IAEA Nuclear Energy Series

No. NP-T-1.17

Basic Principles

Objectives

Guides

Technical Reports

Guidance on Nuclear Energy Cogeneration

IAEA
International Atomic Energy Agency

IAEA NUCLEAR ENERGY SERIES PUBLICATIONS

STRUCTURE OF THE IAEA NUCLEAR ENERGY SERIES

Under the terms of Articles III.A and VIII.C of its Statute, the IAEA is authorized to foster the exchange of scientific and technical information on the peaceful uses of atomic energy. The publications in the **IAEA Nuclear Energy Series** provide information in the areas of nuclear power, nuclear fuel cycle, radioactive waste management and decommissioning, and on general issues that are relevant to all of the above mentioned areas. The structure of the IAEA Nuclear Energy Series comprises three levels: **1 — Basic Principles and Objectives**; **2 — Guides**; and **3 — Technical Reports**.

The **Nuclear Energy Basic Principles** publication describes the rationale and vision for the peaceful uses of nuclear energy.

Nuclear Energy Series Objectives publications explain the expectations to be met in various areas at different stages of implementation.

Nuclear Energy Series Guides provide high level guidance on how to achieve the objectives related to the various topics and areas involving the peaceful uses of nuclear energy.

Nuclear Energy Series Technical Reports provide additional, more detailed information on activities related to the various areas dealt with in the IAEA Nuclear Energy Series.

The IAEA Nuclear Energy Series publications are coded as follows: **NG** — general; **NP** — nuclear power; **NF** — nuclear fuel; **NW** — radioactive waste management and decommissioning. In addition, the publications are available in English on the IAEA Internet site:

http://www.iaea.org/Publications/index.html

For further information, please contact the IAEA at PO Box 100, Vienna International Centre, 1400 Vienna, Austria.

All users of the IAEA Nuclear Energy Series publications are invited to inform the IAEA of experience in their use for the purpose of ensuring that they continue to meet user needs. Information may be provided via the IAEA Internet site, by post, at the address given above, or by email to Official.Mail@iaea.org.

GUIDANCE ON NUCLEAR ENERGY COGENERATION

The following States are Members of the International Atomic Energy Agency:

AFGHANISTAN
ALBANIA
ALGERIA
ANGOLA
ANTIGUA AND BARBUDA
ARGENTINA
ARMENIA
AUSTRALIA
AUSTRIA
AZERBAIJAN
BAHAMAS
BAHRAIN
BANGLADESH
BARBADOS
BELARUS
BELGIUM
BELIZE
BENIN
BOLIVIA, PLURINATIONAL STATE OF
BOSNIA AND HERZEGOVINA
BOTSWANA
BRAZIL
BRUNEI DARUSSALAM
BULGARIA
BURKINA FASO
BURUNDI
CAMBODIA
CAMEROON
CANADA
CENTRAL AFRICAN REPUBLIC
CHAD
CHILE
CHINA
COLOMBIA
CONGO
COSTA RICA
CÔTE D'IVOIRE
CROATIA
CUBA
CYPRUS
CZECH REPUBLIC
DEMOCRATIC REPUBLIC OF THE CONGO
DENMARK
DJIBOUTI
DOMINICA
DOMINICAN REPUBLIC
ECUADOR
EGYPT
EL SALVADOR
ERITREA
ESTONIA
ESWATINI
ETHIOPIA
FIJI
FINLAND
FRANCE
GABON
GEORGIA
GERMANY
GHANA
GREECE
GRENADA
GUATEMALA
GUYANA
HAITI
HOLY SEE
HONDURAS
HUNGARY
ICELAND
INDIA
INDONESIA
IRAN, ISLAMIC REPUBLIC OF
IRAQ
IRELAND
ISRAEL
ITALY
JAMAICA
JAPAN
JORDAN
KAZAKHSTAN
KENYA
KOREA, REPUBLIC OF
KUWAIT
KYRGYZSTAN
LAO PEOPLE'S DEMOCRATIC REPUBLIC
LATVIA
LEBANON
LESOTHO
LIBERIA
LIBYA
LIECHTENSTEIN
LITHUANIA
LUXEMBOURG
MADAGASCAR
MALAWI
MALAYSIA
MALI
MALTA
MARSHALL ISLANDS
MAURITANIA
MAURITIUS
MEXICO
MONACO
MONGOLIA
MONTENEGRO
MOROCCO
MOZAMBIQUE
MYANMAR
NAMIBIA
NEPAL
NETHERLANDS
NEW ZEALAND
NICARAGUA
NIGER
NIGERIA
NORTH MACEDONIA
NORWAY
OMAN
PAKISTAN
PALAU
PANAMA
PAPUA NEW GUINEA
PARAGUAY
PERU
PHILIPPINES
POLAND
PORTUGAL
QATAR
REPUBLIC OF MOLDOVA
ROMANIA
RUSSIAN FEDERATION
RWANDA
SAINT LUCIA
SAINT VINCENT AND THE GRENADINES
SAN MARINO
SAUDI ARABIA
SENEGAL
SERBIA
SEYCHELLES
SIERRA LEONE
SINGAPORE
SLOVAKIA
SLOVENIA
SOUTH AFRICA
SPAIN
SRI LANKA
SUDAN
SWEDEN
SWITZERLAND
SYRIAN ARAB REPUBLIC
TAJIKISTAN
THAILAND
TOGO
TRINIDAD AND TOBAGO
TUNISIA
TURKEY
TURKMENISTAN
UGANDA
UKRAINE
UNITED ARAB EMIRATES
UNITED KINGDOM OF GREAT BRITAIN AND NORTHERN IRELAND
UNITED REPUBLIC OF TANZANIA
UNITED STATES OF AMERICA
URUGUAY
UZBEKISTAN
VANUATU
VENEZUELA, BOLIVARIAN REPUBLIC OF
VIET NAM
YEMEN
ZAMBIA
ZIMBABWE

The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

IAEA NUCLEAR ENERGY SERIES No. NP-T-1.7

GUIDANCE ON NUCLEAR ENERGY COGENERATION

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2019

COPYRIGHT NOTICE

All IAEA scientific and technical publications are protected by the terms of the Universal Copyright Convention as adopted in 1952 (Berne) and as revised in 1972 (Paris). The copyright has since been extended by the World Intellectual Property Organization (Geneva) to include electronic and virtual intellectual property. Permission to use whole or parts of texts contained in IAEA publications in printed or electronic form must be obtained and is usually subject to royalty agreements. Proposals for non-commercial reproductions and translations are welcomed and considered on a case-by-case basis. Enquiries should be addressed to the IAEA Publishing Section at:

Marketing and Sales Unit, Publishing Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
fax: +43 1 26007 22529
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
www.iaea.org/publications

© IAEA, 2019

Printed by the IAEA in Austria
September 2019
STI/PUB/1862

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: Guidance on nuclear energy cogeneration / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2019. | Series: IAEA nuclear energy series, ISSN 1995–7807 ; no. NP-T-1.17 | Includes bibliographical references.
Identifiers: IAEAL 19-01261 | ISBN 978–92–0–104119–7 (paperback : alk. paper)
Subjects: LCSH: Cogeneration of electric power and heat. | Nuclear energy. | Nuclear power plants.
Classification: UDC 621.039.517 | STI/PUB/1862

FOREWORD

One of the IAEA's statutory objectives is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world." One way this objective is achieved is through the publication of a range of technical series. Two of these are the IAEA Nuclear Energy Series and the IAEA Safety Standards Series.

According to Article III.A.6 of the IAEA Statute, the safety standards establish "standards of safety for protection of health and minimization of danger to life and property". The safety standards include the Safety Fundamentals, Safety Requirements and Safety Guides. These standards are written primarily in a regulatory style, and are binding on the IAEA for its own programmes. The principal users are the regulatory bodies in Member States and other national authorities.

The IAEA Nuclear Energy Series comprises reports designed to encourage and assist R&D on, and application of, nuclear energy for peaceful uses. This includes practical examples to be used by owners and operators of utilities in Member States, implementing organizations, academia, and government officials, among others. This information is presented in guides, reports on technology status and advances, and best practices for peaceful uses of nuclear energy based on inputs from international experts. The IAEA Nuclear Energy Series complements the IAEA Safety Standards Series.

This publication provides an overview on the use of nuclear energy for such non-electric applications as the production of heat or desalinated water. It also presents some concepts that were previously developed to be applied in connection with industries, describing technical concepts for combined nuclear-industrial complexes that are being pursued in various Member States today. The scope of this publication is to assess the benefits and practical issues related to using a nuclear reactor in a cogeneration mode to generate not only electric power but also other products: heat, water, energetic liquids or gases, and the like. In some cases, the cogeneration mode may be also suitable for some industrial applications such as process steam for oil recovery and refineries, hydrogen production, and steel and aluminium making. Several examples for nuclear concepts with such industrial applications are presented. This publication is expected to provide users from academia to industry, and from government agencies to public institutions, with basic information on the use of nuclear power in a cogeneration mode.

This publication was compiled by Xing L. Yan of the Japan Atomic Energy Agency based on evaluations of officially issued reports and published papers as well as contributions provided by the experts named at the end of the report. Those experts also reviewed the draft report. The IAEA officer responsible for this publication was Ibrahim Khamis of the Division of Nuclear Power.

EDITORIAL NOTE

This publication has been edited by the editorial staff of the IAEA to the extent considered necessary for the reader's assistance. It does not address questions of responsibility, legal or otherwise, for acts or omissions on the part of any person.

Although great care has been taken to maintain the accuracy of information contained in this publication, neither the IAEA nor its Member States assume any responsibility for consequences which may arise from its use.

Guidance provided here, describing good practices, represents expert opinion but does not constitute recommendations made on the basis of a consensus of Member States.

The use of particular designations of countries or territories does not imply any judgement by the publisher, the IAEA, as to the legal status of such countries or territories, of their authorities and institutions or of the delimitation of their boundaries.

The mention of names of specific companies or products (whether or not indicated as registered) does not imply any intention to infringe proprietary rights, nor should it be construed as an endorsement or recommendation on the part of the IAEA.

The IAEA has no responsibility for the persistence or accuracy of URLs for external or third party Internet web sites referred to in this book and does not guarantee that any content on such web sites is, or will remain, accurate or appropriate.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

A broad range of nuclear reactors is currently available for the supply of energy for electricity and other non-electric applications. Future nuclear reactor concepts incorporating cogeneration features and meeting stricter economic criteria are being developed in many countries. The cogeneration of heat and power or combined heat and power (CHP) operation mode of power plants has long been used in numerous industries worldwide to optimize energy flows and minimize energy losses, thus improving energy (fuel) efficiencies and energy security and reducing industrial CO_2 emissions. Only about one third of the total final energy consumption is consumed in the industry sector.

Member States requested that the IAEA assess the use and applications of small and medium reactors (SMRs) for cogeneration. In its General Conference resolution GC(57)/RES/12.A.4 [1], the IAEA was requested "to develop a report that provides generic guidance on cogeneration options and assesses the economics associated with such options". Another detailed technical report describes the technical and economic aspects of cogeneration [2]. This publication is intended to respond to resolution GC(57)/RES/12.A.4 and provide high level decision makers and planners with highlights of the benefits of cogeneration with NPPs as well as to discuss issues to consider during the implementation of cogeneration with nuclear power.

IAEA resolution GC(57)/RES/12.A.4 noted that potable water shortages are of growing concern in many regions of the world due to population growth, increased urbanization and industrialization and the effects of climate change. The resolution also noted that seawater desalination using nuclear energy has been successfully demonstrated through various projects in some Member States and is generally cost effective while recognizing that the economics of implementation will depend on site-specific factors.

In the cogeneration process a coolant recovers the thermal energy released by fission in the reactor core. The heat is usually converted into electrical power through a turbine generator. Whenever heat is part of the final use, the generated heat can be used directly in concert with electric power conversion; in other words, it can cogenerate electricity and heat or heat-derivative products. Depending on the technology (reactor type, fuel type and temperature level), the cogenerated products may include district heating and cooling, process steam, desalination, hydrogen or steel making. The use of nuclear energy for cogeneration provides major advantages and resulting benefits.

The major advantages of nuclear cogeneration include the following:

- Saving energy by:
  - *Recovering waste heat.* The typical conversion efficiency from heat to electricity is 33%. Hence, about two thirds of the fission energy ends up heating the atmosphere or the cooling water. Cogeneration allows use of part, if not all, of the waste heat.
  - *Offering additional uses of nuclear power.* Nuclear energy is, today, mainly installed to generate electricity. Nuclear cogeneration makes the nuclear energy source available to residential and commercial sectors through district heating as well as to the industry sector through process heat.
- Saving the environment by:
  - *Reducing CO_2 emissions.* Needless to say, nuclear energy is a carbon-free energy source. It is the only controllable baseload source available that does not emit greenhouse gases when operating. Therefore, whenever nuclear heat substitutes for a hydrocarbon energy source, it reduces the amount of CO_2 emitted into Earth's atmosphere. Nuclear energy is undoubtedly part of the solution to fight against climate change.
  - *Reducing nuclear waste.* The fission of uranium atoms results in two medium heavy atoms called fission products. Some of the fission products are highly radioactive and have to be disposed of as nuclear waste. Making use of more energy per fission in a cogeneration mode thereby reduces the quantity of waste generated per unit energy.
- Saving money by:
  - *Delivering cheaper energy.* Waste heat may be recovered from a nuclear reactor at a relatively low cost compared to production costs at a fossil fuel burning plant. Although an initial investment is required

for heat transport and distribution, in many cases, the result is cheaper energy to the consumer. After amortization, nuclear reactor waste heat is the cheapest form of heat.

- *Reducing the need for fossil fuels.* In many countries, oil, gas and coal are expensive imported goods. The expected rarefaction of fossil fuel reserves in the world will tend to make them even more costly in the future. Nuclear cogeneration may reduce the dependence on fossil fuels, relieving trade imbalances and thus improving the security of the energy supply.

The major advantages of nuclear cogeneration include the following:

— Better efficiency: The energy efficiency of a nuclear power plant operated in a cogeneration mode may exceed 80%, significantly higher than the typical efficiency of 33% from today's nuclear power plants (NPPs) that are producing electricity only.
— Better use of energy: Using energy in the right final form and at the right temperature avoids unwanted transformations that are generally sources of poor efficiency and loss.
— Better flexibility: The generation of two or more products like electricity and heat allows possible switching between the two outputs, offering additional flexibility for the electrical grid.
— Better environmental performance: The benefits of cogeneration for the environment are obvious: less heat waste is discharged in the vicinity of the power plant and less water is needed to cool the reactor. More importantly, nuclear heat use will reduce or eliminate the need for fossil fuels for heat, which will help reduce carbon emissions in industrial sectors.

1.2. OBJECTIVE

The objective of this publication is to provide generic guidance on the merits of cogeneration, steps during implementation, and recommendations for Member States embarking on cogeneration with nuclear energy.

1.3. SCOPE

This publication expands on the above benefits of the technology, highlights development activities in the IAEA and elsewhere and considers implementation issues and status of the technology. It covers some techno-economic aspects of both low temperature cogeneration applications, which can be found in district heating, seawater desalination, agricultural and other industrial processes, representing a large potential for integrating nuclear energy cogeneration of heat and electricity and potential high temperature cogeneration applications such as hydrogen production and the use of process heat for industrial applications using advanced high temperature reactors.

1.4. STRUCTURE

Section 2 of this publication discusses the definition of nuclear cogeneration, current operating experiences and the IAEA's activities in this area. Section 3 explores the potential benefits of the use of nuclear energy for cogeneration. Sections 4 and 5 discuss the issues to be considered aspects of implementation, and the generic guidance in nuclear cogeneration projects. Section 6 summarizes the major findings, which include: excellence and practice, developing project plans and taking implementation steps. Section 7 concludes the discussion, while the Appendix provides a series of case studies.

2. NUCLEAR COGENERATION

2.1. WHAT IS NUCLEAR COGENERATION?

Nuclear cogeneration is the simultaneous production of electricity and heat or a heat-derivative product from an NPP. It is an existent, though limited, practice. Further development has significant potential to transform current nuclear energy systems so that they are more versatile and sustainable. In an NPP, thermal energy is harnessed from nuclear fission and converted to heat in the form of steam or hot gas. A portion of the heat, normally 30–50% depending on system design, is converted to electricity and the remainder is usually rejected to the environment as waste. Instead of being rejected, this heat still retains the required energetic pressure and temperature (gained during the conversion process to power), which may be utilized to produce heating or cooling, or as an energy source to produce fresh water, hydrogen or other important products such as oil and synthetic fuel. These may be cogenerated, adding potential benefits to nuclear plants operating in energy markets.

Low temperature heat applications such as district heating and seawater desalination require nuclear heat in the range of 230–250°C. Currently operating water-cooled reactors could easily match the requirement for such applications. However, the current practice of nuclear reactors with high temperature nuclear heat applications such as the ones indicated in Fig. 1 may be divided into two technology groups: the use of steam up to temperatures of 540°C, such as in oil refining and petrochemical production, and the use of a heat exchanger at temperatures up to 950°C, such as hydrogen and coal gasification, which require nuclear heat obtained from advanced reactors that are currently in development.

Cogeneration in nuclear is quite similar to operating a standard combined heat and power plant fed by any other energy source. There are only two specific points to be concerned about: NPP safety and any potential radioactivity transfer through the system up to the main heat transfer line. Safety can be ensured by letting the nuclear system have priority in case of any abnormal situation. In other words, the safety of the NPP does not rely on the operational performance of the cogenerating heat plant. Whatever the heat demand or the power need is from the heat plant, nuclear safety should outweigh any such consideration, as when running the NPP to produce only electricity. A good practical way to prevent any radioactive contamination to a heat application system, for example, is to physically isolate the primary loop of the reactor from the main transfer line. This is obviously done in a pressurized water reactor (PWR) as the secondary loop is already an isolated closed loop system serving as a barrier for contaminants. However, in a boiling water reactor (BWR), an additional water loop would be needed between the heat exchanger/condenser at the turbine output and the main heat transport (MHT) line.

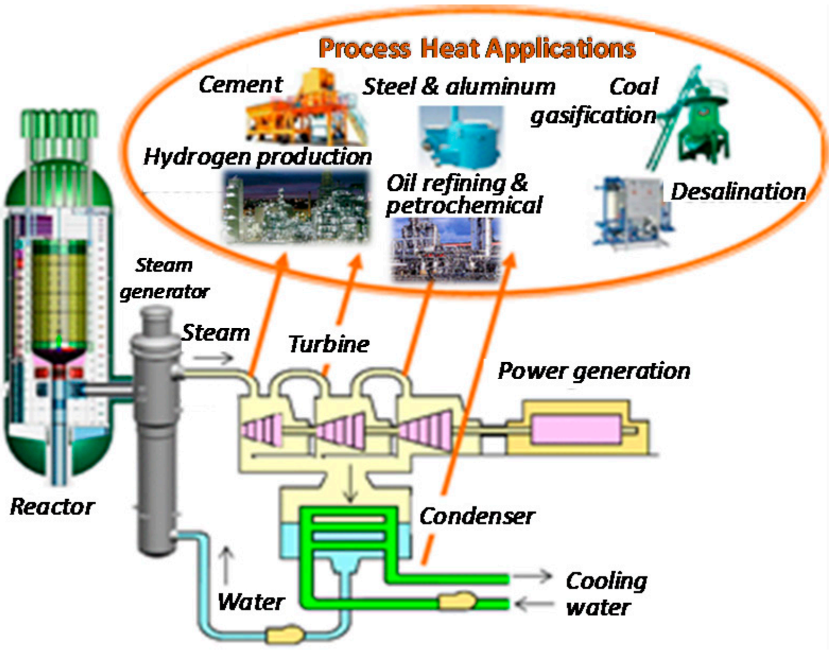


FIG. 1. General scheme for industrial heat applications in nuclear cogeneration.

There are two ways in which nuclear reactors could be used:

— The dedicated heat mode, in which heat is transferred directly through a heat exchanger from the reactor to an intermediate heat transport network and then to the end user or customer.
— The cogeneration mode, in which heat is retrieved through a heat exchanger or extracted as steam from various expansion stages of a turbine or from a condenser. The portion of the heat retrieved, which may be small or large compared with that used for electricity production, is then delivered to the end user with or without an intermediate heat transport network depending on the heat extraction point and on the application's requirement.

Cogeneration of electric and steam power can be an advantageous blending of two well developed technologies, namely: (a) electric power generation with high temperature, high pressure inlet steam and a condensing cycle, and (b) industrial steam generation characterized by production at moderate temperatures and pressures. For district heating applications, hot water or steam should be supplied at temperatures below 200°C. If the desired output heat power is small compared to the nominal electrical power of the reactor, then a bleeding from the low pressure turbine in the machine hall is usually sufficient to provide the required heat. This bleeding can already be found in many reactors where hot steam is purposely extracted at temperatures between 60°C and 140°C to preheat the cold water coming from the condenser prior to feeding the water tank. However, if the heat power requirement is important, then the extraction may be performed following a specifically designed low pressure turbine at the right temperature. In that way, nuclear reactor heat can be fully used. Of course, any intermediate situation between a pure electrical power output (0% heat output) and a complete use of heat (100% heat output) can be obtained by diverting the correct quantity of steam into the corresponding branch. This flexibility can be used to easily follow the heat demand of the district heating network.

2.2. CURRENT STATUS OF NUCLEAR COGENERATION

Although electricity production is the principal function of today's operating nuclear reactors, many of them have been used for cogeneration (i.e. for electricity generation plus desalination, district heating or industrial process heat (see Fig. 2)). These are primarily light water reactors but also include heavy water and liquid metal reactors in a number of countries. The total accumulated experience is about 750 operating years. The district heating reactors are located mainly in Eastern Europe and the Russian Federation — countries subject to long, cold winters. The desalination reactors are located mostly in Japan, Kazakhstan and the United States of America (USA), where they are used to offset a shortage of natural water. Experience with industrial non-electric applications (excluding desalination and district heating) has been achieved to date in seven nuclear reactors in Canada, Germany, India and Switzerland.

Of those reactors used for district heating, the heat power output ranges from 5 to 240 MW(th). The total distributed heat power is around 5000 MW(th), corresponding to an average energy withdrawal of less than 5%.

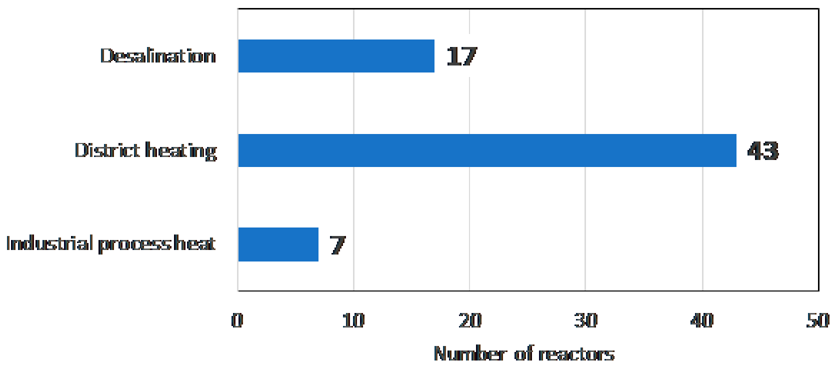


FIG. 2. Cogenerating nuclear reactors in the world.

This means that, even if running in cogeneration mode, the primary output of the reactor is still electrical power. In many cases, heat is used to feed cities a few kilometres from the NPP. For example, in Beznau, Switzerland, the MHT pipeline currently extends to 35 km, and in Kola, in the Russian Federation, even up to 64 km. According to the experience collected, in district heating systems using nuclear heat there has been no identified major issue related to the extraction of heat from an NPP [3, 4]. Pulling out heat from an NPP is almost equivalent to any CHP plant, provided safety is ensured. In that regard, the interaction of the two control-command systems (the NPP and the MHT) has to be worked out, and the priority should always be given to the safe shutdown of the NPP in case of any accidental event. Old systems suffer from high heat losses in generation, transport, distribution and end-use, hindering the rapid spread of nuclear-based district heating systems [5]. In addition, lack of coordination between local and central decision-making boards and national environmental and energy agencies has not helped implement the efficient and economical use of district heating networks. Nevertheless, new projects using nuclear cogeneration of heat and power, including deployment of advanced nuclear reactors, are being envisaged in Member States through their joint efforts, with frequent assistance by the IAEA.

2.3. PAST AND FUTURE IAEA ROLES

The IAEA programme for non-electric applications of nuclear energy continues to support Member States through various forums of information exchange, coordinated research projects and publications. The General Conferences of the IAEA have issued several resolutions in support of the use of nuclear power for seawater desalination [1]. In particular, resolution GC(57)/RES/12.A.4 noted that potable water shortages are of growing concern in many regions of the world, due to population growth, increased urbanization and industrialization and the effects of climate change. Desalinating seawater using nuclear energy has been successful in various projects in some Member States and is generally cost effective. The resolution also noted, with appreciation, the activities the IAEA had carried out and requested that the IAEA develop a report providing generic guidance on cogeneration options and assessing the economics associated with such options. The IAEA's activities related to cogeneration for seawater desalination using nuclear energy are conducted largely within the framework of the Technical Working Group on Nuclear Desalination and integrated water resources management in nuclear facilities.

The IAEA has also been repeatedly requested by Member States through various GC resolutions to assist them in considering the use and applications of SMRs for cogeneration. A broad range of these new reactors are also designed for the supply of energy for non-electric applications. These reactors are attractive because they incorporate enhanced safety features. Interest in SMRs is strong also because they require smaller investments and thus reduce financial risks. 'Small' means less than 300 MW(e) and 'medium-sized' means between 300 MW(e) and 700 MW(e). Many concepts are at some stage of research and development (R&D) around the world. Examples include the 150–300 MW(e) CAREM, an integral type pressurized light water reactor (LWR) being developed in Argentina; the 50–250 MW(e) Flexblue modular underwater design in France; in India, the 304 MW(e) Advanced Heavy Water Reactor, the 500 MW(e) Prototype Fast Breeder Reactor (PFBR-500) at Kalpakkam currently in the commissioning stage, and four 700 MW(e) PHWRs under construction; the Russian Federation's 35 MW(e) KLT-40S barge-mounted integral PWR for cogeneration of electricity and district heating; and several integral pressurized water SMRs in the USA such as the 180 MW(e) mPower, 50 MW(e) NuScale, 225 MW(e) Westinghouse SMR and 160 MW(e) Hi-SMUR (Holtec Inherently Safe Modular Underground Reactor). Table 1 identifies several reactors for cogeneration that are at various stages of commercial development in China, Japan, the Republic of Korea and the USA.

Member States are considering additional possible future non-electric uses, including high temperature steam production, to feed industrial processes and hydrogen production to, first, upgrade low-quality petroleum resources such as oil sands while offsetting carbon emissions associated with steam methane reforming; second, support large scale production of synthetic liquid fuels based on biomass, coal or other carbon sources; and, third, serve directly as a vehicle fuel, most likely using fuel cells. The IAEA has undertaken activities and planned programmes such as those described below to assist Member States in assessing, in depth, various aspects of the non-electric processes suitable for cogeneration.

2.3.1. Coordinated research project on process heat applications

The growing interest of Member States in process heat applications of nuclear energy was one of the major drivers for the IAEA to launch a three year coordinated research project (CRP) on Advances in Nuclear Power Process Heat Applications in 2007 [6]. The CRP addressed the challenges related to such process technologies as hydrogen production and desalination, process to reactor coupling safety, and the economic merits of centralized and distributed production options. With the participation of Argentina, China, France, Germany, Japan, India, the Russian Federation, South Africa and the Syrian Arab Republic, the CRP identified the very high temperature reactor (VHTR) — which is flexible in design, siting, fuel cycle and size — to be a promising technology. It clearly shows the features of a catastrophe-free reactor and is one of the most advanced of the Generation-IV (Gen-IV) reactors in terms of R&D status. It provides a proven coolant temperature range up to 950°C, meeting the heat requirement for a wide range of industrial processes. The CRP reviewed prior experience with coupling nuclear reactors to low temperature processes of district heating and desalination and recommended further design and economic analysis of desalination utilizing the waste heat from the VHTR. That analysis forms the basis of a case study in the present publication. In the high temperature processes, the reactor was identified as being applicable to the production processes of liquid fuels or hydrogen by steam reforming or water splitting. While the feasibility of steam reforming had successfully been demonstrated, the water splitting processes of high temperature electrolysis and thermochemical cycles still has design challenges for which development efforts continue to be made in several Member States [7].

2.3.2. Coordinated research project on nuclear hydrogen economics evaluation

The increasing prospect of hydrogen production using nuclear energy led the IAEA to carry out a CRP, Examining the Techno-Economics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA Hydrogen Economic Evaluation Programme (HEEP) Software. The CRP provides opportunities to exchange information on the status of nuclear hydrogen production in Member States; on remaining challenges to nuclear hydrogen production, with emphasis on the safety of nuclear and hydrogen plant coupling; and on future aspects of the hydrogen economy. The IAEA has developed the HEEP computer software that allows analysing various options of production, storage and transportation for future hydrogen economy. Being the first of its kind, the HEEP is being benchmarked for various scenarios of hydrogen production and distribution from technology selection to system configuration, including financing arrangement. The Member States collaborating on the benchmarking and related HEEP user meetings were Algeria, Argentina, Canada, China, Germany, India, Indonesia, Japan/USA, the Republic of Korea and Pakistan. Reference [8] published the results of the CRP.

2.3.3. Consultancy meetings

To assist Member States in considering cogeneration when embarking on a nuclear build, the IAEA recently organized two related series of consultancy meetings. The first series, on Technical and Economic Aspects of Using Nuclear Energy for Cogeneration Options, was performed to define technical considerations for optimal cogeneration systems, assess the economic competitiveness of cogeneration plants, identify main aspects to be considered during feasibility studies of nuclear power, evaluate safe coupling schemes and analyse the safety of cogeneration plants. The second series, on Economic and Safety Issues of Industrial Applications of Nuclear Energy, was directed to explore the possibility of using nuclear energy for major industrial applications such as oil sands/shale oil recovery, oil enhancement production, for use in refinery and other related applications, to collect information on best practices and available experience on such applications, to compare the advantages and disadvantages of using nuclear power for such applications and to discuss various scenarios for the use of nuclear technology in such applications. The outcomes of these consultancy meetings were presented in two IAEA publications: Opportunities for Cogeneration with Nuclear Energy [2], and Industrial Applications of Nuclear Energy [9].

2.3.4. Plan: Efficiency improvement

With increasing energy demand, cost and availability of alternative energy sources, and concern over the environment, future NPPs could be made more economical through efficiency improvement (i.e. better energy use through cogeneration and waste heat recovery). The IAEA organized a technical meeting of 15 experts from eight Member States. Through the information and options exchanged, major efforts are seen to have been invested in advanced technologies for the recovery or reuse of waste heat or energy, and many opportunities exist to implement them in existing and future reactors. Member States relying on nuclear power could exploit the potential of cogeneration and/or the use of heat discharged from an NPP to increase overall efficiency of the plant and better use energy. While the potential is great, there is also a need for business models to support cogeneration, better understand the licensing framework for cogeneration, and provide training on nuclear cogeneration applications. The IAEA plans follow-up activities to answer some of these needs.

2.3.5. Plan: Recommended CRP on cogeneration

Selling both electricity and non-electrical products commercially remains both attractive and challenging. Member States are developing and deploying nuclear cogeneration designs based on exiting reactors and advanced reactor designs. Cogeneration has the potential to support other low carbon energy systems such as solar and wind through hybrid production of electricity and storage, or from grid coupling of nuclear and renewables. New issues associated with these flexible modes of production would need to be addressed, including safety, operational and licensing requirements. The experts participating in technical and consultancy meetings on non-electrical applications have requested the IAEA to convene a new CRP to provide information on the new challenges and added benefits of cogeneration to the general public and policymakers. An economic assessment and case studies, including business models for cogeneration involving non-electrical applications of nuclear energy, should be performed. Moreover, the IAEA is requested to support Member States in preparing road maps for the short term (5–10 years), medium term (10–20 years) and long term (over 20 years) for cogeneration of district heating and cooling, desalination, production of hydrogen, fuels, chemicals, and consider issuing a specific report for each of these commodities.

2.4. ACTIVITIES OF MEMBER STATES

The cogeneration of heat and power (the CHP operation mode of power plants) has long been used in numerous industries worldwide to optimize energy flows and minimize energy losses, thus improving energy (fuel) efficiencies and energy security as well as reducing industrial CO_2 emissions. About one third of the total final energy consumption is consumed in the industry sector. The amount of electricity that is produced from CHP has been increasing gradually and is today in the order of 6 EJ per year, representing more than 10% of total global electricity production. The share of industrial CHP within the total CHP capacity strongly depends on a country's economic structure, including energy intensive sectors, climate, or the role of district heating. Only a few countries contribute more than 20% CHP to power generation. Countries with high estimated fuel savings from CHP are China, Japan, the Republic of Korea, the Russian Federation, the USA and the European Union [10].

Industries with a high and constant demand for steam and power and the need to handle considerable amounts of by-products or waste fuels are ideally suited for cogeneration. Heat is produced predominantly from fossil fuels, but nuclear energy can also provide heat for various non-electrical applications. The most experience with cogeneration has been acquired with nuclear seawater desalination and district heating.

But cogeneration is also done in other industrial sectors. Among the most energy intensive are the chemical and petrochemical sectors; the iron and steel sectors account for approximately half of the total final industrial energy use. Together, the industrial, food, pulp and paper sectors represent more than 80% of the total electrical capacities at existing CHP installations. Other sectors with a significant industrial energy share are the non-ferrous metals and non-metallic minerals industries. The chemical and petrochemical sector is by far the largest industrial energy user, consuming 879 million tonnes oil equivalent (Mtoe) in 2014, accounting for nearly 30% of all industrial final energy demand and roughly 10% of the world final energy demand. Energy consumption in such industries is responsible for 7% of global CO_2 emissions [11]. A major part of the industrial energy is consumed in the production of a relatively small number of energy intensive commodities [12]. The most widespread industrial CHP systems are gas turbine systems. These are typically fuelled with natural gas; but coal, wood and process by-products are also extensively consumed, especially in large CHP systems, in industrial processes such as heating, cooling, drying and torrefying, or in indirect applications such as the generation of steam, hot water or heated air.

Most industries carry a large potential for nuclear energy to cover a part of their heat/steam demand. If the heat at higher temperature is required for cogeneration applications, some of the electricity production may be sacrificed in some cases. In terms of capacity, the demand for industrial heat has increased drastically during the past decade. Some 50% of users need less than 10 MW(th), some 90% need less than 50 MW(th) and 99% need less than 300 MW(th). The remaining 1%, which covers the cases of exceptionally high demand to 1000 MW(th) and above, represents a large proportion of energy consumption. This last category would be particularly suitable to nuclear applications. Industrial boiler systems are used for heating with hot water or steam in industrial process applications. As a customer can operate more than one boiler, it is the size of the boiler that is most pertinent when deciding on the application of a nuclear boiler [13].

Although nuclear cogeneration has been previously studied and even implemented in some reactors, heat has always been considered a by-product taken as a “free” addition to the main electrical power production. In that sense, steam bleeding from the turbine was generally considered to provide enough thermal energy for local district heating applications. In 2009, an NPP project in Finland introduced, for the first time, the option of a true full-scale district heating application in the design phase of the project [14]. Another study conducted in France showed that current nuclear reactors could be easily modified to efficiently supply large scale heating networks [15]. Those steps open a new perspective in energy management and pave the way for future abundant energy savings.

The potential of nuclear non-electric process heat use is offered in four areas: desalination of sea water, district heating of residential and commercial buildings, industrial process heat supply, hydrogen production and fuel synthesis. Cogeneration can garner the potential. Table 1 highlights several systems pursued by Member States.

TABLE 1. A FEW CURRENT AND FUTURE COGENERATING REACTORS PURSUED IN MEMBER STATES

Plant	Country	Reactor type	Reactor thermal power (MW(th))	Cogeneration product	Plant status
Halden	Norway	BWR	25	Process steam	In operation
Gösgen	Switzerland	PWR	3002	Process steam	In operation
HTR-PM	China	Pebble bed HTGR	2 × 250	Process steam or hydrogen	Under construction
GTHTR300	Japan	Prismatic HTGR	600	Hydrogen, process heat, desalination	Pre-licensing
NGNP	USA	Prismatic HTGR	Up to 625	Steam hydrogen	Preliminary
SMART	Republic of Korea	Integral PWR	330	Desalination, district heat	Design certification

BWR — boiling water reactor; GTHTR300 — gas turbine high temperature reactor; HTGR — high temperature gas cooled reactor; HTR-PM — high temperature reactor-power module; NGNP — next generation nuclear plant; PWR — pressurized water reactor; SMART — system-integrated modular advanced reactor.

2.4.1. Halden boiling water reactor, Norway

The Halden BWR — operated as an OECD project for nuclear fuels and materials investigations — is a natural circulation, boiling heavy water reactor with a thermal power maximum of 25 MW(th) (nominal 20 MW(th)). The

D_2O coolant flows as steam to two steam transformers where its heat is transferred to a secondary circuit, in which the (light) water fluid is further passed to a steam generator. Here, steam is produced in a tertiary circuit delivering process steam at a rate of 30 t/h to a nearby papermill for wood cooking. This heat would alternatively be dumped into a river, which could cause serious thermal pollution. Due to the research character of the reactor, the process steam supply is regulated by the international research programme.

2.4.2. Gösgen pressurized water reactor, Switzerland

Since December 1979, Gösgen 1010 MW(e) PWR has been extracting process steam and feeding it to a cardboard factory and other nearby heat consumers. In the turbine building, about 1% of the steam is diverted from the live steam system to heat a water/steam circuit that runs through a 1.8 km long steam line to the cardboard factory. The line has a maximum capacity of 70 t/h of steam, operating at a pressure of ~1.2 MPa and a temperature higher than 200°C. The quantity of heat transferred is equivalent to about 45 MW(th). In 1996, the system was extended by a small district heating network in nearby municipalities. In 2009, a separate water/steam circuit was built for another paper factory designed for a maximum throughput of 10 t/h of steam at a pressure of 1.5 MPa.

2.4.3. HTR-PM pebble bed high temperature gas cooled reactor, China

Having developed the 10 MW(th) operational HTR-10, a pebble bed high temperature gas cooled (HTGR) test reactor, China is constructing a commercial high temperature reactor — power module (HTR-PM) plant consisting of twin 250 MW(th) reactor units. While initially being used to demonstrate steam turbine power generation, the reactor technology — with an outlet temperature of 750°C — has a longer term objective for industrial heat applications, including process steam and hydrogen production. The Institute of Nuclear and New Energy Technology of Tsinghua University in Beijing is developing a thermochemical iodine–sulphur process and high temperature steam electrolysis (HTSE). They recently successfully ran about 100 NL/hr continuous hydrogen production tests for both processes. The hydrogen technologies are intended for future use with the HTR-PM. China is looking to export the HTR-PM technology, having, since 2016, signed a series of agreements with Saudi Arabia to cooperate in deploying the technology, including desalination cogeneration in the country.

2.4.4. GTHTR300 prismatic high temperature gas cooled reactor, Japan

Having successfully developed and operated the 30 MW(th), 950°C coolant outlet, high temperature engineering test reactor (HTTR) — a prismatic core HTGR — the Japan Atomic Energy Agency (JAEA) is constructing a project on the HTTR to demonstrate cogeneration through electricity generation by a gas turbine and hydrogen production by a thermochemical water-splitting iodine–sulphur process. The plan is to have the system operational by 2022. The project aims to fully develop the system's technology, including the full licensing process required for the 2030 construction of a commercial gas turbine high temperature reactor (GTHTR300) capable of cogenerating hydrogen and desalination. Japan has extensive experience with desalination cogeneration in a number of utility light water power reactors. More information is presented in the Appendix.

2.4.5. NGNP prismatic high temperature gas cooled reactor, USA

The next generation nuclear plant (NGNP) is a modular HTGR having unit thermal ratings up to 625 MW(th), reactor outlet temperatures up to 850°C, and various configurations of heat transport systems that provide steam and/or high temperature fluids. The range of power ratings, temperatures and heat transport system configurations provides flexibility in adapting the modules to specific applications, including cogeneration. The development project for the NGNP was authorized by the USA's Energy Policy Act of 2005. The project is managed by the Idaho National Laboratory with funding through the Department of Energy. The NGNP Industry Alliance of the USA was created in 2010 to promote the development and commercialization of this HTGR.

2.4.6. SMART integral pressurized water reactor, Republic of Korea

SMART is a 330 MW(th) integral PWR being developed for multiple purposes — electricity generation, seawater desalination or district heating — by the Korea Atomic Energy Research Institute (KAERI) in association with domestic user and vendor industries [16]. The national Nuclear Safety Commission granted standard design approval in 2012. Unlike traditional larger PWRs, the SMART installs all major primary components — such as core, steam generators, pressurizer, control element drive mechanisms, and main coolant pumps — in a single steel pressure vessel that eliminates the possibility of a coolant loss accident from a large pipe break. One design of the SMART cogenerates 90 MW(e) of electricity and 40 000 m^3/d of water using four units of multi-effect distillation. In March 2015, the Republic of Korea signed an agreement with Saudi Arabia to assess the feasibility of building two SMART units in Saudi Arabia for desalination cogeneration.

2.5. INTERNATIONAL ACTIVITIES

2.5.1. Generation-IV International Forum

The development of advanced nuclear energy systems under the framework of the Generation-IV International Forum is to be noted [17]. As of 2017, nine countries (Canada, China, France, Japan, the Republic of Korea, the Russian Federation, South Africa, Switzerland and the USA) together with EU countries organized under Euratom are cooperating to develop six reactor systems. Many of those have the potential to provide cogeneration, including hydrogen production, owing to operating temperatures higher than current water-cooled reactors. The core outlet temperatures of each type of reactor lie typically in the following ranges:

— Lead-cooled fast reactor (LFR), 480–570°C;
— Sodium cooled fast reactor (SFR), 500–550°C;
— Supercritical water reactor (SCWR), 510–625°C;
— Molten salt reactor (MSR), 700–800°C;
— Gas cooled fast reactor (GFR) around 850°C;
— Very high temperature reactor (VHTR), 900–1000°C.

For the latter, in particular, hydrogen production is targeted through thermochemical cycles or HTSE.

In order to be technologically deployable as soon as around 2030, the Gen-IV reactors are designed today based on more stringent requirements, which will lead to further progress in nuclear technology by addressing the areas of safety and reliability, proliferation resistance and physical protection, economics and sustainability [18]. Future NPPs will require a robust design and high level safety features to further reduce the probability and degree of core damage. They also need to be flexible in meeting the needs for energy products besides electricity. The penetration of non-electricity markets by supplying process heat for district heating, seawater desalination or hydrogen generation will enhance production efficiencies, flexibility and thus competitiveness, among other benefits.

2.5.2. OECD/NEA programmes

Since 2015, an ad hoc expert group supported by OECD/NEA and comprised of representatives from Canada, Finland, France, Japan, Poland, Slovenia, the United Kingdom and the USA as well as the IAEA and the International Energy Agency (IEA), has been examining the role and economics of nuclear cogeneration in a low-carbon energy future with the objective of developing methodology to assess the costs and benefits of nuclear cogeneration and to identify major challenges (technical, economic, regulatory and societal) that the development/deployment of nuclear cogeneration faces (and the costs to overcome these).[1] The methodology was designed to be as generic as possible, to be applied to various applications (district heating, desalination, high temperature

[1] https://www.oecd-nea.org/ndd/groups/cogen.html

applications, hydrogen production) and to various nuclear reactor technologies (LWR, HTR, etc.). The benefits of the reduction in greenhouse gas (GHG) emissions from nuclear cogeneration will be covered.

In July 2015, the NEA initiated the Nuclear Innovation 2050 (NI2050), a road mapping program to identify R&D strategies and priorities to achieve commercial readiness of innovative sustainable nuclear fission technologies in a fast and cost effective manner. Nuclear cogeneration is fully part of the scope of NI2050, with focuses on diversifying the uses of nuclear energy beyond electricity production and exploiting the synergy of nuclear with intermittent renewable energy through the connection of SMR and hybrid systems. Accordingly, preliminary projects are proposed for cooperation on such demonstrations as coupling HTGR and industrial process on JAEA's HTTR and as a control method for nuclear hybrid systems.

2.5.3. European activities

Europe has the experience, demonstrated motivation and market to deploy large scale nuclear cogeneration. The experience was built on the legacy of major German HTR projects in the 1970s and 1980s, which focused on applications of nuclear process heat coupled with HTR technology. Since 2000, European projects such as INNOHTR, HTR-N, RAPHAEL [19], MICANET [20], EUROPAIRS [21] and ARCHER [22], among others, have invested in the spread and cogeneration development of HTR technology from the European Framework Programmes and other European projects. Several countries in Europe are conducting nuclear cogeneration projects like HTR-PL in Poland or SYNKOPE in Germany. Because of the EU energy policy and main goal of decarbonization scenarios up to 2050, all activities consider using nuclear heat [23].

In 2007, the European Sustainable Nuclear Energy Technology Platform (SNETP), with more than 120 participating stakeholders from research, academia, industry and regulatory organizations, has shown its strategic motivations in a Vision Report [24], and a Strategic Research and Innovation Agenda, which focuses on three priority pillars. One of these pillars is implemented by the Nuclear Cogeneration Industrial Initiative (NC2I), which targets the development of a nuclear cogeneration solution for delivering process heat and steam as well as electricity to industrial facilities, instead of fossil fuel burning cogeneration plants. In 2014, NC2I, jointly with the USA's NGNP Industry Alliance, launched the GEMINI Initiative to demonstrate high temperature nuclear cogeneration with HTGRs. The present phase — the three-year GEMINI+ project — begun in 2017, has grown in partnership with the Asian HTGR technology leaders of JAEA and KAERI. The GEMINI+ is tasked to establish the basis for developing an industrial demonstration of HTGR cogeneration, to identify gaps between demonstration conditions (acceptable site, appropriate financing and business cases, technology and user readiness) and propose plans to address any gaps identified. The basis to be established covers four technical objectives:

(1) Making recommendations to adapt the general licensing processes used in existing LWRs to the specific safety concept of HTGRs;
(2) Defining a reference design with maximum reliance on proven technology for a European cogeneration HTGR;
(3) Developing plans for a demonstration project of the reference design;
(4) Exploring innovations to enhance safety and competitiveness, improve operation flexibility, and explore extended and longer term applications.

The European large industrial market has the potential to use cogeneration in refineries, chemical plants and other industries due to a plug-in strategy by which fossil-fired cogeneration plants can be directly replaced by nuclear reactors offering simultaneously large amounts of process steam and electricity. A market study on energy use in European heat intensive industries of NC2I has surveyed EUROPAIRS and European site mapping for the existing market of industrial steam supply to 87 GW(th) in Europe, representing output from over 400 units of 200 MW(th) modular HTRs.

3. POTENTIAL BENEFITS OF NUCLEAR COGENERATION

Energy concerns exist throughout the world. Limitations on energy resources are problematic and energy use contributes not only to global warming but also to such environmental concerns as air pollution, acid precipitation, ozone depletion, forest destruction and the release of radioactive substances — particularly by coal-fired thermal power plants [25]. These issues must be addressed if humankind is to avoid major societal disruptions and environmental impact. There are various alternative energy options to fossil fuels, including solar, geothermal, hydropower, wind and nuclear energy. While many of the available natural energy resources are limited due to their reliability, quality, quantity and density, nuclear energy has the potential to contribute a significant share of large scale energy supply without contributing to climate change.

Cogeneration helps overcome the main drawback of conventional electrical and thermal systems: the significant heat losses that greatly deteriorate efficiency. Heat losses are reduced and efficiency is increased when cogeneration is used to supply heat to various applications and facilities to well above the level achieved in electrical systems alone.

Many general descriptions and studies of cogeneration systems have been reported, and the basic technology is well understood and proven in existing plants. The following are some examples of existing large cogeneration systems:

- A CHP plant in Switzerland generates 465 MW(th) of heat and 135 MW(e) of electrical power, with an overall efficiency of 75% [26];
- An NPP in Michigan left incomplete due to lack of funding was eventually completed as a gas-fired, combined-cycle cogeneration plant having 12 heat recovery steam generators and gas turbines, and 2 steam turbines, producing 1400 MW(e) and 285 t/h of steam [27];
- Approximately 10 plants are used to generate 240 MW(e) and supply 90% of the 1500 MW(th) thermal demand for the city of Malmo, Sweden (population 250 000) [28];
- Five plants, with a total of 22 units are used to generate 1006 MW(e) and supply 4820 MW(th) for the city of Warsaw, Poland, which is approximately 70% of the heat demand [29].

Among power generation options, NPPs offer unique advantages such as the following:

- Nuclear CHP plants have very low life cycle greenhouse gas emissions;
- A small amount of matter can create a large amount of energy;
- A lot of energy is generated from a single power plant;
- Fuel for NPPs is available in large amounts around the world, with the security of supply ensured for hundreds of years.

Beyond the advantages of single purpose plants, NPPs providing combined electricity generation and non-electric applications can create a variety of additional economic and other benefits for energy producers and users as the resulting shared facilities and higher efficiency translate into increased productivities beyond electric generation, additional means of optimizing production costs, fewer emissions of pollutants, enhanced use of energy and energy security, reduced use and waste of nuclear fuel relative to single purpose plants, additional flexibility and, in many cases, increased reliability of production and improved public acceptance of nuclear energy. Elaborations on some of these points follow.

3.1. BETTER EFFICIENCY

Currently, nuclear energy is mostly used as a source of electricity generation, meaning that about two thirds of the fissioned heat in existing reactors is wasted. Therefore, the direct use of heat energy is highly desirable from an energy efficiency or conservation point of view. It is possible to optimize the use of nuclear heat for both electric and non-electric applications. Nuclear cogeneration is ideally suited for nearby consumers with a need for a constant heat/steam supply; this is particularly good for industrial consumers. Numerous countries have gained experience with cogeneration of nuclear electricity and heat. Still, less than 1% of the heat/steam generated in nuclear reactors is used for non-electric applications [30].

The overall energy efficiency of a cogeneration system is the percentage of the fuel converted to both electricity and useful thermal energy. Cogeneration systems can yield overall efficiencies of 65–90% [25], compared to about 33% in existing NPPs and up to 50% in future reactors used for power generation alone.

3.2. ENHANCED USE OF ENERGY

Current generations of NPPs can support the temperature range (<300°C) of many industrial processes such as desalination, district heating and pulp and paper manufacturing that mostly consume fossil energy today.

Gen-IV concepts [31] are proposed for higher coolant exit temperatures than those supported by most of today's nuclear reactors, which enables — besides the generation of electricity at a higher efficiency — the production of higher temperature heat or steam that can be transferred to selected industrial processes.

Many studies are thus exploring nuclear reactor designs that would meet certain requirements such as producing cheap electricity and high temperature heat to be efficiently coupled with industrial process plants. With respect to the process heat temperature level that they offer, gas cooled reactors, molten salt cooled reactors, and heavy liquid metal cooled reactors appear to be the most promising technologies for higher temperature industrial processes such as hydrogen production. The various nuclear reactor technologies combined with thermally driven hydrogen production processes adaptable to nuclear reactors will complement, not compete with, future nuclear-based process heat/steam generation capabilities.

Cogeneration of nuclear heat adds major advantages such as these:

- Major expansion of a low carbon source of energy to non-electric applications, given a fleet size (national capacity) of power reactors;
- Better use of energy resources; conservation of fossil fuels for applications other than heat or electricity production;
- Best use of heat at the temperatures adapted to needs;
- Matching of industrial application needs.

3.3. BETTER FLEXIBILITY

One major advantage of working in cogeneration mode is the added capability for flexible operation of NPPs, providing more convenient change in electrical output, which is offered as electrical grid services to provide balance or adjustment of the generation and demand. In this manner, cogeneration offers an alternative to load following and/or frequency control [32]. As noted in Ref. [32], it is usually preferable from the plant owner/operator's perspective to operate the plant in steady full load mode (fully rated thermal power and full electrical power, i.e. baseload) as much as possible rather than in flexible mode [5] because it is generally considered the most efficient use of capital investment. However, from the perspective of the electricity system as a whole, and the grid system operator, it may be preferable for NPPs to operate flexibly, when needed by the system, for reasons that are discussed in Ref. [32]. With cogeneration, it may be possible to operate a nuclear unit at steady full thermal power while varying the electrical output, when cogeneration enables the use of the excess thermal power from the reactor that would otherwise be wasted.

Some NPPs in Member States, for example, are currently using part of the thermal power (in some cases up to 15%) to provide heat for industrial or district uses. According to this principle, the heat transfer can be adjusted, allowing the electrical power to be varied while leaving the thermal power extracted from the nuclear core unchanged.

3.4. REDUCED ENVIRONMENTAL IMPACTS

As nuclear is a carbon-free energy source, large savings are expected from the recovery of waste heat from operating NPPs. If one considers a modified nuclear reactor delivering 10 TW(th) of heat per year in addition to the electricity production, the estimated carbon emissions could be reduced by as much as 2 Mt/y of CO_2.

The share of overall GHG emissions in 2010 from the industrial sector was estimated at 21% [33]. The break-up by industrial branches shows that the non-metallic industries (e.g. cement), the iron and steel industries, and the chemical and petrochemical industries are among the largest GHG emitters.

Cogeneration reduces waste and pollution through efficiency. The fission of uranium atoms results in two medium heavy atoms called fission products. Some of the fission products are highly radioactive and need to be disposed of as nuclear waste. Making use of more energy per fission in a cogeneration mode accordingly reduces the quantity of waste generated per unit energy without impact on the front and back ends of the power reactor fuel cycle. When practiced through recovering waste heat of an NPP, cogeneration lowers the amount of heat dumped into the environment.

3.5. ENERGY SECURITY

Nuclear reactors able to produce high quality process steam with typical parameters of 540°C and 18 MPa would allow facilities to meet requirements that arise in a wide range of industrial processes. The petrochemical, chemical, metal, non-metallic mineral, food, and pulp and paper industries are applying energy intensive processes requiring both steam and electric power. Cogeneration provides an economic solution to meet their needs versus the industrial energy supply, which is currently dominated by electricity (34%), produced by fossil fuel, and natural gas (31%).

Nuclear reactors generating very high coolant exit temperatures could be used to assist in the production of synthetic fuels such as methanol, ethanol and their derivatives. This will be an innovative application of nuclear energy and can help meet future demand of fuel for transportation purposes. It represents a huge market presently almost completely based on fossil fuels. Nuclear power could also be used for coal gasification, oil extraction and, ultimately, provide hydrogen fuel free of CO_2 emissions. However, the infrastructure for using synthetic fuels, particularly in the case of environmentally benign hydrogen fuel, is still missing at a larger scale. Innovative applications are being explored primarily with gas cooled reactors because of the high temperature that can be achieved [6].

3.6. BETTER ECONOMICS

Cost effectiveness is a crucial issue for non-electric applications of nuclear power in general. For some applications, proximity of the power plant to users — whether at an industry production site or a population centre — is needed to limit energy or product transmission loss and cost. Some large applications also require the development of infrastructure, such as heat distribution networks for district heating and water distribution systems (water pipes and pumps) for fresh water. Many countries are currently exploring these possibilities [30].

The cost of transmission could grow significantly with distance, as highlighted in a recent study [34]; hence an on-site installation or a location close to the demand site is preferable. Some process heat applications do not necessarily need to be close to populated areas. For example, hydrogen production could be either concentrated in remote industrial centres, transporting the product as needed, or with electricity transmitted to low temperature electrolysers close to the demand [13].

The cost of energy may be reduced when the cogenerating desalination plant is designed for cost effective recovery of the waste NPP heat, instead of firing of fossil fuels [35]. Further cost saving is possible by co-locating with the NPP to share facilities and reduce the loss of steam temperature or pressure in transmission. Taking credit of competitively priced non-electricity products, through waste heat recovery and facility sharing with an NPP, may reduce the effective costs of power generation by as much as 20%, as reported in a recent feasibility study in Japan [35].

3.7. PUBLIC ACCEPTANCE

Public acceptance is directly connected to public perception. It is thus critical to create positive public awareness. The public perception of nuclear power has focused on concerns over safety, proliferation and waste management. As the Three Mile Island, Chernobyl and Fukushima accidents showed, the public was concerned not only about the dangers of radiation to people and the environment, but also about the speed and accuracy of available information. Concerns about proliferation and nuclear terrorism continue to play a role in the public perception of nuclear power.

Public perception is also dependent on many factors specific to a given society, such as the location of the local energy supply, national experience with nuclear power, and national perceptions of environmental considerations. Due to these factors, the public attitude towards nuclear power has changed, as demonstrated recently in many countries. The public perception of nuclear power has gradually turned favourable, due to decades of successful operation of more than 450 NPPs. While the recognition of concerns over climate change and the lack of practicable and affordable alternatives have increased public and private sector interest in nuclear power in the USA, the Fukushima accident and its continual uncertain aftermath has caused public support for nuclear energy to plunge in Japan.

Successful experience with decommissioning and spent fuel management may have contributed to steady public confidence in some countries. In other countries, however, uncertainty with these issues has posed a continual major obstacle to extending or initiating nuclear power programmes.

Cogeneration may improve public acceptance of nuclear power by offering vital products besides electricity (e.g. district heating, and fresh water for drinking and vegetation) to hosting communities, raising living standards and supporting industrialization. Despite limited experience with nuclear seawater desalination, public acceptance of this technology has not been problematic. Two cases confirm this: The first refers to Kalpakkam, where the nuclear desalination plant, based in a water-scarce region, is experiencing demand growth for desalinated water [36]. The second is even more convincing; founded in a desert on the Caspian shore in Kazakhstan, the city of Aktau's industrial development and population growth were supported with water supplied mostly (around 80%) from the Mangyshlak Atomic Energy Complex (MAEC) desalination plant [37].

For any country considering or already operating nuclear power, open communication with all stakeholders (decision makers, public, media and neighbouring countries) on all the issues surrounding nuclear power — benefits, risks, commitments and obligations — is essential in order to build and maintain trust and confidence in a nuclear power programme.

4. ISSUES FOR CONSIDERATION

4.1. ECONOMICS

Economic considerations of cogeneration vary with each process or project. Cogeneration may reduce the amount of power generated by a nuclear plant when the heat input to the cogeneration plant is obtained by extracting steam from the nuclear turbine — as is the case in the SMART design, in which cogeneration of desalination reduces electrical output by 1 MW(e) for each 4000 t/d of water it produces (see Appendix, A.2.1). The economics of cogeneration would thus vary with the local prices of these products and with other factors such as energy and emission credits that might be gained by improving overall energy use efficiency in the NPP. On the other hand, an apparent cost benefit is demonstrated by the GTHTR300 system, where district heating or seawater desalination is performed using recovered exhaust heat from the NPP's gas turbine cycle without penalizing its power generation performance (see Appendix, A.2.3). Cogeneration is site specific and country specific. Hence, the technical and economic feasibility of cogeneration needs to be properly assessed to discern whether such an option is optimal compared with other potential options. As discussed in Ref. [38], a proper assessment of the technical and economic feasibility of cogeneration should be performed to justify the alternatives being considered.

For a district heating system, the investment cost is generally higher than the operating cost. The total cost may be divided into three parts: heat production, transport and distribution. Transport and distribution costs are directly connected to the secondary district heating network and are independent of the heat source. They may vary with the number and density of customers, geographical location and the historical situation of the network. On the other side, heat production costs encompass all modifications in the NPP, including the control–command and the connection to the MHT system. These costs have been evaluated in a recent IAEA report on nuclear cogeneration, in the chapter containing an economic evaluation [2]. Production costs will determine the selling price from the producer (the NPP owner) to the MHT system operator. Constructing the MHT line is the major part of the investment cost. Pipeline construction may add up to 10 M€/km, leading to a total investment cost for a 100 km long heat transport line in the ballpark of a billion Euros. This level of investment is only suitable for large power heat loads. The final cost of heat will be the sum of the investment and operating (including maintenance) costs in the production, transport and distribution of the heat delivered. In order to be competitive in the heat market, nuclear cogeneration should aim at a total heat cost below 50 €/MWh, considering that the average 2009 heat price in European countries was approximately 60 €/MWh [2].

Reliable heat production is another issue in nuclear district heating. The high availability of NPPs (above 80%) does not exclude the potential loss of full power production. Although this is more a concern for the heat system operator than a safety issue per se, the problem could be dealt with in two ways. First, there is generally more than a single reactor operating at a given nuclear site. If two reactors are properly equipped to alternate supply to the heat network, the second reactor can be switched on if the first fails. The probability that both would fail simultaneously is rather low. Second, backup boilers or CHP plants can be installed either on the nuclear site or at each secondary station location to provide heat during planned or unplanned outages. The cost of the backup installation would have to be appropriately factored into the cost of heat delivery.

Regarding nuclear desalination plants, site considerations have been detailed with input from Member States and reported by the IAEA [39]. There are two important factors about sea water intake and reject disposal systems:

— Source identification: surface/bore well, once through/recirculation type, availability, seasonal variations, natural flow directions, etc.;
— Location specific considerations: coastal regulations, fishing and navigational activities in and around the sea water source, availability of primary infrastructures (e.g. roads, power, water, health centres, schools, markets, means of transport).

The sea water source should be near the desalination plant to reduce the cost for the intake system and for bringing raw sea water near the inside battery limits (ISBL) of the plant. For any commercial-sized plants that need to be operated on an around-the-clock basis, raw sea water needs to be available throughout the year in all high and low tide conditions. This helps reduce the cost of the reject/concentrate water disposal, safeguarding the environment. Furthermore, nuclear desalination plants would also need the steam to be drawn from the NPP to the coupling system. Secondary low/high pressure steam must be fed into the heating section (brine heater) of the multistage flash (MSF) or multi-effect desalination (MED) plants and a small quantity of high pressure steam must go to the vacuum system.

To highlight, the steam requirements and quality of the steam taken from India's Madras Atomic Power Station (MAPS) to the cogeneration MSF system are as follows:

— Steam is required for the MSF process at 0.25 MPa absolute pressure to heat brine to a temperature of 121°C and for the steam jet ejector at 1.5 MPa;
— Steam is generated in the low pressure and high pressure intermediate heat exchangers;
— Steam is drawn from MAPS in the primary circuit of the heat exchangers;
— Low pressure steam is extracted from a cold reheat line (i.e. the outlet header of high pressure turbine before the moisture separator);
— High pressure steam is extracted at about 4 MPa from a live-steam header to the hogging (or startup) ejector of MAPS.

In addition to the raw sea water and steam supplies, the product water storage capacity and its distribution system are equally important for the site consideration. Not only does it call for the main distribution reservoir to be nearby, it also calls for defining the intermediate storage capacity for the product water tank. This tank is generally located inside the nuclear desalination plant battery limits to allow proper monitoring of quality and capacity rates for revenue billing according to the dispatch done regularly from the plant. A minimum of a one-hour production capacity is usually determined for intermediate storage tank capacity based on the designed plant capacity of the desalination plant.

While nuclear heat of relatively low temperature may be carried by pipeline to remote users many kilometres away, the cost of doing so would be prohibitively high in the case of high temperature heat because of the expensive construction materials required for the pipeline and the significant parasite heat loss which occurs over distance. To be economical, first, on-site production and usage may be considered where nuclear reactor and heat users are kept within hundreds of metres of each other for safety (see next section). Second, the design choice for heat transport equipment may play a large role in deciding the cost of heat supplied. As an example, an intermediate heat exchanger (IHX) is typically used to transfer heat from the primary side (reactor) to the secondary side (heat transport pipeline). Table 2 compares three counter flow helium-to-helium helical tube-and-shell IHXs designed to supply heat for hydrogen production. Expensive superalloys such as Hastelloy-XR or Inconel 617 are required for heat exchange tubing due to the 950°C operating temperature. Mainly owing to a serial (i.e. topping) cogeneration arrangement, leading to a large logarithmic mean temperature difference (LMTD), Design A requires less than half the specific heat transfer areas (tubing area per unit of heat transferred) than the two other designs that select parallel arrangement (HTTR IHX) or single loop (Design B) to supply heat. More details of these designs are reported elsewhere [40].

TABLE 2. INTERMEDIATE HEAT EXCHANGER DESIGN COMPARISON

	HTTR IHX	IHX Design A	IHX Design B
Thermal rating (MW(th))	10	170	170
Primary inlet/outlet (°C)	950/389	950/850	950/292
Secondary inlet/outlet (°C)	237/869	491/900	200/900
LMTD (°C)	113	157	69
Total heat transfer area (m^2)	215	1448	4700
Specific heat transfer area (m^2/MW(th))	21.5	8.5	27.6

4.2. COUPLING AND RELATED SAFETY

In nuclear cogeneration applications ranging from desalination to hydrogen production, it is critical to dwell on the coupling of NPPs as the source of process/waste heat within the cogeneration system by carefully considering safety, environmental and operational factors in addition to the economics covered previously. Safety is of paramount significance with or without emergency conditions. Analysis of safety related issues driven by the coupling of a nuclear power reactor to a cogenerating plant such as an industrial facility is mandatory. The mutual effects between the reactor operation and the industry units on-site should be clearly assessed, including how failures should be managed from each side.

Safety issues of an NPP operated in cogeneration mode are basically the same as those for the nuclear facility by itself. Nevertheless, there are some specific safety as well as additional operational aspects related to the coupling of the NPP to conventional industrial plants, depending on the reactor type and the nature of the industrial process. The coupling with a nuclear system considers (a) avoiding cross-contamination between the NPP and the industrial process; (b) mitigating application specific design features; and (c) managing thermal disturbance and providing backup heat or power sources in case either plant stops operating (e.g. for refuelling and maintenance).

4.2.1. Avoiding cross-contamination

The main issues in avoiding cross-contamination are preventing radioactivity from migrating from the nuclear reactor to the cogeneration product and preventing corrosive chemicals and contaminants from entering the reactor system from the industrial processes. Coupling of a nuclear heat source to any industrial process heat application can basically be done in two ways: either with heat transfer via an intermediate heat transport loop from the reactor to the industry process, or with heat transfer directly from a (nuclear grade) heat exchanging component in the primary circuit into the chemical process. The former is generally preferred due to the safety advantage and operational flexibility, such as selecting an independent heat transport fluid. In such a scheme, as shown in Fig. 3, one or more closed circuits may be included in the so-called transformation plant between the primary coolant of the reactor and the final user to exclude any possibility of material exchange between the nuclear and user plants.

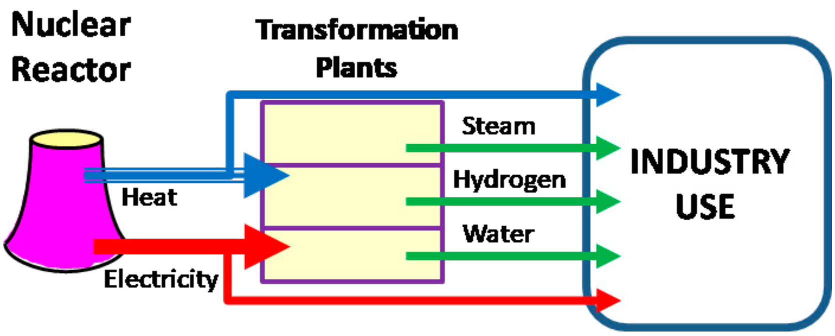


FIG. 3. General scheme for coupling a nuclear reactor to an industrial user plant.

An issue for normal operation of a nuclear reactor is tritium, which is mainly produced in the reactor core during ternary fission and neutron captures on boron (control rods) or beryllium (secondary source rods). In the case of high temperature reactors, most tritium is deposited inside of the core graphite or removed by the online coolant purification system. The intermediate loop may be kept at a slightly higher pressure than either the primary system or the industrial process circuits to prevent cross-contamination (either tritium and other radionuclides from the nuclear side, or chemicals from the process side, entering the intermediate loop through any small surface leak in it). Shutoff valves are also installed along the intermediate loop to isolate the nuclear or chemical plant from any accidental rupture detected in the loop.

But because of its small size, some tritium may permeate the surface and enter the intermediate heat transport loop, where it may again be captured and removed. In such a case, the tritium contamination of the industrial products may be insignificant (i.e. below the sensitivity limit of the measurement) as indicated by experience from the operation of nuclear district heat and desalination plants.

4.2.2. Mitigating application specific design features

The coupling with a nuclear reactor needs to consider application specific safety and operational features. In the case of on-site cogeneration — due to the need to locate a nuclear facility near the process plant — the safety of the combined system is open to a new class of events, including the impact on the nuclear facility from any explosive or toxic material from industrial chemical processes. In hydrogen cogeneration of thermochemical processes with HTGR, the release, dispersive transport and explosion of a hydrogen cloud in the atmosphere have been studied to assess the required minimum separation distance to avoid any risk to the nuclear plant's safety systems. Furthermore, the accidental release of process materials, including sulphur dioxide, sulphur trioxide and sulphuric acid, has been investigated to assess the appropriate separation distances required to protect the nuclear reactor operator's room against the propagation of the toxic gases [41].

4.2.3. Managing thermal disturbance and providing backup

Although modifying the heat output to follow heat demand by the industrial plant will impact the electrical power generation of the NPP, such changes in heat demand are allowed within the limit of nuclear plant load follow capability and would not affect the safe operation of the reactor if the cogenerating plant is designed as a conventional, rather than a nuclear grade, industrial facility, as is usually the case.

Furthermore, in a cogeneration mode, active cooling of the nuclear reactor core is ensured by the heat transformation plant instead of the usual heat sink (sea, river, cooling tower) of the NPP. Any failure of this cooling (rupture of a pipeline, defects in heat exchanger, etc.) will impact the NPP's cooling performance. In that event, priority should always be given to the NPP, with immediate transition from cogeneration to stand-alone electrical operation without tripping the nuclear reactor. In some cases, the transformation and industrial plants offer an alternative heat sink to the NPP. Their huge thermal capacity allows an extremely long grace period for any situation in which the nuclear system requires external cooling. A cogeneration set-up may therefore even enhance the safety level of the NPP. On the other hand, in the case of a shutdown of the NPP, heat and electricity may be provided to industrial users by the standby heat and power sources, such as a conventional CHP plant that is part of the transformation plant.

4.3. LICENSING

The supply of steam and high temperature heat to an industrial process by an NPP generally implies the need to have the nuclear facility near the industrial process due to the technical and economic characteristics of steam or heat transmission. For the design and the site selection, the following general guidelines can be used:

- For a given steam delivery pressure, the unit energy cost of steam transmission increases with distance and decreases with transmission capacity and inlet pressure;
- Steam transmission costs decrease as the steam delivery pressure is decreased;
- The use of compressors in a steam transmission system is generally not economical;
- Heat in the form of hot water can be delivered up to about 150 km with a reported loss of 2%.

The need to locate a nuclear facility near industrial plants, and perhaps population centres, suggests the need for additional considerations of licensability and public acceptance. Potential issues include:

- Requirements for additional safety features;
- The need for plans for the safe and orderly shutdown of the industrial process and sheltering or evacuation of industrial facility staff in the event of an accident;
- The need for detailed plans for public notification, sheltering or evacuation in the event of an accident;
- Additional requirements for public education and programmes to inspire public acceptance.

The specific requirements will be determined by such factors as the reactor type, the nature of the industrial process, the distances to the industrial facility and population centres, and prevailing public attitudes. A new generation of smaller reactors with passive safety features may at least partly mitigate the above issues [42].

The integrated nuclear system should be designed and operated to conform with requirements in the IAEA Safety Standards, and in compliance with the requirements of national regulatory organizations. The system should also comply with national and international standards, regulations and radiological limits.

4.4. STAKEHOLDERS

Most industries need to rely on a secure and economical supply of energy to guarantee continuous and reliable operation of their process units. Ensuring supply security by diversification of the primary energy carriers will become a more important goal, as will limiting the energy consumption effects on the environment.

The supply of heat to the industries should be reliable. Reliability requirements of large industrial users are typically close to 100%. Such high levels can be ensured only by the combination of high reliability heat sources and availability of reserve capacity. The latter is easier to implement by using several production units that are relatively small in comparison with the required capacity or by supplying steam as a relatively small co-product from a group of electricity producing reactors [13].

Cogeneration needs to be prioritized among stakeholders. An industry owning and operating a CHP plant may want to secure its heat need before generating and selling surplus electricity to the external grid. The merit order of products may change for an independent power producer serving the peak electricity need of utilities while selling off-peak heat to process industries.

The possibility of the large scale introduction of distribution systems for heat, steam and electricity supplied from a centralized nuclear heat source (a multiproduct energy centre) could attract and serve different kinds of consumers concentrated in so-called industrial parks.

Because of the much longer lifetimes of nuclear plants versus the chemical plants of industrial processes, reactors initially built to provide energy to some specific industrial applications will most likely have several other uses during their lifetime [43].

5. IMPLEMENTING COGENERATION

5.1. FEASIBILITY

Industrial heat demands are characterized by a wide diversity of countries, branches and energy supply. Heat demand that can be appropriately met by nuclear energy can be classified according to the three different temperature ranges shown in Fig. 4.

— Low temperature level is defined as <150°C, corresponding to the typical demand for district or space heating, desalination, agriculture, and for hot water preparation for washing and food preparation.
— Medium temperature level is in the range of 150°C to 500°C. This heat is normally supplied through steam to provide the evaporating or drying heat in pulp and paper production and to the oil extraction and refining

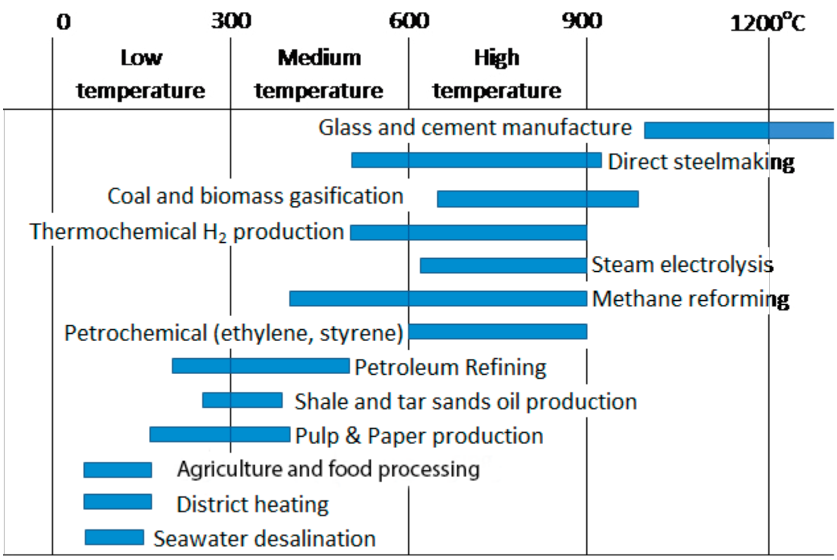


FIG. 4. Temperature ranges of industry specific heat demand.

industries. An application of significant interest to nuclear cogeneration is the intensive steam demanded by shale and tar sands oil production in North America.
— High temperature level constitutes temperatures >500°C. This is needed in many processes such as for petrochemical production, reforming and gasification of hydrocarbons, thermochemical hydrogen production and manufacturing of metals, ceramics or glass.

The reactor coolant and its temperature are basic criteria needed to determine which nuclear concepts are appropriate to couple with an industrial process. Today, LWRs can be readily used in cogeneration mode for hot water or steam production at temperatures typically below 250°C. This allows for applications in a large fraction of final heat requirements like district heating, seawater desalination or industrial uses in the food industry, and the lower temperature end of papermill and petrochemical processes.

Coolant outlet temperatures of the Gen-IV concepts range between 550°C and 900°C and may be compared to all process temperature levels except those for glass and cement manufacture (Fig. 3). More specifically, supercritical water cooled reactors would provide temperatures up to about 500°C. With advanced materials, a lead or lead–bismuth cooled fast reactor system may achieve core outlet temperatures ranging up to 800°C. A graphite moderated, helium cooled high temperature reactor using today's technology may operate at core outlet temperatures up to approx. 750°C, providing steam in secondary circuits at around 550°C. The 750°C HTR-PM with twin reactor units of 250 MW(th) each is under construction in China. VHTR systems would supply heat with a core outlet temperature approaching 1000°C. While both the German Arbeitsgemeinschaft Versuchsreaktor and the Japanese HTTR test reactors have demonstrated successful and safe operation at 950°C, the HTTR was the first (and so far only) nuclear plant that also demonstrated 900°C heat delivery via IHX to the secondary circuit [44]. The use of the nuclear reactor as a high temperature heat source for industrial process heat/steam supply imposes new challenges on reactor fuel and materials [43] and requires further R&D for commercialization.

For cogeneration with existing NPPs, the modifications only affect the turbine hall, which is a non-radioactive zone in a PWR. Following the high pressure turbine and the reheater, part — if not all — of the steam will be directed to a new low pressure turbine. The pressure at the outlet of the new turbine is maintained at a higher level than standard atmospheric pressure. The expanded steam condenses in a large heat exchanger, yielding the corresponding heat to a tertiary water circuit connected to the MHT line. Depending on the output temperature chosen, the condensed water can either be sent directly to the feedwater tank or reheated slightly first. The necessary flexible operation to follow the heat demand variation can be easily ensured through the control of the steam fraction diverted to the new turbine. Overall, the NPP modifications are moderate and most of the work can be realized without impeding usual operation. Several project studies show that distances of about 30–40 km are quite satisfactory for district heating with existing NPPs. Even an 80 km transmission line to a district heating network from the Loviisa-3 WWER-1000 reactor was deemed feasible in a Finnish study [14].

The demands of large industrial users usually have base load characteristics. Therefore, additional backup systems are required which could, of course, also be provided by fossil-fired boilers. Optionally, depending on the industrial plant size, a modular arrangement of two to six smaller-scale nuclear units will be practicable in terms of redundancy, reliability and reserve capacity, all reasons which favour a reduced power size for each nuclear reactor. Smaller power sizes allow for simplicity and robustness via higher safety margins even at higher operational temperatures. The small power size of modular reactors is also favourable for operation in less developed electrical grids.

The high temperature nuclear reactor coolant heat would typically be exported for industrial uses via an IHX. The main purpose of the intermediate circuit is to clearly isolate the industrial site from the nuclear island. In this way, the direct access of primary coolant to the industrial plant — and in the reverse direction, of product gases to the reactor building — can be prevented. The separation makes it possible to operate and maintain the industrial plant as a conventional facility. For economical heat supply, it is necessary to locate these nuclear units as close as possible to the consumer site. At the same time, it is, of course, necessary to take all achievable safety measures. Studies have shown that an HTGR plant and a hydrogen production plant may be located 100–200 m from each other to minimize energy loss [34] while satisfying safety design requirements [41].

5.2. SAFETY

The basic safety objectives for typical nuclear reactors contemplate the safety of individuals, society and the environment, ensure both that radiation exposure is kept below prescribed limits and mitigate the radiological consequences of any accidents, and take all reasonably practical measures to prevent such accidents and keep the likelihood of accidents with serious radiological consequences extremely low [45].

The above three basic objectives for NPPs also apply to nuclear cogeneration. In some cases, safety considerations of cogeneration are enhanced further through the addition of another isolation loop. Therefore, the coupling of a nuclear power system to a cogeneration plant does not impose further safety related considerations. However, as part of an extraconservative approach, coupling still needs to be investigated from the point of view of the safety of the overall nuclear cogeneration system. In this case, the effect that one system might impose on the other is investigated as part of the safety analysis of the integrated system. In fact, some additional requirements may arise and be conceptualized in the design of a cogeneration plant and its integration within the overall nuclear system.

Cogeneration systems consist, in general, of a nuclear power reactor coupled to a cogeneration plant through an isolation heat exchanger. Further considerations which may affect safety are: the interaction between nuclear and cogeneration plants, shared resources, placement of nuclear cogeneration systems close to populated centres and environmental issues arising from the coupling [2].

As mentioned before, specific safety issues caused by the coupling of a reactor system and a cogeneration plant are related to two potential risks:

- The potential for radioactive materials from the nuclear plant to transfer to the cogeneration system during normal operation or because of an incident or accident. In general, two approaches are followed to minimize such a potential: installing an intermediate loop between the reactor and the cogeneration plant, and continuously monitoring the radioactivity level of the product of the cogeneration plant and the coolant in the intermediate loop.
- The potential for more severe reactor system transients induced from the cogeneration plant, either during normal operation or because of an accident. This should be addressed through design and operation.

As with any nuclear installation, the nuclear cogeneration plant should be designed to withstand a large variety of abnormal conditions. The choice of technology for the cogeneration plant is a major factor in determining the way the plant is coupled to the reactor. Two types of coupling are thermal coupling and contiguous coupling. The thermal coupling could have direct safety implications by way of the operational transients that may exist in the nuclear cogeneration plant. Such transients may also have a direct effect on the operation of one system or the other. Hence, an intermediate heat transfer loop that serves as an isolation loop is required in most designs (e.g. a condenser cooling circuit). No such risk is found in contiguous coupling, because the cogeneration system draws only electrical energy from the system, either from the grid alone or by direct connection to the nuclear system, with an auxiliary connection to the grid. In the case of contiguous coupling, the possibility of interaction effects between the nuclear and cogeneration systems is minimal. In cases where limited thermal coupling is required, the potential safety impact should also be assessed.

The partial or total unavailability of the thermal cogeneration plant, which provides a redundant heat sink for the nuclear facility, could result in a partial or total loss of heat sink, causing a possible turbine trip and reactor trip. Major causes of a transient include disturbances such as loss or excess of load in the cogeneration plant. The transient induced by most potential disturbances which lead to the unavailability of the cogeneration plant is not expected to be more severe than those typically considered for an NPP. However, the transient frequency could change because of the connection with the cogeneration plant.

5.3. VALUES ADDED BY COGENERATION

There are quite a few visible and direct benefits of nuclear cogeneration, which affect the public either directly or indirectly through the modifications of industrial processes. That implies the necessity to provide more information and to initiate communication efforts about cogeneration not only for the major stakeholders (governmental institutions, scientific community, decision makers, political parties, etc.) but also for the general public, including schools, non-profit organizations, and economic and social associations.

Making large amounts of fresh water available in arid countries at a low cost is a pressing concern for all inhabitants; proposals would certainly be eagerly sought after. In northern areas, district heating can directly affect the everyday life of many by modifying the source of heat in their homes. Providing information and explaining the benefits gained are of the utmost importance in garnering public support. And if, in the future, nuclear reactors are used to produce hydrogen and/or heat for synthetic liquid fuel production, that will directly modify the transportation sector and the kinds of gas filling ordinary cars.

In all cases, the value added by nuclear cogeneration have to be directly measured in terms of energy savings, improved comfort or environmental benefits like a reduction in GHG emissions.

A recent study [35] demonstrates that an implementation of cogeneration through use of waste heat can offset a significant fraction of the cost of generating nuclear power. The study examines the case of a VHTR power plant carrying out large scale seawater desalination cogeneration. By using the waste heat rejected by the GTHTR300 gas turbine power conversion cycle, the thermal energy savings realized through desalination cogeneration creates a major cost credit against the price of potable water co-produced in the gas or oil fired CCGT power plants, which is a typical choice for desalination practice in the Middle East today. The credit gained cuts the power generation cost by 15% compared with water produced from natural gas desalination plants and more than 30% against water produced from oil powered desalination.

5.4. APPLICATIONS

5.4.1. District heating

About 40% of the primary energy consumed in the world is used to generate heat. Heating buildings is one of the most significant final uses of heat. Apart from traditional biomass burning, heat is mainly provided by burning fossil fuels. If we are seriously concerned about CO_2 release into our atmosphere, switching to a carbon free source for heat is mandatory. Nuclear heat released by fission in currently operating NPPs may be recovered at low cost and used advantageously for district heating [15]. The proven long term experience in the Beznau PWR in Switzerland is described in the Appendix. The general principle is shown in Fig. 5: At the power plant site, modifications only affect the secondary water loop, part of the steam coming out from the reheater being directed to a specific low pressure turbine. The expanded steam is then condensed in a large heat exchanger, delivering the recovered heat to the MHT pipeline. The NPP modifications are quite moderate and may be realized without impeding the usual operation.

Because NPPs are usually far from large cities, the recovered heat has to be transported over long distances to consumer sites. Many technical options are available to transport large amounts of heat (~ GW) over long distances (~ 100 km). One may use a fluid (water, steam, ammonia, methanol, ethanol, etc.) in natural or forced convection, in either a single or in a two-phase flow. Today, the simplest and most advanced technology remains the use of hot water flowing in pre-insulated pipes buried in trenches or installed in an underground tunnel. Significant improvements have been made in recent years in heat piping insulation performance, allowing MHT lines to be designed with extremely low losses (<1% over 100 km). Transporting energy as heat may now compare to transporting electricity.

With technical feasibility being at hand, the only obstacle for a large surge of nuclear cogeneration for district heating is the investment cost. The main cost contribution to the whole system turns out to be the construction of the MHT line. Costs for heat delivered to customers may be made competitive whenever the recovered heat from the NPP exceeds a threshold value (Fig. 6). It would certainly not be worth constructing a long-distance transport line to serve only a few buildings. In many case studies serving large populated areas, the technical–economic calculations show that nuclear district heating can be cost competitive when compared to the cheapest fuel for heat production (natural gas). Competitiveness is even more achievable whenever a carbon tax can be applied or the discount rate for the investment cost lowered. In any case, once the initial investment is amortized, the nuclear heat cost will certainly come out far cheaper than any other fuel source.

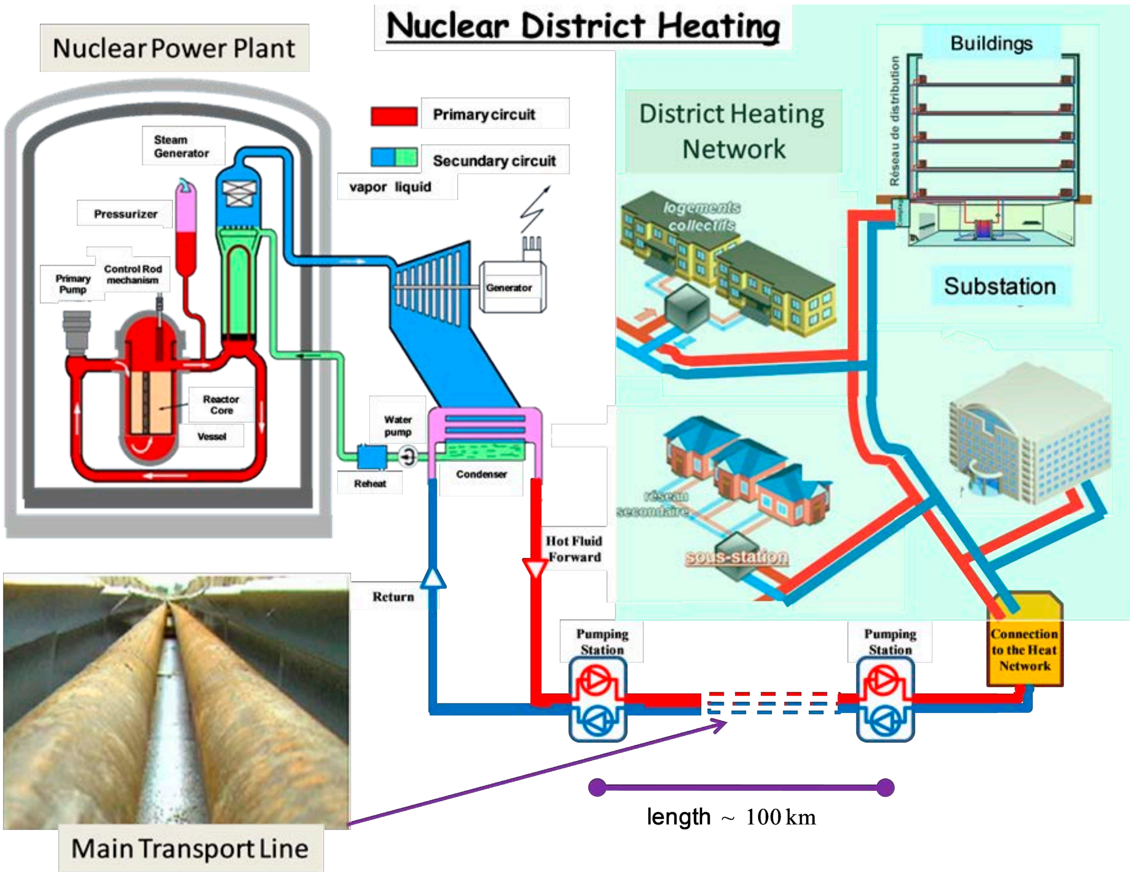


FIG. 5. Principle of nuclear cogeneration for district heating.

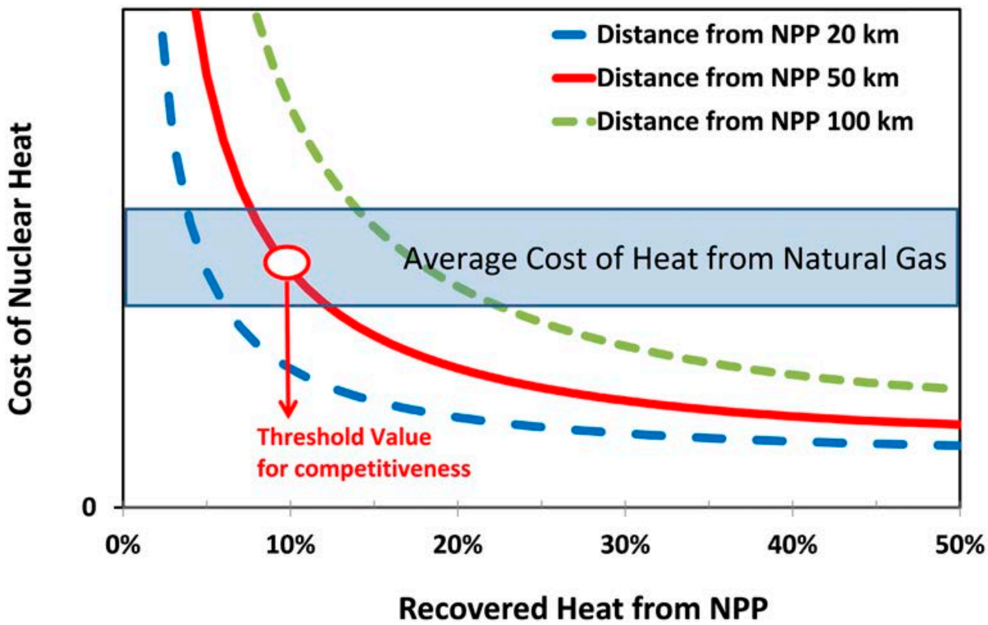


FIG. 6. Total cost of heat from nuclear cogeneration as a function of extracted heat.

5.4.2. Desalination

Fresh water is vital for humankind. It is a matter of survival. An increasing number of places around the world are suffering from water scarcity. The situation is liable to get even worse owing to the combined effect of a growing population, depletion of aquifers and climate change. Seawater desalination is the key technology for solving this issue. Therefore, the number of desalination plants around the world have been steadily increasing recently (160% in 10 years). There are today 14 000 desalination plants generating about 75 million m^3 per day and there is a strong indication that this growth will accelerate. However, seawater desalination is an energy intensive process. Unfortunately, almost all desalination plants rely today on fossil fuels (gas or oil) for their energy needs.

Desalination technologies are based, on the one hand, on water evaporation, using either MSF or MED with or without vapor compression, and on the other hand relying on reverse osmosis filtration. Distillation requires both heat and electricity, whereas separation across a membrane requires only electricity.

Minimizing the cost of water is a requirement for many countries that cannot afford too large of an economic investment. Many years ago, the IAEA established an international working group on nuclear desalination to provide continuous information and technological developments on desalination systems for Member States. It has also developed a toolkit, the Desalination Economic Evaluation Programme (DEEP) [46], for evaluating the final cost of water production. Desalination options modelled include MSF, MED, reverse osmosis and hybrid systems while power options include nuclear, fossil fuel and renewable sources. The economics of desalination is clearly improved through cogeneration, the electricity plant being at the same time used for desalination. Sustainability, environmental considerations and large scale economic aspects make nuclear energy an interesting carbon-free energy source for water desalination.

The electricity generated by an NPP can be easily used for any reverse osmosis plant. The efficiency of the system, however, is capped by that of the NPP (33% for a PWR). Cogeneration with a PWR can be performed by thermal desalination using, for example, vapour extracted from a turbine to heat an MED [45]. About 7–8 MW(th) of heat at a quality appropriate for MED may be extracted for each MW(e) reduction in turbine power, potentially boosting nuclear reactor thermal use by 60–70%. The Republic of Korea's SMART reactor described in the Appendix is one such design. Finally, desalination, using the waste heat recovered from the HTGR advanced power conversion cycles, may further increase the rate of utilization to 80–90%. This is seen in Japan's GTHTR300 design, discussed in the Appendix.

5.4.3. Process heat for industries

Depending on the temperature range, the heat requirement of a specific industrial process may be met by tailoring the configuration of cogeneration with a suitable type of nuclear reactor, as shown in Fig. 7.

In existing NPPs, a power conversion steam turbine is coupled with a nuclear reactor in either a direct cycle (e.g. BWR) or an indirect cycle (e.g. PWR). These cycle arrangements are applied to not only steam turbines but also gas turbines for improved performance efficiency in advanced nuclear reactor designs. Low temperature process heat or steam such as for district heating or desalination may be adequately and cost-effectively cogenerated through power turbine exhaust heat recovery, an example of which is given in Fig. 7. High temperature heat and steam, on the other hand, may be produced with advanced reactors such as HTGRs with the arrangement of an IHX or steam generator. The following are some industrial areas considered for cogeneration with nuclear energy. Additional experience and case studies are included in the Appendix.

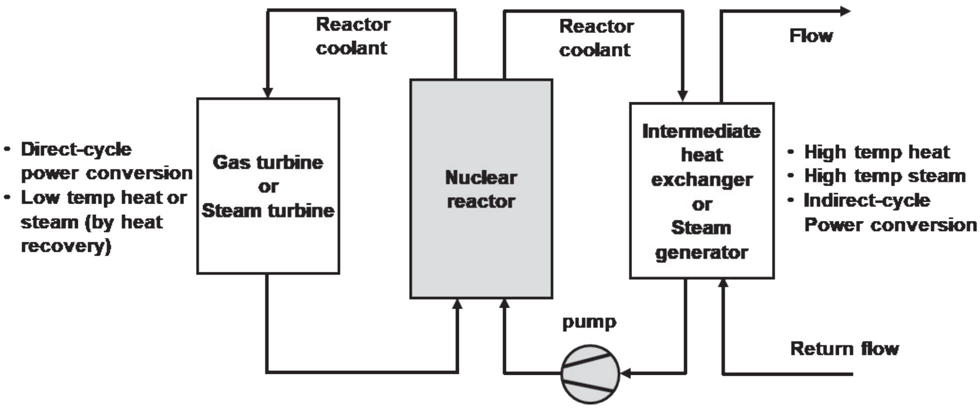


FIG. 7. Generic configuration of industrial cogeneration with a nuclear reactor.

5.4.3.1. Oil and tar sands extraction

One example with near-term prospects is the provision of high temperature heat/steam and electricity in tertiary oil recovery processes that are garnering increasing interest, as production from new conventional oil resources decreases. This sector, in particular, requires massive amounts of hydrogen for the conversion of heavy oils, tar sands and other low-grade hydrocarbons [47]. Hydrogen may be obtained as described in Section 5.4.4.

Due to the increasing share of 'dirty fuels' such as heavy oils, oil shale and tar sands entering the market, the need for both process heat and hydrogen will also increase significantly. In the so-called steam-assisted gravity drainage process, a bituminous well is flooded with steam and the oil produced is retrieved from a separate well. The temperature and pressure of the steam injected into the well are influenced by various factors such as bitumen composition, bitumen properties and sand type; they fall into the typical range of 200–340°C and 10–15 MPa [48]. For larger resources, nuclear could represent a large centralized steam source to be injected at several locations. Fluctuations in oil production could be compensated for by cogeneration of electricity. Canada appears to be an ideal candidate for such a combined system due to its vast amounts of oil sands and its established CANDU nuclear plants.

5.4.3.2. Crude oil refining

A refinery with a throughput of 6–7 million t/year of crude oil consists of many individual plants which typically need a steady heat supply of about 400 MW(th). Due to the complex interaction of the different chemical processes optimized to a very high degree, the potential supply of energy by nuclear power may not be dedicated to a specific process, but rather cover the overall cogeneration of process steam, process heat and electricity. An additional approach will be the important hydrogen generation discussed in the next section. The most widely applied methods for synthesis gas and hydrogen production are processes that involve splitting hydrocarbons. The most important ones established on an industrial scale are steam reforming of natural gas, extraction from heavy oils and gasification of coal. Biomass gasification is currently being tested on a pilot plant scale.

5.4.3.3. Coal liquefaction and gasification

Because of the abundance of coal, its conversion to gaseous or liquid fuels has been applied commercially worldwide. Various types of gasification reactors have been developed which differ by the type of reactor, temperature and pressure range, grain size of the coal and its residence time. Depending on the customers' requirements, respective downstream processing allows the optimized generation of either hydrogen or synthetic natural gas (SNG) or synthesis gas. Synthesis gas output is optimal at high temperatures and low pressures.

Within the frame of the prototype nuclear process heat (PNP) project, two coal gasification processes for SNG production were explored in Germany. With an HTGR, the heat provided by the hot helium can be introduced directly into the gas generator, with another part being used for steam production, and the remainder still being usable for electricity production. To avoid any handling of solid material streams and large amounts of CO_2, SO_2 and ash inside the nuclear containment, it becomes necessary to employ a helium–helium IHX for heat transfer from the primary helium.

In the hydro-gasification process, hydrogen is added to convert — in an exothermal reaction — the coal to SNG, before the synthesis gas is produced in parallel steam reforming and water–gas shift reactions. The nuclear heat input is used here in the steam reforming process to supply the feedstock hydrogen. The advantage of hydro-gasification compared with steam–coal gasification is its 200°C lower pre-heating temperature, which reduces potential corrosive attack. A major drawback is the low conversion rate of not more than 50–60% of the coal. Again, subsequent processes would allow the generation of SNG or methanol.

The PNP activities eventually resulted in the construction and operation of pilot plants for both types of coal gasification under nuclear conditions in which the heat was provided by helium electrically heated up to 950°C. Catalytic and non-catalytic steam–coal gasification of hard coal was verified in a 1.2 MW facility using 950°C helium as the energy source. The hydro-gasification of brown coal (lignite) was realized in a 1.5 MW semitechnical test facility operated for ~27 000 h, and later in a follow-up pilot plant operated with a throughput of 9.6 t/h corresponding to a total power of 50 MW. SNG production occurred at a rate of up to 6400 Nm^3/h.

5.4.3.4. Aluminium production

In the aluminium industry, nuclear energy could assist in the highly energy intensive production of primary aluminium. After mining of the bauxite ore, the manufacturing process consists of two major steps: (i) the extraction of aluminium oxide (Al_2O_3 or alumina) from the bauxite ore (the Bayer process) and (ii) the electrolytic reduction of the alumina to aluminium metal (the Hall–Héroult process). One tonne of Al_2O_3 yields about 0.53 tonne of aluminium. While in the first step the energy required is basically in the form of heat at two temperature levels — about 270°C for obtaining the interim product aluminium hydroxide and above 1000°C for calcination — the second step requires electricity, predominantly. The estimated specific energy consumption in these two steps is 11 GJ per tonne of Al_2O_3 for the Bayer process and 13 000 kWh per tonne of aluminium metal for the Hall-Heroult process.

A potential was seen to integrate nuclear high temperature heat into the Bayer process step. Previous German studies [49, 50] resulted in the development of concepts for process heat exchangers comprising a fluidized powder heat exchanger and an air heater for the high temperature calcination step, a steam generator, and a liquid salt heat exchanger operated at lower temperatures to heat up the sodium hydroxide. Cogenerated electricity can be used in the Hall–Héroult process step. Assuming the above figures of energy consumption, a 600 MW(th) VHTR would provide an estimated 109 MW as process heat, while the remainder would be converted to 245 MW(e) of electricity (assuming 50% thermal efficiency) to result in an annual aluminium production capacity of 165 000 tonnes.

5.4.4. Hydrogen production

The hydrogen used in refining oil for the processes above is primarily obtained from steam reforming of natural gas. Hydrogen may be cogenerated with nuclear heat and power via various routes, as illustrated in Fig. 8, including the following:

— Water electrolysis, using nuclear power;
— Steam electrolysis, using nuclear power and heat in the range of 750–850°C;
— Chemical reforming of fossil fuels and biomass, using nuclear heat in the range of 850–950°C;
— Thermochemical or hybrid water-splitting cycles, using nuclear power and heat in the range of 850–950°C.

These concepts, system designs and the status of their development and deployment around the world have been extensively described [7, 40]. In brief, hydrogen may be readily produced through low temperature water electrolysis supplied by some of the electricity generated in current commercial nuclear plants and, more economically, by the off-peak electricity. In the longer term, hydrogen may be produced through the other processes. All of those processes require high temperatures that may be supplied by advanced reactors, including: the nuclear-heated steam reforming of fossil fuel, which reduces fuel consumption and associated CO_2 emissions

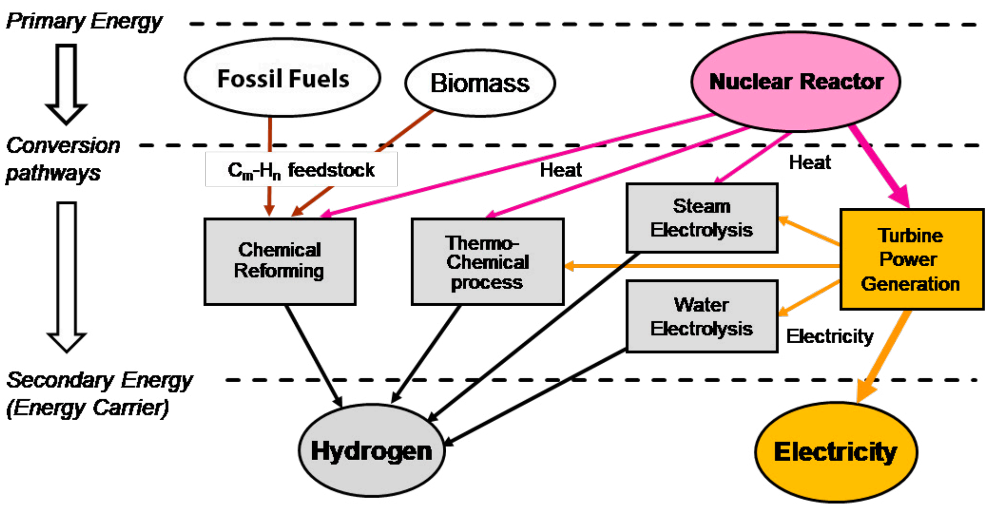


FIG. 8. Nuclear hydrogen cogeneration routes.

by as much as 35% (in the case of methane reforming); the CO_2 emission free thermochemical water splitting cycle or HTSE; and CO_2 neutral gasification of biomass. Since the amount of hydrogen in biomass is only 6–7 wt%, the process is thermally inefficient with a high specific production cost. The hydrogen content of the gas mixture produced depends on the feedstock (peat, wood, agricultural residues), the availability of steam and oxygen, and the process temperatures.

6. NUCLEAR COGENERATION GENERIC GUIDANCE

6.1. EXCELLENCE AND PRACTICE

Nuclear cogeneration is one of the few options that may significantly contribute to climate change mitigation on a large scale. Many countries worldwide have set up nuclear power as a pillar of their national energy strategy to address likely the biggest environmental challenge of the twenty-first century. Nevertheless, if nuclear were restricted to electrical power generation, it would merely cover a fraction of the energy portfolio. Today, nuclear supplies 4% of the world's primary energy and essentially all of it is used for electricity generation. To make a more significant contribution to the world's GHG abatement, it is clear that non-electric energy needs, such as heat and transportation, have to be addressed as well. This calls for considering the potential implementation of nuclear cogeneration as a carbon-free energy source.

Nuclear cogeneration has already been demonstrated in NPPs in many countries. Fifty-three of the 438 nuclear reactors in operation today are equipped to run in cogeneration mode, delivering electricity and heat simultaneously. This mode of operation has proved to be efficient, safe and easy.

6.2. SELECTION OF CRITERIA FOR NUCLEAR COGENERATION

A number of evaluation steps are necessary prior to implementing a cogeneration project. At each step, depending on the stage of assessment of the siting, a report may or must be issued in support of the evaluation. Because some of the work may be performed in parallel, aiming at different targets, the order can be slightly modified. However, the major steps are as follows:

(1) **Assess the added value of the cogenerated product derived from an NPP.**
This needs to be done as a first step to get formal approval from the stakeholders (industry, government entities and private or public investors) backing the project.

(2) **Conduct a feasibility study for the project.**
This is usually done as a preliminary design report, including site location, implementation and details of the connection to the cogeneration plant. A complete study of plant operation, maintenance, transport, distribution and storage will be needed as they relate to the cogenerated product.

(3) **Set up a financial round table.**
Subsequently, as a part of, or independent to, the preliminary design report, the cost and value of the cogenerated product need to be assessed to substantiate the overall economics in order for the stakeholders to consider financing the project.

(4) **Provide a safety file.**
A safety analysis report is prepared and submitted to the relevant regulatory body for nuclear safety. After review and comment by the regulatory body, the complete safety file will initiate a deeper specific risk analysis (including the coupling of the NPP to the cogenerated product plant) and safety considerations in normal and abnormal conditions.

(5) **Conduct an environmental impact assessment.**
Any environmental benefit gained from nuclear cogeneration — such as a reduction in thermal discharge in the plant's vicinity — is assessed. The method of mitigation chosen to minimize the impact of failures

on the environment must also be assessed, as must land use by the project; for example, assessing the MHT line linking the NPP to the cogenerated product plant.

(6) Perform the detailed design study.

This can be worked out provided steps 3, 4 and 5 have gotten approval from the safety authority, from the stakeholders for financing, and from the national and local governments regarding environment and health.

6.3. ASSESSMENT OF NUCLEAR COGENERATION

6.3.1. Design plant layout

As pointed out in this report, cogeneration can offer a nuclear project many benefits. Although it could be retrofitted onto existing reactors, it is preferable to consider cogeneration at the early design stage of the reactor project.

The implementation of cogeneration will basically only affect the secondary circuit loop of the reactor. Depending on the reactor type and on the level of the extracted heat, the modification of the secondary loop may come out as a minor point in the plan or prove to be more important, as the following demonstrates:

— For a PWR, there is no need to add any intermediate circuit as the secondary loop already ensures a physical barrier between the primary radioactive water and the extracted heat. Depending on the temperature required for heat, steam extraction can be performed in many locations of the secondary loop and the heat exchanger can serve as condenser.
— For a BWR, safety requirements will call for the insertion of a secondary loop in between the primary circuit and the extracted steam or hot water. Heat could be extracted in a manner similar to that used in a PWR.
— For an SFR, a sodium–water secondary cooling system will likely be necessary to make the heat extraction suitable with a standard water/water heat exchanger. Other options can be explored (i.e. sodium/gas heat exchangers) but would require extensive R&D and validation.
— For an HTR, the helium coolant works at high temperatures (750–950°C). A steam generator serving as a primary/secondary heat exchanger could be a technical option resulting in a solution like the PWR secondary loop. However, the higher working temperatures of the water loop (up to 550°C) may induce severe corrosion problems not encountered in water reactors. These should be thoroughly assessed and clarified.
— For other reactor designs, nuclear cogeneration can be easy to introduce in the conversion system loop (including thermodynamic issues, material issues, etc.).

6.3.2. Economics and finances

A techno-economic study in support of the simultaneous generation of two or more energy products has to be carried out at an early stage in order to optimize the design for the owner, user and other potential stakeholders. Usually, the purely electric mode is taken as a reference for analysing the added cost value of the other products at the plant level [2]. However, this purely economic approach generally leaves out the other important benefits to the market and society of running the nuclear reactor in cogeneration mode — such as energy security and environmental benefits. First, price stability not only improves, but also GHG emissions are significantly reduced when substituting heat generating plants firing on imported fossil fuel. The number of fatalities or illness due to the production of energy are also reduced. These benefits could be quantified by introducing a carbon tax on CO_2 emissions and by evaluating the external costs incurred by health casualties. Another advantage that can be directly translated into economic value is the flexibility offered by cogeneration, especially for the electric grid — of course, this depends on market incentive and regulation. Because the cogenerated product can be stored in tanks (as hot water, hydrogen or synthetic fuels) and displays high calorific inertia (heat), the NPP can contribute to stabilizing the off-demand equilibrium of the electric grid. All these benefits need to be highlighted to attract stakeholders and investors to finance the project.

6.3.3. Safety

Specific attention needs to be paid to the safety aspects induced by coupling the NPP with the cogeneration unit. In addition to the standard nuclear safety issues encountered in a nuclear plant and the common safety hazards of the industrial transformation plant, the potential interaction between the two systems needs to be addressed. Any single failure of one of the two units should not weaken the safety case established for the other. Defence in depth calls for appropriate protective barriers to be erected in order to prevent any kind of radioactive transfer from the nuclear zone to the industrial zone. An example of a protection by design is the use of higher pressure in the intermediate heat exchanging circuit to prevent any contaminant transfer from the reactor loop to the heat extracted, even in the case of an accidental crack in the heat exchanger.

A subsidiary safety feature resulting from nuclear cogeneration is the availability of an external cooling sink in addition to the usual one available in a standard NPP. After the Fukushima Daiichi nuclear accident, this appears to be a non-negligible redundancy that may prove to secure backup and enhance confidence.

6.3.4. Operation performance

An essential requirement for nuclear energy input to an industrial facility is high flexibility. Due to a demand for steam, electricity and high temperature gas which will vary within certain ranges, it is necessary to adjust to the versatile needs of many different applications of the industrial process heat market. This includes, for example, the acceptance of a full load rejection from steam, electrical or high temperature gas demand, the acceptance of zero steam flow demand and/or zero power demand and/or zero high temperature gas demand, or the accommodation of coincident steam, electrical and high temperature gas demand [51].

In contrast to electricity generation, the needs and requirements of industrial end users for process heat applications are much more versatile in terms of power, temperature, transient capability, availability, reliability and flexibility. Industrial heat is often required as steam under conditions specific to each technological process. The range of steam parameters is determined by the specific industry and is rather large [13]. The operation capability for the nuclear plant to vary the electricity to heat generation ratio within the user-required range needs to be assessed. It may be desired, or even necessary, to switch between the limits of heat production only or electricity production only. The transient capabilities of the reactor under normal or accidental conditions should match the transient loads imposed by the industrial processes, requiring a common control strategy for both islands. Buffer capacities need to be provided.

6.3.5. Environment and health

Environmental and health issues are similar to those for a standard NPP project. No downside effects on the environment are to be expected from running an NPP in cogeneration mode. On the contrary, there are some benefits of extracting heat from the NPP to be used far from the site. This directly translates to a reduction of the quantity of heat dumped near the plant. Therefore, nuclear cogeneration lowers the environmental concern related to the large amount of heat released into the cooling water or the atmosphere. This is the clear advantage of cogeneration. Other environmental benefits include the reduction in water uptake from the sea or a river and, thanks to the higher efficiency of the plant, a corresponding decrease in the quantity of radioactive waste produced per energy unit.

6.3.6. Stakeholder involvement

The main stakeholders will be represented by industries (utilities, vendors, supply chain, energy operators), investors (financial stakeholders), government entities and final consumer representatives (municipalities, states). Their involvement is of the utmost importance to the success of the cogeneration project. They play a key role in promoting and supporting the project not only financially but through active action plans, including R&D funding. Their strategic commitment will ensure competitiveness and sustainability in the long run. The stakeholders serve as delegates between the project management and the end users.

6.3.7. Public information

Raising public awareness is highly recommended to ensure increased public acceptance. Information provided to the public should describe the project location, general objectives, technical details, schedule, costs, stakeholders, employment, and so on. This may be done through the following:

— Communication channels: local meetings, events, citizen initiatives and visits, and/or a project information office, toolkit, Internet, etc.
— Communication formats: brochures, flyers, fact sheets, public hearings, presentations, open exhibits, infographics, a web site, etc.
— Communication messages: state benefits for society, for the local community and for national welfare. The following advantageous features of nuclear cogeneration could be highlighted:
  - Efficiency: recover waste heat;
  - Environment: produce heat carbon-free (reduced GHGs);
  - Economy: provide a long-term, secure and cheap source of energy.

7. CONCLUSION

Cogeneration is the integration of NPPs with other systems and applications. Heat generated by NPPs can be used to produce a vast range of products that may, depending on the reactor's design, include district heating and cooling, process heat, desalination, hydrogen and other products.

Many low temperature cogeneration applications can be found in district heating, seawater desalination, and agricultural and industrial processes, representing great potential for integrating nuclear energy cogeneration of heat and electricity. Seawater desalination requires temperatures up to ~130°C, district heating up to ~170°C, and low temperature industrial processes up to ~250°C. LWRs are adequate to cogenerate with these processes.

The application of nuclear heat in seawater desalination to produce potable water has already gained some operational experience. The desalination technologies MSF, MED and reverse osmosis have matured and are well established, though they have potential for further improvement. Combined with a nuclear reactor, the desalination facility may be dedicated to fresh water production only or may also be used for the cogeneration of electricity. The technical feasibility of integrated nuclear desalination has been successfully demonstrated in various plants worldwide, with proven operating reliability and safety compliance. As any nuclear reactor can in principle provide the energy (low-grade heat and/or electricity) necessary for desalination processes, different options for coupling configurations are possible for deployment of nuclear powered desalination.

District heating is another important example with great potential for nuclear energy integration. District heating networks generally have installed capacities in the range of 600–1200 MW(th) in larger cities, and about 10–50 MW(th) in smaller communities. The potential market is particularly promising in climatic zones with relatively cold winters. Nuclear cogeneration with district heating is an interesting option to consider for three main reasons: First, it is a real game changer in energy efficiency, significantly enhancing the energy production of power plants. Second, it provides a good investment for the future, ensuring a stabilized district heat price over the long term. Once the MHT line is fully amortized, the remaining total heat cost will be significantly lower than any other energy source available by then. Third, it greatly reduces the carbon footprint and may well contribute to a decarbonization of energy in the twenty-first century. Experience with nuclear district heating and electricity cogeneration has been gained in numerous places, particularly where electricity constitutes the main product of NPPs. There is, however, also the option of dedicated nuclear heating reactors.

Process heat or steam is used for a variety of applications in the industrial sector. The pulp and paper industry, textile industries, oil refining, and oil shale and oil sand processing have temperature requirements in the approximate range of 150–500°C, while the reforming and gasification of fossil fuels and biomass, hydrogen production and steelmaking are examples of industrial processes requiring temperatures in the range of 500–1000°C. Some experience with the nuclear energy provision of process steam for industrial purposes has been gained in Canada, Germany, Norway, Switzerland and the United Kingdom. Technical and economic feasibilities, however, remain to be demonstrated on a larger scale. While HTGRs share some of these challenges, they promise supply to the whole spectrum of the process heat market. They differ from LWRs in their much smaller output of process heat. From economical and thermal efficiency points of view, high operational temperatures are key for CHP, because electricity generation losses can be reduced with increasing operational temperatures.

Hydrogen as an energy carrier for the future is subject to a wide range of activities worldwide, but more notably in the USA and the EU with the aim to open the application of nuclear energy for the transportation sector while reducing the present reliance on fossil fuel with its associated price volatility, finite supply and GHG emissions. Using electricity in conventional (low temperature) electrolysers to produce hydrogen presents a near-term option for distributed hydrogen generation. Because of the lower capital investment, it could play an initiating role until larger networks for hydrogen distribution are needed. R&D programmes are ongoing in several countries for high temperature hydrogen production (steam methane reforming, steam electrolysis, thermochemical and hybrid methods) and heat applications from nuclear energy, achieving a laboratory to pilot scale of demonstration and component tests.

This publication makes the following additional conclusions:

— The LWRs available today are the most suitable for cogeneration with district heating and desalination due to their low working-temperature range.
— The high working-temperature ranges of LFRs (550°C), MSRs (~800°C), GFRs (~850°C) and VHTRs (750–950°C) make them suitable for producing industrial process heat and hydrogen along with desalination and district heating when they are used as cogeneration systems.
— Cogeneration may be added to existing NPPs. New builds, particularly many SMRs, are designed with cogeneration applications in mind.
— An NPP working in cogeneration mode can produce as much as 70% more useful energy in the form of combined thermal and electrical energy compared to NPPs working in single generation mode.
— Nuclear heat in the form of hot water can be delivered up to 150 km away at competitive cost and with a reported loss lower than 2%.
— A payback time of five years is expected if an NPP is converted to a cogeneration plant to provide district heat.
— Gen-IV reactors, particularly HTGRs, are more competitive economically than current water reactors for cogeneration because of their ability to produce higher temperature heat and recover more waste heat.
— A medium-size nuclear reactor, such as the advanced CANDU reactor (ACR) or SFR, is perfectly suitable for providing all the energy needs, including steam, electricity, hydrogen and industrial water, for a large crude oil production from oil sands or for a large refinery.

The topics covered in this publication suggest the following recommendations:

— The feasibility of integrating cogeneration systems with NPPs is highly dependent on the NPP site, so there is a need to adequately identify the site while keeping in mind the needs of the people living in the surrounding areas (e.g. in the Gulf region). NPPs should be developed along the coast to utilize cogeneration systems capable of producing fresh water through seawater desalination.
— There is a strong need to carry out further feasibility studies of the existing NPPs to investigate how they can be modified to better use the nuclear fuels in cogeneration mode by recovering their waste and/or process heat.
— R&D are needed to accelerate deployment for a new generation of NPPs with higher coolant temperatures which can help run high temperature thermochemical water splitting cycles for large scale carbon-emission-free hydrogen production.
— Software tools need to be developed that are capable of conducting energy, exergy, cost and environmental analyses for different cogenerating NPPs. Furthermore, they need to integrate thermodynamic, cost and environmental aspects of several cogeneration modes to better assist researchers and governments around the globe in selecting appropriate nuclear cogeneration options based on their performance, cost and environmental limitations.

Appendix

SELECTED EXPERIENCE AND CASE STUDIES

A.1. EXPERIENCE WITH NUCLEAR COGENERATION

Nuclear cogeneration plants have operated in 13 countries [2]. They are mainly used for district heating and desalination. A few are used for low temperature industrial and agriculture applications. Globally, the accumulated experience with nuclear district heating numbers over 500 reactor years, whereas experience with nuclear desalination numbers 250 reactor years. The following sections highlight a few selected systems.

A.1.1. District heating in Switzerland's Beznau plant

The Beznau plant in Switzerland houses twin PWRs (2 × 365 MW(e)). Commercial power generation began in one PWR in 1969 and in the other in 1971, followed by district heating in 1983 and 1984, respectively. The peak district heat load is about 80 MW(th) from each unit, about 10 MW(e) power output is reduced per unit while performing district heating. Together, these reactors serve 11 municipalities of private, industrial and agricultural consumers totalling about 20 000 people. Operation has been reliable.

As shown in Fig. 9, the reactors supply steam to the power generation turbine located in the secondary loop. Some steam, measuring 92°C, is extracted from the lower pressure turbine and directed to a heat exchanger to be used as a thermal energy source to heat the circulating water returning from the district heating network. The water temperature is raised from 50°C to 85°C. The water is reheated to the final condition of 125°C and 1.6 MPa in a second heat exchanger using the 130°C steam extracted from the back of the high pressure turbine. Note that the water is supplied at 125°C in winter while it is lowered to 85°C by using only the low temperature heat exchanger.

The pressurized hot water is circulated in the third loop which runs through the pumping station. The pumping station distributes the hot water to the consumers, who are spread over a wide area, requiring 35 km of main piping and about 85 km of local distribution network. The heat loss is reportedly 1°C per 5 km in the main piping and 15% in the local network. Although the heat loss is relatively higher than with individually customized oil heating, it is accepted as environmentally friendly by the municipalities.

Serviced by the Beznau NPP, Swiss customers are covered by in-depth defence measures against a risk of radioactive contamination. First, the end user loop is located in the fifth loop and provided with four layers of metal barriers between it and the nuclear plant's primary system. Second, the fourth loop, which lumps a smaller number of customers together, is installed to separate the customer from the MHT loop. Third, isolation valves are provided on the main transport loop to prevent, if necessary, any material exchange between the reactor and the local distribution network. Finally, the water pressure of the main transport loop is kept 0.28 MPa higher than the secondary steam, preventing any secondary steam from entering the MHT loop in case of an accidental leak in the water heating heat exchanger tubes. Due to these defence measures, the safety of the district heating cogeneration system is ensured even in cases of simultaneous leaks in the reactor steam generator and the water heating heat exchangers.

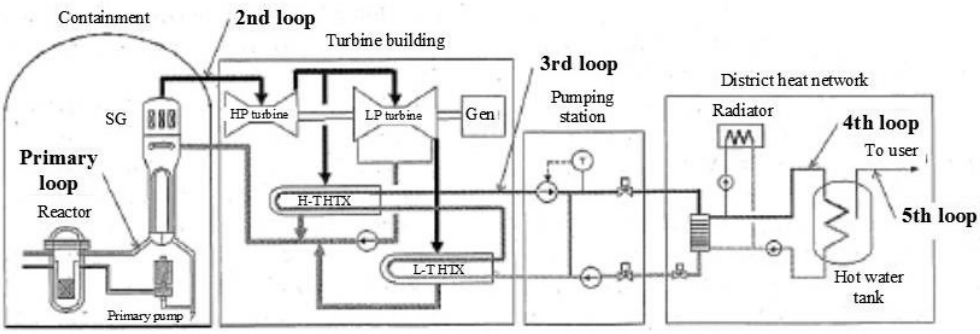


FIG. 9. District heating cogeneration at Beznau nuclear power station in Switzerland.

A.1.2. Nuclear desalination in Japan

Ten of the 60 commercial nuclear reactors in Japan, all located on the coast for access to sea water as a heat sink, are equipped for seawater desalination cogeneration to provide boiler feedwater and in situ potable water uses [39]. The individual plant capacities vary in the range of 1000–2600 m^3/d with a combined total of approximately 14 000 m^3/d. MSF was selected for earlier plants and MED or reverse osmosis was chosen for later plants owing to their greater efficiency.

Figure 10 shows the MSF facility operated since 1978 at the Ohi PWR, where the steam extracted from the steam turbine is sent in a steam converter to produce (through heat exchanging) the intermediate steam heat source for the desalination process.

The desalination plants in Japan's nuclear plants have been in service for more than 30 years, logging collectively some 150 reactor years of operation with no radioactive leakage into the product water. These desalination plants are conventional systems built in a factory and delivered as a package from the manufacturer. They are operated at 50–100% of their full capacity to supplement insufficient or expensive fresh water on site. Desalination is a built-in feature of the initial nuclear plant concept and undergoes regular inspection and maintenance as does any component of the NPP. The experience gained in Japan highly supports the use of nuclear power for seawater desalination worldwide.

FIG. 10. MSF desalination cogeneration plant in the Ohi nuclear plant in Japan.

A.1.3. Nuclear desalination in Kazakhstan

The MAEC station located along the Caspian Sea consisted of a 750 MW(th) SFR (BN-350). Operated from 1973 to 1999, it cogenerated electricity 150 MW(e) and desalination of about 120 000 t/d. It was the largest commercial nuclear desalination plant ever operated in the world [5].

The desalination plant (Fig. 11) consisted of many MED units, with five to seven effects per unit. The exhaust steam (0.6 MPa) from the nuclear plant back pressure turbines was fed into the first effects of the MED. If more steam was available than was needed for desalination, it was used to supply industrial district heating. Steam from fossil boilers extractable from the main steam lines of the NPP provided backup heat for desalination. In fact, switching between the heat sources for the desalination plant was carried out regularly, and no problems arose. To meet daily peak demands of water, reservoirs were used for distilled water and for the feedwater of the steam generators and boilers. The seawater intake channel was about 2 km long and was used to purify silt from the sea water. The brine discharge channel fed into an artificial shallow lake that was connected to the sea. The lake provided aeration of the brine and suspended particle clean up.

The nuclear plant operated for 26 years, accumulating more than 160 000 h of power operation. The reactor was shut down for 20 days twice a year for refuelling and scheduled maintenance. The average load factor achieved was 85%. No sodium leaks were found in either the primary or secondary loop. The analysis of tritium in the nuclear desalination plant streams showed it to be at the background level, close to that found in the sea or in groundwater. Still, measures were taken to reduce the tritium concentration in the distillates for preparing potable water. No adverse effect on the environment and no contamination of the steam and water were experienced. The radiological characteristics of the product water became no different from those of the water produced from the conventional desalination processes. The experience of the MAEC plant demonstrated the feasibility and reliability for large scale desalination cogeneration with an NPP.

FIG. 11. The MED distillation vessels in the MAEC nuclear cogeneration plant.

A.2. SELECTED CASE STUDIES OF NUCLEAR COGENERATION

With improved performance, achieved mainly through passive reactor safety features and greater reactor outlet temperatures, the next generations of NPPs (SMR and Gen-IV systems) that are in varying stages of development are expected to increase the opportunities for cogeneration not only in the number of installations but in a temperature range that includes medium and high temperature processes. Selected case studies are presented below. More cases have been reported elsewhere [2].

A.2.1. Desalination and district heating with SMART by the Republic of Korea

SMART is a 330 MW(th) integral PWR design being developed for multipurpose use (Fig. 12) — electricity generation, seawater desalination or district heating — by KAERI in consortium with a user and vendor [16]. Unlike traditional larger PWRs, SMART installs all major primary components, such as core, steam generators, pressurizer, control drive mechanisms, and main coolant pumps, in a single steel pressure vessel. The integrated arrangement eliminates large primary pipe connections and thus excludes the possibility of a large break loss of coolant accidents. These innovative and advanced features are intended to enhance not only safety but also reliability, performance and operability.

Although the small-sized reactor lacks the economy of scale relative to larger reactors, alternative cost reduction measures include the elimination of large pipes and valves, reactor system modularization, component standardization, factory fabrication and easy site installation, all of which are expected to contribute to a lower construction cost.

In the optimal operation conditions given in Table 3, SMART generates 90 MW(e) of electricity and at the same time supplies steam by extracting it from the turbine mid-stage and transporting it through a steam transformer to a desalination plant to produce 40 000 t/d of potable water. The water output may be raised to 77 000 t/d with the use of a back pressure turbine in which the power output is reduced to 83 MW(e). The desalination system coupled to SMART consists of four units of MED combined with a thermal vapour compressor. Alternatively, SMART may cogenerate electricity and district heating in variable ratios. As an example of a design point, it is estimated that about 80 MW(e) of electricity and 150 Gcal/h of heat can be delivered to the grids. The amount of delivered electricity and heat (~85°C hot water) is quite sufficient to meet the demand from a population of more than 70 000 (~25 000 households).

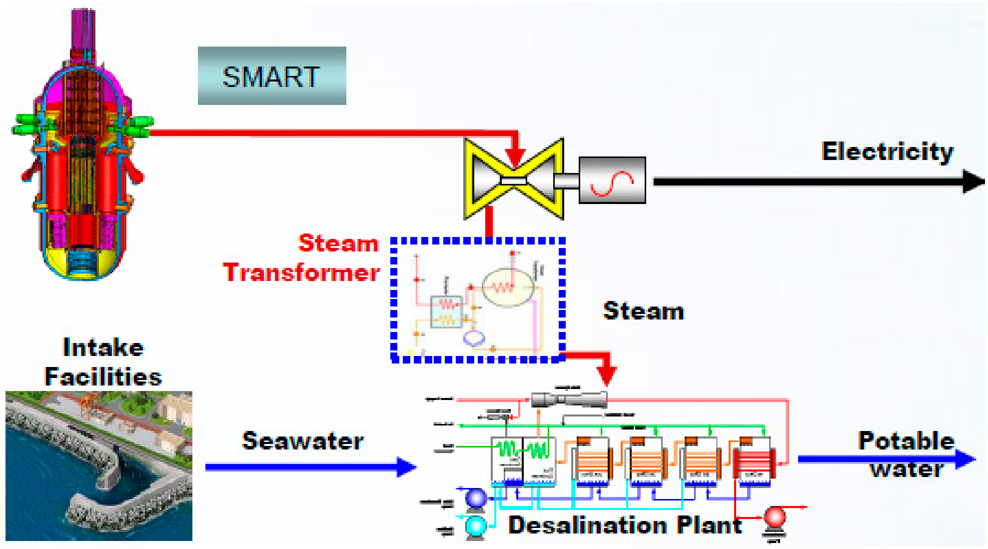


FIG. 12. SMART — An integral 330 MW(th) PWR for cogeneration.

The safety analysis of SMART shows that it remains safe for all design basis events. The low core power density design is proven to provide a thermal margin of more than 15% to accommodate any design basis transients regarding the specified acceptable fuel design limit. Engineered safety systems designed to function automatically on demand consist of a safety injection system, a passive residual heat removal system (PRHRS), a shutdown cooling system and a containment spray system. Additional safety systems include a reactor overpressure protection system and a severe accident mitigation system. Under any circumstances, the reactor can be shut down by inserting control rods or by boron injection. The PRHRS prevents overheating and overpressurization of the primary system in case of emergency events. It removes the decay and sensible heat by natural circulation of a two-phase fluid. The core is maintained undamaged for 36 hours without corrective action by the operator. The reactor overpressure at any design basis event can be reduced by opening the pressurizer safety valve.

After the Fukushima accident, mitigation measures and facilities to cope with severe accidents have become one of the key safety issues. Maintaining continuous and proper core cooling capability after reactor shutdown is very important. The detailed simulation shows that the PRHRS, which works on the secondary side, can remove decay heat and maintain the reactor in a stable condition for over 20 days without power sources and operator action. This grace period may be extended indefinitely if the PRHRS condensate tanks accessible from outside of the containment are periodically replenished.

The risk of radioactive contamination of product water is addressed with two proven mechanisms. The first mechanism is an intermediate loop providing two mechanical barriers — a steam generator and a steam transformer, as shown in Fig. 12, with a pressure reversal between the energy supply and the desalination system. The other mechanism is a continuous radioactivity monitoring system installed in a line of the water production system with an immediate system reaction to follow in case of any detected radioactivity.

A.2.2. Oil recovery and refining with ACR-700 in Canada

The oil sands of Alberta, Canada, hold one of the largest petroleum deposits in the world. Some 286 million L/d of oil was produced from there in 2012. But the production has met with criticism for its impact on the

TABLE 3. SMART DESIGN PARAMETERS

Reactor type		Integral PWR
	Thermal power (MW(th))	330
	Design lifetime (year)	60
	Electric power (MW(e))	100 (80–90 at cogeneration)
	Cogeneration	Seawater desalination 40 000 m^3/d, or district heat (150 Gcal/h)
Fuel and reactor core	Fuel type	UO_2 Square FA
	Enrichment (wt%)	4.95
	Active fuel length (m)	2.0
	No. of fuel assemblies	57
	Core power density (w/cc)	62.6
	Refuel interval (year)	3
Reactivity control	No. of control element banks	49
	No. of control banks/material	49/Ag-In-Cd
	Burnable poison material	Al_2O_3-B4C, GD203-UO_2
Reactor pressure vessel	Overall length (m)	9.8
	Outer diameter (m)	3.96
	Average vessel thickness (mm)	19.8
	Vessel material	SA508 CL-3
Reactor coolant system	Design pressure (MPa)	17
	Operating pressure (MPa)	15
	Core inlet temperature (ºC)	270
	Core outlet temperature (ºC)	310
Steam generator	—	Once through with helically coiled tubes
	No. of steam generators	12
	Design temperature (ºC)	350
	Design pressure (MPa)	17

TABLE 3. SMART DESIGN PARAMETERS (cont.)

Main coolant pump (MCP)	—	Canned motor pump
	No. of MCPs	4
	Flow rate (m^3/h)	2006
	Water head (m)	17.5
Control element drive mechanism (CEDM)	—	Linear pulse motor driven
	No. of CEDMs	49
	Step length per pulse (mm)	4
Make-up system	No. of trains	2
	Operating mode	Active
Secondary system	Feedwater pressure (MPa)	5.2
	Feedwater temperature (ºC)	180
	Steam pressure (MPa)	3.0
	Steam temperature (ºC)	274
	Degree of superheating (ºC)	40

environment (emissions and pollution) because huge extra resources of energy and water are used in mining and upgrading the extremely heavy crudes, relative to conventional oil.

A scheme of nuclear cogeneration based on ACR700, a pressurized heavy water reactor design developed by Canada, has been studied for improved performance of oil production from the oil sands [52]. Figure 13 shows the process flow and energy and material balance of the scheme with a nuclear reactor thermal power of 1900 MW(th) and for a syncrude oil output of 20.7 million L/d. While 1360 MW(th) of the nuclear thermal power is used for steam generation, the balance is taken to generate 200 MW(e) electricity to be used in low temperature water electrolysis for hydrogen production. The refining of the extracted heavy crude or bitumen by hydrogenation is required for transformation into a lighter product (with lower density and viscosity) that can be transported to refineries via pipelines. Nuclear production would trim 77% of CO_2 emissions from the overall process. The process steam flow can be maintained at a constant level with the use of the ‘zero liquid discharge crystallizer’ system (instead of traditional deep-well injection) that enables virtually 100% recycling of the water in a closed cycle. Still, the process consumes large amounts of water as a source of hydrogen.

A.2.3. Multipurpose cogeneration with GTHTR300 by Japan

GTHTR300 is an inherently safe, site-flexible and multipurpose VHTR being developed by JAEA. As a product of Gen-IV technology, the GTHTR300 offers important cogeneration advantages. The reactor coolant temperature is in the 850–950°C range. Such high temperature capability, as proven in JAEA’s HTTR operational test reactor, enables a wider range of cogeneration options, as depicted in Fig. 14, particularly in high temperature heat applications. Several recent cogeneration case studies for the GTHTR300 have been reported [35, 53].

The reactor system combines a high temperature gas cooled reactor with a direct cycle gas turbine to generate power at a thermal efficiency of 45–50% while circulating the reactor coolant. By employing a direct

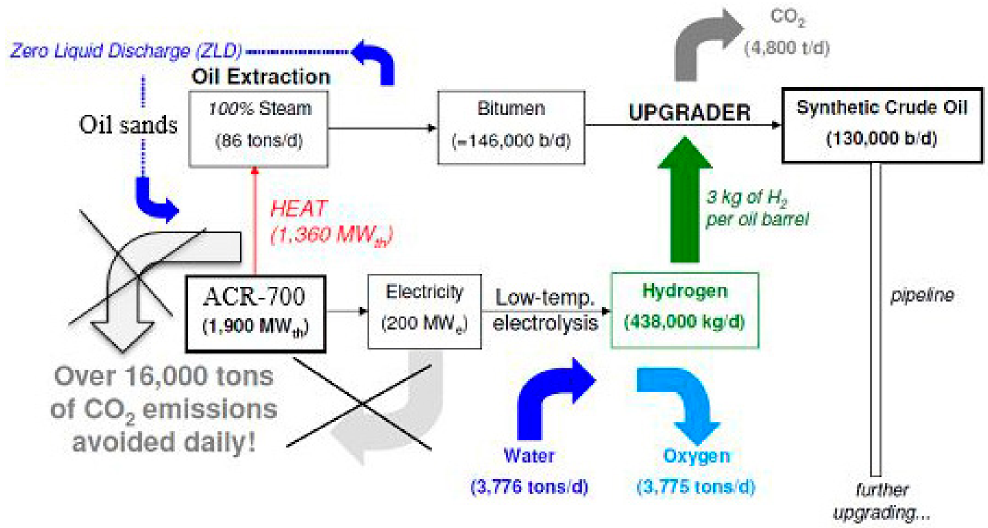


FIG. 13. Scheme of oil recovery from oil sands with ACR-700 cogeneration.

cycle helium gas turbine and eliminating water and steam systems, the design is simplified. The system consists of three functionally oriented pressure vessel units, each housing a reactor core, gas turbine and heat exchangers. The multivessel system facilitates modular construction and independent maintenance access to the functional vessel units. The reactor system is placed below grade in the reactor building. The basic design of the system was completed in 2003 by JAEA and domestic industrial partners Mitsubishi Heavy Industries, Fuji Electric, Nuclear Fuel Industries and others. The reactor system design added high temperature heat application capabilities such as process heat supply and hydrogen production by inserting an intermediate heat exchanger between the reactor and the gas turbine, as depicted in Fig. 14. The low temperature heat applications, including district heating and desalination, use the waste heat of the gas turbine power conversion cycle and thus do not penalize power generation performance. The cogeneration yields thermal efficiency as high as 83%.

While the reactor technologies needed for the GTHTR300 are being developed mainly with construction and operation of JAEA's 30 MW(th) and 950°C test reactor, separate development and testing of key balance of plant component technologies needed for the commercial plant are also being carried out. Those include the high temperature intermediate heat exchanger, helium gas turbine equipment, production-scale fuel fabrication lines and thermochemical hydrogen production process. The design is developed at a pre-licensing basic design stage. The remaining development is expected to be concluded through demonstration of an electricity and hydrogen

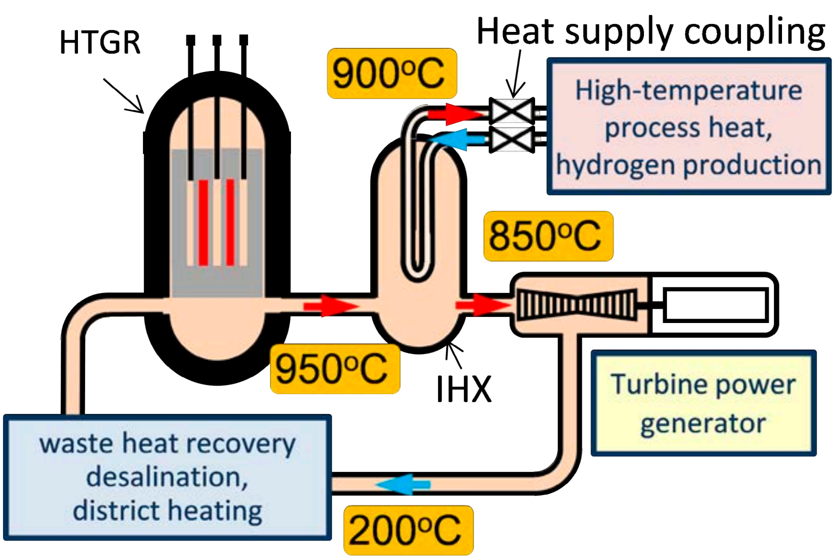


FIG. 14. Scheme of GTHTR300 designed to enable flexible cogeneration as an option.

cogeneration system connected to the HTTR, which will prepare for the design and licensing basis for construction of the lead commercial plant around 2030. JAEA completed the basic design of this cogeneration test plant in 2017.

Typical applications include electric power generation by gas turbine, thermochemical hydrogen production by iodine–sulphur process, desalination cogeneration based on MSF using waste heat only and direct reduction steelmaking, all of which are produced without CO_2 emissions. The cogeneration rate per 600 MW(th) reactor unit is given in terms of several products in Table 4.

The reactor delivers fully inherent safety due to three enabling design features:

— The ceramic coated particle fuel maintains its containment integrity under the design temperature limit of 1600°C.
— The reactor helium coolant is chemically inert and thus lacking any explosive gas generation or phase change.

TABLE 4. GTHTR300 DESIGN PARAMETERS

Reactor type		Prismatic HTGR
	Thermal capacity (MW(th))	600
	Design capacity factor (%)	90
	Design life (years)	60
Coolant/moderator		Helium/graphite
	System pressure (MPa)	7
	Reactivity control mechanism	control rod
	RPV diameter/height (m)	8/23
	Coolant temperature, core outlet (°C)	850–950
	Coolant temperature, core inlet (°C)	587–633
Integral design		No
	Power conversion process	Direct Brayton cycle
	High temperature process heat	Yes
	Low temperature process heat	Yes
	Cogeneration capability	Yes
	Design configured for process heat applications	Yes
Safety features		Inherent
	Fuel type/assembly array	UO_2 TRISO ceramic coated particle
	Fuel block length (m)	1
	Number of fuel columns in core	90
	Average fuel enrichment (%)	14
	Average fuel burnup (GWd/ton)	120
	Fuel cycle (year)	4
	Refuelling outage (d)	30
Cogeneration products (max. output per 600 MW(th) reactor)		
	– Electric power	300 MW(e)
	– Hydrogen production (thermochemical method)	120 t/d
	– Desalination (cogenerated with 300 MW(e) power)	55 000 m^3/d
	– Steelmaking	0.65 million t/year
Nuclear plant design status		Pre-licensing design completed

— The graphite-moderated reactor core is designed with characteristics of negative reactivity coefficient, low-power density and high thermal conductivity.

Because of these features, the reactor core can be cleared of decay heat by natural draft air cooling from outside the reactor vessel for a period of days or months without reliance on any equipment or operator action, even in such severe accident cases as loss of coolant or station blackout, where the fuel temperature will remain below the fuel design limit. The inherent safety allows siting proximate to customers (water consumers, hydrogen users and process heat users) to minimize the cost and loss of high temperature heat supply.

There are two main safety requirements for coupling the NPP with a conventionally operated cogenerating industrial plant (e.g. a hydrogen production plant). The first is protecting the NPP against such hazards as combustible gas leaks and toxic gas leaks from the industrial plants. In the case of hydrogen cogeneration, this is essentially defining a distance of about 100–200 m between the nuclear facilities (reactor building and operator room) and the hydrogen plant. The second is protecting the hydrogen plant as a conventional, non-nuclear facility against radioactive exposure within the limits allowed by country specific regulations. This is addressed by inserting the intermediate (heat supply coupling) loop shown in Fig. 13 between the reactor and the cogeneration plant, and continuously monitoring the radioactivity of the intermediate loop and the product (hydrogen, water, etc.) of the cogeneration plant.

A.2.4. Assessment of waste heat produced by the MARIA reactor by Poland [54]

Nuclear research reactors, in contrast to NPPs, are used mainly as the neutron source for research and do not produce electricity or heat. However, the reactor core must be continuously cooled to maintain operational safety limits. This process generates low temperature waste heat that is irreversibly dispersed into the atmosphere via the secondary cooling system. With proper district heating technologies, that heat may be partially retrieved and reused for heating and domestic hot water purposes.

MARIA research reactor is operated by the National Centre for Nuclear Research in Świerk, Otwock, near the capital of Poland (Warsaw). It is a high flux research reactor with a thermal neutron flux density of 4×10^{14} $cm^{-2}s^{-1}$, and 3×10^{13} $cm^{-2}s^{-1}$ in the case of fast neutrons. Both values correspond with the nominal thermal power of 30 MW(th). MARIA uses low enriched uranium (LEU) fuel elements with ^{235}U enrichment: 19.75% or 19.7% in the form of U_3Si_2 or UO_2 dispersed in aluminium (two types of fuel). MARIA is a hybrid pool-type/channel-type reactor. The fuel elements are settled inside pressurized channels which are located between beryllium blocks, in a rectangular lattice. The number of fuel channels depends on the reactor operating demands; the safety limits determine the maximum power of 1.8 MW(th) per fuel element. The reactor is equipped with two independent primary cooling loops: a fuel channel cooling system and a pool cooling system. Each of the fuel channels is cooled independently with a controlled flow rate and inlet and outlet coolant temperatures. The two cooling loops are connected to a secondary cooling system that removes heat through the wet cooling towers with a mechanical draught. The detailed parameters of the secondary cooling circuit are presented in Table 5.

The MARIA reactor facility consists of several buildings (see Fig. 15) that need a total heat power of 930 kW(th), which is currently supplied using two boilers of 270 kW(th) and 150 kW(th) for buildings A, C and D, and an air stove of 170 kW(th) for building B. Through the year, building A is heated to a temperature of thermal comfort while buildings B, C and D temperatures are set according to reactor staff needs. The MARIA facility has around 100 employees who usually work in building A; buildings B, C and D are visited when necessary. Additionally, several rooms in the facility are cooled by individual compression chillers with a total power of a dozen or so kilowatts. Monthly fuel needs, calculated from actual heavy oil fuel consumption in the boiler house from 2012 to 2016, are shown in Fig. 16.

The possibility of reusing waste heat from the MARIA research reactor, and its applications for district heating using heat pump technologies, is being considered and analysed by the Polish National Centre for Nuclear Research. District heat technologies suitable for coupling with low temperature heat sources have been assessed, and some of them have been proposed for the MARIA facility.

Among the different types of heat pumps, in terms of energy and economics as well as temperature parameters of lower and upper heat sources, the most suitable solution for MARIA seems to be an absorption heat pump. Around the lower heat source, this type of pump is able to use waste heat from 12°C up to even 45~50°C. The temperature of useful heat can be modelled anywhere between 80 and 90°C. Both parameters correspond with the

TABLE 5. SECONDARY COOLING CIRCUIT PARAMETERS

Parameter	Value	Unit
Water flow	2300 ~ 2500	m^3/h
Pressure	0.26 ~ 0.27	MPa
Heated water temperature	41.0	°C
Cooling tower:		
– Number	3	items
– Air flow	195	m^3/min
– Cooling tank voume	900	m^3
Main pumps:		
– Number	2 + 1*	items
– Possible coolant flow	1440	m^3/h
– Raise height	0.24	MPa
After shutdown pumps:		
– Number	3	items
– Possible coolant flow	240	m^3/h
– Raise height	0.13	MPa
Desalination rate	30	m^3/h
Brine pumps flow	16 ~ 26	m^3/h
Salted water tanks:		
– 2 tanks	2 ~ 54	m^3
– 1 tank	11	m^3
Water conductivity	7000	µS/cm
Acidity	3.5 ~ 8.0	pH

* Two are working and one is in reserve.

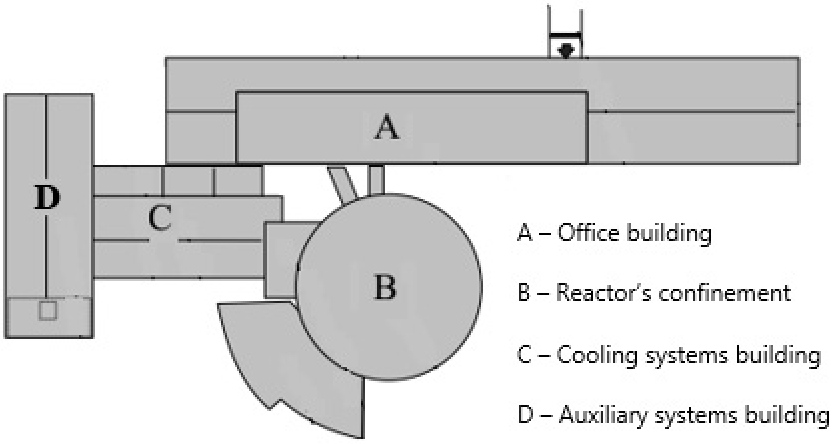


FIG. 15. MARIA reactor facility [54].

parameters of heat supply and demand in MARIA. Coefficient of performance (COP) of absorption heat pumps can reach up to 1.75 and remain unchanged regardless of the temperature of the lower heat source.

A crucial advantage of absorption pumps is their efficient and reliable operation with district heating and high-power refrigeration systems (e.g. conventional power plant cooling circuits) proven over many years of operation. Exemplary parameters of absorption heat pumps for domestic conditions are shown in Table 6. The specificity of absorption heat pump use is a great advantage in combination with the specificity of MARIA reactor operation — absorption heat pump systems need energy in the form of heat to operate properly. In the case of energy absent from the cooling circuit, which allows proper operation of the absorption heat pump, the heat source (e.g. water or steam boiler) used to power the pump can also act as the main heat source for district heating, while with a compression heat pump, such a solution is not possible owing to power differences between the compressor and heat demand.

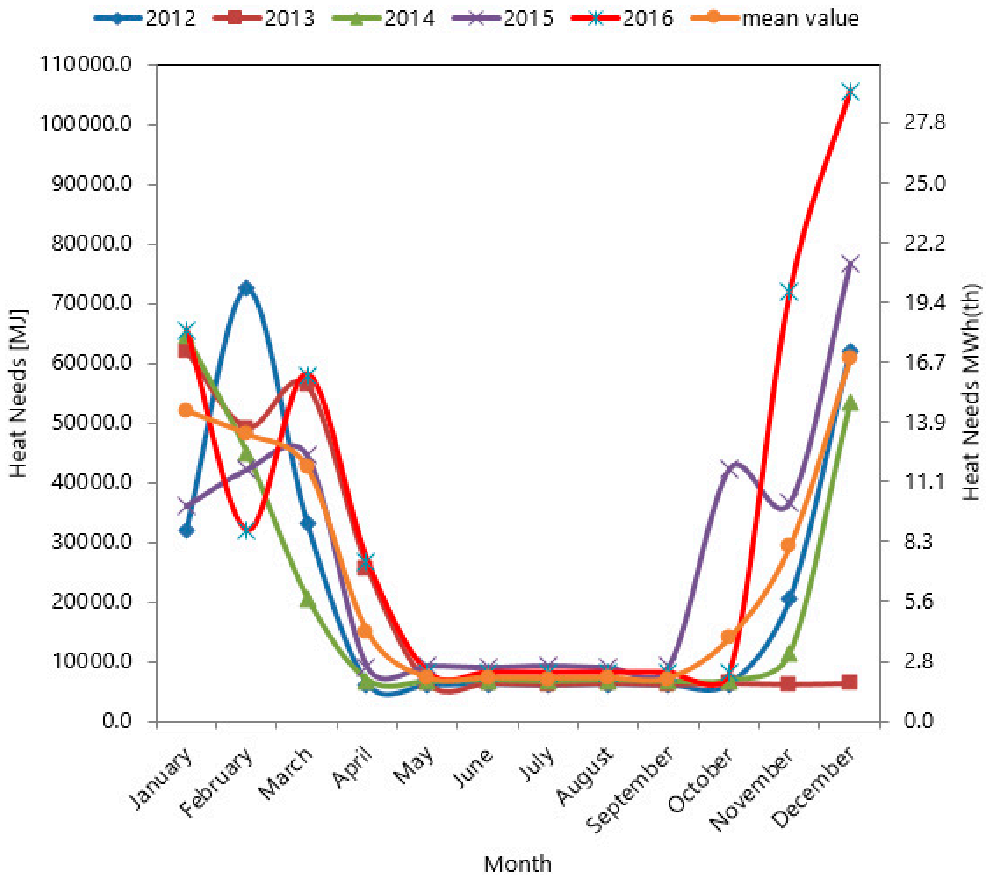


FIG. 16. Mean monthly heat needs in 2012–2016.

TABLE 6. EXEMPLARY PARAMETERS OF ABSORPTION HEAT PUMPS FOR DOMESTIC CONDITIONS

Power range	Up to 100 MW(th) per unit
COP (thermal efficiency)	1.7–1.75
Lower heat source temp. range (°C)	12–45
Upper heat source temp. range (°C)	70–90
Refrigerant	Water or ammonia
Can work in cooling mode	Yes (COP ~0.7)

In addition to the integration of an absorption heat pump with MARIA, and due to temperature changes during the year, a cogeneration system with a three bed adsorption chiller and desalination facility (operating together with the chiller) are proposed to fully utilize the heat during both cold and warm seasons of the year. Additionally, thermal energy storage is proposed as a supporting heat supply during short breaks between reactor operating cycles. For this system, the MARIA nuclear reactor secondary cooling circuit waste heat was introduced as a low source model. The scheme of this system is presented in Fig. 17.

Considering only the demand for space heating and domestic hot water, 2978 GJ of heat is needed through the system. When heat demand for cooling and desalination is added (899 GJ and 1722 GJ, respectively), total heat demand reaches 5599 GJ. More than 2200 GJ of that comes from waste heat recovered from MARIA's secondary cooling circuit.

The economic analysis of such a system revealed that potential investment in a similar system is justified with a payback period of around nine years. A coupled heating/cooling system will pay back in 22 years, which is still acceptable because the producer guarantees heat pump COP even in that long period. Additionally, payback of the investment might by lowered by using one of the government renewable energy funding programmes. It is also worth noting that partial replacement of the heat energy from gas with a heat pump would enable annual savings of 55 000 m^3 of fuel, which means that 188 metric tonnes of CO_2 emissions will be avoided annually.

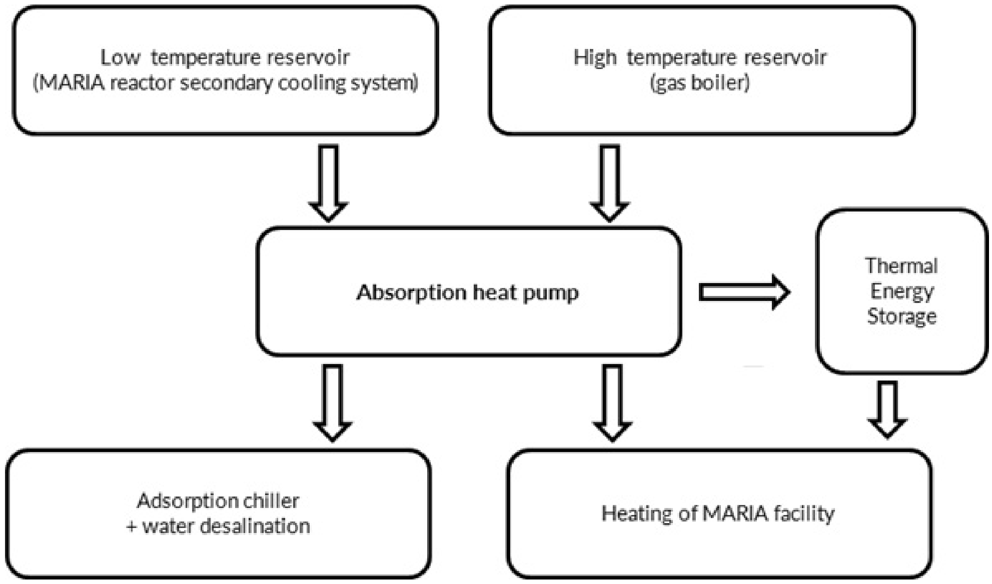


FIG. 17. MARIA facility heating/cooling system.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, General Conferences, Resolutions (related to seawater desalination or cogeneration): GC(43)/RES/15, GC(44)/RES/22, GC(45)/RES/12.A, GC(47)/RES/10.E, GC(49)/RES/12.E, GC(51)/RES/14.A.5, GC(52)/RES/12.A.4, GC(53)/RES/13.A.4, GC(55)/RES/12.A.4, and GC(57)/RES/12.A.4.

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Opportunities for Cogeneration with Nuclear Energy, IAEA Nuclear Energy Series No. NP-T-4.1, IAEA, Vienna (2017).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Aspects of Nuclear Plants Coupled with Seawater Desalination Units, IAEA-TECDOC-1235, IAEA, Vienna (2001).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Status of Nuclear Desalination in IAEA Member States, IAEA-TECDOC-1524, IAEA, Vienna (2007).

[5] WORLD ENERGY COUNCIL, Regulating District Heating and Cogeneration in Central and Eastern Europe, WEC, London (2004).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, Advances in Nuclear Power Process Heat Applications, IAEA-TECDOC-1682, IAEA, Vienna (2012).

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, Hydrogen Production Using Nuclear Energy, IAEA Nuclear Energy Series No. NP-T-4.2, IAEA, Vienna (2013).

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Examining the Technoeconomics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software, IAEA-TECDOC-1859, IAEA, Vienna (2018).

[9] INTERNATIONAL ATOMIC ENERGY AGENCY, Industrial Applications of Nuclear Energy, IAEA Nuclear Energy Series No. NP-T-4.3, IAEA, Vienna (2017).

[10] INTERNATIONAL ENERGY AGENCY, Tracking Industrial Energy Efficiency and CO_2 Emissions, OECD/IEA, Paris (2007).

[11] INTERNATIONAL ENERGY AGENCY, Energy Technology Perspectives 2010: Scenarios & Strategies to 2050, OECD/IEA, Paris (2010).

[12] UNITED NATIONS INDUSTRIAL DEVELOPMENT ORGANIZATION, Global Industrial Energy Efficiency Benchmarking: An Energy Policy Tool, UNIDO, Vienna (2010).

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, Market Potential for Non-electric Applications of Nuclear Energy, Technical Reports Series No. 410, IAEA, Vienna (2002).

[14] FORTUM POWER AND HEAT OY, Environmental Impact Assessment Report, Loviisa 3 project, Fortum, Espoo, Finland (2009).

[15] SAFA, H., Heat recovery from nuclear power plants, Int. J. of Electr. Power & Energ. Sys. **42** 1 (2012) 553–559.

[16] KIM, H.R., “SMART: The first mover in SMR market”, Proc. 18th Pacific Basin Nucl. Conf., Busan, Republic of Korea, 2012, Pacific Nuclear Council, La Grange Park, ILL (2012).

[17] GENERATION IV INTERNATIONAL FORUM project web site, http://www.gen-4.org

[18] GENERATION IV INTERNATIONAL FORUM, Technology Roadmap Update for Generation IV Nuclear Energy Systems, OECD/NEA, Paris (2014).

[19] BOGUSH, E., RAPHAEL: Developing major V/HTR technology, Nucl. Eng. Des. **251** (2012) 369–373.

[20] MICANET, Final Report, European Commission, Michelangelo Network Competitiveness and sustainability of nuclear energy in the European Union: A European vision for nuclear energy and main lines of recommended R&D support, Contract FIKI-CT2001–20180 (2002).

[21] ANGULO, C., et al., EUROPAIRS: The European project on coupling of High Temperature Reactors with industrial processes, Nucl. Eng. Des. **251** (2012) 30–37.

[22] ARCHER project web site (2015), http://www.archer-project.eu/

[23] FÜTTERER, M., CARLSSON, J., DE GROOT, S., DEFFRENNES, M., BREDIMAS, A., European energy policy and the potential impact of HTR and nuclear cogeneration, Nucl. Eng. Des. **271** (2014) 73–78.

[24] EUROPEAN COMMISSION, Special Report, The Sustainable Nuclear Energy Technology Platform: A Vision Report, EUR 22842, Brussels (2007).

[25] DINCER, I., ROSEN, M.A., Exergy: Energy, Environment and Sustainable Development, 2nd edn, Elsevier, Oxford (2012).

[26] HORLOCK, J.H., Some Practical CHP Schemes, Pergamon Press, Oxford (1987).

[27] COLLINS, S., World’s first nuclear to coal conversion a success, Power **136** 4 (1992) 73–80.

[28] MALMO ENERGY AB, District Heating in Malmo, Informational brochure (1988).

[29] JACKOWSKI, T., National Centre for Nuclear Research, Poland, personal communication (30 June 2015).

[30] MAJUMDAR, D., “Desalination and other non-electric applications of nuclear energy”, Nuclear Reaction Data and Nuclear Reactors: Physics, Design and Safety (Proc. IAEA Workshop, Trieste, 2002) 233–251.

[31] PIORO, I.L., Handbook of Generation IV Nuclear Reactors, Woodhead Publishing Series in Energy No. 103, Elsevier, Oxford (2016).

[32] INTERNATIONAL ATOMIC ENERGY AGENCY, Non-baseload Operation in Nuclear Power Plants: Load Following and Frequency Control Modes of Flexible Operation, IAEA Nuclear Energy Series No. NP-T-3.23, IAEA, Vienna (2018).
[33] United States Environmental Protection Agency, https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data
[34] NOMOTO, Y., et al., "Cost performance design for high temperature helium heat transport piping of gthtr300c and httr-gt/h2 plants", International Congress on Advances in Nuclear Power Plants (ICAPP 2017): A New Paradigm in Nuclear Power Safety (Proc. ICAPP 2017, April 24–28 Fukui and Kyoto, Japan), AtomicEnergy Society of Japan (2018).
[35] YAN, X., et al., GTHTR300 cost reduction through design upgrade and cogeneration, Nucl. Eng. Des. **306** (2016) 215–220.
[36] INTERNATIONAL ATOMIC ENERGY AGENCY, Advanced Applications of Water Cooled Nuclear Power Plants, IAEA-TECDOC-1584, IAEA, Vienna (2008).
[37] MURALEV, E.D., et al., "Experience gained in the operation and maintenance of the nuclear desalination plant in Aktau, Kazakhstan", (Proc. of IAEA int. symp. on desalination of seawater with nuclear energy, Taejon, Republic of Korea, May 26–30, 1997), IAEA, Vienna (1997).
[38] LOCATELLI, G., BOARIN, S., PELLEGRINO, F., RICOTTI, M.E., Load following with small modular reactors (SMR): A real options analysis, Energy **80** 1 (2015) 41–54.
[39] INTERNATIONAL ATOMIC ENERGY AGENCY, Introduction of Nuclear Desalination: A Guidebook, Technical Reports Series No. 400, IAEA, Vienna (2000).
[40] YAN, X., HINO, R., Nuclear Hydrogen Production Handbook, CRC Press, Boca Raton, FL (2011).
[41] VERFONDERN, K., YAN, X., NISHIHARA, T., ALLELEIN, H.-J., Safety concept of nuclear cogeneration of hydrogen and electricity, Int. J. Hydrogen Energy **42** 11 (2017) 7551–7559.
[42] CZIK, B.J., KUPTIZ, J., Nuclear power applications: Supplying heat for homes and industries, IAEA Bulletin **39** 2 (1997) 21–25.
[43] HITTNER, D., BOGUSCH, E., FÜTTERER, M., DE GROOT, S., RUER, J., High and very high temperature reactor research for multipurpose energy applications, Nucl. Eng. Des. **241** 9 (2011) 3490–3504.
[44] FUJIKAWA, S., et al., Achievement of reactor-outlet coolant temperature of 950°C in HTTR, J. Nucl. Sci. Technol. **41** 12 (2004) 1245–1254.
[45] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety of Nuclear Power Plants: Commissioning and Operation, IAEA Safety Standards Series No. SSR-2/2 (Rev. 1), IAEA, Vienna (2016).
[46] IAEA, DEEP 5 User Manual (2013),
https://www.iaea.org/sites/default/files/18/08/deep5-manual.pdf
[47] JONES, S., SAGD delivers healthy return on investment, Ziff Energy Group (2009).
[48] NATERER, G.F., DINCER, I., ZAMFIRESCU, C., Hydrogen Production from Nuclear Energy, Springer-Verlag London (2013).
[49] SCHAD, M., DIDAS, U., EBELING, F., KREUZKAMP, G., RENNER, H., Project study on utilization of process heat from the HTGR in the chemical and related industries, Report LURGI GmbH, Frankfurt (1988).
[50] SCHAD, M., Utilization of process heat from the HTRM in the chemical and related industries, Nucl. Eng. Des. **136** (1–2) (1992) 229–235.
[51] IDAHO NATIONAL LABORATORY, HTGR Industrial Application Functional and Operational Requirements, Report INL/EXT-10-19706, INL, Idaho Falls, ID (2010).
[52] COUPEY, J.P., "Recovery of unconventional oil resources", Presentation at the Post-FISA Conference on HTRs for Combined Heat/Electricity and Hydrogen Production, Luxembourg (2006).
[53] YAN, X., KASAHARA, S., TACHIBANA, Y., KUNITOMI, K., Study of a nuclear energy supplied steelmaking system for near-term application, Energy **39** 1 (2012) 154–165.
[54] LIPKA, M., MIGDAL, M., TARCHALSKI, M., The Idea of Using Heat from the MARIA Reactor as a Heat Source for Heat Pump, Country Report to the IAEA Coordinated Research Project on the Application of Advanced Low Temperature Desalination Systems to Support Nuclear Power Plants and Non-Electric Applications, CRP-I35005, IAEA, Vienna (2017).

BIBLIOGRAPHY

Relevant IAEA Publications (including those cited in References)

Nuclear Heat Applications: Design Aspects and Operating Experience, IAEA-TECDOC-1056 (1998).

Hydrogen as an Energy Carrier and Its Production by Nuclear Power, IAEA-TECDOC-1085 (1999).

Introduction of Nuclear Desalination: A Guidebook, Technical Reports Series No. 400 (2000).

Status of Non-electric Nuclear Heat Applications: Technology and Safety, IAEA-TECDOC-1184 (2000).

Safety Aspects of Nuclear Plants Coupled with Seawater Desalination Units, IAEA-TECDOC-1235 (2001).

Design and Evaluation of Heat Utilization Systems for the High Temperature Engineering Test Reactor, IAEA-TECDOC-1236 (2001).

Design Concepts of Nuclear Desalination Plants, IAEA-TECDOC-1326 (2002).

Market Potential for Non-electric Applications of Nuclear Energy, Technical Reports Series No. 410 (2002).

Optimization of the Coupling of Nuclear Reactors and Desalination Systems, IAEA-TECDOC-1444 (2005).

Advanced Applications of Water Cooled Nuclear Power Plants, IAEA-TECDOC-1584 (2007).

Economics of Nuclear Desalination: New Developments and Site Specific Studies, IAEA-TECDOC-1561 (2007).

Status of Nuclear Desalination in IAEA Member States, IAEA-TECDOC-1524 (2007).

Environmental Impact Assessment of Nuclear Desalination, IAEA-TECDOC-1642 (2010).

Advances in Nuclear Power Process Heat Applications, IAEA-TECDOC-1682 (2012).

Hydrogen Production Using Nuclear Energy, IAEA Nuclear Energy Series No. NP-T-4.2 (2013).

New Technologies for Seawater Desalination Using Nuclear Energy, IAEA-TECDOC-1753 (2015).

IAEA Safety Standards Series No. SSR-2/2 (Rev. 1), Safety of Nuclear Power Plants: Commissioning and Operation (2016).

Opportunities for Cogeneration with Nuclear Energy, IAEA Nuclear Energy Series No. NP-T-4.1 (2017).

Industrial Applications of Nuclear Energy, IAEA Nuclear Energy Series No. NP-T-4.3 (2017).

Non-Baseload Operations in Nuclear Power Plants: Load Following and Frequency Control Modes of Flexible Operations, IAEA Nuclear Energy Series No. NP-T-3.23 (2017).

ABBREVIATIONS

ACR	advanced CANDU (deuterium–uranium) reactor
BWR	boiling water reactor
CHP	combined heat and power
CRP	coordinated research project
DEEP	Desalination Economic Evaluation Programme
EU	European Union
Gen-IV	Generation-IV
GFR	gas cooled fast reactor
GHG	greenhouse gas
GTHTR300	gas turbine high temperature reactor of 300 MW(e)
HEEP	Hydrogen Economic Evaluation Programme
HTGR	high temperature gas cooled reactor
HTR	high temperature reactor
HTR-PM	high temperature reactor — power module
HTSE	high temperature steam electrolysis
HTTR	high temperature engineering test reactor
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IHX	intermediate heat exchanger
INL	Idaho National Laboratory, USA
ISBL	inside battery limits
JAEA	Japan Atomic Energy Agency
KAERI	Korea Atomic Energy Research Institute
LFR	lead-cooled fast reactor
LMTD	logarithmic mean temperature difference
LWR	light water reactor
MAEC	Mangyshlak Atomic Energy Complex, Kazakhstan
MAPS	Madras Atomic Power Station, India
MED	multi-effect desalination
MHT	main heat transport
MSF	multistage flash (a water distillation process, usually for seawater desalination)
NC2I	Nuclear Cogeneration Industrial Initiative
NEA	Nuclear Energy Agency
NGNP	next generation nuclear plant
NPP	nuclear power plant
OECD	Organisation for Economic Co-operation and Development
PWR	pressurized water reactor
SFR	sodium cooled fast reactor
SMART	system-integrated modular advanced reactor
SMR	small and medium-sized reactor
SNETP	European Sustainable Nuclear Energy Technology Platform
SNG	synthetic natural gas
VHTR	very high temperature reactor

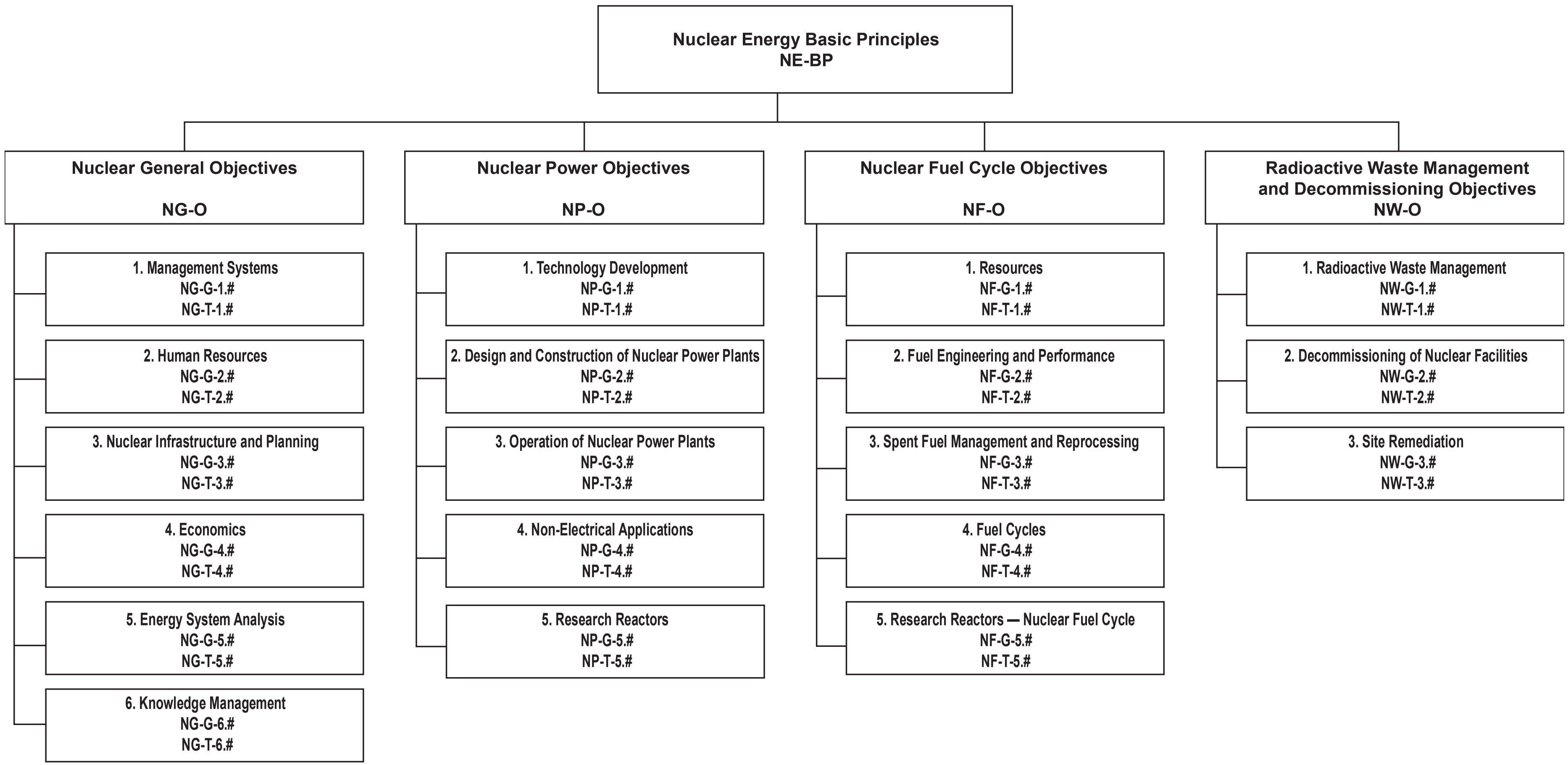
CONTRIBUTORS TO DRAFTING AND REVIEW

Dincer, I.	University of Ontario Institute of Technology, Canada
El-Emam, R.	International Atomic Energy Agency
Jackowski, T.	National Centre for Nuclear Research, Poland
Khamis, I.	International Atomic Energy Agency
Paillère, H.	OECD Nuclear Energy Agency, France
Safa, H.	Commissariat à l’Énérgie Atomique, France
Verfondern, K.	Research Centre Jülich, Germany
Yan, Xing L.	Japan Atomic Energy Agency, Japan

Consultants Meetings

Vienna, Austria: 3–5 September 2014
Istanbul, Turkey: 18–19 June 2015

Structure of the IAEA Nuclear Energy Series



Key

BP:	Basic Principles
O:	Objectives
G:	Guides
T:	Technical Reports
Nos 1-6:	Topic designations
#:	Guide or Report number (1, 2, 3, 4, etc.)

Examples

NG-G-3.1:	Nuclear General (**NG**), Guide, Nuclear Infrastructure and Planning (topic **3**), **#1**
NP-T-5.4:	Nuclear Power (**NP**), Report (**T**), Research Reactors (topic **5**), **#4**
NF-T-3.6:	Nuclear Fuel (**NF**), Report (**T**), Spent Fuel Management and Reprocessing (topic **3**), **#6**
NW-G-1.1:	Radioactive Waste Management and Decommissioning (**NW**), Guide, Radioactive Waste (topic **1**), **#1**

IAEA
International Atomic Energy Agency

No. 26

ORDERING LOCALLY

IAEA priced publications may be purchased from the sources listed below or from major local booksellers.

Orders for unpriced publications should be made directly to the IAEA. The contact details are given at the end of this list.

NORTH AMERICA

Bernan / Rowman & Littlefield

15250 NBN Way, Blue Ridge Summit, PA 17214, USA
Telephone: +1 800 462 6420 • Fax: +1 800 338 4550
Email: orders@rowman.com • Web site: www.rowman.com/bernan

Renouf Publishing Co. Ltd

22-1010 Polytek Street, Ottawa, ON K1J 9J1, CANADA
Telephone: +1 613 745 2665 • Fax: +1 613 745 7660
Email: orders@renoufbooks.com • Web site: www.renoufbooks.com

REST OF WORLD

Please contact your preferred local supplier, or our lead distributor:

Eurospan Group

Gray’s Inn House
127 Clerkenwell Road
London EC1R 5DB
United Kingdom

Trade orders and enquiries:

Telephone: +44 (0)176 760 4972 • Fax: +44 (0)176 760 1640
Email: eurospan@turpin-distribution.com

Individual orders:

www.eurospanbookstore.com/iaea

For further information:

Telephone: +44 (0)207 240 0856 • Fax: +44 (0)207 379 0609
Email: info@eurospangroup.com • Web site: www.eurospangroup.com

Orders for both priced and unpriced publications may be addressed directly to:

Marketing and Sales Unit
International Atomic Energy Agency
Vienna International Centre, PO Box 100, 1400 Vienna, Austria
Telephone: +43 1 2600 22529 or 22530 • Fax: +43 1 26007 22529
Email: sales.publications@iaea.org • Web site: www.iaea.org/publications

19-00571

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA
ISBN 978–92–0–104119–7
ISSN 1995–7807