NON-ELECTRICITY PRODUCTS OF NUCLEAR ENERGY

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- to contribute to sound economic expansion in member as well as non-member countries in the process of economic development; and
- to contribute to the expansion of world trade on a multilateral, non-discriminatory basis in accordance with international obligations.

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NUCLEAR ENERGY AGENCY

The OECD Nuclear Energy Agency (NEA) was established on 1st February 1958 under the name of the OEEC European Nuclear Energy Agency. It received its present designation on 20th April 1972, when Japan became its first non-European full member. NEA membership today consists of 28 OECD member countries: Australia, Austria, Belgium, Canada, the Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Luxembourg, Mexico, the Netherlands, Norway, Portugal, the Republic of Korea, the Slovak Republic, Spain, Sweden, Switzerland, Turkey, the United Kingdom and the United States. The Commission of the European Communities also takes part in the work of the Agency.

The mission of the NEA is:

- to assist its member countries in maintaining and further developing, through international co-operation, the scientific, technological and legal bases required for a safe, environmentally friendly and economical use of nuclear energy for peaceful purposes, as well as
- to provide authoritative assessments and to forge common understandings on key issues, as input to government decisions on nuclear energy policy and to broader OECD policy analyses in areas such as energy and sustainable development.

Specific areas of competence of the NEA include safety and regulation of nuclear activities, radioactive waste management, radiological protection, nuclear science, economic and technical analyses of the nuclear fuel cycle, nuclear law and liability, and public information. The NEA Data Bank provides nuclear data and computer program services for participating countries.

In these and related tasks, the NEA works in close collaboration with the International Atomic Energy Agency in Vienna, with which it has a Co-operation Agreement, as well as with other international organisations in the nuclear field.

FOREWORD

This report was prepared by the OECD Nuclear Energy Agency (NEA) under the guidance of the Committee for Technical and Economic Studies on Nuclear Energy Development and the Fuel Cycle (NDC). It is the outcome of a desk study based upon a comprehensive survey of published literature on the subject matter, including reports from international organisations, national institutes and other parts of the NEA.

Technically nuclear fission reactors in operation or being built can supply non-electricity products. However, while non-electrical applications have been considered since the very beginning of nuclear energy development, they have not been deployed to significant industrial scale in any country so far.

The present report endeavours to investigate: technical requirements for nuclear energy systems to become cost effective for supplying non-electricity products; potential markets for non-electricity products that nuclear energy systems could supply eventually; and policy issues to be addressed for facilitating the development of non-electrical applications of nuclear energy in countries wishing to rely on this option.

The report was reviewed by the NDC and benefited from comments and suggestions from its members. However, its does not reflect automatically the views of all NEA member countries. It is published under the responsibility of the Secretary-General of OECD.

TABLE OF CONTENTS

Tables

Figures

INTRODUCTION

Today, nuclear power plants provide about 16% of the world electricity consumption and in OECD countries the share of nuclear electricity reaches nearly 25%. Nevertheless, because electricity represents less than one third of primary energy uses, nuclear energy provides only about 6% of total energy consumption in the world. If nuclear energy were used for purposes other than electricity generation, it could play a more significant role in global energy supply.

Technically, nuclear reactors which produce energy in the form of heat can supply other energy products than electricity, including district and process heat, potable water, and eventually hydrogen. Also, as demonstrated in non-civil uses and some very limited civil applications, nuclear energy can provide motive power. While non-electrical applications of nuclear energy have been considered since the very beginning of nuclear energy development, they have, for various reasons, not been deployed so far to a significant industrial scale in any country.

Governments wishing to keep the nuclear option open in long term and/or to maintain nuclear industrial capacities might have interest in nuclear non-electricity products in two policy perspectives:

- Deploying those systems in their own country or in the region within its overall energy policy perspective, and
- Building and maintaining the capabilities for those systems to meet their domestic and international demands within their overall R&D and industrial policy perspectives.

In this regard, it is important to assess the capability of nuclear energy systems to supply energy products other than electricity and the potential markets for those products. It is an indispensable element of a comprehensive overview on the role of nuclear energy in policies aiming at sustainable development. Therefore, the overall objective of the NDC study was to provide objective and reliable information and policy recommendations relevant to the interest of member governments.

Accordingly, the study includes:

- Assessment of the current status and the future prospects for non-electricity products of nuclear energy,
- Assessment of the capabilities of nuclear energy systems to provide non-electricity products in a viable and competitive manner, and
- Investigation of strategic issues relevant for the development and deployment of nuclear non-electricity systems.

The first two parts are basically a status report done mainly through the integration of existing literature. The study took advantage of previous work by the IAEA, the NEA, other international organisations and national institutes, in particular in the field of technical capabilities of existing and advanced reactors as well as previous analyses of demand and market for various energy products.[1] The third part was intended to bring in essential added value based on country reports. Since very few country reports have been received, the study could not avoid being very limited at this point in time.

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1. The IAEA already conducted a comprehensive study on *Market Potential for Non-electric Applications of Nuclear Energy* and published its report [1] in 2002. EU is also conducting a study within the *Michelangelo Network for Competitiveness and Sustainability of Nuclear Energy in the European Union*, of which the report is expected to be published in 2005.[2]

CURRENT STATUS AND FUTURE PROSPECTS FOR NUCLEAR NON-ELECTRICITY ENERGY PRODUCTS

Current Status

District Heat

District heat implies the supply of space heating and hot water through a district heating system, which consists of heat plants (usually producing electricity simultaneously) and a network of distribution and return pipes. In many countries, such as central and northern European countries and countries in transition economies, district heat has been widely used for decades. District heating accounts for 11% of total final energy consumption in Central Europe and Ukraine and over 30% in Russia and Belarus. District heating accounts for almost half of the heat market in Iceland (95%), Estonia, Poland, Denmark, Finland and Sweden. Although a large number of district heat suppliers, especially in transition economies, are facing financial and technical problems, district heat is still expected to have great additional potential for meeting a share of heat demand in many countries.

Although it is hard to figure out exact statistics for the current use of district heat in the world, the size of its market can be estimated in relation to the final energy demand that is supplied by centralised sources in the residential, agricultural and commercial sector. An IAEA report [1] took this approach and calculated the total use of centralised heat in 1996 as 119.5 Mtoe based on the IEA world energy database, which requires a heat production capacity of 340 000 MWth assuming an average load factor of 50%.[2]

In a technical perspective, district heating has the following requirements:

- It requires a heat distribution network transporting steam or hot water with a typical temperature range of 80-150°C.
- Due to higher losses over longer transportation, the heat source must be relatively close to the customer, mostly 10-15 km.[3]
- The district heat generation capacities are determined by the size of customer. In large cities the capacity of 600-1 200 MWth is normal and much lower in small communities.
- The annual load factor is normally not higher than 50% since heat is supplied in the colder part of the year.
- To secure reliable supply of heat, a backup capacity is required.

Typically, coal and gas dominate fuels for district heating. Various other heat sources are also used for district heating including biomass materials, waste incineration and waste heat from industrial processes. Usually district heating applies the cogeneration mode, in which waste heat from power production is reused as a source of district heat.

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2. However, it should be noted that about 64% of the total use is concentrated in Russia. The share of Western Europe and Eastern Europe are 15% and 13%, respectively.
3 . The heat source can be located further from the customer (*e.g.* 100 km) depending on the economics based on the size of the plant and the level of insulation technology.

All existing reactor types (light water, heavy water, fast breeder, gas cooled and high temperature) are potentially applicable to cogeneration. Several countries have experiences in nuclear district heating: Bulgaria, Hungary, Russia, Slovakia, Sweden, Switzerland and Ukraine.

Desalinated Water

Desalinated water supply implies the production of potable water from seawater desalination plants and water transportation/storage network. Seawater desalination is a water treatment process that removes salts from seawater to obtain fresh water adequate for irrigation, drinking and industrial use. Considering the shortage of fresh water and the plentifulness of seawater over the world, seawater desalination is an attractive solution, of which the technologies have been well established over the past 50 years.

Seawater desalination has been growing very fast. By the end of July 2002, the total contracted capacity of all desalination technologies was about 32.4 million m^3/day,[4] of which 60% of the capacity was for seawater desalination.[3] This total capacity has almost doubled since 1990. Desalting equipment is used in over 100 countries. Almost half of this desalting capacity is located in the Middle East and North Africa. Saudi Arabia ranks first in overall capacity, with about 24% of the world's capacity. Considering that the share of desalinated water for the supply of household water is very small, there is great potential for seawater desalination until saturation of the market.

There are several commercial technologies available for seawater desalination, among which three typical methods are Multi-Effect Distillation (MED), Multi-Stage Flash Distillation (MSF) and Reverse Osmosis (RO).

In a technical perspective, seawater desalination has the following requirements:

- Heat in the range of 100-130°C is required for MSF and MED. Electricity is required for RO as the primary energy source and for MSF and MED as energy for pumping.
- Depending on the needs of the water customer, the total capacity may range from 100 m^3/day to 60 000 m^3/day with the average unit capacity of 1 900 m^3/day.
- To ensure high reliability a backup source of energy may be required on the site of the desalination facility.

Nuclear desalination implies the production of potable water from seawater using a nuclear reactor as the source of energy (electricity and/or heat). The reactor may be used solely for desalination or may be operated in a cogeneration mode. There have been successful experiences in nuclear desalination at several plants in Japan (12 reactors since 1977) and Kazakhstan (1 reactor since 1973). India is setting up a 6 300 m^3/day MSF-RO hybrid desalination plant connected to two 170 MWe PHWR units at Kalpakkam, which will provide both process water for the nuclear power plant and drinking water in the neighbouring community.

Many countries are showing interest in or going forward with nuclear desalination projects, for domestic use or for exportation, including Argentina, Canada, China, Egypt, France, India, Indonesia, Korea, Morocco, Pakistan, Russia and Tunisia.

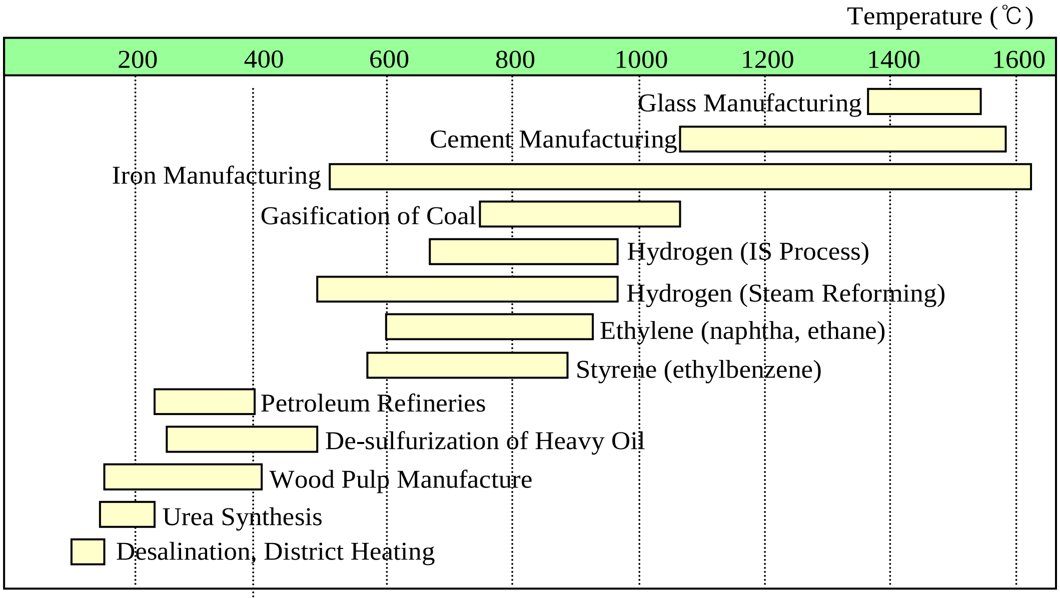
4. This can be covered by about sixty units of 600 MWe reactor assuming it can produce 500 000 m^3/day with 17% of its generation capacity.

Process Heat

Process heat implies the supply of heat required for industrial processes from several centralised heat generation sites through a steam transportation network. Within the industrial sector, at temperatures higher than those needed for district heating and seawater desalination, process heat is used for a variety of applications as shown in Figure 1.

In a similar way as for district heat, the IAEA report [1] took the approach that the size of the process heat market can be estimated in relation to the final energy demand that is supplied by centralised sources in the industrial sector and calculated the total use of centralised process heat in 1996 as 150.1 Mtoe based on the IEA world energy database, which requires a heat production capacity of 240 000 MWth assuming an average load factor of 90%.[5]

Figure 1. Required Temperature for Industrial Processes



Source: Adapted from [2]

In a technical perspective, process heating has the following requirements:

- Due to higher losses over longer transportation, the heat source must be relatively close to the customer.
- The annual load factor is much higher than that in district heating, probably 70-90% since process heat demand does not depend on climatic conditions.
- To secure reliable supply of heat, a backup capacity is required.

As in the case of district heat, all existing reactor types are potentially applicable to producing process heat depending on the required temperature of the processes. There have been some experiences in providing process heat for industrial purposes with nuclear energy in Canada, Germany, Norway and Switzerland. In Canada, CANDU reactors supplied steam for industries such as food processing and industrial alcohol production until their closure in 1998.[6] In Germany, the Stade

5. As in district heat, it should be noted that about 77% of the total use is concentrated in Russia. The share of China, Eastern Europe, the United States and Western Europe are 14%, 6%, 4% and 3%, respectively.
6. Since the closure of the CANDU reactors, the steam supply has been maintained with oil-fired power plants.

PWR has supplied steam for a salt refinery located 1.5 km from the plant from December 1983 until its shutdown in November 2003. In Norway, the Halden Reactor has supplied steam to a nearby factory for many years. In Switzerland, since 1979, the Gösgen PWR has been delivering process steam to a cardboard factory located 2 km from the plant.

Hydrogen

As an alternative path to the current fossil fuel economy, a hydrogen economy is envisaged, where hydrogen would play a major role in energy systems and serve all sectors of the economy, substituting fossil fuels. Hydrogen, as an energy carrier, can be stored in large quantities, unlike electricity, and converted into electricity in fuel cells, with only heat and water as by-products. It is also compatible with combustion turbines and reciprocating engines to produce power with near-zero emission of pollutant. Furthermore, hydrogen can be obtained from various primary energy sources that are domestically available in most countries. Consequently, the hydrogen economy would enhance both the security of energy supply and global environmental quality.

The current worldwide hydrogen production is roughly 50 million tonnes per year.[7] Although current use of hydrogen in energy systems is very limited, its future use could become enormous, especially if fuel-cell vehicles would be deployed on a large commercial scale. For example, the Committee on Alternatives and Strategies for Future Hydrogen Production and Use of the United States [4] assumes, as an upper-bound, that fuel-cell vehicles would enter into the light-duty vehicle market in 2015 in competition with conventional and hybrid electric vehicles, reaching 25% of the market around 2027 and that full replacement of gasoline light-duty vehicles with hydrogen vehicles would occur in 2050. Assuming a fleet of 300 million fuel-cell powered cars in the world, an estimated 120 million tonnes of hydrogen will be required annually just for supplying energy to part of the transportation sector.

The hydrogen economy is getting higher visibility and stronger political support in several parts of the world. In his “State of the Union Address” in 2003, the US President announced a $1.2 billion hydrogen initiative to reverse the growing dependence on foreign oil and reduce greenhouse gas emissions. The Japanese Prime Minister and the Chair of the European Commission made official statements strongly supporting the emergence of a hydrogen economy.

There are many ongoing national programmes aiming at the development of a hydrogen economy such as the Hydrogen Initiative of the United States, the European Hydrogen and Fuel Cell Technology Platform, and fuel cell/hydrogen programmes in Japan and Korea. There are also various international efforts for the realization of a hydrogen economy. Under the leadership of the United States, 15 countries and the European Commission launched the International Partnership for the Hydrogen Economy (IPHE) in 2003 to discuss common areas of interest in, and obstacles to, hydrogen economy in the fields of research, development and demonstration projects, hydrogen policy and regulation, and the commercialisation of hydrogen-based energy technologies.

The adequate supply of hydrogen is a prerequisite for successful implementation of a hydrogen economy. Although hydrogen is abundant in the world, it had to be extracted from compounds containing hydrogen such as fossil fuels, biomass, or water with thermal, electrolytic or photolytic energy. Table 1 shows some technological options that are or will be available for hydrogen production.

As shown in Table 1, nuclear energy is suitable for hydrogen production since nuclear reactors can produce both the heat and electricity required for it. Furthermore, it is the most commercially

7. This is the amount that about 200 large LWRs can provide by electrolysis.

mature non-fossil fuel energy source capable of producing hydrogen on a large industrial scale without significant CO_2 emission.

Several technological options are possible for nuclear hydrogen production, including:

- Electrolysis of water using electricity from nuclear reactors in off-peak periods;
- Steam reforming of natural gas using high temperature heat from nuclear reactors;
- High temperature electrolysis of steam using high temperature heat and electricity from nuclear reactors;
- Thermochemical water splitting using high temperature heat and electricity from nuclear reactors.

Electrolysis of water basically is attractive essentially when cheap electricity is available or high-purity hydrogen is required. The use of nuclear generated electricity in off-peak periods would be economically attractive in the light of the low marginal cost of nuclear power plants.

Currently hydrogen is produced mainly by steam reforming of natural gas/methane. This is a catalytic process involving the reaction of natural gas with steam to produce a mixture of hydrogen and CO_2, requiring temperatures in the range 500 to 950°C. Nuclear-assisted steam reforming has great potential for large-scale hydrogen production in the near term. This well-established process, however, has CO_2 as a waste product.

Table 1. Hydrogen Production Options

Raw Feedstock Options	Typical Processed Feedstock	Production Process Options	Process Energy Source Options	Production Strategy Options
Fossil Fuels Coal Natural gas Oil	Syngas Gasoline Diesel fuel Methanol Ammonia Direct use of raw stock	**Thermal** Reforming Steam reforming Partial oxidation Gasification Pyrolysis **Electrochemical** Electrolysis Photoelectro-chemical **Biological** Photo-biological Aerobic fermentation Anaerobic fermentation	**Thermal** Fossil Renewable Nuclear **Electricity** Fossil Renewable Nuclear **Photolytic** Solar	**Distributed** Fuelling stations Individual buildings On-board **Semi-distributed** Market-centered **Central** Resource-centered
Biomass Lignocellulose Starch Vegetable oils Black liquor	Ethanol Methanol Biodiesel Biogas Sugars Direct use of raw stock			
Waste Material Municipal solid waste Stack gases Waste water	Direct use of raw stock			
Water	Direct use of raw stock			

Source: [5]

Hydrogen can be obtained more efficiently by significantly raising the temperature of water. The electrolysis of steam at higher temperature (800-1000°C) offers several advantages including lower electricity requirement and higher efficiency resulting from lowering the activation barriers at the electrolyte surfaces.

Since direct thermolysis of water requires temperatures over 2 500°C, the thermochemical water splitting process consists of different partial reactions, each running at a lower temperature level (800-1000°C). Thousands of potential thermochemical cycles have been tested to assess their viability and performance for hydrogen production and the most promising for efficiency and practical applicability to nuclear heat sources have been identified, namely iodine-sulphur (IS), bromine-calcium (Br-Ca) and copper-chlorine (Cu-Cl). In addition, a thermochemical hybrid process can be another option, which combines both thermochemical and electrolytic reactions of water splitting and has the possibility of running low-temperature reactions.

Propulsion

The transportation sector in the world consumes about 25% of global energy including road, aviation, rail, pipeline, navigation etc. About 10% of these are for international and national seaborne transportation, for which nuclear energy can be directly utilised.[1] In terms of the quantity of transported goods and fleet capacity, the transportation of oil and its derivatives and the bulk transportation of goods have had the largest share of the market over the past decade.

With some aggressive assumptions for nuclear powered ships towards current oil tankers and large cargo ships, the IAEA report [1] estimated the market potential for nuclear powered ships between 2 400 ships of 15 000 gross tonnes (GT) (for the low estimate) and 4000 ships of 100 000 GT (for the high estimate).

The first application of nuclear energy to ships was for military submarines with PWRs. The first civil application of nuclear powered ship propulsion was for nuclear icebreakers in the former USSR, whose design started in 1953. The first nuclear icebreaker, launched in 1959, operated successfully for 30 years. In total, nine nuclear icebreakers have been built in the former USSR.

There have been some experiences of nuclear powered civil on-surface ships in three other countries: the USA (Savannah), Germany (Otto Hahn) and Japan (Mutsu). These three merchant ships were all equipped with PWRs with a containment around the reactor cooling system. At present only Russia and Japan are conducting studies for the development of civil ship reactors. Since nuclear propulsion has not shown sufficient economics yet, one of the near term tasks, as an IAEA report [1] suggested, would be to demonstrate other projects in which nuclear powered ship propulsion could become competitive.

Long-term Prospects

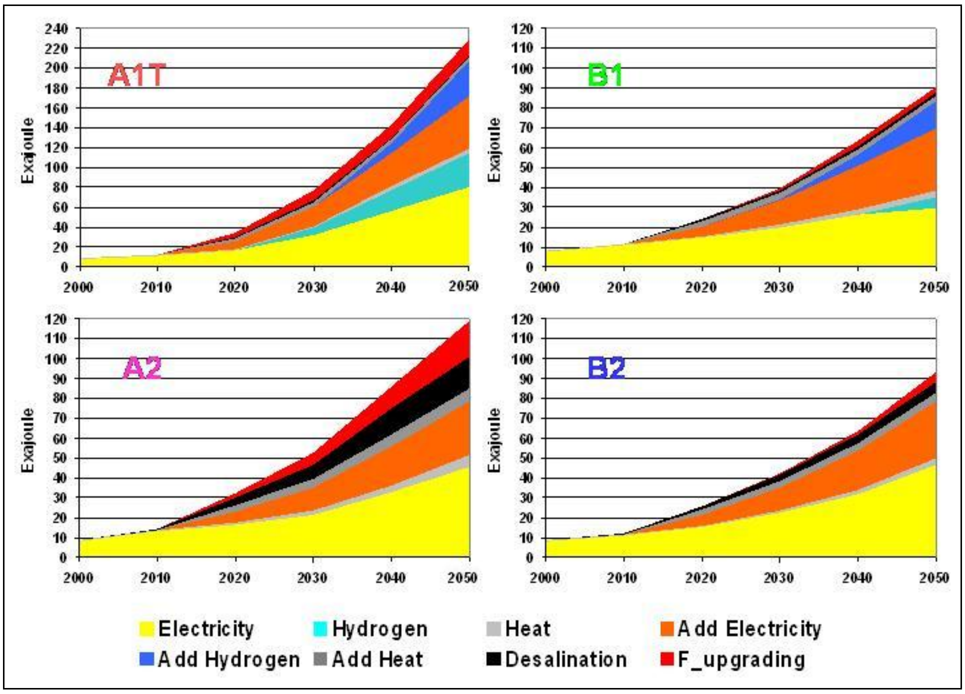
The long-term projection of the demand for non-electricity energy products inevitably includes lots of uncertainties. To overcome these uncertainties, many studies take a scenario approach. The Special Report on Emission Scenarios (SRES), commissioned by the Intergovernmental Panel on Climate Change (IPCC), is a typical example for the projection of future energy use and corresponding greenhouse gas emissions, which presented 40 scenarios extending to 2100.

Rogner & McDonald [6] analysed the following four scenarios among 40 SRES scenarios and elaborated them to project the mid-century market for nuclear energy assuming an aggressive market penetration strategy:

- Scenario A1T: A world of high economic growth and rapid increase of energy demand
- Scenario A2: Heavy reliance on coal and relatively modest economic growth
- Scenario B1: Reductions in material intensity, and the introduction of clean and resource-efficient technologies
- Scenario B2: "dynamics as usual" with intermediate economic growth

This analysis, which was also reflected in the *International Project on Innovative Nuclear Reactors and Fuel Cycle* (INPRO) study [7] of the IAEA, can provide long-term prospects of nuclear non-electricity energy products. This approach looks for additional potential market for nuclear energy under the assumption that the nuclear industry can reduce costs more quickly than its competitors, contrary to the assumption adopted in the original SRES scenarios. The results show that nuclear non-electricity products (heat, hydrogen) play a critical role for the expansion of nuclear capacities in the world as shown in Figure 2.

Figure 2. Long-term Prospects of Nuclear Energy Market



Source: [6]

In the original A1T scenario, the nuclear energy use in 2050 is about 14 times as large as in 2000, of which about 33% would result from non-electrical applications. Based on the aggressive assumptions, the nuclear energy use in 2050 could be about 27 times as large as in 2000, of which about 42% would result from non-electrical applications. In this scenario, nuclear energy's biggest competitor is solar-based hydrogen production. In the A1T Scenario, since there is very little centralised district heat from fossil sources that nuclear heat could displace, the potential additional market for nuclear heat is small. There is also very little use of dirty unconventional fossil fuels and thus little potential demand for nuclear heat for fossil fuel upgrading.[7]

In the original A2 scenario, the nuclear energy use in 2050 is about 6 times as large as in 2000, of which about 12% would result from non-electrical applications. Nuclear technologies are largely used for power generation. Based on the aggressive assumptions, the nuclear energy use in 2050 could be about 39 times as large as in 2000, of which about 13% would result from non-electrical applications. In this scenario the main competitors for nuclear energy are coal technologies.

In the original B1 scenario, the nuclear energy use in 2050 is about 5 times as large as in 2000, of which about 23% would result from non-electrical applications. Based on the aggressive assumptions, the nuclear energy use in 2050 could be about 11 times as large as in 2000, of which about 33% would result from non-electrical applications. In this scenario the main competitors are solar technologies in the hydrogen sector and natural gas and renewable power generation in the electricity sector.

In the original B2 scenario, the nuclear energy use in 2050 is about 6 times as large as in 2000, of which about 7% would result from non-electrical applications. Nuclear technologies are predominantly used for power generation. Based on the aggressive assumptions, the nuclear energy use in 2050 could be about 11 times as large as in 2000, of which about 20% would result from non-electrical applications. In this scenario the main competitors for nuclear energy differ from region to region, depending on regional circumstances such as resource and technology availability.

For each scenario, the lower three values (electricity, hydrogen and heat) are from the original SRES scenario. The upper five values (add electricity, add hydrogen, add heat, desalination and fuel-upgrading) mean additional nuclear markets that would be possible when the aggressive assumptions of Rogner & McDonald [6] are met.

SUPPLY POTENTIAL FOR NUCLEAR NON-ELECTRICITY ENERGY PRODUCTS

Nuclear reactors are capable of providing heat with a wide range of temperatures, which covers the requirements of most non-electric applications. Until now few technical problems to coupling nuclear reactors to various applications have been identified although some safety-related issues of coupled systems may still need more studies.

Current Capabilities for Near-term Deployment

A broad range of nuclear reactors is currently available for the supply of non-electricity energy products, among which some reactors dedicated to non-electricity purposes are presented here.

Water-cooled Reactors

System-integrated Modular Advanced Reactor (SMART): In Korea, the design of a nuclear desalination plant with the SMART reactor is developed to supply 40 000 m^3/day of fresh water and 90 MW of electricity to an area with an approximate population of 100 000 inhabitants or an industrialised complex. SMART is an advanced integral PWR with designed thermal output of 330 MWth, with major components arranged within a single pressure vessel. A detailed design and construction project of a one-fifth scale SMART pilot plant for demonstration of the relevant technologies is currently underway. The SMART desalination plant under construction will be in operation by 2008 and is expected to be commercialised from 2009.[8]

KLT-40 Floating Plant: In Russia, efforts continue on a floating power unit based on a KLT-40 reactor for multipurpose use including desalination and district heating. A nuclear desalination project is foreseen in the Russian Arctic Sea coast area using an RO and/or MED process.

Gas-cooled Reactors

Since current and near-term advanced water-cooled reactors produce temperature under 350°C, reactors capable to provide higher temperature are focusing the interest of advanced reactor designers. National and international efforts are devoted to the development and deployment of nuclear reactors for hydrogen production, especially high-temperature gas-cooled reactors (HTGR).

Pebble-Bed Modular Reactor (PBMR): The PBMR, which uses helium as a coolant, is part of the HTGR family of reactors. More recently, the design has been promoted and revised by the South African utility Eskom, which continues to partner in the design with BNFL among its investors. At around 165 MWe the PBMR is one of the smallest reactors now being proposed for the commercial market. This is considered a marketing advantage because new small units require less capital investments than larger new units. Although its primary mission is for electricity generation, it could be also applied to the supply of heat.

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8 . Based on the SMART desalination plant, Indonesia has conducted an economic feasibility study of introducing nuclear desalination to the Island of Madura and reported a good potential of its economic competitiveness.

High-Temperature Engineering Test Reactor (HTTR): In Japan, the Japan Atomic Energy Research Institute (JAERI) constructed the HTTR with a thermal power of 30 MWth and a reactor outlet coolant temperature of 950°C to establish HTGR technologies and nuclear heat utilisation. JAERI has been conducting studies on the production of hydrogen by using the heat from the HTTR, initially in steam reforming of natural gas and later with the iodine-sulphur thermo chemical process. In April 2004, a coolant outlet temperature of 950°C was achieved in the HTTR, paving the way for the demonstration of direct thermo chemical hydrogen production. Based on the HTTR technologies, JAERI has started design studies for the GTHTR300-cogeneration aiming at producing both electricity by a gas turbine, and hydrogen by a thermochemical process.

HTR-10: The HTR-10 is a 10 MWth pebble bed core HTGR designed, constructed and operated at Tsinghua University in China. The reactor reached its criticality in 2000 and full power operation in 2003. The facility is planned to operate with core outlet temperatures as high as 950ºC to support the development of high temperature process heat and electricity generation technology.

Gas Turbine Modular Helium Reactor (GT-MHR): In the United States, General Atomics proposes the GT-MHR concept, which operates at a thermal power of 600 MWth with an outlet helium temperature in the range 850-1000°C and can be coupled with the thermo chemical hydrogen production process and high temperature electrolysis of steam.

Long-term Expectations

For the future, the Generation IV International Forum (GIF), an international endeavour of ten countries and Euratom, included in the missions for selecting six systems that could be deployed by 2030 or earlier their capabilities to produce non-electricity products as shown in Table 2.

Table 2. Generation IV Reactor Concepts

	Neutron spectrum	Coolant	Temperature (°C)	Fuel	Fuel cycle	Size(s) (MWe)
Gas-cooled Fast Reactors (GFR)	Fast	Helium	850	U-238	closed, on site	288
Lead-cooled Fast Reactors (LFR)	Fast	Pb-Bi	550-800	U-238	closed, regional	50-150 300-400 1200
Molten Salt Reactors (MSR)	Epithermal	Fluoride salts	700-800	UF in salt	closed	1000
Sodium-cooled Fast Reactors (SFR)	Fast	Sodium	550	U-238 & MOX	closed	150-500 500-1500
Supercritical Water-cooled Reactors (SCWR)	Thermal or fast	Water	550	UO_2	open (thermal) closed (fast)	1500
Very High Temperature Gas Reactors (VHTR)	Thermal	Helium	1000	UO_2 prism or pebbles	open	250

Source: adapted from [11]

Gas-cooled Fast Reactor (GFR): The GFR system features a fast-neutron spectrum and closed fuel cycle for efficient conversion of fertile uranium and management of actinides. The reference reactor for GFR is a 600 MWth (288 MWe) helium-cooled system operating with an outlet temperature of 850°C using a direct Brayton cycle gas turbine for high thermal efficiency. It is primarily envisioned for missions in electricity production and actinide management, but with its high outlet temperature it can support thermochemical hydrogen production or other process heat supply. Taking into account its R&D needs for fuel and recycling technology development, the GFR is expected to be deployable by 2025.

Lead-cooled Fast Reactor (LFR): The LFR system also features a fast-neutron spectrum and a closed fuel cycle for efficient conversion of fertile uranium and management of actinides. The system uses a lead or lead/bismuth eutectic liquid-metal cooled reactor. A wide range of unit sizes is envisaged, from factory-built "battery" of 50-150 MWe with 15-20 year life for small grids, to modular 300-400 MWe units and a large monolithic plant of 1 200 MWe. The outlet temperature is 550°C but 800°C would be possible with advanced materials. It is envisioned for distributed generation of electricity and other energy products, including hydrogen and potable water. Given its R&D needs for fuel, materials and corrosion control, the LFR system is estimated to be deployable by 2025.

Molten Salt Reactor (MSR): The MSR system features an epithermal to thermal neutron spectrum and a closed fuel cycle tailored to the efficient utilisation of plutonium and minor actinides. The reference plant has a power level of 1000 MWe. The system operates at low pressure and has a coolant outlet temperature above 700°C, affording improved thermal efficiency. It is primarily envisioned for missions in electricity production and waste burndown. Given its R&D needs for system development, the MSR is estimated to be deployable by 2025.

Sodium-cooled Fast Reactor (SFR): The SFR system features a fast-neutron spectrum and a closed fuel cycle for efficient conversion of fertile uranium and management of actinides. It builds on more than 300 reactor-years of experience with fast neutron reactors over five decades in eight countries. It has a coolant temperature of 550°C. Two variants are proposed: a 150-500 MWe type with actinides incorporated into a metal fuel requiring pyrometallurgical processing on site; and a 500-1500 MWe type with conventional MOX fuel reprocessed in conventional facilities elsewhere. This reactor, although operating at lower temperatures than the HTGR, may be used for hydrogen production with a thermochemical and electrolytic hybrid process, which would require a lower temperature range (500-600°C). Based on the experience with oxide fuel, this option is estimate to be deployable by 2015.

Supercritical Water-cooled Reactor (SCWR): The SCWR system features two fuel cycle options: an open cycle with a thermal neutron spectrum reactor and a closed cycle with a fast-neutron spectrum reactor and full actinide recycle. In either option, the reference plant has a 1 700 MWe power level and a reactor outlet temperature of 550°C. This is a very high-pressure water-cooled reactor that operates above the thermodynamic critical point of water to give a thermal efficiency about one third higher than today's light water reactors from which the design evolves. The supercritical water directly drives the turbine, without any secondary steam system. It is primarily envisioned for missions in electricity production, with an option for actinide management. Given its R&D needs in materials compatibility, the SCWR system is estimated to be deployable by 2025.

Very High-Temperature Gas Reactor (VHTR): The VHTR system uses a thermal neutron spectrum and a once-through uranium cycle. The VHTR system has coolant outlet temperatures above 1000°C for higher efficiency in supplying process heat to a broad spectrum of high temperature and energy-intensive, non-electric processes. It is primarily envisioned for missions in hydrogen production and other process-heat applications, although it could produce electricity as well. The VHTR system is estimated to be deployable by 2020.

STRATEGIC ISSUES FOR DEVELOPMENT AND DEPLOYMENT

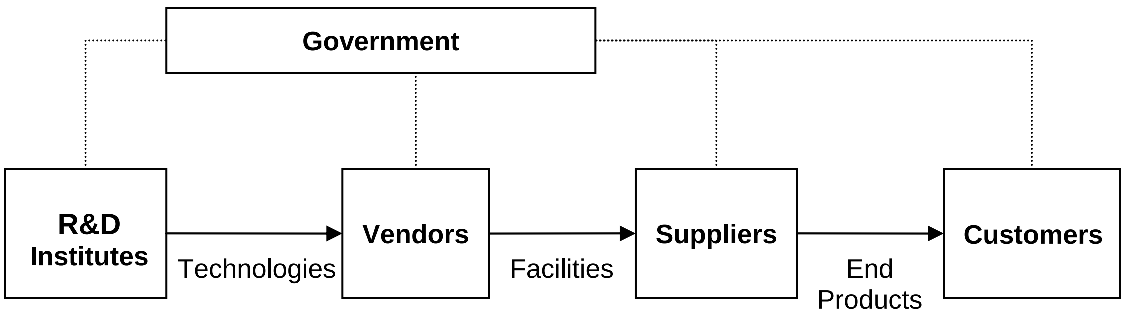
There are many strategic issues to be resolved for the development and deployment of nuclear non-electricity products, which cause their limited deployment up to now. Although these issues are inter-related, for the convenience of discussion they are classified below into four groups: market-oriented issues, technology-oriented issues, resource-oriented issues, and social and legal issues.

Market-oriented Issues

Market Characteristics

For effective discussion of market-oriented issues, a simplified market chain for non-electricity energy products is assumed (see Figure 3). Although it is possible that one organisation performs multiple functions, *e.g.* supplier, vendor and R&D institute, each function is assumed to be performed by a different actor. End-users (customers) get relevant products (heat, hydrogen, potable water) or services (transportation) they need from suppliers. Suppliers get the production capacities (heat generation, desalination, hydrogen production, large ships) they need from vendors. Vendors get relevant technologies (reactor, coupling) from R&D institutes. The governments can have direct or indirect control over the actors.

Figure 3. Simplified Market Chain for Non-electricity Energy Products



In Figure 3, we can distinguish three different kinds of market: end product market, facility market and technology market. In the end product market, customers have several alternatives among which they can choose. For instance, space heating: customers can choose individual heating using gas or electricity, or district heating according to the availability and their preferences. For vehicle fuels, they can choose fossil fuels, electricity or hydrogen according to what kind of vehicles they have or decide to buy. Also in the facility market, suppliers have several alternatives. For example, district heat suppliers can choose facilities producing heat with fossil fuels, waste incineration or nuclear reactors. Hydrogen suppliers can choose facilities producing hydrogen with various methods including nuclear reactors.

The deployment of a nuclear non-electricity product requires a good understanding of its market characteristics and of the actors in the market (suppliers, vendors and research institutes) including their relationships and related policy directives. The analysis should include not only current markets but also future markets, especially for hydrogen.

Market Size

For the deployment of a nuclear non-electricity product, its potential market size would be a critical factor for vendors to adjust their capacities. Although some studies estimate potential market sizes for nuclear non-electricity products, it should be noted that markets evolve with time. A primary factor determining the market size is the competitiveness of the corresponding end product such as district heat, desalinated water, process heat and hydrogen. For instance, if district heat loses its competitiveness in the heat market, the size of the district heat facility market where nuclear vendors compete with other vendors would also be reduced. This adds lots of uncertainties to vendors since they do not have control over the competitiveness of district heat.

Nuclear energy has the potential to play a significant role in a hydrogen economy but there are large uncertainties on the hydrogen demand growth rate and eventual level as well as on the share of nuclear energy in total hydrogen supply. The role of nuclear energy will be dependent on how the hydrogen economy will be shaped in the transition period as well as in its final stage. Many factors will influence the implementation rate and characteristics of hydrogen economy, including maturity of relevant technologies, economic growth, life patterns and social acceptance. According to how early and how deeply hydrogen will penetrate as an energy carrier in various sectors of the economy, the requirements for nuclear hydrogen production development will be different. For example, if demand for distributed hydrogen production prevails rather than for centralised production, the development of small- and medium-size reactors would be relevant. Otherwise, large units might be more effective.

However, in turn, the development of nuclear non-electricity product technologies may affect the competitiveness of the corresponding end product through providing timely attractive options. This was the case of gas turbines for power generation developed by the gas industry, which greatly enhanced the competitiveness of gas in power generation. In this connection, it is essential for the nuclear energy sector to be involved and participate actively in the assessment of demand for end products and in particular in the prospective studies on hydrogen economy implementation.

Competitiveness of Nuclear Energy

Basically the competitiveness of nuclear energy in the non-electricity product market will be the same as in the electricity market. Although it might differ depending on countries or regions, the cost advantage of nuclear energy versus alternatives is seldom dramatic and there is no reason to assume that it will compete favourably in non-electricity product markets in countries where it is not the cheapest electricity generation option. However, some breakthroughs in terms of new technology, new environment such as the increase of gas/oil price, enforcement of carbon taxes, and significant increase of relevant demand, may change the situation.

Although many studies present results indicating the competitiveness of nuclear energy for non-electrical application, more concrete analyses based on real data from the operation or demonstration of relevant systems are needed to back up those studies.

Initiation of Actions

In order to launch a market for nuclear non-electricity products, it is necessary that the suppliers place their orders to the manufacturers and that these have the capacities to deliver the required installations. Who will initiate an action is like the chicken and egg problem. Suppliers will not invest in a facility that may not be profitable. It is hard for them to be sure without seeing some real systems from vendors. Moreover vendors will not invest in the development of systems for which the demand is not known. Research institutes cannot afford the development of new systems by themselves. Many research institutes suggest advanced ideas, but are not in a position to implement them in an industrial scale.

Some triggering effort from governments in support to the development of nuclear non-electricity product development, in cooperation with vendors, could be considered within national energy policy measures.

If niche markets could be found for non-electrical application of nuclear energy, it would foster the development of adapted nuclear systems. A thorough investigation of potential niche markets would be valuable, although niche markets are likely to be country-specific.

An example of niche-market is provided by Canada where there is renewed interest in the use of nuclear heat for the recovery of oil-sands bitumen from the huge deposits (about 300 billion bbl of oil) in Northern Alberta. The option currently preferred for new projects is recovery of bitumen by a process called Steam-Assisted Gravity Drainage (SAGD). This melts the bitumen in situ by injection of steam at moderate pressure (2 to 2.5 MPa). Using about 2 to 2.5 volumes of condensate per volume of bitumen recovered, the quantities of steam are very large. An Advanced CANDU Reactor (ACR) of 700 MWe would produce enough steam to supply the recovery of about 140 000 bbl bitumen/day (22 000 m^3/day), at the large end of the range of current projects. Studies consistently show nuclear-produced steam to be cheaper than steam produced from natural gas (the current energy source) unless the price of natural gas is less than 4 $Can/GJ. Because of the modest pressure of steam required for the SAGD process, it would be extracted from a back-pressure turbine generating about 100 MWe. The mix of electricity and steam could be varied to suit the demands of individual SAGD projects.

Technology-oriented Issues

Most technologies adapted to non-electrical application of nuclear energy are not yet proven. For example, large scale hydrogen production by nuclear energy would require the development of fuel cells, relevant reactors, thermochemical processes and other supporting technologies. Even those technologies that have been proven need more development for reaching better economical performance. For instance, HTGR technology has not yet achieved commercial maturity, and not been tested for heat application.

Furthermore, for successful penetration in the market, early demonstration is critical. Especially, the long-term prospects for alternative technology options for hydrogen production will depend to a certain extent on early demonstration of feasibility and viability. Selection of strategic paths is important. For instance, nuclear assisted steam methane reforming could be pursued as an early nuclear option, which will facilitate further market penetration of more innovative nuclear hydrogen production technologies. In this regard, early involvement of industry in the development would be valuable.

The current reactor safety levels are satisfactory as demonstrated by the continued successful operation of reactors all over the world. This will also be the case for reactors used to generate non-electricity products. However, since the reactors would be associated with facilities to produce non-electricity products, additional safety concerns may result from the coupling of reactors, for instance, with desalination facilities, plants using high-temperature heat or hydrogen production facilities. Furthermore, since reactors would be located near densely populated area in some cases such as district heating, additional safety requirements may apply.

Nuclear non-electricity products require corresponding infrastructures such as distribution networks, which involve huge investment and operation costs. It will be very helpful for a newcomer in the market to have an opportunity of sharing existing infrastructure if applicable (*e.g.* heat distribution network). Otherwise, the newcomer has to bear the overall burden of implementing the required infrastructure. Governmental measures such as financial support may alleviate this obstacle to the development of non-electrical application of nuclear energy.

Resource-oriented Issues

The deployment of nuclear non-electricity products implies increased demand for new reactors and relevant infrastructures, which would require lots of resources including capital, sites, manpower and nuclear fuel. Their availability would be critical for the deployment of nuclear non-electricity products.

The degree of deployment of nuclear non-electricity product facilities largely depends on the availability of capital investment. Due to the limitedness of capital, harsh competition is expected among many energy options to get the required capital investments. Nuclear non-electricity products may compete even with electricity generation. According to an IEA report [8], total investment required for the energy-supply infrastructure worldwide over the period 2001-2030 is expected to amount to $16 trillion, or $550 billion a year. Capital needs are expected to grow steadily through the period. The average annual rate of investment is projected to rise from around $450 billion in the current decade to $630 billion in 2021-2030. This compares with estimated investment of $410 billion in 2000.

Another factor to consider is market liberalisation, which has added new challenges and uncertainties for investors. They are more reluctant to finance new projects since they are more exposed to risk than they were in regulated markets.

A large share of potential customers for nuclear non-electricity products, especially in the case of seawater desalination, are in developing countries, which are not in position to finance the required infrastructure and new facilities and would require huge capital investment from foreign industrialised countries.

Uranium is plentiful and advanced nuclear technologies can broaden the resources that can be used as nuclear fuel. However, uranium production capabilities supported by known conventional resources recoverable at a cost of less than USD 80/kgU are expected not to satisfy projected future world uranium requirements through 2020 even in the low demand cases [9]. Thus, secondary sources such as excess commercial inventories, low-enriched uranium (LEU) derived from highly-enriched uranium (HEU) warheads, re-enrichment of tails and spent fuel reprocessing, will remain necessary to ensure adequate supplies in the near term. However, secondary sources are expected to decline in importance, particularly after 2020.

In the long run, uranium requirements will have to be increasingly met by the expansion of existing production capacity, together with the development of additional production centres or the introduction of alternative fuel cycles. Recognising that natural uranium resources, although very large, are by definition finite, a significant deployment of nuclear non-electricity products would enhance the attractiveness of advanced fuel cycle options more efficient in the use of the energy content of natural resources, uranium and thorium.

NEA member countries are facing possible demographic downturns in their nuclear industries [10]. In spite of many initiatives in the area of nuclear education and training, they would still require more engineers and scientists having nuclear knowledge than are graduating. As fewer and fewer high quality technical graduates become available, the competition for them would be greater and there are signs already that the nuclear industry is losing out. This is of concern to the nuclear industry as the majority of the scientists and engineers working in it do not have nuclear specialist education. These concerns would become more prominent if non-electrical application of nuclear energy would be deployed in a large scale. However, it seems likely that advances in technology development would attract young talents.

Social and Legal Issues

The use of nuclear energy for non-electricity energy products is likely to face the same obstacles as electricity generation, or any other application. Addressing public concerns regarding nuclear safety, radioactive waste management and disposal and weapon proliferation is a prerequisite when considering a broad deployment of nuclear energy to supply non-electricity energy products which might entail much more than doubling the number of reactors in operation worldwide.

As more nuclear reactors would be deployed, stronger anti-nuclear movement could be expected. Therefore, too optimistic projection for the application of nuclear energy to non-electricity products needs careful consideration. For some nuclear non-electricity products, such as district heat, additional public concerns are expected due to the closeness of reactors to densely populated areas.

In countries where no nuclear energy facility is in operation, the introduction of the new energy source requires the implementation of a legal framework and regulatory bodies for safety and licensing. Building that kind of infrastructure is a burden that some countries may not be prepared to bear.

FINDINGS AND RECOMMENDATIONS

As shown in the IAEA study [1], the potential non-electricity product market open to nuclear energy seems to be very large; district heat, process heat and desalinated water in the near term, and hydrogen in the long term. For example, assuming that current district heat in the world would be replaced by nuclear energy, it would mean the addition of 340 1000 MWth reactors. However, the reality does not match the potential. Even though the high potential needs to be considered in a vision for the future, realistic demand needs to be assessed.

From the beginning of the project, some basic questions related to the real deployment of nuclear non-electricity products have been raised such as:

- If nuclear energy has so high potential in the non-electricity product market, why has its deployment been so limited? Can one expect some dramatic changes in this market situation?
- Who will or should initiate actions for the deployment of non-electricity application of nuclear energy: the government, R&D institutes, vendors or suppliers? If necessary, how to motivate vendors or suppliers? Would some policy measures (tax reduction, subsidies, carbon tax, …) really work?
- What are the thoughts of suppliers and vendors (nuclear and/or non-nuclear) in the current market?
- What’s the role of the government? Do governments consider seriously all nuclear options in their national energy policies for greenhouse gas reduction and energy security?

Common sense provides reasonable-guess answers to the above questions but more investigations are required to support an authoritative report. Deeper studies including market analyses are needed for enhanced understanding of realistic projected demand, which can be carried out only with the support of national experts providing relevant input data. Also, country-specific information is needed to analyse the reasons for the limited deployment of non-electrical application of nuclear energy and to draw some policy recommendations. Since very few country reports had been received, this part of the study is not complete. Furthermore, comprehensive technology assessments for non-electric applications of nuclear energy could be valuable, focusing on other aspects which require further investigation.

With its limitations, the present report leads to the following preliminary findings and/or recommendations:

- There is a need to understand better the market and to increase communication with key actors. Convincing all actors in the market (customers, suppliers, vendors, research institutes and government) is critical for the introduction of nuclear non-electricity products in the market. In this regard, the establishment of some interest groups on nuclear applications in the market would be valuable. Considering that a large part of non-electricity energy demand is in developing countries and that developed countries would provide relevant technologies, it would be better to have some connections between developed countries and developing countries especially in the case of nuclear desalination.
- According to the demand pattern in the market, the requirements for nuclear systems will be different. For example, if demand for distributed rather than centralised hydrogen production prevails, the development of small- and medium-size reactors would be relevant. The development of nuclear non-electricity product technologies, in turn, may affect the shaping

of the demand pattern through providing timely attractive options. In this connection, it is essential for the nuclear energy sector to be involved and participate actively in the discussions on non-electricity application including hydrogen economy.

- For the successful penetration in the market early demonstration is critical. Especially, the long-term prospects for alternative technology options for hydrogen generation will depend to a certain extent on early demonstration of feasibility and viability. For instance, nuclear assisted steam methane reforming could be pursued as an early nuclear option, which will facilitate further market penetration of more innovative nuclear hydrogen production technologies.

- In the light of recent trends in energy markets, strong competition is expected between alternative options to supply non-electricity products. For example, there are many technical options for hydrogen production and a large number of technologies, such as steam reforming of methane, steam coal gasification with sequestration of CO_2 and solar photovoltaic process, are already available or under development. Nuclear non-electricity production technology should be ready for deployment and competitive on deregulated market although the demand for relevant reactors is unlikely to be comparable to mass reactor orders that occurred in the 60's and 70's.

- The development of nuclear non-electricity product technologies, especially hydrogen production technologies, requires long-term commitment with many uncertainties. All stakeholders in government bodies and the industry have a role to play for the eventual success of relevant technologies. Co-ordination and joint efforts are essential in organising R&D programmes, infrastructure building and policy making to address the challenges of developing competitive and efficient technical processes.

- In countries wishing to rely on nuclear energy in the long term, the role of governments for the emergence of non-electrical applications of nuclear energy is very important in terms of basic R&D, initial technology development and policy making to create a favourable business environment without interfering with market mechanisms.

- International co-operation is essential to ensure the design and implementation of nuclear systems efficient for non-electrical applications of nuclear energy such as hydrogen production. In particular, the efforts required in the field of nuclear R&D, and infrastructure building, are likely to be beyond individual country capabilities. In this context, undertakings like GIF, for example, can enhance the synergy between national programmes and the effectiveness of the overall efforts.

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