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A Technical, Economic and Environmental Evaluation Study of Utilising Fixed, Single and Dual-Axis Solar Photovoltaic Systems in Boubyan and Failaka Islands in Kuwait

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Abstract: Implementing renewable energy technologies, such as solar energy, is an important step towards meeting the increasing demand for electricity in Kuwait. This would be a very helpful way of minimising the negative environmental impacts of conventional power plants. This study reports on the results of a comprehensive technical, environmental and economic evaluation of the use of a grid-connected solar photovoltaic system to generate electricity at Boubyan and Failaka islands in Kuwait. The study also evaluated the effects of using single and dual-axis tracking systems. The results showed that the obtained performance parameters are excellent and fall within the standard reference ranges of the solar photovoltaic systems. The use of tracking systems is highly beneficial and energy production increased by approximately 26% and 31% respectively as a result of implementing single and dual-axis tracking systems. The computed levelized cost of electricity (LCOE) results were \$0.076 /kWh, \$0.064 /kWh and \$0.066 /kWh respectively for fixed, single and dual-axis tracking systems. These obtained values are less than the LCOE of the conventional Kuwaiti power plants, therefore making the proposed systems economically feasible. In addition, the results revealed that single-axis tracking systems are the best option. Life cycle assessment (LCA) analysis shows that the annual energy payback time (EPBT) results obtained in this paper were 1.84, 1.46 and 1.41 years respectively. The average total CO_2 emission rate was 49.58 CO_2, eq/kWh, 39.25 CO_2, eq/kWh and 37.84 CO_2, eq/kWh for single and dual-axis tracking systems respectively.

Keywords: Performance Parameters, Tracking Systems, Energy Payback Time, Life Cycle Assessment

Introduction

The use of renewable energy resources as a strategic alternative to fossil fuels has increased significantly. This is due to political, economic and environmental issues such as high oil prices and environmental pollution. Renewable energy technologies play an important role in reducing the negative impacts of producing electricity by burning fossil fuels such as oil and natural gas in conventional power plants.

The state of Kuwait is keen to increase the use of clean energy resources, such as solar and wind power, to meet its growing demand for electricity. This is clearly set out in the Kuwaiti government’s plan to meet 15% of its total electricity needs from renewable sources by 2030 (Al-Rashidi, 2017). The geographical location of Kuwait places it in a favourable position to utilise wind and solar resources (Al-Maamary *et al*., 2017; El-Katiri, 2014; Al-Rashidi, 2017).

Researchers who have investigated several potential sites for solar photovoltaic energy in Kuwait (Al-Enezi *et al*., 2011; Al-Rashidi, 2019, 2017; Al Otaibi and Al Jandal, 2011; Hajiah *et al*., 2012) have found that there is considerable potential for solar energy.

From an economic perspective, the Levelized Cost Of Electricity (LCOE) method is the most widely used tool to economically evaluate the feasibility of solar energy systems (Branker *et al*., 2011; Hernández-Moro and

Martínez-Duart, 2013; IRENA, 2012; Kang and Rohatgi, 2016). This approach provides important information that will accordingly help to judge the feasibility of the proposed energy systems by comparing between them in terms of the price of produced energy per power unit. In this study, a comparison analysis was conducted between the proposed PV systems at two different sites and Kuwaiti conventional power plants in terms of electricity generation price per kWh.

The environmental evaluation part of this study is based on published research in the renewable energy field showing that estimating the amount of greenhouse gases (GHGs) that would be avoided by implementing renewable technology systems and life-cycle assessment (LCA) are the most commonly used methods used to environmentally evaluate the solar photovoltaic systems (Alsema, *et al*., 2006; Alsema, *et al*., 2005; Fthenakis and Kim, 2011; Hong *et al*., 2016; Kim *et al*., 2014; Stoppato, 2008; Al-Rashidi, 2017).

The main objective of this study was to investigate a 1MW grid-connected photovoltaic system to generate electricity at two sites in Kuwait. The scope of this study includes technical, economic and environmental parameters in order to provide a clear assessment for the use of solar photovoltaic energy in Kuwait.

Methods

Selected Sites and Metrological Data

The Failaka and Bubiyan islands are the proposed sites for investigation in this study. They are 48 km^2 and 683km^2 in area respectively; Fig. 1 shows their locations on the Kuwaiti solar map.

Long-term satellite meteorological data has been collected from the Kuwait Institute for Scientific Research (KISR, 2014). The main collected data are solar irradiance, temperature and wind speed.

Table 1: Design array configuration and PV module specifications (CS, 2018; SMA, 2018)

Number of modules	4000
Array configuration	200 strings 20 modules in series
P_{max}	250 W_p
V_{mpp}	29.73 V
I_{mpp}	8.4 A
V_{oc}	37.6 V
I_{sc}	8.91 A
Efficiency	15.23%
Inverter model	SunnyCentral 500CP XT
Operating voltage	430-850 V

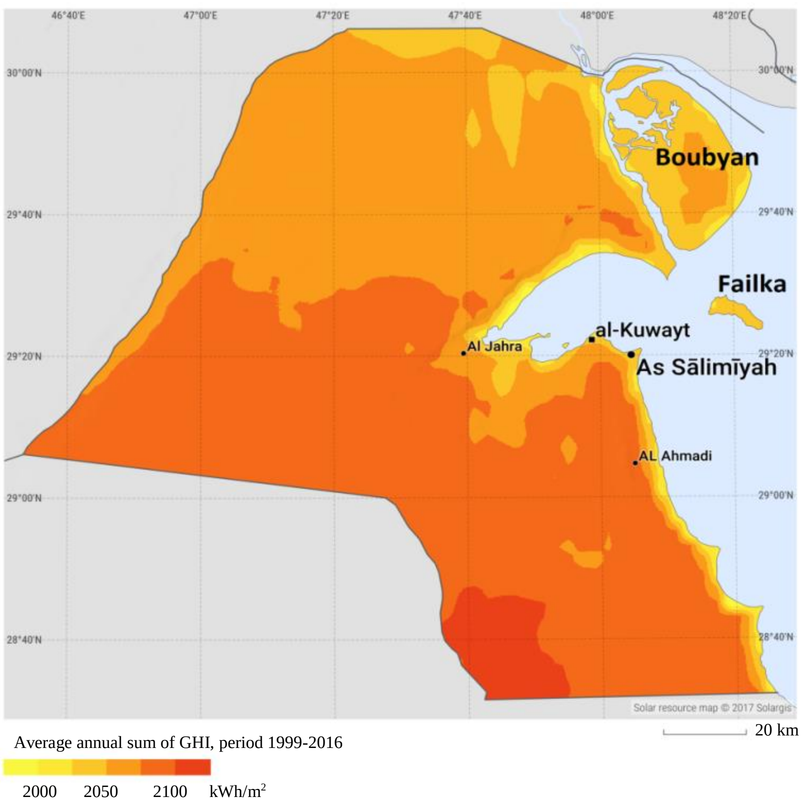

Fig. 1: Site locations on the Kuwait solar map (KISR, 2014; AL-Rashidi, 2019)

The proposed PV System

A 1000KW (1MW) capacity grid connected solar photovoltaic system was investigated at the proposed sites. The selection of the type of solar modules and inverters takes into account the climate of the country, as the very hot summer temperatures will definitely affect the efficiency and performance of the proposed system. Therefore, si-poly model (S250P60 professional) PV modules and a sunny central 500CPXT inverter were selected. The types of modules and inverters selected offer a high level of performance and greater reliability in hot regions such as Kuwait (Rashed, 2014; Al-Rashidi, 2017). Table 1 lists the design array configuration of the proposed PV system.

Technical Performance

After obtaining the results from simulations using the PVsyst software of the proposed PV systems, the performance parameters (final yield (YF), reference yield (YR), performance ratio (PR) and capacity factor (CF)) of the proposed PV systems at the selected sites were calculated based on the International Energy Agency (IEA) criteria (Marion *et al*., 2005).

The following four equations were used to calculate the performance parameters:

$$YF = E_{AC} / P_{PV,\ rated} \quad (1)$$

$$YR = (H_t)\ (kWh/m^2) / G\ (1\ kW/m^2) \quad (2)$$

$$PR = YF / YR \quad (3)$$

$$CF = E_{AC} / (P_{PV,\ rated}\ x\ 8760) \quad (4)$$

Economic Evaluation

In order to compare electricity generation from the conventional power plants in Kuwait and the proposed PV systems, economic evaluation analysis was conducted based on the levelized cost of electricity (LCOE) approach. The installation cost, operation maintenance costs (OM) and capital recovery factor (CRF) are the main inputs used to calculate LCOE values. Table 2 lists the used input parameters used in the analysis. In this study, the LCOE was determined using the following equations (Smestad, 2008; Al-Rashidi, 2017):

$$\text{LCOE} = \frac{Annual\ cost + 0M}{Annual\ Output} \quad (5)$$

$$\text{Annual Cost} = (Installation\,Cost \times CRF) + 0M \quad (6)$$

CRF is the capital recovery factor and is given in the following equation:

$$\text{CRF} = \frac{i \times (1+i)^n}{(1+i)n - 1} \quad (7)$$

$$\text{Installation Cost} = Capital\,Cost \times Station\,Capacity \quad (8)$$

Recently, a significant decrease in the installation cost from $5 /kW has been observed; it is expected to be approximately $1/kW in 2020 (Nemet *et al*., 2017). This will definitely be a positive indication for the future implementation of solar photovoltaic systems (Nemet *et al*., 2017; Al-Rashidi, 2017). The installation costs for the proposed PV systems are shown in Table 3 (Chung *et al*., 2015; Kang and Rohatgi, 2016; NREL, 2016; Al-Rashidi, 2017). The OM cost was set to 3% of the investment cost per year (Ramadhan and Naseeb, 2011; Zweibel, 1999; Al-Rashidi, 2017).

Table 2: Input Parameters (Al-Rashidi, 2017)

Parameter	Value	Unit
Capacity	1	MW
Installation Cost		
Fixed tracking	1.77	
Single-axis tracking	1.91	$/W
Dual-axis tracking	2.05	
OM	3% of installation cost per year	$
Interest Rate (i)	5	%
Project Life (n)	25	year

Table 3: Assumed installation rates (Al-Rashidi, 2017)

Scenario (No.)	Fixed ($/W)	Single-axis ($/W)	Dual-axis ($/W)
1	1.0	1.08	1.16
2	1.5	1.62	1.74
3	2.0	2.16	2.32
4	2.5	2.70	2.90
5	3.0	3.24	3.47

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Sensitivity Analysis

A sensitivity analysis was conducted to cover large numbers of changeable parameters, such as installation costs, which directly affect the obtained LCOE values. In this analysis, a range of different installation costs was assumed, varying from 1 to 3 \$/kW (Table 3).

For the interest rate, five scenarios, ranging from 0 to 10%, were set for the analysis. The assumed lifetime values for the sensitivity analysis were from 20 and 40 years.

Life Cycle Assessment (LCA)

One of the most important environmental issues is to consider the amount of energy required to produce solar photovoltaic elements such as solar modules. This would create more accurate assessments when investigating the negative impacts of photovoltaic solar energy on the environment in terms of global warming. The LCA is the best approach that can be used in this regard, as it includes all the stages that all PV system elements pass through, from the acquisition of raw materials through to the recycling stage.

It is estimated that between 2699 and 5150 MJ/m^2 is required for the production of multi-Si modules (Wong *et al*., 2016). For the analysis in this study, the data used to conduct the LCA are listed in Table 4.

Energy Payback Time (EPBT) and the CO_2 emission rate were calculated using equations 9 and 10 respectively (Fthenakis *et al*., 2011; Basu, 2011):

$$EPBT = total\ energy / annual\ power \quad (9)$$

$$\begin{aligned} &CO_2 emission\ rate\left[g - CO_2, eq / kWh\right] = \\ &total\ CO_2 emission\ during\ lifecycle\left[g\ CO_2\right] / \\ &annual\ power\ generation\ x\ lifetime \end{aligned} \quad (10)$$

Environmental Benefits

The environmental benefits of using PV systems are represented here in terms of the amount of greenhouse gas (GHG) emissions that would be avoided as a result of implementing the proposed PV systems instead of conventional power plants in Kuwait. This would be obtained by calculating the equivalent amount of GHG emissions resulting from conventional power plants.

Results and Discussion

The performance parameters of the proposed sites were determined on an annual basis. The detailed results of the performance parameters study are shown in Table 5. It can be seen that the average amount of energy produced was 1693 MWh in terms of the fixed tracking systems, it was 2140 MWh and 2225.65 MWh for the single and dual-axis tracking systems, respectively.

The average performance ratio for the fixed tracking systems, the single-axis and dual-axis tracking systems was 77.9%, 77.7% and 77.65% respectively. These obtained values are within the standard reference of the PV systems (Aste and Del Pero, 2010). Table 6 lists the performance ratio values for different countries.

The effect of using single and dual-axis tracking systems is significant, which can be seen in the annual produced energy, which increased by 26.4% and 31.5% for the single and dual-axis tracking systems respectively.

The average capacity factors were 19.33% for fixed tracking systems and 24.43% and 25.05% for single and dual-axis tracking systems, respectively; these obtained results are within the standard typical capacity factor reference (Hajiah *et al*., 2012). Table 5 clearly shows that the obtained yield factor results are excellent compared with other countries in the solar energy field (Table 7).

Table 4: Input data for LCA analysis

Energy	Value	Reference
Single-axis tracker	4 kWh/kW	(Perpinan *et al*., 2008)
Dual-axis tracker	12 kWh/kW	(Al-Rashidi, 2017)
Total energy		
Fixed tracking	1.69 kWh/kW	
Single-axis tracking	2.14 kWh/kW	
Dual-axis tracking	2.23 kWh/kW	

Table 5: Performance parameters (Al-Rashidi, 2019)

Site	Annual production (MWh/year)	Yield factor (kWh/kW/year)	Yield reference	Performance ratio (%)	Capacity factor (%)
Bubiyan Island					
Fixed	1713	1713	2197.9	77.9	19.55
Single-axis Tracking System	2171	2171	2794.7	77.7	24.78
Dual-axis Tracking System	2260	2260	2910.1	77.7	25.80
Failaka Island					
Fixed	1673	1673	2147.9	77.9	19.10
Single-axis Tracking System	2109	2109	2716	77.7	24.08
Dual-axis Tracking System	2191.3	2191.3	2823.4	77.6	25.01

Table 6: Selected different performance values for multi-Si PV from literature (Al-Rashidi, 2017)

Location	Mounting type	Performance ratio (%)
Western Europe	Ground mounted	75
North Africa	Rooftop	85
Japan	Rooftop	77
Southern Europe	Ground mounted	87
Europe	Rooftop	75
Turkey	Ground mounted	83
Gobi desert	Rooftop	75
Southern Europe	Rooftop	75
China	LS-PV	75

Table 7: Yield factors of different countries (data taken from Hajiah *et al*., 2012 Al-Rashidi, 2017)

Country	Yield factor (YF) (kWh/kW/year)
Germany	400-1300
Japan	470-1230
Netherlands	400-900
Italy	450-1250
Switzerland	450-1400

Table 8: LCOE results (Al-Rashidi, 2019)

Site	LCOE ($/kWh)
Bubiyan Island	
Fixed	0.075
Single-axis Tracking System	0.063
Dual-axis Tracking System	0.065
Failaka Island	
Fixed	0.076
Single-axis Tracking System	0.065
Dual-axis Tracking System	0.067

Table 9: Total CO_2 emission rate and EPBT

Site	EPBT (Year)	GHG (CO_2g/kWh)
Boubian Island		
Fixed tracking system	1.82	48.96
Single-axis Tracking System	1.44	38.68
Dual-axis Tracking System	1.39	37.25
Failaka Island		
Fixed tracking system	1.86	50.13
Single-axis Tracking System	1.48	39.82
Dual-axis Tracking System	1.43	38.42

Table 10: The CO_2, SO_2 and NO_x emissions

Site	CO_2 (tons)	SO_2 (tons)	NO_x (tons)
Boubian Island			
Fixed tracking system	1028	1.71	0.26
Single-axis tracking system	1303	2.17	0.33
Dual-axis tracking system	1356	2.26	0.34
Failaka Island			
Fixed tracking system	1004	1.67	0.25
Single-axis tracking system	1265	2.11	0.32
Dual-axis tracking system	1315	2.19	0.33

The detailed LCOEs results are listed in Table 8. The average obtained results were 0.076 $/kWh for the fixed tracking systems and 0.063 and 0.065 $/kWh for the single and dual-axis tracking systems respectively. These values decreased by 15.23% and 12.58% as a result of using single and dual-axis tracking systems respectively.

In order to compare the LCOE values of the proposed PV system in this study with electricity production in Kuwaiti conventional power plants, the LCOE value for the Kuwaiti conventional power plants was set to 0.12 $/kWh (Ramadhan and Naseeb, 2011). Accordingly, it is apparent that all LCOE values are lower than 0.12 $/kWh; the proposed PV systems are therefore economically feasible. In addition, Table 8 reveals that the tracking systems have obvious impacts on the obtained LCOEs as they decreased significantly as a result of implementing solar tracking systems, specifically single-axis tracking systems.

Figure 2 illustrates LCOE versus other scenarios. The computed LCOE values ranged from 0.043 and 0.128 $/kWh for the fixed tracking systems and between 0.037 and 0.11 $/kWh, 0.038 and 0.113 $/kWh for the single and dual-axis tracking systems respectively. This means that the proposed PV systems are economically feasible for all scenarios, except scenario 5, as its calculated LCOE is more than 0.12 $/kWh.

The effect of installation costs on the LCOE values is directly proportional to the LCOE values (Fig. 3). Figure 4 introduces the LCOE values with different interest rates; the computed LCOE values varied between 0.044 and 0.117 $/kWh for the fixed tracking systems and between 0.037 and 0.100 $/kWh and 0.038 to 0.102 $/kWh for the single and dual-axis tracking systems, respectively.

Figure 5 displays the obtained LCOE values for different lifetime periods. According to recently conducted research and the fact that this technology has still not reached maturity, the results obtained in this analysis are excellent.

Table 9 lists the obtained CO_2 emission rates and EPBT for the proposed PV systems at Boubyan and Failaka islands. The computed average EPBT is 1.84 years for the fixed tracking system where the average EPBT for the single and dual-axis tracking system is 1.46 years and 1.41 years respectively. The average CO_2 emission rates are 49.58 g-CO_2,eq/kWh for the fixed tracking systems and 39.25 g-CO_2,eq/kWh and 37.84 g-CO_2,eq/kWh for the single-axis and dual-axis tracking systems respectively.

The effects of GHGs on the environment were investigated. Table 10 shows the CO_2, SO_2 and NOx emissions that would be avoided as a result of implementing the proposed PV systems. An average amount of 1,116 tons of CO_2, 1.69 tons of SO_2, and 0.225 tons of NOx would be avoided by using the fixed tracking systems.

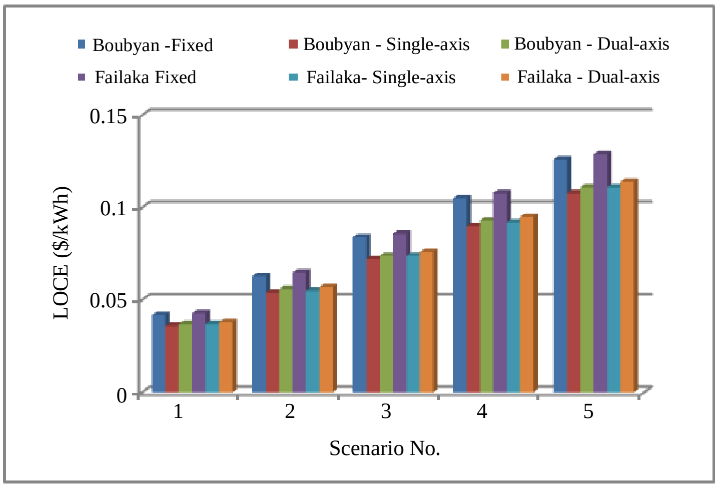

Fig. 2: LCOEs for different scenarios with different tracking systems

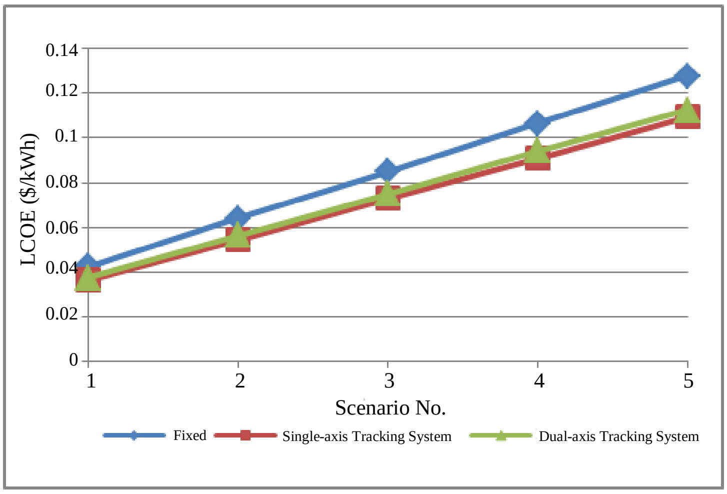

Fig. 3: Average LCOEs for different scenarios (Al-Rashidi, 2019)

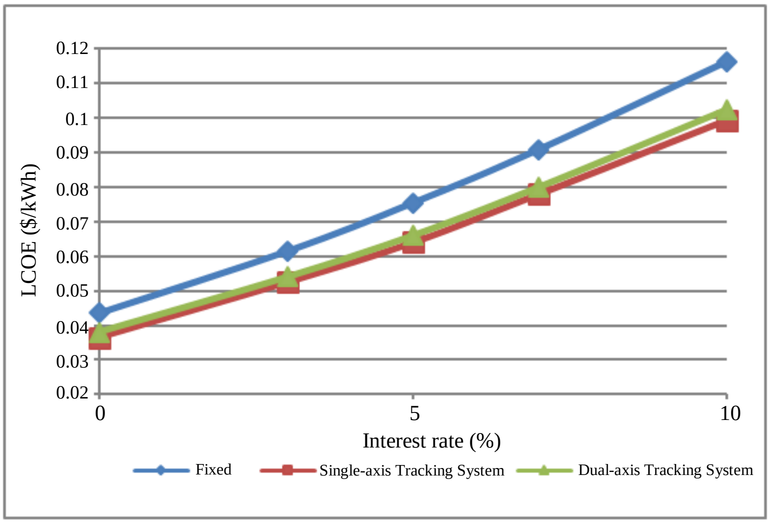

Fig. 4: Average LCOEs for different interest rates (Al-Rashidi, 2019)

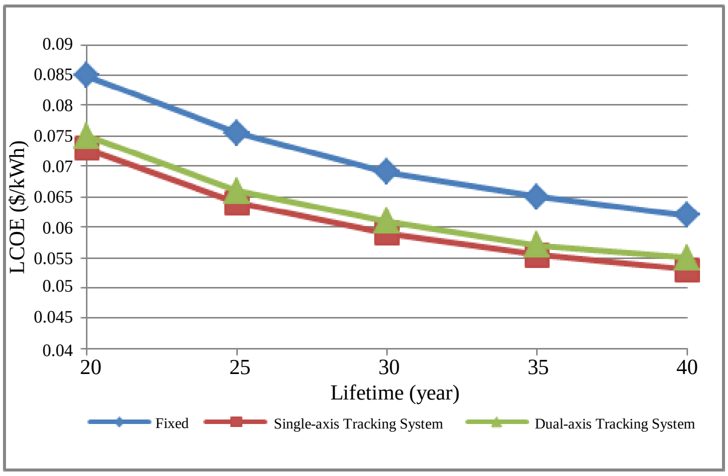

Fig. 5: Average LCOEs for different lifetime periods (Al-Rashidi, 2019)

Conclusion

The main performance parameters of a 1MW grid-connected PV system were investigated at Boubyan and Failaka islands in Kuwait, along with an assessment of the effect of utilising single and dual-axis solar tracking systems. The amount of electricity produced varied between 1673 and 1713 MWh for the fixed tracking systems and from 2109 and 2171 MWh and 2191.3 and 2260 MWh for the single and dual-axis tracking systems respectively. The amount of energy produced increased by 26% and 31% due to the use of single and dual-axis tracking systems respectively.

The average computed LCOE values were $0.076 /kWh for the fixed solar tracking systems and $0.064 /kWh, $0.066 /kWh for the single and dual-axis tracking systems respectively. The results of LCOE analysis revealed that the proposed PV system is economically feasible and the single-axis tracking system is the best option. Optimistic results can be drawn from the sensitivity analysis for the future of implementation of the solar photovoltaic energy in Kuwait.

The energy payback time and the average total CO_2 emission rate values computed in this research are encouraging and stand to make a positive contribution in terms of achieving environmental targets. In addition, the emission of large amounts of greenhouse gases would be avoided.

References

Al Otaibi, A. and S. Al Jandal, 2011. Solar photovoltaic power in the state of Kuwait. Proceedings of the 37th IEEE Photovoltaic Specialists Conference, Jun. 19-24, IEEE Xplore press, Seattle, WA, USA. DOI: 10.1109/PVSC.2011.6186598.

Al-Enezi, F.Q., J.K. Sykulski and N.A. Ahmed, 2011. Visibility and potential of solar energy on horizontal surface at Kuwait area. Energy Proc., 12: 862-872. DOI: 10.1016/j.egypro.2011.10.114Get

Al-maamary, H.M.S., H.A. Kazem and M.T. Chaichan, 2017. Renewable energy and GCC States energy challenges in the 21st century: A review. Int. J. Comput. Applied Sci., 2: 11-18. DOI: 10.24842/1611/0018

Al-Rashidi, A., 2017. Investigating the feasibility of solar photovoltaic systems in Kuwait. Loughborough University.

Al-Rashidi, A., 2019. Feasibility Study of Utilising 1 mw Grid-Connected Solar Photovoltaic System in Boubyan and Failaka Islands. 1st Edn., Oxford, United Kingdom, ISBN: 978-1-912532-05-6.

Alsema, E. and D. Wild-Scholten, 2006. Environmental impacts of crystalline silicon photovoltaic module production. Mater. Res. Soc. Symp. Proc., 895: 1-160. DOI: 10.1557/PROC-0895-G03-05

Alsema, E.A., M.J. De Wild-Scholten and V.M. Fthenakis, 2006. Environmental impacts of PV electricity generation - a critical comparison of energy supply options. Proceedings of the 21st European Photovoltaic Solar Energy Conference, Sept. 4-8, Dresden, Germany. DOI: 10.4229/24thEUPVSEC2009

Aste, N. and C. Del Pero, 2010. Technical and economic performance analysis of large-scale ground-mounted PV plants in Italian context. Prog. Photovoltaics Res. Appl., 18: 371-384. DOI: 10.1002/pip.984

Branker, K., M.J.M. Pathak and J.M. Pearce, 2011. A review of solar photovoltaic levelized cost of electricity. Renew. Sustain. Energy Rev., 15: 4470-4482. DOI: 10.1016/j.rser.2011.07.104

Chung, D., C. Davidson, R. Fu, K. Ardani and R. Margolis, 2015. U.S. Photovoltaic prices and cost breakdowns: Q1 2015 benchmarks for residential. Commercial and Utility-Scale Systems, National Renewable Energy Laboratory.

CS, 2018. A world of complete PV solutions. A world Complet. PV Solut.

El-katiri, L., 2014. Prospects for renewable energy in GCC states: Opportunities and the Need for Reform.

Fthenakis, V., R. Frischknecht, M. Raugei, H.C. Kim and E. Alsema *et al*., 2011. Methodology guidelines on life cycle assessment of photovoltaic electricity. Methodol. Guidel. Life Cycle Assess. Photovolt. Electr. IEA PVPS T, International Energy Agency Photovoltaic Power Sys.

Fthenakis, V.M. and H.C. Kim, 2011. Photovoltaics: Life-cycle analyses. Sol. Energy, 85: 1609-1628. DOI: 10.1016/j.solener.2009.10.002

Hajiah, A., T. Khatib, K. Sopian and M. Sebzali, 2012. Performance of grid-connected photovoltaic system in two sites in Kuwait. Int. J. Photoenergy. DOI: 10.1155/2012/178175

Hernández-Moro, J. and J.M. Martínez-Duart, 2013. Analytical model for solar PV and CSP electricity costs: Present LCOE values and their future evolution. Renew. Sustain. Energy Rev., 20: 119-132. DOI: 10.1016/j.rser.2012.11.082

Hong, J., W. Chen, C. Qi, L. Ye and C. Xu, 2016. Life cycle assessment of multicrystalline silicon photovoltaic cell production in China. Sol. Energy, 133: 283-293. DOI: 10.1016/j.solener.2016.04.013

IRENA, 2012. IRENA Renewable energy cost analysis series.

Kang, M.H. and A. Rohatgi, 2016. Quantitative analysis of the levelized cost of electricity of commercial scale photovoltaics systems in the US. Sol. Energy Mater. Sol. Cells, 154: 71-77. DOI: 10.1016/j.solmat.2016.04.046

Kim, B.J.U., J. Lee yong, K. Kim hwan and T. Hur, 2014. Evaluation of the environmental performance of sc-Si and mc-Si PV systems in Korea. Sol. Energy 99: 100-114. DOI: 10.1016/j.solener.2013.10.038

KISR, 2014. Kuwait Institute for Scientific Research.

Marion, B., J. Adelstein, K. Boyle, H. Hayden and B. Hammond *et al*., 2005. Performance parameters for grid-connected PV systems. Proceedings of the 31st IEEE Photovoltaic Specialists Conference, Jan. 3-7, IEEE Xplore press, FL, USA, pp: 1601-1606. DOI: 10.1109/PVSC.2005.1488451

Nemet, G.F., E. O'Shaughnessy, R. Wiser, N. Darghouth and G. Barbose *et al*., 2017. Characteristics of low-priced solar PV systems in the U.S. Appl. Energy, 187: 501-513. DOI: 10.1016/j.apenergy.2016.11.056

NREL, 2016. Distributed generation energy technology capital costs.

Perpinan, O., E. Lorenzo, M. Castro and R. Eyras, 2008. Energy payback time of grid connected PV systems: Comparison between tracking and fixed systems. Prog. Photovolt Res. Appl., 17: 137-147. DOI: 10.1002/pip.871

Ramadhan, M. and A. Naseeb, 2011. The cost benefit analysis of implementing photovoltaic solar system in the state of Kuwait. Renew. Energy, 36: 1272-1276. DOI: 10.1016/j.renene.2010.10.004

Rashed, A., 2014. Personal communication.

SMA, 2018. SMA solar technology.

Smestad, G.P., 2008. The basic economics of photovoltaics. Sol. Energy New Mater. Nanostructured Devices High Effic. STuC8. DOI: 10.1364/SOLAR.2008.STuC8

Stoppato, A., 2008. Life cycle assessment of photovoltaic electricity generation. Energy, 33: 224-232. DOI: 10.1016/j.energy.2007.11.012

Wong, J.H., M. Royapoor and C.W. Chan, 2016. Review of life cycle analyses and embodied energy requirements of single-crystalline and multi-crystalline silicon photovoltaic systems. Renew. Sustain. Energy Rev., 58: 608-618. DOI: 10.1016/j.rser.2015.12.241

Zweibel, K., 1999. Issues in thin film PV manufacturing cost reduction. Sol. Energy Mater. Sol. Cells 59: 1-18. DOI: 10.1016/S0927-0248(99)00019-7