sonbong in the variant of the Recovery scenario where the PWR power is used domestically, and less is used for co-firing with coal. This reduction in HFO in coal-fired power plants occurs because coal-fired power generation is decreased in the "Domestic" variant of the 2005 recovery scenario[ff].

[ee] We have assumed that some heavy oil is and will be used in industry beyond HFO use for magnesite production, but we do not know in which subsectors the oil is used. This use of HFO in "non-specified" subsectors totaled about 40% of our estimate of total industrial use of heavy fuel oil in 1990.

[ff] In fact, the proportion of HFO used in the fuel for coal-fired plants is higher in the "Domestic Use" variant than in the "Export" variant: 5.0 percent versus 3.5 percent (respectively).

Figure 6: Demand for Heavy Fuel Oil in the DPRK Under Different Scenarios



4.4. Estimate of DPRK Production of Plutonium and Other Radioactive Wastes

The extent of the DPRK's current inventory of radioactive materials and radioactive waste is not known precisely, but reportedly includes about 50 tonnes of spent fuel and up to 25 kilograms of plutonium[30]. The amount of radioactive materials and radioactive waste that will be produced when the KEDO-supplied PWRs begin operation will quickly dwarf these existing inventories, and is fairly straightforward to estimate. Assuming that the PWRs operate at a capacity factor of 75 percent in 2005 (as in our Recovery scenarios), the quantities of radioactive wastes generated would be as shown in Table 1. Plutonium production will be on the order of 400 kilograms per year, and the total spent fuel to be placed in interim or final storage will be about 40 tonnes. This quantity of spent fuel (after several years storage in cooling ponds) would require approximately four "dry casks"[gg], at a total cost of on the order of $US 1.5 to 3 million—a relatively small sum compared with the capital cost (estimated at $4.5 billion of the reactors themselves. Much more likely than dry cask storage—although that remains an option—is re-export of spent fuel to an as-yet undetermined location.

[gg] Data from US Department of Energy (1994), Multi-purpose Canister Evaluation: A Systems Engineering Approach. Report DOE/RW-0445, September, 1994. The multipurpose canister (interim storage, transport, and final disposal) described in this document is designed for PWR spent fuel. This document indicates a cost of $354,000 per cask. The rough cost range we provide is intended to include ongoing monitoring and evaluation costs.

Table 1:

Implied Annual Nuclear Materials and Waste Production from KEDO-supplied PWRs as of 2005 (Recovery Scenarios)

Reactor Capacity (MW)	2000
Annual Electricity Production (TWhe)	13.14
Spent Fuel (te heavy metal)	37.4
Plutonium (kg)	374
Strontium-90 (curies)	5,306,102
Cesium 137 (curies)	6,053,440
Low-Level Wastes (cubic meters)	
High Estimate	1,501
Low Estimate	878
Low-Level Wastes (Curies)	
High Estimate	8,000
Low Estimate	2,279
Dry Casks needed, Spent Fuel Storage	4

Under the terms of Agreed Framework, the DPRK's current inventory of spent fuel is being placed into storage/transport canisters under international supervision. This process of "canning" the spent fuel is proceeding more or less according to schedule, and is approximately 80 to 90 percent complete as of this writing[31]. The process of placing the fuel in canisters is necessary both to stabilize the fuel for storage and to render it suitable for shipping out of the country for reprocessing. The placement of the fuel in canisters is therefore designed to be reversible: the canisters can be opened and fuel can be removed for reprocessing. It is expected that the canning process will be completed as or before the major components of the PWRs are delivered to the DPRK.

Given the above estimates of the DPRK plutonium inventory and of nuclear materials production by the KEDO-supplied PWRs, compliance or non-compliance with the terms of the Agreed Framework offers the following overall outcomes:

1. Assuming the terms of the Agreed Framework are adhered to, the existing nuclear facilities in the DPRK will remain frozen, with existing stocks of spent fuel (shortly) stabilized and under international supervision. This means that the DPRK will have effectively zero plutonium at its disposal until the KEDO-supplied PWRs are operating. When the PWRs come on line, roughly 400 kg of plutonium will be generated each year, but this larger amount (compared with existing DPRK stocks) of plutonium will come into being under a regional and international political climate that is more cooperative—as a result, in part, of all of the cooperative arrangements necessary for the construction and operation of the PWRs—than it is today. Thus the larger quantity nuclear material generation is offset by better international supervision and control over the material.
2. If the terms of the Agreed Framework are abrogated, production of smaller amounts of plutonium in the DPRK may continue, but will take place within a much less cooperative political environment. Plutonium production in the DPRK in this case may be substantially hidden from international oversight[hh], and diversion of existing stocks of nuclear material becomes more possible.

[hh] A discussion of the ramifications of the Agreed Framework is provided in L. S. Spector (1996), "U.S.-DPRK Agreed Framework on Nuclear and Related Issues: Congressional Testimony", chapter 4 in Peace and Security in Northeast Asia: The Nuclear Issue and the Korean Peninsula, Young Whan Kihl and Peter Hayes, editors. M.E. Sharpe, Armonk, NY.

5. Implications of Results, and Strategies for Cooperation

5.1. Summary of Current Situation, and Impact of KEDO Activities

Electricity production in the DPRK has fallen dramatically since 1990. This decline, however, has more to do with the weakness of the DPRK economy than from a specific problems in the DPRK electricity sector, although the two problems are definitely related. A major uncertainty is how fast the hydroelectric plants that were damaged by the floods of 1995 and 1996 can be restored to their pre-flood capabilities. Assuming that the hydro capacity can be restored, at least in large part, with in a few years, our general conclusion is that under virtually any scenario, the DPRK will probably have adequate electricity generation capacity to meet its own needs through the year 2005 without adding to its existing stock of generating facilities (including those recently completed or nearing completion). Under scenarios assuming recovery of the DPRK economy, the existing generation and coal-mining capacity will be used at near-1990 levels by 2005. Using the power plants at those levels will almost undoubtedly require substantial rehabilitation or upgrading of many units, as well as of the transmission and distribution system. If recovery continues past 2005 (and one assumes that it would), more generating capacity or electricity imports will probably be needed shortly after 2005. The timing of this need, however, depends on whether A) electricity from the KEDO-supplied PWRs is exported or used internally, and B) the status, by that time, of the thermal and hydro power plants listed as "under construction" as of 1996. Coal supplies should be adequate to fuel generation under any circumstance[ii], the major uncertainty being the status of the coal transport infrastructure. Under a scenario that postulates a continued decline in the DPRK economy, the present generation capacity is much more than adequate.

KEDO heavy fuel oil shipments to the DPRK presently allow the operation of the oil-fired plant at Sonbong. In the absence of the KEDO deliveries, the Sonbong plant would be used considerably less, if at all, due to lack of HFO. The HFO supplied by KEDO is also used in coal-fired plants to help to increase the energy content of the fuel. This helps to offset what is reportedly the declining quality of coal used in power plants, and helps to boost the efficiency of coal-fired power generation. The use of thermal power plants, both coal- and oil-fired, has grown markedly more important over the last two years due to the damage to hydroelectric facilities. Absorption of the KEDO HFO (along with domestically-refined supplies) by the DPRK economy will be more difficult under a "Decline" scenario, as more of the oil will have to be diverted to coal-fired power plants.

The importance of the transfer of the KEDO-supplied PWRs to the DPRK is primarily in its security and political implications. The major accomplishments of the transfer, if it is successful, will have been having brought the DPRK into cooperative contact with the ROK and the other KEDO partners, to have reduced the potential for nuclear proliferation, and to have started a series of greater engagements between the DPRK and other nations within and outside of the region. The importance of the PWRs to the energy sector in the DPRK is, in our view, a secondary matter, as the same generation capacity (or effective capacity) could very likely be supplied for far less money if investments in

---

[ii] Although it is unknown how competitive the overall economics of continued coal production in the DPRK may ultimately be relative to other fuels—such as natural gas—if such fuels become available.

upgrading and refurbishing the energy supply and demand infrastructure in the DPRK, plus investments in selected cost-effective new generation, were pursued instead. Paradoxically, the use of the KEDO-supplied reactors within the DPRK grid will likely require a substantial rehabilitation of the transmission and distribution system, and likely other related energy and transport infrastructure as well. These required "spin-off" improvements may ultimately prove more useful to the DPRK than the nuclear reactors themselves.

5.2. Strategies for Cooperation and Engagement

If the conditions of the Agreed Framework continue to be upheld, KEDO oil deliveries continue to be made, work on the PWRs proceeds as planned, and peace talks between the DPRK, ROK, and other parties are productive, circumstances should be conducive to engaging the DPRK in bilateral and multilateral cooperation activities on a number of fronts. A few possibilities are[jj]:

Cooperation on Technology Transfer for Manufacturing of Efficient Electricity-Sector Equipment and Renewable Technologies

Sustained economic recovery in the DPRK will likely require that a large portion of the electricity-sector infrastructure—including electricity supply and demand equipment—will have to be substantially refurbished or completely replaced. Cooperation to assist the DPRK in *manufacturing these types of devices*, for the domestic use and potentially to export to other countries, will help toward recovery. Cooperation to establish such manufacturing capability would also ultimately reduce pollution within the countries of the Northeast Asia, and would reduce trans-boundary transport of pollution to the rest of the region. Upgrading the electricity-sector infrastructure in the DPRK would help to make their electricity systems more technically suitable for participation in a regional power grid. *Cooperation on production of renewable energy technologies* is also an attractive possibility from an economic and environmental perspective. Wind turbine-generators are another intriguing possibility, given the apparent success of such ventures in former East-bloc nations[32] and the historical emphasis on machinery manufacture in North Korea. *Promotion of domestic production of energy-efficient products* is another potential cooperation strategy. This approach could involve ventures such as establishment of foreign-owned factories for making appliances, lighting products, and other types of energy-efficiency equipment, as well as joint ventures between foreign companies and concerns in North Korea, China, and other countries in which foreign technology is licensed for production in the region. Examples of foreign-owned factories and licensing of technologies abound in the developing world, including a number of ventures in Eastern Europe and the Former Soviet Union and in China. It is likely that the earliest examples of such technology transfer to the DPRK (in particular) will come in the context of ventures in the Rajin Sonbong Free-Trade Zone.

In addition to assistance in manufacturing new energy-sector devices, and perhaps of more immediate concern, the DPRK will likely need help in retrofitting key power plants and T&D infrastructure. The oil-fired generation facility in the DPRK at Sonbong, for example, could likely be converted to combined-cycle operation, with a considerable increase in both capacity and generating efficiency. Retrofitting coal-fired plants for pollution control, fuel substitution (such as natural gas and

---

[jj] A more complete discussion of opportunities for regional cooperation is contained in P. Hayes and D. Von Hippel, Comparative Approach to Regional Cooperation for a Clean, Efficient Electric Power Industry, prepared for the Conference: "Comparative Approaches to Cooperative Development of Power Systems for Northeast Asia", organized by the Northeast Asia Economic Forum, Ulaan Baatar, Mongolia, August 18 - 20, 1997. The authors' other works on the topic of the DPRK energy sector (as listed earlier in this paper) also provide suggestions as to topics for cooperative projects involving the DPRK.

low-sulfur oil), widening the use of fluidized-bed boilers and potentially integrated gasification combined-cycle coal-fired units, boiler refurbishing, the addition of boiler process control equipment, and a host of other upgrades to existing infrastructure will be necessary to assist the DPRK into a Recovery mode. Many countries inside (Japan, the ROK, and Russia) and outside (the United States) Northeast Asia have the expertise needed to help with these infrastructural upgrades.

Involving the Private Sector in Investments and Technology Transfer

Much of the money and other assistance necessary to help the DPRK toward recovery and economic development will have to come from the more flexible and fast-moving private sector. It is likely that inducements and guarantees—possibly supplied by other governments of the region—will be necessary in order to mediate the risk to private firms of dealing with the DPRK.

As noted above, one way that the governments of the region, and governments of other countries with an interest in what happens in Northeast Asia (including the United States and Russia) can help in this regard is to *promote joint ventures and licensing agreements*. The governments of the region and other interested parties, should promote joint ventures and licensing agreements between DPRK concerns (governmental or otherwise) and foreign firms with energy-efficient technologies to produce. Compact fluorescent light bulb factories are a commonly-cited example of potential energy technology transfers[33]. A wide variety of efficient industrial equipment and controls (including adjustable speed drive motors and improved industrial and utility boilers), efficient household appliances and components, and efficient building technologies have already been introduced to China through commercial channels are being or will be manufactured there. Local manufacturing can be instrumental in reducing the cost of cleaner technologies, including pollution control equipment, renewable electricity generation equipment, and energy-efficiency technologies. Funding is needed to adapt imported "clean" technologies so that they can be manufactured locally and so that they are applicable to local conditions[kk].

Cooperation on Nuclear Issues

As the ROK will play a major role in providing equipment for and constructing the nuclear plants in the DPRK, nuclear cooperation between those countries, at least as far as plant assembly, fuel production, and (probably) operation, is a given. The issue of how to manage the various categories of nuclear waste, however, has not been settled in a satisfactory way in the DPRK or, for that matter, in any of the countries of the region. Proposals have been made for an "Asiatom"—a cooperative regional organization designed to coordinate nuclear activities in the countries of the region (and possibly, in the more distant future, found and manage a regional waste repository)[ll]. Even short of such a formal regional organization, the ROK, Japan, and have expertise and technology in techniques for handling of nuclear materials that could be made available to assist the nuclear program of the DPRK[mm].

[kk] Adaptation of technologies would include, for example, making particular devices suitable for the unit sizes and fuel compositions found in-the country where they are to be manufactured and applied.

[ll] See, for example, Atsuyuki Suzuki (1996), A Proposal on International Collaboration with Nuclear Power Development in East Asia,; and Jor-Shan Choi (1996), An East Asian Regional Compact for the Peaceful Use of Nuclear Energy, both prepared for the Energy Workshop of the Northeast Asia Cooperation Dialogue V, Institute of Foreign Affairs and National Security, Seoul, Korea, September 11-12, 1996.

[mm] A forthcoming Nautilus Institute Report (Two Scenarios of Nuclear Power and Nuclear Waste Production in Northeast Asia) will describe the authors' analysis of spent fuel projections and technical options for interim storage of nuclear materials for the countries of the region.

Cooperation on Environmental Quality

The DPRK at present has neither the financial resources nor the expertise to simultaneously mount a meaningful assault on its environmental problems and promote a sustained recovery without substantial cooperation from countries inside and outside the region. Of the many environmental concerns currently facing the nations of Northeast Asia, the problem of "acid rain" or "acid precipitation" presents perhaps the most potent combination of immediate and ongoing impact and regional scope. Acid rain, caused primarily by emissions of nitrogen and sulfur oxides, is already having an environmental and economic impact in the countries of Northeast Asia. Acid gas emissions from the DPRK affect both the DPRK and other countries of the region, and the DPRK is also the recipient of acid rain exported from its neighbors[nn].

Helping the DPRK to address acid rain issues, including providing assistance with reducing acid gas emissions and with monitoring of acid rain and its impacts, may provide an approach that indirectly addresses some of the underlying energy infrastructure issues in the DPRK in a way that acceptable to the DPRK and welcomed by its neighbors. Assistance with acid gas emissions reduction could take several forms, including:

- *Providing the DPRK with fuel oil that has a lower sulfur content*. Use of the relatively high-sulfur HFO supplied by KEDO may or may not result in higher emissions of SO_x than combustion of the fuels that the DPRK would be forced to use in the absence of KEDO supplies[oo], but making lower-sulfur HFO available to the DPRK would certainly reduce SO_x emissions by roughly 14,000 tonnes per year during the years KEDO supplies HFO[pp]. This reduction is equivalent to under 2 percent of our estimate of 1990 DPRK SO_x emissions, but is more than 3 percent of 1996 emissions.
- *Helping the DPRK with modifications of boilers and burners to improve efficiency* (and thus reduce all pollutant emissions) *or to add simple "end-of-pipe" emissions reduction equipment* to selected plants[qq]. A UNDP project to introduce Chinese fluidized-bed boiler technology to the DPRK is already underway. This project could be augmented by assistance from KEDO or others, and might provide a vehicle for interesting and engaging China (and re-engaging Russia, as a supplier of less-expensive and DPRK-compatible infrastructure) in DPRK energy issues.
- Help to provide training in soil conservation and in environmentally sustainable methods of high-yield agriculture.

[nn] Hayes, P., and L. Zarsky (1995), "Acid Rain in a Regional Context", in Science and Technology Policy Institute and the United Nations University's Joint Seminar on "The Role of Science and Technology in Promoting Environmentally Sustainable Development. Science and Technology Policy Institute and The United Nations University, Seoul, Republic of Korea, June, 1995. The Hayes and Zarsky paper builds on and summarizes ongoing work on the "RAIN-Asia" project, a joint effort of the International Institute for Applied Systems Analysis (IIASA), Argonne National Laboratory, and many others. See, for example, D. Streets et al, "Emissions and Control", work in progress in RAINS-Asia: An Assessment Model for Acid Rain in Asia. April, 1995.

[oo] Estimation of the net effect of use of KEDO-supplied oil on SO_x emissions involves consideration of the amount of hydroelectric production that would have been used in the absence of KEDO HFO, the amount and types of domestic coal that would replace the KEDO oil, and the relative efficiencies of combustion of HFO versus domestic coal.

[pp] Assumes low-sulfur fuel oil (LSFO) of 0.6 weight percent sulfur or less, HFO sulfur content of about 2 percent, and combustion of the full allotment of KEDO-supplied HFO in boilers lacking equipment to control SO_x emissions.

[qq] See Von Hippel, 1996 (Von Hippel, D. (1996), Technological Alternatives to Reduce Acid Gas and Related Emissions from Energy-Sector Activities in Northeast Asia. Paper prepared for Second Policy Study Group Meeting on "Energy, Environment and Security in Northeast Asia", Nautilus Institute for Security and Sustainable Development, Berkeley, California, USA.), for a review of the technical alternatives for reducing acid gas emissions.

In addition, the DPRK has some acid rain monitoring sites that could be incorporated into regional Northeast Asia monitoring networks. Providing assistance with this integration process would help to build confidence within the DPRK and between the DPRK and its neighbor countries.

Strengthening Regulatory Agencies and Educational/Research Institutions in the DPRK

There is a need to strengthen a variety of North Korea's government institutions—particularly those whose mandate includes environmental performance—through a combination of provision of information, persuasion of leaders, training of personnel, and supplying institutions with needed equipment. Many of these tasks are being started by UNDP and other ongoing programs.

One general area in which DPRK institutions could be strengthened is in their ability to *implement standards, and enforce them*. DPRK officials have made general statements about their support for energy efficiency and environmental protection. The next step is to codify these in terms of quantitative standards for the efficiency of new appliances and equipment, as well as stringent effluent standards for new—and perhaps eventually, existing—factories, power plants, residential heating boilers, vehicles and other major sources of pollution. Once standards are set, it will be necessary to create the capability to enforce them by recruiting and training enforcement personnel and supplying them with the tools necessary to do their job (testing equipment and adequately equipped labs, for example) and the high-level administrative support needed for credible implementation of sanctions.

There is not as yet in the DPRK, a single *center of technical excellence* that is devoted to the study and promotion of *energy efficiency and renewable energy* opportunities. We would encourage the formation of such an institution, which could be modeled on existing institutions like the Beijing Energy Conservation Center and a similar Center in Russia[34]. It is possible that the Center for the Rational Use of Energy (CRUE), formed within the existing Institute of Thermal Engineering under a UNDP project, could be strengthened through a combination of North Korean and extramural support into such a center of excellence. The first step will be to start training current CRUE staff in the fundamentals of energy-efficient technologies and analysis.

6. Endnotes

[1] Von Hippel, D., and P. Hayes (1995), The Prospects for Energy Efficiency Improvements in the Democratic People's Republic of Korea: Evaluating and Exploring the Options. Nautilus Institute Report, Nautilus Institute for Security and Sustainable Development, Berkeley, California, USA. P. Hayes and D.F. Von Hippel (1997), "Engaging North Korea on Energy Efficiency". Chapter 9 in Peace and Security in Northeast Asia: The Nuclear Issue and the Korean Peninsula, Young Whan Kihl and Peter Hayes, editors. M.E. Sharpe, Armonk, NY. Von Hippel, D.F., and P. Hayes (1996) "Engaging North Korea on Energy Efficiency". The Korean Journal of Defense Analysis, Volume VIII, No. 2, Winter 1996. Pages 177 - 221.
[2] Nikkei Shimbun, 5/19/97, "ROK Vice Prime Minister Understands Japan's Careful Stance on Food Aid to DPRK". Page 8.
[3] Korean Peninsula Energy Development Organization (KEDO, 1996), Korean Peninsula Energy Development Organization, Annual Report, 1995. KEDO, Washington, DC, July 31, 1996.
[4] Von Hippel, D., and P. Hayes (1995), The Prospects for Energy Efficiency Improvements in the Democratic People's Republic of Korea: Evaluating and Exploring the Options. Nautilus Institute Report, Nautilus Institute for Security and Sustainable Development, Berkeley, California, USA. P. Hayes and D.F. Von Hippel (1997), "Engaging North Korea on Energy Efficiency". Chapter 9 in Peace and Security in Northeast Asia: The Nuclear Issue and the Korean Peninsula, Young Whan Kihl and Peter Hayes, editors. M.E. Sharpe, Armonk, NY. Von Hippel, D.F., and P. Hayes (1996) "Engaging North Korea on Energy Efficiency". The Korean Journal of Defense Analysis, Volume VIII, No. 2, Winter 1996. Pages 177 - 221.
[5] Federal Research Division, US Library of Congress (1993), North Korea, A Country Study. Edited by Andrea M. Savada. Research completed 1993. US Government Printing Office, Washington, DC, USA. Available (in part) on the World-wide web at http://lcweb2.loc.gov/frd/nktoc.html#nk0006.
[6] United Nations (1994), 1994 Energy Statistics Yearbook. United Nations, New York, NY, USA.
[7] Moiseyev, V. (1996), The Electric Energy Sector of the DPRK Paper presented at the workshop on "Security on the Korean Peninsula," November 21, 1996, Diplomatic Academy, Moscow, sponsored by the Center for Nonproliferation Studies at the Monterey Institute of International Studies (with funding from the Rockefeller Foundation).
[8] Trigubenko, M. (1991), "Industry of the DPRK". Paper presented at Korea Development Institute symposium, Seoul, ROK, October, 1991. Quoted in The Economist Intelligence Unit (1993?), China, North Korea Country Profile 1992-1993. The Economist Intelligence Unit, London, United Kingdom.
[9] Document in authors' files [VO1].
[10] Trigubenko, M. (1991), "Industry of the DPRK". Paper presented at Korea Development Institute symposium, Seoul, ROK, October, 1991. Quoted in The Economist Intelligence Unit (1993?), China, North Korea Country Profile 1992-1993. The Economist Intelligence Unit, London, United Kingdom.
[11] Moiseyev, V. (1996), The Electric Energy Sector of the DPRK Paper presented at the workshop on "Security on the Korean Peninsula," November 21, 1996, Diplomatic Academy, Moscow, sponsored by the Center for Nonproliferation Studies at the Monterey Institute of International Studies (with funding from the Rockefeller Foundation).
[12] Document in authors' files [EE1].
[13] United Nations (1994), 1994 Energy Statistics Yearbook. United Nations, New York, NY, USA.
[14] Document in authors' files [EE1].
[15] Federal Research Division, US Library of Congress (1993), North Korea, A Country Study. Edited by Andrea M. Savada. Research completed 1993. US Government Printing Office, Washington, DC, USA. Available (in part) on the World-wide web at http://lcweb2.loc.gov/frd/nktoc.html#nk0006.
[16] Trigubenko, M. (1991), "Industry of the DPRK". Paper presented at Korea Development Institute symposium, Seoul, ROK, October, 1991. Quoted in The Economist Intelligence Unit (1993?), China, North Korea Country Profile 1992-1993. The Economist Intelligence Unit, London, United Kingdom.
[17] Document in authors' files [EE1].
[18] Document in authors' files [EE1].
[19] ROK Ministry of Unification (1996), "Electric Generation Capacity and Actual Generation". Obtained from World-wide web site http://www/unikorea.go.kr/eng/ja/table/enk21.htm.
[20] Moiseyev, V. (1996), The Electric Energy Sector of the DPRK Paper presented at the workshop on "Security on the Korean Peninsula," November 21, 1996, Diplomatic Academy, Moscow, sponsored by the Center for Nonproliferation Studies at the Monterey Institute of International Studies (with funding from the Rockerfeller Foundation).

[21] A. Karabanov (1993); personal communication.
[22] Korea Energy Economics Institute (KEEI, 1991), Yearbook of Energy Statistics, 1991. KEEI, Seoul, Republic of Korea.
[23] Moiseyev, V. (1996), The Electric Energy Sector of the DPRK Paper presented at the workshop on "Security on the Korean Peninsula," November 21, 1996, Diplomatic Academy, Moscow, sponsored by the Center for Nonproliferation Studies at the Monterey Institute of International Studies (with funding from the Rockefeller Foundation).
[24] Hayes, P. (1997), "Supply of Light-Water Reactors to the DPRK". Chapter 3 in Peace and Security in Northeast Asia: The Nuclear Issue and the Korean Peninsula, Young Whan Kihl and Peter Hayes, Editors. M.E. Sharpe, Armonk, New York, USA.
[25] UNDP (1994), Studies in Support of Tumen River Area Development Programme. Prepared by KIEP, Seoul, ROK for the UNDP, July, 1994.
[26] Barber Associates, LDC Nuclear Power Prospects, 1975-1990: Commercial, Economic and Security Implications, ERDA-52 UC-2, p. 11-8.
[27] Von Hippel, D., and P. Hayes (1995), The Prospects for Energy Efficiency Improvements in the Democratic People's Republic of Korea: Evaluating and Exploring the Options. Nautilus Institute Report, Nautilus Institute for Security and Sustainable Development, Berkeley, California, USA. P. Hayes and D.F. Von Hippel (1997), "Engaging North Korea on Energy Efficiency". Chapter 9 in Peace and Security in Northeast Asia: The Nuclear Issue and the Korean Peninsula, Young Whan Kihl and Peter Hayes, editors. M.E. Sharpe, Armonk, NY. Von Hippel, D.F., and P. Hayes (1996) "Engaging North Korea on Energy Efficiency". The Korean Journal of Defense Analysis, Volume VIII, No. 2, Winter 1996. Pages 177 - 221.
[28] Von Hippel, D., and P. Hayes (1997) Demand for and Supply Of Electricity And Other Fuels in the Democratic People's Republic of Korea (DPRK): Results and Ramifications for 1990 Through 2005, Prepared for the Northeast Asia Economic Forum/East-West Center. Nautilus Institute, Berkeley, CA, USA.
[29] Korea Energy Economics Institute (KEEI), Yearbook of Energy Statistics, 1996. KEEI, Seoul, ROK. 1996.
[30] United States General Accounting Office (1997), Report to the Chairman, Committee on Energy and Natural Resources, U.S. Senate. Nuclear Proliferation: Implementation of the U.S./North Korean Agreed Framework on Nuclear Issues. US GAO, Washington, DC, USA. Report # GAO/RCED/NSIAD-97-165.
[31] Conversation with E. Fei, US Department of Energy, 8/15/97.
[32] Martinot, E. (1994), Technology Transfer and Cooperation for Sustainable Energy Development in Russia: Prospects and Case Studies of Energy Efficiency and Renewable Energy. Energy and Resources Group, University of California at Berkeley, Berkeley, California, USA. [Summary of a Ph.D. Dissertation - Draft]
[33] Sathaye, J., R. Friedmann, S. Meyers, O. de Buen, A. Gadgil, E. Vargas, and R. Saucedo (1994), "Economic Analysis of Ilumex: A Project to Promote Energy-Efficient Residential Lighting in Mexico". Energy Policy, February, 1994, pp. 163 - 171.
[34] Chandler, W. U., Z. Dadi and J. Hamburger (1993), U.S .- China Cooperation for Global Environmental Protection. Pacific Northwest Laboratory, Richmond, Washington, USA. Chandler, W. U. (1993), AISU's China Program Update June 1993. Battelle, Pacific Northwest Laboratory, Richmond, Washington, USA.