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New Advanced Small and Medium Nuclear Power Reactors: Possible Nuclear Power Plants for Australia

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SUMMARY. In recent years interest has increased in small and medium sized nuclear power reactors for generating electricity and process heat. This interest has been driven by a desire to reduce capital costs, construction times and interest during construction, service remote sites and ease integration into small grids. The IAEA has recommended that the term "small" be applied to reactors with a net electrical output less than 300 MWe and the term "medium" to 300-700 MWe. A large amount of experience has been gained over 50 years in the design, construction and operation of small and medium nuclear power reactors. Historically, 100% of commercial reactors were in these categories in 1951-1960, reducing to 21% in 1991-2000.

The technologies involved include pressurised water reactors, boiling water reactors, high temperature gas-cooled reactors, liquid metal reactors and molten salt reactors. Details will be provided of two of the most promising new designs, the South African Pebble Bed Modular Reactor (PBMR) of about 110 MWe, and the IRIS (International Reactor Innovative and Secure) reactor of about 335 MWe. Their construction costs are estimated to be about US$1,000/kWe with a generating cost for the PBMR of about US1.6c/kWh. These costs are lower than estimated for the latest designs of large reactors such as the European Pressurised Reactor (EPR) designed for 1,600 MWe for use in Europe in the next decade.

It is concluded that a small or medium nuclear power reactor system built in modules to follow an increasing demand could be attractive for generating low cost electricity in many Australian states and reduce problems arising from air pollution and greenhouse gas emissions from burning fossil fuels.

1. Introduction

A total of 441 nuclear power plants were operating in 30 countries at the end of 2002 and producing 16% of global electricity. These plants represent a mature technology with over 10,000 reactor operating years of experience. In addition, the construction of seven new reactors started in 2002 bringing the total under construction to 32.

The International Atomic Energy Agency (IAEA) has recommended that the term "small" be applied to reactors with a net electrical output of less than 300MWe and the term "medium" to 300-700MWe. Historically, 100% of commercial reactors were in these two categories in 1951-1960, 55% in 1961-1970, 16% in 1971-1980, 25% in 1981-1990 and 21% in 1991-2000. In addition, a large number of nuclear-powered ships were built with reactors of < 300MWe and many research reactors of < 100MWe.

Interest has increased in recent years in small and medium reactors for generating electricity and process heat. This interest has been driven by a desire to reduce capital costs, construction times and interest during construction, service remote sites and ease integration into small grids. The present paper reviews past work and recent work on new advanced designs of small and medium power reactors and suggests that one of these systems may be suitable for generating low cost electricity in Australia.

2. Technology of Small and Medium Reactors

The technologies used in small and medium nuclear reactors over the last 50 years have been diverse:

- Pressurised water reactors;
- Boiling water reactors;
- High temperature reactors;
- Liquid metal reactors; and
- Molten salt reactors.

Many of the early designs were improved and increased in power output in an evolutionary way, and a power output of 1,300MWe became common in many countries. The safety systems of these evolved systems were largely "active" in the sense that they involved electrical or mechanical operation on command. Some engineered systems operated passively, eg. pressure relief valves. A high level of redundancy was built into all of these reactors.

In recent years and in new designs, inherent or passive safety has been given greater attention. In these systems safety depends only on physical phenomena such as convection, gravity or resistance to high temperatures, not on the functioning of engineered systems. It has been possible at the same time to reduce the complexity of the many sub-systems and thereby reduce capital costs and maintenance costs. The evolution to larger sizes to reduce costs has been replaced with simplification, modular construction and passive or inherent safety concepts.

3. Review of Small and Medium Reactors

A list of small and medium reactors with development well advanced is given in **Table 1**. The list includes four types: pressurised and boiling water reactors, high temperature gas-cooled reactors, liquid metal cooled reactors, and molten salt reactors.

Some countries have had a considerable experience in the design, construction and operation of small reactors for remote sites or for special purposes eg. desalination. Examples of these are:

- The Russian KLT-40 reactor which is well proven in ice breakers and now proposed for remote areas on land or on barges to produce heat and 35MWe and to operate for three years without refuelling. After a 12-year cycle the reactor would be taken to a central facility for overhaul and storage of spent fuel.
- Technicatome in France has developed the NP-300 design from its submarine power plants and is aiming it at export markets for power, heat and desalination. It can be built with outputs of 100-300MWe and up to 500,000 m^3/day desalination.
- Four small reactors are operating at the Bilibino co-generation plant in Siberia. These four 62MWt units are a graphite-moderated boiling water design and produce steam for district heating and 11 MWe each. They have operated since 1976 and are claimed to be cheaper than fossil fuel alternatives in the Arctic region.
- The TRIGA power system is a PWR concept developed by General Atomics based on its well-proven TRIGA research reactors. The power system is planned as a 64MWt, 16.4MWe pool reactor operating at relatively low temperature.

Table 1. List of Small- and Medium-Reactors with Development Well Advanced

Name	Electrical Power Output & Type	Developers
CAREM	27 MWe PWR	CNEA & INVAP, Argentine
KLT-40	35 MWe PWR	OKBM, Russia
MRX	30 - 100 MWe PWR	JAERI, Japan
IRIS (See section 4.2)	335 MWe PWR	Westinghouse, USA, & others
SMART	100 MWe PWR	KAERI, Korea
NP-300 (See section 3)	100 - 300 MWe PWR	Technicatome, France
Modular SBWR	50 MWe BWR	GE & Purdue University, USA
PBMR (See section 4.1)	114 MWe HTGR	ESKOM, South Africa, & others
GT-MHR (See section 4.3)	285 MWe HTGR	GA, USA, & others
BREST	300 MWe LMR	RDIPE, Russia
FUJI	100 MWe MSR	ITHMSO, Japan, Russia, USA
TRIGA (See section 3)	16.4 MWe PWR	GA, USA
ACR-700 (See section 4.3)	700 MWe PWR	AECL. Canada

4. Promising New Modular Designs

In this short review paper, and in the short time available for presentation in the conference, it is not possible to provide the details and the relative merits of all of the designs listed in Table 1. The following sections will therefore provide outlines of two promising designs which have attracted considerable interest worldwide. These are the South African Pebble Bed Modular Reactor (PBMR) of about 110 MWe, and the IRIS (International Reactor Innovative and Secure) reactor of about 335 MWe.

These designs will then be compared with two other new designs of medium-sized reactors:

- The Advanced CANDU Reactor, ACR-700, from Atomic Energy of Canada Ltd (700MWe) based on evolutionally development of its successful CANDU 600MWe design built in recent years in China and Korea; and
- The Gas-Turbine-Modular Helium Reactor, GT-MHR (285MWe modules) developed by General Atomics, USA, and optimised to burn plutonium.

4.1 The Pebble Bed Modular Reactor (PBMR)

The PBMR illustrates the application of advanced high temperature gas-cooled technology based on considerable experience in the building of innovative designs in the 1960s and 1970s, particularly in the USA and Germany.

The South African Electricity Utility, ESKOM, currently operates two Framatome-designed 900MWe PWRs at its Koeberg Nuclear Power Station near Capetown. ESKOM has been studying the feasibility of introducing high temperature gas-cooled reactors into the South African network since 1993 as well as for export. The initial project was to design a Pebble Bed Modular Reactor with a 100MWe module to operate at a 900°C outlet temperature with helium cooling coupled to a direct helium cycle turbine. The fuel was based on a proven German design of coated uranium particles contained in moulded graphite spheres of 60 mm diameter (slightly smaller than tennis balls).

Further design optimisation occurred such that by 1998 the revised design was for a module of 114MWe (285MWt) output capable of load-following with on-load fuel management and a 40 year lifetime. The capital cost was estimated to be less than US$100M per module and the target generating cost was about US$1.6c/kWh. These costs were remarkably low and were competitive with electricity production costs in coal-fired stations close to South African coal mines and probably anywhere in the world.

The concept involved building the modules in a centralised factory in 2, 4 and 8-pack layouts (see Figure 1) and these would allow the modules to be brought on line successively as they are completed on site. Four modules are claimed to fit on a site the size of a football field.

The PBMR reactor consists of a vertical steel pressure vessel lined with graphite bricks. The vessel is connected to two turbo compressor units which are connected to the generator, power turbine and recuperator (see Figure 2). The fuel balls contain uranium dioxide particles triple-coated with silicon carbide and pyrolytic carbon in 60 mm diameter moulded graphite spheres (see Figure 3). The helium turbine development has been undertaken with industry and the University of Potchefstroom where a test rig was operated successfully to demonstrate a closed cycle multi-shaft turbine on a recuperated Brayton cycle (see test rig in Figure 4).

The Environmental Impact Assessment process has been completed and final reports sent to the South African Dept of Environmental Affairs and Tourism. It is expected that construction of the demonstration module and associated fuel plant at Koeburg will be approved shortly. The estimated low capital cost of about US$1,000/kWe and low generating cost are expected to make the project attractive for export.

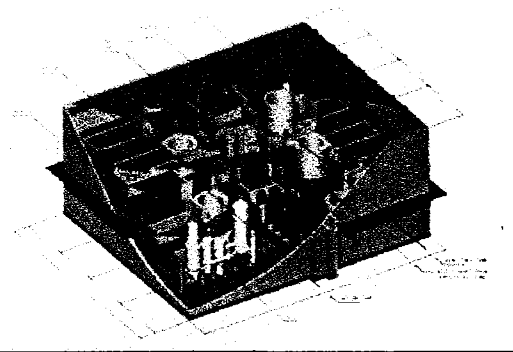

Figure 1. Schematic of 8-pack layout

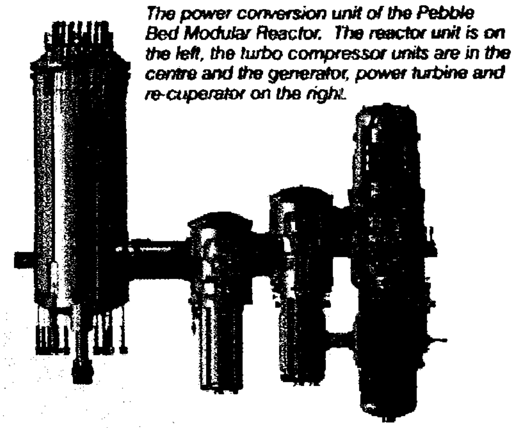

Figure2. Layout of Main Components

Figure 3. PMBR Fuel Balls

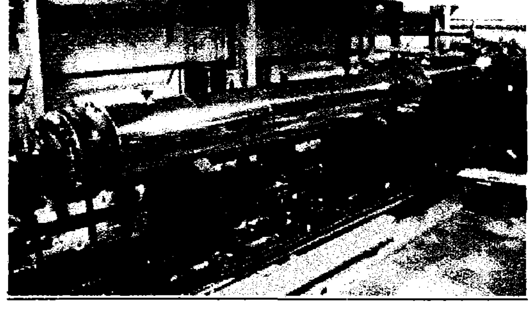

Figure 4. Test Rig for Helium Turbine

4.2 The International Reactor Innovative and Secure (IRIS)

The IRIS concept is based on well established PWR technology but with an integral primary coolant system and circulation by convection. It is being offered in single or multiple modules of 1,000MWt (about 335MWe).

The IRIS program was started in late 1999 by Westinghouse and was one of the winning proposals in the first Nuclear Energy Research Initiative of the US Dept of Energy. It then moved through the preliminary design stage and the start of the licensing process and is being considered as one of several designs for an early site permit by three US utilities.

The IRIS project is based on proven PWR technology but has a number of innovative features, one of which is development by an international partnership of industry (8), academia (12), research organisations (5) and power producers (2). The project was conceived to meet four objectives: enhanced safety, improved economics, reduced waste, and improved proliferation resistance.

Some distinguishing characteristics are: an integral configuration which addresses all four aims; use of high burn-up fuel and long core life, eg. four years without shutdown, thus reducing maintenance costs and improving proliferation resistance; containment design practically eliminating small-to-medium loss of coolant accidents; a 'Safety by Design' approach to eliminate or minimise potential accidents.

All of the main primary coolant components - core, coolant pumps, steam generators, pressuriser, control rod drive mechanisms - are within the reactor pressure vessel (Figure 5). Coolant water flow is upward through the core. Although the reactor vessel is larger than a traditional reactor vessel, the overall containment is much smaller.

A unique aspect of the steam generators (SGs) is that the high pressure coolant flows on the outside of the tubes. Thus the SG tubes are in compression and tensile stress corrosion cracking (which is claimed to be responsible for 70% of SG failures) is eliminated. The proponents of IRIS believe that its defence in depth and safety-by-design approach is so strong that some of the current licensing requirements can safely be relaxed.

The present planning is to proceed to design certification by 2008-2010 and to deploy a first-of-a-kind module by 2012-2015. The economic analysis was stated to be favourable with the capital cost of multiple modules of 335MWe being in the range US$1,000-1,200/kWe. It was also believed that the reactor could compete with other nuclear and non-nuclear plants in world markets.

A schematic layout of a plant with two twin modules totalling 1,340MWe is shown in Figure 6.

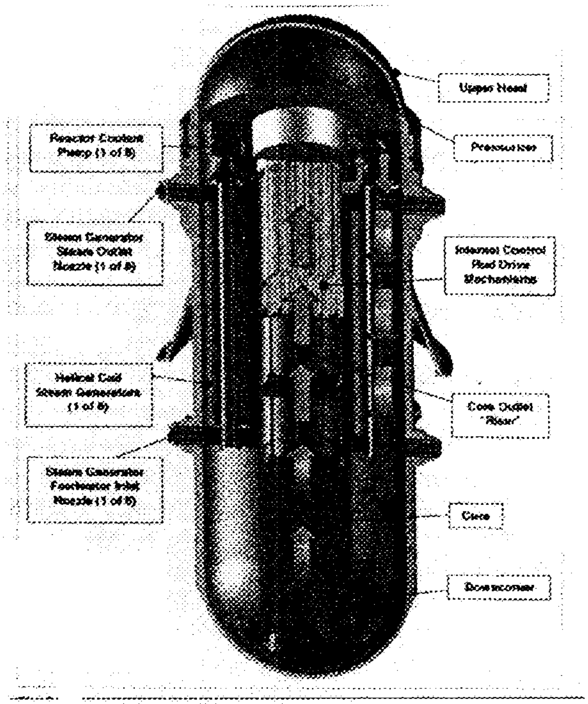

Figure 5. Layout of Main IRIS Components

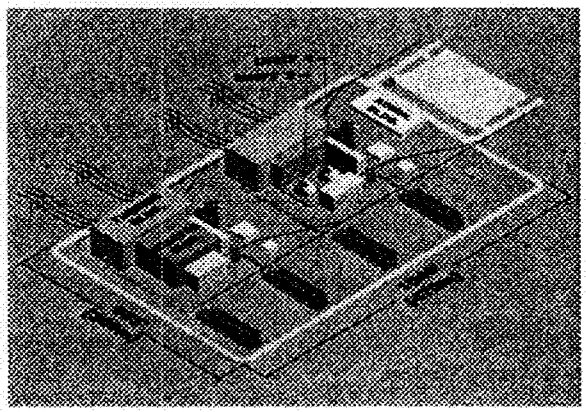

Figure 6. Schematic Layout of Two Twin Module IRIS Plants of 1,340 Mwe Total Capacity

4.3 Comparisons with Other New Designs

The Advanced CANDU Reactor, ACR-700

This system was designed by Atomic Energy of Canada Ltd (AECL) as a new 700MWe version of the most recent CANDU 6 (700MWe) design with features from the CANDU 9 (900MWe) design. It uses light water coolant instead of heavy water and 2% enriched uranium fuel in an advanced fuel bundle design instead of natural uranium.

These changes have reduced the size of the core considerably from a diameter of 6.3 to 4.35 m. Heavy water is still used as a moderator but not as a coolant, thus saving 75% of the costs of the heavy water inventory of the original CANDU 6 design. A simpler heat transport system also reduces costs. Another major change is to move to a negative void reactivity design instead of a positive void reactivity design and this is expected to strengthen its licensability in overseas markets more familiar with the negative void characteristics of PWR reactors. The operating temperature and pressure of the design have been increased over the previous CANDU 6 design leading to increased efficiency. Some passive safety features have also been used.

Overall, the cost reductions are expected to lead to a capital cost in the region of US$1,000/kWe for multiple units. The recent experience in constructing CANDU 6 plants in China and Korea has led to confidence in the claim that the ACR-700 can be constructed in 48 months from contract signing to commercial operation and 36 months from first concrete pour to fuel loading.

A schematic diagram of the layout of the main containment building and turbine hall for ACR-700 is shown in Figure 7.

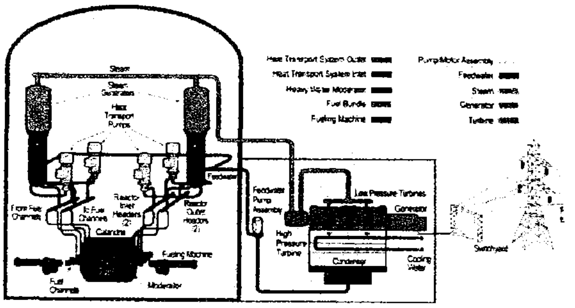

Figure 7. Containment Building and Turbine Hall

The Gas-Turbine-Modular Helium Reactor, GT-MHR

This design is from an international project in which the main participants are from the USA, Russia, France and Japan. General Atomics, USA, developed a modular design of a helium-cooled high temperature reactor as part of a US DOE program. It initially used steam turbines but later moved to gas turbines. The DOE then stopped funding for new reactor designs in the late 1970s.

GA then proposed that the GT-MHR design should be optimised to burn plutonium derived from military decommissioning programs and signed a MOU with the Russian Minatom in 1995 for this purpose. Framatome, France, joined the project in 1996 and Japan's Fuji Electric joined in 1997. The project was then planned in four stages. The conceptual design stage was completed in 1997. The detailed design stage was completed in 2002. The third stage was to build a prototype in Russia at Seversk but this has been delayed. The fourth stage would be to develop a commercial version for world marketing.

The basic design is for a modular plant of 600MWt (285MWe). Each module consists of two pressure vessels mounted side by side in a concrete containment 35m below ground level. One vessel contains the reactor and the other the power conversion equipment connected to the reactor by a dual concentric duct. A cross section of the main components is given in Figure 8.

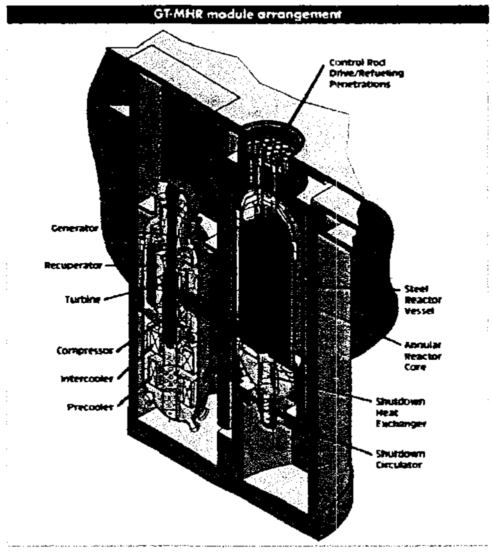

Figure 8. Main Components in GT-MHR

The helium coolant outlet temperature is 850°C and 70 bar (7Mpa) pressure with the exit gas from the turbine at 510°C and 26 bar (2.6 Mpa). The helium then goes through a regenerative heat exchanger and a water cooled heat exchanger before entering a two-stage compressor with intercooler. The system is expected to give an overall efficiency of nearly 50%.

The core uses a prismatic design based on standard GA technology. It has 61 columns of replaceable graphite reflector blocks containing no fuel arranged in a hexagon. This is surrounded by 102 columns of fuel-bearing blocks, ten blocks high, forming an annular core of 48m outside diameter and 8m height. This is surrounded by a ring of replaceable graphite blocks (see Figure 9). The core contains pure plutonium oxide kernels coated in a triple layer of porous carbon, silicon carbide and pyrolytic carbon. These are formed into compacts and the compacts into hexagonal-shaped fuel elements (see Figure 10).

No uranium is used to dilute the plutonium so that no secondary plutonium is produced. The GT-MHR can therefore consume 90% of the plutonium fuel in a single pass in a period of 840 equivalent full power days. This is much higher than any other type of reactor. The core is designed to be recharged in layers after about 280 equivalent full power days. The result

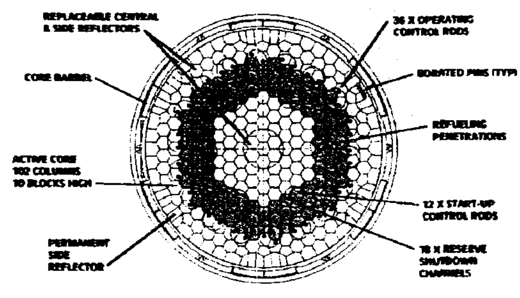

Figure 9. Core Layout in GT-MHR

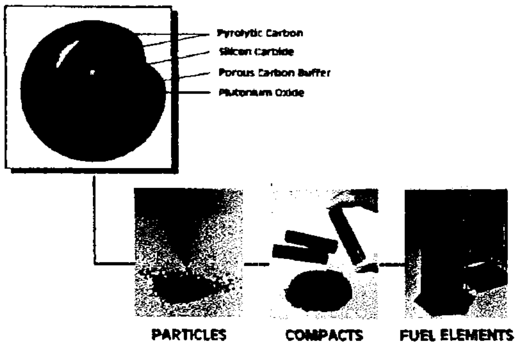

Figure 10. Structure of Fuel Balls in GT-MHR

is that if three four-module plants were built (each plant producing 1,140MWe), they could dispose of 50te of weapons grade plutonium in a 25 year period as well as producing 75,000MW-years of electricity. The reactor is claimed to have very good passive safety features and can withstand loss of coolant circulation and loss of coolant inventory without operator intervention or the use of active safety systems.

The cost was estimated in 1996 to be US$3billion, equivalent to less than US$1,000/kWe, which was less than an equivalent light water reactor.

4.4 Comparative Electricity Costs

The relative costs of generating electricity from coal, gas, nuclear and renewables varies considerably depending upon location and a number of economic assessment factors, eg. discount rates. Coal is, and will remain, economically attractive in many countries which have abundant domestic resources, especially if these are close to load centres. Gas is competitive in many countries using combined cycle plants although there is uncertainty on the future price of gas.

From the outset, the features of nuclear power have been its relatively high capital costs and low fuel costs compared with coal- and gas-fired plants. However, nuclear power has been shown to be competitive with fossil fuels in many countries, eg. France, Japan, Korea. A study published by the OECD's Nuclear Energy Agency in 1998 provided cost projections for the period 2005-2010. The study showed that nuclear costs were lower than coal and gas in France, Russia, Korea, Spain, Canada and China.

A new French government study has assessed the cost of electricity in 2003 euro c/kWh for a plant starting up in 2015 as follows: 3.04 for nuclear, 3.2-3.4 for coal and 3.5 for gas. If external costs were taken into account these costs increased to: 3.30 for nuclear, 4.24 for gas and 4.8-4.95 for coal. The nuclear plant was assumed to be the new European Pressurised Water Reactor (EPR) at a basic capital cost of 1,043 euros/kWe, compared with 569 euros/kWe for gas and 1276-1,400 euros/kWe for coal.

4.5 The Australian Electricity Situation

Australia relies very heavily (85%) on coal for its supply of electrical energy for residential and industry use and on petroleum products for transport. While renewable sources are becoming used increasingly, they are unlikely to contribute more than a few percent over the next two decades.

The Electricity Supply Association of Australia estimates that electricity demand will increase at 3% per year to 2020. This represents a 70% increase on current demand and a need to construct about 50,000MWe of new capacity. If this was to be based on coal the environmental impact would be considerable, while if based on gas it would require the discovery of one or more major new gas resource areas and still contribute to greenhouse gas emissions.

It is therefore suggested that nuclear power should be evaluated as part of Australia's future energy needs, taking into account cost competitiveness, including all external costs, and environmental factors.

One of the small- or medium-reactor systems described in this paper may be appropriate for the Australian situation. A modular reactor system with modules added to the grid system progressively every two to three years could easily be integrated into the grid systems of any of the Australian states, even those currently with small grids, eg. Tasmania and the Northern Territory. These modular plants would also be suitable for remote towns and areas with large mining or processing plants.

The estimated capital and generating costs of the advanced modular plants of about US$1,000/kWe and US2c/kWh, are equivalent to AUS$1,500/kWe and AUS3c/kWh. The capital cost is higher than those for coal-fired or combined cycle gas plants in Australia and many other parts of the world. However, the generating cost could be competitive especially as the future cost of gas over the next two decades is not known with certainty. The cost would be even more competitive if external costs were included for coal and gas. Such plants would also have the advantage of reducing problems arising from air pollution and greenhouse gas emissions from burning fossil fuels.

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