Nuclear Hydrogen Production

Rami El-Emam

CONTENTS

Introduction to Hydrogen Production

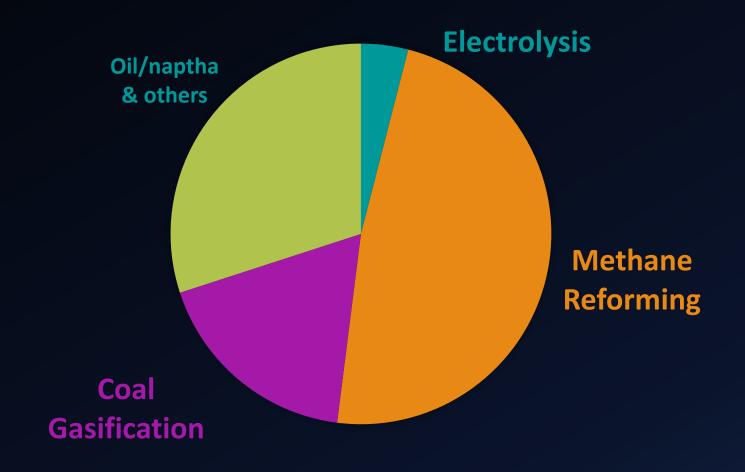
Coupling Routes

Generation-IV for Hydrogen Production

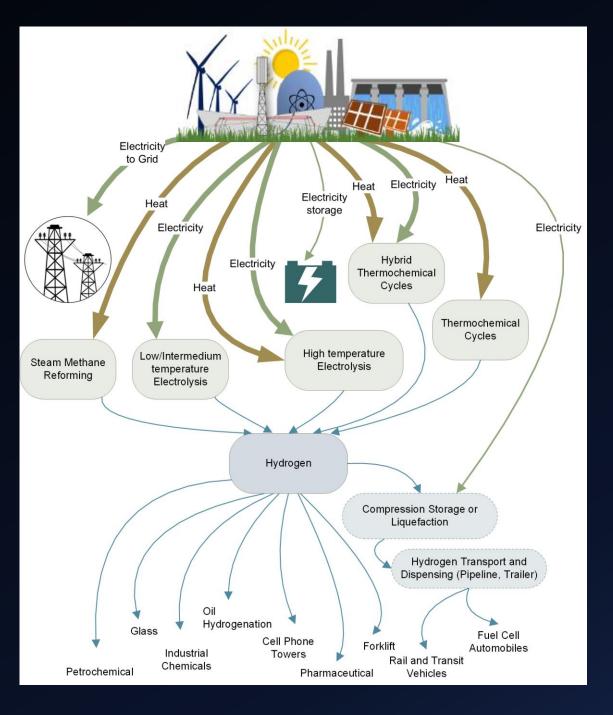
Clean Hydrogen Technologies

Technoeconomics of Hydrogen Production

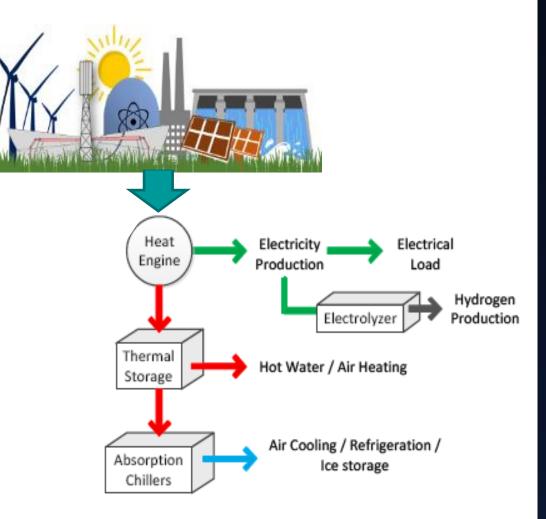
Hydrogen Today!



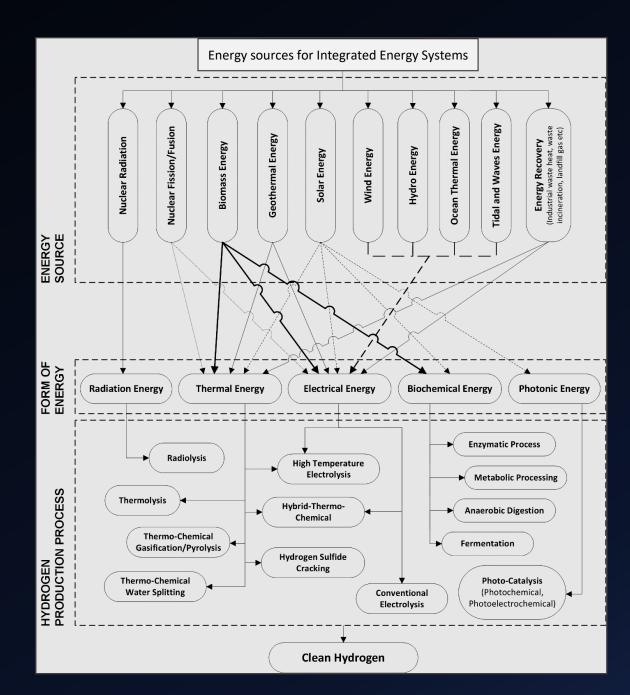
Routes for Clean Hydrogen Production



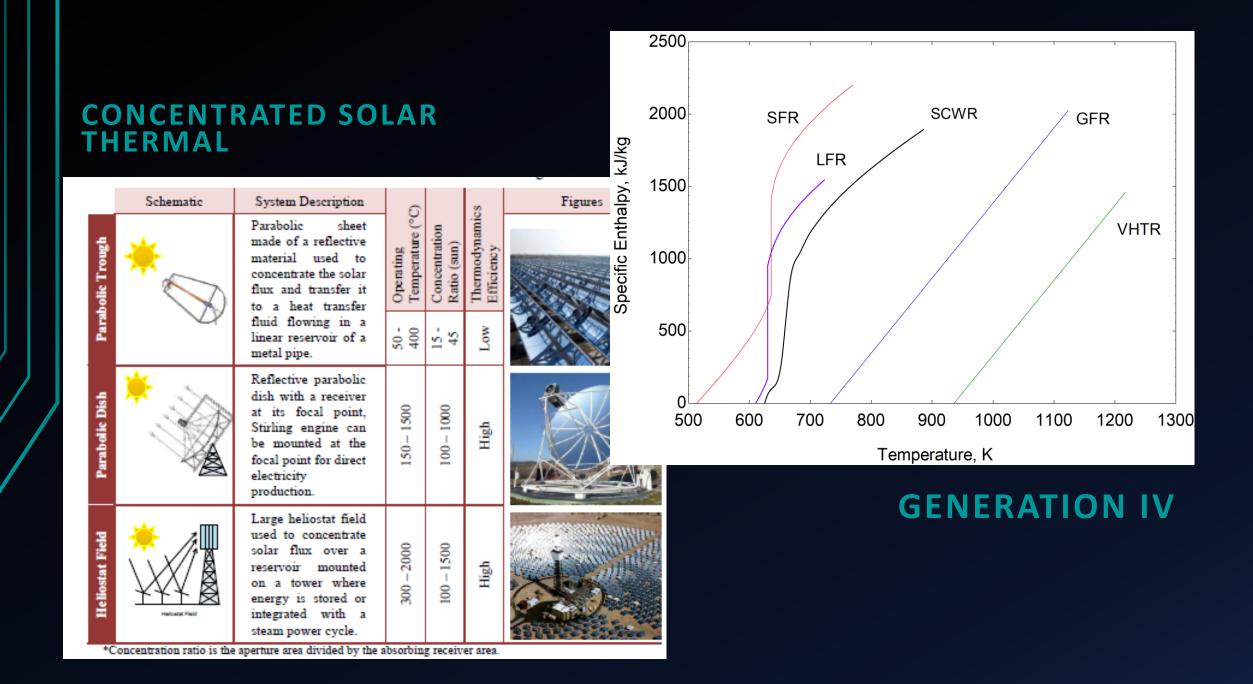
Why Multi-generation



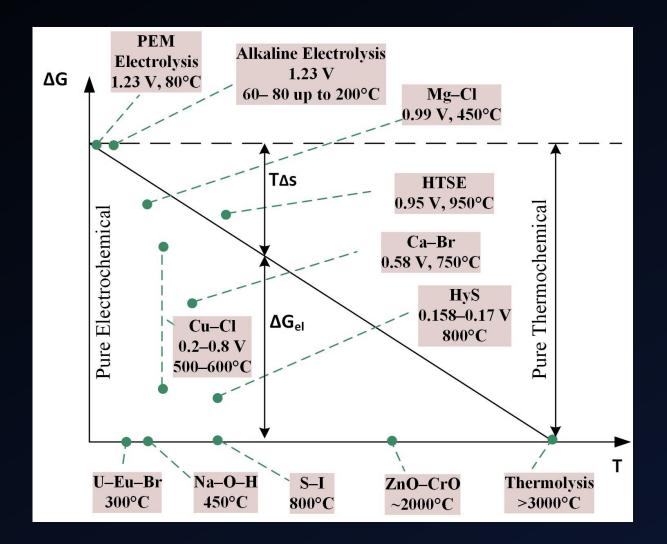
ROUTES FOR CLEAN HYDROGEN USING INTEGRATED ENERGY SYSTEMS



APPLICATIONS OF MULTIGENERATION INTEGRATED ENERGY SYSTEMS	District/process heating 80– 120°C	Reverse Osmosis desalination	Thermal desalination 85– 160°C	Pulp & paper manufacturing 200–400°C	Methanol production 250– 350°C	Heavy oil desulfurization 300–500°C	Petroleum refining 300– 400°C	Methane reforming 700– 1000°C	Thermochemical H2 cycles 800–1000°C	Hybrid thermochemical cycles 450–800°C	PEM electrolysis 60–90°C	Alkaline electrolysis 80–200°C	High temperature electrolysis 750–1000°C	Biomass gasification 800– 900°C	Coal gasification 900–1400°C	Steel making 900–1200°C
Generation IV reactors																
Super Critical Water Reactor 500–625°C	•	•	•	•	•	•	•	•		•	•	•				
Very High Temperature Reactor 750–950°C	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Sodium cooled Fast Reactor 450–550°C	•	•	•	•	•	•	•	•		•	•	•				
Gas cooled Fast Reactor 750–850°C	•	•	•	•	•	•	•	•		•	•	•	•	•		
Molten Salt Reactor 650–850°C	•	•	•	•	•	•	•	•	•	•	•	•	•	•		
Lead cooled Fast Reactor 450–800°C	•	•	•	•	•	•	•	•	•	•	•	•	•			
Solar Energy Systems																
Photovoltaic ~ 60°C		•									•					
Concentrated Photovoltaic <80°C		•									•					
Parabolic Trough 50–550°C	•	•	•	•							•					
Linear Fresnel Lens 150–250°C	•	•	•								•	•				
Linear Fresnel Reflector >300°C	•	•	•								•	•				
Power Tower/Heliostat 300–800 up to 2,000°C	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Parabolic Dish Engine ~650°C up to 1,200°C	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
Wind Turbine Farms		•									•					
Geothermal Energy System	•	•	•								•	•				



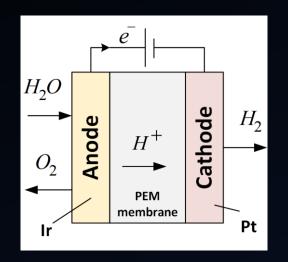
Which Hydrogen Technology to use!



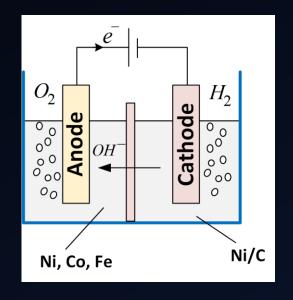
Which Hydrogen Technology to use!

Electrolysis

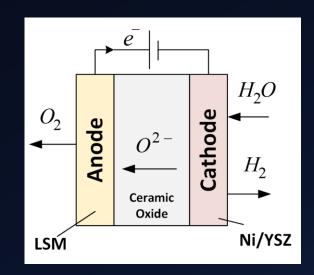
PEM Electrolysis



Alkaline Electrolysis

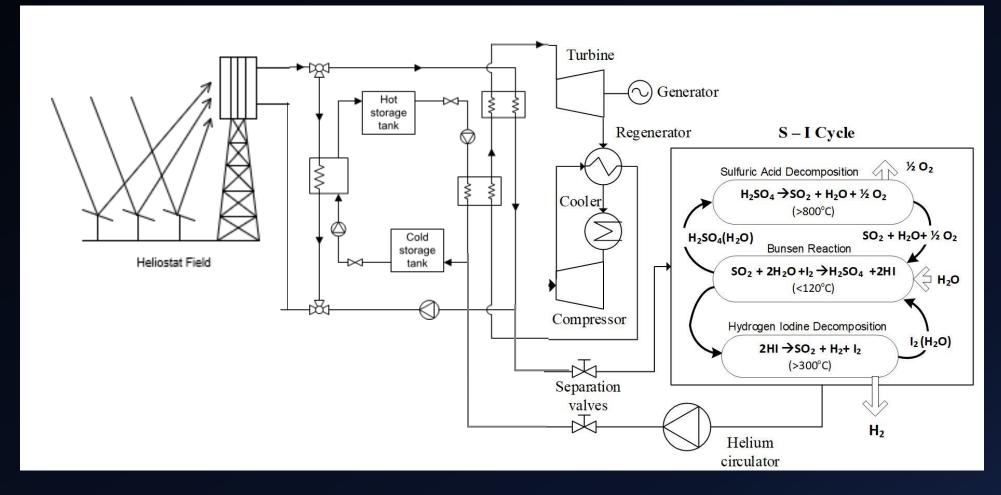


High Temperature Electrolysis



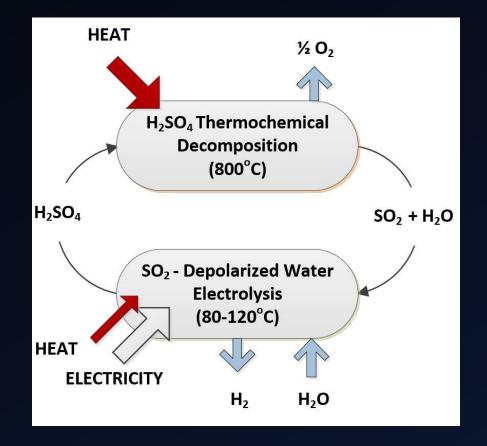
Thermochemical Processes

Sulfur – Iodine



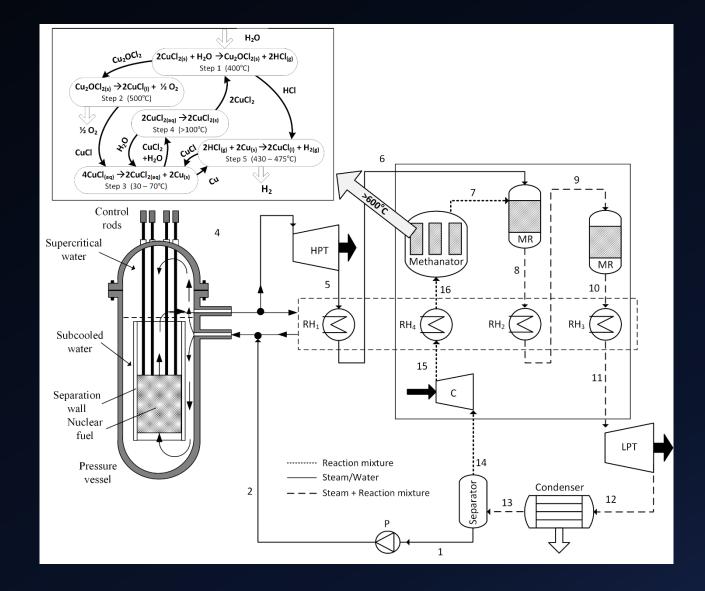
Thermochemical Processes

Hybrid Sulfur Process

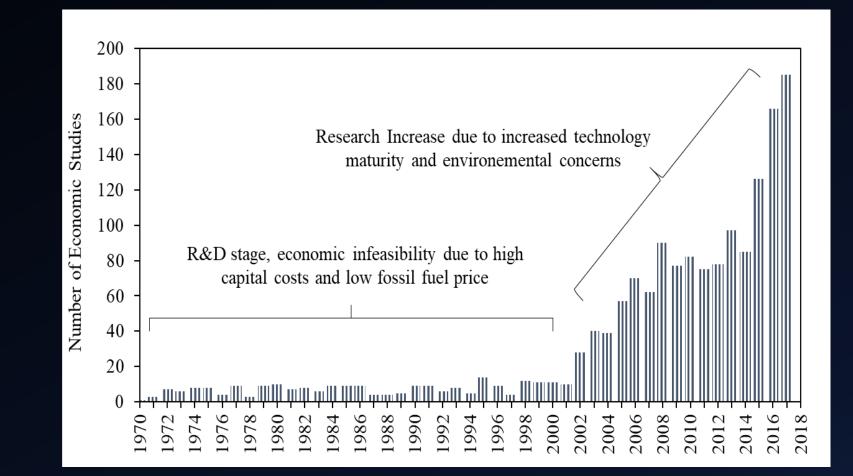


Thermochemical Processes

Hybrid Copper-Chlorine

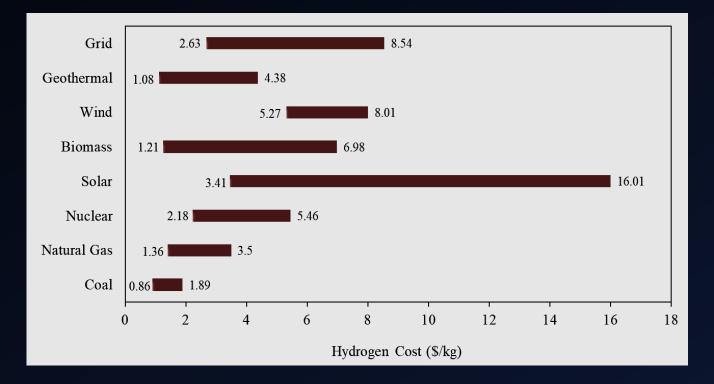


HYDROGEN TECHNOECONOMICS!

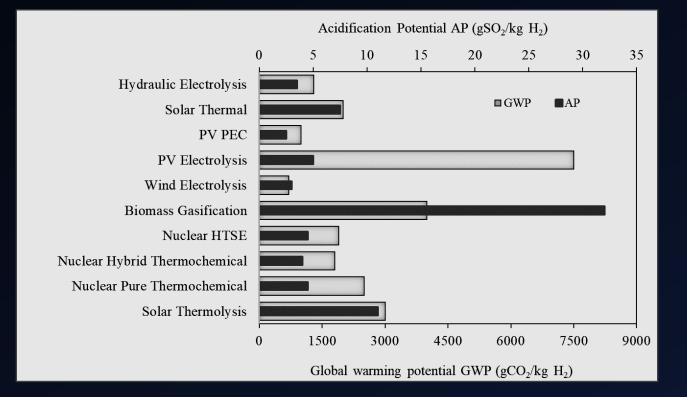


Studies on hydrogen economics by year

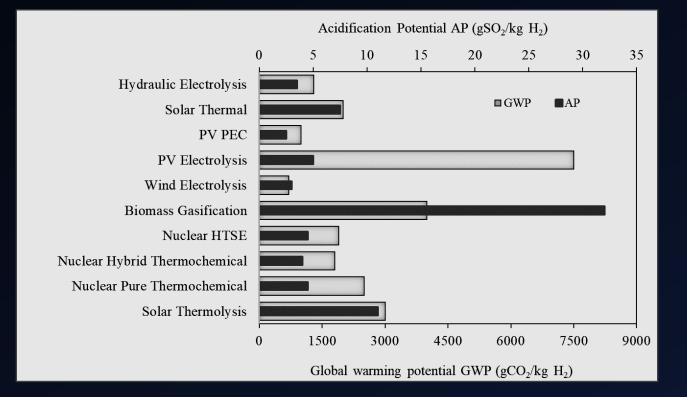
COST RANGE OF HYDROGEN PRODUCTION TECHNOLOGIES BASED ON ENERGY SOURCE



AVERAGED VALUES OF GWP AND AP FOR SELECTED HYDROGEN GENERATION TECHNOLOGIES



AVERAGED VALUES OF GWP AND AP FOR SELECTED HYDROGEN GENERATION TECHNOLOGIES



SOME TOOLS OF ASSESSING HYDROGEN ECONOMICS

HEEP

HEEP is a single window-based software, developed by the International Atomic Energy Agency (IAEA) to perform economic analysis for large-scale nuclear hydrogen production. HEEP estimated the levelized cost of produced hydrogen by utilizing around 20 input parameters of technical, economic, and chronological data, using discounted cash flow model. Power credit method is applied for the calculation of thermal and electricity cost when both are needed for the hydrogen plant. The tool can analyze different scenarios of hydrogen storage and transportation.

G4Econs

G4Econs is a Microsoft Excel-based application, developed by the Economic Modelling Working Group (EMWG) of GIF. It calculates the Levelized Unit Electricity Cost (LUEC) from the reactor module, and the Levelized Unit Hydrogen Cost (LUHC) from the energy-products model, based on the required energy type for the hydrogen plant technology. More information on the tool can be found on GIF website (G4Econs, 2018).

H2A

H2A (Hydrogen Analysis) is developed by the Department of Energy (DOE), USA, with the contribution of several national Labs and universities. H2A calculates the levelized cost of hydrogen for various options of large-scale hydrogen production using coal and biomass gasification, natural gas reforming, nuclear and wind energy. H2A Analysis Group also developed three other models for a larger scope of analysis, these are the Hydrogen Delivery Scenario Analysis Model (HDSAM), the Hydrogen Refueling Station Analysis Model (HRSAM), and the Heavy-Duty Refueling Station Analysis Model (HDRSAM). More information can be found at the website of Hydrogen and Fuel Cells Program of DOE (DOE, 2019).

H2FAST

H2FAST (Hydrogen Financial Analysis Scenario Tool) is developed by the NREL to provide a quick and in-depth financial analysis for hydrogen fueling stations. More information on the tool can be found at the website of NREL (NREL - H2FAST, 2018).

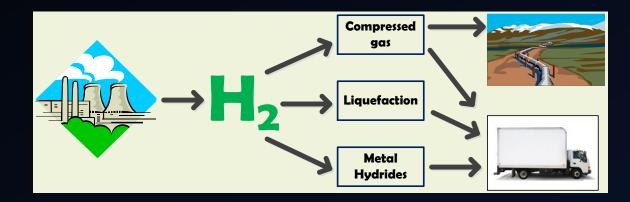
The IAEA HEEP: Description & Case Studies CONTENTS

- Introduction to HEEP and its Features
- Demonstration of HEEP
- Comparative Case Studies
- Benchmarking

Hydrogen Economic Evaluation Programme (HEEP)

Models different combination of different available options for heat

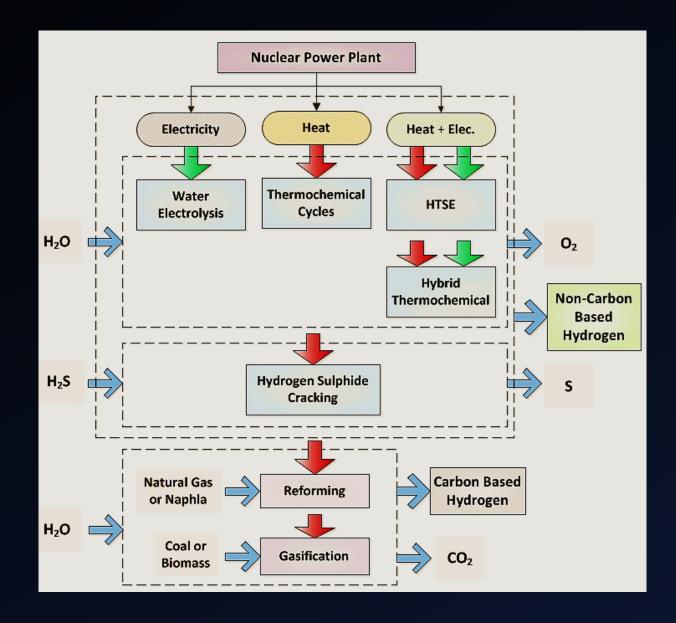
source, process of hydrogen generation and its storage and transportation.



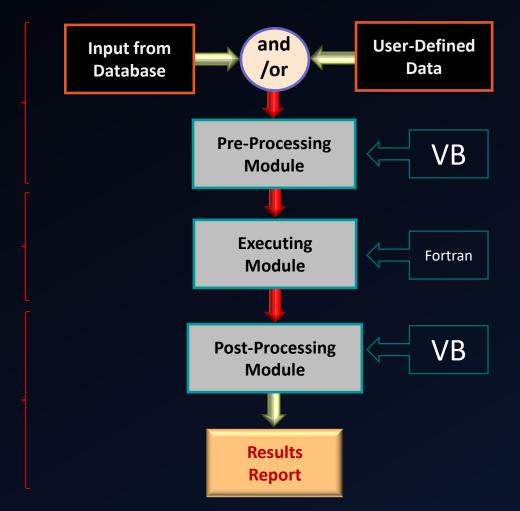
Main Features of HEEP:

- 1. Single window based tool.
 - 2. Expandable database/library To build new cases using library files.
 - 3. Models effect of location of hydrogen plant with respect to NPP.
 - 4. Models electricity generation and supply along with heat.

H2 Production Technologies in HEEP



HEEP Modules



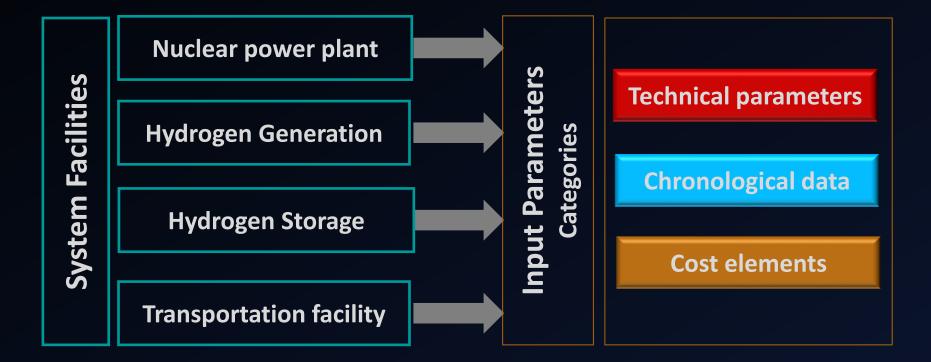
Pre-processing module for providing data

Executing module estimating levelized cost of hydrogen generation

Post-processing module for viewing results generated by HEEP

Type of Data Input to HEEP

Input Information Categorisation



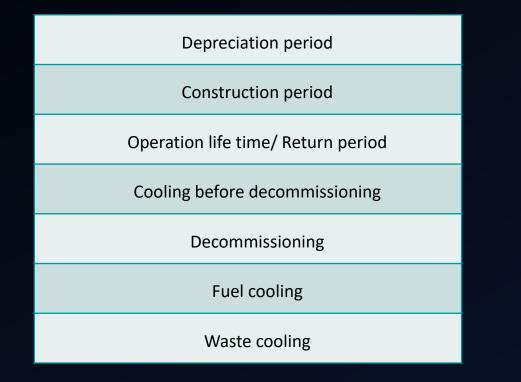
Technical features of HEEP

Technical parameters

	Nuclear Power Plant (NPP)	Hydrogen Generation Plant (HG)						
•	Installed capacity per unit (MWth)	 Hydrogen generation rate (kg/yr) 						
•	Number of units	 Number of units 						
•	Capacity and availability factor of unit	 Thermal power required for installed capacity (MWth) 						
•	Thermal power available for Hydrogen generation (MWth)	 Capacity and availability factor of unit 						
•	Thermal efficiency of unit (if electricity is generated)	Process efficiency						
_								
	Hydrogen Storage Facility (HS)	Transpor	tation Facility					
	Hydrogen Storage Facility (HS) Type of hydrogen storage (Gaseous/Liquid/Hydride)	Transpor Vehicle	tation Facility Pipelines					
_	Type of hydrogen storage (Gaseous/Liquid/Hydride)	-						
•		Vehicle	Pipelines					
_	Type of hydrogen storage (Gaseous/Liquid/Hydride)	Vehicle Transportation distance	Pipelines Transportation distance					
_	Type of hydrogen storage (Gaseous/Liquid/Hydride) Capacities, power and auxiliary requirements of storage	Vehicle Transportation distance Vehicle H ₂ Capacity	Pipelines Transportation distance Pipe equivalent radius					
_	Type of hydrogen storage (Gaseous/Liquid/Hydride) Capacities, power and auxiliary requirements of storage	VehicleTransportation distanceVehicle H2 CapacityFuel Cost	Pipelines Transportation distance Pipe equivalent radius Inlet pressure of Hydrogen					

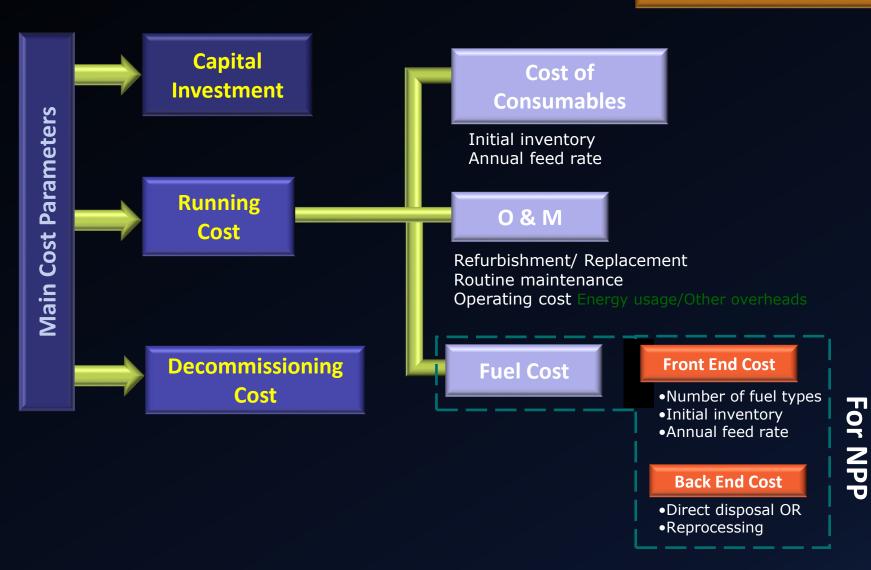
Time periods of Events affecting Cost Estimation

Chronological data

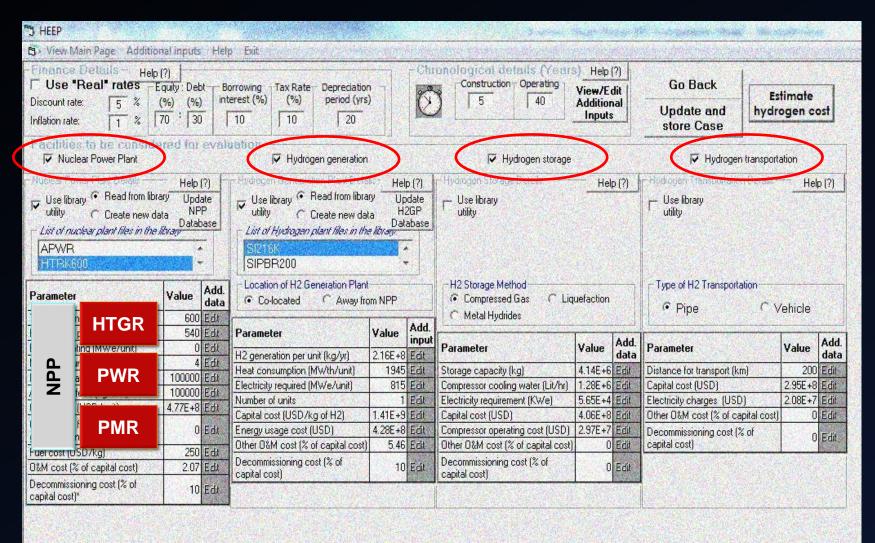


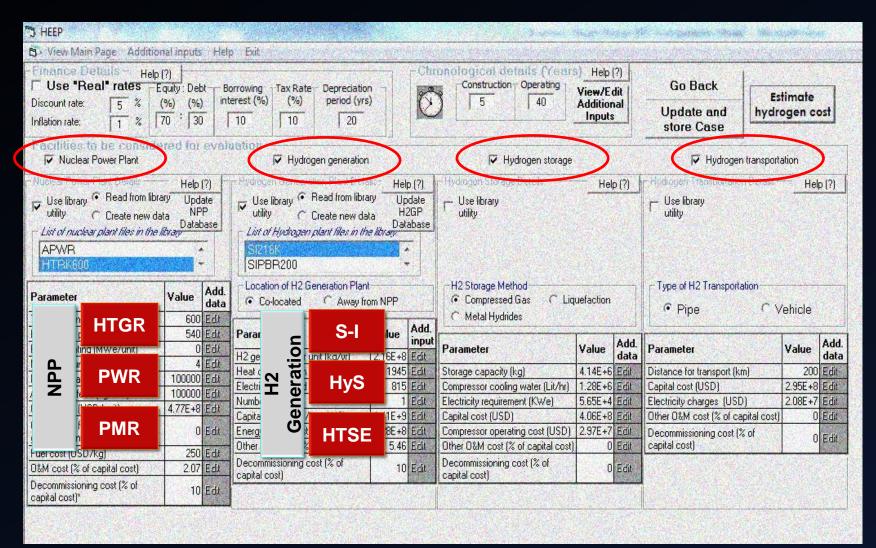
Parameters of Cost Calculation

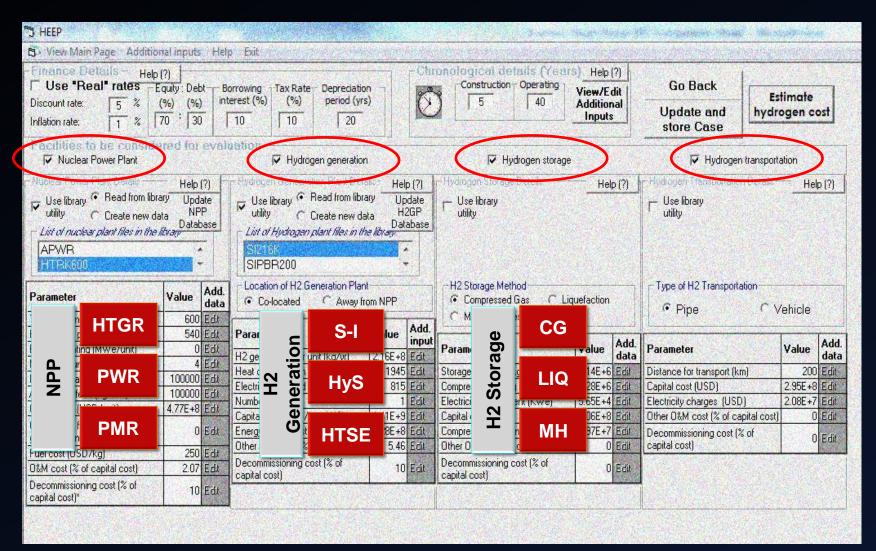
Cost elements

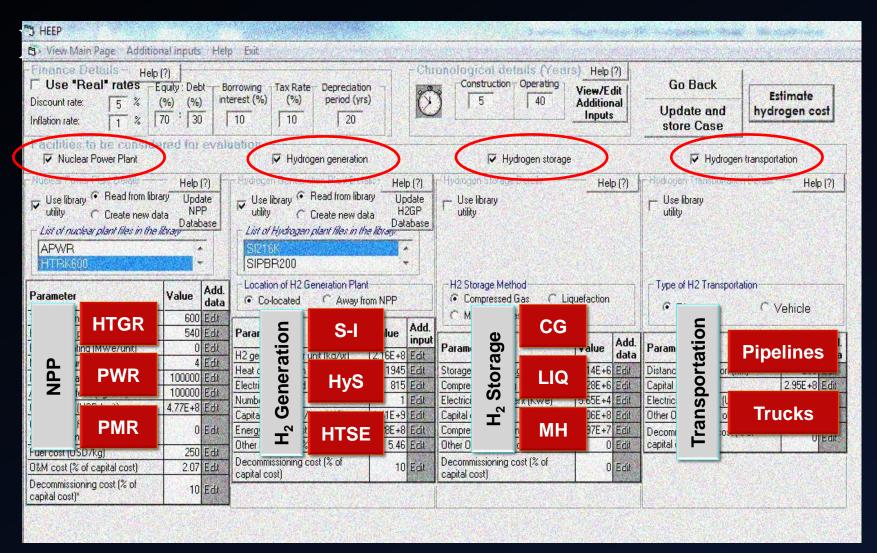


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Demonstration of HEEP

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IAEA International Atomic Energy Agency

Press centre Employment Contact

Hydrogen Economic Evaluation Program (HEEP)

The IAEA Hydrogen Economic Evaluation Program HEEP was developed and released by the International Atomic Energy Agency (IAEA) as a free tool which can be used to assess the economics of large scale hydrogen production using nuclear energy. The software can be used to evaluate the economics of the four most promising processes for hydrogen production: high and low temperature electrolysis, thermochemical processes including S-I process, conventional electrolysis and steam reforming.

The IAEA HEEP software is suitable for comparative studies not only between nuclear and fossil energy sources for hydrogen production but also for solely hydrogen production or cogeneration with electricity. The HEEP models are based on some economic and technical data, and on cost modelling which include various aspects of hydrogen economy including storage, transport, and distribution with options to eliminate or include specific details as required by the users.

Download **HEEP** software

Hydrogen Economic Evaluation Programme



IAEA International Atomic Energy Agency

For any query regarding this software please contact: Dr. I. Khamis, Nuclear Power Technology Development Section, Division of Nuclear Power, IAEA.

💿 Email: I.Khamis@iaea.org

Developed for International Atomic Energy Agency by BARC

Currency settings	Conversion	USD
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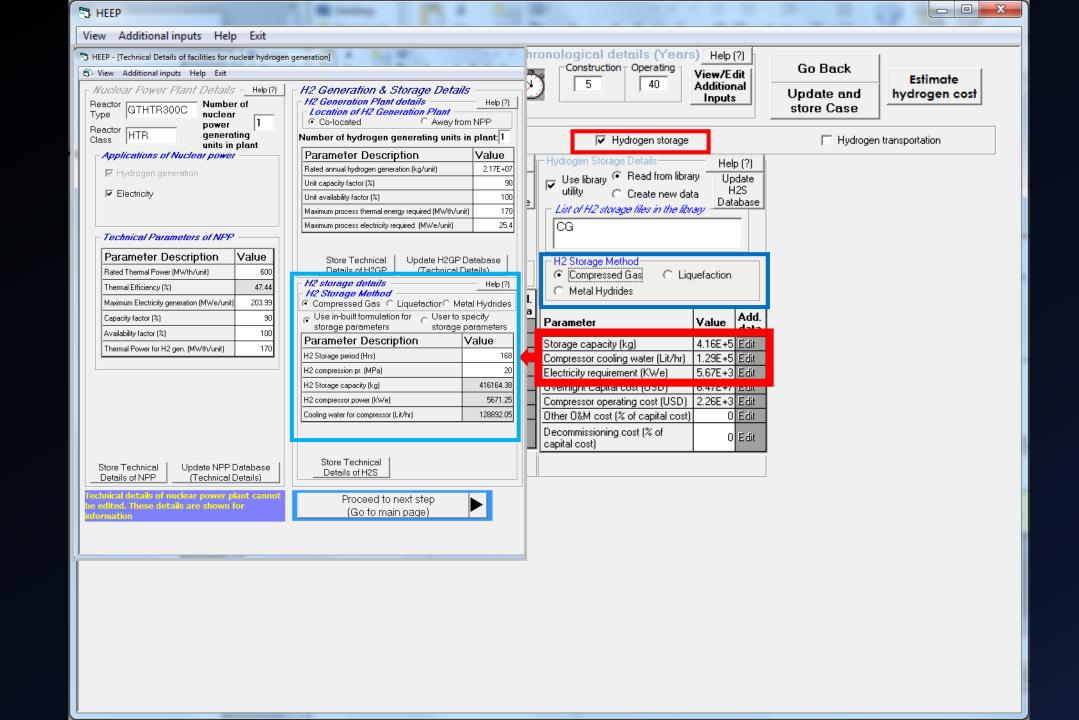
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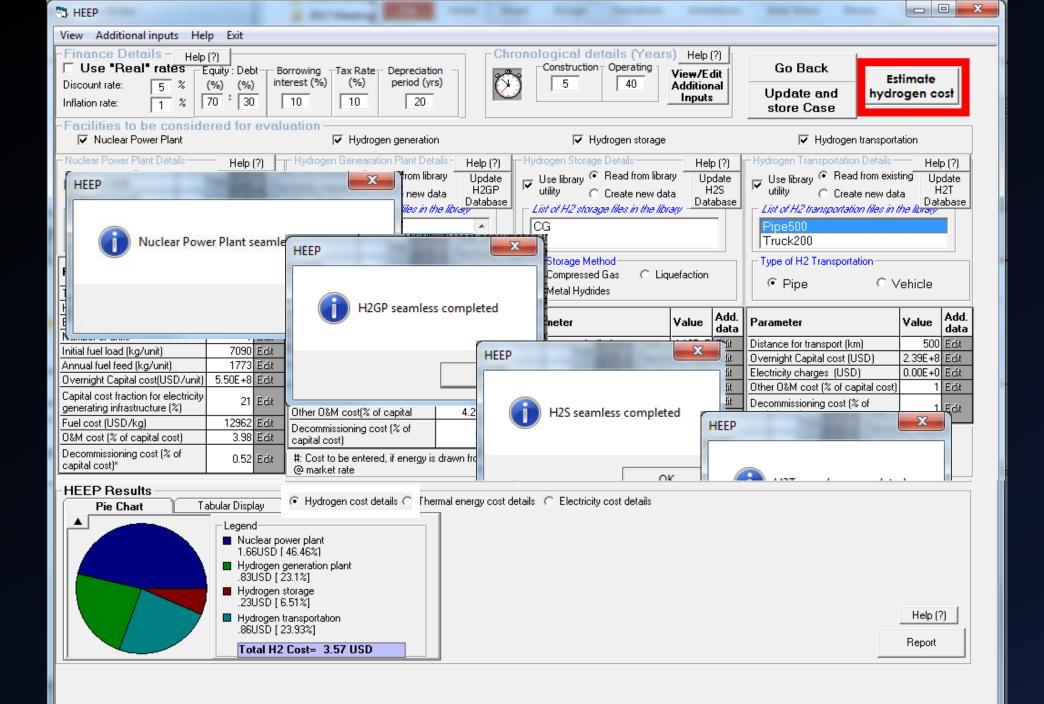
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Number of units Initial fuel load (kg/unit)	7000	Edit Edit	Heat consumption (MWth/unit)		DEdit			
Annual fuel feed (kg/unit)		Edit	Electricity required (MWe/unit)	25.4	4 Edit			
Overnight Capital cost(USD/unit)			Number of units Overnight Capital cost(USD/unit) 1.43E+8	Edit			
Capital cost fraction for electricity generating infrastructure (%)	21	Edít	Energy usage cost# (USD) Other 0&M cost(% of capital	0.00E+0				
Fuel cost (USD/kg) 0&M cost (% of capital cost)	12962 3.98	Edit Edit	Decommissioning cost (% of capital cost)) Edit			
Decommissioning cost (% of capital cost)*	0.52	Edit	#: Cost to be entered, if energy i @ market rate	is drawn fro	m grid			



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Initial fuel load (kg/unit)	7090	Edit	Electricity required (MWe/unit)	25.4		Storage capacity (kg) Compressor cooling water (Lit/hr)	4.16E+5 Edit 1.29E+5 Edit		
Annual fuel feed (kg/unit)	1773		Number of units		Edit	Electricity requirement (KWe)	5.67E+3 Edit		
Overnight Capital cost(USD/unit)	5.50E+8		Overnight Capital cost(USD/unit)			Overnight Capital cost (USD)	6.47E+7 Edit		
Capital cost fraction for electricity generating infrastructure (%)	21	Edit	Energy usage cost# (USD) Other 0&M cost(% of capital	0.00E+0 4.26		Compressor operating cost (USD)	2.26E+3 Edit		
Fuel cost (USD/kg)	12962	Edit	Decommissioning cost (% of			Other O&M cost (% of capital cost)	0 Edit		
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T HEEP			
HEEP - [Technical Details of facilities for nuclear hydrogen	n generation]		
- View Additional inputs Help Exit		X	
Nuclear Power Plant Details - Help (?) Reactor Type GTHTR300C Reactor Class HTR Provide the sector	H2 Generation & Storage Details H2 Generation Plant details Location of H2 Generation Plant © Co-located Number of hydrogen generating units in plant	H2 Transportation Details Hep (?) Type of H2 Transportation Transport by Vehicle Transport by Vehicle Pipe line Transportation	Go Back Update and store Case
Applications of Nuclear power Image: Hydrogen generation Image: Electricity Technical Parameters of NPP Parameter Description Value Rated Thermal Power (MWth/unit) 600 Thermal Efficiency (%) 47.44 Maximum Electricity generation (MWe/unit) Capacity factor (%) 90 Availability factor (%) 100	Parameter Description Value Rated annual hydrogen generation (kg/unit) 2.17E+07 Unit capacity factor (%) 90 Unit availability factor (%) 90 Unit availability factor (%) 100 Maximum process themal energy required (MWth/unit) 170 Maximum process electricity required (MWe/unit) 25.4 Store Technical Update H2GP Database Details of H2GP (Technical Details) H2 storage details Help (?) H2 storage Method © Use in-built formulation for storage parameters Use to specify storage parameters Parameter Description Value	Oetails of pipeline transportation Use in-built formulation to calculate pipe line transportation parameters User to provide pipe line transportation parameters Parameter Description Value Transport distance (km) 200 Equivalent diameter of Pipe (m) 0.25 Friction factor 0.01 Temperature of H2 (K) 293 Delivery Pressure (MPa) 5 Inlet pressure (MPa) 5 Compressor Power (kWe) 3941.77	✓ Hydrogen transportation Hydrogen Transportation Details Help (?) ✓ Use library Read from existing Update H2T List of H2 transportation files in the library Pipe500 Truck200 Type of H2 Transportation ✓ Vehicle d. Parameter Value Add.
Image: Thermal Power for H2 gen. (MW/th/unit) 170 Image: Thermal Power for H2	H2 Storage capacity (kg) 416000 H2 compressor power (kWe) 5670 Cooling water for compressor (Lit/hr) 518000	Store Technical Update H2T Database Details of H2T (Technical Details) Proceed to next step (Go to main page)	Distance for transport (km) 500 Edit Overnight Capital cost (USD) 2.39E+8 Edit Electricity charges (USD) 0.00E+0 Edit Uther U&M cost (% of capital cost) 1 Edit Decommissioning cost (% of capital cost) 1 Edit

T3 HEEP			
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B View Additional inputs Help Exit			
- Nuclear Power Plant Details - Help(?)	⊤ H2 Generation & Storage Details ——	- H2 Transportation Details — Help (?)	Go Back
Reactor Turno GTHTR300C Number of	H2 Generation Plant details Help (?)	Type of H2 Transportation	Estimate
Type Carrier nuclear power 1	Co-located Co-located Co-located	 Transport by Vehicle 	Update and hydrogen cost
Cless HTR generating	Number of hydrogen generating units in plant:	 Pipe line Transportation 	store Case
Applications of Nuclear power	Parameter Description Value		Telludrasan hannasatatian
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	Unit capacity factor (%) 90		Hydrogen Transportation Details Help (?)
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	Maximum process electricity required (MWe/unit) 25.4	Details of vehicle transportation	e List of H2 transportation files in the literary
Technical Parameters of NPP		·	Pipe500
Parameter Description Value	Store Technical Update H2GP Database	Parameter Description Value	Truck200
Rated Thermal Power (MW/th/unit) 600	Details of H2GP(Technical Details)	Transport distance (km) 200	
Thermal Efficiency (%) 47.44	H2 storage details	Capacity of vehicle (kg of H2) 180	Type of H2 Transportation
Maximum Electricity generation (MWe/unit) 203.99	Compressed Gas ○ Liquefactior○ Metal Hydrides Action Action	Average Speed of vehicle (km/hr) 40	C Pipe O Pipe
Capacity factor (%) 90	C Use in-built formulation for C User to specify	Milage of vehicle (km/Lit) 2.5	
Availability factor (%) 100	storage parameters storage parameters	Loading Time per vehicle trip (hrs) 2	
Thermal Power for H2 gen. (MWth/unit) 170	Parameter Description Value H2 Storage capacity (kg) 416000		d. Parameter Value Add.
<u> </u>	H2 storage capacity (kg) 416000 H2 compressor power (kWe) 5670		Distance for transport (km) 200 Edit
1	Cooling water for compressor (Lit/hr) 518000		Overnight Capital cost (USD) 1.65E+7 Edit
2			Fuel cost & driver's pay (USD) 1.69E+7 Edit
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4			capital cost)
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Details of NPP (Technical Details)		Details of H2T(Technical Details)	
Technical details of nuclear power plant cannot be edited. These details are shown for	Technical details of hydrogen generation plant cannot be edited. These details are shown for	Proceed to next step 📃 📘	
information	information	(Go to main page)	



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	Capital Cost (Debt)	Capital Cost (Equity)	0&M and Refurbishmen	Consumable Cost	Decomr Cost	^{missior} Fuel Cost	Total of the facility				
Nuclear Power Plant	0.33	0.39	0.39	0	0.0	1 0.55	1.66				
Hydrogen Generation Plant	0.22	0.29	0.31	0	0	-	0.83				
Hydrogen storage	0.1	0.13	0	0	0		0.23				
Hydrogen Transportation	0.46	0.26	0.12	0	0.0	1 -	0.86				Help (?)
Total of all facilities	1.11	1.07	0.83	0	0.0	1 0.55	3.57]			Report
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Overnight Capital cost(USD/unit)	5.50E+8 Edit			Overnight Capital cost (USD)	6.47E+7 Edit	Other O&M cost (% of capital cost)	1 Edit	
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		ables [OUSD (0%)] nissioning [OUSD (.34%)]					Help (?)	
		05USD (36.94%)]					Report	

5 HEEP			A survey state					
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Capital cost fraction for electricity	21	Edit	Energy usage cost# (USD)	0.00E+0 Edít	Compressor operating cost (USD)	9.08E+3 Edit	Decommissioning cost (% of	1 Edit
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		M [011	USD (23.8%)]					
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	🗖 De	commiss	sioning [OUSD (.25%)]					
	🗖 Fu	el [.011	USD (27.52%)]					Report

Hydrogen Economic Evaluation Programme

International Atomic Energy Agency

For any query regarding this software please contact: Dr. I. Khamis, Nuclear Power Technology Development Section, Division of Nuclear Power, IAEA. (I. Khamis@iaea.org) Developil in International Journis Borgy Agency by NARC

Table - 1: Finance details (using 'Nominal' rates)

Discount rate	5%
Inflation rate	1
Equity/Debt	70% : 30%
Borrowing interest	10%
Tax rate	10%

Table - 2: Time Period (years)

Construction	5
Operation	40

Table - 3: Nuclear Power Plant Details

Thermal rating (MWth/unit)	600
Heat for H2 plant (MWth/unit)	170
Electricity rating (MWe/unit)	203.99
Number of units	1
Initial fuel load (kg/unit)	7090
Annual fuel feed (kg/unit)	1773
Overnight Capital cost(USD/unit)	5.50E+8
Capital cost fraction for electricity generating infrastructure (%)	21
Fuel cost (USD/kg)	12962
O&M cost (% of capital cost)	3.98
Decommissioning cost (% of capital cost)*	0.52

Table - 4: Hydrogen Generation Plant Details H2 generation per unit (kg/yr) 2.17E+07 Heat consumption (MWth/unit) 170 Electricity required (MWe/unit) 25.4 Number of units 1

	-
Overnight Capital cost(USD/unit)	1.43E+8
Energy usage cost# (USD)	0.00E+0
Other O&M cost(% of capital cost)	4.26
Decommissioning cost (% of capital cost)	0

Table - 5: Hydrogen Storage Details

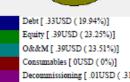
Storage capacity (kg)	4.16E+5
Compressor cooling water (Lit/hr)	5.18E+5
Electricity requirement (KWe)	5.67E+3
Overnight Capital cost (USD)	6.47E+7
Compressor operating cost (USD)	9.08E+3
Other O&M cost (% of capital cost)	0
Decommissioning cost (% of capital cost)	0

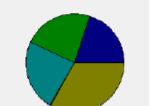
Table - 6: Hydrogen Transportation Details

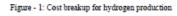
Distance for transport (km)	500
Overnight Capital cost (USD)	2.39E+8
Electricity charges (USD)	0.00E+0
Other O&M cost (% of capital cost)	1
Decommissioning cost (% of capital cost)	1



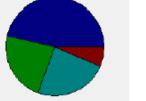
3







Nuclear power plant 1.66USD [46.49%] Hydrogen generation plant .83USD [23.11%] Hydrogen transportation□86USD [23.94%] Hydrogen storage□23USD [6.52%]



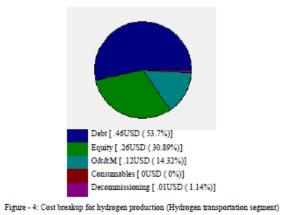
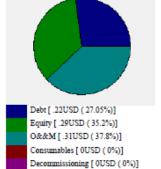


Figure - 3: Cost breakup for hydrogen production (Hydrogen generation plant segment)



Debt [.1USD (43.39%)] Equity [.13USD (56.48%)] O&&M [0USD (.18%)] Consumables [OUSD (0%)] Decommissioning [0USD (0%)]

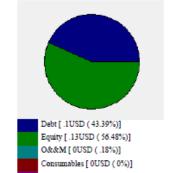


Figure - 5: Cost breakup for hydrogen production (Hydrogen storage segment)

Comparative Case Study

Capacity and thermal specifications of the considered cases of nuclear power plant and hydrogen generation plant

Parameter	<u>CASE I</u>	<u>CASE II</u>	<u>CASE III</u>	<u>CASE IV</u>
Nuclear Power Plant	PBR NPP	PMR NPP	HTGR NPP	
Thermal rating per unit	$200 \text{ MW}_{\text{th}}$	$200 \text{ MW}_{\text{th}}$	$600 \text{ MW}_{\text{th}}$	$600 \text{ MW}_{\text{th}}$
Number of Units	4	6	4	6
Electricity rating, MW _e /unit (eff.)	-	160 (40%)	-	110 (40%)
Thermal heat of $ m H_2$ plant, MW $_{ m th}/ m unit$	200	200	540	324.167
Specific capital cost, \$/MW _{th}	1,495,000	367,500	874,500	874,500
Capital cost, M\$	1,196	441	2,100	3,465
O&M cost, %	1.79	1.94	2.07	2.07
Fuel cost, \$/kg	77	110.55	275	275
Hydrogen Generation Plant				
Annual Hydrogen generation, ton	72,000	72,000	216,000	216,000
Thermal energy required, MW _{th}	800	800	1945	1945
Electric energy required, MW _e	272	272	815	815
Capital cost, M\$	762	673	1,550	1,550
Energy usage cost M\$	157	64.75	441	89.60
O\$M cost, %	5.34	5.5	5.46	5.46

H2 Storage

Hydrogen storage period, h	168
Unit cost of cooling water for storage, \$/ML	0.00022
O&M cost for hydrogen storage, %	5
<u>Liquefaction</u>	
Cooling water flow rate of Liquefaction, L/kg H_2	209
Daily Boil-off rate, %	0.1
<u>Metal Hydride</u>	
Specific Heating power, MJ/kg H ₂	23.26
Hydride cooling, L/kg H ₂	209

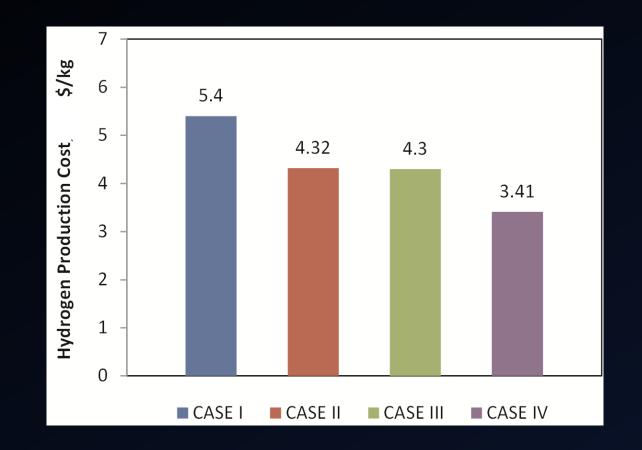
H2 Transportation

Vehicle		Pipelines	
Transportation distance, km	300	Transportation distance, km	500
Vehicle H ₂ Capacity, kg	180	Pipe equivalent radius, mm	125
Fuel Cost, c\$	125	Inlet pressure of Hydrogen, bar	53.2
Loading Time per trip, min	120	Delivery pressure, bar	50.0
Average speed, km/h	40	Temperature of Hydrogen, K	293
Mileage of vehicle, km/L	2.5	Friction factor	0.01
Decommissioning cost, %	0.5	Decommissioning cost, %	1
<u>0&M cost, %</u>	0.1	O&M cost, %	1

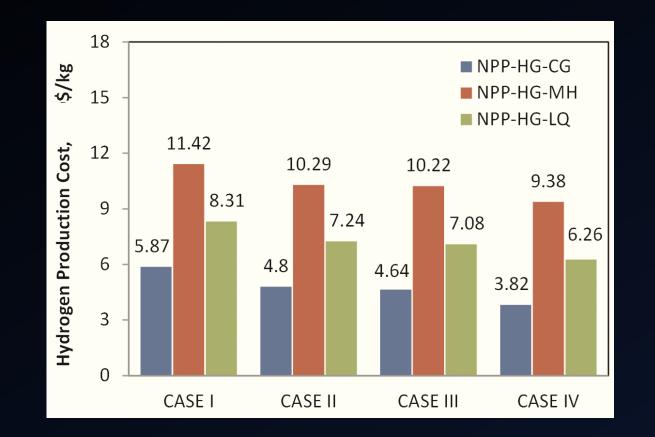
Time periods and financial parameters considered in the analysis

General Cost and Operating parameters	
Discount rate	5%
Inflation rate	1.2%
Interest rate	10%
Tax rate	10%
Equity : debt	70%:30%
Depreciation period	20 year
Construction period	3 year
Operation life time/ Return period	60 year
Cooling before decommissioning	12 month
Decommissioning	10 year
Fuel cooling	24 month
Waste cooling	24 month
Capacity factor	90%
availability factor	100%
Unit cost of grid electricity, c\$/kWh	6.6

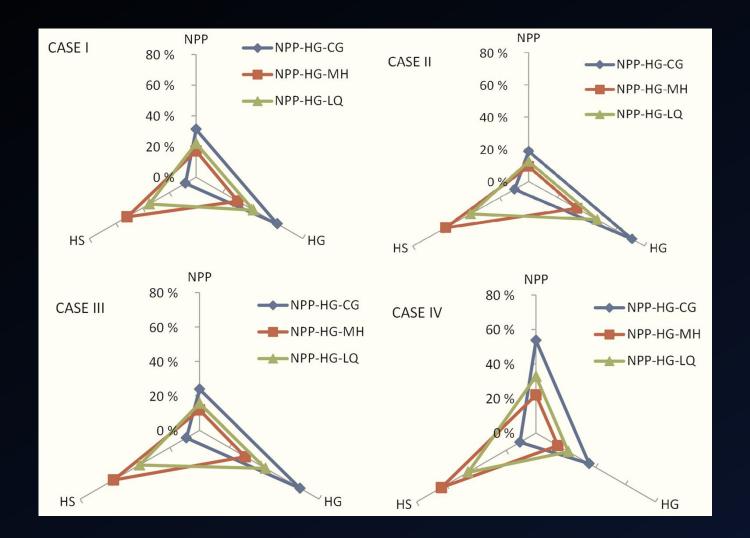
	CASE I. II	CASE III, IV	
HYDROGEN STO	RAGE		
Compressed Gas			
Storage capacity, ton	1,381	4,142	
Electric power required, MW _e	18.80	56.45	
Compressor cooling water, L/s	118.79	356.18	
Capital cost, M\$	186	447	
Compressor operating cost, M\$	10.9	32.7	
Cooling water charges, \$	8,248.42	24,668.16	
Liquefaction			
Storage capacity, ton	1,390	4,171	
Electric power required, MW _e	82.76	248.3	
Liquefier cooling water, L/s	480.5	1441.5	
Capital cost, M\$	192	397	
Storage electricity charges, M\$	54.9	164.8	
Cooling water charges, \$	38,158	114,668	
Metal Hydrides			
Storage capacity, ton	1,380	4,142	
Heating power required, MW _{th}	53.10	159.3	
Hydride cooling water, L/s	477.16	1,431.7	
Capital cost, M\$	3340	10000	
Cost of energy for hydride cooling, \$	30,134	90,228	
HYDROGEN TRANSPO	DRTATION		
Vehicle Transportation			
Capital cost, M\$	77.60	232.8	
Fuel cost, M\$	120	360	
Annual drivers' wages, M\$	12.80	38.41	
Pipe Transportation for Compressed Gas Storage			
Compressor power, MW _e	13.12	11.79	
Capital cost, M\$	272	263	
Electric power charges, M\$	7.58	6.82	



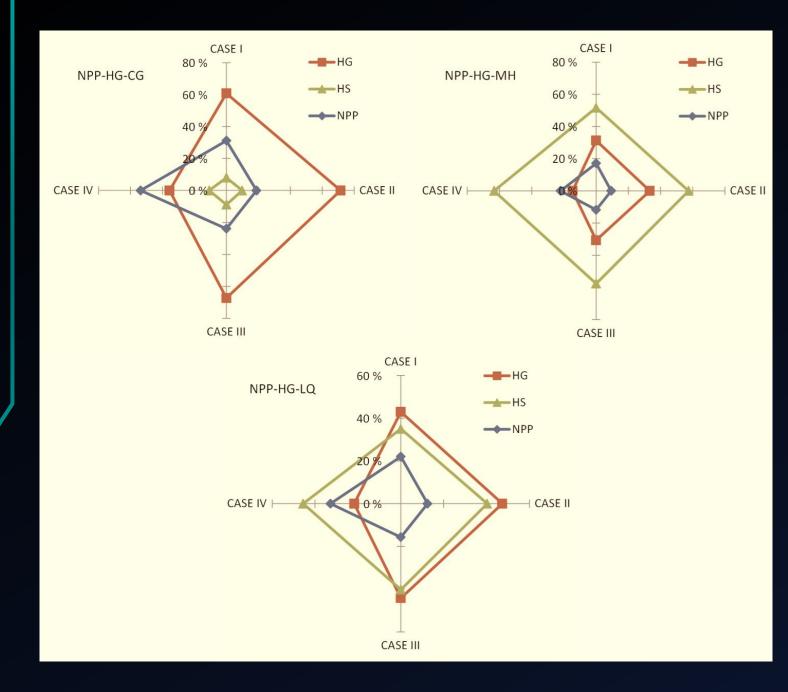
Comparison of hydrogen cost for hydrogen production only



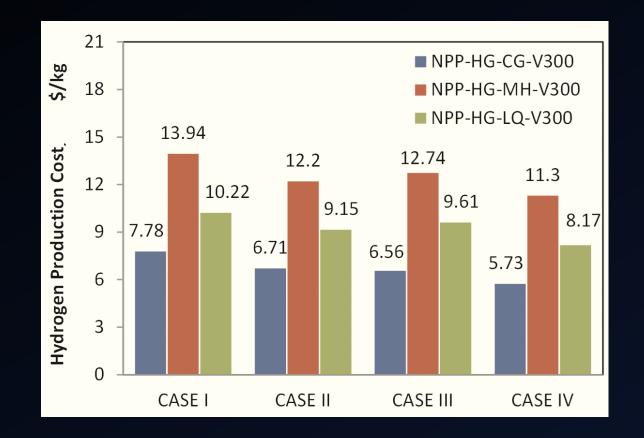
Cost of hydrogen for different storage options at the different cases



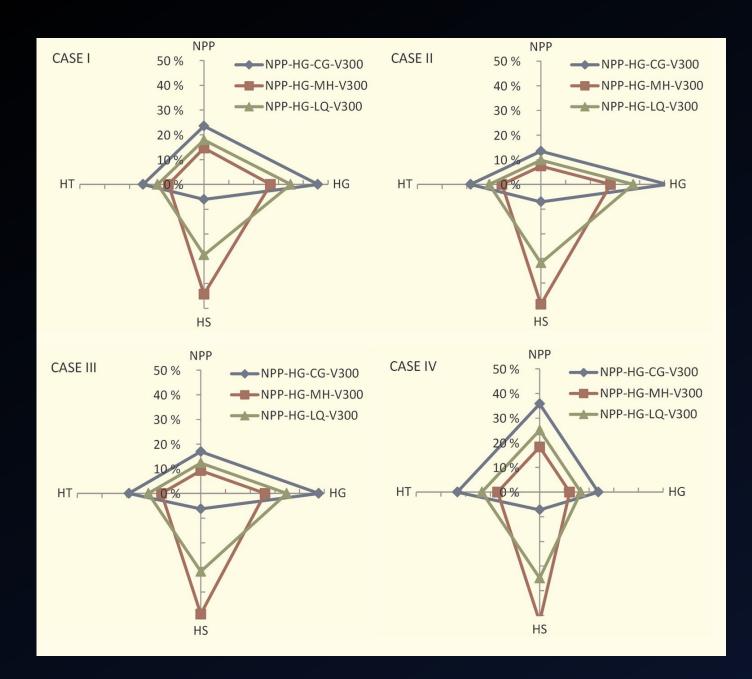
Contribution percentage of plant units on hydrogen generation cost for the different cases considering different storage plants shown for each case



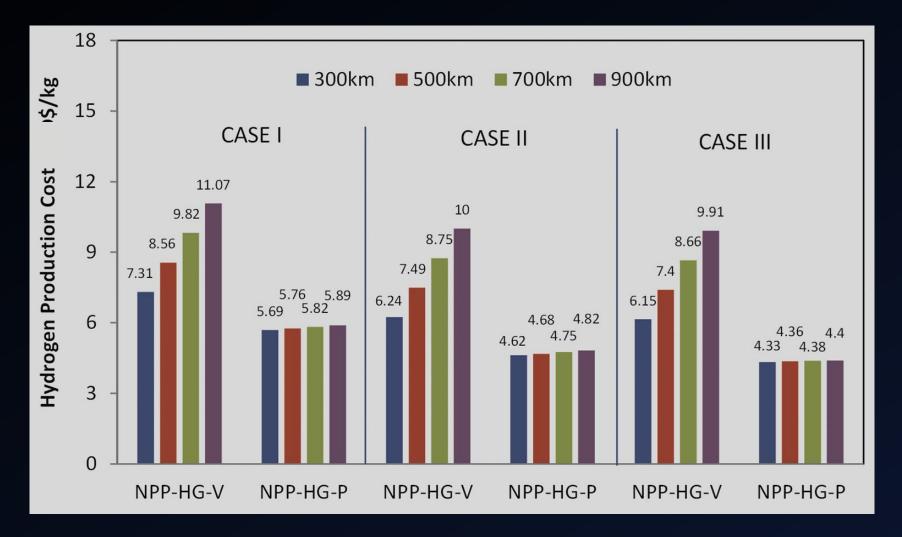
Contribution percentage of plant units on hydrogen generation cost for the different cases shown with respect to the storage method.



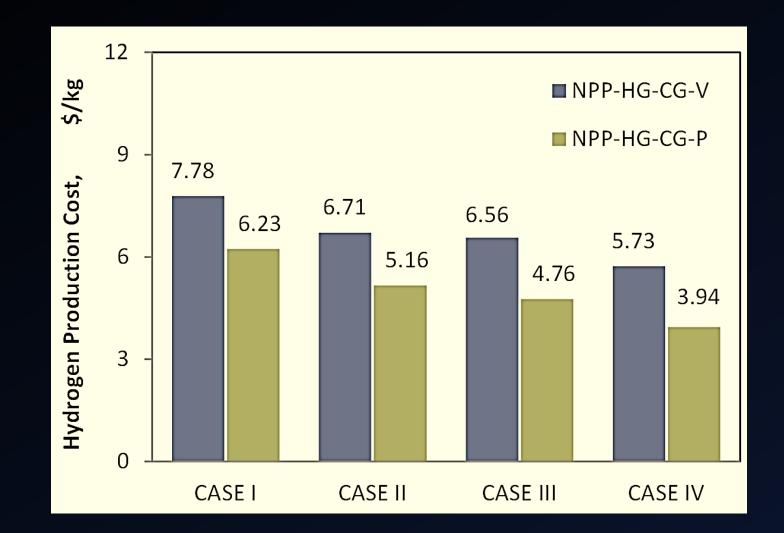
Cost of hydrogen production for different storage and transportation options



Contribution percentage of plant units on hydrogen generation cost for the different cases considering different storage plants shown for each case.



Cost of hydrogen for the considered cases at different transportation distances



Cost comparison for vehicle and pipeline transportation considering the integration of compressed gas storage plant to the generation system

I. GENERIC CASES

Case Studies

	Case I	Case II	Case III	Case IV	Case V
Nuclear Power Plant	2 x 359.5 MWe APWR	2 x 719.0 MWe APWR	2 x 1117.1 MWe APWR	2 x 509.3 MWth HTGR	2 x 630.7 MWth HTGR
Hydrogen Generation Plant	CE 4 kg/s	CE 8 kg/s	CE 12 kg/s	HTSE 4 kg/s	SI 4 kg/s

Technical and Financial Features: Nuclear Power Plants

	Case I	Case II	Case III	Case IV	Case V	
Nuclear Power Plant	APWR	APWR	APWR	HTGR	HTGR	
Number of units	2	2	2	2	2	
Capacity factor (%)	93	93	93	90	90	
Availability factor (%)	100	100	100	100	100	
Thermal rating (MW _{th} /unit)	1089	2178	3385	510	630.7	
Heat for H ₂ plant (MW _{th} /unit)	0	0	0	510	630.7	
Electricity rating (MW _e /unit)	359.5	719.0	1117	0	0	
Initial fuel load (kg/unit)	27000	54000	75000	14000	18000	
Annual fuel feed (kg/unit)	9000	18000	25000	5000	6000	
Capital cost (CC) (USD/unit)	3.16×10 ⁹	4.66×10 ⁹	5.96×10 ⁹	4.02×10 ⁸	6.05×10 ⁸	
CC for power gen. infrastructure	10%	10%	10%	0	0	
Fuel cost (USD/kg)	1850	1365	1260	3660	5535	
O&M cost (% of cc)	1.66	1.67	1.66	5.84	1.82	
Decommissioning cost (% of cc)	2.8	2.8	2.8	10	10	

Technical and Financial Features: Hydrogen Generation Plants

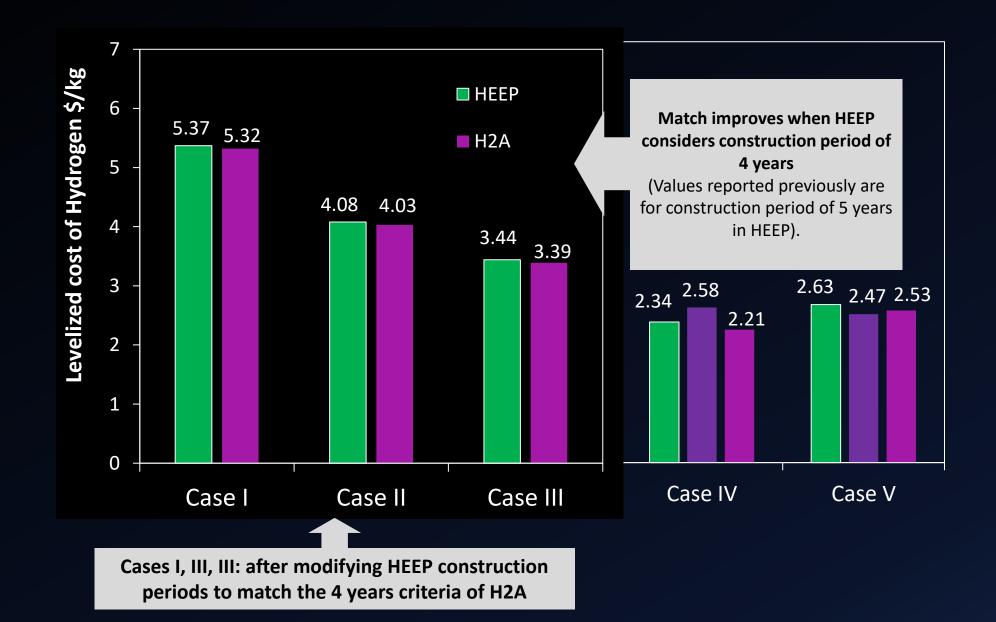
	Case I	Case II	Case III	Case IV	Case V	
Hydrogen plant design	CE	CE	CE	HTSE	SI	
Number of units	1	1	1	1	1	
Capacity factor (%)	80	93	80	90	90	
Availability factor (%)	100	100	100	100	100	
H ₂ generation rate (kg/year/unit)	1.26×10 ⁸	2.53×10 ⁸	3.92×10 ⁸	1.26×10 ⁸	1.26×10 ⁸	
Heat consumption (MW _{th} /unit)	0	0	0	1020	1261.4	
Electricity consumption (MW _e /unit)	719	1438	2234	0	0	
Non-process electricity consumption (MW _e /unit)	0	0	0	0	42.8	
Capital cost (USD/unit)	4.28×10 ⁸	8.45×10 ⁸	1.31×10 ⁹	4.59×10 ⁸	6.66×10 ⁸	
Energy usage cost (USD)	0	0	0	0	2.7×10 ⁸	
O&M cost (% of cc)	4	4	4	17.23	6.68	
Decommissioning cost (% of cc)	10	10	10	10	10	

Technical and Financial Features: Chronological and Financial Data

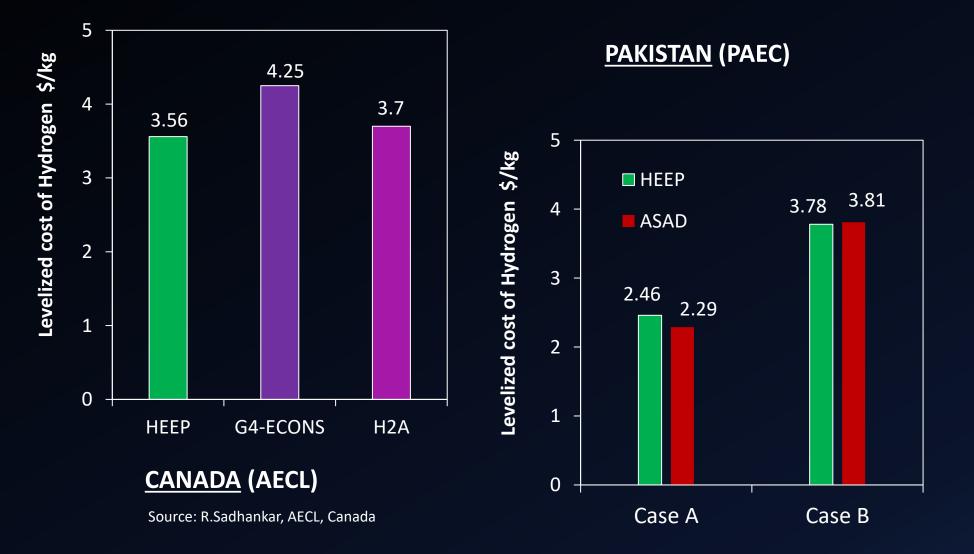
	Case I	Case II	Case III	Case IV	Case V
Construction period (yr)	5	5	5	3	3
Operation period (yr)	40	40	40	40	40
Decommissioning (yr)	10	10	10	10	10
Refurbishment (yr)	1	1	1	1	1
Spent fuel cooling (yr)	2	2	2	2	2
Waste cooling (yr)	10	10	10	10	10
Cooling before decommissioning (yr)	2	2	2	2	2

Discount rate	5%
Inflation rate	1%
Finance equity: debt	70%:30%
Borrowing interest	10%
Tax rate	10%
Depreciation period	20 year

Results



HEEP Benchmarking: Results of Other Studies



Comparison of HEEP vs H2A

H2A	HEEP
 Debt portion of the construction cost is assumed to be incurred in the first year of the construction period itself. The repayment of this entire debt component (market borrowing) starts from the first year of construction period distributed over debt repayment period evaluated at the given interest rate. 	 Debt part is incurred in each year of the construction period. The debt part is calculated based on the fraction of cash flow during that year and debt to equity ratio. The repayment of debt part borrowed in each year starts from the respective year in which they have been incurred, for a duration of debt repayment period.
• MS Excel spreadsheet based interface for modeling the hydrogen generation plant alone.	 An input interface and post-processing module developed in Microsoft Visual Basic Mathematical computations are done using Fortran routines.
 The costs details of plants and facilities (source of heat/electricity, storage and transportation) associated with hydrogen production are to be provided as externalities. Construction period – 4 years only 	 The costs details of plants and facilities (source of heat/electricity, storage and transportation) associated with hydrogen production can be provided as input parameters Construction period – no limits

Justification for the variation between HEEP & H2A:

- The construction period specified is 5 years.
- H2A cannot account for construction period more than 4 years.

II. COUNTY BASED CASES

Four detailed Case studies for HEEP Benchmark:

GEN-IV reactors for hydrogen production

Country Specific Case Studies

	JAPAN	CHINA	GERMANY	CANADA		
Nuclear power plant	GTHTR300	HTR-PM	HTR-SR	SCWR		
H2 production process	S-I	S-I	SR	S-I	HyS	CuCl
Thermal efficiency%	46.98	-	20.34	46.98	-	32.2
Hydrogen production (kg/MW _{th} h)	12.28	10.90	102.8	4.16	6.9	7.5
Hydrogen cost (\$/kg)	2.46	3.78	3.61	4.1	4.74	5.34