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Comparative cost evaluation of nuclear hydrogen production methods with the Hydrogen Economy Evaluation Program (HEEP)

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ABSTRACT

In this paper, a comparative cost assessment of some selected nuclear hydrogen production methods is performed with various options of hydrogen storage and transportation by employing Hydrogen Economy Evaluation Program (HEEP), as developed by International Atomic Energy Agency (IAEA). This HEEP software package is treated as one the most comprehensive ones with various nuclear hydrogen generation options. In the HEEP database, there are three different nuclear power plant options and three hydrogen production plant options included. The cost estimations for capital, fuel, decommissioning, O&M, and consumables are performed and evaluated in addition to the thermal energy and electricity cost details. These cost estimations include various hydrogen storage and transportation options. The hydrogen storage options considered are mainly compression, liquefaction and metal-hydride storage, which are available in the HEEP database. Furthermore, both pipeline and vehicle transportation costs are considered for cost calculations and evaluations.

Introduction

Global energy demand tends to increase with increasing population and welfare. In this regard, energy has been a critical element in shaping local and international policies of countries and their economies, environmental policies, sustainable issues, social dimensions, etc. [1]. Fossil fuel based energy systems are treated as non-sustainable due to their finite reserves and environmental effects. The shift from fossil fuels to nuclear and renewable resources is expected due to the increase in energy demand accompanied by growing concerns over environmental issues, such as global warming.

Hydrogen is expected by many energy experts and stakeholders to become the most important fuel for solving energy and environmental problems as we currently face. It is carbon-free and does not emit greenhouse gases and hence does not contribute to global warming. Hydrogen is treated as a promising candidate to be an excellent energy carrier that helps expand markets for renewable and nuclear energy resources,

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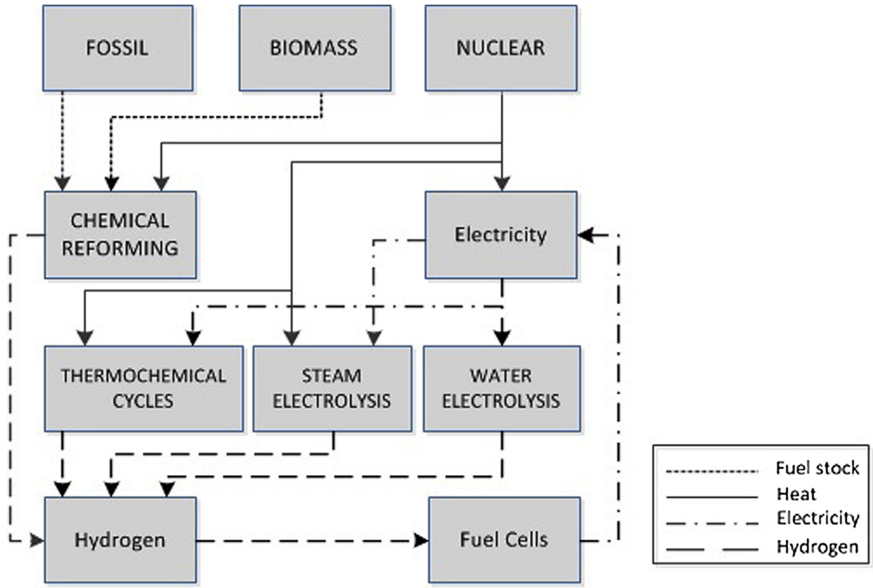

Fig. 1 – Hydrogen production methods from various energy sources (Adapted from Refs. [4,5]).

as well as contributing to sustainability and resolving environmental issues [2]. Hydrogen exists in abundance in nature in the form of water, but not alone which brings a need to produce it for use in a sustainable and environmentally-friendly manner. There are several methods of achieving this, including steam reforming of natural gas, coal gasification, water electrolysis and thermochemical water decomposition [3–5]. The main methods for production of hydrogen from various energy sources are summarized in Fig. 1.

Nuclear hydrogen production can be made by low-temperature electrolysis, high-temperature electrolysis, thermochemical, and hybrid processes. Low temperature electrolysis is simply splitting water into hydrogen and oxygen using electrical power which possesses a high amount of electricity consumption (~1.23 V/molH_2O). High-temperature electrolysis, which can also be called steam electrolysis, is a method to split steam into hydrogen and oxygen. Electrical energy requirement for splitting steam is lower than that of liquid water, and higher efficiencies can be obtained by using heat as a part of energy source. This method is not yet commercially available whereas a lab scale solid oxide electrolysis cell (SOEC) is demonstrated by Idaho National Laboratory (INL) [6].

Thermochemical processes are known as a series of some chemical reactions to split water into hydrogen and by-products using high and/or medium grade heat. Although these processes seem to be using only heat as the energy source, additional electrical power is required for additional or required electrolytic processes. The original Sulfur–Iodine (SI) process has been proposed by General Atomics (GA) and 75 L/h production is achieved through three key reactions. Japan Atomic Energy Agency (JAEA) continued the SI process with a plan to construct a 2 tons/day hydrogen with connection to a nuclear reactor. Hybrid Sulfur Cycle (HyS) is a two-step process, having a maximum working temperature of around 800°C. A modified HyS has been introduced in Japan, to decrease the maximum temperature range to (500–700 °C) [7]. The hybrid copper–chlorine (Cu–Cl) cycle is a medium temperature cycle having 3 to 5 steps with different configurations including both thermochemical and electrochemical steps. This process is led by Argonne National Laboratory (ANL), Atomic Energy of Canada Ltd (AECL), and Atomic Energy

Table 1 – Nuclear reactors and their specifications for hydrogen generation (Adapted from Ref. [6]).

Reactor type	Coolant	Reactor coolant temperature (°C)	Reactor size range (MWt)	Hydrogen production route
Light water reactors (PWR, AP, EPR)	Light water	280–325	2000–4080	Water electrolysis
Heavy-water reactors (CANDU, ACR)	Heavy water	310–319	2000–3200	Water electrolysis
Supercritical water reactor (S-LWR, CANDU, SCWR)	Light water	430–625	1600–2540	Water electrolysis, Thermochemical
Liquid metal fast reactors (SFR, LFR)	Sodium: lead: lead bismuth	500–800	45–3000	Water electrolysis, Thermochemical CH_4 reforming
Molten Salt Reactors (AHTR)	Salts	750–1000	900–2400	Water&steam electrolysis, Thermochemical CH_4 reforming
Gas-fast Reactors (GFR)	Helium	850	600–2400	Water&steam electrolysis, Thermochemical CH_4 Reforming
High-Temp. Reactors (HTGR, VHTR)	Helium	750–950	100–600	Water&steam electrolysis, Thermochemical CH_4 reforming

Commission (CEA) of France [8]. Several other types of thermo-electro-chemical cycles are under research to be linked for nuclear hydrogen production. Some nuclear reactor parameters with reactor temperature ranges for nuclear hydrogen production are summarized in Table 1.

In this study, a cost assessment of various nuclear hydrogen production plants is carried out using the HEEP software, which was developed by International Atomic Energy Agency (IAEA) [9]. A comparative cost assessment of various nuclear-based hydrogen production methods is performed by considering hydrogen storage (compressed gas, liquefaction, metal hydrides), and transportation (pipeline and truck) scenarios.

Software utilization

The present HEEP software package developed by IAEA is an improved and newly released one for evaluation and economic analysis of large-scale nuclear hydrogen production with storage and transportation options [10]. Some hydrogen production methods, such as low and high temperature electrolysis, thermo-electro-chemical hydrogen production and steam methane reforming can be comparatively evaluated in terms of economics. Capacities, total capital cost, initial and annual fuel costs, etc. are included for cost estimation [11]. Some technical features of this HEEP software package are summarized in Table 2.

Further technical details and specific case studies about the HEEP software package, including cost items (capital or fixed cost, operational costs, decommissioning cost), and execution module for levelized costs of hydrogen production are found elsewhere [10–14].

In this study, comparative cost estimation of hydrogen generation from nuclear power is conducted. Several scenarios of hydrogen storage and transportation are considered for comparison are represented in Fig. 2. For every nuclear plant, one type of hydrogen generation plant is considered. The hydrogen produced is stored in all three storage options and two transportation options, except for metal hydride storage and liquefaction, which cannot be fed in to pipeline.

The calculation of levelized hydrogen cost is made by the HEEP as the ratio of sum of present value of generated hydrogen, storage, and transportation to present value of gross hydrogen generated [10].

$$C_{H_2} = \frac{E_{NPP}(t_0) + E_{H_2GP}(t_0) + E_{H_2T}(t_0)}{G_{H_2}(t_0)} \tag{1}$$

where E, C and G refer to expenditures, and subscripts NPP, H_2GP, and H_2T refer to nuclear power plant, hydrogen generation and storage, and hydrogen transportation, respectively. The present values of expenditures are calculated with the following definition [10,11]:

$$E(t_0) = \sum_{t\_i}^{t\_f} \frac{CI_t(t_0)}{(1+r)^{t-t_0}} + \sum_{t\_i}^{t\_f} \frac{R_t}{(1+r)^{t-t_0}} + \sum_{t\_i}^{t\_f} \frac{DC_t}{(1+r)^{t-t_0}} \tag{2}$$

Here, CI, R and DC refer to capital investment expenditures, facility running expenditures and decommissioning expenditures for the year t, respectively. Subscript 0 is for the base year, and r is real discount rate. The present value of the gross hydrogen generation for the time t_0 is given as follows:

$$G_{H_2}(t_0) = \sum_{t\_i}^{t\_f} \frac{G_{H_2}(t_0}{}$$

Table 3 – Description of various cases of nuclear power plant and Hydrogen generation plant used in HEEP.

Parameter	Case I	Case II	Case III	Case IV
	PBR NPP	PMR NPP	HTGR NPP	
Nuclear Power Plant				
Thermal rating per unit	200 MW_{th}	200 MW_{th}	600 MW_{th}	600 MW_{th}
Number of units	4	6	4	6
Electricity rating, MW_e/unit (efficiency)	–	160 (40%)	–	110 (40%)
Thermal heat of H_2 plant, MW_{th}/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	2100	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

Results and discussion

In this study, three different nuclear power reactors are considered, as provided by the HEEP; Prismatic core (PMR), Pebble Bed (PBR) and High Temperature Reactor (HTGR). Four different configurations are considered as tabulated in Table 3. Hybrid Sulfur (HyS) thermochemical plant is considered for hydrogen production. For Cases I and II, as shown in Table 3, the Nuclear Power Plant (NPP) supplies the heat required for the hydrogen generation process. However, in Cases III and IV, electricity production is considered to share in supplying part of the electric power demand of the hydrogen generation plant operation. The electric power required for the hydrogen production and other devices in the integrated system units is supplied from the grid with the unit costs given in Table 4. The capital cost of the plant is calculated for the proposed cases based on the data provided by the HEEP.

In Case I, as given in Table 3, four PBR units of 200 MW thermal capacity are coupled with one thermochemical plant that provides 72,000 ton of hydrogen annually. In Case II, one hydrogen generation unit is integrated with six units of PMR nuclear power plant with 200 MW thermal capacity. 160 MW of electric power is considered from the NPP which is assumed to operate at 40% efficiency. The power produced shares in providing part of the hydrogen generation plant. This appears in the energy usage cost difference between Cases I and II. For Cases III and IV, HTGR is considered with two different plant capacities. In Case III, four units of 600 MW thermal power units are used to satisfy the heat demand of the hydrogen production plant which has annual production of 216,000 ton. The integration of two more units, in Case IV, results in a reduction of more than 78% of the electric energy cost of the hydrogen production plant as the electric demand of the hydrogen generation from the grid drops to 155 MW_e. An increase of 10% of the capital cost is considered for electricity generation utility when electric power generation is considered, i.e., Cases II and IV. Also operation and maintenance cost for the power generation utility is considered to be the same as for the corresponding plant. Tables 4 and 5 present the base case financial and operation parameters for the integrated system units.

Table 4 – Time periods and financial parameters considered in the analysis (base case).

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
Waster cooling	24 month
Capacity factor	90%
Availability factor	100%
Unit cost of grid electricity, c$/kWh	6.6
Storage	
Hydrogen storage period, h	168
Unit cost of cooling water for storage, $/ML	0.00022
O&M cost for hydrogen storage, %	5
Liquefaction	
Cooling water flow rate of Liquefaction, L/kg H_2	209
Daily Boil-off rate, %	0.1
Metal Hydride	
Specific Heating power, MJ/kg H_2	23.26
Hydride cooling, L/kg H_2	209

Table 6 shows the details of the storage and transportation alternatives that are coupled with the hydrogen generation plant. The cost, capacity and other parameters shown are joint for Cases I and II, and Cases III and IV. This is because the PMR and PBR cases use the same hydrogen generation plant, and the other capacity and the specifications of the hydrogen generation coupled with the NPP in the other two cases are the same. For pipeline transportation, only compressed gas storage option is applicable.

The results presented in this section are shown for different integration scenarios of the proposed nuclear power plant (NPP), hydrogen generation (HG), hydrogen storage (HS); i.e.: compressed gas (CG), metal hydride (MH) and liquefaction (LQ), and transportation by vehicles (V) and pipelines (P). The results in Fig. 3 show the specific hydrogen production cost with respect to the four proposed cases considering hydrogen generation without taking the storage or transportation into the analyses calculations. The results shown here appear to be reasonably accurate and consistent with the data presented in the literature [10,11]. Even with the 60% increase in the capital cost of the nuclear power plant in Case IV compared with Case III, the cost of hydrogen generation is decreased by 20%.

Table 5 – Transportation options considered in HEEP analyses (base case).

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
O&M cost, %	0.1	O&M cost, %	1

Considering the integration of different storage options, for each case, as shown in Fig. 4; the metal hydride storage plant is higher with 27%, 29.5%, 30.7%, and 33% than the liquefaction method and 48.5%, 53.3%, 54.6%, and 58% than the compressed gas storage method, for the Cases I, II, III and IV respectively.

Figs. 5 and 6 show the breakup of the hydrogen production cost with respect to the integrated plant units. The results shown in these two figures consider three different storage plants with no transportation integration. Hence, only NPP, HG, CG, MH and LQ are considered. Fig. 5 shows the percentage of the contribution of the different units for each case of the four cases separately. In Fig. 6, same results are obtained with respect to the different cases for each storage method separately to compare each unit contribution for the different cases. The results show that for the cases with metal hydride storage plant experience higher contribution from the hydrogen storage plant as it is 5.9$ and 5.89$, per kg, for storage cost in Case I, II and Case III, IV, respectively. For metal hydride scenario, hydrogen production cost is 11.42, 10.29, 10.22 and 9.38 for the different proposed cases, as shown in Fig. 4.

It can be seen in Fig. 6, for the compressed gas storage alternative, Case II experiences the lowest contribution from the NPP as the capital cost is relatively smaller, compared to

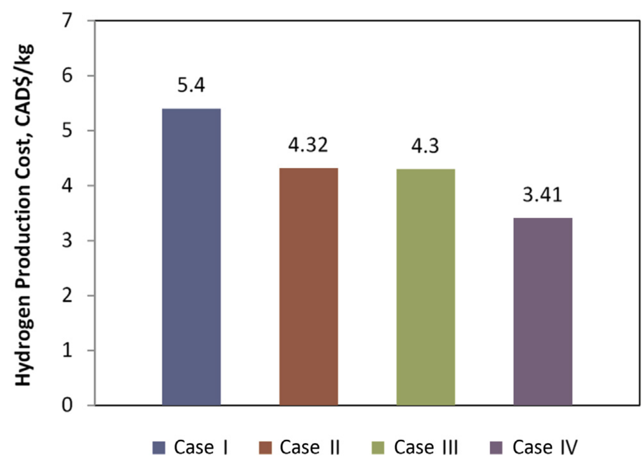

Fig. 3 – Comparison of hydrogen production costs only for four cases.

Table 6 – Details about Hydrogen storage and Transportation options.

	Cases I, II	Cases III, IV
Hydrogen storage		
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	10,000
Cost of energy for hydride cooling, $	30,134	90,228
Hydrogen transportation		
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

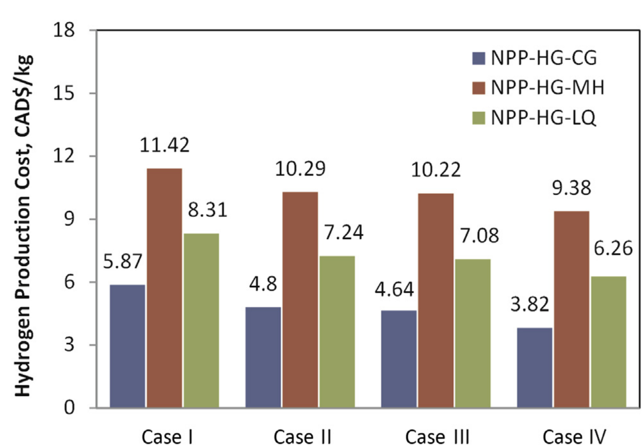

Fig. 4 – Hydrogen production costs for various storage options under various cases.

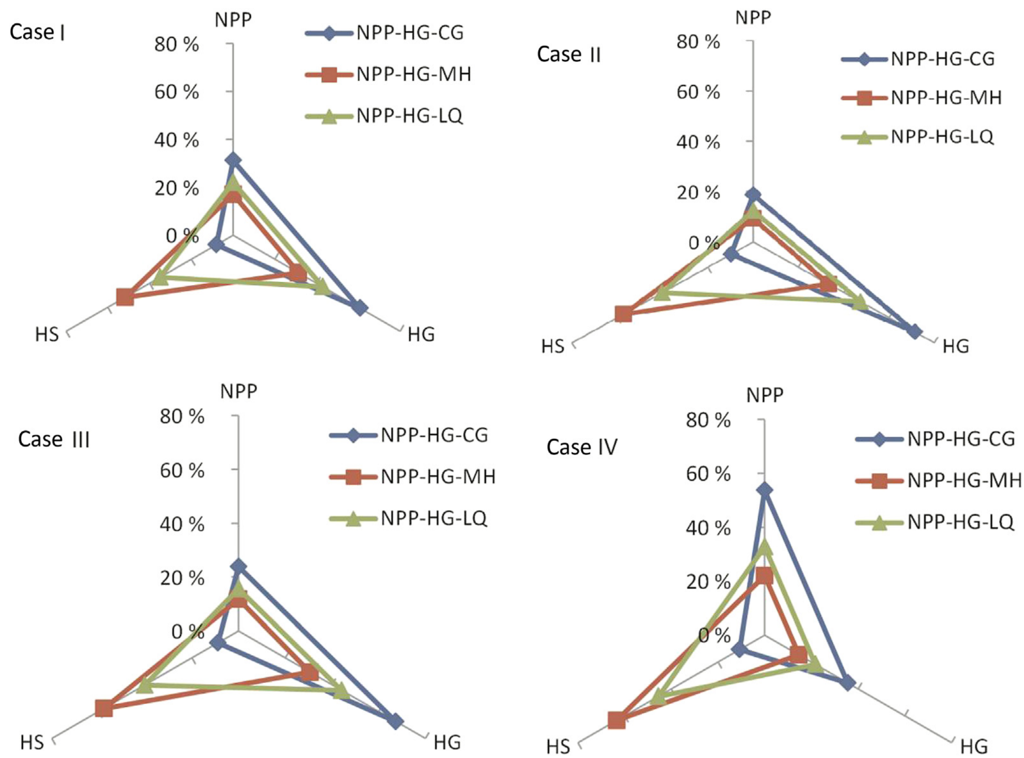

Fig. 5 – Contribution percentages of plant units on hydrogen production costs for the cases considering different storage options as shown for each case.

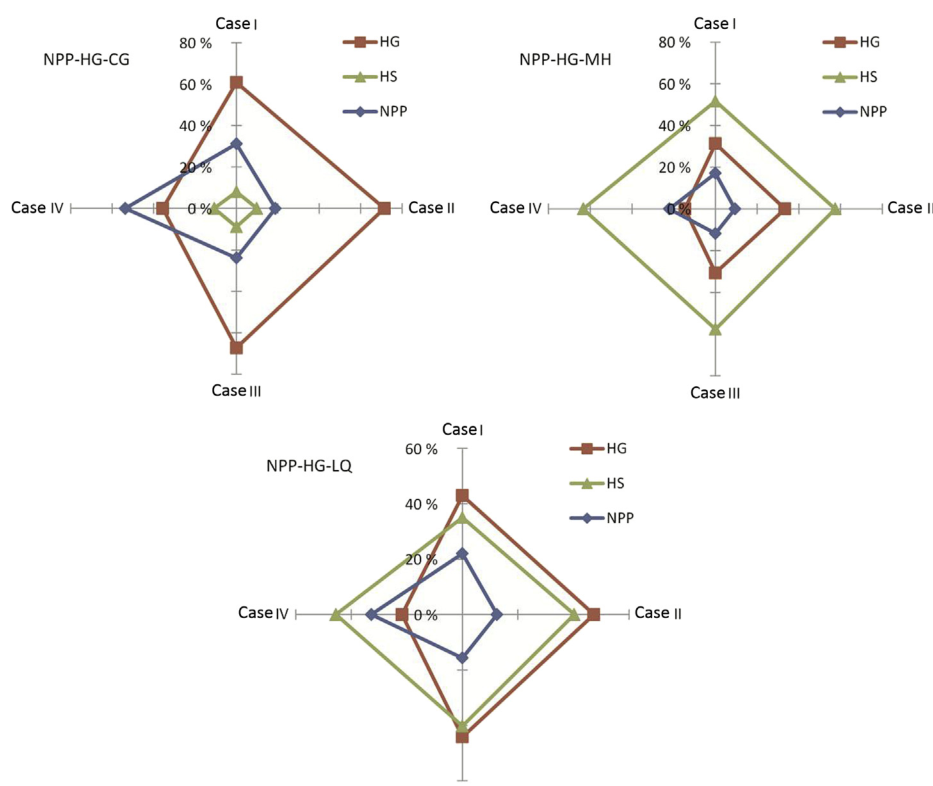

Fig. 6 – Contribution percentages of plant units on hydrogen production costs for the cases with respect to the storage method considered.

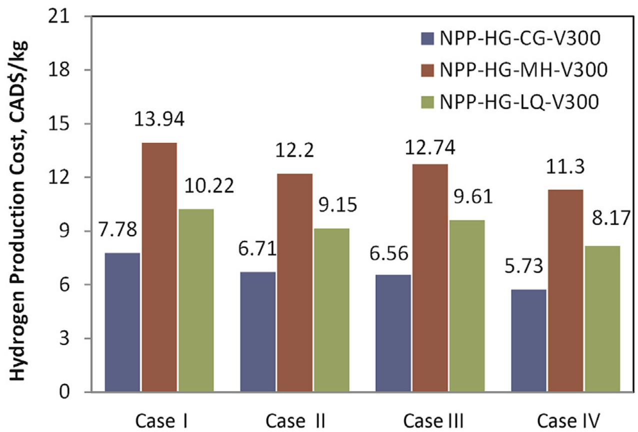

Fig. 7 – Hydrogen production costs for different storage and transportation options.

other cases. On the other hand, Case IV has the highest contribution in the hydrogen production cost from the NPP, but the hydrogen generation plant contribution is the lowest, compared with the other cases as a result of covering almost 80% of the electricity demand of the generation plant from the NPP produced power.

The results in Fig. 7 show the three different storage cases with the main four different generation plants considering the transportation using vehicles option. The distance travelled for transportation is taken as 300 km for the sake of comparing the cost of hydrogen production with the proposed systems. Same trend of results is achieved with respect to the difference between the storage alternatives which are shown in Fig. 4. However, an increase of 33%, 40%, 41%, and 50% in the total cost of hydrogen production occurs for the four different cases, with integration of the transportation via vehicle trips for the specified distance, when compared with the results given in Fig. 4.

Figs. 8 and 9 show the breakup of the hydrogen production cost for the production, storage and transportation scenarios for the four different cases proposed in this study. Vehicle trips are considered as for transportation with a travelling distance of 300 km. The obtained results agree with the results reported in Figs. 5 and 6, with the percentage increase of the cost caused by the transportation increment which is illustrated earlier in Fig. 7.

The results shown in Table 7, which are also presented in Fig. 10 show a comparison of vehicle and pipeline options for transportation of the generated hydrogen considering no hydrogen storage option. Different transportation distances are tested. It is clear that with the increase of the distance, a great increase in the cost occurs when using vehicles trips for transportation compared with the pipeline option, that experience a relatively lower increase in the cost. This shows that for the distance less than 300 km, vehicle transportation may be considered, but it is not recommended for longer trips.

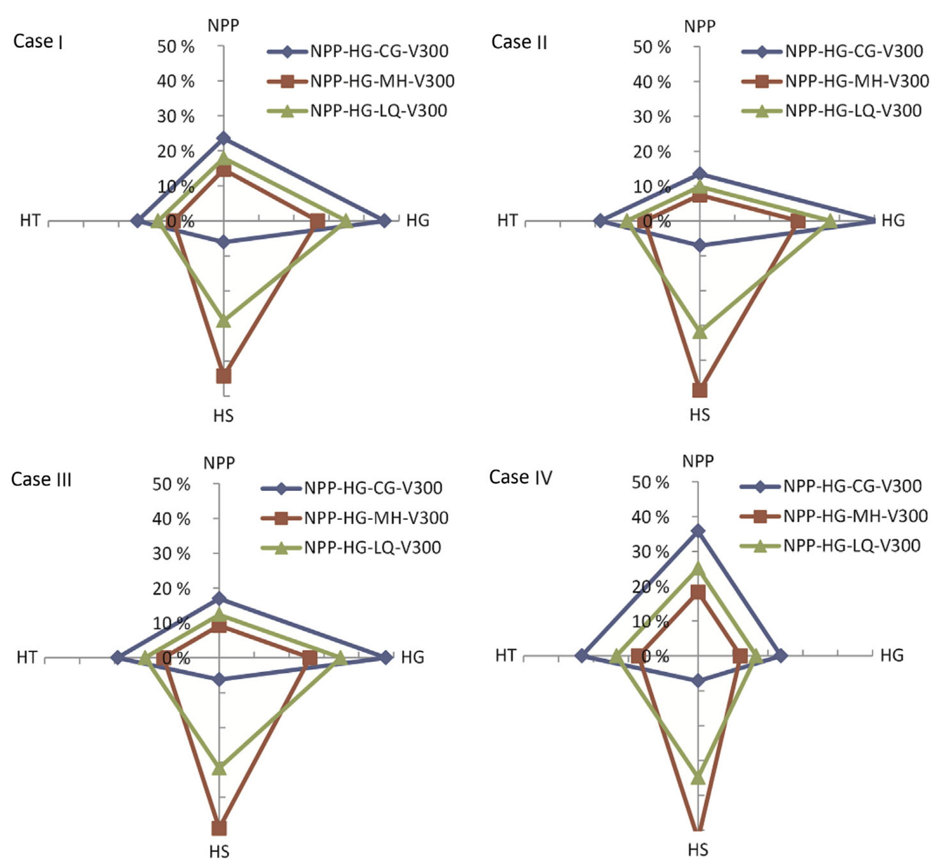

Fig. 8 – Contribution percentages of plant units on hydrogen production costs for the cases considering different storage options for each case.

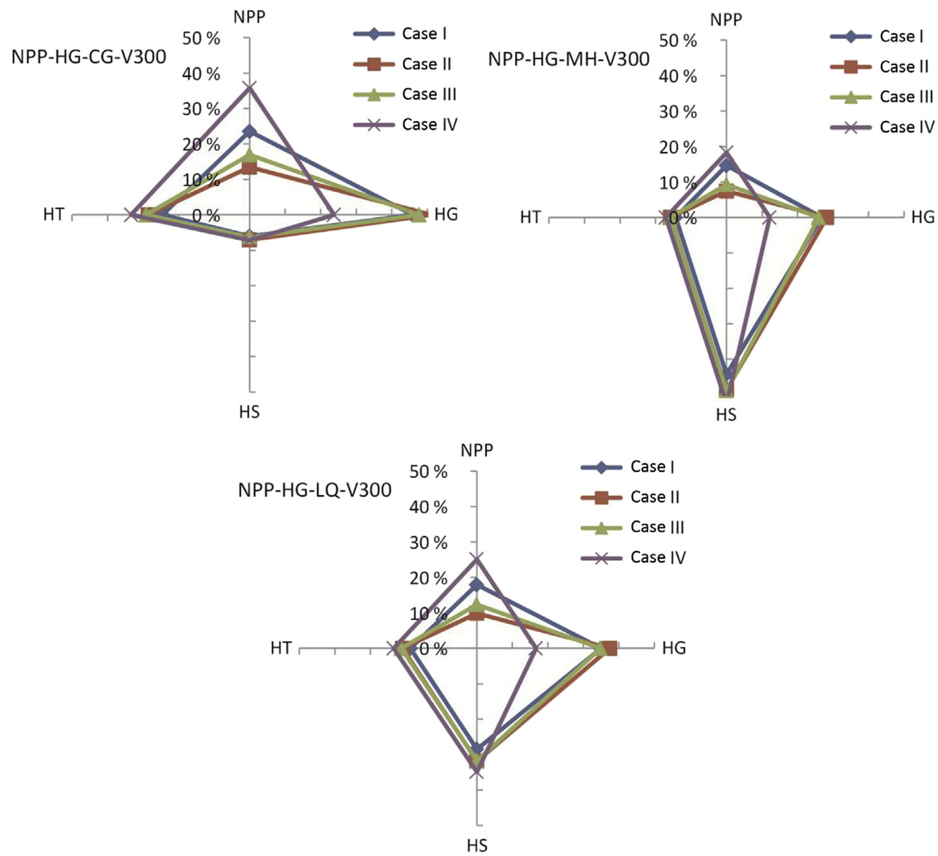

Fig. 9 – Contribution percentages of plant units on hydrogen production costs for the cases considered with respect to the storage method.

Fig. 11 shows the costs of hydrogen production for different transportation methods when considering integrating compressed gas storage plant with the four different cases of hydrogen generation. The results shown are for 300 km vehicle trips when 500 km of transportation distance is considered for the pipeline option. The use of the pipeline option is still much more cost effective (by about 30–45%), compared with using vehicle trips. However, pipeline transportation is not applicable with the other hydrogen storage plant option.

Conclusions

In this study, the HEEP software, developed by IAEA, is utilized in order to comparatively assess the levelized costs of hydrogen production under various storage and transportation cases. Three different options are considered as provided by the HEEP; Prismatic core (PMR), Pebble Bed (PBR) and High Temperature Reactor (HTGR). Four different configurations are introduced for cost comparison and contributions of plants in the total cost of the system, by varying several parameters. The results obtained from the present study are listed as follows:

- The 6-Unit-600 MW_{th} HTGR based nuclear hydrogen generation plant (Case IV) has the lowest hydrogen cost by 3.41 CAD$/kg, compared to other cases considered.
- The costs of hydrogen for metal hydride storage plant are higher than the costs for liquefaction storage option by 27%, 29.5%, 30.7% and 33% and the costs for compressed

Table 7 – Costs of hydrogen production for different transportation distances (considering no storage option is included).

	Case I		Case II		Case III	
	Vehicle	Pipelines	Vehicle	Pipelines	Vehicle	Pipelines
300 km	7.31	5.69	6.24	5.69	6.24	5.69
500 km	8.56	5.76	7.49	5.76	7.49	5.76
700 km	9.82	5.82	8.75	5.82	8.75	5.82
900 km	11.07	5.89	10	5.89	10	5.89

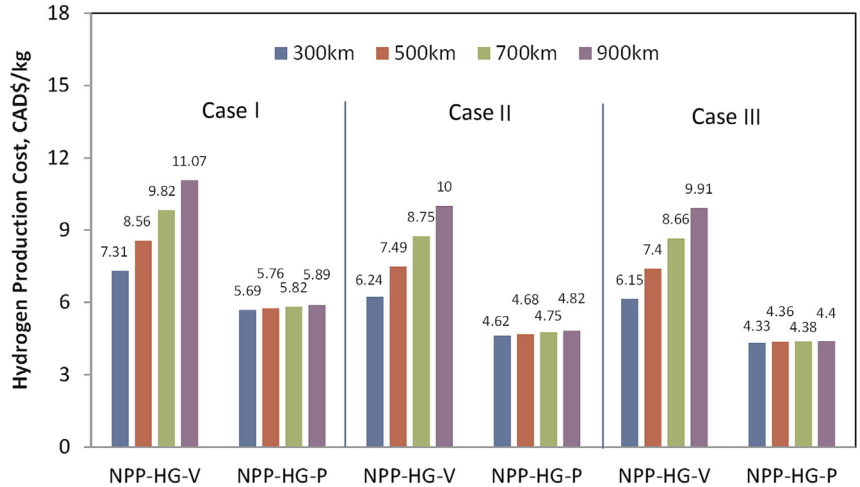

Fig. 10 – Hydrogen production costs for the cases considered at different transportation distances.

gas storage by 48.5%, 53.3%, 54.6%, and 58%, respectively, for the four cases considered.

- When storage and transportation options are added to overall plants, a substantial increase in the hydrogen cost by 20%–55% is observed compared to hydrogen production alone.
- The cases with metal hydride storage option bring up higher contribution to total hydrogen cost. This is due to higher capital cost of the metal hydride.
- The hydrogen cost increase up to 33%, when a vehicle transportation option is added to all cases (300 km distance). This increase in cost is mainly due to fuel cost for vehicle transportation.
- The cost of hydrogen production using pipeline transportation appears to be 30–45% less expensive compared with vehicle transportation for the system coupled with compressed gas storage plant.
- A little change in the hydrogen production cost with the transportation distance for pipeline transportation when compared to vehicle trips makes the former to be more appropriate option for transportation especially for distance more than 300 km. It is calculated that cost is doubled when using vehicles for 900 km distance.
- The number of units, thermal and electrical rating of the nuclear plant, type of hydrogen generation plant, and types of hydrogen storage have strong influence on the total cost of hydrogen production.

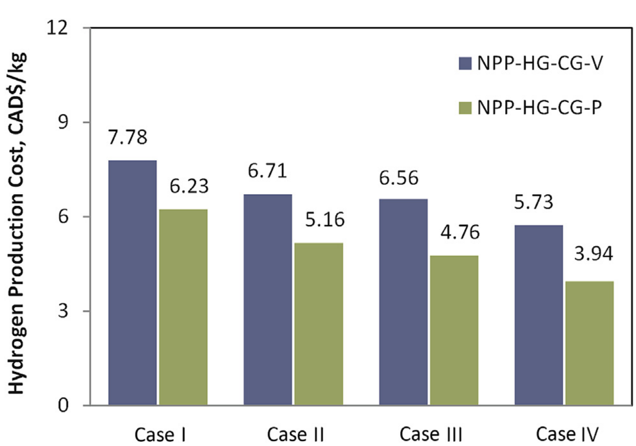

Fig. 11 – Cost comparisons for vehicle and pipeline transportation methods considering the integration of compressed gas storage option to the production plant.

In summary, the HEEP software package is a user friendly software package with a convenient way to estimate hydrogen cost from various plant configurations. This package is now under further development by IAEA to extent its library with more options on nuclear hydrogen production, storage and transportation.

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Nomenclature

AECL	Atomic energy Canada Limited
AHTR	Advanced high temperature reactor
ANL	Argonne National Laboratory
CANDU	Canada deuterium uranium
CE	Conventional electrolysis
EPR	European pressurized reactor
GA	General Atomics
HEEP	Hydrogen economy evaluation program
HTGR	High temperature reactor
HTSE	High temperature steam electrolysis
HyS	Hybrid Sulfur
IAEA	International atomic energy agency
INL	Idaho National Laboratory
LFR	Lead-cooled fast reactor
LWR	Light water reactor
O&M	Operational & Maintenance

PBR	Pebble bed core
PMR	Prismatic core
PWR	Pressurized water reactor
SCWR	Supercritical water-cooled reactor
SFR	Sodium-cooled fast reactor
S-LWR	Super light water reactor
SMR	Steam methane reforming
VHTR	Very high temperature reactor

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