IAEA | Nuclear Energy

# 65th IAEA General Conference


## Innovations in the Production and Use of Nuclear Hydrogen for a Clean Energy Transition

A Hybrid Event of In-Person and Virtual on WebEx

**Tuesday, 21 September 2021, 10:00 – 11:30 CET**

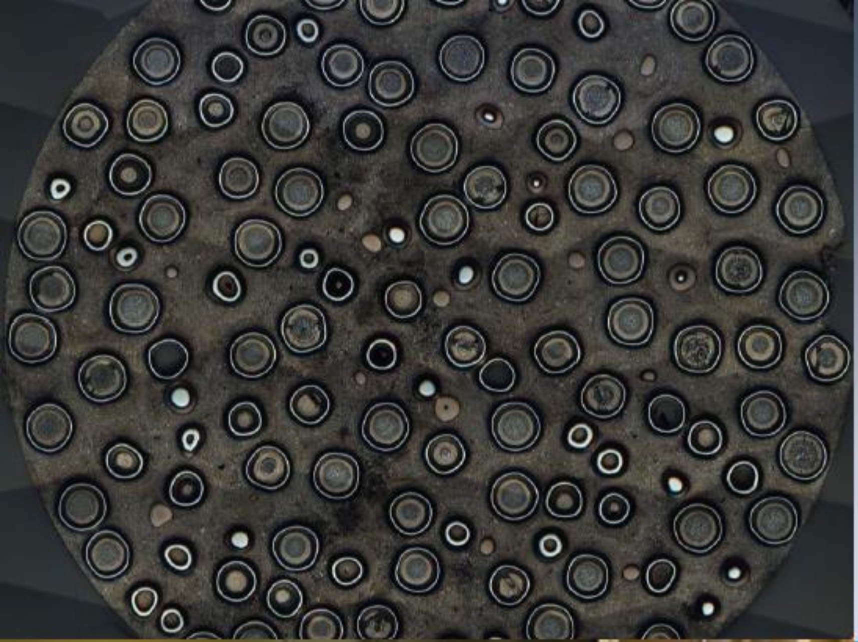
**Conference Room C3, C Building, 7th Floor**

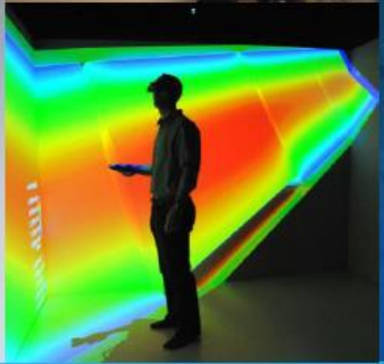
# Innovations in the Production and Use of Nuclear Hydrogen for a Clean Energy Transition

Hybrid Event during the 65th IAEA General Conference, Tuesday, 21 September 2021, 10:00-11:30 CEST

## Event Programme

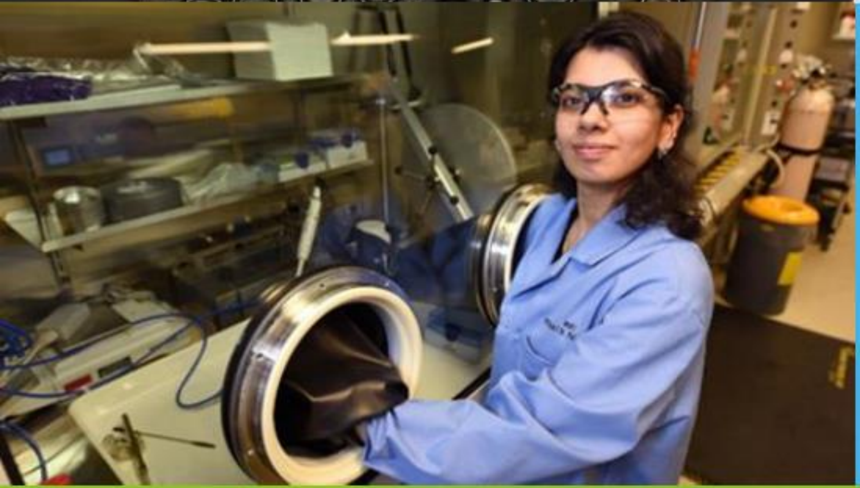
| | |
|---|---|
| Opening Remarks | **Mr Mikhail CHUDAKOV**<br>IAEA Deputy Director General, Head of the Department of Nuclear Energy |
| Shifting the Nuclear Paradigm: Leveraging Today's LWRs and Tomorrow's Advanced Reactors for Affordable Clean Hydrogen Production | **Mr Richard BOARDMAN**<br>Director for Energy and Environment Science and Technology Programs Office, Idaho National Laboratory, USA |
| Nuclear Hydrogen: Lessons learned from a Canadian case study | **Mr David CAMPBELL**<br>Director, Bruce Power Centre for Next Generation Nuclear, Nuclear Innovation Institute, Canada |
| Development of nuclear-hydrogen power engineering in Russia for economics decarbonization | **Mr Nikolay KODOCHIGOV**<br>Advisor to the Director General, JSC “Afrikantov OKBM”, Nizhniy Novgorod, Russian Federation |
| Decarbonising hydrogen in a net zero economy | **Mr Kees Jan STEENHOEK**<br>Director, Government Affairs, URENCO<br>**Mr Felix CHOW-KAMBITSCH**<br>Head of Commissioned Projects, Western Europe, Aurora Energy Research |
| IAEA power system modelling with hydrogen – example of sensitivity studies | **Mr Francesco GANDA**<br>Nuclear Engineering Expert (INPRO), IAEA Department of Nuclear Energy |
| Questions and Answers | |
| Closing Remarks | **Ms Alina CONSTANTIN**<br>Associate Nuclear Engineer, Nuclear Power Technology Development Section, IAEA Department of Nuclear Energy |



**Richard Boardman**
Technology Development Lead

**Shannon Bragg-Sitton**
National Technical Director for Integrated Energy Systems



# Innovations in the Production and Use of Nuclear Energy for Zero-Emissions Products

Idaho National Laboratory

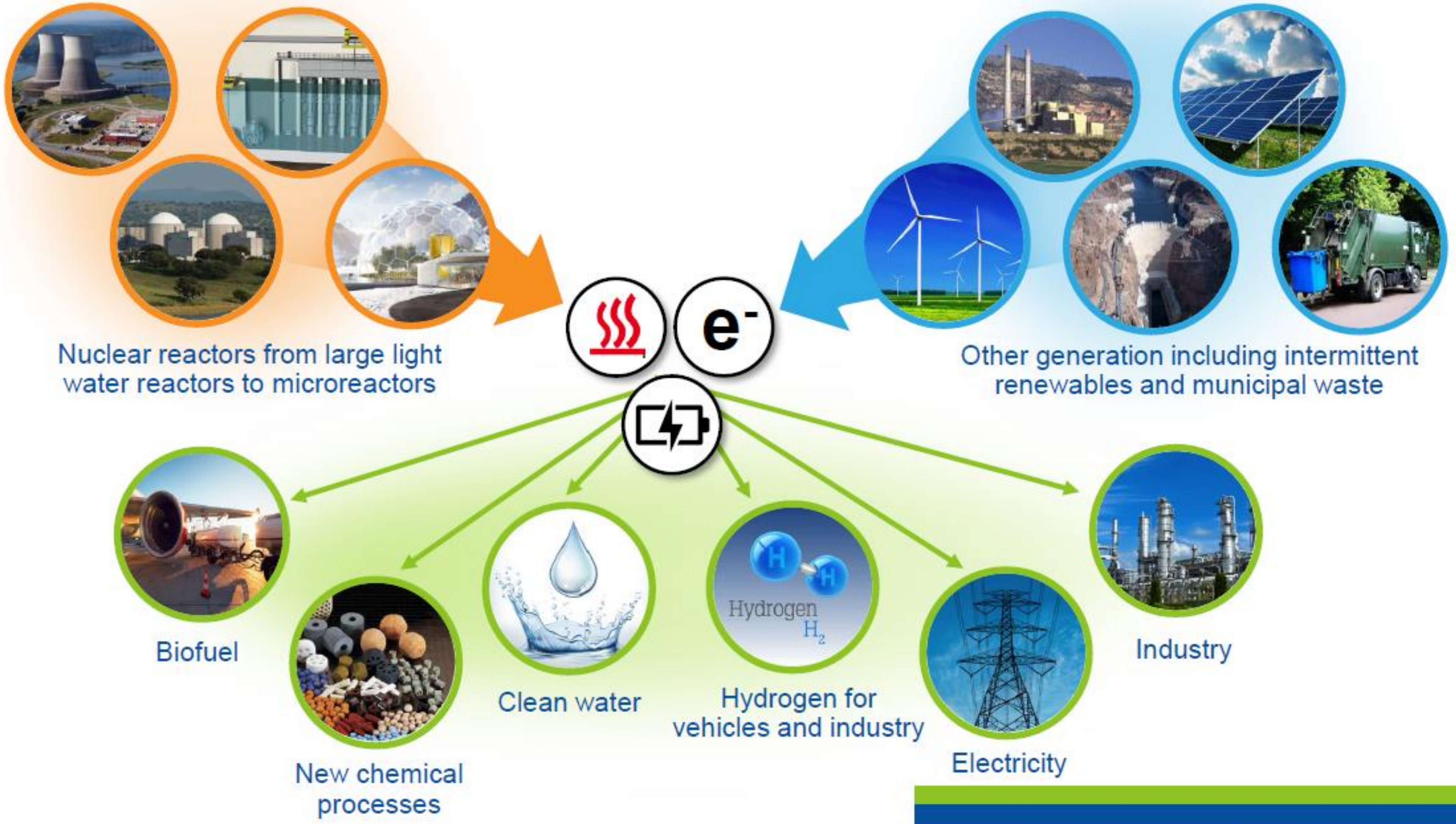
# Transforming the energy paradigm

## Today

Electricity-only focus

## Future Energy System

Integrated grid system leverages contributions from nuclear fission beyond electricity



# Advanced reactor future state: One size does not fit all

Researchers at Idaho National Laboratory are collaborating with industry and academia to develop nuclear reactor concepts of various sizes for various use cases.

# Advanced Reactor Design Concepts

## Benefits:

- Enhanced safety
- Versatile applications
- Reduce waste
- Use advanced manufacturing to save money

*60+ private sector projects under development*

## SIZES

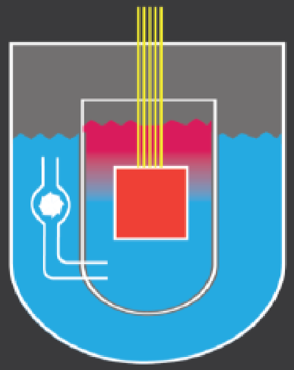
**SMALL**
**1 MW to 20 MW**
Micro-reactors
*Can fit on a flatbed truck. Mobile. Deployable.*

**MEDIUM**
**20 MW to 300 MW**
Small Modular Reactors
*Factory-built. Can be scaled up by adding more units.*

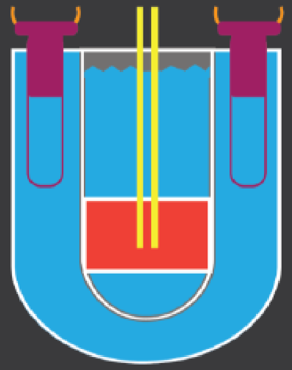
**LARGE**
**300 MW to 1,000 + MW**
Full-size Reactors
*Can provide reliable, emissions-free baseload power*

*Advanced Reactors Supported by the U.S. Department of Energy*

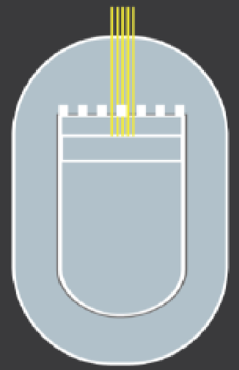
## TYPES



**MOLTEN SALT REACTORS –** Use molten fluoride or chloride salts as a coolant. Online fuel processing. Can re-use and consume spent fuel from other reactors.

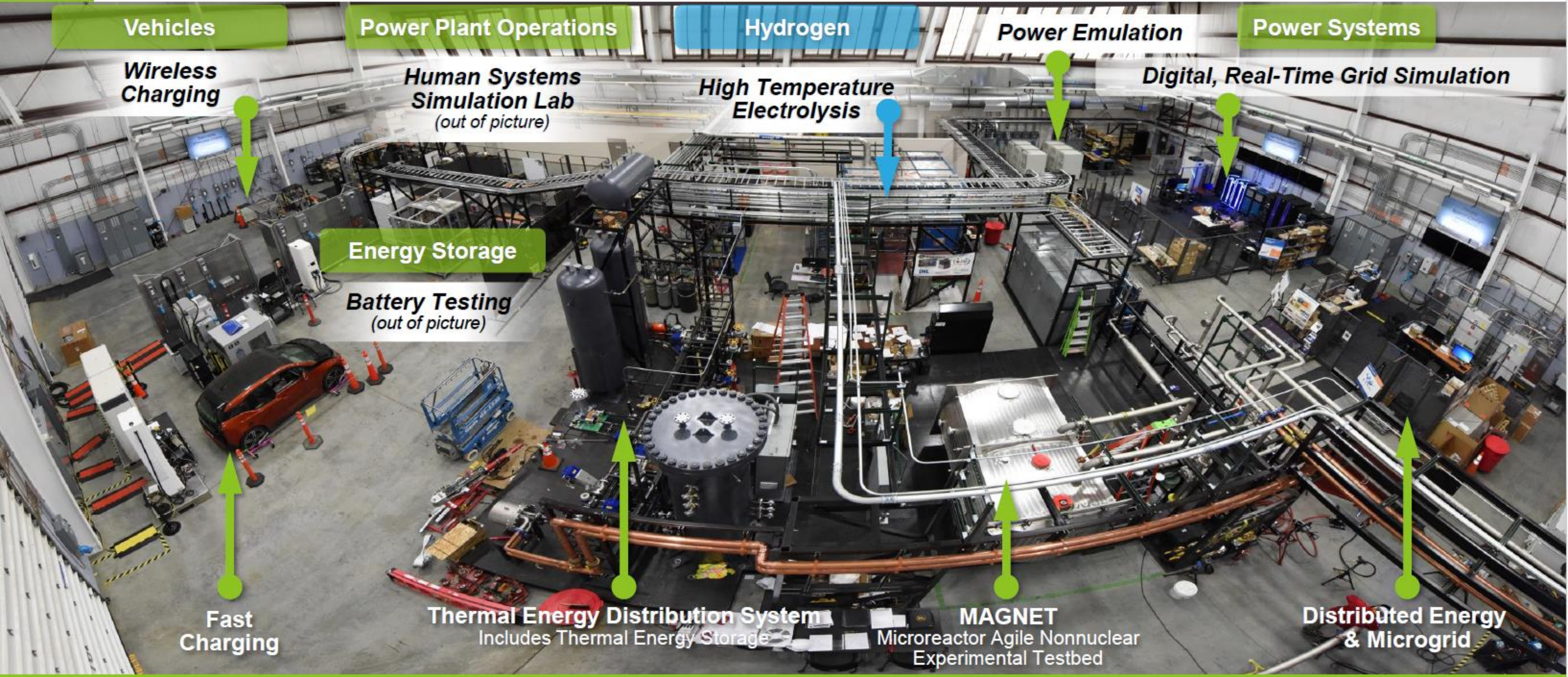


**LIQUID METAL FAST REACTORS -** Use liquid metal (sodium or lead) as a coolant. Operate at higher temperatures and lower pressures. Can re-use and consume spent fuel from other reactors.



**GAS-COOLED REACTORS –** Use flowing gas as a coolant. Operate at high temperatures to efficiently produce heat for electric and non-electric applications.

# Integrating systems for the nation’s net-zero future



# Dynamic Energy Transport and Integration Lab (DETAIL)

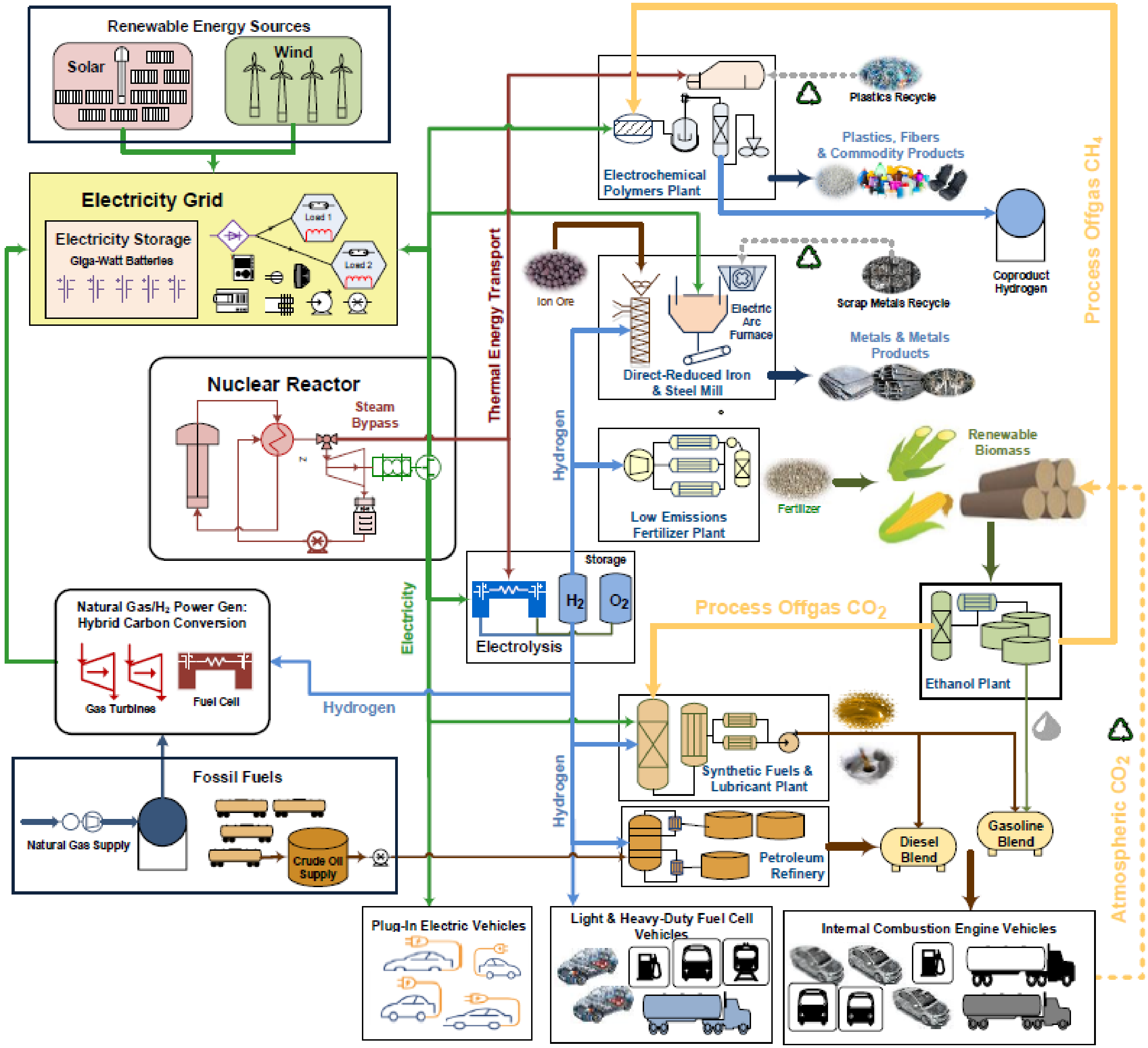
**Electricity Grid Simulation**

**New Operating Concepts for Nuclear Reactors**

**Steam Electrolysis Stacks and Modular Systems**

**Thermal Energy Generation and Transport**

# A new Paradigm: Integrated Energy Systems with Nuclear




- **Industrial energy needs**
  - Electricity
  - Steam
  - Heat (Thermal Power)
- **Target Large Industries**
  - Transportation fuels
  - Fired heaters / Steam boilers
  - Polymers & Plastic
  - Iron & Steel
  - Fertilizers
  - Minerals
- **Keys to success**
  1. Hydrogen is key energy currency
  2. Flexible operations can support the grid
  3. Energy storage is imperative

ENERGY earthshots U.S. DEPARTMENT OF ENERGY | Hydrogen

# Hydrogen Energy Earthshot

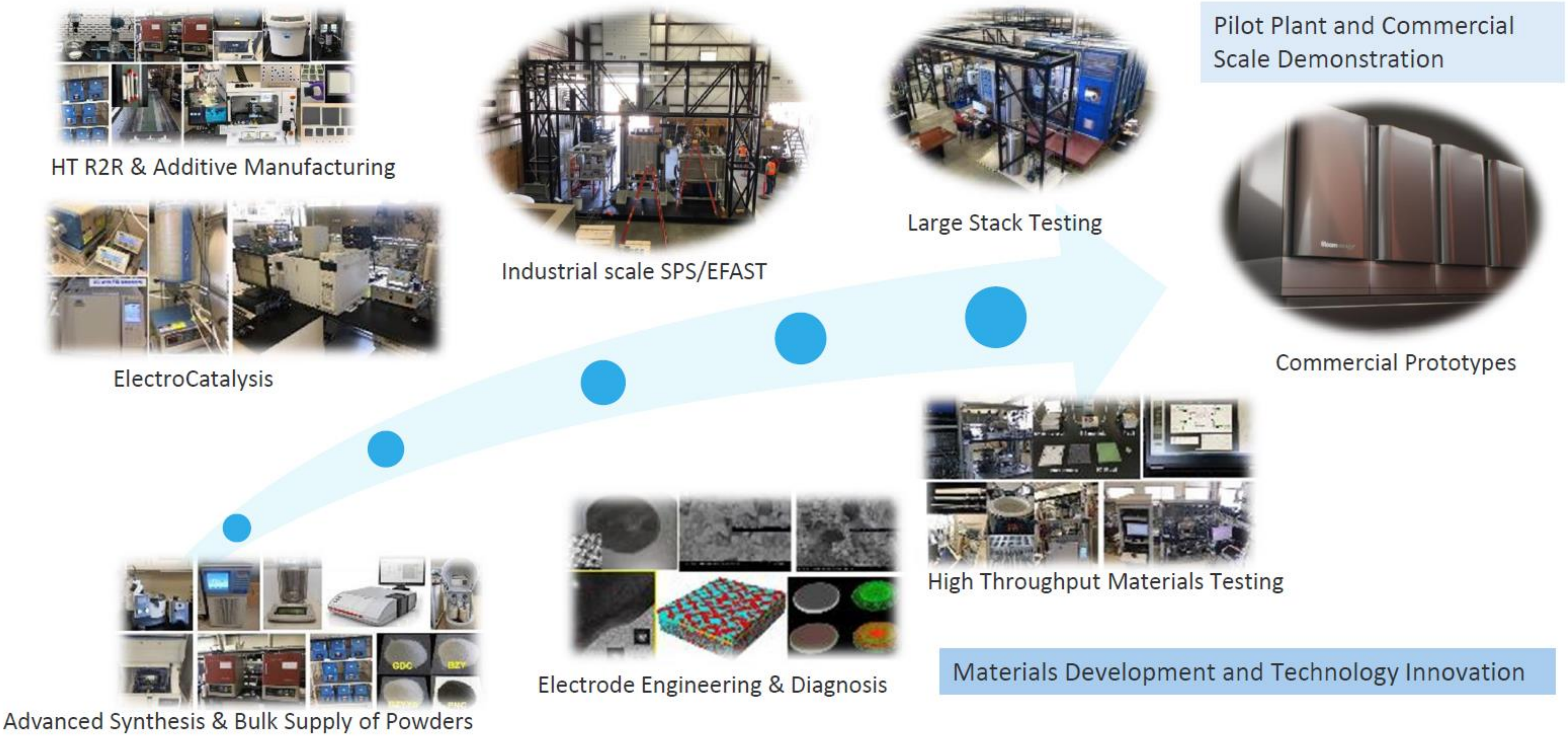
## "Hydrogen Shot"

## "1 1 1"
## $1 for 1 kg clean hydrogen in 1 decade

Launched June 7, 2021

# Electrolysis Technology Development and Commercialization

H2NEW U.S. DEPARTMENT OF ENERGY



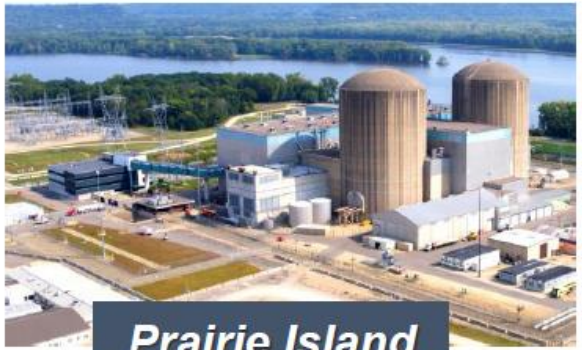
# Joint EERE-NE Hydrogen Production Demonstration Projects at NPP

- Demonstrate hydrogen production using direct electrical power offtake from a nuclear power plant (NPP)
- Develop monitoring and controls procedures for scaleup to large commercial-scale hydrogen plants
- Evaluate power offtake dynamics on NPP power transmission stations to avoid NPP flexible operations
- Produce hydrogen for captive use by NPPs and first movers of clean hydrogen

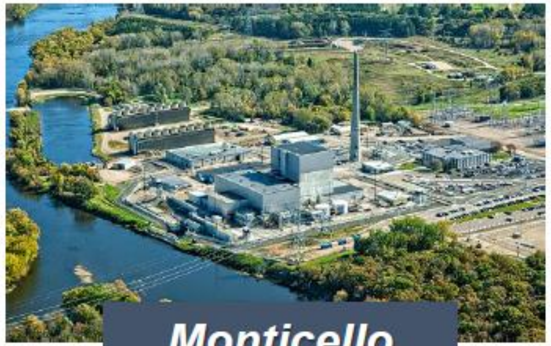
***Davis-Besse Nuclear Power Plant LTE-PEM Vendor 1***

***Nine Mile Point Nuclear Power Plant LTE/PEM Vendor 2***

***Thermal & Electrical Integration at an Xcel Energy Nuclear Plant HTE/Vendor 1***

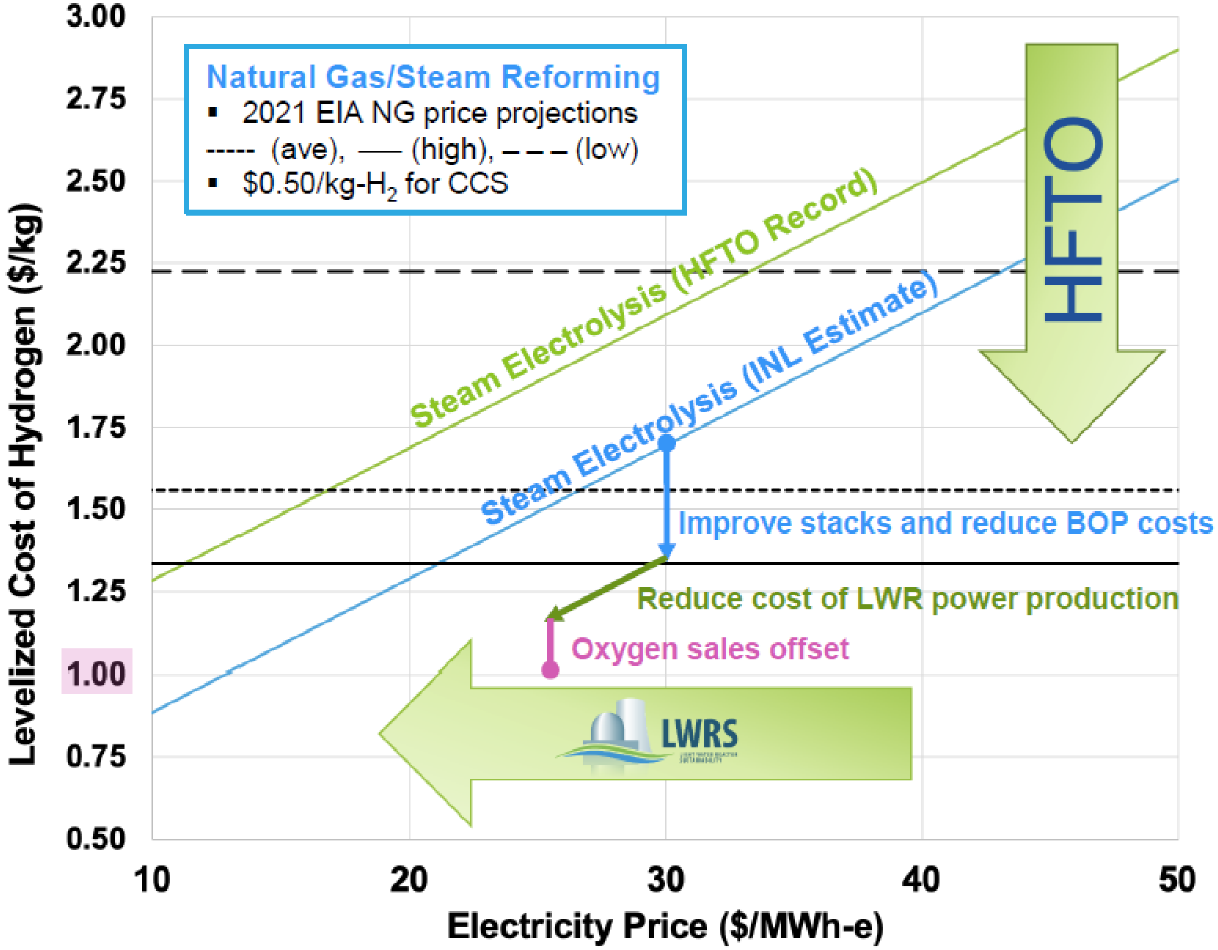


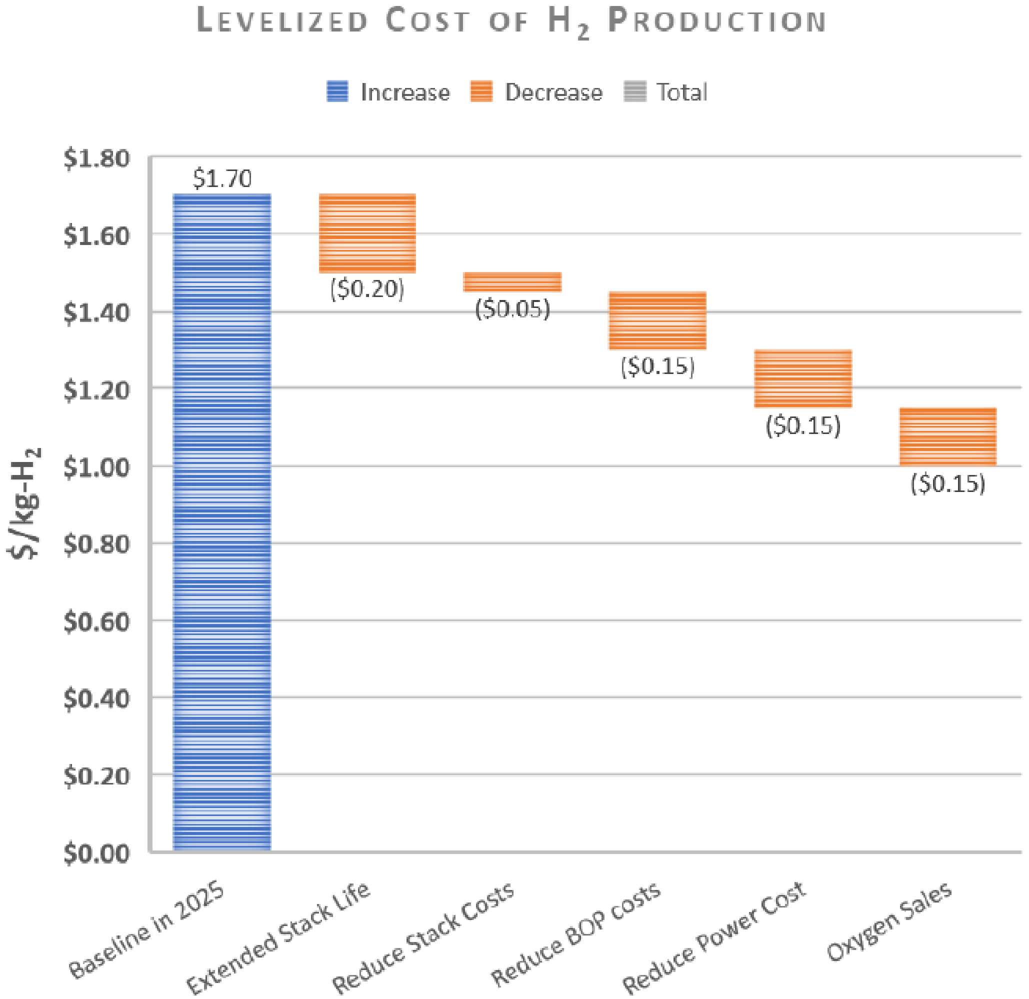
***Prairie Island***



***Monticello***

# Two paths to $H_2$ Earthshot Target
## ($1/kg-$H_2$ within a decade)



Idaho National Laboratory

- Production of Net-Zero Energy Services & Products
- Manufacturing of Supply Chain Reactors and Components

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INNOVATION
INSTITUTE

# Nuclear Hydrogen:

## Lessons learned from a Canadian case study

The Bruce Power Centre for Next Generation Nuclear

Sep 21, 2021

# We are a clean energy think tank



david.campbell@nii.ca

# The Centre is supported by Bruce Power

BrucePower™
Innovation at work

**>6,400 MW** capacity from eight CANDU reactors

**30%** of Ontario's electricity

**2064** is the new expected lifespan for 6 of 8 units upon refurbishment


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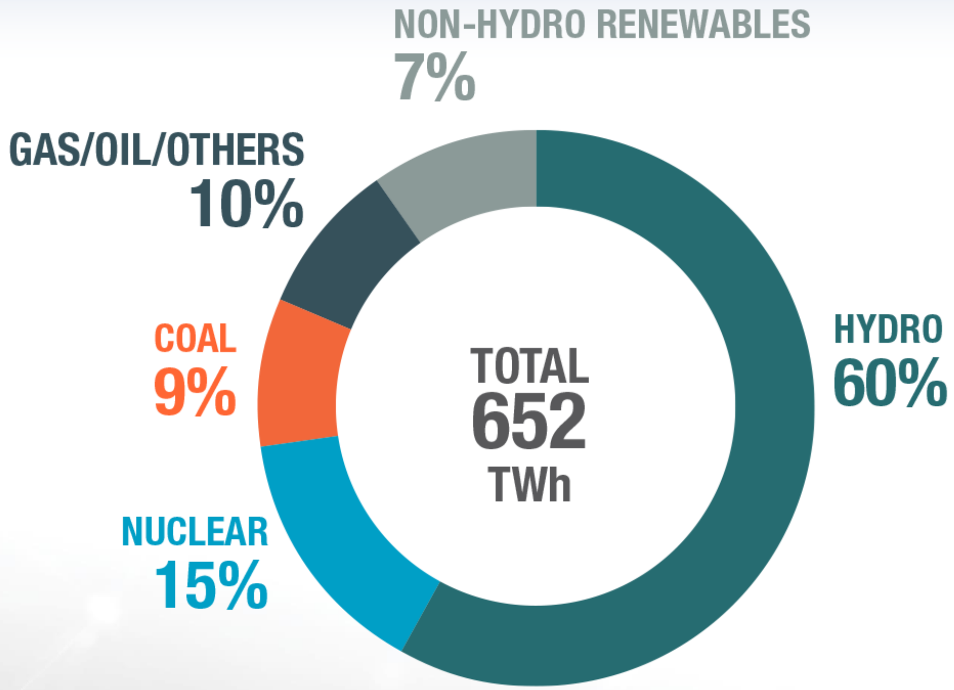
# Canada has a relatively clean electricity grid





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# The future decarbonization challenge is more difficult

**BUILDINGS**

- Home heating

**TRANSPORT**

- Personal vehicles
- Trucks
- Trains

**HEAVY INDUSTRY**

- Shipping
- Steel and cement
- Agriculture


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# Hydrogen is already well-developed in Canada

## Hydrogen in Canada today

- ✓ **Top 10** hydrogen producers in the world
- ✓ **>100** established companies
- ✓ **>90%** of global hydrogen bus fleet powered by Canadian fuel cells

## The vision for 2050

- **Top 3** global clean hydrogen producers
- **30%** of end use energy
- **>5 million** FCEVs on the road
- **~350,000** jobs

**$H_2$ Opportunity**

| | 2030 | 2050 |
|---|---|---|
| % of Delivered Energy | 6% | 30% |
| Hydrogen Demand | 4 Mt-$H_2$ | 20 Mt-$H_2$ |
| GHG Emissions Abated | up to 45 Mt-$CO_2$e | up to 190 Mt-$CO_2$e |


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# Meeting future targets requires major electricity buildout

The National Hydrogen Strategy projects hydrogen will account for 13-30% of end use energy by 2050

A recent report by the Centre studied the implications of this projection:

**18%** OF ENERGY DEMAND → **10 MT/y** OF HYDROGEN → **436 TWh** OF NEW ELECTRICITY GENERATION


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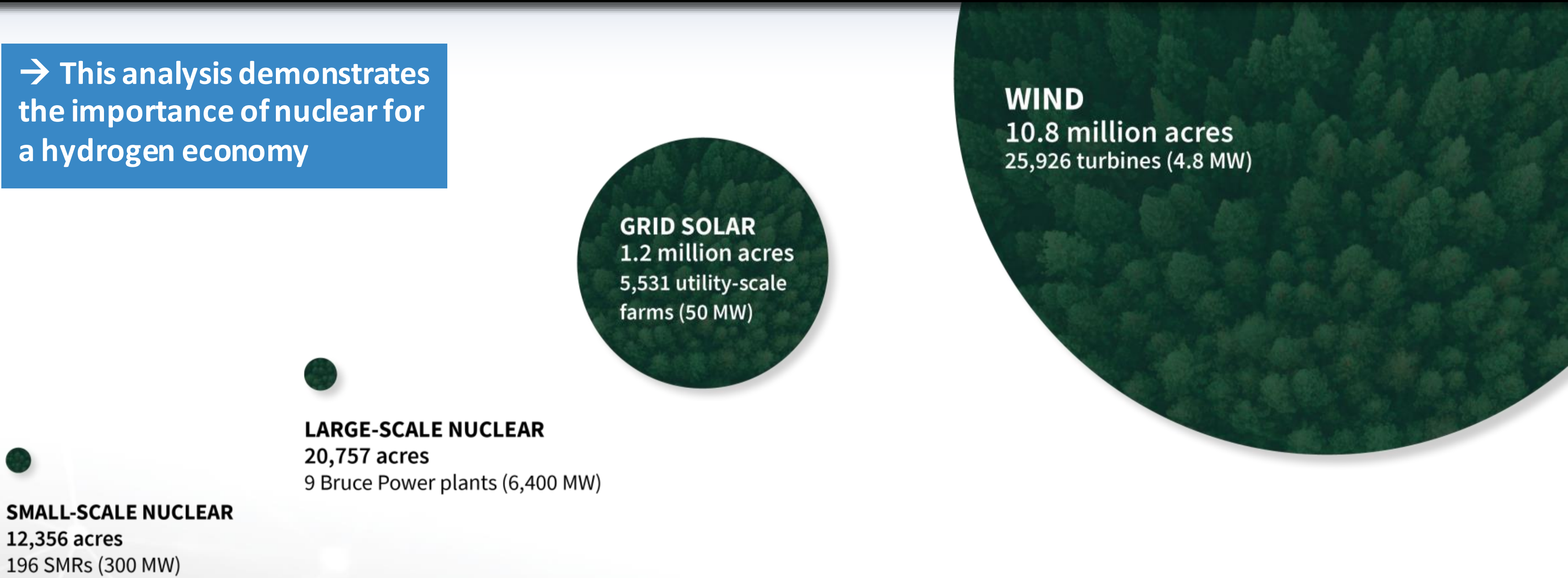
# How much land it will take to generate 436 TWh

**→ This analysis demonstrates the importance of nuclear for a hydrogen economy**





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# A policy space is emerging to support hydrogen development

**Federal hydrogen strategy**

**Carbon price**

**Clean Fuels standard**

Canada



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# Canada has a number of promising hydrogen projects underway

The Transition Accelerator

→Edmonton, AB
→Hydrogen transport corridor

BALLARD®

→Burnaby, BC
→Batteries for FCEVs

Hydro Québec

→Verennes, QC
→90 MW electrolyzer facility

ENBRIDGE®

→Markham, ON
→Natural gas blending pilot


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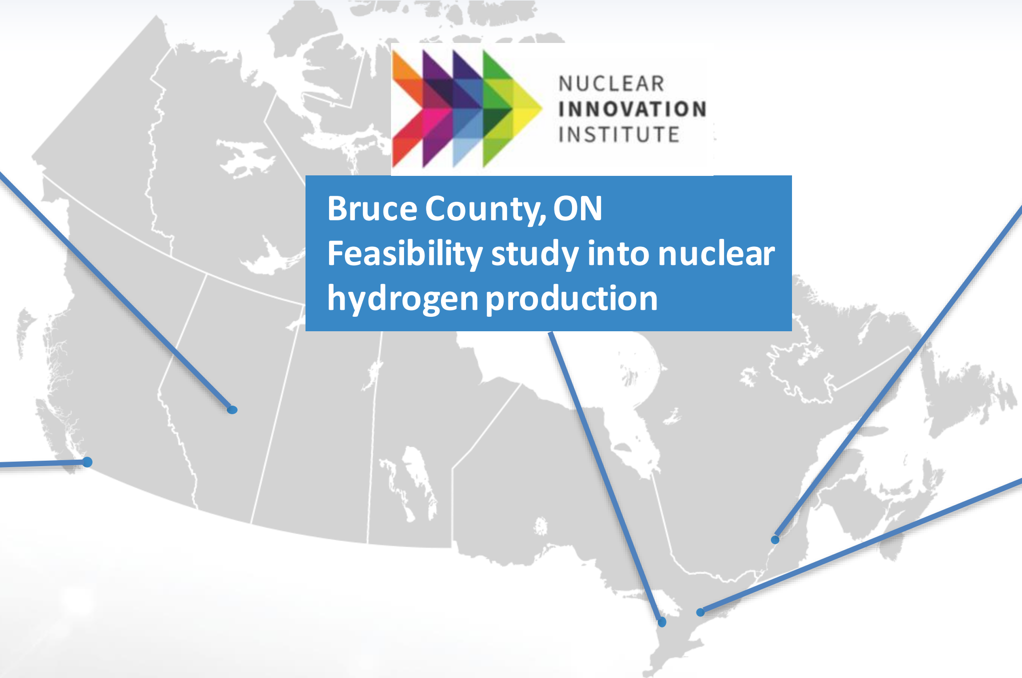
# Canada has a number of promising hydrogen projects underway



The Transition Accelerator

→Edmonton, AB
→Hydrogen transport corridor

BALLARD®

→Burnaby, BC
→Batteries for FCEVs

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**Bruce County, ON**
**Feasibility study into nuclear hydrogen production**

Hydro Québec

→Verennes, QC
→90 MW electrolyzer facility

ENBRIDGE

→Markham, ON
→Natural gas blending pilot


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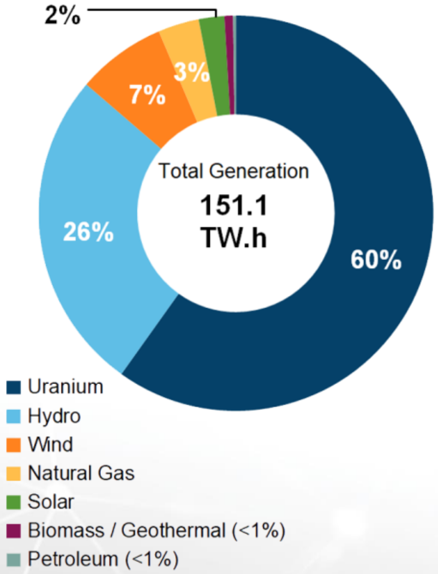
# Hydrogen can capitalize on Ontario's clean nuclear power

**Ontario electricity mix (2018)**




**Clean grid** → The Ontario electricity system is about 93% emissions-free

**60%** → Nuclear supplies the majority of generation

**Surplus baseload** → Intermittent surplus creates opportunity

**There is potential for surplus baseload and off-peak generation to support the production of low-carbon hydrogen**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# The study explores the opportunity for a pilot project

**The Centre's study is exploring:**

1. Technical feasibility for hydrogen production
2. Business case for local hydrogen market

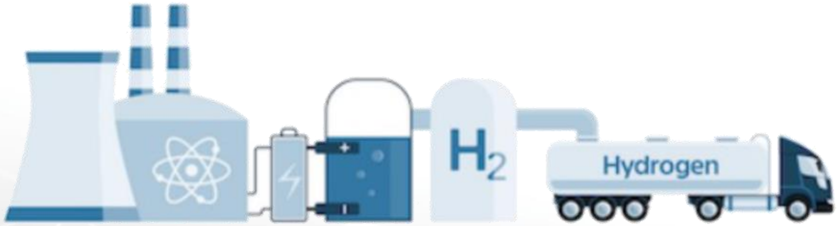


Image credit: NEI Magazine

**Scope:**

- Launched in May, and nearing completion
- Partnership with Bruce Power and Greenfield Global
- 5 MW electrolyzer on or near the Bruce Power site
- Hydrogen to be sold to local customers


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# Some outstanding questions to start a hydrogen economy

## For industry

- ✓ How do we demonstrate the tie between nuclear and hydrogen to the public?
- ✓ Are electrolyzers better placed alongside reactors, or at the source of demand?
- ✓ How do we prepare for future hydrogen opportunities presented by SMRs?

## For policymakers

- ✓ Will governments provide the incentives needed to start the market?
- ✓ What other policies can make hydrogen more competitive with fossil fuels?
- ✓ Are governments prepared to adapt regulations, codes and standards?
- ✓ What will be done to begin preparing infrastructure, like pipelines and fuelling stations?

**Answering these questions requires commitment and action**


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# THANK YOU

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# Development of Nuclear Hydrogen Energy in Russia for Decarbonizing the Economy

IAEA GC65 side event Innovations in the Production and Use of Nuclear Hydrogen for a Clean Energy Transition

September 21, 2021

**Alekseev S.V., Rosenergoatom, JSC**
**Ponomarev-Stepnoy N.N., Rosenergoatom, JSC**
**Petrunin V.V., Afrikantov OKBM JSC**
**Kodochigov N.G., Afrikantov OKBM JSC; speaker**

# Hydrogen as ROSATOM's New Key Product

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The hydrogen energy is considered as a way to decarbonize the economy and to reduce the greenhouse gas emissions.

In 2018, the Rosatom State Corporation included the hydrogen energy into the priority areas of the technology development. The hydrogen energy includes hydrogen large-scale production, storage, transportation and application. The nuclear hydrogen energy opens additional possibilities for decarbonizing the industry, power engineering and transportation.

From 2021, Rosenergoatom has launched an investment project aimed at developing nuclear hydrogen energy technologies. The project is set to:

- develop technologies and FEED of a nuclear power-and-process station with high-temperature gas-cooled reactors to produce hydrogen from natural gas;
- develop a pilot project aimed at hydrogen production via water electrolysis using the power produced by an NPP;
- develop the infrastructure components of hydrogen power industry and system-based support of its functioning and safety.

# Hydrogen Energy in the Energy Strategy of Russia (1)

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**The hydrogen energy in Russia has gained support on the national level.**

In his Presidential Address to the Federal Assembly of April 21, 2021, Russian Federation President Vladimir Putin mentioned that:

“We need new comprehensive approaches to the development of our energy sector, including new solutions for nuclear generation in such advanced areas as hydrogen energy and energy storage. We have to react to the challenges of climate change, adapt agriculture, industry and all the infrastructure to them, create a sector for utilization of carbon emissions...”

# Hydrogen Energy in the Energy Strategy of Russia (2)

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The Russian Government has approved:

The Energy Strategy of the Russian Federation until 2035.

Plan of Measures on *Development of Hydrogen Energy in the Russian Federation* until 2024.

Russia's Hydrogen Energy Development Concept.
The concept defines the priority methods of hydrogen production until 2035 via water electrolysis at NPP and at nuclear power-and-process station (NPPS) using fossil raw materials with zero $CO_2$ emissions.
The concept calls for creating hydrogen industrial clusters and implementing pilot projects.

# State Support Measures for the Development of Nuclear Hydrogen Energy Technologies

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**Decision made to increase the capacity factor of nuclear power plants (NPP)** via electrolysis production with electric power taken at prime cost

**Investments** for the construction of nuclear power-and-process stations (NPPS) for a large-scale hydrogen production

**Stimulation of zero-carbon development** of transport, industry and local energy consumption sector based on hydrogen technologies

**Granting preferential treatment** to export supplies of hydrogen and hydrogen technologies

**Promotion of zero-carbon development**

# Rosenergoatom's Investment Project Roadmap

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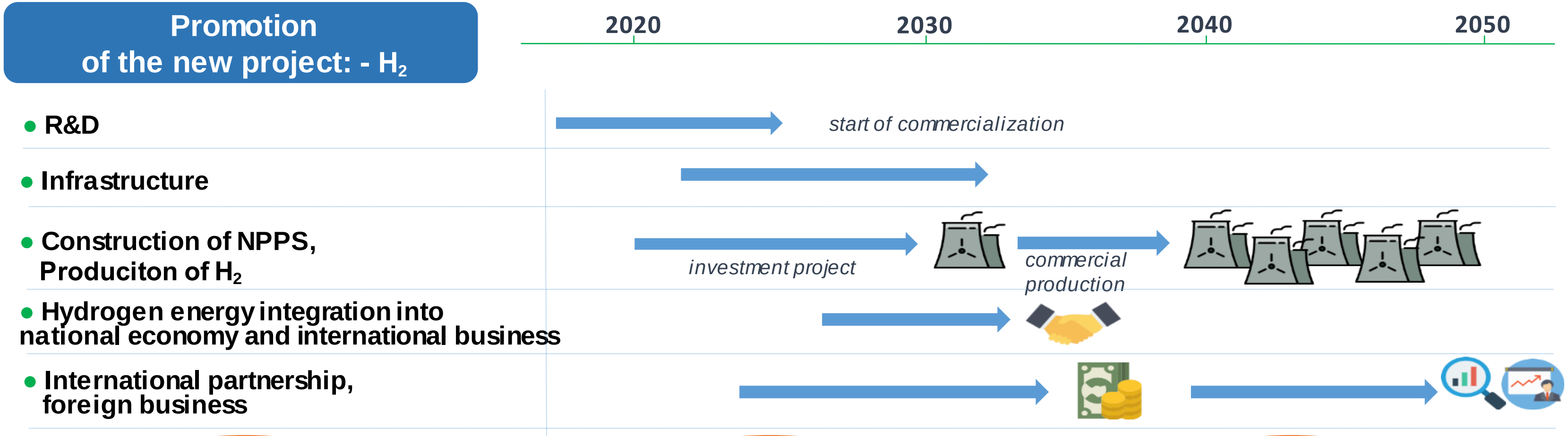


## Phase 1

R&D, development of technologies, design documentation with testing of pilot commercial modules of the main production components and of H2 consumption (between 2020-2024)

## Phase 2

Construction of a pilot commercial NPPS, development of the hydrogen energy infrastructure components and strategic partnerships (2030)

## Phase 3

Deployment of the $H_2$ supply system and modules. Hydrogen energy infrastructure and commercialization. Large-scale environmentally friendly Hydrogen production

# Investment Project - Water Electrolysis at Kola NPP

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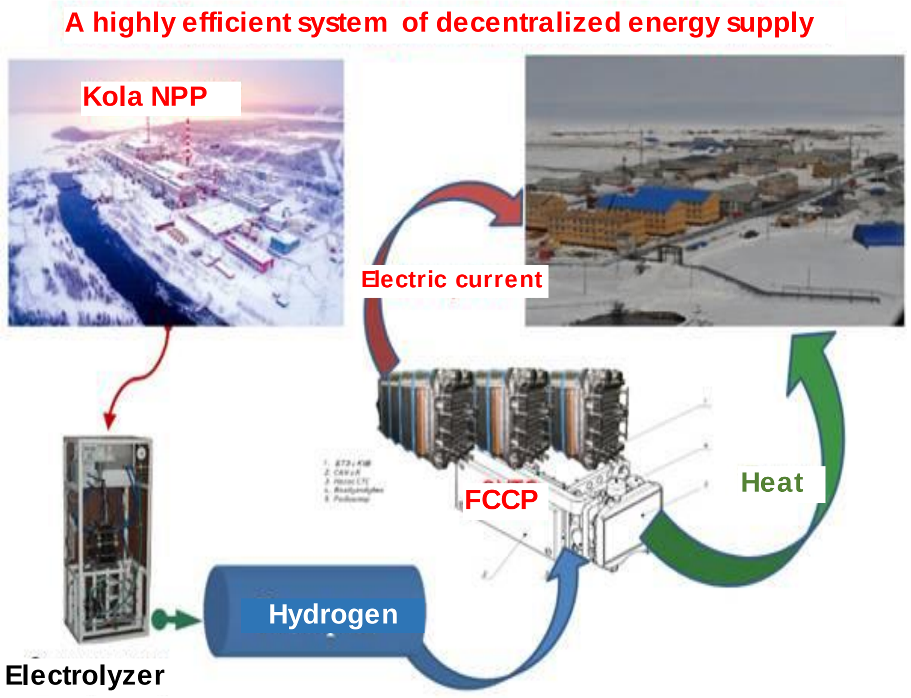
The hydrogen production pilot project includes construction of a pilot plant for testing electrolyzers and gaining experience in hydrogen storage, transportation and application.

The Kola NPP can supply up to 55 MW(e) for water electrolysis. Hydrogen is intended for hydrogen fuel cells to supply heat and electricity to isolated northern areas of Russia.

Military review magazine, 04.02.2021




FCPP — fuel cell power plant

# Investment Project for the NPPS Development

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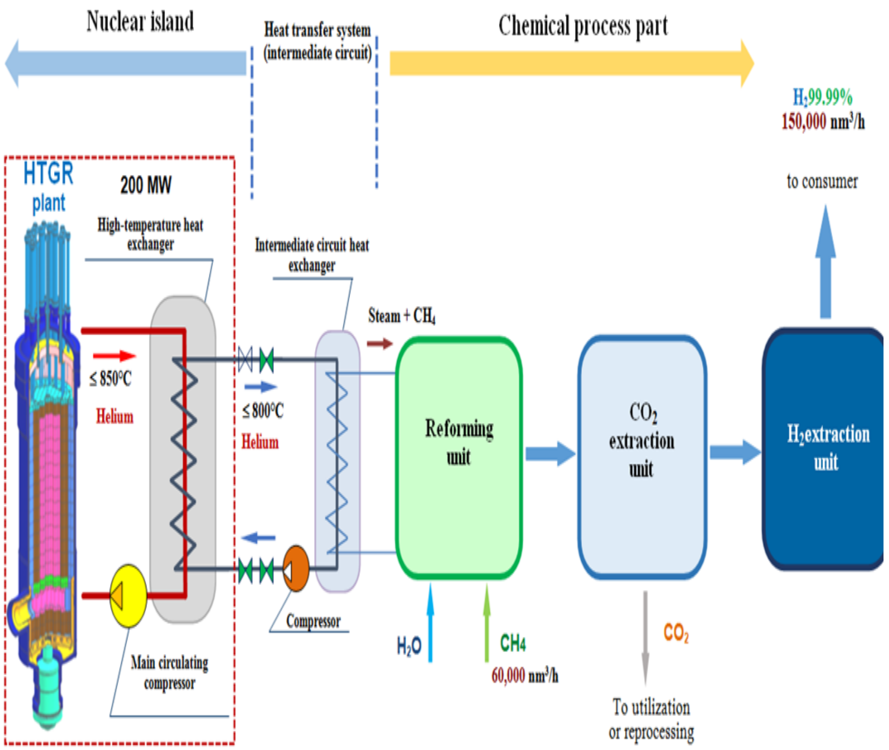
The flowchart of one NPPS module includes:

- a nuclear island with a HTGR
- a heat transfer intermediate circuit
- a chemical process part for steam methane reforming

The NPPS consists of (not shown in the flowchart):

- a natural gas purification system
- a water preparation system
- a $CO_2$-to-liquid-phase conversion facility
- an installation of hydrogen preparation for transportation (option is not selected)



# NPPS Nuclear Island and Hydrogen Segment Integration

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The NPPS nuclear and hydrogen segments have different approaches to safety assurance.

Nuclear island: It is based on the principle of defense-in-depth with barriers preventing emissions.

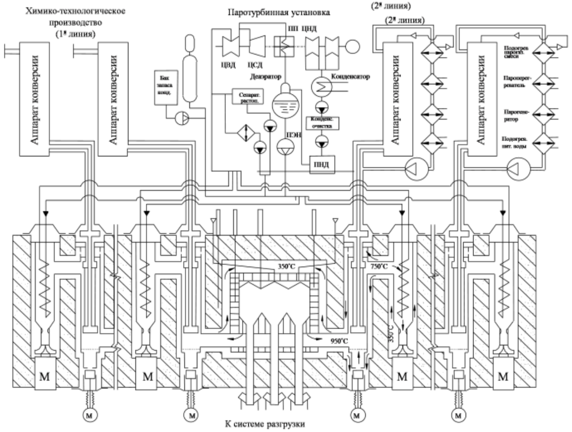
Hydrogen Segment: It is based on the principle of excluding the formation of explosive mixtures and arrangement in an open space.

The contradiction is solved by physical separation of these segments and engineering solutions aimed at preventing and mitigating the consequences of accidents in the NPPS hydrogen segment.

The task is to deliver the hydrogen to the end consumer. Russian experience in the development of nuclear-hydrogen facilities in the 1970s and 1980s: the best option is to integrate an NPPS with a large hydrogen consumer. For example, the design of an NPPS with VG-400 provided for up to 2,720 tons of hydrogen per day to be supplied to the Kirovo-Chepetsk Chemical Combine for ammonia synthesis

## VG-400 Design

**Проект РУ ВГ-400 с шаровыми твэл разрабатывался для когенерации высокопотенциального тепла и электроэнергии в составе пилотной энерготехнологической станции для производства водорода для синтеза аммиака при производстве минеральных удобрений.**




**Технические характеристики АЭУ ВГ-400**

| Характеристики | Значение |
|---|---|
| Тепловая мощность, МВт | 1060 |
| Тепловая мощность передаваемая в ХТЧ, МВт (производительность ХТЧ по аммиаку, т/сут) | 353 (2720) |
| Тепловая мощность передаваемая в ПТУ, МВт (электрическая мощность, МВТ) | 722 (300) |
| Число петель в 1 контуре | 4 |
| Температура гелия в 1 контуре: | |
| - на выходе из активной зоны, °C | 950 |
| - на входе в активную зону, °C | 350 |
| - на входе в ПГ, °C | 750 |
| Число петель промежуточного гелиевого контура | 4 |
| Температура гелия в промежуточном гелиевом контуре: | |
| - на выходе из промежуточного ТО, °C | 900 |
| - на входе в промежуточный ТО, °C | 400 |
| Параметры пара: | |
| - температура, °C | 540 |
| - Давление, МПа | 17,2 |



Nuclear Power Plants with HTGR. - Monography, JSC “Afrikantov OKBM”, 2017.

# Investment Project for the NPPS Development

Technical characteristics:

Number of reactor units: 4 units

HTGR power unit capacity: 200 MW(th)

$H_2$ capacity of a unit: 110,000 tons/year

NPPS thermal power: 800 MW

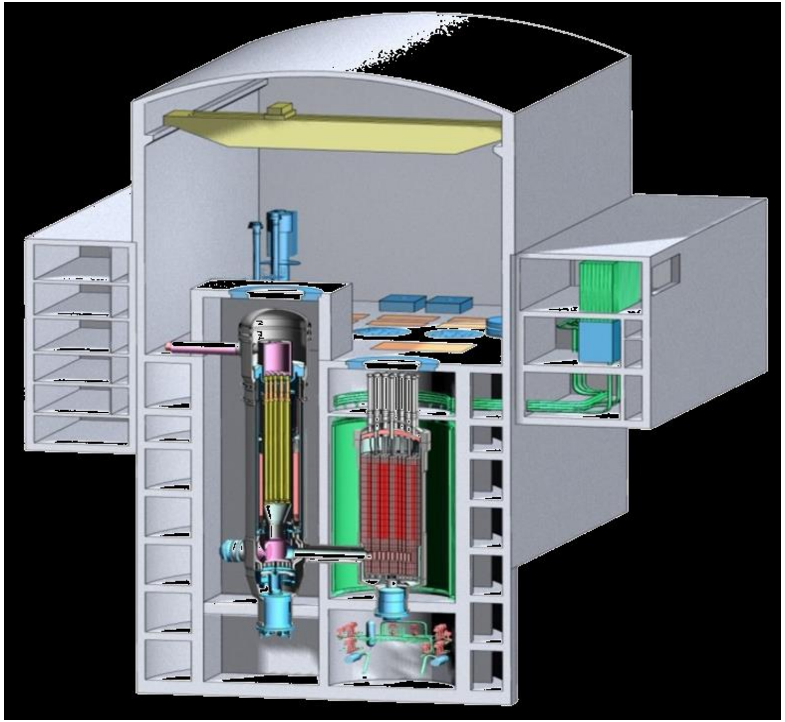
$H_2$ capacity of an NPPS: 440,000 tons/year

Hydrogen purity, at least: 99.99%

Primary helium temperature: 850°C

Secondary helium temperature: 800°C

Steam-methane mixture temperature: 750°C



Magazine “Gas Industry”, vol.11(776), November 2018; Presentation for the Scientific Session of the Russian Academy of Sciences “Nuclear and Hydrogen Power Engineering”, 75 years of Nuclear Industry, 08.12.2020

# Investment project: NPPS R&D

R&D program on the key areas of NPPS project involves:

- Verification of the codes based on the existing calculation and experimental data.
- Development of a general mathematical model of the chemical process segment and its experimental verification.
- Development of NPPS mathematical model.
- Graphite qualification based on all types of testing of the available graphite grades.
- Fuel development and qualification, pilot plant construction
- Irradiation testing of the existing materials for high temperatures and updating of the norms applied for the strength analysis of the reactor plant components.
- Development and verification of the main components of the reactor, compressors, safety systems, fuel handling systems, etc.

# Investment project: NPPS R&D

Calculation and experimental work to ensure safety at all stages of work with hydrogen and other hazardous gases in its production, mathematical and experimental modeling of combustion and explosion processes.

Creation of regulatory structure, including IAEA documents for the development and licensing of the design.

Development of the hydrogen commercial production technology based on HTGR heat and on steam methane reforming without $CO_2$ emissions, including research work at the test facilities.

Study of the options for burial or recycling of the spent nuclear fuel and graphite when it comes to commercial construction of NPPS with HTGR in the future.

# Conclusion

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1. Development and commercialization of technologies required for safe, environmentally-friendly nuclear hydrogen energy, including consumption, storage, distribution, and nuclear-assisted production of hydrogen is an advanced priority area of scientific and technical development and international cooperation of the Rosatom State Corporation. It is planned to organize the hydrogen production with zero $CO_2$ emissions at the existing NPPs by water electrolysis and at an NPPS with HTGR and chemical process segment by natural gas reforming.
2. The nuclear hydrogen energy in Russia enjoys the state support which is detailed in the Russian Federation Government Decrees and includes measures aimed at stimulating the development of hydrogen technologies. Russia has the required resources and scientific and technical potential for the development of hydrogen technologies and their effective application in various branches of economy and for export supplies.

# Conclusion

3. From 2021, ROSATOM has been implementing an investment project on the development of nuclear hydrogen energy technologies.

The main results of FEED show that the large-scale environmentally-friendly hydrogen production can be organized based on HTGR using the heat for natural gas reforming.

The development of components for hydrogen storage and usage as well as of technologies for long-distance transportation is underway.

# Decarbonising hydrogen in a net zero economy

IAEA GC65 Side Event

Dr. Felix Chow-Kambitsch (felix.chow@auroraer.com)

21 September 2021

# Aurora's new study explores the potential for nuclear to participate in the hydrogen economy

## Research questions

1. **Routes to decarbonise**
Can costs and emissions be reduced by including nuclear in a net-zero strategy?

2. **The hydrogen economy**
How could renewables and new nuclear technologies influence the hydrogen economy?

3. **The role of nuclear**
Can new nuclear business models provide flexibility to the grid, displace fossil fuels and improve nuclear economics?

Authored by:

AURORA ENERGY RESEARCH

Commissioned by:

urenco The Energy to Succeed

Additional inputs from:

LUCID CATALYST

IAEA

eDF

# We modelled a range of scenarios to investigate the impacts of differing levels of nuclear advancement on achieving net-zero

AURORA

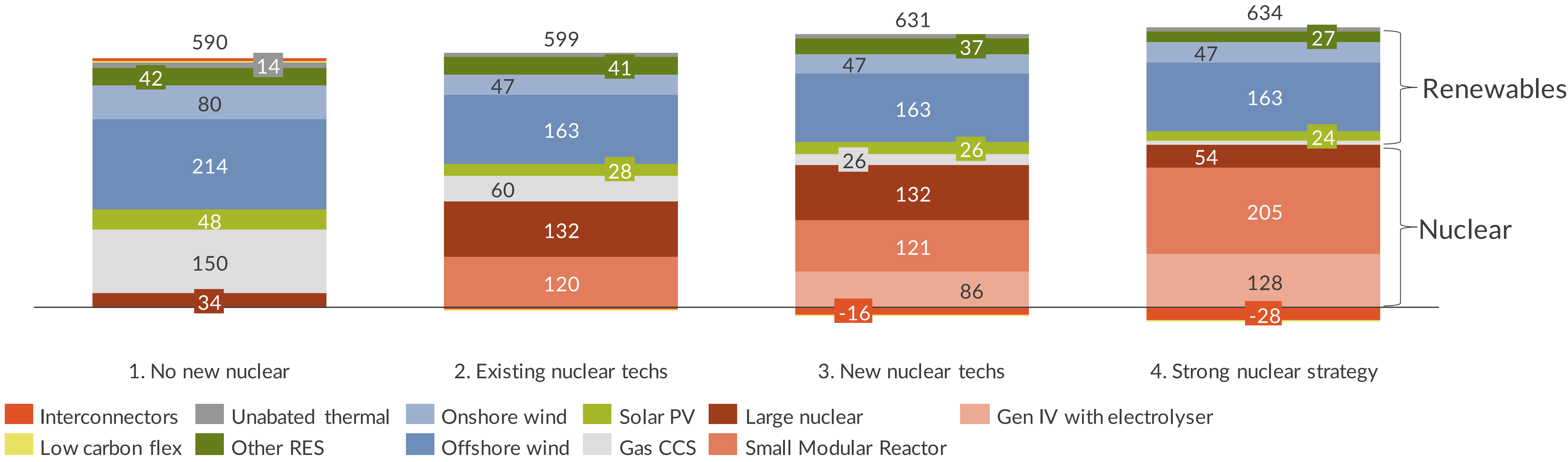
## Using the Great Britain (GB) as a case study, in a high hydrogen scenario:

Increasing nuclear ambition

1. No new nuclear | 2. Existing nuclear techs | 3. New nuclear techs | 4. Strong nuclear strategy

### GB electricity production and net imports in 2050

TWh




Source: Aurora Energy Research

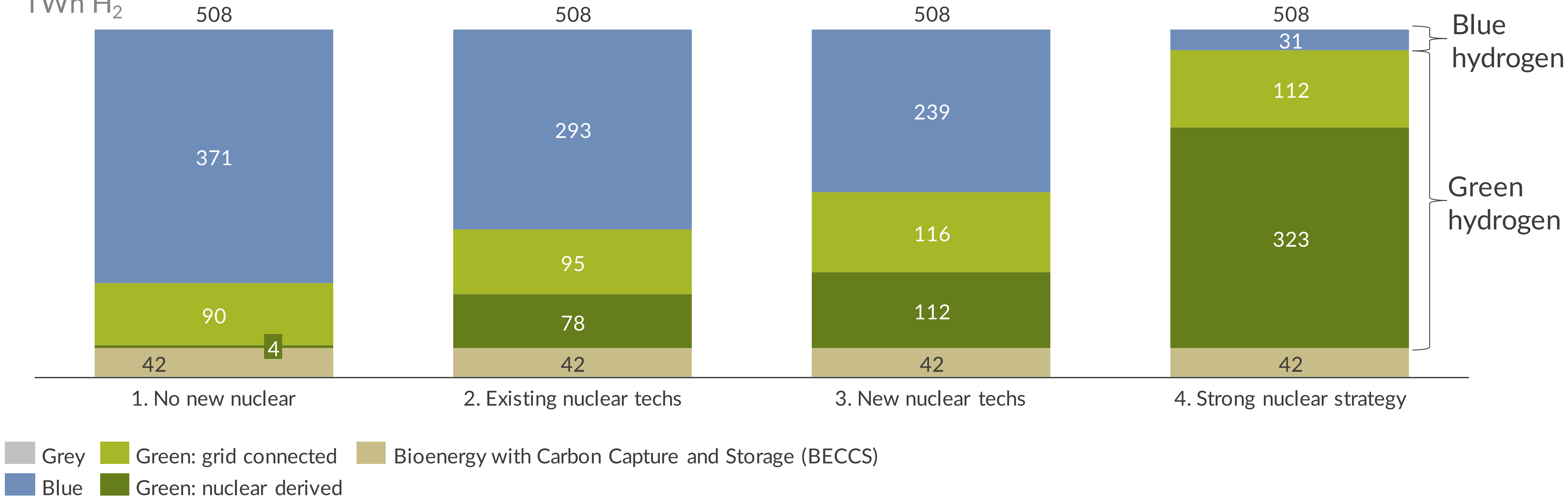
# The scenarios suggests strong nuclear pathways reduce reliance on fossil fuels in the hydrogen economy…

Increasing nuclear ambition

| 1. No new nuclear | 2. Existing nuclear techs | 3. New nuclear techs | 4. Strong nuclear strategy |
|---|---|---|---|

## GB gross hydrogen production in 2050

TWh $H_2$




Source: Aurora Energy Research

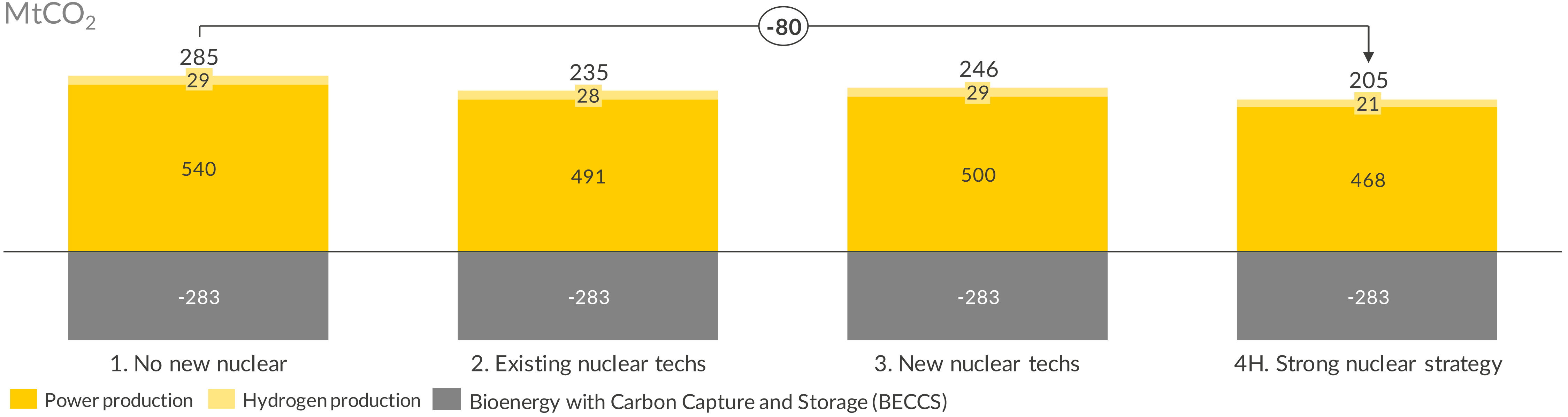
# ...lower emissions...

Increasing nuclear ambition

| 1. No new nuclear | 2. Existing nuclear techs | 3. New nuclear techs | 4. Strong nuclear strategy |
|---|---|---|---|

## GB cumulative emissions from electricity and H2 production (2021-50)

$MtCO_2$




## GB emissions from electricity and $H_2$ production in 2050 excluding BECCS

$MtCO_2$

| 8.6 | 5.5 | 4.4 | 3.0 |
|---|---|---|---|

Source: Aurora Energy Research

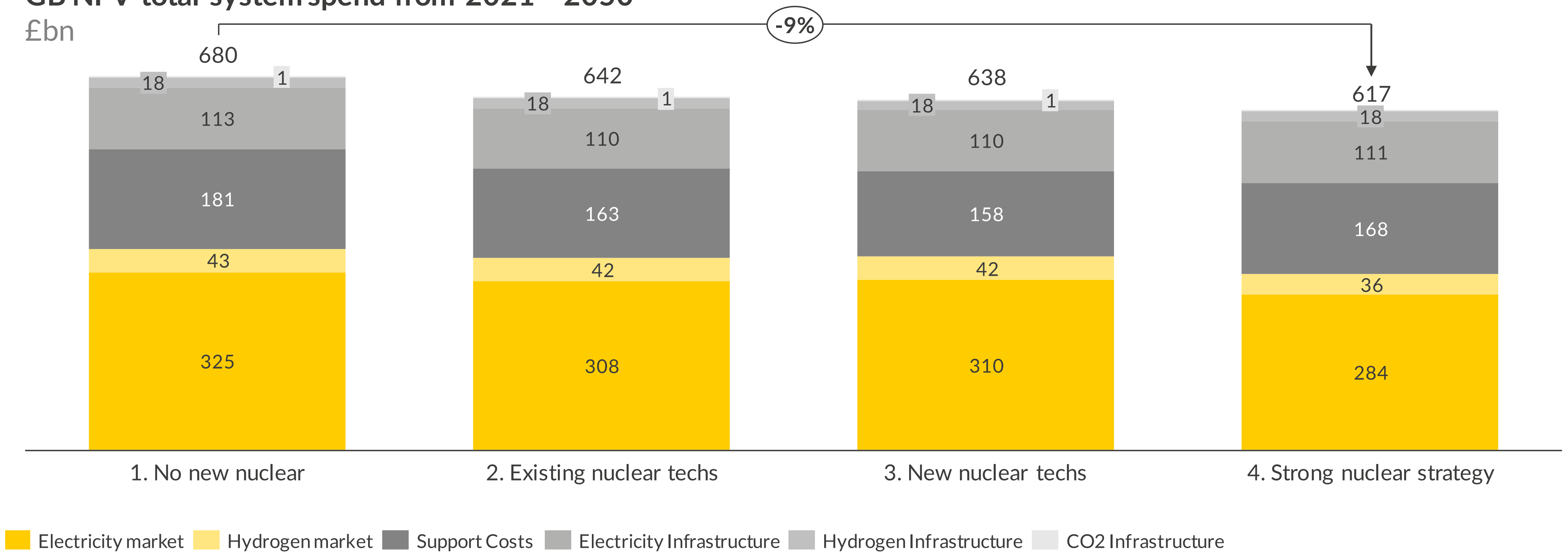
# …and lower system costs

Increasing nuclear ambition

| 1. No new nuclear | 2. Existing nuclear techs | 3. New nuclear techs | 4. Strong nuclear strategy |
|---|---|---|---|

**GB NPV total system spend from 2021 – 2050[1]**

£bn




1) Costs are discounted using a rate of 5%.

Source: Aurora Energy Research

# Key insights of the full report are:

AURORA

1. Deploying renewables and nuclear for power and hydrogen is required to ensure rapid decarbonisation and reduced reliance on fossil fuels
2. Achieving $H_2$ volumes required for net-zero without fossil fuels will be challenging without support for electrolytic $H_2$ from RES and nuclear
3. Including nuclear with co-located electrolysers alongside high RES is economically efficient, reducing total system spending by 6-9% (NPV from 2021 – 2050)
4. Novel business models for nuclear energy (i.e. small modular reactors and Gen IV reactors) can provide cost competitive and scalable sources of zero carbon electricity and hydrogen
5. Careful market design and policy support structures are required to get to net-zero
6. Broader potential benefits of technology mixes should be considered

Source: Aurora Energy Research

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ENERGY RESEARCH

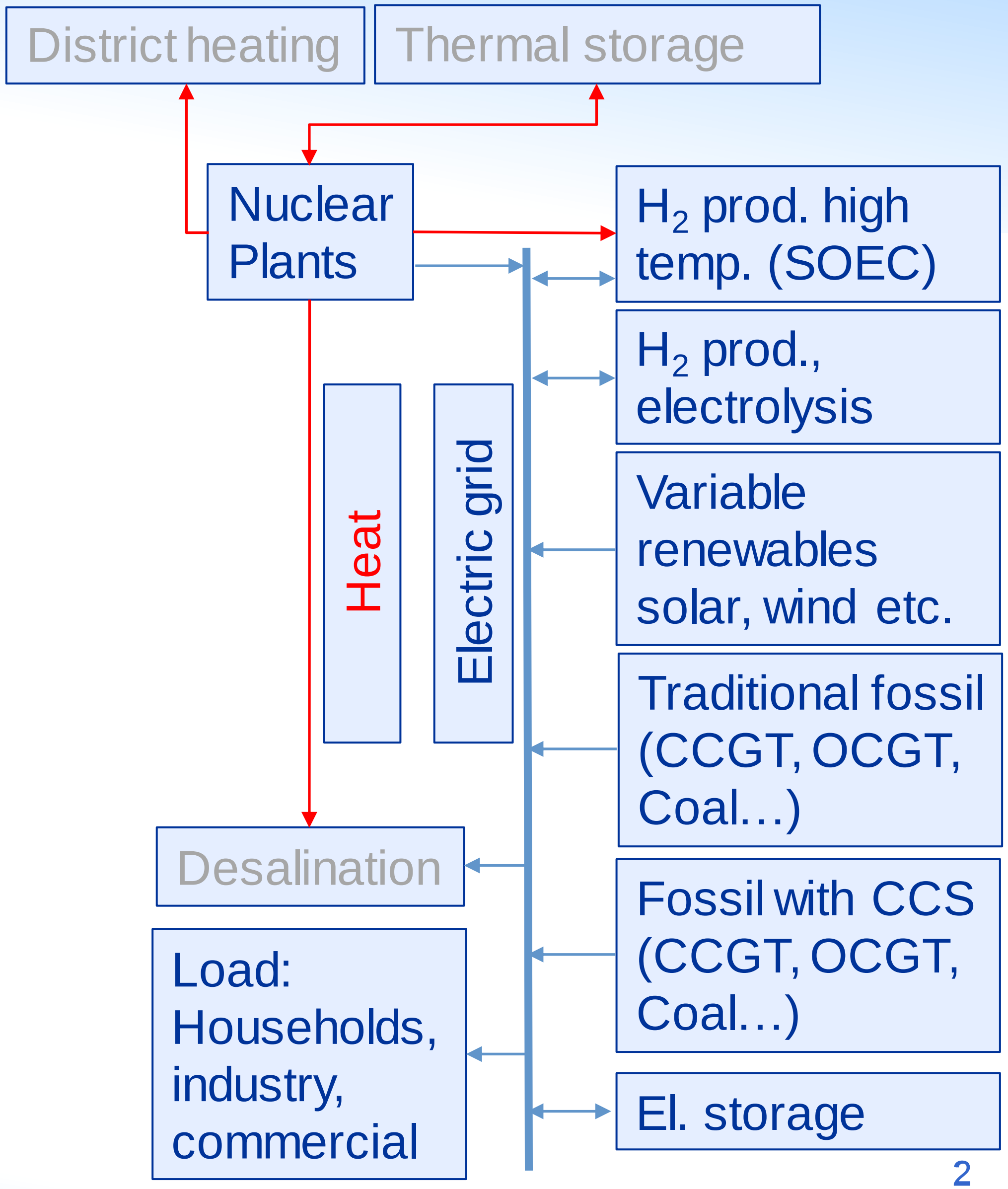
# IAEA Power System Modelling with $H_2$ Example of Sensitivity Studies

F. Ganda, B. Boyer (INPRO)
M. Cometto, H. Paillère (PESS)
A. Constantin, S. Monti (NPTDS)

GC side event – 21 Sep 2021

# Integrated Energy System Analysis: FRAMES

- Growing interest in integrated energy systems (Member States and IAEA), in particular with nuclear and renewables
- IAEA is developing an in-house capability (FRAMES)
- Can quantify the value that nuclear brings to low-carbon energy systems, and inform policy
- FRAMES can also highlight the performance of nuclear for non-electric applications ($H_2$ production, district heating, desalination, etc.)



# IAEA-FRAMES in a nut-shell

**INPUT** (Most important parameters)

- Demand profile (hourly for 1 y)
- VRE load factors (hourly for 1 y)
- CAPEX, OPEX & other costs of each technology
- Operational constraints (ramp rates, min up/down time etc.)
- $CO_2$ intensity of each technology
- Cap on $CO_2$ emissions of the entire system

```
# Run file for relaxed CapExp/UC/ED clustered integrated model
# F. Ganda - 21-02-2020

for {period in 0..H_period} {
#   The load/wind/hydro etc need to be revisited: right now all identical
        let {h in 1..H}    LOAD_EL_NORM[h,1]  :=   LOAD1_8784[H_start+h+H*period]
        let {h in 1..H} SOL_DIS[h,1]  :=    SOL1_DIS_8784[H_start+h+H*period];
        let {h in 1..H}   SOL_C[h,1]  :=    SOL1_C_8784[H_start+h+H*period];
        let {h in 1..H}    WIND_N[h,1]  :=   WIND1_N_8784[H_start+h+H*period];
        let {h in 1..H}    WIND_F[h,1]  :=   WIND1_F_8784[H_start+h+H*period];
        let {h in 1..H}  HYDRO1[h,1]  :=  HYDRO1_1_8784[H_start+h+H*period];
        let {h in 1..H}  HYDRO2[h,1]  :=  HYDRO1_2_8784[H_start+h+H*period];
        let {h in 1..H}  HYDRO3[h,1]  :=  HYDRO1_3_8784[H_start+h+H*period];
        let {h in 1..H}  HYDRO4[h,1]  :=  HYDRO1_4_8784[H_start+h+H*period];
#  Load and VRE data for the 2nd zone
#       let {h in 1..H}    LOAD_EL_NORM[h,2]  :=   LOAD2_8784[H_start+h+H*period]
#       let {h in 1..H} SOL_DIS[h,2]  :=    SOL2_DIS_8784[H_start+h+H*period];
#       let {h in 1..H}   SOL_C[h,2]  :=    SOL2_C_8784[H_start+h+H*period];
#       let {h in 1..H}    WIND_N[h,2]  :=   WIND2_N_8784[H_start+h+H*period];
#       let {h in 1..H}    WIND_F[h,2]  :=   WIND2_F_8784[H_start+h+H*period];
#       let {h in 1..H}  HYDRO1[h,2]  :=  HYDRO2_1_8784[H_start+h+H*period];
#       let {h in 1..H}  HYDRO2[h,2]  :=  HYDRO2_2_8784[H_start+h+H*period];
#       let {h in 1..H}  HYDRO3[h,2]  :=  HYDRO2_3_8784[H_start+h+H*period];
#       let {h in 1..H}  HYDRO4[h,2]  :=  HYDRO2_4_8784[H_start+h+H*period];
     for {r in 1..R} {
     for {i in 1..C} {        # Create indexed parameters on Clusters
         let ISTATE[i,r] := ISTATE_L[i+C*(r-1)];
         let C_FIX_CAP[i,r] := C_FIX_CAP_L[i+C*(r-1)];
         let C_FIX_OPX[i,r] := C_FIX_OPX_L[i+C*(r-1)];
         let C_var_fuel[i,r] := C_var_fuel_L[i+C*(r-1)];
         let C_var_opex[i,r] := C_var_opex_L[i+C*(r-1)];
         let P_max_MW[i,r] := P_max_MW_L[i+C*(r-1)];
         let P_min_PC[i,r] := P_min_PC_L[i+C*(r-1)];
         let Eta[i,r] := Eta_L[i+C*(r-1)];
         let HTH2[i,r] := HTH2_L[i+C*(r-1)];
```

PARTS OF THE OBJECTIVE FUNCTION PARTS RELATED TO H2 PRODUCTION

$$min \sum_c \sum_h \sum_r P\_TOT_{c,h,r} * (C\_var\_fuel_{c,r} + C\_var\_opex_{c,r}) + [\ldots] +$$

$$+[\ldots]+$$

$$+\sum_r (MAX\_H2\_PROD\_EL_r * FCOST\_H2\_PROD\_EL_r * H/8760) +$$

$$+\sum_r (MAX\_H2\_PROD\_SI_r * FCOST\_H2\_PROD\_SI_r * H/8760) +$$

$$+\sum_r (MAX\_H2\_PROD\_SMR_r * FCOST\_H2\_PROD\_SMR_r * H/8760) +$$

$$+\sum_r (MAX\_H2\_PROD\_SMRCCS_r * FCOST\_H2\_PROD\_SMRCCS_r * H/8760) +$$

$$+\sum \sum H2\_smr\_var\_cost * h2\_prod\_smr + $$

- **FRAMES finds the *optimum*, i.e. the "*best that can be done*" from the cost viewpoint, to satisfy a given electricity, $H_2$ and heat demand.**
- ***This provides a quantitative and defensible basis for informing policy making*, as well as to support analyses of a variety of technical requirements.**

**OUTPUT** (Most important)

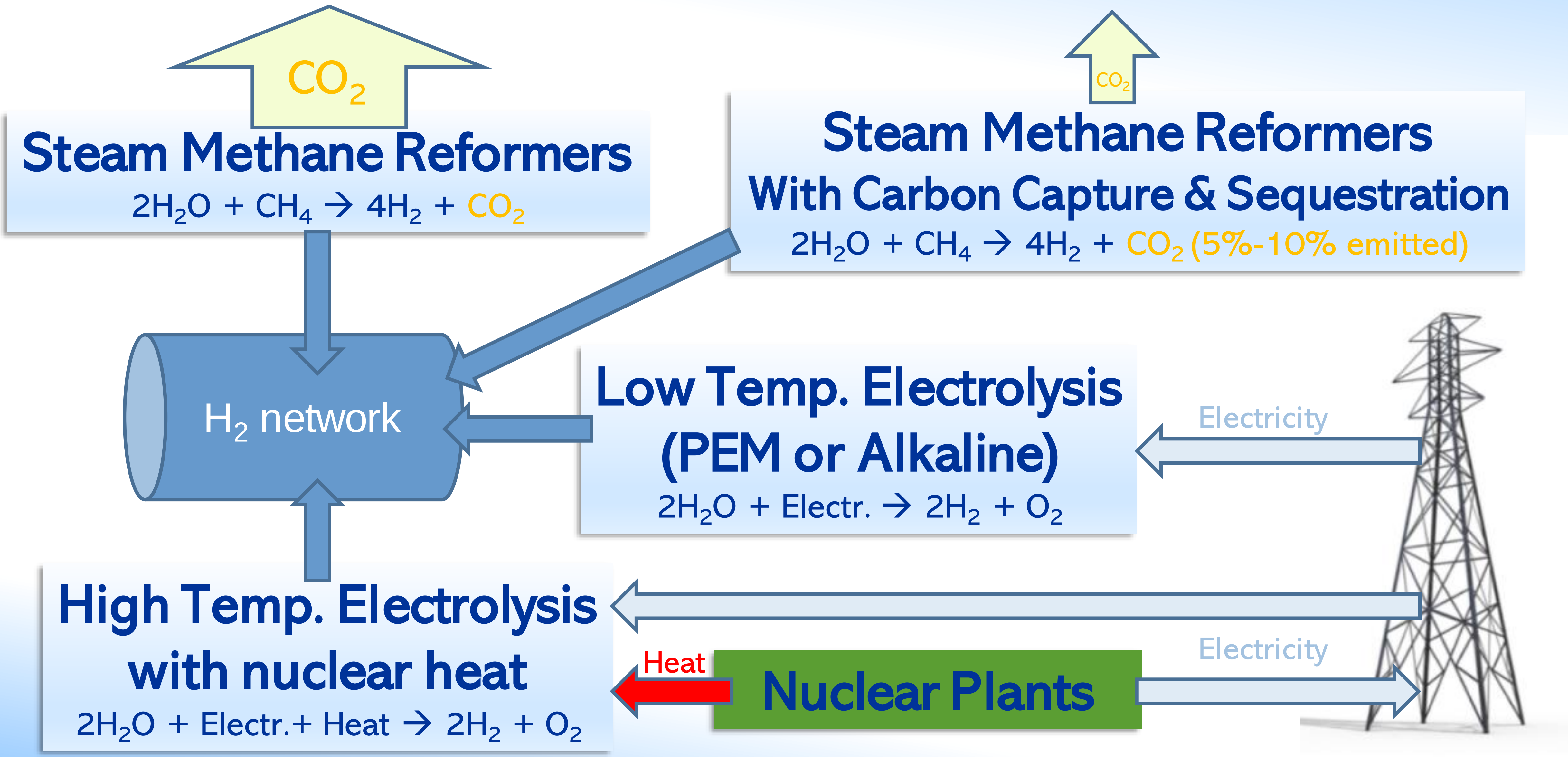
- Optimal capacity of each technology (with respect to cost) (Nuclear, coal, gas, VRE, batteries etc.)
- Optimal power level of each technology (hourly)
- Total system costs
- Total curtailment of renewables
- Transmission power flow if multi-zone model
- Hydrogen production if included

# Four $H_2$ production options in FRAMES

- Conventional steam methane reforming (SMR) of natural gas;
- Steam methane reforming of natural gas with CCS (i.e. blue hydrogen);
- Low temperature electrolysis using grid electricity (PEM or Alkaline);
- High temperature processes using nuclear heat. It can be thermochemical cycles (e.g. S-I, Cu-Cl etc.) or high temperature steam electrolysis (HTSE).

FRAMES allows to study the relative competitiveness of the four processes under different sets of assumptions: $CO_2$ emission limits, costs of the various technologies, etc.

# $H_2$ production modelling in FRAMES

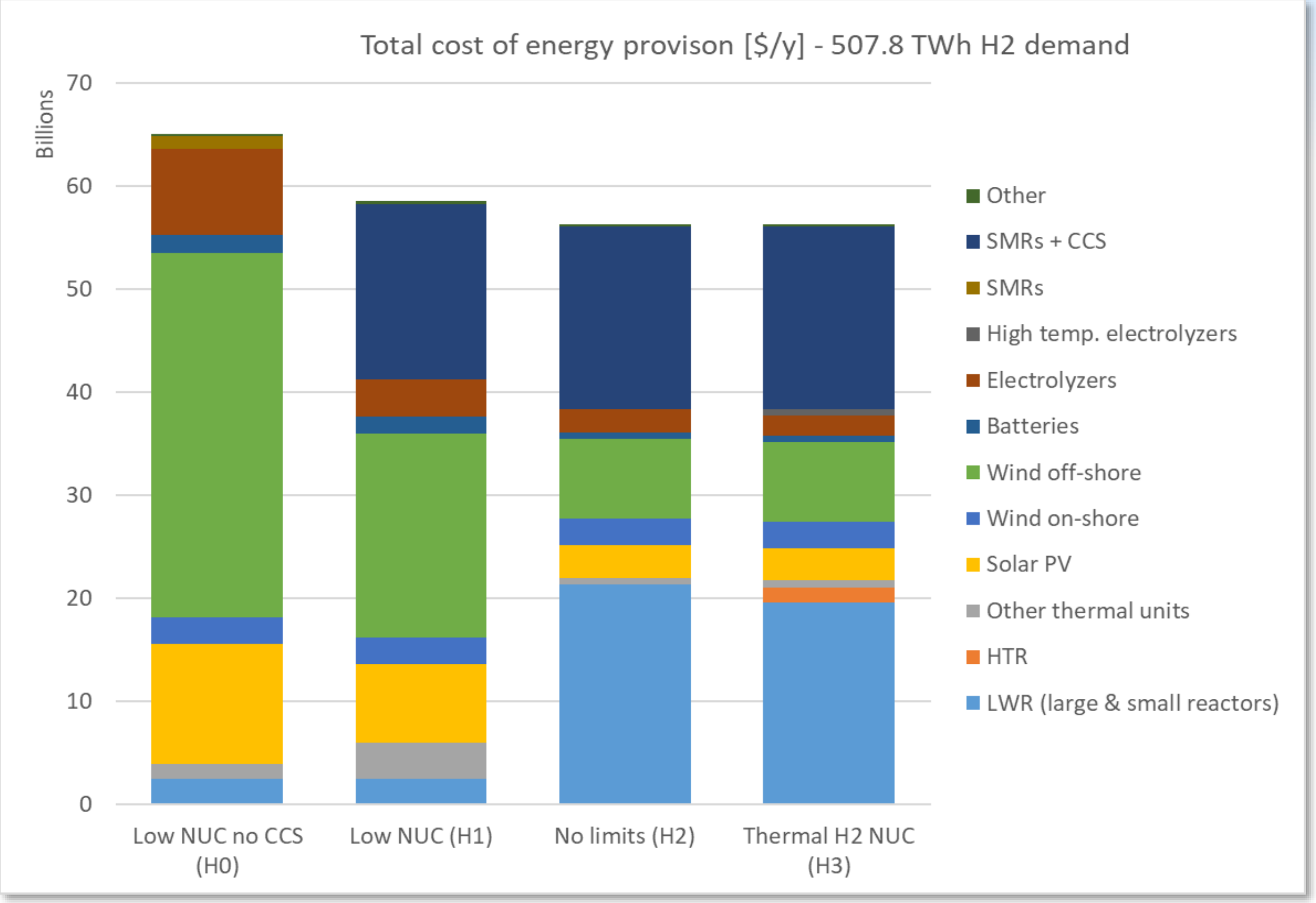


# IAEA performed several sensitivities studies, in addition to scenarios consistent with URENCO/Aurora

The IAEA FRAMES results were found to be broadly consistent with the Aurora's results, despite some modelling differences.

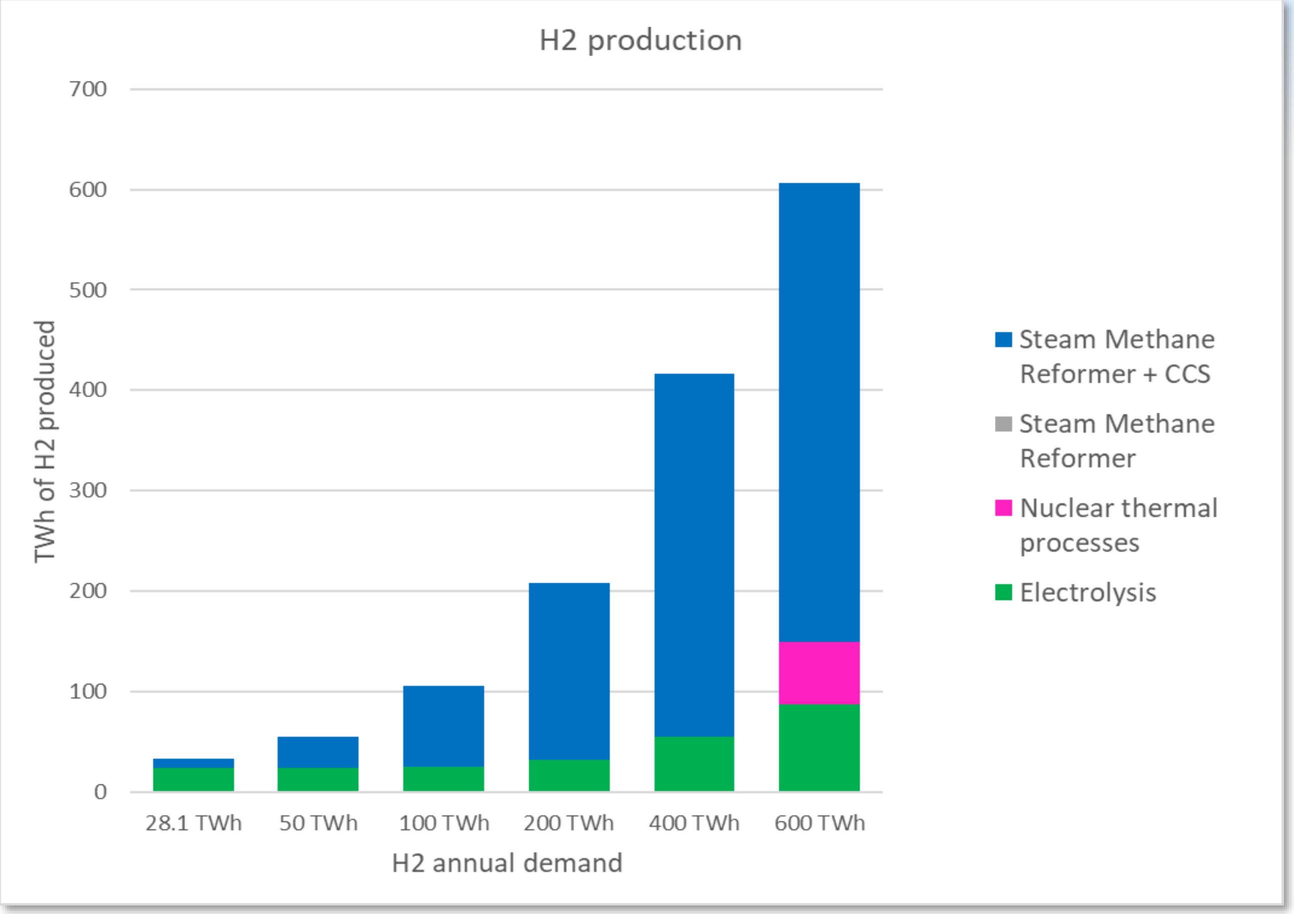
- Time marching approach (Aurora, 2020-2050) vs. static approach (IAEA, 2050)
- Included only generation costs (IAEA) vs. additional system costs (Aurora)
- Different approach in setting the carbon conditions (carbon price vs. carbon constraint)
- IAEA performed additional sensitivity scenarios:
  - Very low $H_2$ demand scenario;
  - No CCS;
  - Cost of capital for low-carbon technologies;
  - Construction cost of nuclear.

# Achieving net zero with nuclear reduces the cost of energy provision




Systems with nuclear are less costly, *even* assuming large cost reductions of renewables (i.e. VRE significantly cheaper than nuclear on a levelized cost basis).

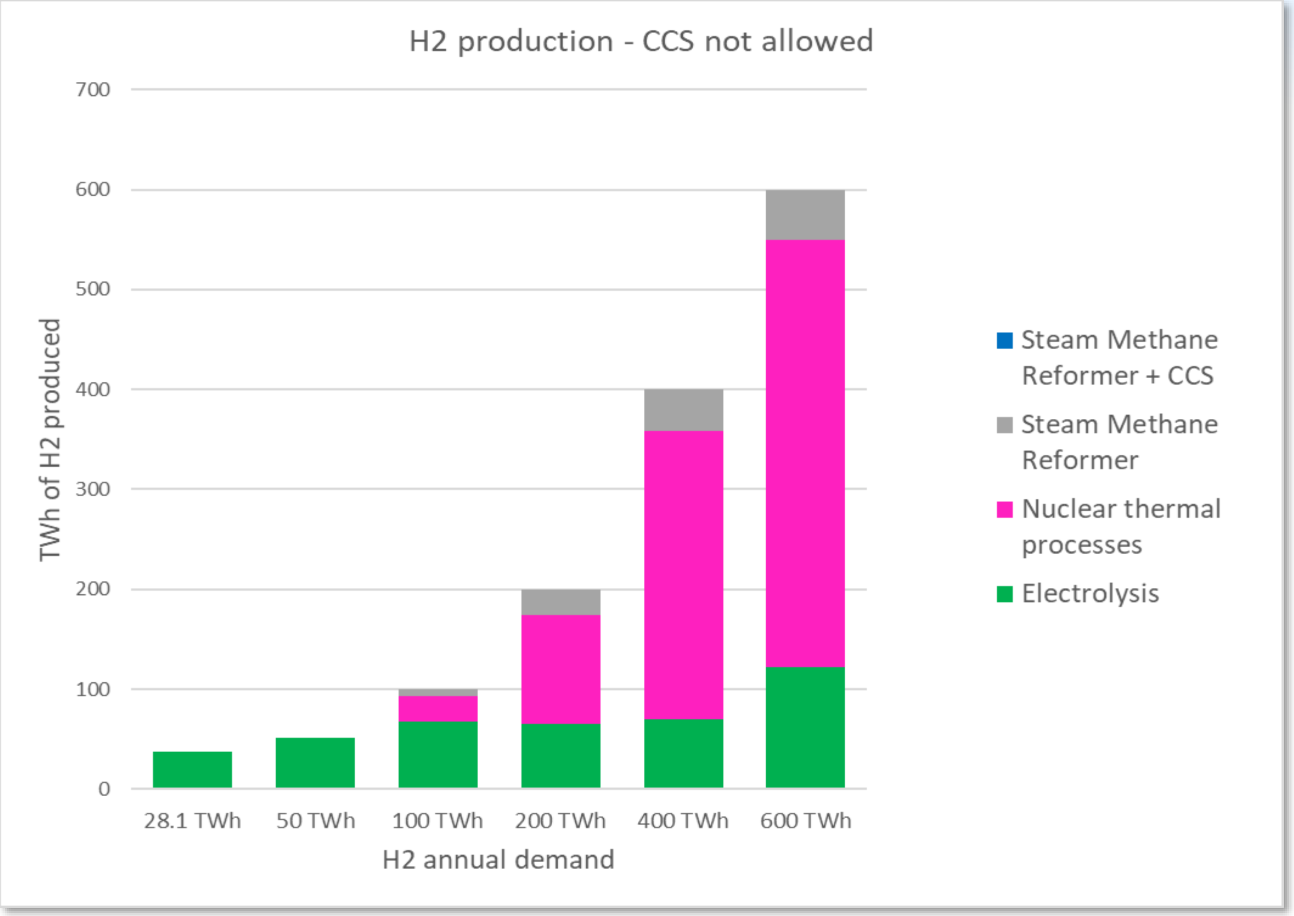
# Steam methane reforming with CCS plays the leading role in producing large amounts of $H_2$




The high level of SMR deployment depends on some key assumptions:

- Fugitive $CH_4$ emissions from SMR+CCS have not been considered.
- High $CO_2$ capture rate (90%)
- Natural gas price (~$6/MMBTU).

# In the absence of CCS, nuclear plays the leading role in producing low-carbon $H_2$ through the use of nuclear heat




These results depend on the relative cost of the various low-carbon technologies.

# Conclusions

- The IAEA is developing FRAMES as an in-house modelling capability for integrated systems assessment.
- FRAMES can help quantify the value that nuclear brings to low-carbon energy systems, and its complementarity with renewables.
- It can inform policy and other techno-economic evaluations: e.g. optimal technologies for $H_2$ production, including with nuclear heat.
- Currently, FRAMES is used to analyse nuclear energy's role in decarbonization strategies.
- Collaborations on complex energy system modelling and methodologies with MSs could be considered in the future.

IAEA
International Atomic Energy Agency

# *Thank you!*