IAEA Activities on Nuclear Cogeneration for Non-electric Applications of Nuclear Energy

Ibrahim Khamis
Senior Nuclear Engineer
Department of Nuclear Energy
International Atomic Energy Agency
1.1.6 Support for Non-electrical Applications of Nuclear Power

I. Khamis

- Nuclear seawater desalination
- Nuclear hydrogen production
- Nuclear energy heat for industry

Support to Near-Term Deployment

Website: https://www.iaea.org/topics/non-electric-applications
Nuclear Reactors & Applications

- **Industry** (using isotopes & Radiations)
- **Hydrology** (various nuclear techniques & tracers)
- **Mining** (isotopic dating)
- **Agriculture & Food** (radiations & Tracers)
- **Medicine** (diagnosis through radioisotopes, radiography, radio-pharmaceuticals, gammagraphy, sterilization…etc)
- **Art** (dating, non-destructive examination)
- **Environment** (analysis using nuclear techniques)
- **Space exploration** (nuclear batteries, space navigation)
- Etc.
Routes of Nuclear Cogeneration

- Electric Power
  - Steam
  - Hydrogen
  - Water
  - Other products

- Process Heat
  - Heat loss

Nuclear Power Plant

Processing Plants
Nuclear Power & Non-electric Applications

Proven technology: with 79 operative reactors and 750 reactor-years experience
Optimizing the use of nuclear reactors: Cogeneration/Multigeneration

Reactor outlet coolant 850-950°C

50,000 m³/day Seawater desalination

Industrial heat applications

Material processing (Co-60)

Hydrogen cogeneration
Market Opportunities for HTRs in North America (future)

For petroleum industry, synthetic fuel, ammonia and hydrogen production

Total: 810 Reactors
600 MWth Each Module

75 GWt
Petrochemical, Refinery, Fertilizer/Ammonia plants and others

60 GWt
Oil Sands/Oil Shale
Steam, electricity, hydrogen & water treatment

36 GWt
Hydrogen Market

249 GWt
Synthetic Fuels & Feedstock
Steam, electricity, high temperature fluids, hydrogen

110 GWt
Electricity

125 Reactor Modules*
30 Reactor Modules
60 Reactor modules
415 Reactor Modules
180 Reactor Modules

Assuming conservative market penetration.

*All module #s assume only 25% of market

Source: Lewis Lommers, AREVA US
Market Opportunities for HTRs in North America (future)

Japan Markets for HTGR (for CO2 reduction)

CO2 emission
11.9 hundred million tone (2010)

30% Decrease with HTGR

<table>
<thead>
<tr>
<th></th>
<th>Automobile</th>
<th>Steal making</th>
<th>Civil</th>
<th>Others</th>
<th>Power generation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>17%</td>
<td>13%</td>
<td>3%</td>
<td>23%</td>
<td>26%</td>
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<td></td>
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<td>Petrochemistry 8%</td>
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30% decrease

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<thead>
<tr>
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</thead>
<tbody>
<tr>
<td></td>
<td>1%</td>
<td>4%</td>
<td>3%</td>
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</table>

Fuel-cell powered automobile
Hi. temp. heat
Steam
H2 (Fuel)
16% decrease
HTGR : 30 plants

Steal making with H2 reduction
Hi. temp. heat, H2 (reductant)
9% decrease
HTGR : 20 plants

Petrochemical plant
Hi. temp. heat, Steam
5% decrease
HTGR : 15 plants

1 plant : 4x 600 MWt HTGRs

Japanese Markets : 180 HTGRs (600MWt/reactor)

Source: X. Yan, JAEA
Cogeneration: for hydrogen production
Use of off-peak power (from currently operation NPPs)

<table>
<thead>
<tr>
<th>Method</th>
<th>$/kg</th>
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<tbody>
<tr>
<td>Conventional Electrolysis ($0.05/kW hr &amp;&gt; 1000 kg/day)</td>
<td>4.15</td>
</tr>
<tr>
<td>Dedicated nuclear HT Steam Electrolysis HTSE plant</td>
<td>3.23</td>
</tr>
<tr>
<td>Off-peak grid electricity ($0.05/kW hr), HTSE</td>
<td>2.5</td>
</tr>
<tr>
<td>Large-scale Steam Methane Reforming</td>
<td>2.5</td>
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</table>

First-of-a-kind Project, announced in September 2019:
- DOE selected INL & (Akron & Xcel Energy & APS) utilities to partner on Integrated Energy Systems to Pair Carbon-Free Nuclear Energy in Hybrid Applications to Produce Hydrogen.
- “The two-year project led by FirstEnergy Solutions will initially demonstrate and deploy a 1- to 3-MWe low-temperature electrolysis unit to produce commercial quantities of hydrogen. The first site, planned for 2020, is FirstEnergy Solution’s Davis-Besse Nuclear Power Station near Toledo, Ohio”. INL News Release
Current Status:

Total Number of Operating Reactors today is 449 reactors with total net electrical capacity of 392,116 MWe.

Imagine: the waste heat from these reactors: ~ 1 000 000 MW(th)!!

Assume: ~ 25% recovery of waste heat i.e. re-use of 250 000 MW(th)

This is equivalent to daily reduction of 1 - 2 Million tonnes of CO₂ emissions.

Based on the type of fossil fuel would be used to cover this thermal demand.
Values of Nuclear Cogeneration

- Better Efficiency
  - Up to 80% energy efficiency
  - Open new sectors for nuclear power

- Better Environmental impacts
  - Reduce the waste heat dumped to environment,
    - Additional heat sink

- Better Use of energy
  - Optimize energy efficiency
  - Match industrial application needs at the right temperature

- Better Flexibility
  - In future energy planning
  - In operating nuclear power plants & Grid
  - In diversifying energy outputs
Challenges for Cogeneration (1)

- Public acceptance
- Disparity between characteristics of nuclear reactors & heat markets
- National position & Regulations (political will, Government commitment..etc) on cogeneration
- Availability of qualified human resources
- Selecting the most appropriate NPP (based on demand and grid capacity)
Challenges for Cogeneration (2)

- **Industry trends:**
  - Require small amount of heat 1-300 MWth, majority < 10 MWth,
  - Buy energy but not risk build it
  - Demonstrate newly (HTR) NPPs tailored for industry

- **Economics**
  - Licenseability of tailored cogeneration NPPs with ensured safety

- **Siting**

- **Business model**

- **Etc..**

HTR=High Temperature Reactor
Typical Areas of activities

- *Info Exchange & Training Forums*
- *Coordinated Research Projects*
- *Tools development, Maintenance & upgrade*
- *Publications: Technical Reports/papers*
<table>
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<tr>
<th>Date</th>
<th>Event Description</th>
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<tr>
<td>February 11-14</td>
<td>Regional Workshop on Non-Electric Nuclear Applications: Options, Technology Readiness and Available IAEA Toolkits</td>
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<td>(Prague, Czech Rep.)</td>
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<td>April 08 - 10</td>
<td>Technical Meeting on the Role of Nuclear Hydrogen Production in a Low Carbon Economy</td>
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<td>(Vienna)</td>
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<td>July 22 – 24</td>
<td>Technical Meeting on Specific Considerations for the Deployment of Nuclear Cogeneration Projects</td>
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<tr>
<td>(Vienna)</td>
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<td>September 02 – 04</td>
<td>Technical Meeting on Assessing the Deployment of Small and Medium Sized or Modular Reactors and High Temperature Reactors for Cogeneration Applications</td>
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<tr>
<td>(Vienna)</td>
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<tr>
<td>October 12 – 16</td>
<td>ICTP-IAEA Workshop on Physics and Technology of Innovative High Temperature Nuclear Energy Systems</td>
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<td>(Trieste, Italy)</td>
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<td>18 September 2019</td>
<td>General Conference Side Event on: Reactor Technology Innovation to Support Integration of Renewable Energy Systems and Nuclear Installations</td>
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<tr>
<td>Vienna</td>
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<tr>
<td>Technical Meeting on Assessing Technologies that Enable Nuclear Power to Produce Hydrogen</td>
<td>22-24 June</td>
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<td>Technical Meeting on Potential Schemes for Licensing Nuclear Cogeneration Plants</td>
<td>1-3 September</td>
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<tr>
<td>Second Research Coordination Meeting on Assessing Technical and Economic Aspects of Nuclear Hydrogen Production for Near-Term Deployment</td>
<td>1-3 April</td>
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**Objective:**

- Investigate the prospects of using waste heat generated in High Temperature Reactors.
- Evaluate the potential of all advanced reactor designs for process heat applications.

**Results:** published in 2012 as an IAEA-TECDOC-1682
Title: Examining the Techno-Economics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software

Duration: 2011-2015

Objective:
- Examine aspects of nuclear hydrogen production
- Validate HEEP through benchmarking exercises
- Promote international collaboration among IAEA Member States.

Meetings:
17-18 October 2013
17-19 December 2013
16-18 Dec 2014
15-17 Dec 2015  Final

Participants:
Algeria, Argentina, Canada, China, Germany, India, Indonesia, USA/Japan, Rep. of Korea, USA/Rep. of Korea
Title:

Objectives:
- Assess gained experience from R&D on nuclear hydrogen production in MSs.
- Assess potential near-term deployment of nuclear hydrogen production.

IAEA Coordinated Research Projects (CRP)

1st RCM Meeting: 03-05 December 2018
IAEA Tool on Nuclear Hydrogen Production

HEEP  Hydrogen Economic Evaluation Programme

System Facilities
- Nuclear power plant
- Hydrogen Generation
- Hydrogen Storage
- Transportation facility

Input Parameters Categories
- Technical parameters
- Chronological data
- Cost elements

Compressed gas
Liquefaction
Metal hydrides
Evaluates the economics of the most promising processes for hydrogen production

HEEP

Tools

International Atomic Energy Agency

Hydrogen Economic Evaluation Programme

For any query regarding this software please contact:
Dr. J. Koyama, Nuclear Power Technology Development Section, Division of Nuclear Power, IAEA
Email: J.Koyama@iaea.org

Developed by International Atomic Energy Agency by WAEC
HEEP Features

- Hydrogen generation
- Hydrogen storage
- Hydrogen transportation

Facilities to be considered for evaluation:
- Nuclear Power Plant
HEEP Results

Contribution of each plant & facility

Directly give contribution of each plant & facilities in total H2 cost.

Components of levelised electricity cost

Provides levelised cost of unit energy in the form of heat and/or electricity as an output.

Models the location of H2 generation plant with respect to the nuclear power plant, and
Facilitates the study of effect of source of electricity/heat energy on the cost of hydrogen generation.
**HydCalc** is a single window calculator to make rough estimate of the hydrogen production cost utilizing different technologies.

**HydCalc** provides cost value of hydrogen based on average estimated CO₂ release.

**HydCalc** also considers the effect of CO₂ tax on the production cost.

**HydCalc** uses current price estimate from publications and articles in open literature.
Nuclear Hydrogen Production Toolkit

- Up-to-date information
- Link to IAEA tools
- Highlights of IAEA Publications
- News on IAEA Activities
- Newsletter on nuclear hydrogen production
DEEP can be used for performance and cost evaluation of various power and seawater desalination cogeneration configurations.

The latest version DEEP 5.11 was released in late 2017.
IAEA Tool on Nuclear Desalination

DEEP Desalination Economic Evaluation Programme

- Modern User Interface
- Bankable financial analysis
- Powerful sensitivity analysis
- Detailed Reports
- Versatile scenario Manager
DE-TOP 2.0 models the steam power cycle (Rankine cycle) of different water cooled reactors or fossil plants, and coupling with other non-electrical applications.

Simulation operation with of non-electric applications as: Desalination, District Heating or Process Heat.
Potential use

Energy evaluation and selection of optimal extraction options.

Cost-benefit analysis of different extraction options
  - Max Water capacity
  - Power lost to heat ratio
  - Flexibility
  - Investments Costs
  - O&M Costs

Support technical evaluation
  - Mass flows extracted, sizing components
  - Power/water ratio, flexibility
IAEA TOOLKIT

Nuclear Desalination

- Up-to-date information
- Link to IAEA tools
- Highlights of IAEA Publications
- News on IAEA Activities
- Summaries of the TWG-ND
- Newsletter on nuclear desalination
WAMP helps in the selection of cooling systems by evaluating three different criteria: Water resources, environmental, economical.

WAMP estimates water needs in NPPs especially for water cooled nuclear power plants.

WAMP estimates both the needs for cooling water and other essential systems.
The Tool to enhance Severe Accident Management

The SAMG-D describes the elements necessary to develop a full package of Severe Accident Management Guidelines (SAMG), which serve to achieve the main goals of severe accident management at a Nuclear Power Plant (NPP). Severe accident management is a subset of accident management as follows:

Accident management is the taking of a set of actions during the evolution of a beyond design basis accident:
(a) To prevent the escalation of the event into a severe accident;
(b) To mitigate the consequences of a severe accident;
(c) To achieve a long term safe stable state.

The second aspect of accident management (to mitigate the consequences of a severe accident) is also termed severe accident management. It includes measures to:
(1) terminate the progress of core damage once it has started,
(2) maintain the integrity of the containment as long as possible and
(3) minimize releases of radioactive material.

See Accident Management, Anticipated Operational Occurrence, Beyond Design Basis Accident, Design Basis Accident, Operational states, Severe Accident, and Severe Accident Management.

Guidelines that have been developed for the operating staff for managing severe accidents are called Severe Accident Management Guidelines (SAMG).

The SAMG-D is also an education and training tool to help plant staff understand the context of severe accidents and the associated procedures and guidelines. The SAMG-D describes the elements that a full package of SAMG should encompass to achieve the goals of severe accident management. It is set up to help utilities to select proper SAMG products from the various vendors and implement those at their plants. The SAMG-D is designed for use with LWRs and PWRs. The SAMG-D is not designed to independently construct a full SAMG package.

The IAEA Nuclear Power Technology Development Section (NPTDS) developed the SAMG-D also as a contribution to the IAEA Action Plan on Nuclear Safety.

Please, before starting the use of SAMG-D have a look at the DISCLAIMER and the information provided in About.
The objective of this document is to establish a common understanding of users’ requirements and the terms under which vendors can supply suitable reactor designs and desalination technologies; address the common challenges and concerns related to the design and operation of nuclear cogeneration plants, with focus on nuclear desalination for near-term deployment; and identify a roadmap for implementation of such projects.
Publications

International Journal of Hydrogen Energy
Volume 42, Issue 6, 9 February 2017, Pages 3566-3571

International collaboration in the IAEA nuclear hydrogen production program for benchmarking of HEEP
R.S. El-Emam, I. Khamis

Energy Conversion and Management

Prospects of Nuclear Energy for Hydrogen Production
I. Khamis

International Journal of Hydrogen Energy
Available online 1 May 2018
In Press, Corrected Proof

Advances in nuclear hydrogen production: Results from an IAEA international collaborative research project
R.S. El-Emam, I. Khamis

Benchamarking of Economic Models for Nuclear Hydrogen Production
Ramakant Sadhankar, Lauralee Sopczak, Donald Ryland (CNL), Rami El-Emam, Ibrahim Khamis (IAEA)

International Journal of Hydrogen Energy
Available at www.sciencedirect.com
journal homepage: www.elsevier.com/locate/he

An overview of the IAEA HEEP software and international programmes on hydrogen production using nuclear energy
I. Khamis
International Atomic Energy Agency (IAEA), Wagramer Strasse 5, P.O. Box 100, A-1400 Vienna, Austria

EEP: A new tool for the economic evaluation of the hydrogen economy
I. Khamis, U.D. Malhe

Sponsored International Conference
2018 Pacific Basin Nuclear Conference
Advancing and Sustaining Nuclear Energy
Conclusions

Nuclear energy (using Large or SMRs) can:

- Penetrate major energy sectors now served by fossil fuels like:
  - seawater desalination
  - district heating
  - Hydrogen production
  - heat for industrial processes

Nuclear cogeneration is feasible and economically viable:
- Provide near-term, greenhouse gas free, energy for all energy intensive processes
Thank you!