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Hydrogen production from excess power in small hydroelectric installations

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Abstract

A brief review shows that hydrogen production from small hydraulic power systems is thermodynamically and technically feasible. Particularly, excess power in existing installations may be used to make the hydrogen production economically feasible. In this study, a simulation model has been developed regarding hydraulic power and hydrogen production systems, and a cost and economics to find out the economical feasibility of hydrogen production. The simulation code is used to carry out a parametric study of small hydraulic power—hydrogen production systems, and also feasibility of existing hydraulic power stations in a case study. In the latter case, the data from 13 installations in Turkey have been used. It has been found that the hydrogen production rate is about 100 ton/year/MW installed power of electrolytic process plant and the cost varies from 3.9 to 8.6 \$/GJ (0.55 to 1.21 \$/kg) when the hydrogen production plant capacity factor is above 50%.

Keywords: Hydrogen; Electrolytic; Hydropower; Excess power

1. Introduction

There is a class of small and medium size hydraulic power stations used in remote areas, either to supply regional demand and/or connected to the grid to provide peak demand. The excess power in these stations may be used to supply a hydrogen production plant using electrolysis process. There is another class of small hydraulic power stations, which are abandoned because of low demand, and/or expensive operation and maintenance, i.e., because of low-capacity factor, the electrical energy cost is high. They may be operated to produce hydrogen and if economical to run them, to supply also low demand of electrical energy. Hydrogen produced, a chemical commodity, can be stored, sold to chemical industry or used as domestic and industrial needs, or converted to hydrogen-rich fuels.

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The idea to produce hydrogen from small hydraulic stations is not new and has been proposed and studied sporadically over the last few decades (see, for example, [1,2]). During the last decade there have been various paper studies [3–7], but no known applications. Gretz et al. [3] studied technical and economical feasibility of electrolytic hydrogen from hydroelectricity generated by Hydro Quebec and transport it over the Atlantic to Europe. They published several reports on various phases of their study (see, for example, [4]). Andreassen et al. [5] studied technical and economical feasibility of producing hydrogen from hydroelectricity in Norway to transport by various means to Germany. They based their study on a 100 MW as well as 20 MW hydraulic power. Ouellette et al. [6] studied hydrogen production from remote excess hydroelectricity potential in two specific locations in Canada. They considered various scenarios for storage and transportaion and usage. They found that hydrogen from excess power may be produced at relatively low costs. Their study was a site specific and did not present a general simulation model and/or correlations. In a feasibility study similar to earlier ones in the literature, Soltermann and Da

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Nomenclature

C	cost
E	annual production
F	charge rate
H_D	GJ hydrogen production per day, GJ/day
I	current supplied to electrolyzer, A
i	operating current density
i_r	rated current density, mA/cm^2
j_i	effective interest rate
k_1	current independent fraction of the cell and accessory costs
k_2	installation related fraction of the cell and accessory costs
n	write-off period (years)
P	power, production
PCF	hydrogen production plant capacity factor
r_i	annual interest rate
SCF	hydraulic power station capacity factor
V_i	electrolyzer voltage at the operating current density
V_r	cell voltage at the rated current density, V
v	hydrogen production rate (m^3/s)
x_k	input power
x_m	separator area cost parameter in \$/m^2
x_R	rectifier cost in \$/kW AC

Greek letters

η_R	rectifier efficiency

Subscripts

a	annual, available
dc	during construction
EE	electrical energy
EL	electrolyzer
H_2	hydrogen
i	installed
om	operation and maintenance
om$_i$	initial value of operation and maintenance
su	start-up

Silva [7] carried out a comparison between Brazilian and other international potential hydroelectricity-hydrogen production projects, and showed that Brazilian potential was as competitive as the others.

This brief literature review shows that excluding one case, the paper studies have been concentrated on electrolytic hydrogen production from dedicated hydraulic power stations. There has not been any study aiming to develop a general simulation model for performance and cost and economics of hydrogen production from excess power in small hydraulic power stations. The aim of this study is to develop a model for electrolytic hydrogen production from excess hydroelectricity of small hydropower stations, validate it by using the developed methodology in a case study, and to derive useful information and correlations.

2. System description

The hydraulic power-electrolyzer system studied consists of the following major components: small hydraulic power system + electrolyzer system. The small hydraulic power systems are usually less than 20 MW, which are mostly used to supply local electrical energy needs and also to provide peak power for grid connected systems. The system includes the necessary dam, intake and discharge subsystems, buildings, hydraulic and electrical machines. The electrolyzer system is a “turn-key” installation consisting of electrolyzer cells, water treatment unit, compressor to compress generated hydrogen if necessary or without compressor delivering hydrogen at process pressure (see, for example, [8]).

3. Simulation model and code

The simulation code consists of the following models:

- to calculate the electrical energy cost from hydraulic power systems;
- to calculate hydrogen production and cost from electrolyzer systems;
- to determine product cost and economics.

These models are briefly reviewed in the following sections.

3.1. Hydraulic power system model

Hydraulic power system size and annual load factor are used as base to calculate annual electrical energy production at its location. For a given specific power station, cost calculation is done using standard costing techniques [9]. If and when the system cost is known, the cost of electrical energy is calculated using the levelized cost method, which will be presented later.

In carrying out the parametric study for the general case, due to difficulty in determining a generalized hydraulic power system cost, the electrical energy cost will be taken as a variable parameter.

3.2. Electrolyzer model

Since the electrolyzers are manufactured using modular techniques, their power range satisfies easily the requirements of small hydraulic power stations.

Hydrogen production by electrolyzers can be determined with the following dimensional relation often used in the literature [10]:

$$v = 1.22 \times 10^{-7} I, \tag{1}$$

where I is the current supplied to the electrolyzer in A and v is the hydrogen production in m^3/s.

3.3. Cost estimation model

The cost of product is determined based on the total investment required for a hydraulic power station—hydrogen generating system, operation and maintenance costs, and the production rate of hydrogen. The costs of the major items such as installed hydraulic system and electrolyzer are taken as a base.

The cost for a hydraulic power system depends on a particular site and installation and usually is evaluated based on the costing techniques. For order of magnitude investment estimates, the system cost of hydraulic power stations of small size may be assumed to be about 1200$/kW (see, for example, [11]), although in this study we will not use this simplification.

Due to highly competitive business environment, electrolyzer manufacturers are usually reluctant to provide price quotations on any electrolyzer to couple with hydraulic power systems. Therefore, we attempted to estimate the installed cost of industrial electrolyzers by using the methodology presented by Leroy and Stuart [12]:

$$C_{\mathrm{EL}} = 775 H_{\mathrm{D}} \left(\left(\frac{k_1}{i} + \frac{1-k_1}{i_r} \right) x_m + 0.5 k_2 \left(\frac{1}{i} + \frac{1}{i_r} \right) x_m + \frac{V_i x_{\mathrm{R}}}{100 \eta_{\mathrm{R}}} \right),$$

$$x_m = \frac{V_r i_r x_k}{100}, \tag{2}$$

The parameters for unipolar electrolyzers are $k_1 = 0.90$, $k_2 = 0.45$, $x_k = 251$ \$/kW DC, $i = 200$ A, $i_r = 134.00$ mA/cm^2, $V_r = 1.74$ Volt, $V_i = 2.04$, $\eta_{\mathrm{R}} = 0.96$, $x_{\mathrm{R}} = 142$ \$/kW AC, all updated to constant 2002\$. H_{D} = (hourly maximum hydrogen production in GJ) × (24 h). C_{EL} is the electrolyzer installed cost in \$(2002).

The first term in the parentheses is related to cell and accessories, the second is related to installation and start-up, etc., finally the third is rectifier cost. Hence Eq. (2) gives the installed cost of a system, which includes the equipment to run it by using AC power. H_{D} is determined based on the installed hydraulic power, since it is assumed that the electrolyzer system will be run not only to use the excess power but also at times when there is no electrical energy demand, i.e., at full hydraulic system power. This is accomplished by calculating the electrical current required by the electrolyzer at full power, which is determined at the installed power of the hydraulic installation and using Eq. (1).

The validation of Eq. (2) has been done by estimating the installed cost of two electrolyzer systems studied in the literature [13,14]. The first is a 100 MW system, the installed cost of which is given as $\$33.2 \times 10^6$ in \$1982. Using Chemical Engineering Cost Index it is found as $\$48.1 \times 10^6$ in \$2002. The second is a 400 MW system, its installed cost is given as $\$154.71 \times 10^6$ in \$1990. Its updated cost is $\$185.65 \times 10^6$ in \$2002. Eq. (2) gives $\$48.6 \times 10^6$ for the first and $\$182.8 \times 10^6$ both in \$2002. The absolute value of deviation is 1% for the first and 1.5% for the second. In addition, in comparison to the price range for electrolyzer systems of 5–15 MW quoted in [6], Eq. (2) gives, after suitably adjusting in exchange rate and price index, similar price range.

3.4. Cost and economics

The major guidelines for economics in determining costs are as follows:

- the investment is 100% financed by borrowing the required capital from financial institutions for 25 years for the hydraulic power system and 20 years for the electrolyzer system;
- it is in constant 2002 US dollar, the interest rate is 5% per year;
- operation and maintenance is 2% of the start up cost for hydraulic system and 5% for electrolyzer system;
- plant life for economic write-off is 25 years for the hydraulic power system and 20 years for the electrolyzer.
- the annual charge rate for capital recovery, F_{c}, is assumed to be 15%.

The start-up and the levelized operation and maintenance costs are

$$C_{\mathrm{su}} = (1 + i_{\mathrm{dc}})(1 + r_{\mathrm{dc}})^n C_t, \tag{3}$$

$$F_{\mathrm{om}} = F_{\mathrm{om}_i} \frac{\Sigma (1 + r_i)^n (1 + j_i)^{-n}}{\Sigma (1 + j_i)^{-n}}. \tag{4}$$

The cost of hydrogen, \$/GJ hydrogen, by the system is calculated as

$$C_{\mathrm{H_2}} = (F_{\mathrm{c}} + F_{\mathrm{om}}) \times C_{\mathrm{su}} / P_{\mathrm{a}}, \tag{5}$$

where C_{su} is the total investment at start-up, F_{om} is the levelized annual operation and maintenance cost factor evaluated by Eq. (4), F_{om_i} is the initial operation and maintenance cost factor which is assumed 2% or 5% of C_{su} and P_{a} is the annual production.

Alternately, hydrogen cost $C_{\mathrm{H_2}}$ in \$/GJ can be calculated using Eq. (2), annual hydrogen production $P_{\mathrm{H_2}}$ in GJ, cost of electrical energy C_{EE} in \$/kWh and the capital charge rate, F:

$$C_{H_2} = \frac{F C_{EL}}{P_{H_2}} + 186\,\frac{v_i C_{EE}}{\eta_R} \tag{6}$$

where F is 17% or 20%, which is the sum of the capital charge rate of $F_c = 15\%$ and operation and maintenance cost of $F_{om} = 2\%$ or 5%.

For "turn-key" electrolyzer systems, Eq. (6) gives almost the same result as that by Eq. (5) with $C_{su} \approx C_{EL}$ determined by Eq. (2).

Finally, we should note that no consideration is given to the credits of by-products, such as heavy water or oxygen.

4. Results and discussion

A parametric study on small hydraulic power-electrolyzer systems has been carried out and presented in Figs. 1–3.

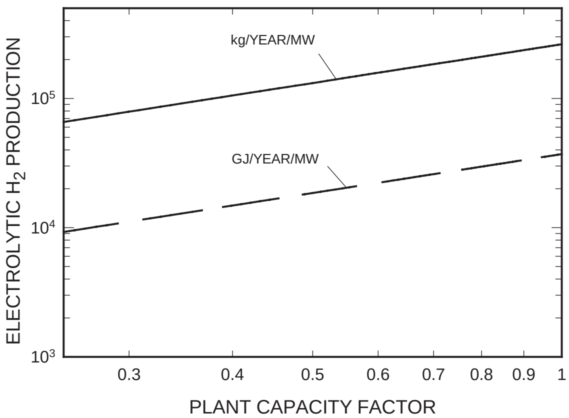

Fig. 1. Electrolytic hydrogen production rate as a function of hydrogen production plant capacity factor.

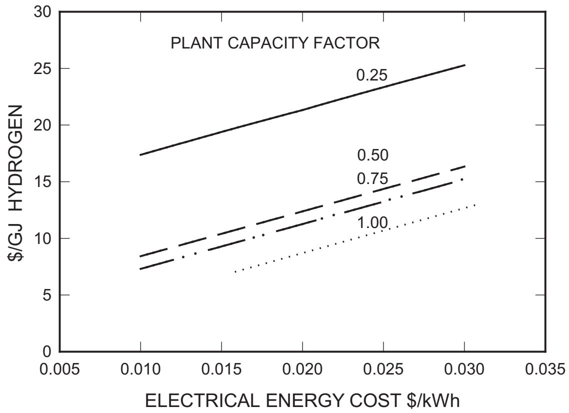

Fig. 2. Electrolytic hydrogen cost in \$/GJ as a function of electrical energy cost with various plant capacity factor as a parameter.

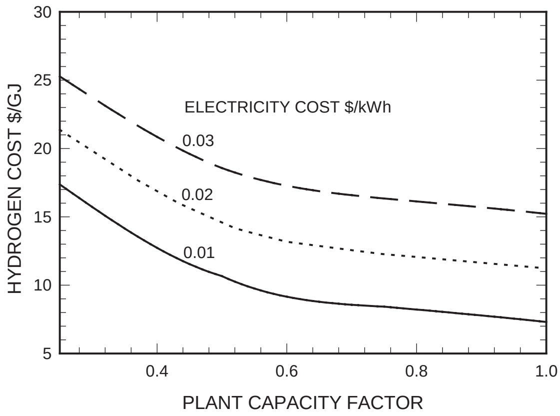

Fig. 3. Electrolytic hydrogen cost in \$/GJ as a function of plant capacity factor with various electrical energy cost as a parameter.

The governing parameters for a hydraulic power-electrolytic hydrogen production plant are electrical energy cost, hydrogen production plant capacity factor (or hydropower capacity factor) and installed power. We define the hydrogen production plant capacity factor, PCF as the ratio of power available for hydrogen production to installed power of the hydraulic power station.

We define also a hydraulic power station capacity factor, SCF, which is the ratio of power used to generate electrical energy to installed power of the hydraulic power station. These two capacity factors are related to each other since the excess power is the un-utilized power in a hydraulic power station.

$$\mathrm{PCF} = P_a/P_i,$$

$$\mathrm{SCF} = 1 - \mathrm{PCF}. \tag{7}$$

We present in Fig. 1 the annual electrolytic hydrogen production in kg and GJ/MW power hydrogen production plant as a function of the plant capacity factor. In this figure, plant capacity factor PCF = 1 represents the case for a system in which the hydraulic power station is dedicated 100% to produce hydrogen. Hence, the hydrogen production plant is run at its full capacity. PCF < 1 represents the cases when it is run at its partial capacity, although the cost of investment, operation and maintenance remains the same.

We see that as expected the hydrogen production increases linearly with the hydrogen production plant capacity. Hydrogen production from a 1 MW plant varies from 65,000 kg/year for 0.25 plant capacity factor to 260,000 kg/year for a dedicated system. This is expected since at the lower limit only, 25% capacity of the installed power is used to generate hydrogen. Similar observations can also be made for hydrogen energy in GJ/year produced per MW power.

Hydrogen energy cost in \$/GJ as a function of electrical energy cost in \$/kWh from the hydraulic power station is presented in Fig. 2. Plant capacity factor, PCF is a variable parameter as shown in the insert. The electrical energy cost from hydraulic power stations varies from 0.01 to 0.03 \$/kWh and the four values of plant capacity factor PCF covers the range considered in Fig. 1. We can see that the general trend of hydrogen cost is a linear increase with increasing electrical energy cost, which conforms the findings in the literature (see, for example, [13]). Following our observation in Fig. 1, we see also the hydrogen production cost increases if the hydrogen production plant is only utilized partially. For the best case, i.e., dedicated hydraulic power station-hydrogen production plant, the cost varies from about 7 \$/GJ (0.99 \$/kg) at 0.01 \$/kWh to 15 \$/GJ (2.12 \$/kg) at 0.03 \$/kWh. The cost increases with decreasing PCF but it appears that this variation is non-linear. This situation is better appreciated if we cross plot the same data, cost versus PCF.

We present the results in Fig. 3, which shows hydrogen cost as a function of capacity factor with electrical energy cost as a parameter. Following the results in Fig. 2 the effect of electrical energy cost is linear. We see that for a given electrical energy cost, hydrogen cost decreases non-linearly with plant capacity factor. This observation is in agreement with the findings in the literature (see, for example, [12]) and is a result of non-linear cost relationships used in cost and economics calculation. In fact, the annual cost of investment, operation and maintenance rests the same while the production varies from zero, resulting theoretically in an infinite value for production cost and decreasing to a lower limit of production cost when the plant runs at full capacity. The results show that for PCF > 0.5 represents a favorable range, particularly interesting for hydrogen production using excess hydraulic power from small size installations where the demand for electrical energy is less than 50% of the hydraulic power capacity.

5. Case study

A case study was carried out using data from thirteen small and medium size power stations in Turkey [11]. Names of power stations and basic data are given in Table 1. We note that the installed power range of these installations is from 2.56 to 62 MW. Although the last two power stations are medium size stations, they are retained here since the analysis presented earlier will equally apply medium size hydraulic power stations. The hydraulic power station capacity factor, SCF varies from 8.9% to 74%. According to [11] they are used mostly for local electrical energy demand and/or to provide peak power to the grid. We can also note that the majority is old installation, the capital cost is written-off and the major annual cost is for operation and maintenance only. The electrical energy cost is given in \$(2000)/kWh, which is used without modification.

The electrical energy cost data from Table 1 is plotted as a function of installed hydraulic power in Fig. 4. We see that the electrical energy cost varies from 4.34 to 0.55 cent/kWh and the general trend is decreasing cost with increasing installed hydraulic power, which is an expected trend.

The electrical energy cost for SCF = 0.95, i.e., at full capacity except down time, is computed using the cost model. The results are also shown in Fig. 4 for comparison. When excess power is used for hydrogen production, i.e., when the hydraulic power station is run at full capacity, the cost of electrical energy is reduced considerably.

The computed electrical energy cost for SCF = 0.95 is re-plotted as a function of hydraulic power station capacity factor, SCF in Fig. 5. The hydrogen production plant capacity factor, PCF is also added on the top scale of the figure. The trend is an increasing electrical energy cost with increasing SCF, which is expected since for higher SCF, the economy of excess electrical energy production is not high, hence the cost reduction is only marginal.

Table 1
Hydraulic power stations data from [11]

	Name	Year	P_i (MW)	SCF %	GWh/year	10^{-2}\$/kWh
1	Kayakoy	1956	2.56	52.6	10.4	0.92
2	Kiti	1966	2.76	28.0	5.0	1.67
3	Girvelik	1963	3.04	74.0	18.3	1.28
4	Zernek	1989	3.50	16.9	4.1	3.10
5	Ceyhan	1958	3.60	69.8	21.7	0.35
6	Atakoy	1989	4.80	24.7	6.3	4.34
7	Kovada I	1960	8.25	10.2	2.6	2.27
8	Kockopru	1993	8.80	20.3	10.8	1.20
9	Cag	1968	14.40	43.8	30.6	1.05
10	Tercan	1990	15.00	28.4	36.8	1.28
11	Camligoze	1994	16.00	8.9	21.3	0.24
12	Karacaoren	1990	32.00	36.5	74.8	0.86
13	Adiguzel	1996	62.00	28.1	128.0	0.55

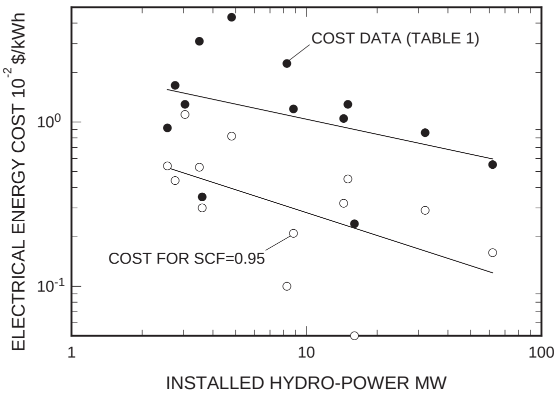

Fig. 4. Electrical energy cost as a function of installed hydraulic power: the upper part is the cost data from Table 1, and the lower is computed cost for SCF = 0.95.

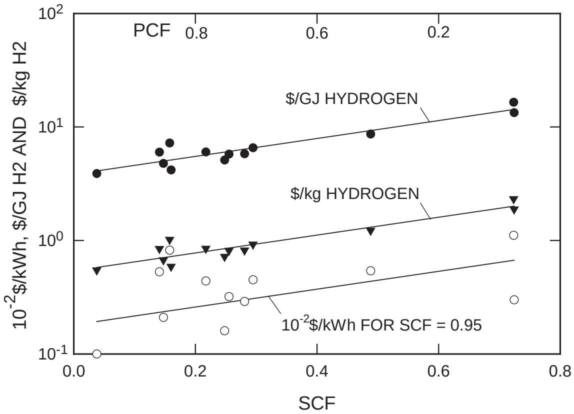

Fig. 5. Electrical energy and electrolytic hydrogen costs as a function of hydraulic power station capacity factor for thirteen power stations listed in Table 1.

Using the data of Table 1 and the cost and economics methodology, we calculated electrolytic hydrogen cost in \$/GJ (and also in \$/kg) and shown in the same Fig. 5. The electrolytic hydrogen cost varies from about 3.9 to 16.5 \$/GJ (or 0.55–2.32 \$/kg), which is very competitive. As expected, the cost decreases with increasing PCF as in Fig. 3. The theoretical results for electrolytic hydrogen production cost using the data correlate well with SCF or PCF; the correlation coefficient is 0.87.

We present the annual hydrogen production in kg/year/MW and GJ/year/MW in Fig. 6 as a function of SCF. PCF is also shown on the top scale. The variations are similar to those of Fig. 1: the hydrogen production is an increasing function of the hydrogen production plant capacity factor, PCF and naturally it is a decreasing function of the hydraulic power station capacity factor, SCF. The order of magnitude of production in kg or GJ is in concordance with the theoretical results of Fig. 1. We see that the theoretical

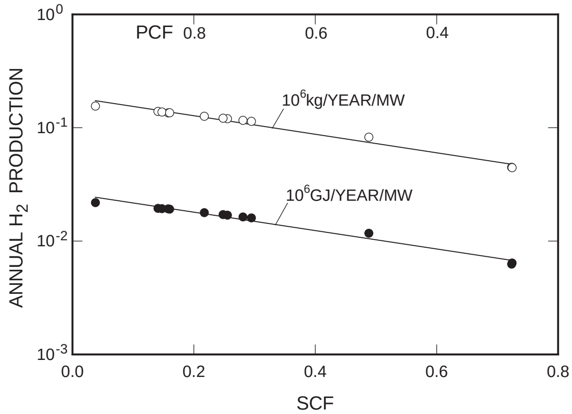

Fig. 6. Annual electrolytic hydrogen production in kg/MW and GJ/MW as a function of hydraulic power station capacity factor for thirteen power stations listed in Table 1.

results using the data from thirteen stations produced good correlations for annual electrolytic hydrogen production rate as a function of CSF or PCF; the correlation coefficient is 0.935. Following correlations may be useful to determine an order of magnitude of hydrogen production from excess hydroelectricity of small and medium size hydraulic power stations.

$$P_{H_2}(\text{GJ/year}) = 26,120 \times 10^{-0.81\text{SCF}},$$

$$P_{H_2}(\text{kg/year}) = 185,940 \times 10^{-0.81\text{SCF}}, \tag{8}$$

where SCF is the hydraulic power station capacity factor.

6. Conclusions

A theoretical model has been developed to simulate hydrogen production from excess power of small hydraulic power stations using electrolytic process. A parametric study has been carried out taking electrical energy cost and plant capacity factor as variable parameters. Hydrogen production rate, electrical energy and hydrogen production costs have been determined. In a case study of thirteen small and medium size hydraulic power stations, the performance parameters have been calculated by using the developed methodology.

It is shown that the developed methodology can be used to carry out feasibility studies for hydraulic power stations, existing or new, operated with a lower than usual capacity factor. Whether the power station is operated at full or partial capacity, it is known that annual costs of investment, operation and maintenance remain usually constant. For this reason, hydrogen production using the excess power in an electrolytic process is generally feasible from thermodynamic, technological and perhaps economical points of view. However, before attempting a detailed design project, a preliminary design including an economical feasibility study is desirable. The methodology and the results presented in this study as well as the derived correlations Eq. (8) may be useful in this case.

The case study showed that especially for hydraulic power stations operated at low-capacity factors, say below 50%, the hydrogen cost may be very competitive, even with that manufactured from fossil fuels. In fact, hydrogen from steam methane reforming has a cost range of at least twice that is determined in this case study.

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