Opportunity of Hydrogen Production in Renewable Power Plants: Case of Island of Mauritius

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***Abstract*—Excess power is an inherent feature of renewable energy systems where the produced renewable energy exceeds the demand load and the storage systems are fully charged. In contrary to the grid-connected renewable systems where the excess power is feed into the grid, in case of standalone system the excess power is either dumped or used for green hydrogen production. This paper presents a heuristic size optimisation algorithm for the sizing of water electrolyser which minimises the levelised cost of hydrogen production. The algorithm is used to investigate the potentials of using the excess power of PV-battery system designed for Island of Mauritius for hydrogen production.**

Keywords—excess power, PV-battery system, size optimisation, water electrolysis, hydrogen production, exhaustive search, MOHRES

I. Introduction

Hydrogen has been produced and used for many years in industry. A significant amount of hydrogen is produced using fossil fuels which releases CO_2 and contribute heavily in climate change [1]. Currently, the annual worldwide hydrogen production is around 70 million tonnes which is the source of 830 million tonnes of carbon dioxide emissions per year [2]. Water electrolysis-based technology (WET) is another method of producing hydrogen by splitting water molecules into oxygen and hydrogen using electric current. The cost of hydrogen produced by water electrolyser is significantly influenced by its electricity consumption and price [3, 4].

Recent decade has seen a huge increase in installed renewable power and expected to increase rapidly in future [5]. Under the large renewable penetration in power sector for standalone applications, significant excess power is dumped due to intermittent nature of renewable energy resources. Utilising renewable excess power in hydrogen production has the potential to reduce the environmental impact, enhance the cost-effectiveness, and stimulate the implementation of hydrogen production via water electrolysis [1, 4, 6-11]. Water electrolyser size is another factor that influences the cost of hydrogen production. For instance, sizing an electrolyser to absorb 20% of excess solar energy penetrating a local grid is conducted in [12]. Analysis of the local network characteristics shows that the ideal electrolyser capacity is 300 kW where up to 700 kW capacity is feasible. Another example is presented in [13] where wind-hydrogen system size optimisation is investigated for maximising the return on equity with respect to hydrogen prices and wind power fluctuation. the results show that hydrogen production is only feasible at 4.34 €/kg hydrogen price or higher with 92 % level of confidence. In other words, increasing the electrolyser size will increase the hydrogen production costs hence the hydrogen price to reach the desired feasibility. Reducing wind energy curtailment by hydrogen production via water electrolyser is analysed in [14]. Two scenarios of grid connected wind hydrogen system, below 5 MW and above 6 MW electrolyser capacities, are examined. The results show that the wind energy utilisation increases as electrolyser size increases in both scenarios. However, payback period increases as well where the costs of electrolyser increment pace exceeds the hydrogen price increment. In general, increase of electrolyser size is proportional to electricity consumption and hydrogen production providing that appropriate level of load is applied otherwise it may lead to exponential increase in costs [15].

This paper explores the potential of producing hydrogen using the excess renewable power of standalone PV-battery system in Island of Mauritius which otherwise is dumped to keep the network balanced. An algorithm is proposed for size optimisation of the water electrolyser to minimise the levelised cost of hydrogen production.

II. Technical and Economic Models

This section presents the technical and economic models used in preforming the optimisation of water electrolyser for Island of Mauritius case.

The levelised cost of hydrogen LC_{H_2} can be calculated as follows:

$$LC_{H_2} = \frac{C_a}{M_{t,H_2}} \quad (1)$$

where, C_a is annualised cost of electrolyser, and M_{t,H_2} is the total annual mass of hydrogen produced and can be calculated by the following:

$$M_{t,H_2} = \frac{(\sum_{i=1}^{8760} P_{EL,i})3600}{2V_{EL}F} \quad (2)$$

where, $P_{EL,i}$ load of electrolyser at hour i, V_{EL} is working voltage of the electrolyser, and F is Faraday's constant.

The annualised cost of the electrolyser is given by the following [16]:

$$C_a = TLSC \frac{d(1+d)^{N_S}}{(1+d)^{N_S-1}} \quad (3)$$

where, d is the discount rate, and N_s is the lifespan of the system. The fraction in equation (3) represent the uniform cost recovery factor. the total lifespan cost of the electrolyser $TLSC$ calculated by the following:

$$TLSC = \sum_{j=0}^{Ns} \frac{C_j}{(1+d)^j} \quad (4)$$

where, C_j is the annual costs in year j including capital (purchasing and installation) C_c, operation and maintenance $C_{O\&M}$, and replacement C_r costs during the lifespan of the system and are given as follows:

$$\mathrm{C_i = C_{u,el} S_{el}} \quad (5)$$

$$\mathrm{C_c = C_i(1 + \alpha_{inst,el})} \quad (6)$$

$$\mathrm{C_{O\&M} = \alpha_{O\&M,el} C_i} \quad (7)$$

$$\mathrm{C_r = n_{r,el} C_c} \quad (8)$$

where, C_i is the initial cost of the electrolyser as a function of unit cost ($C_{u,el}$) and the size of the electrolyser (S_{el}), $\alpha_{inst,el}$ is the installation cost fraction, $\alpha_{O\&M,el}$ is the operation and maintenance cost fraction, and $n_{r,el}$ is the number of replacements. It is calculated by the following:

$$n_{r,el} = \left\lceil \frac{N_S T_{el}}{N_{el,nom}} \right\rceil \quad (9)$$

where, T_{el} and $N_{el,nom}$ are operation time and nominal lifespan of electrolyser respectively.

III. Problem Formulation and the Optimisation Algorithm

A. Problem formulation

This subsection illustrates the problem formulation using the mathematical models presented earlier and analyses the system performance at its nominal power.

Assuming all parameters of the electrolyser are constant, the independent and dependent variables, are $\vec{X}$ and $\vec{Y}$ respectively, can be defined as the following:

$$\vec{X} = \{P_{elec,nom}, P_{EL}, T_{el}\} \quad (10)$$

$$\vec{Y} = \{M_{t,H_2}, TLSC, LC_{H_2}\} \quad (11)$$

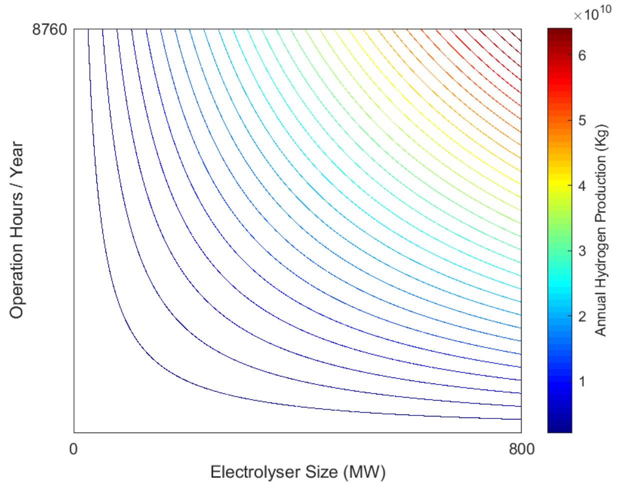

Fig. 1. Typical annual hydrogen production as a function of electrolyser size and operation hours.

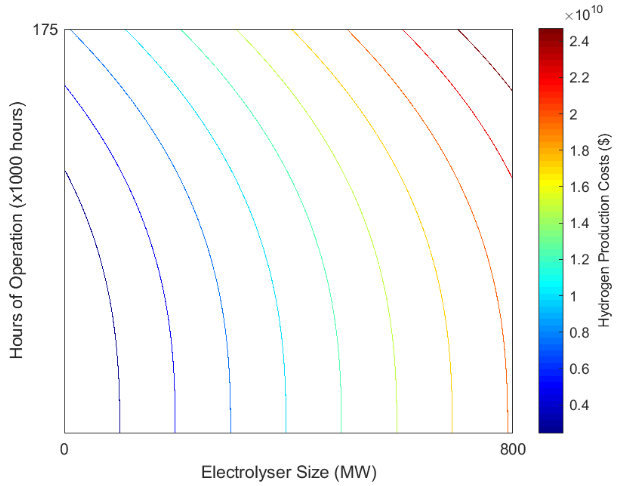

Fig. 2. Typical hydrogen production costs as a function of electrolyser size and operation hours.

Although the hour of operation and nominal power of the electrolyser became linearly dependent in terms of hydrogen production (Fig.1), they are not in terms of $TLSC$ (Fig.2). Nevertheless, levelised cost of hydrogen remains constant providing that the electrolyser always operates at its nominal power during its lifespan.

However, using excess power of optimised renewable energy system reduces $\vec{X}$ to the following:

$$\vec{X} = \{P_{elec,nom}\} \quad (12)$$

where P_{EL} and T_{el} are determined by the excess power distribution (Fig.3). Now, the level of applied load and its duration are variable (i.e. operation of a given electrolyser at its nominal power not always guaranteed). Consequently, using small electrolyser may lead to curtailment of hydrogen production at a desired cost while using large electrolyser to utilise all excess power produces maximum mass of hydrogen but increase the costs exponentially on the other hand. Hence, electrolyser size optimisation is needed.

B. Exhaustive search algorithm

To obtain the optimum size of the electrolyser, the proposed algorithm using exhaustive search is explained below.

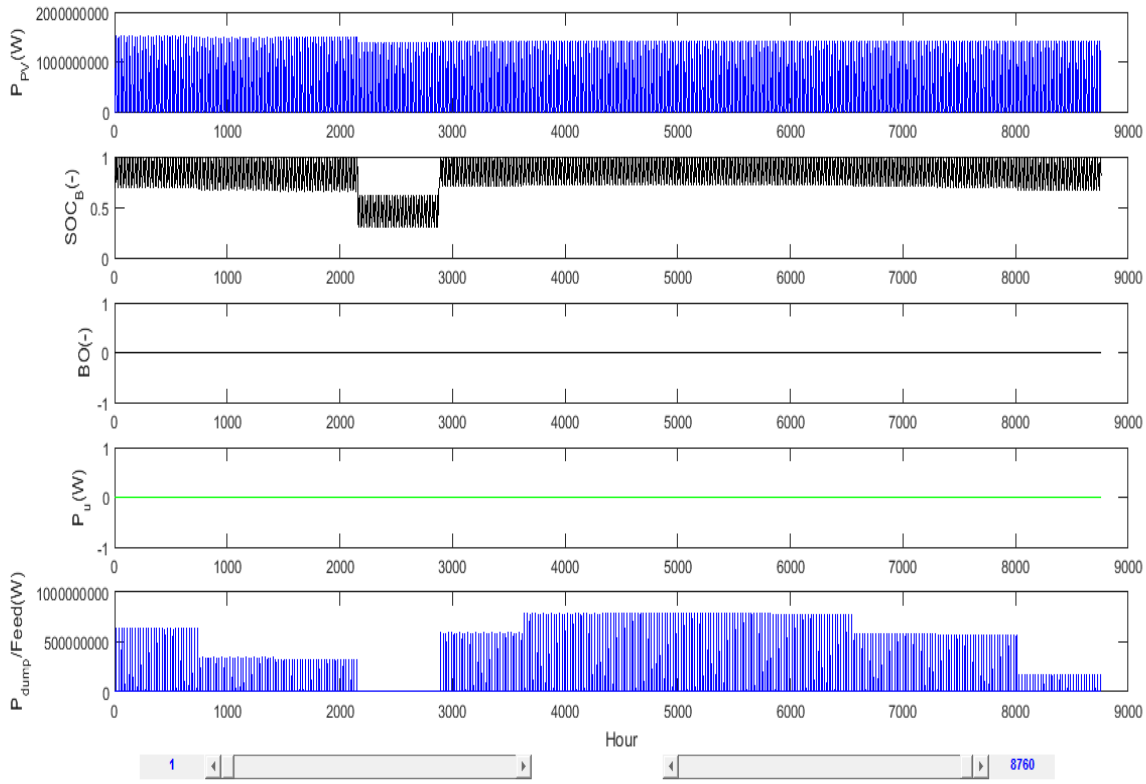

Fig. 3. Power balance of PV-battery system for Island of Mauritius.

The nominal power of electrolyser at j^{th} iteration is calculated by the following:

$$P_{EL,nom} = P_{excess,min} + j\Delta p \tag{13}$$

where, $j = 0, 1, 2, \dots, m$, Δp is step size, and m is mesh size which are given by the following:

$$\Delta p = \frac{P_{excess,max} - P_{excess,min}}{m} \tag{14}$$

For a given nominal power of water electrolyser, do the following:

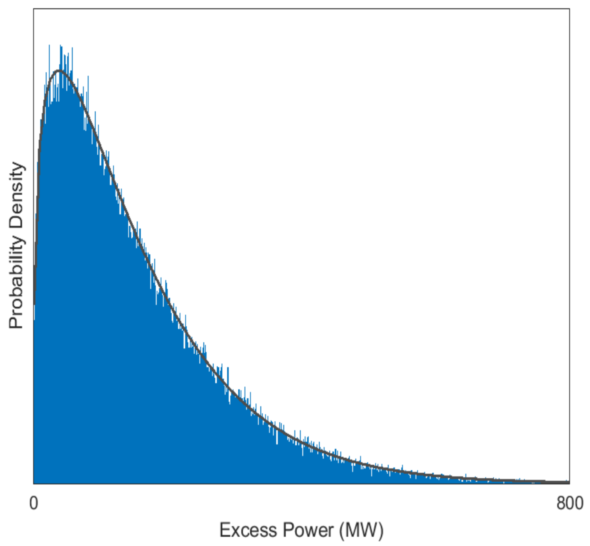

Fig. 4. Typical excess power probability distribution of optimised renewable energy system

- Step 1: Find the actual power (hourly averaged) through the year: $P_{EL,i} = \min\{P_{excess,i},\ P_{EL,nom}\}$ for $i = 1,2,..,8760$
- Step 2: Find the number of hours that the electrolyser works during the year ($P_{EL,i} > 0$).
- Step 3: Use the number of hours to determine the actual life of the electrolyser.
- Step 4: Use $P_{EL,nom}$ to calculate the capital and the operation and maintenance cost of the electrolyser using equations (5), (6),and (7) where: $S_{el} = f(P_{EL,nom})$.
- Step 5: Use the actual life to find the number and the year of replacement, and from there the replacement cost using equations (8) and (9).
- Step 6: Use the cost components obtained in Steps 4 and 5 above to calculate the total lifespan cost using equation (4).
- Step 7: Calculate the annualised cost of water electrolyser using equation (3).
- Step 8: Calculate the amount of hydrogen produced by the electrolyser per year using equation (2).
- Step 9: Calculate the levelised cost of hydrogen production using equation (1).

IV. PV-Battery System Excess Power Case Study

The power balance of the optimised PV-battery system is preformed using MOHRES (Multi-objective Optimisation of Hybrid Renewable Energy System under uncertainties) [17] based on solar resources of Island of Mauritius to serve electricity demand of the whole country and shown in Fig.4. The first chart is the PV power profile. The charging and discharging cycles of the battery are shown in the second chart. There are no backouts duration and the unmet load is zero as presented by the third and fourth charts respectively. The last chart is the excess power profile. As shown in Fig.4, the standalone system is dumping annual excess energy of order of GWh which does not seem wise. Therefore, we consider adding an electrolyser to the system to produce hydrogen with the excess power.

Since the uncertainties are involved in power balance due to the intermittent nature of solar energy, the range of excess power with the most likelihood to occur during the lifespan operation of the power system is much smaller than the maximum excess power.

Applying this principle to Island of Mauritius PV-battery system, the minimum and maximum excess power are 0 and 799.82 MW respectively. Using probability density function with a bin of 100, 4 MW excess power has the highest density (0.83322 @ $P_{excess} = 4MW$). In other words, the electrolyser will operate at 4 MW load most of the time during the lifespan of PV-battery system. Sizing the electrolyser at 4 MW excess power and excluding higher load levels may lead to curtailment of excess power utilisation. To obtain the optimum size of the electrolyser, the cost and hydrogen production for each electrolyser in terms of a nominal power, from the minimum to the maximum excess power is calculated by the algorithm explained previously.

The output of the algorithm can be represented by the following:

$$f(P_{EL,nom,}M_{t,H_2}, LC_{H_2}) = 0 \quad (15)$$

The objective is to optimise the size of water electrolyser for a minimum levelised cost of hydrogen production. Therefore, equation (12) for our case becomes:

$$LC_{H_2} = f(P_{EL,nom,}M_{t,H_2}) \quad (16)$$

Since there is no constraint in total mass produced by the system, the objective function reduces to the following:

$$LC_{H_2} = f(P_{EL,nom}) \quad (17)$$

Using $\Delta P = 1MW$, the cost of hydrogen production for each water electrolyser (from $P_{EL,nom} = 1\ MW$ to $P_{EL,nom} = 800MW$) is shown in Fig. 5.

The optimum size of the water electrolyser for the best utilization of excess energy of PV-battery system is 20 MW nominal power (Fig. 6).

V. Discussion

Utilising excess power adds a total of 94.36 million USD to TLSC of the of PV-battery system. However, the total amount of 272.6 million tons of hydrogen per year is the potential hydrogen production with the optimum size of the water electrolyser of 20 MW in Island of Mauritius at a lowest cost of hydrogen production per kg $(< 34.7$ ¢/kg$)$. A key assumption of such low hydrogen price is that electricity supplied to the water electrolyser is assumed to be free as it would be dumped otherwise. Also, the hydrogen storage or transport is not included in the analysis. In other words, the hydrogen produced is assumed to be consumed locally per production bases such that no or insignificant storage needed relative to the system size.

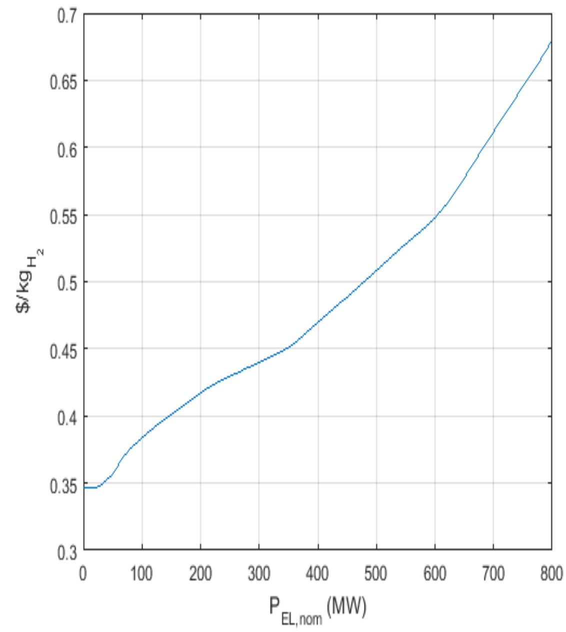

Fig. 5. The cost of hydrogen production as a function of the electrolyser nominal power (1 to 800 MW).

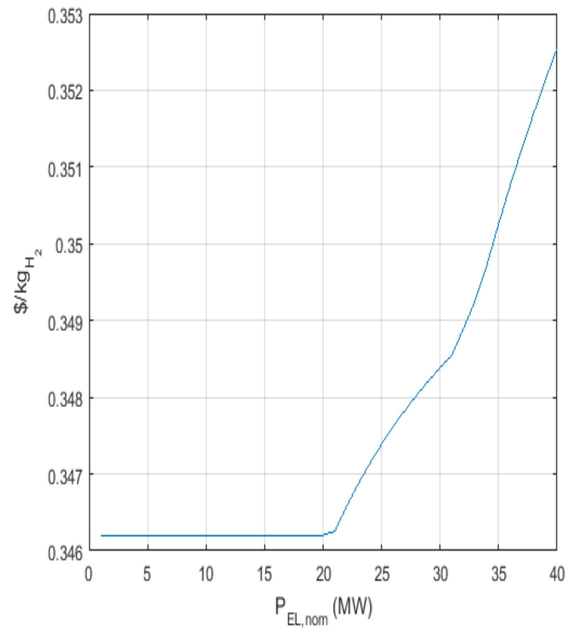

Fig. 6. The cost of hydrogen production as a function of the electrolyser nominal power (1 to 40 MW).

VI. Conclusion

Utilising the excess power produced by standalone hybrid renewable energy systems for hydrogen production has become a topic of research as the number of installed renewable energy systems grows. Sizing the electrolyser and the auxiliary components is not straightforward due to the variation of excess power with time. On one hand, sizing the electrolyser based on the highest excess power leads to under-utilised and over-designed hydrogen production systems. On the other hand, using small electrolysers leads to underutilisation of the excess power produced by the renewable energy system. The size optimisation algorithm presented in this paper allows to find the optimum size of the electrolyser through a cost-benefit analysis. In the presented case study, the algorithm is used to solve an unconstraint optimisation problem. Without loss of generality, the algorithm can be used for constrained problems. For instance, inclusion of constraints on TLSC imposed by the budget limitation or constraints on minimum or maximum daily production can be easily included in the algorithm.

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