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Co-production of electricity and hydrogen from wind: a comprehensive scenario-based techno-economic analysis

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Abstract

The aim of this study is to investigate the economic prospects of producing electricity and hydrogen using wind energy under different scenarios. For this, the most essential criteria to investors including Levelized Cost of Wind-generated Electricity (LCOWE), Levelized Cost of Wind-based Hydrogen (LCOWH), payback period, and rate of return are examined. Technical and environmental impacts are factored into the LCOWE formulation to obtain comprehensive insight. Owing to the uncertain nature of future, five degradation rates concerned with wind turbine performance and five likely rates as to the future value of money are investigated under the scenarios of I) installing wind electricity to replace fuel oil electricity, II) to replace natural gas electricity and III) without considering environmental penalties. The results indicate that LCOWE would be in the range of 0.0325 - 0.0755 $/kWh, while the corresponding LCOWH being in the range of 1.375 - 1.59 $/kg. Moreover, the payback period of the related LCOWE and LCOWH would be in the range of 2.55 - 9.48 yr during the lifetime of wind power plant and 3.91 - 8.41 yr during that of hydrogen production site, respectively. The corresponding rate of return pertinent to the above-mentioned ones would be respectively in the range of 14.15-23.54% and of 9.87-21.55%.

Key words: Wind-powered hydrogen production; Levelized Cost of Wind-generated Electricity (LCOWE); Levelized Cost of Wind-based Hydrogen (LCOWH); Economic analysis.

Nomenclature			
A_{I1}	Total amount of incomes within year 1	n	Entire lifetime of the project
A_{C1}	Total amount of costs within year 1	N_T	Number of installed turbines
c	Scale parameter	NPW	Net Present Worth
CF	Capacity factor of wind turbine	OM	Operation and maintenance cost
CI	Capital (initial) investment	PBP	Payback Period
C_R	Nominal capacity of the turbine	P_n	The nominal power of a wind turbine
$C_{u,e}$	Unit cost of electrolyzer	PWI	Present worth of incomes
d	Degradation rate of wind power plant	PWC	Present worth of costs
E_e	Energy required by electrolyzer	REP	Replacement cost
ENV	Environmental cost	ROR	Rate of Return
$EUAP$	Equivalent Uniform Annual Profit	SV	Salvage value
EWT_1	Electricity obtained within year 1	t	Lifetime of electrolyzer
f	Difference between interest rate and inflation	$\bar{v}$	Mean wind speed
i	The number of year	v_i	Cut-in speed
k	Shape parameter	v_o	Cut-out speed
kg_{CO_2}	Kilo of CO_2	v_r	Rated speed
LCOWE	Levelized cost of wind-generated electricity	yr	Year
LCOWH	Levelized cost of wind-based hydrogen	η_e	Electrolyzer efficiency
M_{H2}	Mass of produced hydrogen	η	Rectifier efficiency of electrolyser
$MARR$	Minimum Attractive Rate of Return	Γ	Gamma function

1. Introduction

1.1. Motivation and incitement

The global movement toward net-zero emission future and the tipping point in renewable energy prices such as wind and solar has remobilized interests in clean energy careers such as hydrogen. However, one major obstacle confronting the investment in such technologies, especially by the developing countries, is the lack of detailed economic evaluation concerned with prospective costs and incomes of utilizing renewable energies.

Chief among renewable means of producing electricity is wind turbine emitting almost zero pollutants when being utilized [1]. According to the World Wind Energy Association (WWEA) and International Renewable Energy Agency (IRENA), wind energy capacity has been experiencing a dramatic growth over the past few years, reaching 594 GW as of 2019, and consolidating its position as the second most favorable renewable resource. Top 3 countries exploiting on-shore wind energy are China, the USA and Germany, respectively with installed capacities of around 204.5, 103.5 and 53.3 GW as of 2019. Nevertheless, developed countries are briskly exploiting wind energy while the share of developing countries is still small [2, 3]. For instance, Iran with 302.2 MW capacity harnesses only 2.2% of its total wind capacity. Similar pattern is expected to be seen in the case of the emerging hydrogen market.

The principal element holding this type of countries back from renewable technology investment might be the uncertainty about the future of these projects which is of course inherent.

One solid solution to stimulate the investment in renewable technologies is the introduction of reliable technoeconomic decision support tools. Of several decision criteria with respect to the investment in renewable energy projects, Levelized Cost of Wind-generated Electricity (LCOWE), Levelized Cost of Wind-based Hydrogen (LCOWH), payback period (PBP), and rate of return (ROR) have been introduced as the most decisive factors [4, 5]. LCOWE simultaneously takes technical, environmental and economic aspects of wind turbine utilization into account, LCOWH does likewise concerning hydrogen production system [4]. Additionally, PBP provides details about the expected time to reach profitability from the beginning of the project.

Obtaining a comprehensive and close-to-reality provision as to the economic results of embarking on renewable energy application may be subject to some unpredictable events. To overcome the issue of uncertainty in the future, a plausible remedy is to scrutinize all possible scenarios bounded by the best and the worst ones. In this case, the assessment can confirm which scenario is profitable and cost-effective.

1.2. Literature survey and existing research gap

Ample research works were conducted to evaluate the economic feasibility of renewable electricity and hydrogen generation. After carefully surveying the literature, it drew the authors' attention that there was not performed an economic analysis of exploiting wind energy in Iran for the purposes of electricity and hydrogen generation in which LCOWE, LCOWH, PBP of electricity generation, PBP of hydrogen production, ROR of electricity generation, and ROR of hydrogen production would be anticipated under different scenarios as to the future value of money. Table 1 contains the main differences between the present study and the most recent papers about the economic assessment of electricity and/or hydrogen production via various means.

Table 1. The difference in the criteria of economic analysis between the recent literature and this study (Differences with this study is shown by check mark)

LCOE	LCOH	PBP	ROR	Wind energy utilization for water electrolysis	Refs.
-	✓	-	✓	-	[6]
-	✓	✓	✓	✓	[7-9]
-	✓	✓	✓	-	[10-13]
-	-	-	✓	-	[5,14]
-	✓	-	-	✓	[15]
✓	-	✓	✓	✓	[16-29]
-	✓	✓	-	✓	[30]
✓	-	✓	✓	✓	[31]
-	-	✓	✓	-	[32-38]
-	-	✓	✓	✓	[39-41]
-	✓	✓	✓	-	[42-45]
-	✓	✓	✓	✓	[46,47]
-	-	-	-	-	[48]
-	-	✓	✓	-	[49,50]
-	-	✓	-	✓	[51]
-	-	-	-	✓	[52,53]
✓	-	-	-	✓	[54-56]

-	-	-	✓	✓	[57]
-	-	✓	✓	✓	[58]
✓	-	✓	✓	-	[59]
-	-	-	✓	-	[4,60]
✓	-	-	-	-	[61]
✓	-	-	✓	✓	[62]
✓	✓	✓	✓	✓	This study

1.3. Contribution

This study introduces a detailed arithmetical method of calculating LCOWE, LCOWH, PBP, and ROR which can be modeled by Excel. More importantly, environmental and technical aspects of deploying wind turbines are factored into the calculations of LCOWE. However, the focus of the study is solely on an LCOWH without the inclusion of the cost of safety, compression and storage of hydrogen. The reason behind this approach is that the process of hydrogen generation itself in the hydrogen supply chain would be the most important phase, therefore other costs can then be added to it in order to project the final cost of hydrogen. As a case study, we have considered Lutak city one of the aptest places in Iran with regard to wind resources. As a general goal, the methodology proposed in the content of the study can considerably aid researchers and decision makers with similar interest to analyze the economic feasibility of renewable hydrogen production for a given location.

As to novelty, this is the first study analyzing and elucidating the most likely economic aspects of wind-powered electricity and hydrogen generation in Iran under the condition in which the future value of money would be uncertain. Literature review reveals that Iran, as a developing country, has not seen a thorough and comprehensive economic viability study concerned with renewable-based electricity and hydrogen production therein all crucial factors of LCOWE, LCOWH, PBP and ROR have been estimated. Furthermore, the readers may confront the question of how the model will work for larger cases. The answer is in this model the most vital and effective criterion is the future value of money which will be just impacted by the discount rate and inflation. For this, the proposed model can be expanded and used for hybrid systems, thus only the value of the capital and replacement costs would change.

2. Case study location

Iran's low renewable energy development is not comparable with its suitable geographical location enjoying great wind and solar resources. This is mostly due to the fact that Iran is one of the richest nations regarding fossil fuel resources and consequently the country has firmly relied on this type of energy. This has, nonetheless, raised concerns among Iranian people worrying about the future and depleting nature of underground sources. In addition, consuming oil-based electricity is truly exacerbating environmental pollution in major cities of Iran.
According to Renewable and Sustainable Energy Organization of Iran (SATBA), north-west, north-east, and south-east of the country possess considerable potentials of wind energy [63]. Among these areas, the province of Sistan and Baluchestan situated in the south-east of Iran has been a promising candidate for exploiting wind energy. The aforementioned province is

one of the poorest areas in Iran lacking in job opportunities which makes it eminently suitable case study, since this project would create temporary and permanent jobs for both skilled and simple labor. Another reason for selecting this province as the case study is that most of its parts are flat deserts causing decline in the construction costs. Whereas the other wind-rich parts in the north-east and the north-west are covered with hills and trees ending in the dissipation of time and funds if they were chosen. For this, one of the most suitable cities in Iran in terms of receiving wind energy, Lutak, located in the eastern province of Sistan and Baluchestan is examined to accomplish the purpose of this paper.

3. Methodology

Econometrics leading to virtually precise knowledge about costs imposed and incomes earned in a project can play a substantial role in avoiding further money and time losses. Fig. 1 demonstrates the key path of the model presented in the study.

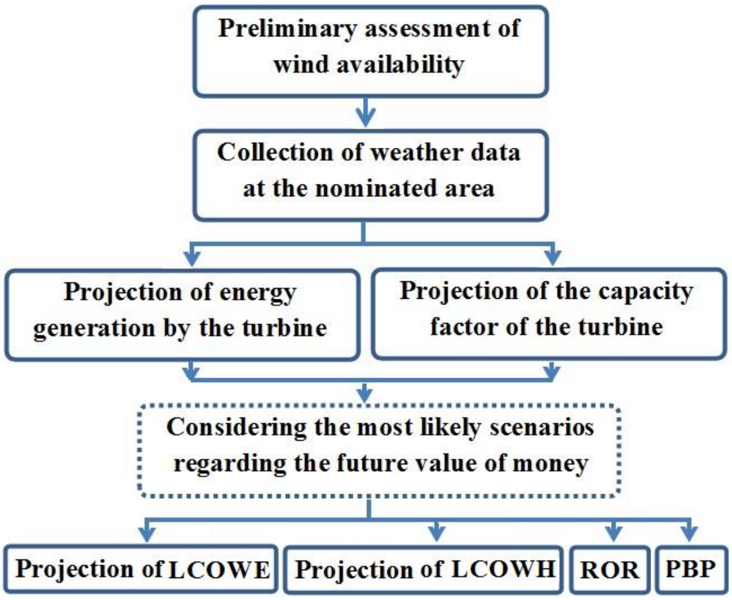


Fig. 1. The key steps of the economic assessment model.

3.1. Levelized cost of wind-generated electricity (LCOWE)

In a project pertaining to renewable electricity, there is one main factor taking economic and technical aspects into account and also projecting lifecycle of costs and incomes called LCOWE. It refers to the average cost of generating 1 kWh of electricity, which is defined as the ratio of net present worth of all costs to the amount of obtained electricity during the lifetime of the project. To acquire its value in $/kWh, Eq. (1) is utilized [4].

$$LCOWE = \frac{\sum_{i=0}^{n} \frac{CI+OM+REP-ENV}{(1+f)^{i}}}{\sum_{i=1}^{n} \frac{EWT_1}{(1+d)^{i-1}}} \quad (1)$$

CI denotes capital investment including the price of all apparatus associated with wind-based electricity generation. OM is operation and maintenance cost which should be paid every year up to the end of the project. REP implies replacement cost after terminating lifetime of any equipment in the project. ENV signifies environmental cost showing that LCOWE takes environmental impact into consideration, in addition to technical aspect. As shown, the latter cost is subtracted from the summation of other costs since generating power via the wind turbines would stem CO_2 emission and this will finally result in saving costs regarding pollutant penalties. Moreover, f indicates the difference between the two rates of interest and inflation [4]. d means degradation factor of the wind power plant caused by some unpredictable conditions in the future. n is the lifespan of the project mainly dependent on the wind turbine's lifetime and i shows the number of year. Eventually, EWT_1 denotes the total amount of electricity obtained in year 1 and this value can be computed in kWh/yr by Eq. (2) [4].

$$EWT_1 = N_T \times C_R \times CF \times 8760 \tag{2}$$

where, N_T refers to the number of the wind turbines installed in the wind power plant. C_R and CF represent the nominal capacity and the capacity factor of the turbine. The latter can be projected using Eq. (3) [14].

$$CF = \frac{e^{-(v_i/c)^k} - e^{-(v_r/c)^k}}{(v_r/c)^k - (v_i/c)^k} - e^{-(v_o/k)^k} \tag{3}$$

here, v_i, v_o and v_r are respectively designated to cut-in wind velocity, cut-out wind velocity and rated wind velocity which are declared as the characteristics of the turbine. Also, k and c are respectively the parameters of shape and scale and can be obtained by Eqs. (4) and (5) in which Γ means the Gamma function [5].

$$k = 0.83 \times \bar{v}^{0.5} \tag{4}$$

$$c = \frac{\bar{v}}{\Gamma \times (1 + \frac{1}{k})} \tag{5}$$

3.2. Levelized cost of wind-generated hydrogen

To make hydrogen, there are several means among which water electrolysis is one of the most common methods. Hence, to proceed with the study, it is presumed that the wind-powered hydrogen production system contains an Alkaline water electrolyzer. In this regard, the key factor of economic aspect in a renewable hydrogen production system is LCOWH, the cost that will be incurred to gain 1 kg of hydrogen during the lifetime of the hydrogen production system (Eq. (6)) [4, 64].

$$\mathrm{LCOWH} = \frac{\mathrm{C_{u,e}} \frac{\sum_1^t M_{\mathrm{H2}} \times \mathrm{E_e}}{t \times 8760 \times \mathrm{CF} \times \eta_\mathrm{e}} + \mathrm{LCOWE} \times \frac{\sum_{i=1}^{20} EWT_i}{20}}{\sum_1^t M_{\mathrm{H2}}} \tag{6}$$

in which, $C_{u,e}$ is the unit cost of electrolyzer and η_e denotes its efficiency. E_e represents the electric power required by the water electrolyzer system. M_{H2} refers to the amount of hydrogen produced after electrolyzing water. t indicates the lifetime of the electrolyzer. To project M_{H2}, Eq. (7) is utilized [4] where η represents rectifier efficiency of the electrolyzer.

$$M_{H2} = \frac{EWT}{E_e} \times \eta \quad (7)$$

3.3. Payback period

One of the most appealing factors in any project is payback period which determine the time needed to recover the capital investment. To this end, yearly costs incurred and annual incomes earned should be ascertained to predict annual profit, then PBP can be guessed by Eq. (8) [5, 65].

$$\text{PBP}=\frac{CI}{EUAP} \quad (8)$$

$EUAP$ referring to Equivalent Uniform Annual Profit can also be obtained by subtracting the amount of yearly costs from the amount of yearly incomes after selling electricity and then making them uniform.

It is practically complex to make incomes and costs uniform, but it is solvable when they follow a geometric series. This means that costs (or incomes) grow or decline year after year with a constant coefficient [65]. In this paper, the coefficient for incomes and costs are respectively d and f. It is delineated as Fig. 2 in which the following relation (Eq. (9)) show how the values of incomes are connected. In the case of evaluating costs, f is put instead of d.

$$A_i = A_1 \times (1 - d)^{i-1} \quad (9)$$

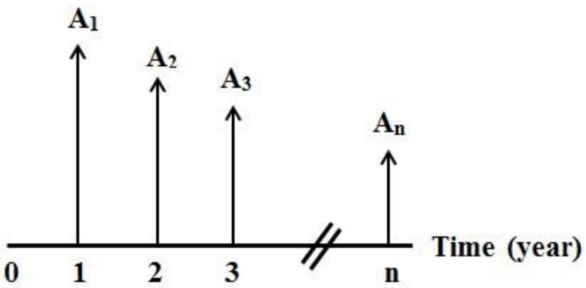


Fig. 2. Annual incomes, following a geometric series, reduce by the uniform gradient of d.

At first, Eq. (10) is used to compute present worth of all annual incomes following the geometric series. Worth mentioning that incomes are the same for all values of f and are reduced by the constant coefficient of d (they are just influenced by different values of d). Moreover, as costs are just influenced and declined by the constant value of f (not affected by d), therefore present worth of them can be calculated using Eq. (11) [65].

$$PWI = \begin{cases} A_{I1} \times \left[\dfrac{1-(1+d)^n \times (1+f)^{-n}}{f-d}\right], & d \neq f \\ \dfrac{n \times A_{I1}}{1+f}, & d = f \end{cases} \quad (10)$$

$$PWC = \frac{n \times A_{C1}}{1+f} \quad (11)$$

where A_{I1} and A_{C1} respectively imply the amount of income and cost at the end of the first year. Eventually, $EUAP$ is projected by Eq. (12).

$$EUAP = (PWI - PWC) \times \left[\frac{f \times (1+f)^n}{(1+f)^n - 1}\right] \xrightarrow{if\ f=0} \frac{(PWI - PWC)}{n} \quad (12)$$

3.4. Rate of return

Rate of return is a popular decision variable for investors. Generally, an investor has a Minimum Attractive Rate of Return (MARR) as a reference point, so any potential project with an ROR higher than MARR would be desirable investment option. MARR usually refers to the interest rate which banks dedicate to their clients' savings account. In crude terms, if ROR of investing on wind-based electricity generation were higher than that of banks, unforeseen and unpredictable risks inherent in any project could be worth taking. One way to evaluate ROR is to utilize Net Present Worth (NPW) technique. In this regard, NPW must be equated to zero and this can only be met by the unique amount of ROR. Therefore, Eq. (13) should be satisfied to ascertain ROR related to the project [65].

$$NPW=0 \rightarrow PWC-PWI=0 \rightarrow PWC=PWI \quad (13)$$

where PWC and PWI indicate present worth of costs and incomes, respectively. Eventually, if relation ROR>MARR were true, then investment in the project might be acceptable. Otherwise, ROR<MARR, starting the project would be unreasonable.

4. Analysis

To proceed with the study, 10-minute wind velocity data pertinent to the height of 40 m recorded between 2013 and 2017 in Lutak were gathered from Iranian Meteorological Organization (IRIMO) [66]. Additionally, a 100-kW wind turbine, with cut-in velocity of 3.5 m/s, rated velocity of 10 m/s, cut-out velocity of 20 m/s and rotor diameter of 21 m (with the commercial name of Northern Power Systems 100/21- 40m) was analyzed [67]. Due to the unpredictable and intermittent nature of wind speed, yearly average amount of energy produced by the aforementioned turbine (calculated by wind speed data during the 5-year period) constituted the amount of electricity which would be generated within the first-year operation of the turbine. Employing Eq. (2) indicated that approximately 338,936 kWh of electricity would be gained within the first year as EWT_1. Afterwards, some terms and conditions, as illustrated in Table 2, should be postulated for estimating LCOWE and LCOWH.

Table 2. The terms and postulations for estimating LCOWE and LCOWH.

Costs, terms and conditions	Assumed values
Capital investment (initial investment) of wind power plant would equate to the aggregation of the three following costs: I) Wind turbine, II) Installation and implementation of the wind turbine including tariffs on importing the turbine from overseas, specialists' wages for	 I) $1,000 per its nominal capacity [4, 63] II) 40% of the wind turbine price [4]

installing the turbine, and implementation of electricity distribution network	
III) Converter, assumed to utilize "KACO Inverter Powador 60.0TL3 Ver XL" model with a 7-year lifetime.	III) €5,785 (=5,785×1.1=$6,363.5) [68]
Operation and maintenance costs per year including wages incurred by routine reviews, tax, insurance, and land rent	6% of capital investment [69]
Cost of releasing a ton of CO_2 emission into the environment, as environmental penalty	$36.3 [4]
The difference between the interest rate and inflation which is shown by f	0, 1%, 2%, 3%, 4% and 5% *
The degradation rate (reduction factor) of the wind turbine performance which is shown by d	0, 0.01, 0.02, 0.03, 0.04, 0.05 **
The amount of CO_2 emissions when using electricity generated by fuel oil power plants	0.277 kg_{CO_2}/kWh [70]
The amount of CO_2 emissions when using electricity generated by natural gas power plants	0.2 kg_{CO_2}/kWh [70]
Scrap value of equipment incorporated into the project	0 ***
The type of the electrolyzer	Alkaline
The amount of energy required by the electrolyzer	5 kWh/Nm^3 (or 55.6 kWh/kg) [4]
The unit cost of the electrolyzer, $C_{u,e}$, and its efficiency, η_e	384 $/kW and 75% [71] ****
The price of selling wind-generated electricity	0.12 $/kWh [72]
The price of selling renewable hydrogen	$8, $9 and $10
The lifetime of the wind power generation plant	20 yr
The lifetime of the wind-based hydrogen generation site, the lifetime of the electrolyzer	7 yr

* Given the fact that the economy of Iran is volatile, therefore inflation and interest rates are not fixed to put into the calculations. By virtue of this, several values would be deemed as the most likely scenarios.

** Since an inherent nature of the project is that it could be subject to some unforeseen destructive conditions weakening the wind turbine performance, therefore several values bounded by the best-case scenario (d=0) and the worst-case scenario (d=0.05) would be taken into account for the calculations.

*** This value would not be factored in the calculations, as the cost of which is virtually negligible compared to other expenses and revenues.

**** The electrolyzer cost is assumed for the time when it would be mass-manufactured. Moreover, the electrolyzer modeled in the system is presumed to follow variations in the wind power plant output.

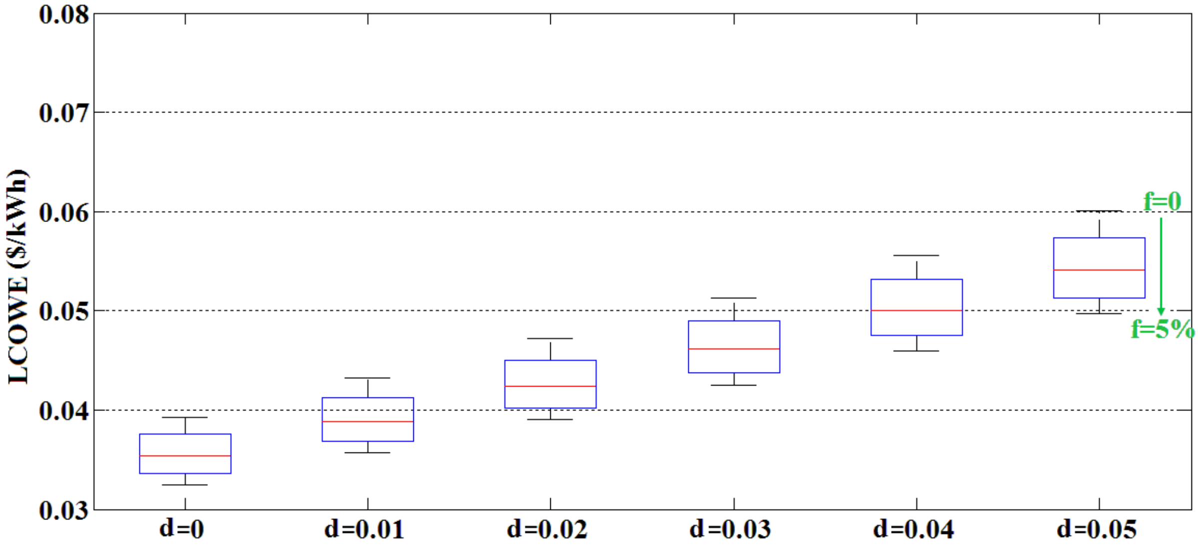
The calculations implied that the total output energy made by the under-study turbine declined significantly by 2,344 MWh, from 6,779 to 4,435 MWh, when the value of d rose from 0 to 0.05. Table 3 demonstrates electricity generation during 20 years for different values of d.

Table 3. Electricity generation (MWh/yr) over the 20-year lifetime of the project for different values of d.

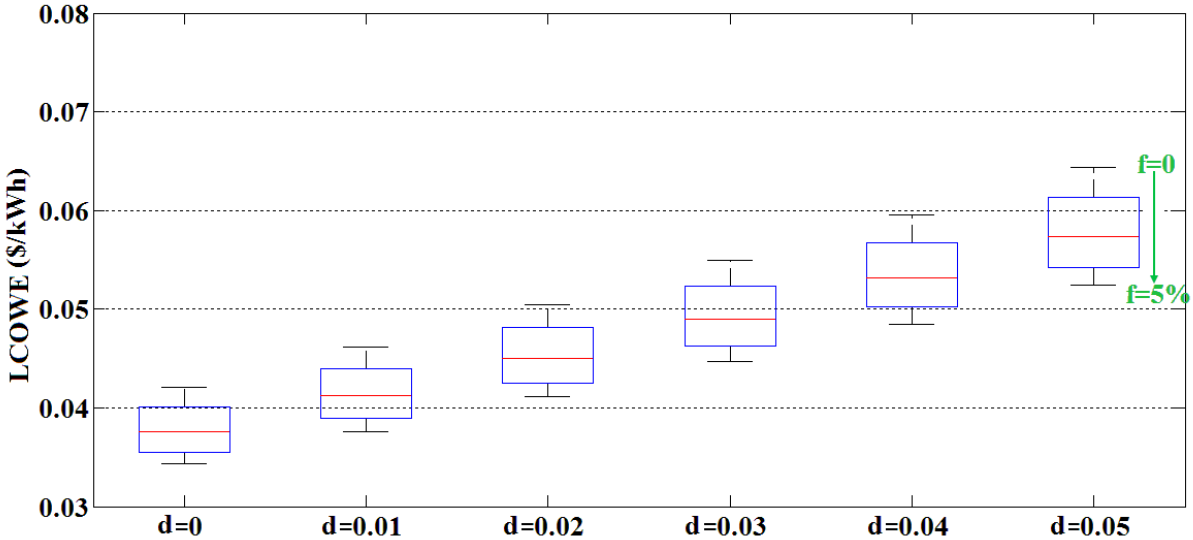
Year (i)	Degradation rate of wind power plant (*d*)					
	0.0	0.01	0.02	0.03	0.04	0.05
1	339	339	339	339	339	339
2	339	336	332	329	326	328
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
19	339	283	237	199	167	141
20	339	281	233	193	161	134
Sum	6,779	6,177	5,653	5,194	4,791	4,435

4.1. LCOWE calculation

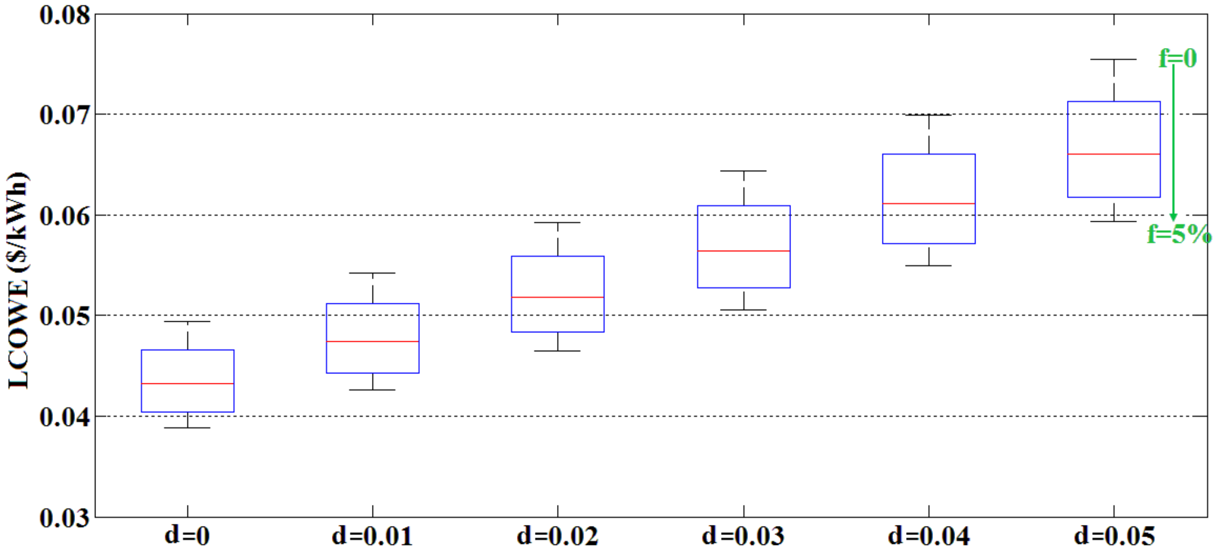
Taking into consideration all the aforementioned postulations, the results indicated that LCOWE would be 0.0393 $/kWh when d=0, f=0 and applying energy generated by the wind turbine instead of fuel oil-based electricity. This amount rose by 0.0208 to 0.0601 \$/kWh when the worst-case scenario was considered (d=0.05). Furthermore, LCOWE was computed 0.0421 \$/kWh when d=0, f=0 and natural gas-generated electricity was planned to be replaced by wind-based electricity; On the other side, in the worst-case scenario, d=0.05, LCOWE became 0.0644 \$/kWh. When not factoring the environmental-related cost in the calculations, LCOWE increased from 0.0494 \$/kWh (d=0 and f=0) to 0.0755 \$/kWh (d=0.05 and f=0). In the scenario when f was postulated 5% (the interest rate would be less than the inflation rate by 5%) and d=0, the values of LCOWE would equate to 0.0325, 0.0343 and 0.0388 \$/kWh for the cases of using wind-based electric power instead of fuel oil-generated electricity, instead of natural gas-generated electricity and not considering environmental impact, respectively. Since the government will purchase a kWh of wind-generated electricity at a price of \$0.12 and all LCOWE values are less than that, so wind energy utilization for electricity generation would be reasonable and lucrative even for the worst-case scenario scrutinized in the paper. Using MATLAB software, Fig. 3 depicts the candle charts of LCOWE for all the values of d and f.



(a)



(b)



(c)

Fig. 3. LCOWE under the scenarios of utilizing wind-based electric power as the replacement for (a) fuel oil-generated electricity, (b) natural gas-generated electricity, and the scenario of (c) not factoring the environmental cost in the calculations.

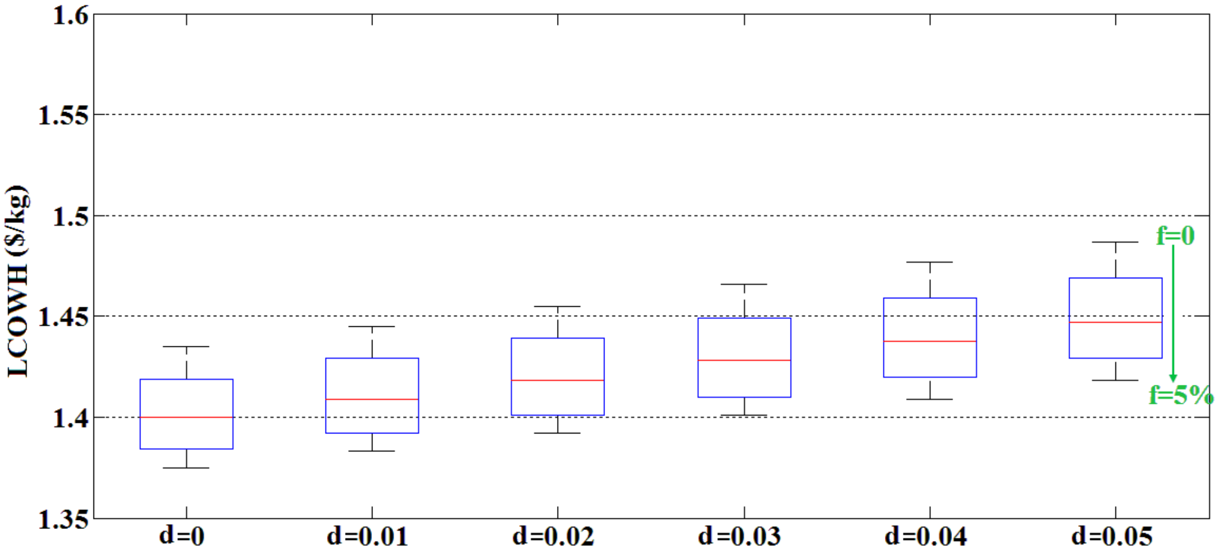
4.2. LCOWH calculation

To estimate LCOWH, capacity factor of the turbine under investigation should be projected. For this, parameters k and c were computed 2.18 and 7.79, respectively. Then, CF was obtained 42.69% using Eq. (3). Further, the mass of hydrogen which could be gained each year under different scenarios were calculated by Eq. (7) and the values are shown in Table 4.

Table 4. Yearly mass of hydrogen production (ton) during 7-year lifetime of the electrolyzer for different values of d.

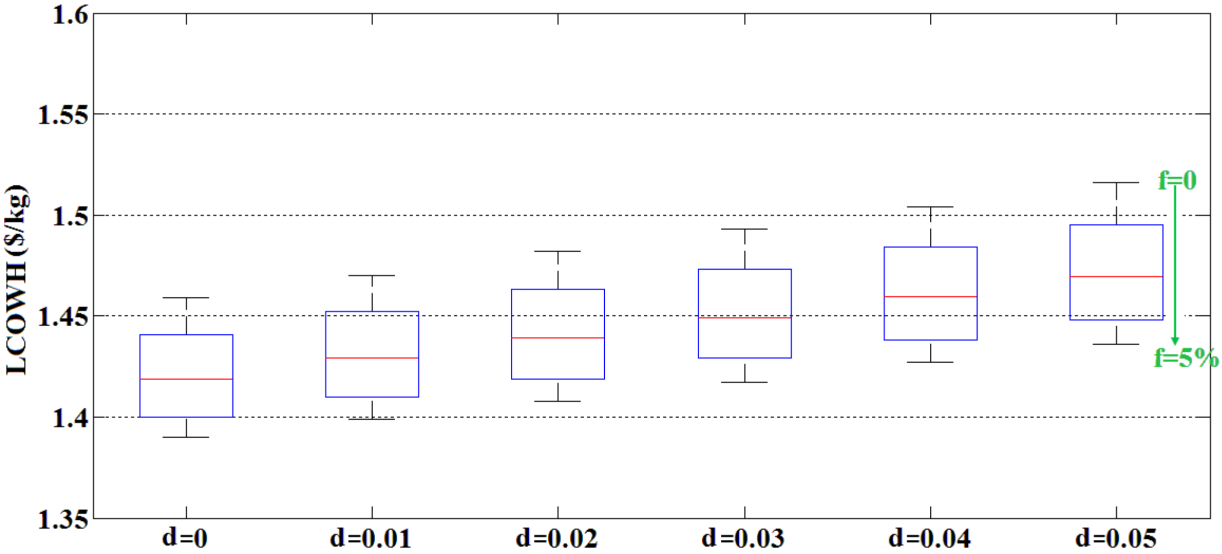
Year (i)	**Degradation rate of wind power plant (*d*)**					
	0.0	0.01	0.02	0.03	0.04	0.05
1	5.49	5.49	5.49	5.49	5.49	5.49
2	5.49	5.43	5.38	5.33	5.28	5.23
3	5.49	5.38	5.27	5.17	5.07	4.98
4	5.49	5.33	5.17	5.02	4.88	4.74
5	5.49	5.27	5.07	4.87	4.69	4.51
6	5.49	5.22	4.97	4.73	4.51	4.30
7	5.49	5.17	4.87	4.59	4.34	4.09
Sum	**38.43**	**37.29**	**36.22**	**35.2**	**34.26**	**33.34**

Having projected the yearly amount of hydrogen production, the values of LCOWH for all scenarios were estimated using Eq. (6). The results revealed LCOWH related to each individual amount of d would diminish if f rose. For instance, LCOWH was computed 1.435 $/kg when f=0, d=0 and replacing wind-generated electricity instead of fuel oil-based electricity, while it would reduce by 0.06 $/kg if f grew to 5%. Fig. 4 includes the candle charts of LCOWH under different scenarios in which the maximum LCOWH was 1.59 $/kg. From this, it can be inferred that selling a kg of hydrogen more than $1.59 could be deemed lucrative. However, there is no valid reference regarding the exact price of renewable hydrogen in Iran.



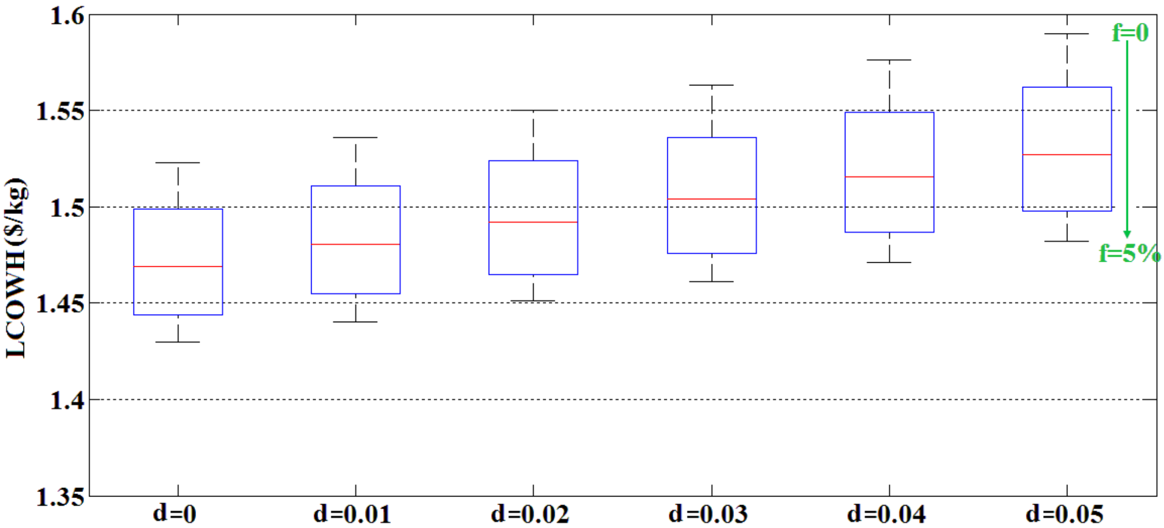
1.6
1.55
1.5
1.45
1.4
1.35
LCOWH ($/kg)
f=0
f=5%
d=0
d=0.01
d=0.02
d=0.03
d=0.04
d=0.05

(a)



1.6
1.55
1.5
1.45
1.4
1.35
LCOWH ($/kg)
f=0
f=5%
d=0
d=0.01
d=0.02
d=0.03
d=0.04
d=0.05

(b)



1.6
1.55
1.5
1.45
1.4
1.35
LCOWH ($/kg)
f=0
f=5%
d=0
d=0.01
d=0.02
d=0.03
d=0.04
d=0.05

(c)

Fig. 4. LCOWH under the scenarios of utilizing wind-based electric power as the replacement for (a) fuel oil-generated electricity, (b) natural gas-generated electricity, and the scenario of (c) not factoring the environmental cost in the calculations.

4.3. Payback Period of wind-based electricity and hydrogen generation

To precisely estimate the time of reaching to the break-even point or the exact time required to recover the initial costs, $EUAP$ depending on annual costs and incomes should be projected. It must be clarified that annual costs are equal to the difference between OM and ENV costs. Consequently, in the case of not considering environmental cost, they equate to just OM. Table 5 demonstrates annual incomes after selling wind electricity when considering different values of d. It should be noted that annual incomes are uniform when d=0.0 and annual costs are uniform as well when f=0. Whereas incomes as to the other four amounts of d and costs related to the other values of f are not uniform. Thus, it is essential to make them uniform to be able to calculate PBP. In other words, incomes are subject to decline as long as the performance of turbine degrades, and also costs reduce when f rises.

Table 5. Annual incomes by selling wind electricity at the price of 0.12 $/kWh and annual costs under different scenarios

i	Annual incomes by selling wind electricity ($)						Annual costs when using wind-generated electricity instead of fuel oil-based electricity ($)					
	d=0.0	d=0.01	d=0.02	d=0.03	d=0.04	d=0.05	f= 0	f= 1%	f= 2%	f= 3%	f= 4%	f= 5%
1	40,672.3	40,672.3	40,672.3	40,672.3	40,672.3	40,672.3	5,373.8	5,320.6	5,268.4	5,217.3	5,167.1	5,117.9
2	40,672.3	40,269.6	39,874.8	39,487.7	39,108.0	38,735.5	5,373.8	5,267.9	5,165.1	5,065.3	4,968.4	4,874.2
.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.	.	.
19	40,672.3	34,002.7	28,477.1	23,890.7	20,077.0	16,900.2	5,373.8	4,448.1	3,688.7	3,064.6	2,550.6	2,126.6
20	40,672.3	33,666.1	27,918.7	23,194.9	19,304.8	16,095.4	5,373.8	4,404.0	3,616.4	524.5	2,452.5	2,025.3

Table 5. (Continued)

year	Annual costs when using wind-generated electricity instead of natural gas-based electricity ($)					
	f= 0	f= 1%	f= 2%	f= 3%	f= 4%	f= 5%
1	6,321.1	6,258.5	6,197.2	6,137.0	6,078.0	6,020.1
2	6,321.1	6,196.6	6,075.7	5,958.3	5,844.2	5,733.5
3	6,321.1	6,135.2	5,956.5	5,784.7	5,619.5	5,460.4
.	.	.	.	.	.	.
.	.	.	.	.	.	.
.	.	.	.	.	.	.
19	6,321.1	5,232.3	4,339.0	3,604.9	3,000.3	2,501.5
20	6,321.1	5,180.5	4,253.9	3,499.9	2,884.9	2,382.4

Having obtained $EUAP$ for all scenarios, the values of PBP were projected and are illustrated in Table 6. The results proved that the more the amount of degradation rate, the more the PBP. For instance, in the case when f=0 and deploying wind-generated electricity as the replacement for fuel oil-based electricity, PBP would rise from 4.15 to 7.06 years if d increased from 0 to 0.05. For the case when d=0, as f became more, the PBP declined (PBP decreased from 4.26 to 2.61 years when f rose from 0 to 5% under the scenario of applying wind-generated electricity as the replacement for natural gas-based electricity.).

Table 6. PBP (yr) of the wind turbine utilization for electricity production in Lutak under different scenarios.

	Replacing wind-generated electricity instead of fuel oil-based electricity						Replacing wind-generated electricity instead of natural gas-based electricity						Not factoring the environmental cost in the calculations					
	d= 0	d= 0.01	d= 0.02	d= 0.03	d= 0.04	d= 0.05	d= 0	d= 0.01	d= 0.02	d= 0.03	d= 0.04	d= 0.05	d= 0	d= 0.01	d= 0.02	d= 0.03	d= 0.04	d= 0.05
f= 0	4.15	4.62	5.15	5.73	6.37	7.06	4.26	4.77	5.33	5.95	6.64	7.40	4.59	5.18	5.85	6.61	7.47	8.46
f= 1%	3.73	4.67	5.19	5.76	6.39	7.07	3.83	4.83	5.39	6.01	6.69	7.44	4.12	5.30	5.98	6.75	7.62	8.62
f= 2%	3.37	4.73	5.24	5.80	6.42	7.09	3.46	4.90	5.46	6.07	6.75	7.49	3.71	5.43	6.12	6.90	7.78	8.80
f= 3%	3.06	4.79	5.29	5.85	6.45	7.11	3.14	4.98	5.53	6.14	6.81	7.55	3.36	5.57	6.27	7.06	7.97	9.00
f= 4%	2.79	4.85	5.35	5.89	6.49	7.14	2.86	5.06	5.61	6.22	6.88	7.62	3.06	5.73	6.44	7.25	8.17	9.23
f= 5%	2.55	4.91	5.41	5.95	6.53	7.17	2.61	5.15	5.70	6.30	6.96	7.69	2.79	5.89	6.62	7.45	8.39	9.48

As to PBP of investing on wind-powered hydrogen generation plant, it has been postulated that the price of selling renewable hydrogen in Iran would be 8, 9 and 10 \$/kg and major initial cost would equal the aggregation of the wind turbine, the inverter and the electrolyzer. To this end, it has also been assumed that all electricity generated by the turbine would be used just to produce hydrogen via the electrolyzer during its 7 years lifespan.

The part of $\mathrm{C_{u,e}}\frac{\sum_1^t M_{\mathrm{H2}} \times \mathrm{E_e}}{t \times 8760 \times \mathrm{CF} \times \eta_\mathrm{e}}$ used in Eq. (6) and known as the cost of electrolyzer [64] refers to the summation of capital cost and present value of first operation and maintenance cost (this OM cost occurs when t =1). Hence, these must be separated for estimating PBP. Therefore it has been assumed that 94% of the whole cost of $\mathrm{C_{u,e}}\frac{\mathrm{M_{H2}} \times \mathrm{E_e}}{t \times 8760 \times \mathrm{CF} \times \eta_\mathrm{e}}$ would go for purchasing the electrolyzer at the present time (when t =0). The remainder (6% of $\mathrm{C_{u,e}}\frac{\mathrm{M_{H2}} \times \mathrm{E_e}}{t \times 8760 \times \mathrm{CF} \times \eta_\mathrm{e}}$) would be factored in the calculations as present worth of cost concerned with operating and maintaining the electrolyzer during the first year.

The calculations implied that some values of PBP would be more than the total lifetime of the electrolyzer, 7 years, (Table 7). It is also conspicuous that the more the price of selling hydrogen, the less the PBP.

Table 7. PBP (yr) of the wind turbine utilization for hydrogen production in Lutak under different scenarios.

		Replacing wind-generated electricity instead of fuel-oil-based electricity						Replacing wind-generated electricity instead of natural gas-based electricity						Not factoring the environmental cost in the calculations					
		d= 0	d= 0.01	d= 0.02	d= 0.03	d= 0.04	d= 0.05	d= 0	d= 0.01	d= 0.02	d= 0.03	d= 0.04	d= 0.05	d= 0	d= 0.01	d= 0.02	d= 0.03	d= 0.04	d= 0.05
PBP (yr) when the price of hydrogen would be \$8	f= 0	5.15	5.30	5.46	5.62	5.78	5.96	5.29	5.45	5.62	5.79	5.97	6.15	5.69	5.88	6.07	6.28	6.49	6.71
	f= 1%	5.14	5.55	5.71	5.87	6.04	6.22	5.28	5.71	5.88	6.05	6.24	6.43	5.66	6.17	6.37	6.58	6.80	7.03
	f= 2%	5.12	5.80	5.96	6.13	6.31	6.50	5.26	5.97	6.14	6.33	6.52	6.72	5.63	6.46	6.67	6.89	7.12	7.36
	f= 3%	5.11	6.06	6.23	6.40	6.58	6.77	5.24	6.24	6.42	6.61	6.81	7.01	5.61	6.77	6.99	7.22	7.45	7.70
	f= 4%	5.10	6.32	6.50	6.68	6.87	7.06	5.22	6.52	6.70	6.90	7.10	7.31	5.58	7.09	7.31	7.55	7.80	8.05
	f= 5%	5.08	6.59	6.77	6.96	7.15	7.35	5.21	6.80	7.00	7.20	7.40	7.62	5.55	7.41	7.65	7.89	8.15	8.41
PBP (yr) when the price of hydrogen would be \$9	f= 0	4.47	4.60	4.73	4.87	5.01	5.15	4.58	4.71	4.85	4.99	5.14	5.30	4.87	5.03	5.19	5.35	5.53	5.71
	f= 1%	4.46	4.81	4.94	5.08	5.23	5.38	4.56	4.93	5.07	5.22	5.37	5.53	4.85	5.27	5.43	5.60	5.78	5.97
	f= 2%	4.45	5.02	5.16	5.30	5.45	5.61	4.55	5.15	5.30	5.45	5.61	5.77	4.83	5.51	5.68	5.86	6.05	6.25
	f= 3%	4.44	5.24	5.38	5.53	5.69	5.85	4.54	5.38	5.53	5.69	5.85	6.02	4.81	5.77	5.94	6.13	6.32	6.52
	f= 4%	4.43	5.47	5.61	5.76	5.92	6.09	4.52	5.61	5.77	5.93	6.10	6.27	4.79	6.03	6.21	6.40	6.60	6.81
	f= 5%	4.42	5.70	5.85	6.00	6.17	6.34	4.51	5.85	6.01	6.18	6.35	6.53	4.77	6.30	6.49	6.68	6.89	7.11
PBP (yr) when the price of hydrogen	f= 0	3.95	4.06	4.17	4.29	4.41	4.54	4.03	4.15	4.27	4.39	4.52	4.65	4.26	4.39	4.52	4.67	4.81	4.97
	f= 1%	3.94	4.24	4.36	4.48	4.61	4.74	4.02	4.33	4.46	4.58	4.72	4.85	4.24	4.59	4.73	4.88	5.03	5.19
	f= 2%	3.93	4.43	4.55	4.67	4.80	4.94	4.01	4.53	4.65	4.78	4.92	5.06	4.23	4.80	4.95	5.10	5.26	5.42
	f= 3%	3.92	4.62	4.74	4.87	5.00	5.14	4.00	4.72	4.85	4.99	5.13	5.27	4.21	5.02	5.17	5.33	5.49	5.66
	f= 4%	3.92	4.81	4.94	5.07	5.21	5.35	3.99	4.93	5.06	5.20	5.34	5.49	4.20	5.24	5.40	5.56	5.73	5.90

f= 5%	3.91	5.01	5.14	5.28	5.42	5.56	3.98	5.13	5.27	5.41	5.56	5.72	4.18	5.47	5.63	5.80	5.97	6.15

4.4. ROR of wind-generated electricity and hydrogen

Another significant economic factor aiding investors in making the most plausible decision is ROR. Since risks are inherent in any project, so ROR should be more than MARR. To estimate ROR, NPW is equated to zero and this can only happen with a unique amount of ROR. In this regard, all costs and incomes are put into year 0. Then the following relation must be solved by trying different amounts of ROR to obtain the unique one.

$CI +$ Present worth of REP+ Present worth of $OM -$ Present worth of ENV= Present worth of Incomes earned after selling wind electricity (14)

The above-mentioned relation leads to the following formulation:

$$CI + \frac{REP}{(1+ROR)^{8}} + \frac{REP}{(1+ROR)^{16}} + OM\frac{(1+ROR)^{20}-1}{ROR(1+ROR)^{20}} - ENV\frac{(1+ROR)^{20}-1}{ROR(1+ROR)^{20}} = \begin{cases} A_{I1} \times \left[\frac{1-(1-d)^{20} \times (1+ROR)^{-20}}{d+ROR}\right], & d \neq 0 \\ A_{I1} \times \frac{(1+ROR)^{20}-1}{ROR(1+ROR)^{20}}, & d = 0 \end{cases} \quad (15)$$

The results indicated that the least amount of ROR among all scenarios would be 14.149% when not considering environmental costs and d =0.05. This value of ROR means if MARR is less than 14.149%, then the project is sensible. Table 8 illustrates the values of ROR computed under the different scenarios.

Table 8. ROR of the wind turbine utilization for electricity production in Lutak under the different scenarios.

Scenarios	ROR (%)					
	d= 0.0	d= 0.01	d= 0.02	d= 0.03	d= 0.04	d= 0.05
Replacing wind-generated electricity instead of fuel-oil-based electricity	23.542	22.378	21.197	19.995	18.771	17.518
Replacing wind-generated electricity instead of natural gas-based electricity	22.859	21.661	20.442	19.198	17.924	16.614
Not factoring the environmental cost in the calculations	21.071	19.777	18.446	17.073	15.645	14.149

To obtain ROR concerning wind-powered hydrogen production project, the amount of ROR in the lifetime of the electrolyzer should be anticipated. In this regard, after 7 years the wind turbine can be sold as its lifetime will not be over and can operate for 13 more years. To this end, at the end of the electrolyzer's lifespan, the value of turbine would be deemed as salvage value and should be transferred into year 0. Also, the value of the turbine after 7 years would be postulated 65% of its capital cost. This condition comes from the fact that the turbine will have passed its 7 years and it will have only 13 years to operate, which means the ratio of 13 to 20 will remain. Moreover, there is no need to replace any main apparatus during the 7 years, which means REP cost would be zero. Eventually to estimate ROR, the following relation must be solved.

Capital investment of purchasing the wind turbine and inverter + the price of the electrolyzer+ Present worth of operation and maintenance of the turbine and electrolyzer− Present worth of ENV −Present worth of salvage value of the turbine= Present worth of incomes earned after selling hydrogen (16)

here, this leads to Eq. (17).

$$CI + 0.94\left(C_{u,e}\frac{M_{H2} \times E_e}{t \times 8760 \times CF \times \eta_e}\right) + 0.06\left(C_{u,e}\frac{M_{H2} \times E_e}{t \times 8760 \times CF \times \eta_e}\right)\frac{(1+ROR)^7-1}{ROR(1+ROR)^7} + OM\frac{(1+ROR)^7-1}{ROR(1+ROR)^7} - ENV\frac{(1+ROR)^7-1}{ROR(1+ROR)^7} - 0.65\frac{Price\ of\ turbine}{(1+ROR)^7} = \begin{cases} A_{I1} \times \left[\dfrac{1-(1-d)^7 \times (1+ROR)^{-7}}{d+ROR}\right], & d \neq 0 \\ A_{I1} \times \dfrac{(1+ROR)^7-1}{ROR(1+ROR)^7}, & d = 0 \end{cases} \tag{17}$$

Table 9 shows the calculated values of ROR considering the likely prices of renewable hydrogen under different scenarios.

Table 9. ROR of the wind turbine utilization for hydrogen production in Lutak under the different scenarios.

Scenarios	The price of hydrogen ($/kg)	ROR (%)					
		d= 0.0	d= 0.01	d= 0.02	d= 0.03	d= 0.04	d= 0.05
Replacing wind-generated electricity instead of fuel oil-based electricity	8	14.760	14.256	13.748	13.237	12.723	12.208
	9	18.339	17.814	17.284	16.749	16.21	15.668
	10	21.550	21.004	20.450	19.891	19.327	18.758
Replacing wind-generated electricity instead of natural gas-based electricity	8	14.163	13.649	13.131	12.610	12.086	11.560
	9	17.781	17.246	16.706	16.161	15.612	15.060
	10	20.971	20.415	19.852	19.282	18.707	18.128
Not factoring the environmental cost in the calculations	8	12.605	12.064	11.518	10.970	10.419	9.866
	9	16.324	15.763	15.197	14.626	14.050	13.472
	10	19.463	18.879	18.288	17.690	17.087	16.480

5. Discussion

Since hydrogen has been regarded as the most indispensable solution for the decarbonization of transport sector, studying hydrogen production technologies seems imperative; This can also result in achieving the purpose of greenhouse gas reduction which is the prime target of the Paris Agreement [73,74]. As of today, approximately 96% of hydrogen generated per annum has stemmed from the process of reforming fossil fuel feedstocks [75] and this proportion has bred major irreversible issues to the environment [76]. The remainder has been produced via the water electrolysis process which embody significant benefits [77]. Nevertheless, the latter means using water as the source of hydrogen should be scaled up and more importantly entail renewables to accomplish the aforementioned aims of the Paris Agreement in years to come. Hence, the provision of hydrogen production cost is of prominent value for ascertaining whether or not it is cost competitive.

To anticipate the most likely cost which would be imposed by renewable hydrogen, the main phases of supply chain of this process namely I) production, II) storage, III) transportation, IV) safety, and V) delivery should constitute [78]. However, renewable hydrogen generation which is the first phase of this chain plays the determinant role in predicting the average cost of hydrogen. For this reason, in the proposed model here, the fundamental phase of the hydrogen supply chain which is the production step was assumed for projecting the preliminary cost of hydrogen generation. Worth mentioning that other related costs concerned with hydrogen storage, transportation, safety and delivery can then be added to the model.

To discuss the cost of storage phase as the second phase, it should be noted that the development of gaseous hydrogen compression and storage technologies and also improvements in their efficiencies have implied this phase in the hydrogen supply chain may add rough 0.3 $/kg to the cost of the first phase. However, liquefication of hydrogen for storage is expected to add almost 1.59-1.94 $/kg to the first phase. Other expenses relevant to the phases of transportation, safety and delivery are highly dependent upon the distance between the place of hydrogen production plant and the point of use [79]. All in all, this study sought to predict the cost of wind-based hydrogen generation as the very first phase of the hydrogen supply chain.

Owing to the very high suitability of the under-study area in Iran regarding wind energy potential, the price of wind-based electricity was calculated relatively low. These predicted low amounts of LCOWE breed the fact that the price of wind-based hydrogen generation in the future would be low as well, since LCOWH is exceedingly contingent upon LCOWE. Additionally, a prospective price for the electrolyzer, 384 $/kW, was assumed because the study sought to establish a futuristic blueprint for renewable hydrogen production in Iran. By virtue of these, the computed values of LCOWH might seem low for the current time, yet reachable in the future.

6. Conclusion

This study particularly aimed at economic assessment of wind-powered electricity and hydrogen generation scheme. In this regard, the city of Lutak enjoying a great deal of wind was examined using arithmetical methods of evaluating projects. So as to acquire practical results, 5 different reduction factors and 5 rates for the future value of money were considered as the possible scenarios. The main results are as follows:

- In the scenario when d=0, f=0 and replacing wind-generated electricity instead of fuel oil-based electricity, LCOWE would be 0.0393 $/kWh. This value rose to 0.0421 and 0.0494 $/kWh for the cases of replacing wind-generated electricity instead of natural gas-based electricity and not factoring the environmental cost in the calculations, respectively.

- Even though the largest amount of LCOWE was obtained 0.0755 $/kWh (it would occur when d=0.05, f=0 and not taking the environmental cost into account), it is by far less than the price of buying renewable electricity in Iran by the government which is 0.12 $/kWh.
- Since LCOWH is directly contingent upon LCOWE, therefore it was computed under the 3 scenarios of I) replacing wind-generated electricity instead of fuel oil-based electricity, II) replacing wind-generated electricity instead of natural gas-based electricity, and III) not factoring the environmental cost in the calculations. When d=0 and f=0, the LCOWH related to the aforementioned schemes respectively were 1.435, 1.459 and 1.523 $/kg.
- In the worst-case scenario when d=0.05, f=5% and not factoring the environmental cost in the calculations, PBP of generating wind electricity was estimated 9.46 years. This implies that all the capital investment would be recovered when midyear of the 10th year has passed during the 20 years lifetime of the project. With regard to the hydrogen production system with lifespan of 7 years, PBP related to the worst-case scenario would be 8.41, 7.11 and 6.15 years if a kg of hydrogen were sold 8, 9 and 10 $, respectively.
- ROR of investing on electricity production ranged between 14.149% and 23.542% for all the scenarios. Moreover, this range concerning ROR of investing on hydrogen production was from 9.866% to 21.55%.

As the results of the economic analysis revealed that electricity generation using wind energy in the aforementioned area of Iran would be cost effective, then authorities, policy-makers and private investors can embark on wind-based electricity production knowing that they would reach profitability much sooner than the end of the project lifespan. On the other side, renewable hydrogen production using wind energy consists in the situation of economic in Iran in the years to come. However, with the aid of the government and supporting plans, it could be lucrative.

7. Future research direction

The following suggestions can contribute to the field:

- Economic assessment of providing electricity for the hydrogen generation system via hybrid power plants.
- Evaluating the policies supporting and/or confronting the scheme of renewable-based hydrogen production in Iran in order to attain more applicable knowledge about the matter.
- Optimal sizing of the components under technical constraints and practical issues for the economic dispatching using bio-inspired algorithms which can be found in Refs [80-86].

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