The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

2245-12

Joint ICTP-IAEA Advanced School on the Role of Nuclear Technology in Hydrogen-Based Energy Systems

13 - 18 June 2011

HEEP: The tool for Comprehensive Cost Assessment of Hydrogen from Nuclear Energy- A brief introduction

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HEEP: The tool for Comprehensive Cost Assessment of Hydrogen from Nuclear Energy- A brief introduction

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Outline of presentation

- Background
- Ideas guiding the logic building in the HEEP
- Inputs for HEEP
- Preliminary Benchmarking of HEEP
- Concluding remarks

Background

Pathways for hydrogen production- Conventional methods and nuclear route

- Selection of pathways
  - National policy
  - Availability of resources
  - Effects of utilisation of resources for hydrogen production
  - Competitive economics

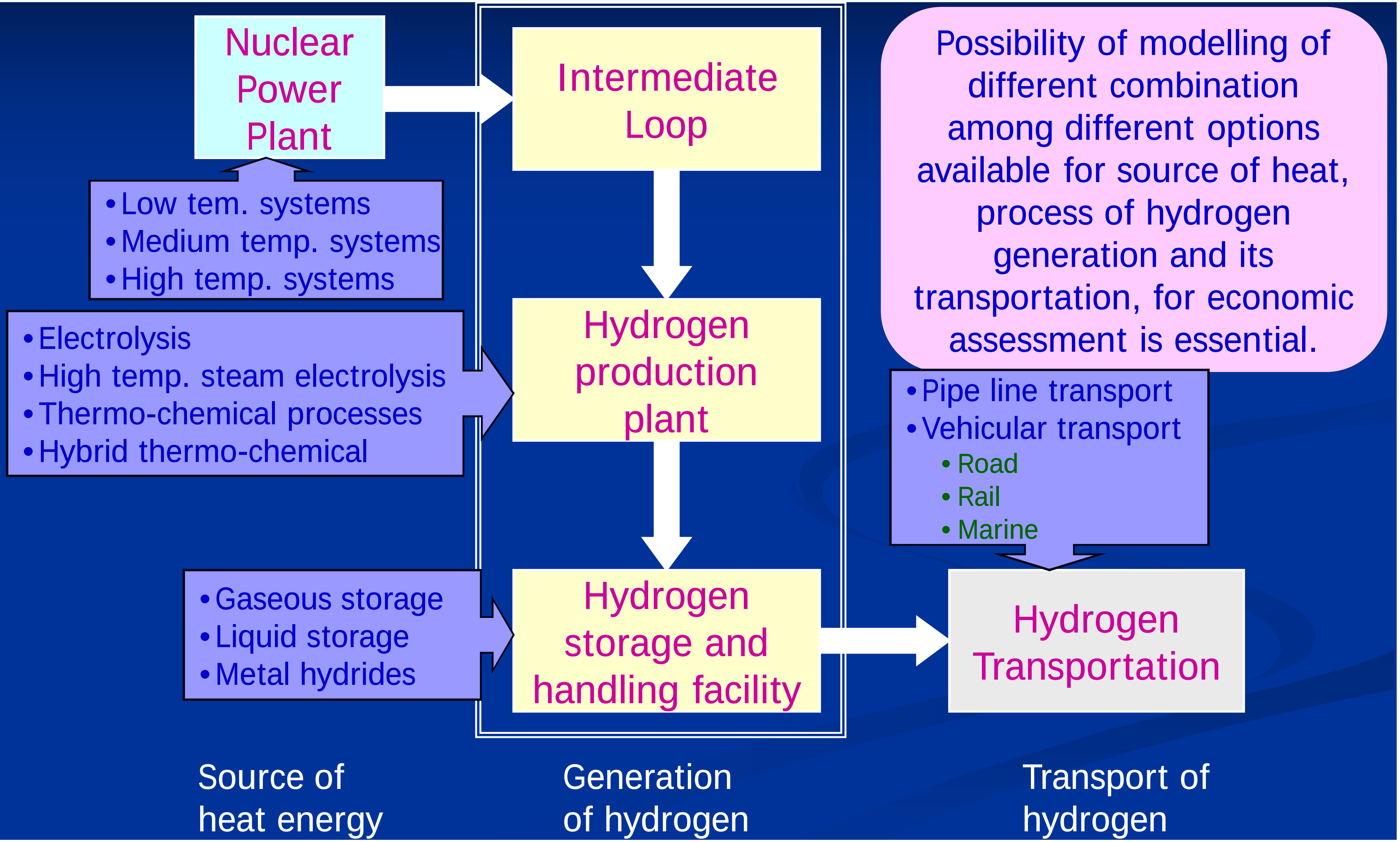
- IAEA initiated development of comprehensive cost assessment software 'HEEP'
- BARC developed HEEP under Contractual Service Agreement with IAEA

Members of HEEP development team

Name	Contribution to HEEP development
I.V. Dulera	Technical studies
U.D. Malshe	Pre-processor and co-ordination with IAEA
P.P. Kelkar	Mathematical formulation
A. Antony	Execution module
A. Basak	Post processing module

Ideas guiding the logic building of HEEP

Wide range of options being developed globally for hydrogen production using nuclear power 1/2



Wide range of options being developed globally for hydrogen production using nuclear power 2/2

- Vigorous R&D is underway to minimise technical hurdles in nuclear hydrogen production

  - Nuclear reactors

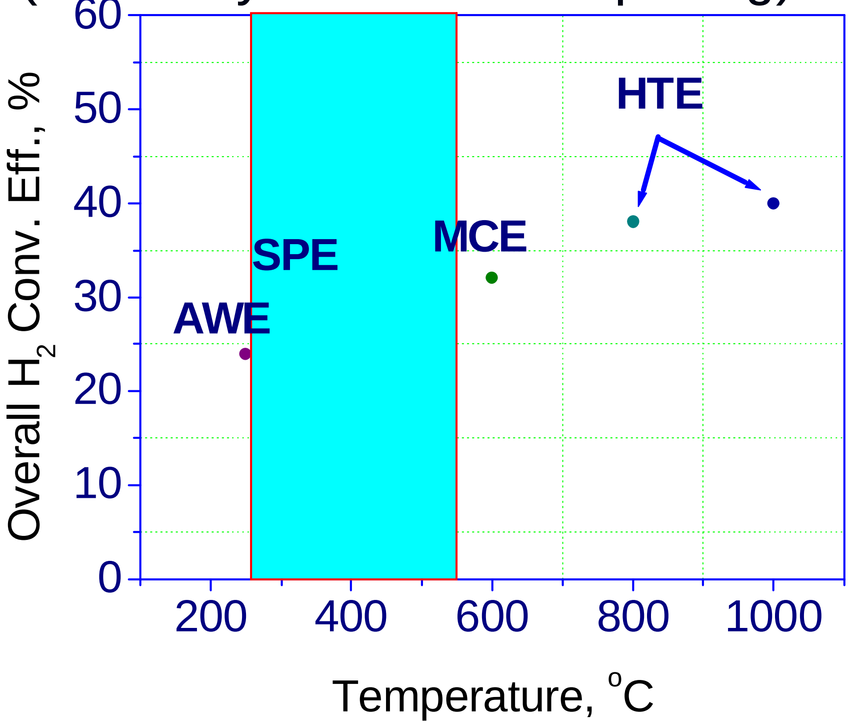
  - Hydrogen generating process

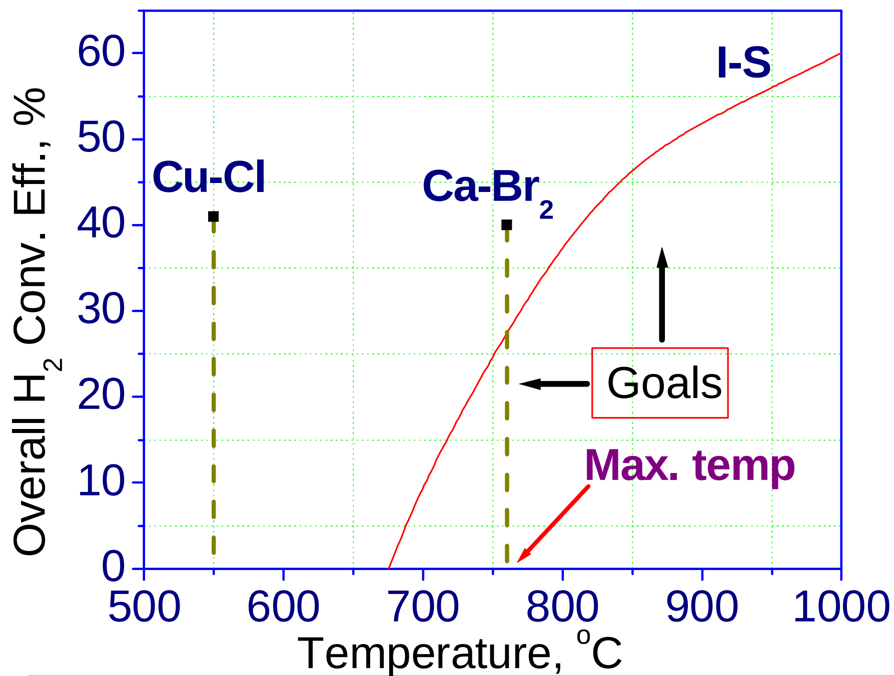
Needs expandable database so that a desired combination among different options available for source of heat, process of hydrogen generation and its transportation can be modelled.

Efficiency of different processes

Electrolysis ← Water → Thermo-chemical cycle

(Electricity driven water splitting) (Thermal driven chemical reactions sequence)





Electrolysis Processes:
AW: Alkali Water, MC: Molten Carbonate
SP: Solid Polymer, HT: High Temperature

Ref: IAEA-TECDOC-1085: Hydrogen as an energy carrier and its production by nuclear power

Thermo-chemical Processes:
Cu-Cl: Copper - Chlorine, Ca-Br$_2$: Calcium-Bromine, I-S: Iodine-Sulfur Process

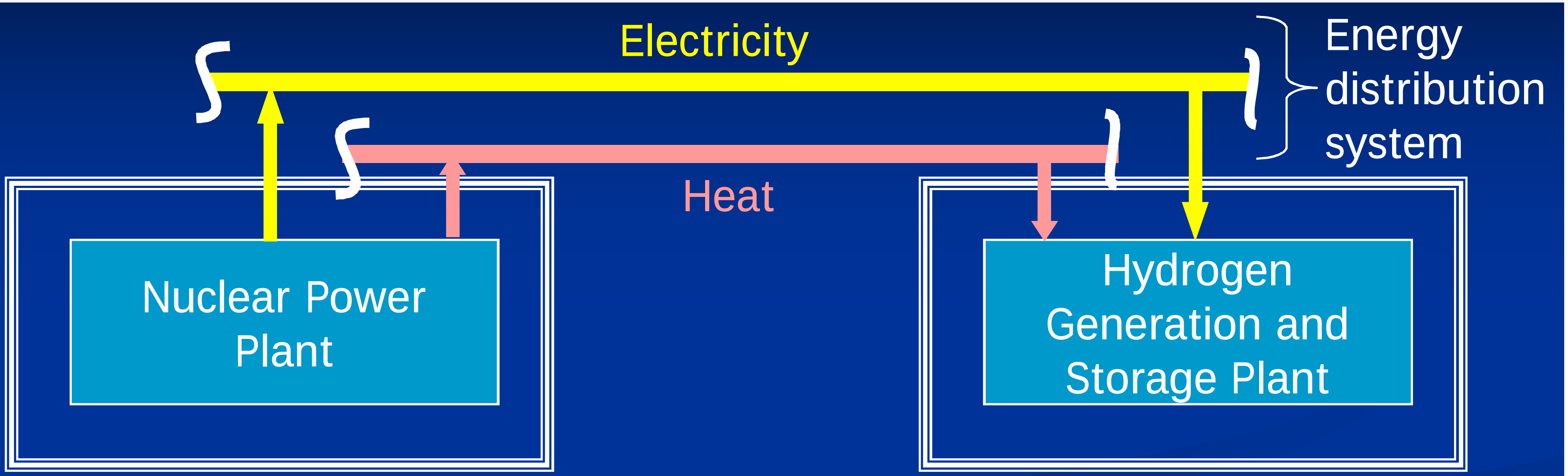
Ref: High Efficiency Generation of Hydrogen Fuels Using Nuclear Power, G.E. Besenbruch, L.C. Brown, J.F. Funk, S.K. Showalter, Report GA–A23510 and ORNL Website

Economics of hydrogen production will depend strongly on plant availability factor as well as process efficiency
(Some interesting cases needed to be modelled)

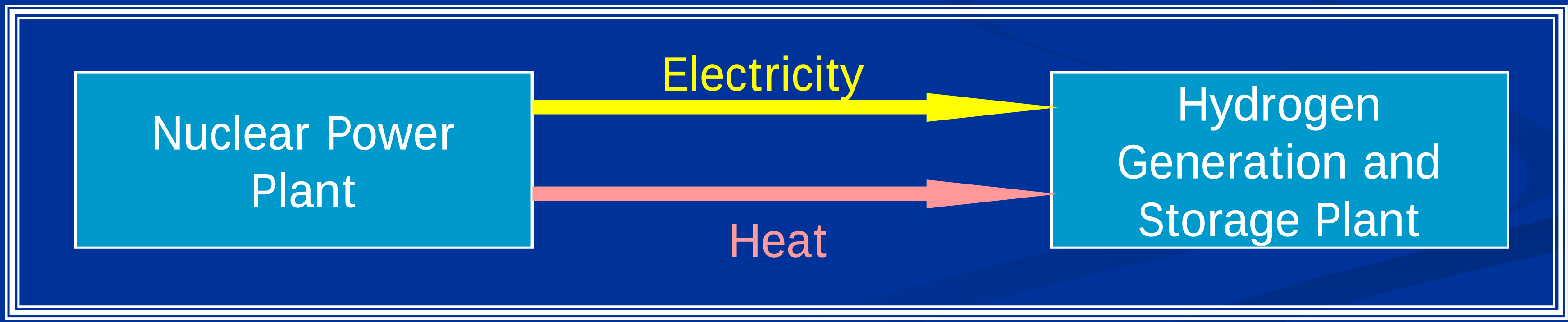
- High and medium temperature processes - Higher efficiency but lower availability factor
  - Multiple redundant systems and components with
  - Increased capital costs
- Electrolysis based system – Lower efficiency but higher availability factor
  - Little or no redundant system and components
  - Lower overall costs

Necessity of accounting efficiency and availability of plant for assessment of hydrogen economy

Location of hydrogen production plant is also important in hydrogen economy

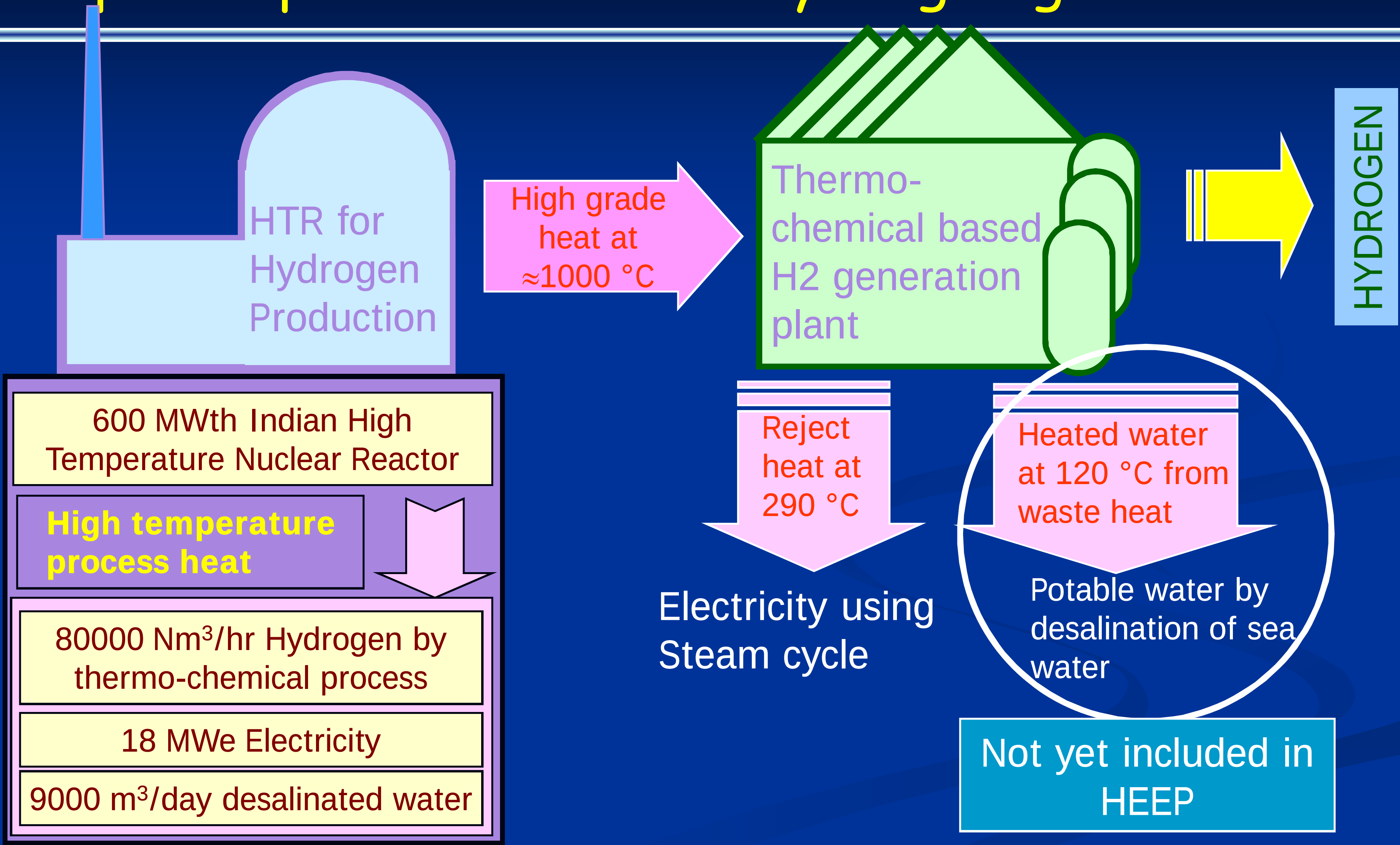


Hydrogen generation and storage plant located away from nuclear power plant



Co-located hydrogen generation plant and nuclear power plant

Necessity to consider other application of nuclear power plant other than hydrogen generation

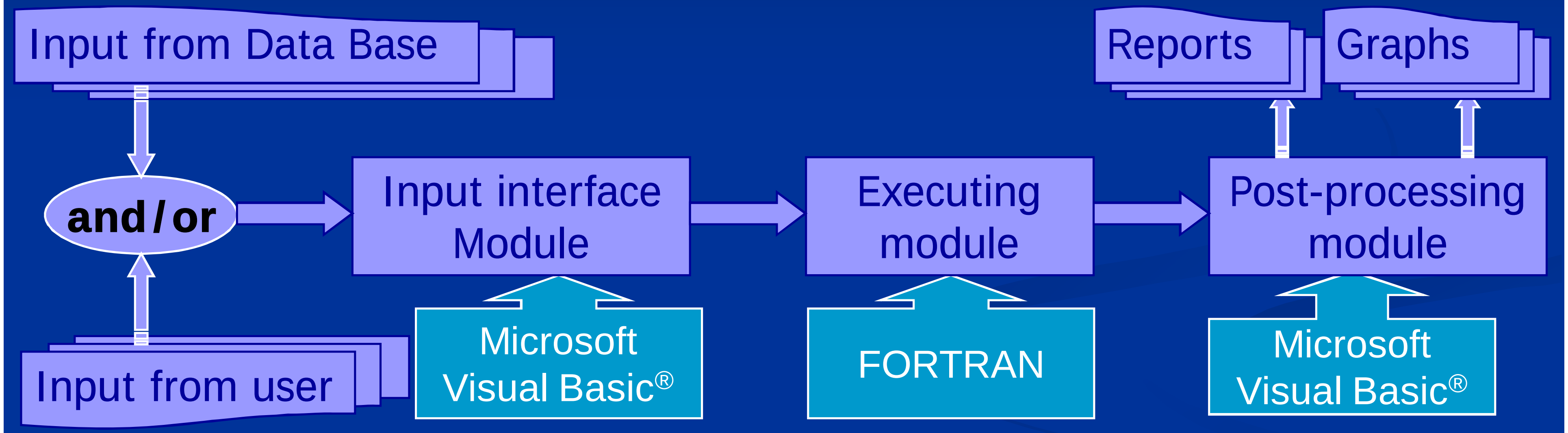


In a long-term time frame Indian HTRs aims to satisfy total energy needs of a region in the form of hydrogen, electricity and potable water

Some important features of HEEP

- “Single” window based tool considering source to end user
- Models different combination among different options available for source of heat, process of hydrogen generation and its transportation
- Expandable database/library
  - To build new cases using library files as a starting point
  - Input from existing case files
- Models effect of location of hydrogen generation plant with respect to nuclear power plant
- Models electricity generation and supply along with heat

The structure of HEEP



Inputs for HEEP

Categorisation of input information for HEEP

Facilties	Categories of input parameters
Nuclear power plant	Technical parameters
	Chronological data
	Cost elements
Hydrogen generation and storage plant	Technical parameters
	Chronological data
	Cost elements
Hydrogen transportation facility	Technical parameters
	Chronological data
	Cost elements

Technical details affecting the cost estimation

- Nuclear power plant
  - Number of units
  - Installed capacity per unit (MWth)
  - Capacity and availability factor of unit
  - Thermal power available for H2 generation (MWth)
  - Thermal efficiency of unit (if electricity is generated)

For quick estimates of hydrogen storage and transportation components, programming is based on formulation described in the following reference: ***"Costs of Storing and Transporting Hydrogen", Wade A. Amos, NREL/TP-570-25106, November 1998, NREL***

- Hydrogen generation plant
  - Number of units
  - Thermal power required for installed capacity (MWth)
  - Capacity and availability factor of unit
  - Process efficiency
  - Hydrogen generation rate (kg/yr)
- Hydrogen storage facility
  - Type of hydrogen storage (Gaseous/Liquid/Hydride)
  - Capacities, power and auxiliary requirements of storage devices
- Hydrogen transportation
  - Pipeline transportation (distance, pipe size, etc.)
  - Vehicular transportation (mileage, capacity, driver's wages, etc.

Time periods of various events affecting the cost estimation

	Nuclear power plant	Hydrogen generation and storage facility	Hydrogen transportation facility
Construction period	✓	✓	✓
Operating period	✓	✓	✓
Cooling before de-commissioning	✓	✓	✓
Decommissioning period	✓	✓	✓
Number of refurbishments	✓	✓	✓
Refurbishment period	✓	✓	✓
Spent fuel cooling period	✓	X	X
Waste cooling period	✓	X	X

Different cost components considered in the programme

For Nuclear power plant

Major cost components

- Capital investment
  - Capital cost (Construction, equipment, etc.)
  - Equity-Debt ratio, interest on borrowings etc.
  - Cash flow during construction
- Running cost
  - Fuel cost
    - Front end cost
      - Number of fuel types
      - Initial inventory
      - Annual feed
      - Rate
    - Back End cost
      - Direct disposal
        OR
      - Reprocessing
  - Cost of consumables
    - Initial inventory
    - Annual feed
    - Rate
  - O&M cost
    - Routine O&M
    - Refurbishment
- Decommissioning Cost

Different cost components considered in the programme

For H2 generation, storage and transportation facility

Major cost components

- **Capital investment**
  - Capital cost (Construction, equipment, etc.)
  - Equity-Debt ratio, interest on borrowings etc.
  - Cash flow during construction
- **Running cost**
  - **Cost of consumables**
    - Initial inventory
    - Annual feed
    - Rate
  - **O&M cost**
    - Routine O&M
    - Refurbishment
- **Decommissioning Cost**

Calculation of cost of hydrogen

- Hydrogen cost is estimated in two steps.

  - First step: calculation of levelised cost of energy (thermal and electrical, if generated)delivered by nuclear power plant.

  - Second step: Uses nuclear power plant results as input along with other user specified information to calculate levelised cost of hydrogen generation

Mathematical formulation

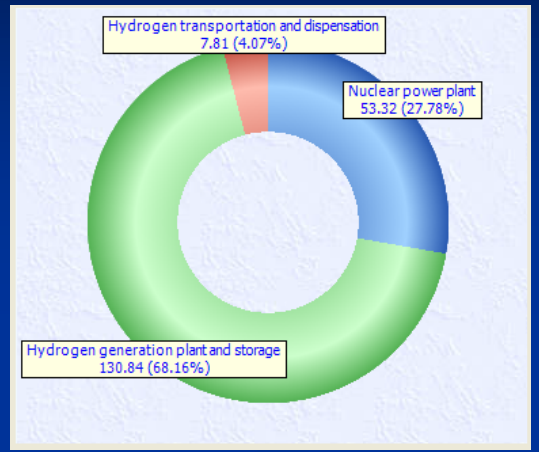
- The programme estimates "Levelised Cost of Hydrogen Generation"
  - Uses discount rate to work out present value of money required over the entire life period
- Levelised Cost of Nuclear Hydrogen (LCHG)

$$LCHG = \frac{E_{npp}(t_0) + E_{H2GP}(t_0) + E_{H2T}(t_0)}{G_{H2}(t_0)}$$

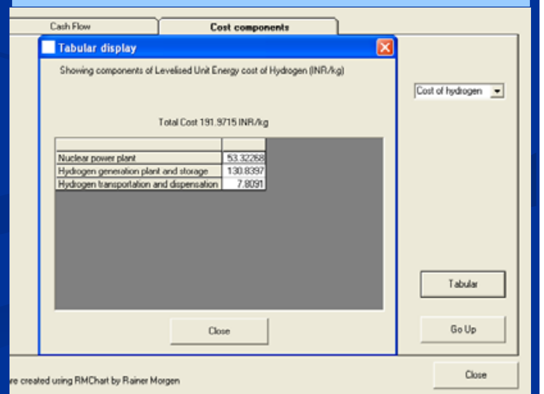
  - Where,
    - $E_{npp}(t_0)$ – Present value of expenditures of nuclear power plant
    - $E_{H2GP}(t_0)$ – Present value of expenditures of Hydrogen Plant
    - $E_{H2T}(t_0)$ – Present value of expenditures of Hydrogen Transport
    - $G_{H2}(t_0)$ – Present value of gross generation of hydrogen

Post-processing of HEEP results

- Multi-level display of results in the pie-chart form
  - First level: Contribution of each plant and facility
    - Nuclear power plant
    - Hydrogen generation and storage plant
    - Hydrogen transportation
  - Second level: Contribution of various cost elements for each facility
    - Capital cost
    - Fuel cost in case of nuclear power plant
    - O&M cost
    - Decommissioning cost
- Report generation
  - Reports are generated in “html” format



Features provided to view results in tabular form also



Preliminary Benchmarking of HEEP

Korean study to estimate cost of hydrogen generation

- The Korean Atomic Energy Research Institute (KAERI) carried out study on the estimation of cost of hydrogen production by S-I thermo-chemical based plant coupled to high temperature reactors.
  - "Preliminary Cost Estimates for Massive Hydrogen Production using SI Process", K.J. Yang, K.Y. Lee and T.H. Lee, HTR2008-58142, 4th Intl. Topical Meeting on High Temperature Reactor technology, 2008, Washington, USA
- G4-ECONS methodology was appropriately modified to evaluate levelized cost of hydrogen.

General description of the reference cases for preliminary benchmarking of HEEP

- Reference cases of Korean study:
  - Two-different nuclear core types viz. prismatic core (PMR) and pebble bed core (PBR) supplying heat for hydrogen generating plant based on S-I process.
- Four different cases resulting from four different configurations of nuclear plants with S-I thermo-chemical process analysed
  - 4 units of 600 MW(th) PMR supplying thermal energy to produce 216000 tonnes of hydrogen annually
  - 4 units of 200 MW(th) PMR supplying thermal energy to produce 72000 tonnes of hydrogen annually
  - 10 units of 600 MW(th) PBR supplying thermal energy to produce 225000 tonnes of hydrogen annually
  - 4 units of 200 MW(th) PBR supplying thermal energy to produce 72000 tonnes of hydrogen annually
- Electricity for hydrogen generation (non-process electricity) taken from the distribution grid at market rate of 0.06 US$/kWh

Reference case description for preliminary benchmarking of HEEP (Nuclear power plant)

CASES	CASE-I	CASE-II	CASE-III	CASE-IV
Nuclear reactor capacity	600 MWth	200 MWth	250 MWth	200 MWth
NPP configuration	4 units (PMR)	4 units (PMR)	10 units (PBR)	4 units (PBR)
Capacity factor	90%	90%	90%	90%
Availability factor	*100%*	*100%*	*100%*	*100%*
Construction period	3 years	3 years	3 years	3 years
Operating life	60 years	60 years	60 years	60 years
Cooling before decommissioning	*1 year*	*1 year*	*1 year*	*1 year*
Decommissioning period	*9 years*	*9 years*	*9 years*	*9 years*
Spent fuel cooling period	*2 year*	*2 year*	*2 year*	*2 year*
Waste cooling period	*2 year*	*2 year*	*2 year*	*2 year*
Capital cost	*1835.8 M$*	*867.575 M$*	*2944.45 M$*	*1088.75 M$*
Annual fuel cost	120.6 M$	40.2 M$	112.5 M$	36 M$
O&M Cost	38 M$	16.8 M$	56.4 M$	19.5 M$
Decommissioning cost	*Nil*	*Nil*	*Nil*	*Nil*

Reference case description for preliminary benchmarking of HEEP (Hydrogen generation)

CASES	CASE-I	CASE-II	CASE-III	CASE-IV
Rated hydrogen generation	216000 te/yr	72000 te/ yr	225000 te/yr	72000 te/yr
Non-process electricity*	*815 MWe*	*272 MWe*	*849 MWe*	*272 MWe*
Construction period	3 years	3 years	3 years	3 years
Operating life	60 years	60 years	60 years	60 years
Cooling before decommissioning	*1 year*	*1 year*	*1 year*	*1 year*
Decommissioning period	*9 years*	*9 years*	*9 years*	*9 years*
Capacity factor	90%	90%	90%	90%
Availability factor	100%	100%	100%	100%
Capital cost	1410 M$	673.325 M$	1564.75 M$	693.15 M$
O&M cost	77 M$	37 M$	77 M$	37 M$

*: derived based on total non-process electricity charges indicated in the report

Reference case description for preliminary benchmarking of HEEP (Hydrogen storage)

- The reference case did not consider hydrogen storage.

  - Hydrogen storage in compressed gas form considered with storage period of “0” hrs giving the storage capacity to be “0”. Additionally, storage pressure considered to be atmospheric pressure.

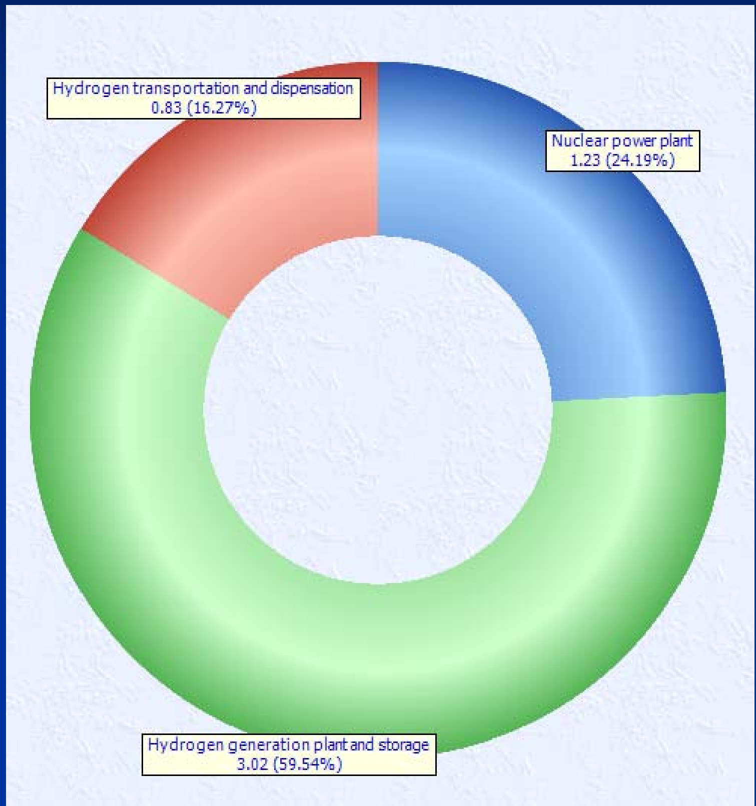
  - Programme thus calculates other relevant cost elements that depend on the storage period and compressor pressure as ‘nil’

Reference case description for preliminary benchmarking of HEEP (Hydrogen transport)

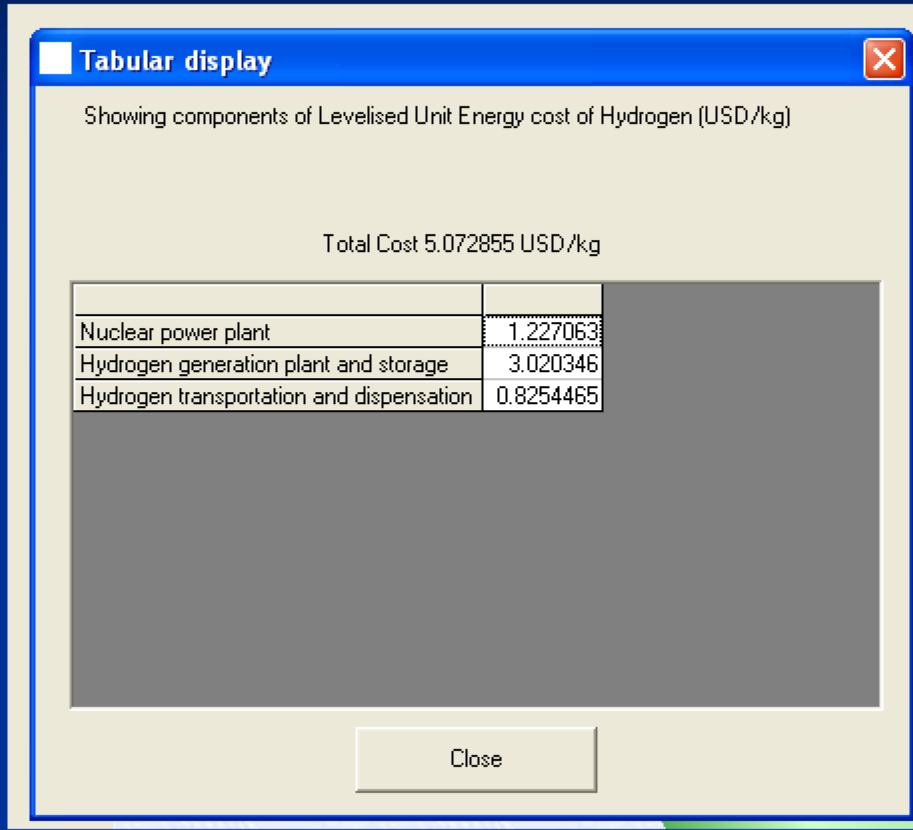
PARAMETER	VALUE
Vehicle capacity	180 kg
Average speed of vehicle	40 km/hr
Mileage of vehicle	2.5 km/lit
Loading-unloading time per trip	2 hours
Procurement period of vehicle	3 years
Life of vehicle	15 years
Refurbishment cost	100%
Number of refurbishments	4 nos.
Capital cost per vehicle	100000 $
Annual salary of driver	5000 $
Price of fuel	0.75 $/lit
Routine maintenance of vehicle	1% of total cost

- The reference case did not consider hydrogen transportation, but for completion above parameters are assumed.

Results for CASE-I (Level-1)



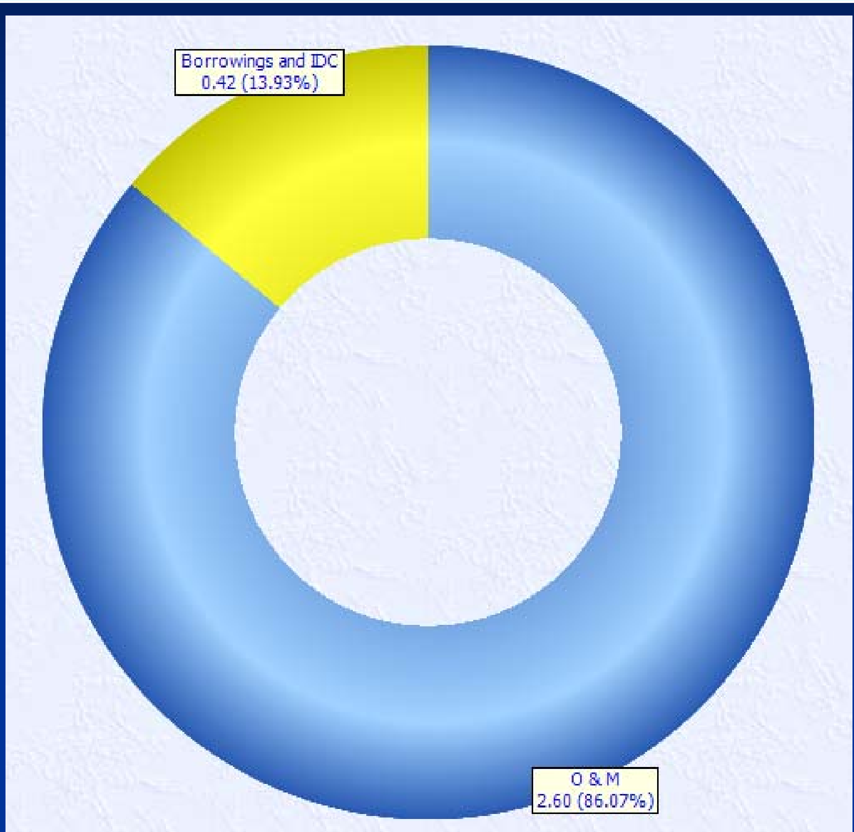
Pie-chart form showing contribution of each unit

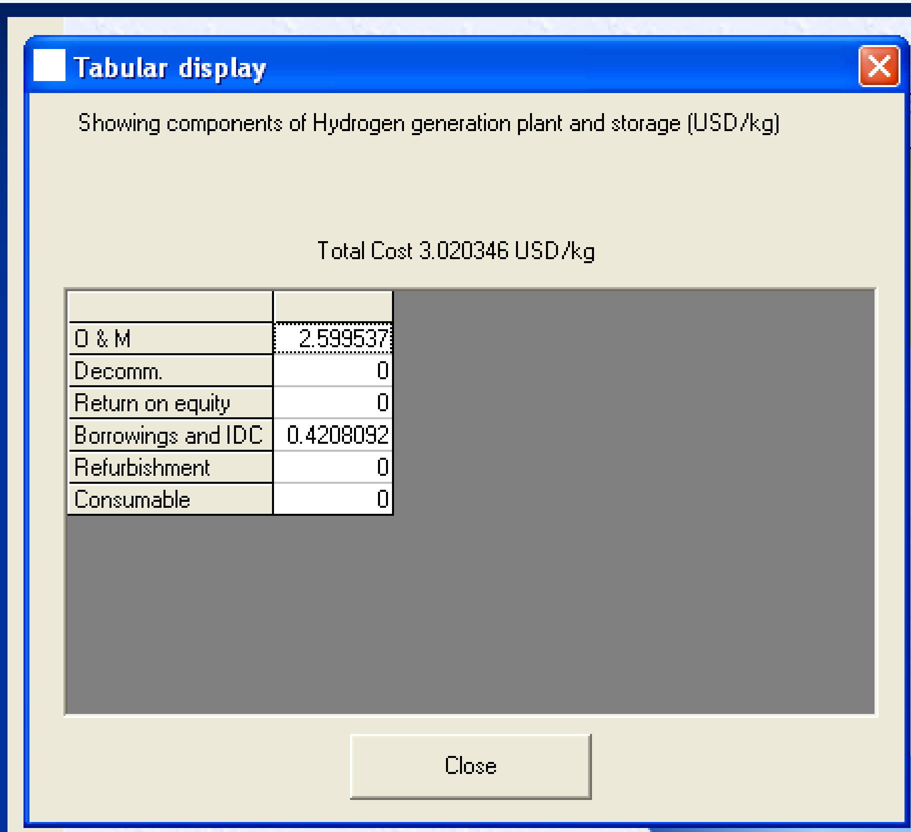


Nuclear power plant	1.227063
Hydrogen generation plant and storage	3.020346
Hydrogen transportation and dispensation	0.8254465

Tabular form showing contribution of each unit

Results for CASE-I (Level-2)



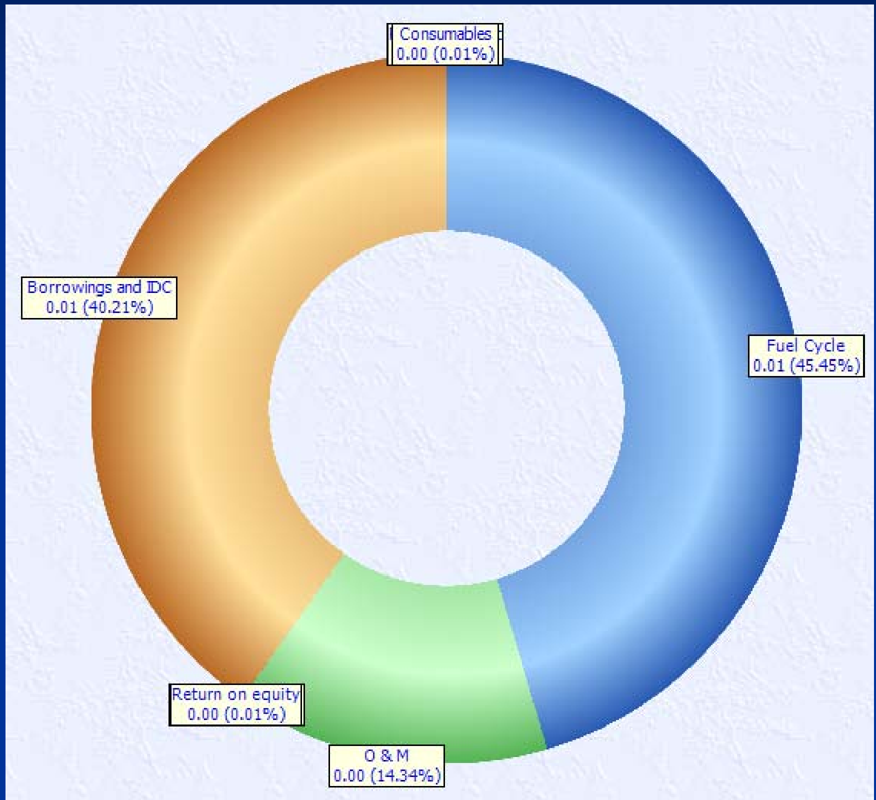


O & M	2.599537
Decomm.	0
Return on equity	0
Borrowings and IDC	0.4208092
Refurbishment	0
Consumable	0

Pie-chart form showing cost component of hydrogen generation and storage unit

Tabular form showing cost component of hydrogen generation and storage unit

Results for CASE-I (Thermal energy cost)



Pie-chart form showing cost component of thermal energy from nuclear power plant

Tabular display

Showing components of Levelised Unit Energy Cost of Thermal Energy from NPP (USD/kWth)

Total Cost 1.400037E-02 USD/kWth

Fuel Cycle	6.363036E-03
O & M	2.008344E-03
Decommissioning	0
Return on equity	0
Borrowings and IDC	5.628987E-03
Refurbishment	0
Consumables	0

Close

Tabular form showing cost component of thermal energy from nuclear power plant

Comparison of results- Contribution of units (NPP, hydrogen generation and transportation)

CASE	Levelised cost of Hydrogen ($/kg)					
	HEEP results					KAERI results
	Total levelised cost of hydrogen	Nuclear power plant component	Hydrogen generation & storage component	Hydrogen transpor-tation cost component	Nuclear power plant + hydrogen generation & storage	
CASE-I	5.07	1.23	3.02	0.83	4.25	4.06
CASE-II	5.82	1.62	3.38	0.83	5.00	5.56
CASE-III	5.36	1.50	3.03	0.83	4.53	4.48
CASE-IV	6.02	1.79	3.40	0.83	5.19	5.86

Comparison of results- Cost components

Cost comp-onent	CASE-I		CASE-II		CASE-III		CASE-IV	
	HEEP	KAERI	HEEP	KAERI	HEEP	KAERI	HEEP	KAERI
NPP capital	12%	10%	15%	10%	17%	19%	19%	9%
NPP fuel	13%	16%	12%	11%	11%	12%	10%	15%
NPP O&M	4%	5%	5%	5%	5%	6%	6%	5%
SI plant capital	10%	8%	12%	8%	10%	9%	12%	8%
SI plant O&M	61%	62%	56%	66%	57%	54%	54%	63%

Concluding remarks

Concluding remarks

- HEEP- consider large number of input variables affecting cost of hydrogen production

- Results of HEEP- encouraging and in good agreement with earlier studies.

- First version- available for download from IAEA's website.

- Software is evolving to reach a mature state

Concluding remarks

- Scope for further updating
  - To develop/modify input interface for different levels of users and usage
    - Beginners and advanced users
    - Quick estimates and detailed estimates
  - Building intelligence to avoid/warn erroneous inputs

Thank you