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A generic methodology to evaluate economics of hydrogen production using energy from nuclear power plants

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ABSTRACT

Hydrogen, the deemed future transportation fuel can be produced from nuclear assisted energy sources. Assessment of economics of hydrogen production using energy from nuclear power plants is vital for asserting its competitiveness with competing technologies. A generic method is presented in this paper to evaluate Levelised Hydrogen Generation Cost, based on the discounted cash flow analysis. The method is illustrated by consideration of a typical case of hydrogen production via conventional electrolysis using electrical energy supplied from a pressure tube type boiling light water cooled heavy water moderated reactor concept.

Introduction

Economic competitiveness is one of the main criteria for selection of a particular technology from among various available alternate technologies. Levelised unit cost of the deliverable from the technology can be taken as a figure of merit for the economic competitiveness. Presently, various hydrogen production technologies are being explored world over. Hydrogen has a potential to be realized as a popular fuel in transportation sector. Several known processes exist for the production of hydrogen. The process varies among each other with respect to overall efficiency of production and source of energy. The energy input for production can be sourced from fossil fuelled plants or nuclear fuelled plant or non-conventional energy sources such as solar, wind etc. Nuclear reactor coupled processes minimse environmental pollution and is suitable for large scale production of hydrogen. Energy input in the form of heat and electricity can be supplied from the nuclear power plant to the hydrogen generation plant. High temperature nuclear reactors are suitable for production of large quantity of hydrogen through high efficiency process like Sulphur-Iodine (SI), High Temperature Steam Electrolysis (HTSE), Hybrid Suphur (HyS) process etc. which require high temperature heat. Since the temperature of heat obtainable in conventional light water reactors are not suitable for high

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Nomenclature

AIDP	annual installment of debt payment ($/yr)
ATCF	after tax cash flow ($)
BTCF	before tax cash flow ($)
CE	capital expenditure ($)
CF_i	cash flow during the year 'i' ($)
C_c	unit fuel material conversion cost ($/kg)
C_d	unit cost for spent fuel disposal($/kgHM)
C_e	unit fuel material enrichment cost ($/SWU)
C_f	unit cost for fuel fabrication ($/kgHM)
C_p	unit fuel material purchase cost ($/kg)
C_{pu}	cost of recovered plutonium ($)
C_r	unit cost of reprocessing ($/kgHM)
C_{ru}	cost of recovered uranium ($)
C_{rTh}	cost of recovered thorium ($)
C_{ts}	unit cost for spent fuel transportation and storage ($/kgHM)
D	deprecation($)
DC_t	decommissioning cost payment during the year t($)
DP_CI_t	depreciation payment on the capital cost during the year t($)
$DP\text{-}RF_t$	depreciation payment on the refurbishment cost during the year t($)
Dbto(t)	the outstanding debt in year 't' ($)
EQ_t	equity payment during year t ($)
ER	enrichment ratio (–)
F_c	fuel material conversion cost($)
F_d	spent fuel direct disposal cost ($)
F_e	fuel material enrichment cost($)
F_f	fuel fabrication cost ($)
F_p	fuel material purchase cost ($)
F_r	spent fuel reprocessing cost ($)
F_t	total fuel cycle cost ($)
F_{ts}	spent fuel transportation & storage cost($)
FV	future value($)
H2Production	annual hydrogen production(kg/yr)
IN_t	the interest paid during the year 't' ($)
LC	levelised cost ($/kg)
Lft	load factor (%)
M_{rpu}	recovered mass of plutonium(kg)
M_{rTh}	recovered mass of thorium(kg)
M_{rU}	recovered mass of uranium(kg)
N_{rp}	debt repayment period(yrs)
OM_t	operation and maintenance cost payment during the year 't'($)
OPE	operating expenses($)
PN_t	debt principal payment during year t($)
PV	present value($)
R	revenue generated($)
RF_t	cost of refurbishment paid during the year t($)
S	separative work unit ($/kg)
T	taxed paid ($)
TD	the total debt in each year ($/yr)
c_{pu}	unit cost of recovered plutonium ($/kg)
c_{rTh}	unit cost of recovered thorium ($/kg)
c_{ru}	unit cost of recovered uranium ($/kg)
d	discount rate (%)
ir	interest rate (%)
l_c	material loss during conversion(%)
l_e	material loss during enrichment(%)
l_f	material loss during fabrication(%)
m_f	mass of fuel handled (kg)
t_c	lead time for fuel material conversion(yr)
t_{con_st}	construction start year (yr)
t_{con_en}	construction end year(yr)
t_{dc_st}	decommissioning start year (yr)
t_{dc_en}	decommissioning end year (yr)
t_d	time at which disposal cost is incurred (yr)
t_e	lead time for enrichment of fuel material (yr)
t_{end}	end time of cash flow (yr)
t_f	lead time for fuel fabrication (yr)
t_{op_st}	plant operation start year (yr)
t_p	lead time for procurement of fuel material (yr)
t_{pu}	time at which plutonium is recovered from spent fuel by reprocessing (yr)
tr	tax rate (%)
t_{rf_st}	refurbishment start year (yr)
t_{rp}	time at which reprocessing cost is incurred (yr)
t_{rpy_yr}	year to which debt repayment is done (yr)
t_{ru}	time at which uranium is recovered from spent fuel by reprocessing (yr)
t_s	time at which transportation and storage cost is incurred (yr)
t_{start}	start time of cash flow (yr)
t_{Th}	time at which thorium is recovered from spent fuel by reprocessing (yr)
x_f	fraction of feed (%)
x_p	fraction of product (%)
x_t	fraction of tail (%)

Subscript

i	no. of year (yr)

temperature processes; production of hydrogen through low temperature processes is only feasible in current light water reactors. The technical specification of light water reactors is suitable for production of hydrogen through the route of conventional electrolysis process.

Assessment of economics of hydrogen production using nuclear power is important for comparing the economic competitiveness with other generation technologies. Literature survey shows that several published papers are available as given in Ref. [1–14] which mainly covers the technology aspects of hydrogen production from the nuclear power. But in the area of economic analysis limited number of publication are only available. For example, the study cited in Ref. [15,16], describes the economics of hydrogen production from SI process and [17] discusses HTSE based hydrogen production. However the models used for the economic analysis are described only in a limited way in these references.

A few computer codes are also available for assessment of hydrogen economy such as G4-ECONS [18] and DoE's H2A analysis code [19] and both are spread sheet based software. A study of the underlying modeling employed in G4-ECONS computer code shows that in that code capital cost is modeled fully as market borrowing and no consideration is given to equity modeling. The discount rate and interest rate were taken equal in G4-ECONS computer code. Time line factors like lag and lead time are not considered for fuel cycle cost estimation. Being a generic code G4-ECONS do not model tax. The model described in this paper has the flexibility in modeling the capital cost as a mixture of debt and equity, considers both interest rate and discount rate separately, comprehensively model the fuel cycle cost taking into consideration the time lead and lag, and more importantly it takes into account the cash flow towards tax payment which represent an actual representation of cases in given market condition.

The major difference between the model presented here and the models used in H2A analysis computer code is that the later do not estimate the energy costs from nuclear power plant exclusively. It model only cost elements of hydrogen generation plant. Construction period of maximum of 4 years only can be modelled in H2A. No such limits in the model presented in this paper. In a way the model presented in this paper is more realistic in simulating the economics of hydrogen generation from nuclear energy in expected actual market conditions as can be seen from the following descriptions.

This paper deals with the modelling of economics of hydrogen generation from nuclear energy source. A case study has also been given in the paper. Since the aim of this paper is mainly to present a generic methodology for the assessment of economics of hydrogen production through energy derived from nuclear power plants rather than going into technological details, the specifics of technology of hydrogen production process are not covered here. The following sections elaborate the details of the methodology.

Basis of the methodology

The formulation described in this paper is based on the Discounted Cash Flow (DCF) methodology [20–23], to arrive at a Levelised cost for hydrogen produced from a hydrogen generation plant coupled to a nuclear power plant. By definition the levelised cost is the uniform constant price at which the hydrogen is to be sold over the life time of the plant to recover all the expenses incurred during the life cycle of the plant to achieve a no loss or no profit condition at the intended discount rate called as Internal Rate of Return (IRR).

The fundamental principle of this approach is that the amount of money received or spent in future is worth less than the money received or spent today and vice versa. For example at a discount rate or interest rate of 10%, $ 1000/- of today will be equivalent to $ 1100/- after one year or an amount of $ 1100/- after one year worth only $ 1000/- of today. In any project the cash flow in the form of both costs and benefits occurs at different time intervals at different magnitude. Considering this underlying principle of economics, algebraically addition of cash flows for the purpose of analysis will leads to incorrect values. Hence, for the purpose of cash flow analysis, the concept of 'value of money' shall be accounted by a process called 'discounting' to arrive at the present worth or value of the cash flow.

The present value, PV, of future payment, FV, which is incurred 'i' years from now is given by

$$PV = \frac{FV}{(1+d)^{i}} \tag{1}$$

where, 'd' is the discount rate. Discount rate represents the cost of the capital employed in the project. It also represents the minimum cut-off return below which investors may not be interested in investing in the project. The discounting process is indicated in Fig. 1.

In a nuclear power plant (NPP), typically, the life cycle cost profile consists of cash flows at various stages; during construction, operation, front end and back end fuel cycle and decommissioning (Fig. 2). During construction of the reactor, capital cost is incurred all throughout the construction period for fabrication, erection and commissioning of various system, structure and components. When the reactor starts operational, additional expenditures are incurred in the form of fuel cycle costs; both front end and back end, operation and maintenance charges (fixed and variable), refurbishment costs for major replacements etc. Costs are incurred for fabrication of the finished fuel for initial full core loading also. During operation of the reactor the spent fuel is reprocessed (if reprocessing option is considered for back end) and wastes are disposed off. The useful materials (Plutonium, Reprocessed Uranium or Thorium) recovered during the reprocessing will have credits since they can be suitably used for fabrication of fresh fuel bundles. If direct disposal is employed for the spent fuel; costs are considered for storage, cooling, transportation and final disposal of the waste. Finally the decommissioning costs are incurred for decommissioning of the nuclear power plant. During the operation the product (electricity) is sold out to earn revenue. The expenditure is indicated by green coloured boxes and revenue generated in blue coloured boxes in the Fig. 2. Similar cash flow is considered for hydrogen generation plant life cycle also.

The Discounted Cash Flow method discounts the series of expenditures and revenue generated over the life span to their present value with respect to a specified reference year by applying a discount rate. The cash flows which are made up of

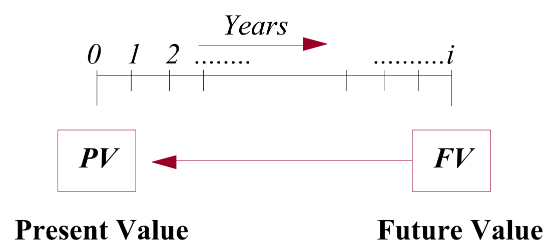

Fig. 1 – Discounting process.

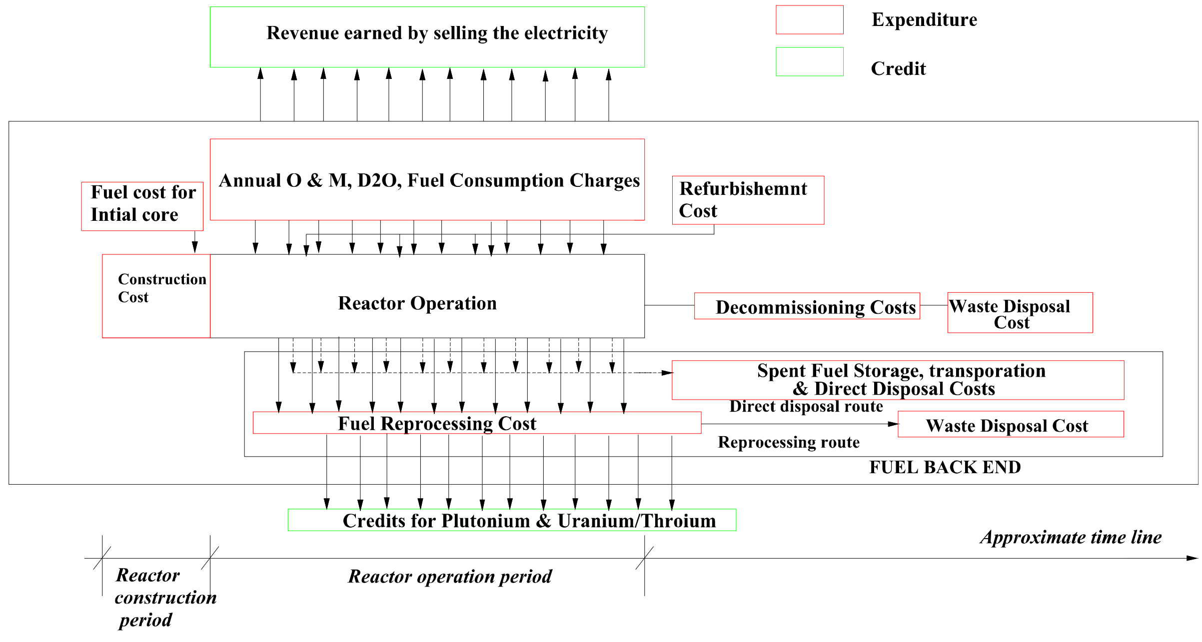

Fig. 2 – Typical life cycle cost for a nuclear power plant.

costs and revenues are brought to the present value at the specified discount rate. Fig. 3 shows the simplified block diagram of cash outflow and inflow for an NPP.

The present value (PV) of any cash flow (CFi) during the year '*i*' in the reference year '*io*' at discount rate '*d*' is calculated as:

$$PV[CF_i] = \sum_{i=t_{start}}^{i=t_{end}} \frac{CF_i}{(1+d)^{i-i_o}} \tag{2}$$

where, t_{start} and t_{end} are the start and end time of the cash flows.

Present value of expenditures is calculated by summation of present value of all expenditures associated with capital cost, O&M cost, decommissioning cost etc.

$$PV[Expenditure] = PV[CF_i] \tag{3}$$

The revenue is generated by sale of the product at given cost. Present value of revenue generated by sale of hydrogen at Levelised Cost (LC) can be given by:

$$PV[Revenue] = \sum_{i=t_{start}}^{i=t_{end}} \frac{LC*H_2Production}{(1+d)^{i-i_o}} = LC*\sum_{i=t_{start}}^{i=t_{end}} \frac{H_2Production}{(1+d)^{i-i_o}} = LC*PV[H_2Production]$$

Here H_2Production is the annual hydrogen produced by the plant and is computed by Eq (4)

$$PV[H_2Production] = \sum_{i=t_{start}}^{i=t_{end}} \frac{P_t \times 8760 \times Lf_t}{(1+d)^{t-t_0}} \tag{4}$$

where *Pt* is the production capacity of hydrogen plant and *Lft* is the load factor.

For net cash flow to be zero, which is the breakeven point for no loss, no profit condition, present value of expenditures should be equal to present value of revenue or Net Present Value (NPV) shall be zero (i.e., where the total present value of

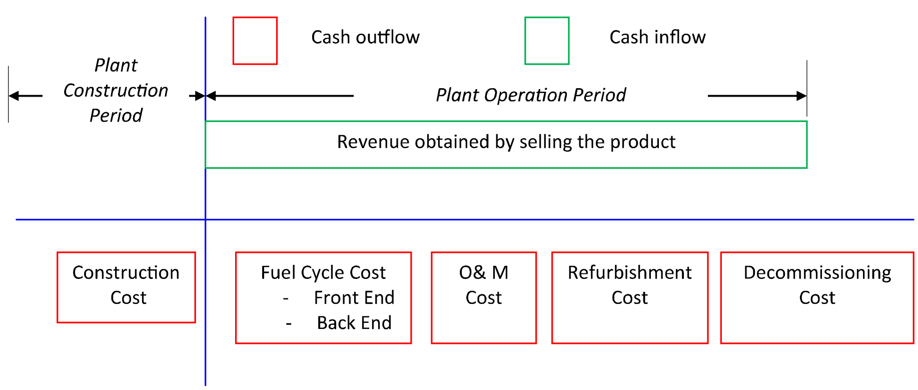

Fig. 3 – Block diagram of Cash inflow & out flow entities.

the sequence of cash inflows is equal to the present value of the cash amount invested). Thus,

$$\begin{aligned} &PV[Expenditure] = PV[Revenue] \\ &PV[CF_i] = LC*PV[H_2Production] \\ &LC = \frac{PV[CF_i]}{PV[H_2Production]} \end{aligned} \tag{5}$$

This is the basic equation. When tax payment is also involved, the evaluation of levelised cost is treated in the following manner based on the basic principles of economics [24].

First present value of After Tax Cash Flow *(ATCF)* is computed from Before Tax Cash Flow *(BTCF)* minus taxes paid. *BTCF* is defined as difference between the net income and capital expenditure *(CE)*. Taxes paid *(T)* are computed on the net income after depreciation *(D)* at a tax rate of '*tr*'. Net income is computed by the difference between revenue generated *(R)* by sale of product (hydrogen or energy either in the form of electricity or heat) and Operating Expenses *(OPE)*. Based on these basic economic principles the following expressions can be derived. Fig. 4 shows the cash flow accounting details. The following formulation can be derived based on this.

$$\begin{aligned} &PV(ATCF) = PV(BTCF - T) = 0 \\ &where,\ T = tr\cdot(R - OPE - D),\ BTCF = R - OPE - CE \\ &PV[(1-tr)\cdot(R - OPE - D) + D - CE] = 0 \\ &PV[CE] = PV[(1-tr)\cdot(R - OPE - D) + D] \\ &PV[R] = PV\left[\frac{CE - D\cdot tr}{1 - tr} + OPE\right] \end{aligned} \tag{6}$$

$$LC = \frac{PV\left[\frac{CE - D\cdot tr}{1-tr} + OPE\right]}{PVof(H2production)} \tag{7}$$

CE: Includes Equity (EQ), Principal component of Debt (PN), Refurbishment Cost (RF)

OPE: Operating expenses are Fuel Cycle Cost (F), O&M cost (OM), Interest Payment (IN), Decommissioning Cost (DC)

Fuel cycle cost

Fuel cycle costs consists of both Front End and Back End costs including credits (Fig. 5). Front end costs are costs incurred in fuel material purchase, conversion, enrichment and fabrication. These costs are incurred in advance (lead time) with respect to the time of loading of the fuel bundle to the reactor. Total fuel cycle cost at a given time'*t*' is given by the expression

$$F_t = F_p + F_c + F_e + F_f + F_{ts} + F_r + F_d - C_{pu} - C_{ru} - C_{rTh} \tag{8}$$

$$F_p = \frac{\frac{C_p\cdot ER\cdot m_f}{(1-l_f)\cdot(1-l_c)\cdot(1-l_e)}}{(1+d)^{-tp}};\quad F_c = \frac{\frac{C_c\cdot ER\cdot m_f}{(1-l_f)\cdot(1-l_e)}}{(1+d)^{-tc}};\quad F_e = \frac{\frac{S\cdot C_e\cdot m_f}{(1-l_f)}}{(1+d)^{-te}};$$
$$F_e = \frac{\frac{S\cdot C_e\cdot m_f}{(1-l_f)}}{(1+d)^{-te}} \tag{8a}$$

where F_p is the fuel material purchase cost, $F_{c,}$ is the conversion cost, F_e is the enrichment cost, F_f is the fuel fabrication cost, F_{ts} is the fuel storage and transportation cost, F_r fuel reprocessing cost, F_d is the waste disposal cost. All these costs are expressed in $.

C_p is the unit purchase cost of fuel material ($/kg)
C_c conversion cost ($/kg)
C_e is enrichment cost in $/Separative Work Unit (SWU)
S is the SWU/kg
C_f is fuel fabrication cost in $/kgHM
m_f is the mass of fuel handled in kg

$l_{c,}$ l_e *and* l_f are the losses in each activity of conversion, enrichment and fabrication. t_p, $t_{c,}$ t_e and t_f are the advance periods (lead time) for procurement of raw material, conversion, enrichment and fabrication. Where, *ER* is enrichment ratio calculated based on fraction of Feed (x_f), Product (x_p), and Tail (x_t).

$$ER = \frac{x_p - x_t}{x_f - x_t},\ \text{and}\ \ S = V(x_p) - V(x_t) - ER*(V(x_f) - V(x_t)), \tag{8b}$$

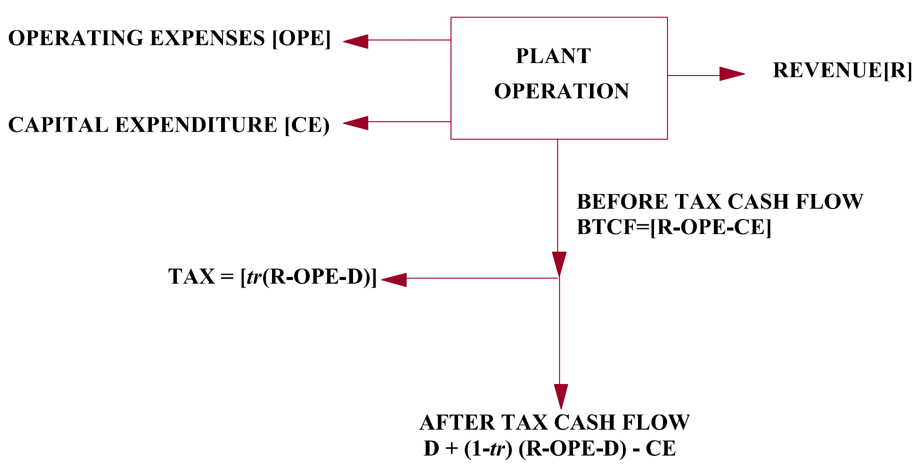

Fig. 4 – Cash flow for taxation.

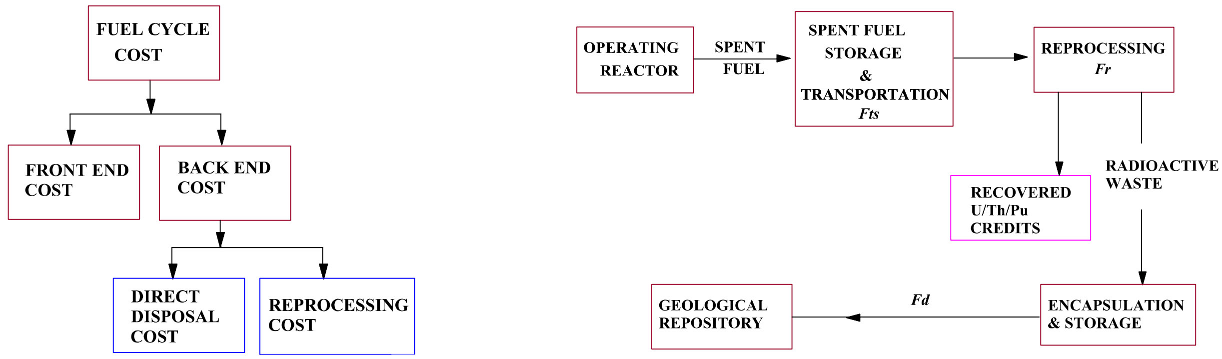

Fig. 5 — Fuel cycle cost elements.

$$\text{Where,}\quad V(x) = (2x-1)*\ln\left(\frac{x}{1-x}\right) \tag{8c}$$

Back End cost

- Storage and transportation, F_{ts}
- Reprocessing, F_r
- Waste disposal, F_d

$$F_r = \frac{C_r \cdot m_f}{(1+d)^{trp}},\quad F_{ts} = \frac{C_{ts} m_f}{(1+d)^{ts}}, F_d = \frac{C_d \cdot m_f}{(1+d)^{td}} \tag{8d}$$

Credits

- Cost of recovered Plutonium, C_{pu}
- Cost of recovered Uranium, C_{ru}
- Cost of recovered Thorium, C_{rTh}

$$C_{ru} = \frac{M_{rU} c_{ru}}{(1+d)^{tru}},\quad C_{rTh} = \frac{M_{rTh} c_{rTh}}{(1+d)^{tTh}},\quad C_{rpu} = \frac{M_{rpu} c_{rpu}}{(1+d)^{tpu}} \tag{8e}$$

Where, M_{rU}, M_{rTh}, M_{rpu} are the recovered masses of uranium, thorium and plutonium (Pu) in kg. c_{ru}, c_{rTh}, c_{rpu} are the unit costs of recovered uranium, thorium and plutonium in \$/kg. *trp*, *ts*, *td*,*tru*, *tTh* and *tpu* are the respective time in which the costs are incurred in the backend process. No market price is established for Pu as it is not subject to trade. But, a value for Pu can be assigned by calculating the difference of front end cost of Mixed Oxide (MOX) fuel (excluding Pu) and equivalent Low Enriched Uranium (LEU) fuel as described in Ref. [25]. Cost of recovered masses of uranium and thorium can also be computed based on the methods mentioned in Ref. [25].

Modeling of debt

The construction cost can be sourced in the form of equity and debt (Fig. 6). Debt portion can be borrowed from the market at an interest rate of '*ir*'. For the cash flow analysis the debt borrowed is broken down into principle (*PN*) and interest payment (*IN*) as given below.

$$AIDP = \frac{TD \cdot ir \cdot (1+ir)^{N_{rp}}}{(1+ir)^{N_{rp}} - 1} \tag{9}$$

AIDP, is annual installment of debt payment
TD, is the total debt in each year

$$Dbto(t) = Dbto(t-1) - PN(t-1) \tag{10}$$

$$IN(t) = Dbto(t) \cdot ir \tag{11}$$

$$PN(t) = AIDP - IN(t) \tag{12}$$

ir is the interest rate
N_{rp} debt repayment period
Dbto(t) is the outstanding debt in year 't'
IN(t) is the interest paid during the year 't'
PN(t) is the principal paid during the year 't'

The numerator of Eq (7) is given below:

$$PV\left[\frac{CE - D.tr}{1-tr} + OPE\right]$$

The above equation can be expanded as follows after substituting the values for *CE*, *D* and *OPE*. Where *CE* is the sum of equity cash flows (EQ_t), debt principal payment (PN_t) and cash flow towards refurbishment (RF_t). *D* is the sum of depreciation cash flow for both capital (DP_CI_t) and refurbishment ($DP\text{-}RF_t$). OPE is the sum of cash flows for fuel cycle

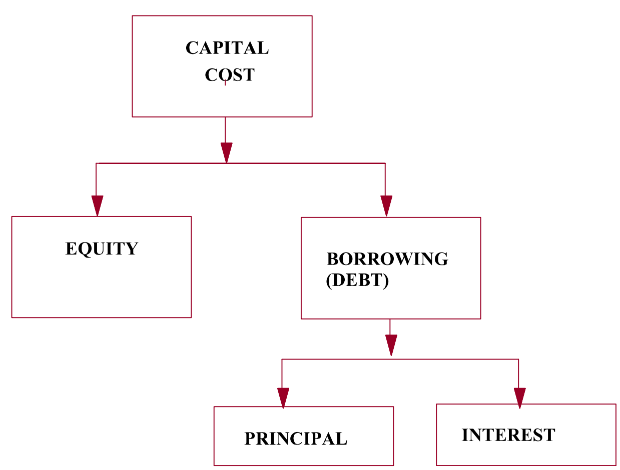

Fig. 6 — Capital cost modeling.

(F_t), O&M (OM_t), interest payment (IN_t) and decommissioning (DC_t). The tr is substituted as tax_rate.

$$PV\left[\frac{(EQ_t + PN_t + RF_t) - (DP\_CI_t + DP\_RF_t)*tax\_rate}{1 - tax\_rate} + (F_t + OM_t + IN_t + DC_t)\right]$$

After substituting these values and rearranging, the above equation will become Eq (13), in which the present values are represented by summation of discounted values of each cost component over the relevant time period over which each costs are incurred.

$$\frac{\sum_{t_{con\_st}}^{t_{con\_en}}\frac{EQ_t}{(1+d)^{t-t_0}} + \sum_{t_{con\_st}}^{t_{rpy\_yr}}\frac{PN_t}{(1+d)^{t-t_0}} - tax\_rate*\sum_{t_{op\_st}}^{t_{dp\_en}}\frac{DP\_CI_t}{(1+d)^{t-t_0}}}{(1-tax\_rate)} + \frac{\sum_{t_{op\_st}}^{t_{op\_en}}\frac{RF_t}{(1+d)^{t-t_0}} - tax\_rate*\sum_{t_{rf\_st}}^{t_{dp\_en}}\frac{DP\_RF_t}{(1+d)^{t-t_0}}}{(1-tax\_rate)} + \sum_{t=t_{con\_st}}^{t_{rpy\_yr}}\frac{IN_t}{(1+d)^{t-t_0}} + \sum_{t=t_{op\_st}}^{t_{op\_en}}\frac{OM_t}{(1+d)^{t-t_0}} + \sum_{t=t_{op\_st}}^{t_{op\_en}}F_t + \sum_{t=t_{dc\_st}}^{t_{dc\_en}}\frac{DC_t}{(1+d)^{t-t_0}} \tag{13}$$

EQ_t, Equity portion of capital investment expenditures at year t
PN_t, Principal portion of the debt repaid during year t
IN_t, Interest portion of the debt repaid during year t
DP_{CI}_t, Depreciation charges for capital investment during year t
OM_t, Operation & Maintenance charges (both fixed & variable) at year t
RF_t, Refurbishment expenditures at year t
F_t, Total fuel cycle cost
DP_{RF}_t, Depreciation charges for refurbishment at year t
DC_t, Decommissioning cost
tax_rate: % Tax rate
t_{con_st}, t_{con_en}, is the construction start and end year
t_{rpy_yr}, year to which debt repayment is done
t_{op_st}, t_{op_en}, plant operation start and end year
t_{dp_en}, depreciation end year
t_{rf_st}, refurbishment start year
t_{dc_st}, t_{dc_en}, decommissioning start year, end year

Modeling of dual purpose plant

In a dual purpose nuclear power plant which produces both electricity and heat energy, power credit methodology [26], also used by G4ECONS [18], has been applied to arrive at the cost of electricity produced. According to this methodology, a reference single-purpose plant which produces thermal energy alone is considered whose energy output is equivalent to the dual purpose plant. If the amount of net energy generated by the single-purpose plant is E_{th} and if C_{th} is the total expenses incurred for this plant, the cost of thermal energy (C_{kWth}) is calculated by the equation $C_{kWth} = C_{th}/E_{th}$.

The total expenses (C_2), for the dual purpose plant which produces both the electricity (W_e) and the (lesser) net saleable thermal power (E_2) is calculated. Here, E_2 is lower than E_{th} because of the energy used for electricity in the dual-purpose plant, and C_2 is higher than C_{th} because of the extra electricity production expenses. The electricity is then charged by these expenses and afterwards credited by the net salable power costs ($C_2 - E_2(C_{kWth})$) as depicted in Fig. 7.

The cost of the electricity (C_{ele}) is then calculated by Eq (14)

$$C_{ele} = \frac{C_2 - E_2(C_{kWth})}{W_e} \tag{14}$$

Case study

The methodology presented in this paper can be used to simulate the economics of hydrogen from the setup of dual purpose nuclear plant generating both electricity and heat and connected to a hydrogen generation plant (HGP) as shown in Fig. 8. As per the requirement, both electricity and heat or heat only or electricity only can be considered for generation of hydrogen. For conventional electrolysis process only electrical energy is used. Process like HTSE, both electricity and heat are used. The levelised unit energy cost of electricity and thermal energy can be computed and which serves as the input energy costs to the hydrogen generation plant based on the quantities of thermal and electrical energy the hydrogen plant uses. Both technical and financial parameters are used in the estimation of the unit costs as indicated in Fig. 8.

For study, a simpler case of an NPP coupled to conventional electrolysis hydrogen generation plant is considered. For this purpose a representative pressure tube type boiling light water cooled heavy water moderated reactor of 300 MWe design capacity is considered to serve as the energy input for hydrogen generation plant. The cost elements considered for this reactor are representative only. It is assumed that the entire electrical energy available after the use of in-plant needs is completely used for the production of hydrogen. The hydrogen generation plant is assumed to be based on the conventional electrolysis principle, employing Proton Exchange Membrane (PEM) electrolysis units.

The gross energy available after the auxiliary consumption of the plant (6%) is 282 MWe at 100% capacity factor which produces hydrogen of 1.476 kg/s at conversion efficiency of 73% for the conventional electrolysis corresponding to hydrogen calorific value of 142 MJ/kg. An electricity consumption of 54.3 kWh/kg of H_2 produced by the plant is considered [27]. The technical and financial parameters of both nuclear and hydrogen generation plant are listed in Tables 1 and 2.

Capital cost of the NPP is $677 M, O&M cost is taken 2% of the capital cost. 70% of the capital cost is sourced from the market as debt at an interest rate of 8%. Remaining portion of 30% constitute the equity. 20 year debt repayment period is considered. The capital cost is incurred during 5 years of construction period at instalment of 10%, 20%, 40%, 20% and 10%. The initial fuel requirement is 65000 kg and annual fuel requirement is 6000 kg. The reactor uses MOX fuel. Cost of finished fuel is taken as $1500/kgHM. The reactor adopts direct disposal of waste for the back end of fuel cycle. The total cost towards spent fuel transportation, storage, encapsulation &

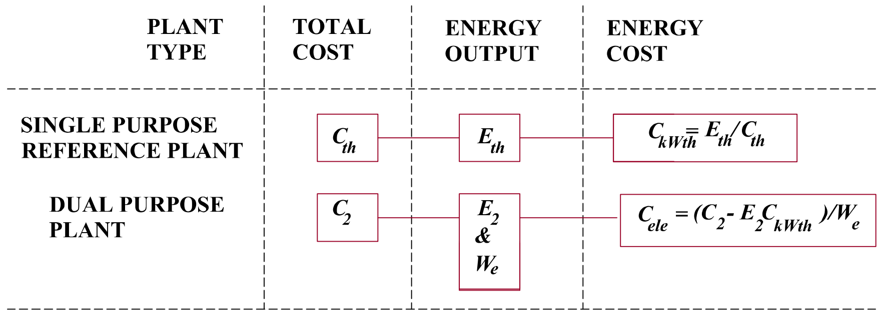

Fig. 7 — Dual power plant modeling.

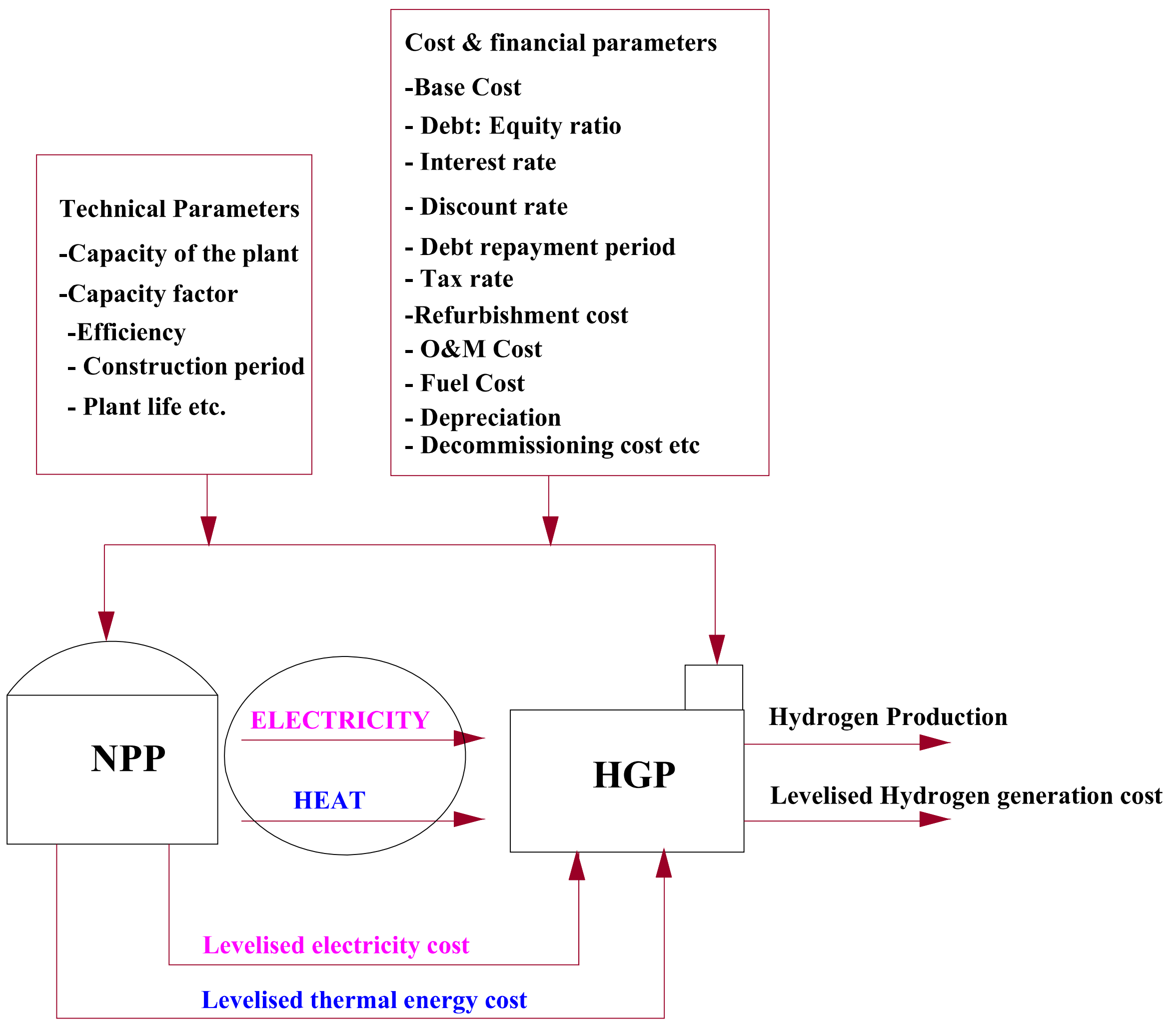

Fig. 8 — Parameters used for generation cost estimation.

geological disposal cost taken as $ 600/kgHM [28]. Decommissioning cost is 10% of the capital cost. The cost parameters for used for hydrogen generation plant are derived from the NREL study [27] for the hydrogen generation capacity considered in this study. For the PEM based hydrogen plant, capital cost is taken as $256 M which is derived considering a linear scaling relationship of capital cost and plant output from reference [27]. It is also assumed that 47% of capital cost is spent on PEM stacks and remaining 53% is used to construct balance of plant [27].

Annual O&M expenses are taken as 4% of capital cost. Since the life of PEM electrolysis units is limited, it is assumed that 1/8th of electrolysis modules are replaced every year. Demineralised water consumption is assumed as

Table 1 – Parameters for NPP & HGP.

Common parameters for both nuclear power plant & hydrogen production plant	
Capacity factor	90%
Construction period	5 years
Nuclear power plant details	
Reactor type	Pressure tube type boiling light water cooled heavy water moderated reactor
Capacity	300 MWe
Number of units	1
Capital investment	$677 M
Annual O&M	$13.5 M (2%)
Initial Fuel load	65000 kg
Annual fuel load	6000 kg
Fuel cost	$1500/kgHM
Back-end fuel cycle option	Direct disposal
Spent fuel transportation, storage, encapsulation & geological disposal cost	$600/kgHM
Decommissioning cost	10% of Capital cost
Hydrogen production plant details	
Process type	Conventional Electrolysis
Hydrogen generation	1.476 kg/s
Capital cost	$256 M Stacks of PEM cells: $120 M (47%) Balance of plant: $136 M (53%)
Annual O&M expenses	$10.24 (4%)
Refurbishment	1/8th of PEM stack is replaced every year
Demineralised water consumption	4.192×10^{8} L/yr
DM Water cost	4.78×10^{-04} $/L
Decommissioning cost	10% of capital cost

Table 2 – Financial parameters.

Parameter	Value
Real discount rate	10%
Equity to Debt ratio	30:70
Interest on borrowings	8%
Tax rate	30%
Depreciation period	20 years
Return period for market borrowing	20 years
Cash flow % during construction period	10%, 20%,40%,20%,10%
Important time periods	
Operating life	40 years for both plants

4.192×10^{8} L/yr, at a cost of 4.78E-04 $/L [27]. Decommissioning cost is taken as 10% of capital cost. Cash flow profile and debt-equity ratio is assumed same as that of NPP. Tax rate of 30% and depreciation period of 20 years based on straight line method is considered. Return period for market borrowing is 20 years. Operating life of both NPP and HGP is 40 years. A real discount rate of 10% is considered. The analysis can be carried out either in constant price level or current price level. We use constant price level method and all the costs figures are based in the year 2014. A computer program is developed based on the formulations mentioned in this paper and the problem was run for the case under study with the parameters indicated in the Tables 1 and 2.

Results and discussions

It can be seen from the Table 3 that the O&M cost component is the highest contributor (71.21%) to the hydrogen cost. Majority of O&M cost is due to the nuclear energy input cost in the form of electricity. NPP cost components are taken care in the O&M cost itself. Capital cost contribution to HGP plant is 18%. The refurbishment cost contribution is 9.46%. Consumable cost, which represents the DM water consumption cost, is 0.45% and decommissioning constituting 0.13%. The total contribution of NPP is 66% as shown in Table 4 and remaining contribution of 34% is from HGP.

Further detailed break up is shown in Table 5 in which NPP & HGP component are broken into various cost components. Note that in case of NPP, the nuclear fuel component is also a contributor to the generation cost. The capital cost component of NPP also plays a major role. Out of the total capital cost contribution of 3.05 $/kg, around 72% is due to NPP, and remaining 28% due to HGP capital cost. Thus NPP capital cost mainly dictates the hydrogen cost. Large reactors tend to have lower specific capital cost, which improves the economics of hydrogen production. This justifies large scale production of hydrogen from large NPPs. Electrolysis cells with higher life can reduce the generation cost as the refurbishment cost reduces for cells with longer life. Other aspect is to improve the overall efficiency, by using hydrogen generation process having better efficiencies and lower hydrogen cost can be attained. With conventional electrolysis over-all efficiency of production is low. This means that high temperature reactors with higher efficiency compared to light water reactors coupled with high efficiency hydrogen processes will have lower hydrogen cost due to higher overall efficiency.

Fig. 9 shows the hydrogen cost variation with respect to real discount rate. It can be seen that as discount rate increases the hydrogen generation cost also increases. It means that economics of hydrogen production improves in scenarios where the cost of investment is low.

Variation in levelised cost due to change in capital cost of both NPP and HGP are studied. Fig. 10 shows the variation. The X-axis represents percentage increase and decrease of capital cost from the reference value. The graph indicates that the

Table 3 – Hydrogen cost components.

Component	Levelised Hydrogen Cost $/kg	%
Capital	0.84	18.75
O&M	3.19	71.21
Refurbishment	0.41	9.46
Consumable	0.02	0.45
Decommissioning	0.006	0.13
Total	4.48	

Table 4 – Plant wise contribution.

Component	Levelised Hydrogen Cost $/kg	%
NPP	2.95	66
HGP	1.53	34
Total	4.48	

Table 5 – Plant wise detailed contribution.

Facility	Capital Cost	O& M	Refurbishment	Consumable cost	Decommissioning	Fuel cost	Total
NPP	2.21	0.3	–		0.02	0.41	2.94
HGP	0.84	0.26	0.41	0.02	0.01	–	1.54
Total	3.05	0.56	0.41	0.02	0.03	0.41	4.48

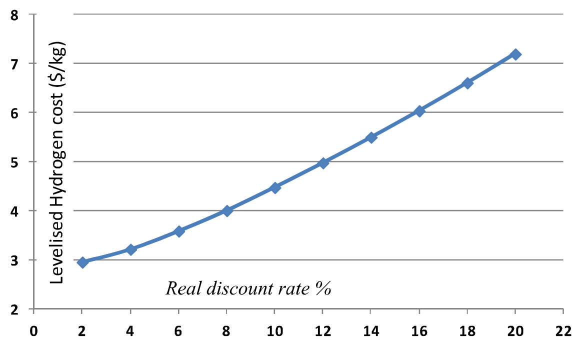

Fig. 9 – Hydrogen cost variation with discount rate.

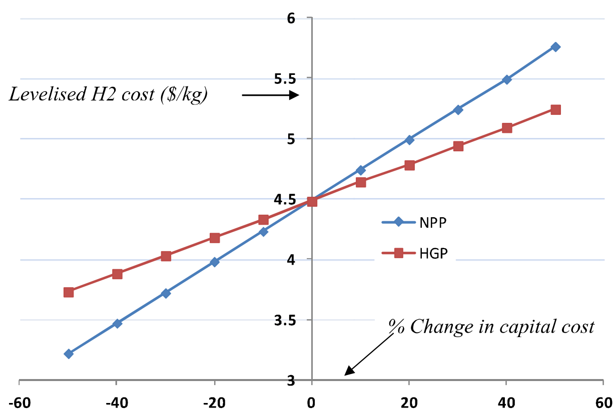

Fig. 10 – Sensitivity to capital cost variation of NPP & HGP to hydrogen cost.

change in NPP capital cost is more pronounced effect on the levelised cost compared to HGP. This shows that one of the effective methods to reduce the cost of hydrogen is to reduce the capital cost of the associated NPP.

Conclusions

A generic methodology for assessment of economics of hydrogen from nuclear power plant assisted energy sources based on Discounted Cash Flow analysis is described which can be used for computation of the levelised unit hydrogen generation cost. The methodology comprehensively models the various cost components of NPP and HGP along with its fuel cycle for the NPP. Realistic situation where in sourcing of the construction cost through a mixture of equity and debt is dealt with. The model also takes into account tax payments. All relevant cost components are modeled to reflect the actual scenario. Dual purpose application in which heat and electricity is used as energy input for production of hydrogen is also modeled. As a case, a pressure tube type boiling light water cooled heavy water moderated reactor, which produce hydrogen through conventional electrolysis is studied where only one type of energy is used (electricity) for hydrogen production.

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