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Hydrogen Production at the Forecourt from Off-Peak Electricity and Its Role in Balancing the Grid

Abdulla Rahil, Rupert Gammon, Neil Brown

Abstract**—**The rapid growth of renewable energy sources and their integration into the grid have been motivated by the depletion of fossil fuels and environmental issues. Unfortunately, the grid is unable to cope with the predicted growth of renewable energy which would lead to its instability. To solve this problem, energy storage devices could be used. Electrolytic hydrogen production from an electrolyser is considered a promising option since it is a clean energy source (zero emissions). Choosing flexible operation of an electrolyser (producing hydrogen during the off-peak electricity period and stopping at other times) could bring about many benefits like reducing the cost of hydrogen and helping to balance the electric systems. This paper investigates the price of hydrogen during flexible operation compared with continuous operation, while serving the customer (hydrogen filling station) without interruption. The optimization algorithm is applied to investigate the hydrogen station in both cases (flexible and continuous operation). Three different scenarios are tested to see whether the off-peak electricity price could enhance the reduction of the hydrogen cost. These scenarios are: Standard tariff (1 tier system) during the day (assumed 12 p/kWh) while still satisfying the demand for hydrogen; using off-peak electricity at a lower price (assumed 5 p/kWh) and shutting down the electrolyser at other times; using lower price electricity at off-peak times and high price electricity at other times. This study looks at Derna city, which is located on the coast of the Mediterranean Sea (32° 46′ 0 N, 22° 38′ 0 E) with a high potential for wind resource. Hourly wind speed data which were collected over 24½ years from 1990 to 2014 were in addition to data on hourly radiation and hourly electricity demand collected over a one-year period, together with the petrol station data.

Keywords**—**Hydrogen filling station off-peak electricity, renewable energy, off-peak electricity, electrolytic hydrogen.

I. INTRODUCTION

THERE are many applications of hydrogen; for example, it can be used as long term energy storage or energy carrier that can be reconverted to electricity by using fuel cell or the hydrogen can be exploited in many areas such as fertilizer production or vegetable hydrogenation. One suggested usage of hydrogen is as a fuel since it has zero emission [1]-[4]; however, commercialization of hydrogen as an alternative fuel is not easy as it is still expensive (wind hydrogen price is \$7–11/kg at present, with future target costs of \$3–4/kg) compared with fossil fuels even with environmental properties [5], [6]. Most of the hydrogen cost comes from the cost of capital and electricity, and for a large scale system, the electricity cost is more effective than the investment cost [7], [8]. Hydrogen production with high renewable energy penetration has been analysed in many areas, since these cases require flexibility of operation to accommodate the variability and intermittency of wind turbines [9]-[11]. Production of hydrogen from excess electricity in the Irish system was investigated in [12] and it was shown that to reach profitability, low electricity price and high hydrogen selling price are required. This was also studied in [13] which points out that using some non-curtailed or peak time power is necessary. Off-peak electrolyser operation could lead to a reduction in the hydrogen cost as studied in the case of the Danish system [14] and also in the Canadian context [15]. Production of hydrogen at the forecourt using off-peak electricity was investigated, and different scenarios of electricity price were tested ranging from 0.01 \$/kWh to 0.24 \$/kWh, varied hourly and taking into account the hourly hydrogen demand. It was concluded that using off-peak electricity hardly reduced the variable cost and at the same time required more storage, more compressors and a large electrolyser system which led to an increase in the investment cost [16]. Combining the wind electricity with utility was also tested with fixed peak and off-peak times [17].

II. HYDROGEN PRODUCTION OVERVIEW

Hydrogen can be produced on site at a hydrogen filling station or at a large central area. Building a large central area could reduce the cost of hydrogen production; however, this would increase the cost of transportation [18]. There are three main forms of hydrogen transportation which are:

1) Compressed hydrogen in trailers;
2) Liquid hydrogen in tanker trucks;
3) Hydrogen pipeline.

Compressed hydrogen is very expensive because of the lower gas energy density and higher cost of compression. Liquid hydrogen also requires intensive energy which adds to the cost of the process. The least expensive storage technique is using a pipeline; however, building a pipeline requires the hydrogen usage to be diffused widely in order to achieve the desired economic targets [19]. On-site hydrogen production reduces the cost by eliminating the need for transportation and is in line with the current hydrogen situation. Hydrogen can be produced from many sources, with steam reforming being the cheapest way although it has some environmental problems. The cleanest hydrogen production is from the electrolysis method in which the injected electricity comes from renewable sources [20].

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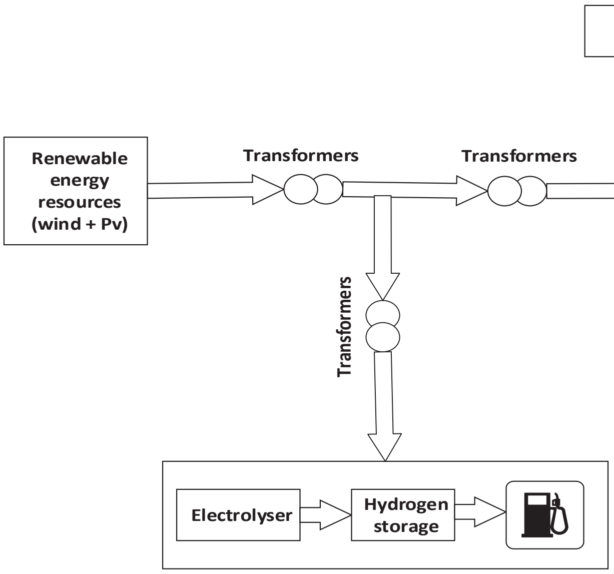

Fig. 1 System component

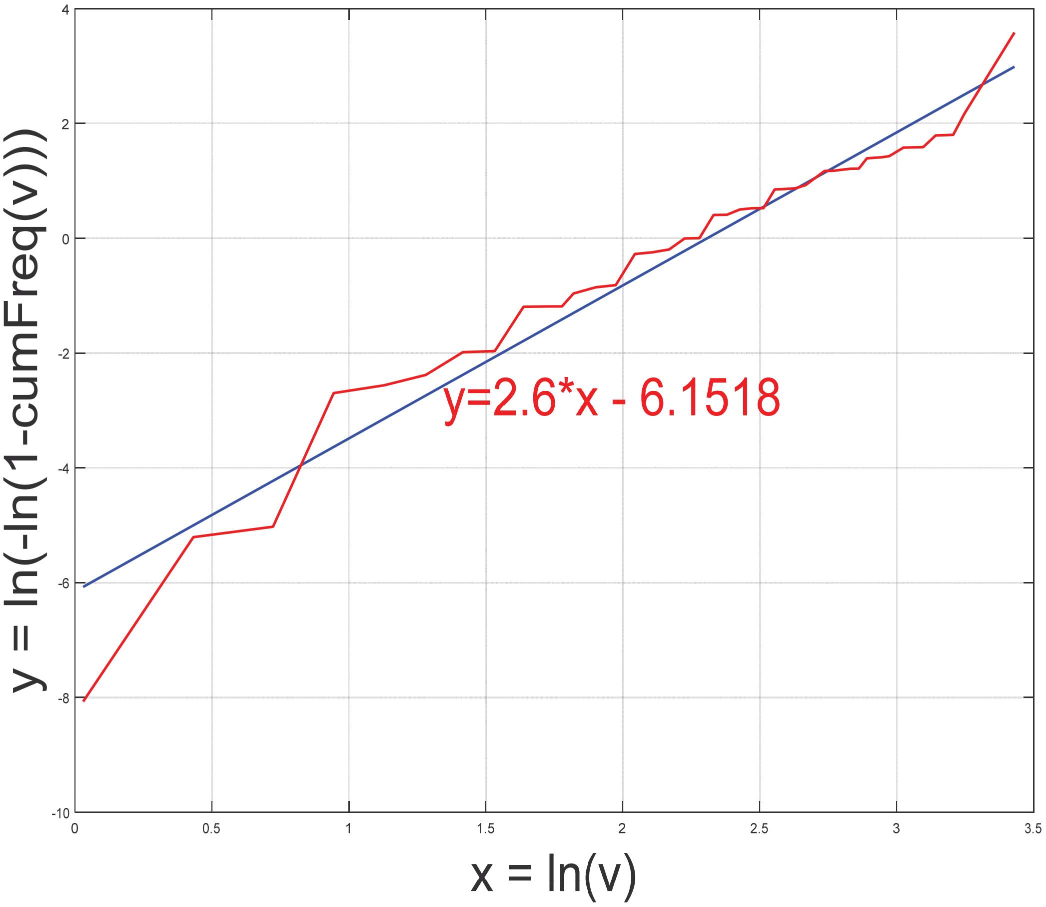

Fig. 2 Linearized curve and fitted line comparison

III. SYSTEM COMPONENT

This system consists of an electricity supplier and garage forecourt (electrolyser and storage). Since the study focuses on cost, all parts regarding control etc. are ignored. Fig. 1 shows the system design.

A. Electricity Generation

In this study, the off-peak electricity comes from renewable energy systems (wind and solar). The size of wind turbine and PV panels was estimated depending on the demand in the area which represents nearly 6% of the total electricity consumption in Libya with an average value of 298 MW. The wind power is easily calculated by using:

$$\mathbf{P(t)} = \begin{cases} \mathbf{P_{rated}} \times \frac{\mathbf{V(t)-Vin}}{\mathbf{Vr-Vin}} & \mathbf{Vin \le V(t) \le Vout} \\ \mathbf{P_{rated}} & \mathbf{Vr \le V(t) \le Vout} \\ \mathbf{0} & \mathbf{V(t) < Vin \cup V(t) > Vout} \end{cases} \quad (1)$$

where, P_rated is the rated power, V(t) is the daily wind speed, Vin, Vout, Vr are the characteristic parameters determined by the wind turbine curve. The following formula is used to change actual wind speed to desired wind speed

$$\mathbf{V(z) = V(z_r)(\frac{Z}{Z_r})^{\,n}} \quad (2)$$

where, V(z_r) is the original raw wind speed at 10 m, V(z) is the adjusted wind speed at the turbine hub; Z is the hub height, reasonably being assumed to be 80 m, and Z_r is the original measurement height (10 m) of the raw wind speed data; n is the friction coefficient (which varies from 0.09 when it is very unstable, to 0.41 when it is very stable). In order to determine the capacity factor of the wind turbine it is necessary to determine the number of turbines in the system. The Weibull probability distribution function and the cumulative Weibull distribution function are used to analyse the wind speed, and the graphical method is used to determine the K and C parameter. From Fig. 2: k= 2.6655 and C= 10.0534.

Regarding PV systems, the output power can be easily calculated by using:

$$E = A * r * H * PR \quad (3)$$

where: E: energy(kWh), A: total solar panel area (m^2), r: solar panel yield (%), PR: Performance ratio, coefficient for losses (range between 0.9 and 0.5, default value = 0.75), H: daily solar irradiation. In this paper, the rated power of PV system is assumed to be 40 MW, and the rest comes from wind turbines. After determining the size of these sources regarding the demand, the hourly surplus energy is extracted and presented in Fig. 2.

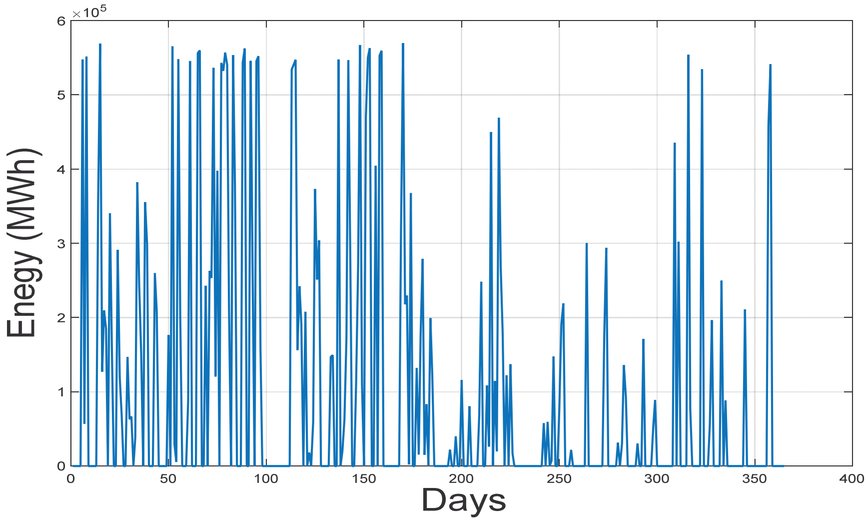

Fig. 3 Surplus energy for a year

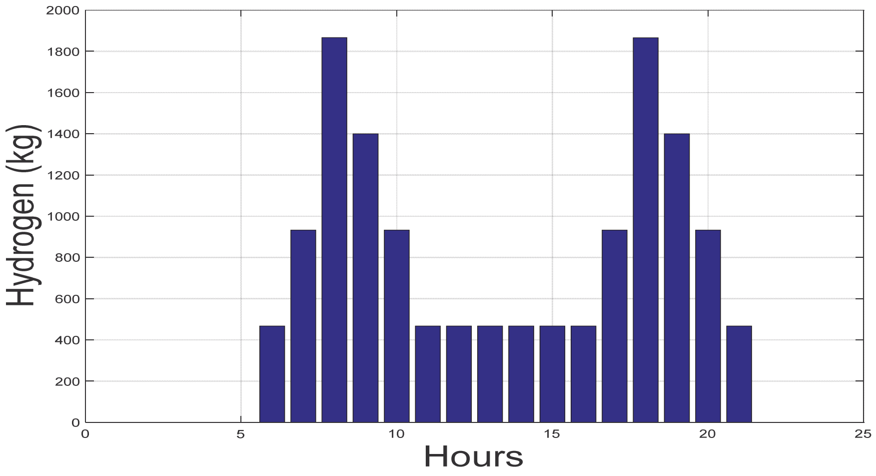

Fig. 4 Daily hydrogen demand

B. Hydrogen Demand

There are many ways to show how many kilograms of hydrogen equal one gallon of fossil fuels. As hydrogen stations are not available in many areas of the world, especially in Middle Eastern countries such as Libya, it would be useful to find a way to replace fossil fuel stations with hydrogen stations. One way would be to use the details and efficiency of fossil fuel engines, hydrogen engine efficiency and higher heating values of fossil engines and hydrogen as:

$$Q_{H2} = \frac{Q_{ff} \times LHV_{ff} \times \mu_{ff}}{LHV_{H2} \times \mu_{H2}} \quad (4)$$

where: $\boldsymbol{Q_{ff}}$: demand of fossil fuel of station(L), $\boldsymbol{LHV_{ff}}$: fossil fuel lower heating value (kWh/kg), $\boldsymbol{\mu_{ff}}$: efficiency of fossil fuel engine [-], $\boldsymbol{LHV_{H2}}$: hydrogen lower heating value, $\boldsymbol{\mu_{H2}}$: efficiency of fossil fuel engine [-]. Fig. 3 shows the hourly hydrogen consumption during a day. Technical details of wind turbine, and electrolyser system are shown in Tables I and II, respectively.

TABLE I
TECHNICAL DATA FOR THE M. TORRES TWT 1.65-82 TURBINE

Rated power	1.65 MW
Cut-in wind speed	3 m/sec
Rated wind speed	15 m/sec
Cut-out wind speed	25 m/sec
Survival wind speed	52.5 m/sec
Diameter	82 m
Swept area	5,365 m²
Hub height	70/80 m
Number of blades	3

TABLE II
MAIN PARAMETERS OF THE STATION

Electrolyser capacity	14000 kg/day
Hydrogen storage tank	6000 kg
Allowed minimum level in tank	600 kg
Hydrogen consumption	14000 kg
Price of power	12 p/kWh
Initial value in storage tank	5000 kg
Electrolyser efficiency	54.6 kWh/kg

IV. OPTIMIZATION

The linear optimization is applied to solve this problem. The objective function of the system should meet the following goals:

1) Fully utilize the surplus power;
2) Minimize the hydrogen cost;
3) Serve all customers without any deficiency.
4) The final hydrogen level must equal the initial value of hydrogen in tank.

The objective function below is similar between the three scenarios with different electricity prices.

$$\min(C * H_{2production}) \quad (5)$$

$$\text{st:} \quad 0 \le \left(P + P_{surplus}\right) \le cap_{electrolyser}$$

$$Tank\_min \le Hy\_in\_tank \le Tank\_size$$

$$Hy_{in_{tank}}(t+1) = Hy_{in_{tank}}(t) + Hy_{pro(t)} - H\_y\_cons$$

$$Hy_{pro(t)} = \left(P(t) + P_{surplus}(t)\right)/54.6$$

where: C: hydrogen cost (£),$P_{surplus}$:surplus power, P: backup power, $Hy_{in_{tank}}$: hydrogen in tank, $Hy_{pro(t)}$: hydrogen production at time (t), H_y_cons: hydrogen consumption at time(t). Note: all cost prices (storage, capital cost and compressor cost) are based on real costs in 2005

V. SIMULATION

The optimization algorithm is implemented in MATLAB with three different scenarios.

1) Standard tariff (1 tier system) during the day (assumed 12 p/kWh) while still satisfying the hydrogen demand (one-day simulation).
2) Using off-peak, low priced electricity (assumed 5p/kWh) and shutting down the electrolyser at other times (daily simulation).
3) Using low price off-peak electricity and high price electricity at other times (daily simulation).

In the first scenario, the electricity price is 6.8 £/kg which is very expensive since the price for electricity is the normal constant price for all scenarios, and from Fig. 5, the other targets are satisfied. In the second scenario, the electricity cost is reduced by nearly three quarters from £6.8 to £2.8, but this does not mean that the hydrogen cost will definitely decrease, because using off-peak electricity leads to an increase in the size of the electrolyser to absorb energy as much as possible in order to produce a large amount of hydrogen to satisfy the load, since the objective is not just to reduce the cost. In addition, this large amount of hydrogen requires a large storage space which means an increase in the cost. For the last scenario, the price fluctuates from £5.8 to £6.3 depending on many factors such as the quantity of surplus power usage and backup power usage, and the size of storage, because in this optimization, the priority is given to the surplus power, which means satisfying the demand first and storing the rest to use it later. Table III summarises these scenarios, and Fig. 5 shows the hydrogen in tank in each scenario.

TABLE III
HYDROGEN OPTIMIZATION SCENARIOS

	Scenario 1	Scenario 2	Scenario 3
Hydrogen production	14000(kg/day)	7.9389×10^{5}	33.7115×10^{6}
Electricity usage (MWh)	764	43346	202650
Total electricity cost (£)	95713	2.2767×10^{6}	2.1948×10^{7}
Electricity cost per kg of hydrogen (£/kg)	6.8	2.8	5.9

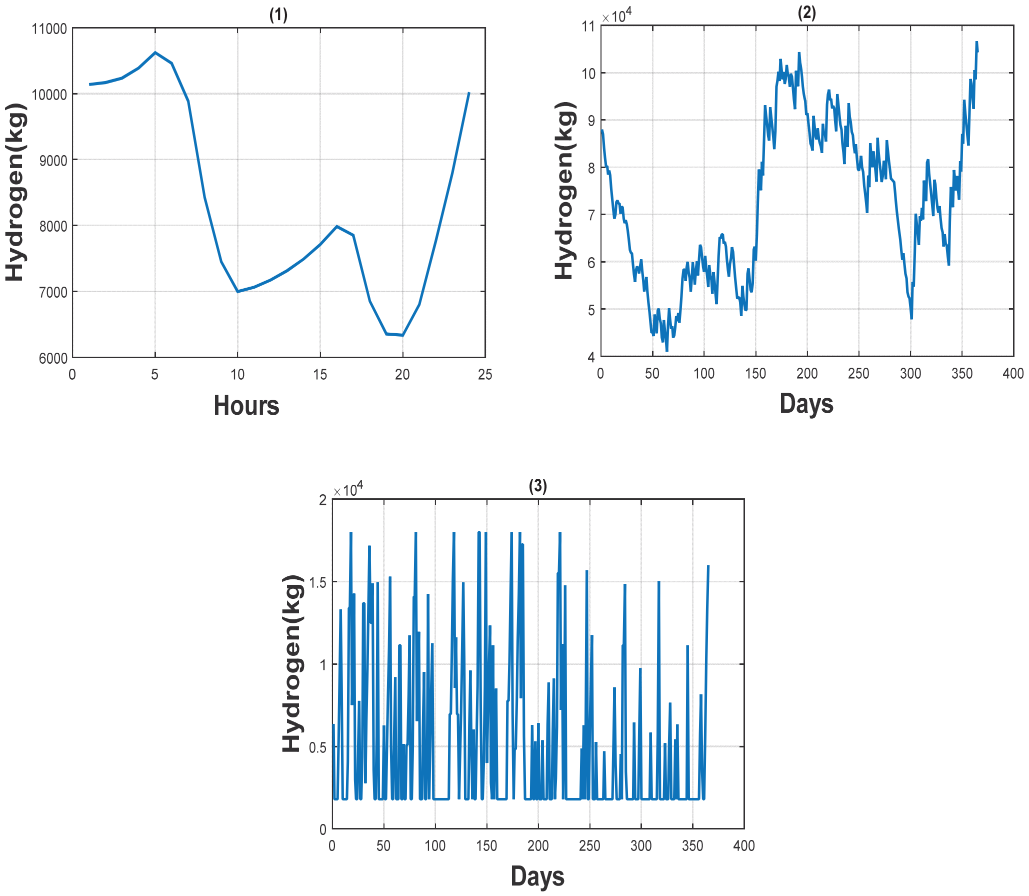

Fig. 5 Hydrogen in tank

VI. CONCLUSION AND FUTURE WORK

This optimization has been implemented to achieve a number of goals: balancing the grid by absorbing surplus power, reducing the cost of hydrogen by choosing the cheapest electricity tariff; and using hydrogen as a fuel and guaranteeing satisfaction at times. Three scenarios were tested as mentioned above: standard tariff (12 p/kWh), off-peak tariff (5 p/kWh) and low price during off-peak electricity and high price at other times. It was concluded that:

1) The cheapest electricity cost per kg occurred in the second scenario (£2.8) followed by the third scenario (5.8-6.3) while the most expensive (£6.8) was seen in the first scenario.
2) Generally, the commercial price of hydrogen requires a reduction in the other parts of the system (investment cost etc.)
3) Changing the policy especially regarding renewable energy sources could enhance the hydrogen production targets since, when a new agreement to reduce emissions is released, it is necessary to take bold steps to achieve this.

Future works will focus on the following points:

1) Setting new peak and off-peak electricity prices according to the time at which the electrolyser is used as well as the cost of the hydrogen. In the other words, pricing is lower than off peak during off-peak times and higher than peak during peak times;
2) Applying optimization for many garage forecourts which have varying hydrogen.

REFERENCES

[1] F. Gutiérrez-Martín, J. García-De María, A. Baïri and N. Laraqi, "Management strategies for surplus electricity loads using electrolytic hydrogen," International journal of hydrogen energy, vol 34, no 20, pp. 8468-8475, 2009.

[2] C. Mansilla, J. Louyrette, S. Albou, C. Bourasseau and S. Dautremont, "Economic competitiveness of off-peak hydrogen production today–A european comparison," Energy, vol 55, pp. 996-1001, 2013.

[3] D. Johansson, P. Franck and T. Berntsson, "Hydrogen production from biomass gasification in the oil refining industry–a system analysis," Energy, vol 38, no 1, pp. 212-227, 2012.

[4] M. Balat, "Potential importance of hydrogen as a future solution to environmental and transportation problems," International journal of hydrogen energy, vol 33, no 15, pp. 4013-4029, 2008.

[5] S. Sharma and S. K. Ghoshal, "Hydrogen the future transportation fuel: From production to applications," Renewable and sustainable energy reviews, vol 43, pp. 1151-1158, 3 2015.

[6] J. Alazemi and J. Andrews, "Automotive hydrogen fuelling stations: An international review," Renewable and sustainable energy reviews, vol 48, pp. 483-499, 8 2015.

[7] Wood, H. He, T. Joia, M. Krivy and D. Steedman, "Communication—Electrolysis at high efficiency with remarkable hydrogen production rates," Journal of the electrochemical society, vol 163, no 5, pp. F327-F329, 2016.

[8] J. Ivy, "Summary of electrolytic hydrogen production: Milestone completion report," 2004.

[9] P. Caumon, M. L. Zulueta, J. Louyrette, S. Albou, C. Bourasseau and C. Mansilla, "Flexible hydrogen production implementation in the french power system: Expected impacts at the french and european levels," Energy, vol 81, pp. 556-562, 2015.

[10] R. Loisel, "Power system flexibility with electricity storage technologies: A technical–economic assessment of a large-scale storage facility," International journal of electrical power & energy systems, vol 42, no 1, pp. 542-552, 2012.

[11] Dincer and C. Acar, "Review and evaluation of hydrogen production methods for better sustainability," International journal of hydrogen energy, vol 40, no 34, pp. 11094-11111, 2015.

[12] González, E. McKeogh and B. Gallachoir, "The role of hydrogen in high wind energy penetration electricity systems: The irish case," Renewable energy, vol 29, no 4, pp. 471-489, 2004.

[13] E. Troncoso and M. Newborough, "Electrolysers for mitigating wind curtailment and producing 'green' merchant hydrogen," International journal of hydrogen energy, vol 36, no 1, pp. 120-134, 1 2011.

[14] C. Jørgensen and S. Ropenus, "Production price of hydrogen from grid connected electrolysis in a power market with high wind penetration." International journal of hydrogen energy, vol 33, no 20, pp. 5335-5344, 10 2008.

[15] G. Naterer, M. Fowler, J. Cotton and K. Gabriel, "Synergistic roles of off-peak electrolysis and thermochemical production of hydrogen from nuclear energy in canada," International journal of hydrogen energy, vol 33, no 23, pp. 6849-6857, 2008.

[16] J.I. Levene, M.K. Mann, R. Margolis, and A. Milbrandt, "Http://Www.nrel.gov/docs/fy05osti/37612.pdf," In Orlando, Florida, 2005.

[17] W. Xiao, Y. Cheng, W. J. Lee, V. Chen and S. Charoensri, "Hydrogen filling station design for fuel cell vehicles," Industry applications, IEEE transactions on, vol 47, no 1, pp. 245-251, 2011.

[18] L. Zhao and J. Brouwer, "Dynamic operation and feasibility study of a self-sustainable hydrogen fueling station using renewable energy sources," International journal of hydrogen energy, vol 40, no 10, pp. 3822-3837, 2015.

[19] R. S. El-Emam, H. Ozcan and I. Dincer, "Comparative cost evaluation of nuclear hydrogen production methods with the hydrogen economy evaluation program (HEEP)," International journal of hydrogen energy, vol 40, no 34, pp. 11168-11177, 2015.

[20] C. Acar and I. Dincer, "Impact assessment and efficiency evaluation of hydrogen production methods," International journal of energy research, vol 39, no 13, pp. 1757-1768, 2015.

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