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International Atomic Energy Agency

Assessing Technical and Economic Aspects of Nuclear Hydrogen Production for Near-term Deployment

Insights from the IAEA CRP I35006

Acknowledgment

- Algeria
  Rafika Boudries
- Argentina
  Ana Bohe
- China
  Jian-Qiang Wang
- Greece
  Melpomeni Varvagianni
  Nicos Catsaros
- India
  Indravadan Dulera
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  Shriniwas Rao
  Prashant Kelkar
  Abhishek Basak
  Ahmed Nafees
- Japan
  Xing Yan
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Overview of the CRP

IAEA TECDOC SERIES

IAEA-TECDOC-1859

Examining the Technoeconomics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software

IAEA

- **Objective of the CRP**:
  - ✓to assess gained experience from R&D on nuclear hydrogen production in MSs and
  - ✓to assess potential near-term deployment of nuclear hydrogen production
- **Participation:**
  - ✓10 participating MSs
  - ✓5 research contracts (Algeria, Argentina, Greece, Russian Federation, Turkey)
  - ✓5 agreements (China, India, Japan, Saudi Arabia, USA)
- **Research Coordination Meetings**
  - ✓1st: 3-5 Dec 2018 (Vienna)
  - ✓2nd: 19-21 Oct 2020 (virtual)
  - ✓3rd: 15-17 Nov 2021 (virtual)

Outcomes of the past CRP:
[Examining the Technoeconomics of Nuclear Hydrogen Production and Benchmark Analysis of the IAEA HEEP Software | IAEA]

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Country	*Organization*	Contract/Agreement
ALGERIA	Centre de Développement des Energies Renouvelables (CDER)	C 22556: Assessing Technical and Economic Aspects of Nuclear Hydrogen Production for Near-term Deployment
ARGENTINA	Comisión Nacional de Energía Atómica (CNEA) de Argentina	C 22528: Upscaling of Experimental Facilities for Nuclear Hydrogen Production Through Gasification of Argentine Solid Fuels
CHINA	Shanghai Institute of Applied Physics, Chinese Academy of Sciences	A 22562: Evaluation of MW Grade TMSR-Nuclear Hydrogen Production Using Solid Oxide Electrolyser Technology
GREECE	National Center of Scientific Research "Demokritos"	C 23530: Identifying Adequate SMR Technology for Innovative H2 Production, Compression and Storage
INDIA	BARC	A 22635: Technical and Safety Studies for Integration of High Temperature Reactors with Iodine-Sulphur Process Based Hydrogen Production Plant and Upgradation of the Software HEEP for Economic Assessment of Hydrogen Production
JAPAN	JAEA	A 22549: Evaluation of Nuclear Hydrogen Production Technologies and Prospectus for Deployment
RUSSIAN FEDERATION	National Research Center Kurchatov Institute	C 22560: Assessing Potential of High Temperature Reactor Facilities of Russian Design for Hydrogen Production
SAUDI ARABIA	Umm Al-Qura University	A 22516 : Thermo-Economic Analysis and Optimization of a Large-Scale Nuclear Hydrogen Production Utilizing High Temperature
TURKEY	Karabuk University	C 22554: Economics and Integration of Hybrid Thermochemical Cycles to Near Future Nuclear Reactors for Hydrogen Production
USA	Purdue University	A 22480: Safety and Scaling Analysis of Nuclear Hydrogen Production Schemes with Current and Near Future Nuclear Plants

Publications

Argentina/ CNEA	2020	Canavesio, C., Nassini, D., Nassini, H. E., Bohe, A. E., **Study on an original cobalt-chlorine thermochemical cycle for nuclear hydrogen production**, International Journal of Hydrogen Energy, 45 (49), 26090-26103 (2020). https://www.sciencedirect.com/science/article/pii/S0360319919331519
China/ SINAP	2019	Guan, C., et al., **Molten salt synthesis of Nb-doped (La, Sr) FeO3 as the oxygen electrode for reversible solid oxide cells**, Materials Letters, 245, 114-117 (2019). https://doi.org/10.1016/j.matlet.2019.02.116
	2019	Wang, J., Dai, Z., Xu, H., **Research Status and Prospect of Comprehensive Utilization of Nuclear Energy**, Bulletin of Chinese Academy of Sciences, 34, 4, 460-468 (2019).
Turkey/ Karabuk University	2019	El-Emam, R. S., Ozcan, H., **Comprehensive review on the techno-economics of sustainable large-scale clean hydrogen production**, Journal of Cleaner Production 220, 593-609 (2019). https://www.sciencedirect.com/science/article/abs/pii/S0959652619303361
	2020	Funda, A., Ozcan, H., **Turkey's industrial waste heat recovery potential with power and hydrogen conversion technologies: A techno-economic analysis**, International Journal of Hydrogen Energy (2020). https://www.sciencedirect.com/science/article/pii/S0360319920342610
	2020	El-Emam, R., Ozcan, H., Zamfirescu, C., **Updates on promising thermochemical cycles for clean hydrogen production using nuclear energy**, Journal of Cleaner Production 262 (2020)
Saudi Arabia/ Umm Al-Qura University	2018	AlZahrani, A., Dincer, I., **Modeling and performance optimization of a solid oxide electrolysis system for hydrogen production**, Applied Energy, 225, 471-485 (2018). Modeling and performance optimization of a solid oxide electrolysis system for hydrogen production - ScienceDirect
	2021	AlZahrani, A., Dincer, I., **Exergoeconomic analysis of hydrogen production using a standalone high-temperature electrolyzer**, International Journal of Hydrogen Energy, 46, 27, 13899-13907 (2021). Exergoeconomic analysis of hydrogen production using a standalone high-temperature electrolyzer - ScienceDirect

Algeria: Techno-economic study of hydrogen production using a hybrid nuclear-PV solar system

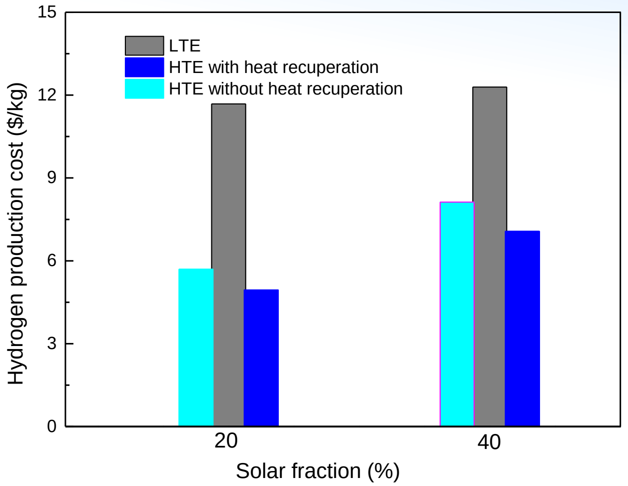
CSI: Rafika BOUDRIES

Centre de Développement des Energies Renouvelables (CDER)

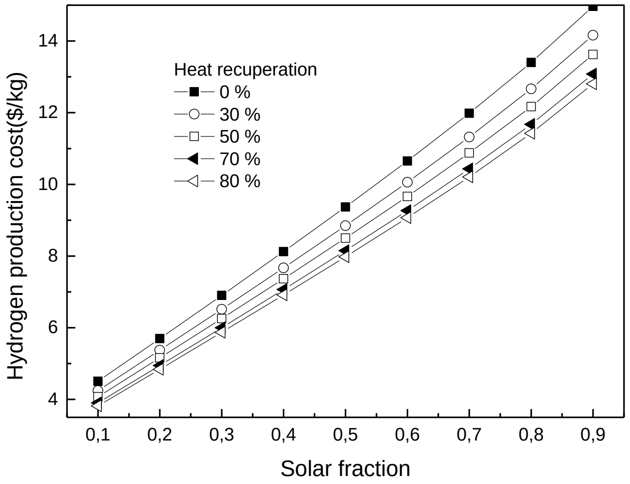
- Cost analysis of nuclear-based hydrogen production by electrolysis
- Investigate competitiveness of nuclear-based hydrogen production with solar-based hydrogen production cost
- Techno-economic study of hydrogen production using a hybrid nuclear-solar system (HTR – solar PV) and SOEC for high temperature steam electrolysis

With establishment of relevant SOEC characteristic parameters

- ➢ Assessment of the evolution of
  - ✓ useful PV panel area with solar fraction and daily solar insolation
  - ✓ hydrogen production cost with solar fraction and daily solar insolation
  - ✓ hydrogen production cost with solar fraction and PV cell efficiency
- ➢ Study of the effect of heat recuperation on H cost
- Comparison of costs between HTSE obtained H and LTE obtained H



- Decrease in hydrogen production cost at HTE and this decrease increases with heat recuperation
- HTSE production more competitive than LTE.



Hydrogen cost increases with increasing solar insolation at different heat recuperation fractions.

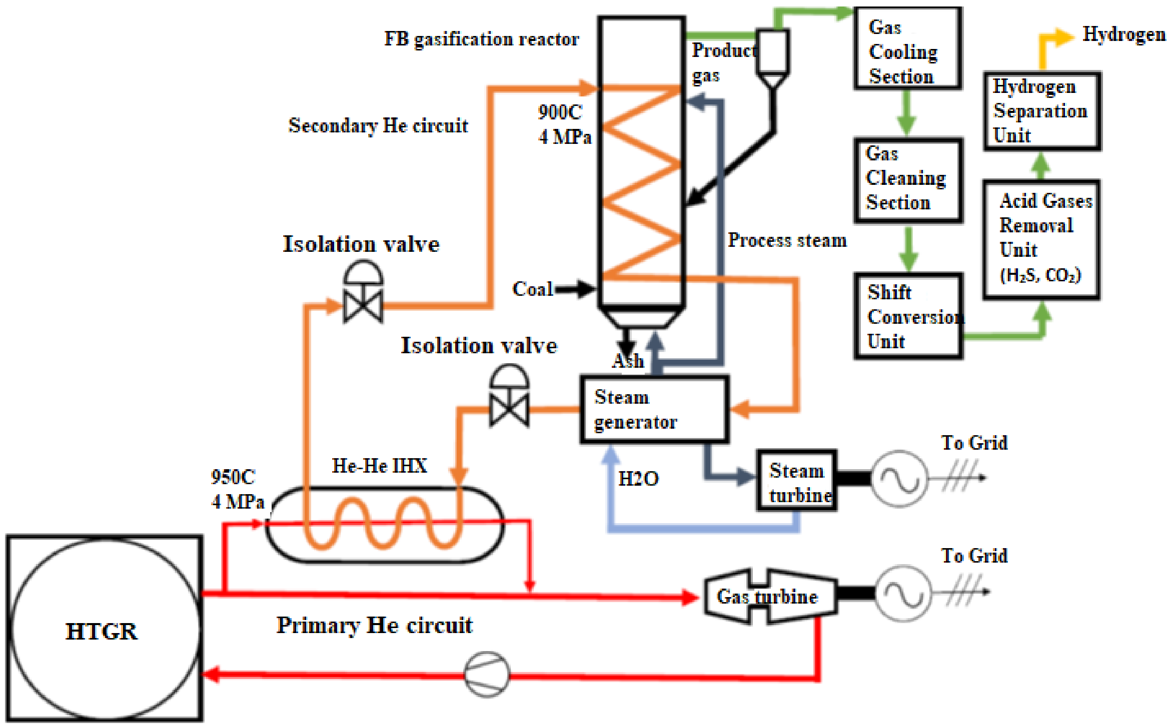
The cost of H production is highly affected by the solar fraction, and the solar irradiance on the PV panel.
There are decreases in H production cost with increase either in PV cell efficiency, solar insolation or recuperation of the heat.
The rate of decrease depends on the solar fraction.

Argentina: Techno-economic feasibility study on the nuclear-assisted steam gasification of Argentine Rio Turbio coal for hydrogen production

CSI: Ana BOHE

Comisión Nacional de Energía Atómica (CNEA)

- Evaluation of different HTGR designs to be potentially used as heat source for the nuclear-assisted steam gasification process
- Selection of the gasification technology to be implemented for processing the Rio Turbio coal in an indirectly heated gasification rector - **High-Temperature Winkler (HTW) gasification process**
- Heat balance analysis and sizing of an indirect-heating gasification reactor to be constructed as a Demonstration Plant, and critical evaluation of technical alternatives for upscaling the indirect-heating gasification reactor to a more commercial phase
- Evaluation of most critical safety issues for the coupling between the HTGR and the gasification plants
- Development of the plant layout for the safe coupling between a HTGR and a Demonstration Gasification Plant for hydrogen production
- preliminary calculations with the IAEA HEEP code to evaluate the economic feasibility of using a HTGR with 950ºC core outlet temperature for electricity generation and hydrogen production through a nuclear-assisted Demonstration Gasification Plant in the Rio Turbio site



Layout of the Steam Gasification Demonstration Plant for processing the Rio Turbio coal for hydrogen production

Maximum thermal output of the gasification reactor is in the order of **10 MW**

China: Evaluation of MW Grade TMSR-Nuclear Hydrogen Production Using Solid Oxide Electrolysis Cell (SOEC) Technology

CSI: Jian-Qiang WANG

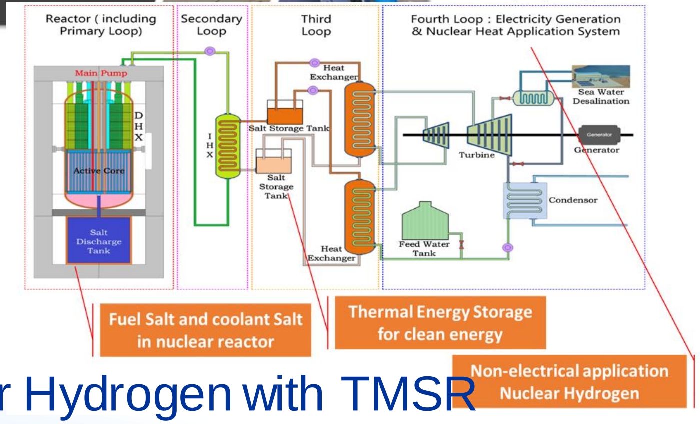
Shanghai Institute of Applied Physics

- Study of material performance (SOEC)
  ✓LSCF cathode material
  ✓BZCY electrolyte material
  ✓Capacity of production in the range of kg
  ✓Development of anode supported cell
  ✓Oxide coatings (e.g. Co-Mn-O spinel) to increase the service life
- Improvement of electrolysis performance of single cells and development of high-performance solid oxide stacks
  ✓Single stack scale: up to 7.2kW
  ✓Peak hydrogen production rate: ~2.3 Nm^3/h
  ✓Electric consumption: ~3.2kWh/Nm^3 H_2
  ✓Tested stable operating time: ~ 3000 h
- Set up MW scale HTSE system
  ✓Completed the core design of 20kW, 200kW, and 2MW SOEC systems:
  process flow, material and heat balance, long-period operating equipment data, process equipment, electrical load
  ✓Complete the core technical documents:
  pipeline and instrument flow chart, electrical equipment specification, instrument general specification, pipeline stress specification
- System modelling for optimized heat integration technology
- Coupling of the HTSE system with Thorium Molten Salt Reactor (TMSR)
- Evaluation of economic and safety aspects of the TMSR nuclear hydrogen production plant
  ✓Safety analysis for molten salt long-distance heat transfer circuit used for coupling nuclear and HTSE system
  ✓Reducing the SOEC cost by improving the cell performance and service life, and scaling up

Production Equipment of Solid Oxide Cells and stacks

Construction of 20kW Hydrogen Production Pilot Program Based on SOEC Technology

Parameters	Value
rated power	20 KWe
Operating temperature	750 °C
Hydrogen production rate	~6 Nm3/h
Current density	0.25 A/cm2
Gas pressure	≤5 bar
Daily Hydrogen	~10 kg/day



Nuclear Hydrogen with TMSR

China: Evaluation of MW Grade TMSR-Nuclear Hydrogen Production Using Solid Oxide Electrolysis Cell (SOEC) Technology

CSI: Jian-Qiang WANG
Shanghai Institute of Applied Physics

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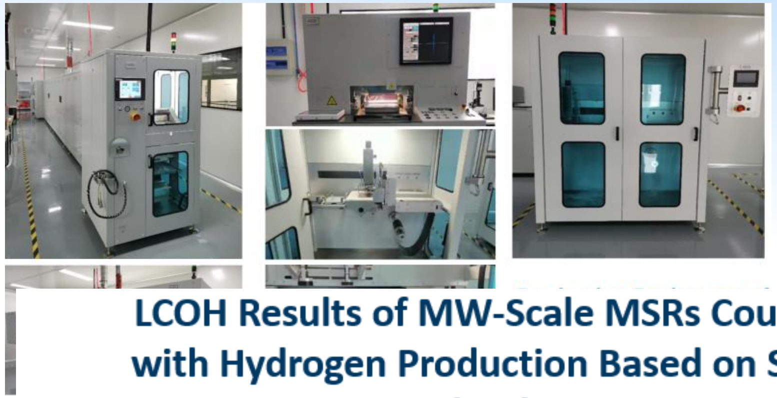


Construction

nology

LCOH Results of MW-Scale MSRs Coupled with Hydrogen Production Based on SOEC Technology

Power Plant Type	MSR	MSR
Thermal rating (MWth/unit)	300	600
output temperature tn'(℃)	650	650
Heat for H2 plant (MWth/unit)	23	47
SOEC Scale(MWe/unit)	127	262
TH (MWe/unit)	3	6
H2 generation per unit (kg/yr)	3.21E+07	6.60E+07
LCOH ($/kg)	**3.85**	**3.83**

Tool: HEEP

Nuclear Hydrogen with TMSR

Greece: Identifying Adequate SMR Technology for Innovative Hydrogen Production, Compression and Storage

CSI: Melpomeni VARVAGIANNI

National Center for Scientific Research "DEMOKRITOS"

- Investigate the appropriate solution for the energetic transition from lignite-fired power plants in the Western Macedonia Region (Northern Greece)
  - ✓Selected SMR designs:
    - CAP200 (China) – PWR
    - International Reactor Innovative and Secure (IRIS) – PWR
    - DMS (Japan) – BWR
    - IMR (Japan) – PWR
    - VK300 (Russian Federation) – BWR
    - Westinghouse SMR (USA) – PWR
    - NUWARD (France)
- Selected the hydrogen storage method: metal hydrides
- performance of a cost analysis for a SMR and hydrogen electrolysis production with a MH compression system

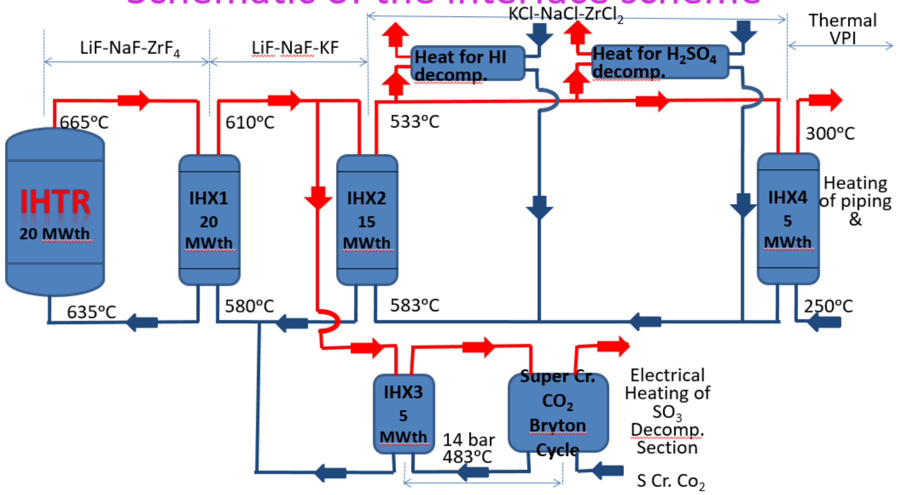
India: Technical and safety studies for integration of high temperature reactors with Iodine-Sulphur process based hydrogen production plant and upgradation of the software HEEP for economic assessment of hydrogen production

CSI: Indravadan DULERA

Bhabha Atomic Research Centre (BARC)

- **India has an active programme for development of the IS process.**
- Closed loop operation demonstrated at 30 Nlph of H production
- Closed loop metallic system setup for 150 Nlph of H production
- New technologies developed:
  - ✓multistage counter-current Bunsen reactor in tantalum
  - ✓membrane reactor for HI decomposition
  - ✓bayonet type SO_3 decomposer in silicon carbide
  - ✓improved surface area catalyst for SO_3 decomposition
- Investigation of various options to couple 20 MWth Innovative High Temperature Reactor (IHTR) to the IS plant, while considering challenges related to heat transfer, material compatibility and code design requirements
  - ✓ IHTR is under design in India for demonstration of hydrogen production using IS process:
    - 20 MWth, molten salt cooled, pebble bed type reactor
    - Primary salt: LiF-NaF-ZrF4
    - Secondary salt: LiF-NaF-KF
    - Core inlet/outlet: 635 °C/665 °C
    - Moderator/reflector: Graphite
    - Structural material: Ni-Mo-Cr-Ti alloy
- Detailing of the selected design option for the intermediate heat exchangers and intermediate piping
- Identification of areas significant for safety studies
- Update of the HEEP tool

Schematic of the interface scheme



Update of HEEP

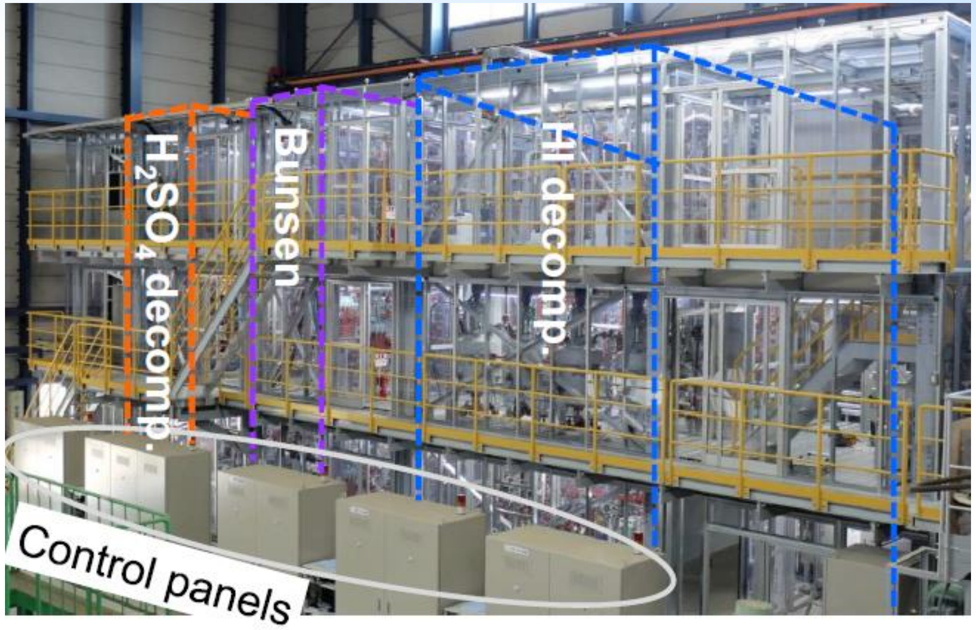
- Included feature to generate report in Excel format
- Developed feature for studying sensitivity of specific parameter on hydrogen cost
  - ✓ discount rate
  - ✓ interest on borrowing
  - ✓ equity
  - ✓ construction period

Japan: R&D for IS thermochemical process for hydrogen production

CSI: Xing YAN

Japan Atomic Energy Agency (JAEA)

- Focus on R&D for thermochemical hydrogen production using the IS cycle to extend the period of stable hydrogen production at the facility and examine the integrity of the process reactors and components in high temperature and/or highly corrosive working conditions.
  - Long term continuous H production tests – at a rate up to 30 L/h
  - Acquiring corrosion data after the long-term H2 production tests
  - Investigation of structural materials for each process environment (H2SO4 decomposer, heat exchanger, Bunsen reactor, piping, HI decomposer) from corrosion tests



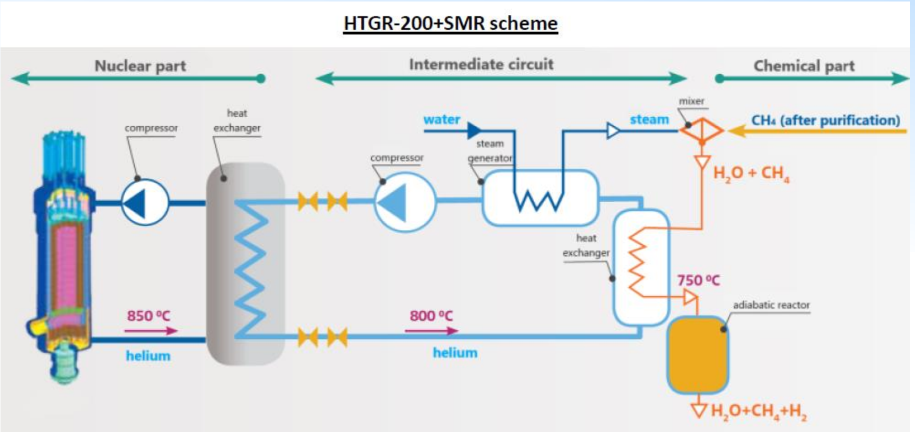
IS-process H_2 production test facility

National objective:
By 2030, to establish a coupling technology and perform hydrogen production tests at HTTR

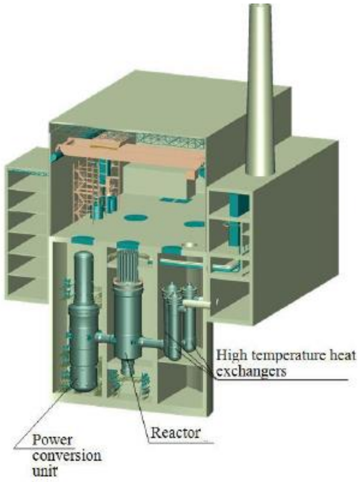
Russian Federation: Assessing Potential of High Temperature Reactor Facilities of Russian Design for Hydrogen Production

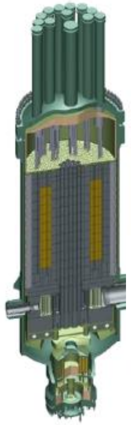
CSI: Andrey BALANIN
NRC Kurchatov Institute

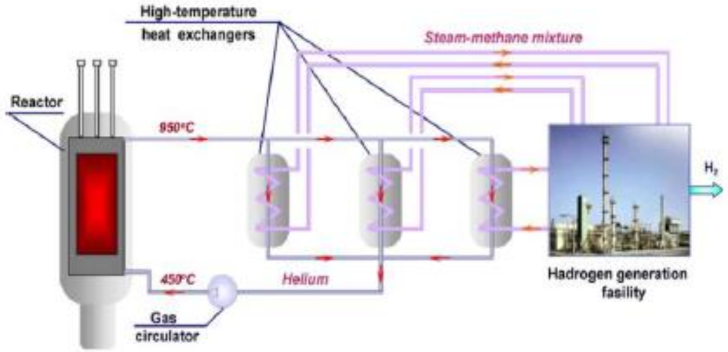
- Review of HTRs designed in Russia with potential for H production (HTGR, FGCR, MSR)
- MHR-T (600 MWt) and HTGR-200 (200 MWt) were selected for analysis, necessary data was collected
- Number of electrolysis facilities available on market selected for comparison, necessary data collected
- Models of technical-economic assessment of unit costs of hydrogen production for selected facilities were developed
- Technical-economic assessments of hydrogen production were carried out for following cases:
  ✓SMR and HTSE with MHR-T energy source of heat and electricity
  ✓SMR with HTGR-200 energy source of heat
  ✓Electrolysis and compression using electricity from outside source
  ✓Simplified verifications of several cases with HEEP
- Approach of multi-criteria assessment of using nuclear reactors for H production was tested for several cases



HTGR-200 + Steam Methane Reforming (SMR) is a latest design, developed by JSC Afrikantov OKBM based on MHR-100 design for power generation and technological purposes, including H production.



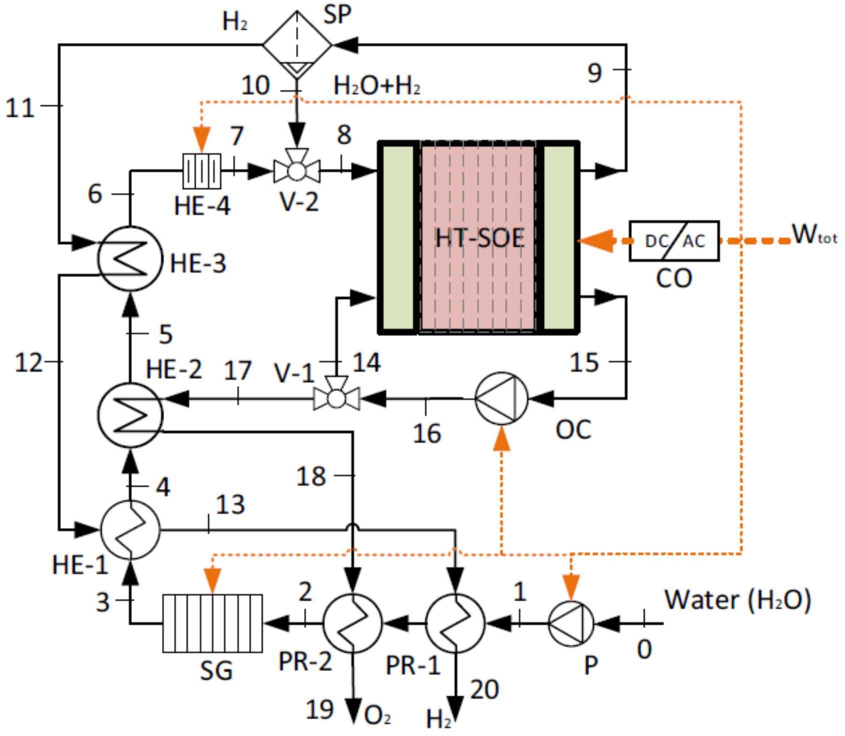




Saudi Arabia: Thermo-Economic Analysis and Optimization of a Large-Scale Nuclear Hydrogen Production Utilizing High Temperature Electyrolysis

CSI: Abdullah ALZAHRANI
Umm Al-Qura University

- Holistic plant model for hydrogen production comprising a nuclear reactor and an electrolysis component
- Adjusting of the critical cost and technical parameters considering WCR and HTGR technologies (APR 1400 and HTR-PM)
- Model for the SOE stacks
- Techno-economic analysis of integrating SOE plants with WCR and HTGR for large-scale hydrogen production

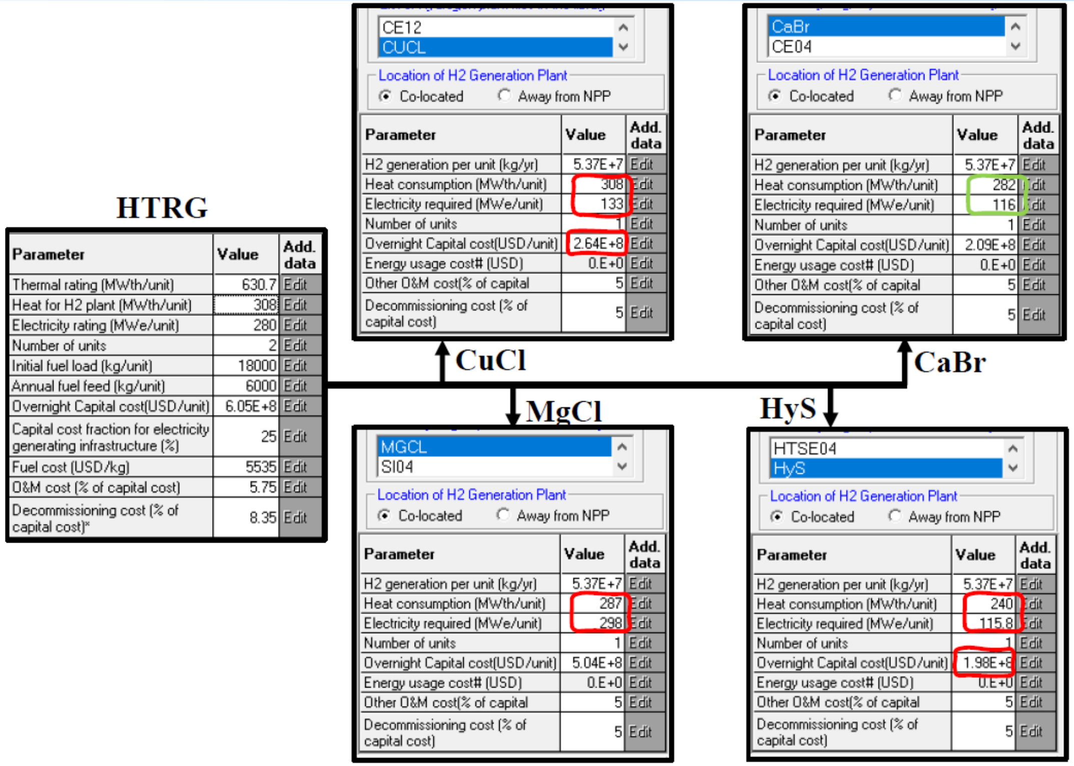


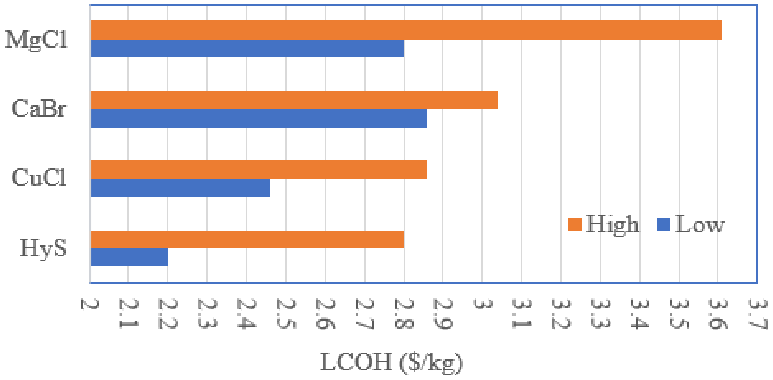
Schematic layout of the 1 MWe SOE hydrogen production plant

Turkey: Economics and Integration of Hybrid Thermochemical Cycles to Nuclear Reactors for Hydrogen Production

CSI: Hasan OZCAN
Karabuk University

- Development of hydrogen production plant configurations considering advanced reactor technologies (CANDU-SCWR and HTGR) with HyS, CuCl, MgCl and CaBr cycles
- Performing thermodynamic and economic analysis to specify the most feasible options to be employed
- Effect of scaling of hybrid cycle configurations on H production costs
- Adapting the most feasible hybrid thermochemical cycles to IAEA-HEEP software package
- Comparative economic assessment of adapted hydrogen systems with storage and transportation





Cost comparison of the considered hybrid cycles with HTGR
HyS cycle has the lowest hydrogen cost based on results with HEEP

United States: Safety and Scaling Analysis of Nuclear Hydrogen Production Schemes with Current and Near Future Nuclear Plants

CSI: Shripad REVANKAR

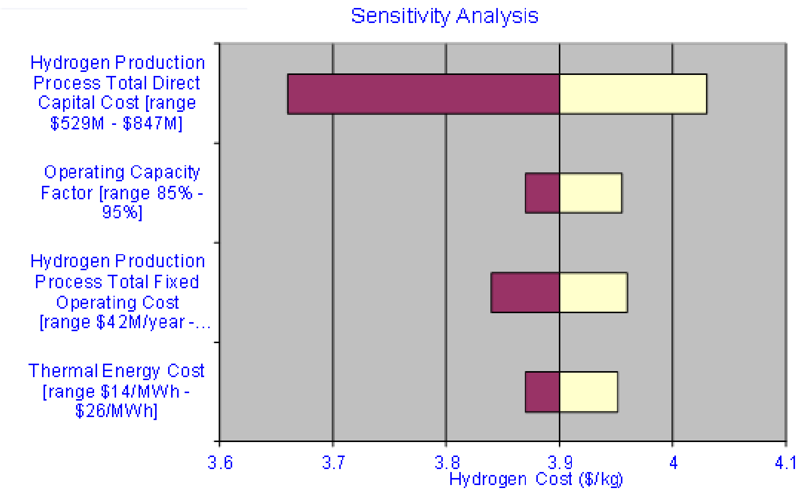
Purdue University

- Developed integrated dynamic model of Nuclear Reactor - Hydrogen Plants
  - ✓HTGR and IS hydrogen production
  - ✓HTGR- HTE
  - ✓LWR (PWR and BWR) – LTE – PEM Electrolyzer (Recent US Industry DOE Initiative)
  - ✓Integrated Nuclear Renewable Energy System
- Scaling analysis for the integrated nuclear hydrogen production systems considering various nuclear reactor technologies
- Process flow diagrams for nuclear hydrogen system
- Techno-economic analysis of the integrated systems, comparison H2A results with HEEP results

✓ Analysis Tools:
- •First principle-based models for nuclear plants verified with codes: RELAP5, MELCOR
- •Hydrogen Production Systems – ASPEN PLUS
- •Economic Analysis H2A, HEEP

Cases	APWR-CE	APWR-CE	APWR-CE	HTGR-HTSE	HTGR-SI
NPP	$4.36	$ 3.22	$ 2.67	**$1.11**	$1.28
HPP	$1.69	$ 1.69	$ 1.68	**$1.18**	$1.68
Total	$6.05	$ 4.91	$ 4.35	**$2.29**	$2.96
Malshe-India Results	$5.53	$4.14	$3.56	**$2.24**	$4.91
			H2A (2019)	**$3.90**	

H2A Analysis for HTE with HTGR 600MW



From the CSIs:

"This precious opportunity in the CRP is unique for the researchers in SINAP to let more people know about our research and also gain insight in the related research conducted by the international community. It also provides an opportunity for development of our technologies and conduct additional research to investigate if the HTSE system is suitable while coupled with other energy sources such as wind, solar, Gen-III and some other Gen-IV reactors. Besides, the HEEP tool developed by IAEA simplifies the cost assessment of nuclear hydrogen production."

- Prof. Dr. Jian-Qiang Wang, Shanghai Institute of Applied Physics, China

"The theoretical feasibility study on nuclear-assisted gasification process applied to the Argentine Rio Turbio coal is very important for our country to provide the technical arguments needed during the decision making process regarding to the nuclear hydrogen production through the gasification of domestic coals. Aspects like the most convenient HTGR design, the maximum size of the gasification plant according to the present state of technologies, and the most critical safety issues to be considered for the coupling of the nuclear reactor and gasification plant, have been clarified through this study. Moreover, the experimental activities for pyrolysis and gasification tests conducted at bench-scale are also very important to evaluate the gasification behaviour of Argentine domestic coal in fluidized bed reactor conditions, as a function of the operational parameters (reaction temperature, partial pressure of reactive gases and coal particle size)."

- Dr. Ana Ester Bohé, Comisión Nacional de Energía Atómica (CNEA) de Argentina

Questions?

Alina Constantin
Nuclear Power Technology Development Section
a.constantin@iaea.org

Thank you!