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Design of a solar PV power plant at KFU premises

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Abstract. This research project involves the design of an on-grid solar photovoltaic system on a $6500m^2$ triangular-shaped land at the King Faisal University (KFU) campus. This project consists of two parts: general knowledge of Solar PV systems and design aspects of the solar PV system. The first part highlights key theoretical knowledge about PV systems, i.e., the definition of a PV system, the types, current technologies, and the components of the system. The second part presents the design aspects of an on-grid PV system and shows some standards used in designing, and sizing PV components including the distance between arrays and comparison between vertical and horizontal mounted PV panels. The proposed modeling approach utilizes PVsyst solar simulation program to help optimize and design the proposed solar PV system. Based on the performed numerical calculations, the final design consisted of 8 inverters rated at 110kVA each and 1200 panels rated at 540W to get the maximum output power to feed the 1MW water treatment plant. Several scenarios were carried out using different economic parameters. For the optimal scenario, the total operation cost using the 650 kW PV system is estimated to be 451,215 SAR with savings of 109,425 compared to the grid alone scenario. This translated to 0.254 SAR/kWh. In terms of oil and pollution and oil savings, the optimal results for adding the 650 kW PV system yield he life cylce cost anaylsis yield savings of more than 17,000 oil barrels and more than 23 thousand tons of CO_2. The corresponding monetary revenues are about 13.4 million SAR.

Introduction

The Kingdom of Saudi Arabia launched the National Renewable Energy Program, aiming to activate the local resources to produce and benefit from renewable energy opportunities. It is planned to produce at least 9.5 GW of renewable energy by 2023, which is anticipated to increase by 2030. This program will contribute to supporting the Kingdom's economy and providing jobs. The proposed project will be an opportunity to contribute to this program [1]. The project will be based on solar energy, which is one of the most important sources of renewable energy. It involves designing a photovoltaic (PV) solar power plant at King Faisal University premises. The university is in Al-Ahasa, which is one of the best areas in the Kingdom to benefit from solar energy. The design will be an on-grid solar PV power plant on a triangular land of $6,500\boldsymbol{m^2}$ granted for energy projects at the university. It will supply the university's electricity network (Additional to the existing network from Saudi Electric Company).

The paper is organized as follows: In section 2, the authors compare (a) the existing solar PV systems and (b) water treatment power supplies. Section 3 is devoted to describing the design methodology and the proposed grid-connected PV at KFU. Section 4 describes the performance of the designed PV system using the PVGIS software tool and the economic analysis of the proposed system. The paper is concluded with Section 5 where the conclusions, recommendations, and future improvement of the design are discussed.

Literature Review and Problem Statement.
The three main existing solar PV types that are commercially applied are off-grid, on-grid, and hybrid PV solar grids. Each type has its own advantages and disadvantages, and it actually comes down to what the customer demands to gain from solar PV panel installation. The three types are compared in Table 1 below.

TABLE 1. Comparison of: off-grid, on-grid, and hybrid PV solar grids

Type	Advantages	Disadvantages	Notes
Off-grid	No need for transmission and distributions lines	Expensive energy storage devices	Valid for remote areas (mountains, far from the grid)
Grid-connected	Energy exchange with the grid.	If the grid is down, the load is not served	
Hybrid	Available 24 hours, Grid energy exchange	Expensive energy storage devices	areas with high wind potential

Water treatment power supplies
Water treatment plants (WTPs) are used to treat and recycle used water from industries, residential and commercial customers, and agriculture. The water treatment power supplies can use either the local power grid or a renewable energy source. Typical water treatment plants are supplied through conventional power plants. With recent improvements in renewable energy and increasing pollution issues, municipalities and owners start using renewable energy sources such as solar PV, Wind, Hydro, fuel cells, and storage. In fact, several WTPs are supplied with solar energy. For instance, the Greenskies Renewable Energy project shown in Figure 1 consists of a 137-kW solar array in Sprague, Connecticut, generating solar electricity for the Sprague wastewater treatment plant [1]. It is located on adjacent property and provides 80% of the power needed at the plant. Meanwhile, Figure 2 shows a sewage treatment with solar-produced green hydrogen [2].

Figure 1. Greenskies 137-kW Solar Array at the Water Treatment Plant [1].

Figure 2. A Water Treatment Facility Operated by Aqualia [2]

Potential Resources in Saudi Arabia

1) Solar PV potential resources in Saudi Arabia: The expansion of power generation in Saudi Arabia is necessary to meet the expected growth of power demand. Solar energy resources can be used effectively in Saudi Arabia due to the high solar irradiation, vast rainless area, and long-term sunshine [3].

2) Wind resources in Saudi Arabia are moderate and are high in coastal areas: Saudi Arabia has the potential to produce more than 200GW of onshore wind energy with an average capacity factor of 35.2%, higher than most countries paving the way in wind energy generation including the US (33.9%), UK (27.8%), Denmark (28.4%) and Germany (19%). By 2025, Saudi Arabia aims to generate 10 GW of wind energy, creating more than 7,500 jobs and

contributing more than $15 billion to Saudi Arabia's gross domestic product [5]. Potential renewable energy sites in Saudi Arabia including Al Jawf, Tabuk, Najran, Taif, and Yadamah have high wind speeds and promising capacity factors to make wind energy projects a reality.

3) Hydro resources in Saudi Arabia: The electricity production from hydroelectric sources (kWh) in Saudi Arabia was reported at 0 kWh in 2014. However, in 2016, the desalination plant located in the city of Ras Al-Khair is one of the highest hydropower-producing cities, with an average production of 18 million and 977 thousand megawatts per hour. This was followed by the desalination plant in the city of Jubail, which produced about 10 million and 366 thousand megawatts per hour, followed by a desalination plant in the city of Ras Al Khair, which produced about 5 million and 453 thousand megawatts per hour as shown in Figure 5 [7].
4) Fuel cells in Saudi Arabia: Saudi Arabia is seeking to develop and utilize all the various energy resources, with which the Kingdom is endowed. And to get all possible advantages of fuel cells in the kingdom, the Ministry of Energy has signed many memoranda of understanding (MoUs) with several entities for implementing pilot projects for hydrogen fuel-cell-based vehicles, buses, trains, and transportation applications and sustainable jet fuel production in selected areas and roads in various cities in the Kingdom [8].
5) Energy storage is being considered in Saudi Arabia in the last few years. The Red Sea project has the largest energy storage facility in the world. The battery storage facility will supply the Red Sea project with renewable energy during the night when there is no possibility of solar power generation. It will also ensure supply in the case of outages when shutdowns occur due to potential faults or sandstorms affecting production. The blend of solar and wind power generation will also guarantee a reliable supply of energy to this tourism destination [9].

Because of the high potential and focus on solar PV resources in the KFU site, the authors have recommended designing a power system for the 1 MW water treatment plant.

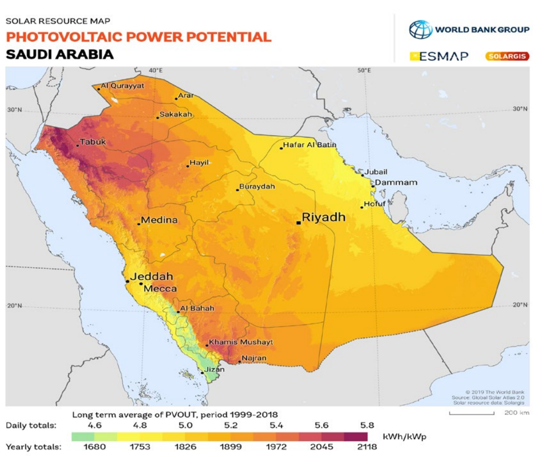

Fig 3. Photovoltaic Power Potential in Saudi Arabia [4]

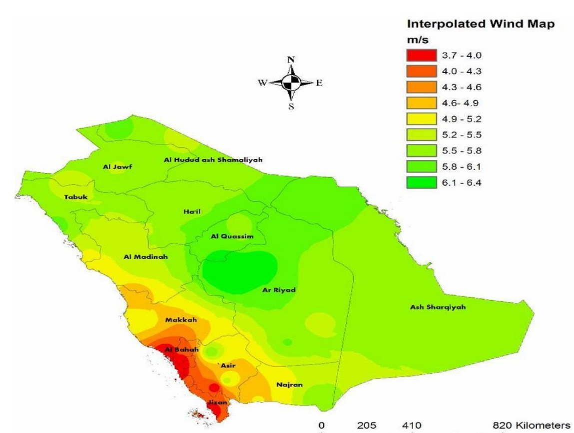

Fig 4. Wind Energy Map of Saudi Arabia [6]

Design methodology of the proposed solar PV system

The main objective of this paper is to present the mechanical design of a grid-connected solar PV system as well as calculate its power production capabilities. The designed system feeds the water treatment plant which is subjected to the following constraints:

a. Water treatment plant power requirements.
The existing WTP at KFU is operated through the Saudi Electricity Company (SEC) grid. It is supplied using a 3-phase transformer rated at 1 MVA (13.8kV/380 V). Therefore, the size of the PV plant must not exceed 1 MVA since it is expected that excess energy from the solar PV system could be sold to the local electricity company.

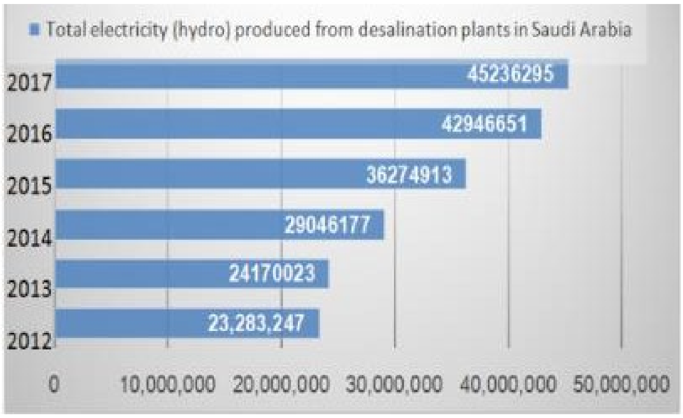

Figure 5. Hydroelectric Power between 2012 to 2017 in Saudi Arabia [7]

b. Limited land area.
The area of the allotted piece of land for this project is approximately 6500 m^2, with a useful land area to accommodate the solar PV system anticipated at 5850 m^2. The schematic drawing of the allotted land is described in the following Figure 6. As shown in the figure, the land is triangular with 162 m as a base, 82 m as height, and 115 m from the right and left sides.

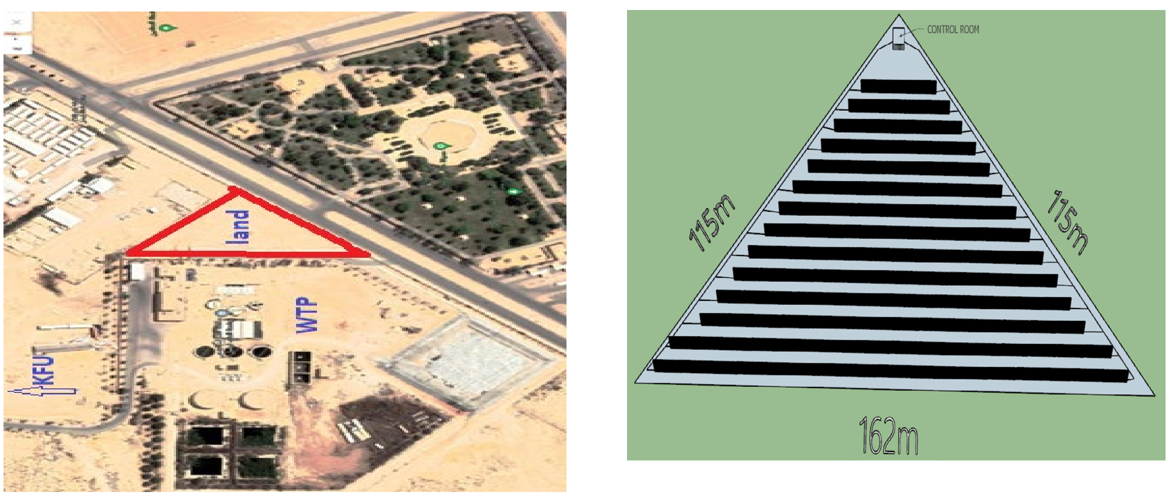

Figure 6. Solar PV land layout and surrounding Infrastructure.

c. The solar array spacing.
In this project, the best dimensions of solar panels to use are (2.3m×1.1 m) with 540 W per panel and 3.3 m array spacing. That was considered based on the shape of the land.

d. Solar PV Standards and Design.
The applied PV standards in the project are listed in Table 2 and the final single-line diagram of the solar PV system is shown in Figure 7. The final Single line diagram of the solar PV system connected to the WTP is shown in Figure 8. Table 3 lists the final design components. The 1 MW transformer is already installed.

Table 2. Engineering Standards [10-14]

Standard Code	Standard details
IEC 62548:2016	Photovoltaic (PV) arrays - Design requirements [10].
IEC TS 62738:2018	Ground-mounted photovoltaic (PV) power plants - Design guidelines and recommendations [11].
IEC 62446-1:2016	Photovoltaic (PV) systems - Requirements for testing, documentation, and maintenance - Part 1: Grid-connected systems - Documentation, commissioning tests, and inspection [12].
IEC 62109-2:2011	Safety of power converters for use in photovoltaic power systems - Part 2: Particular requirements for inverters [13].
UL 1741:2021	Inverters, Converters, Controllers, and Interconnection System Equipment for Use With Distributed Energy Resources [14].

Table 3. Final Design Solar PV System Components

Item	Description	Size/Number
PV system size	5850 m^2	648 kW
Solar panels	P_{rated}=540 W, V_m=41.76V, I_m=12.94A, η=20.89%	1200
DC-AC inverters	110 kVA	8
AC Combiner boxes	400A 1000V	4
DC Combiner boxes	160A 1500V	8
Disc. DC Switch	250A	8

Performance and Economic Analysis of the Grid PV System at KFU.
The PV system energy performance is carried out using PVGIS. The monthly energy production is listed in Figure 10.

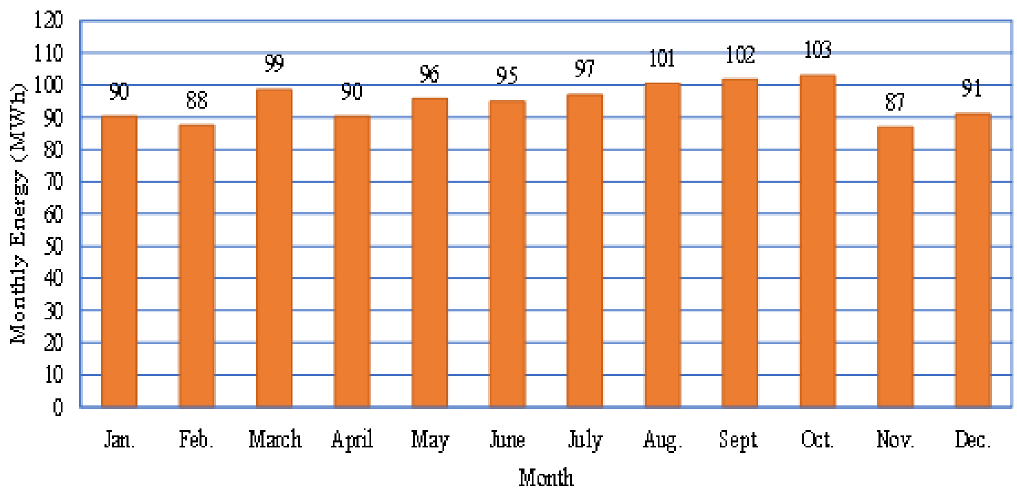

Figure 10. Monthly Output of the Solar PV Power Plant [15].

The life cycle cost analysis results for four different scenarios are listed in Table 4.

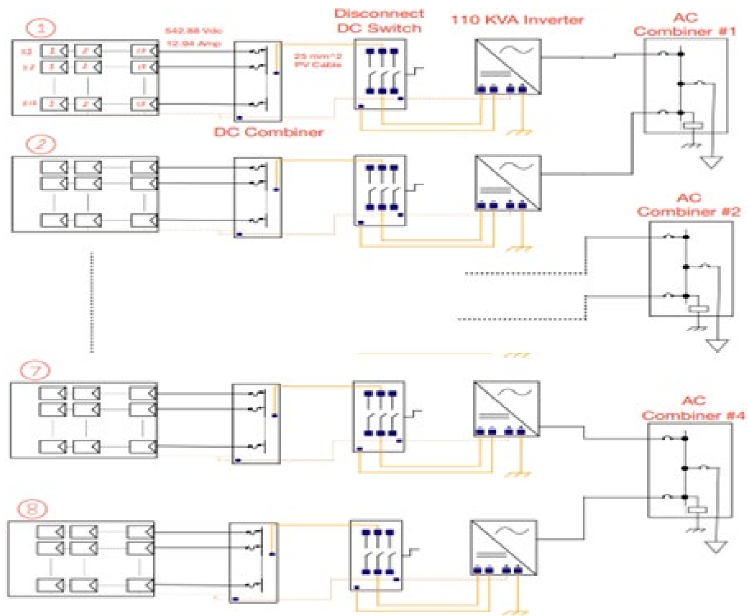

Figure 7. Single Line Diagram of the Solar PV System [Ref: own elaboration].

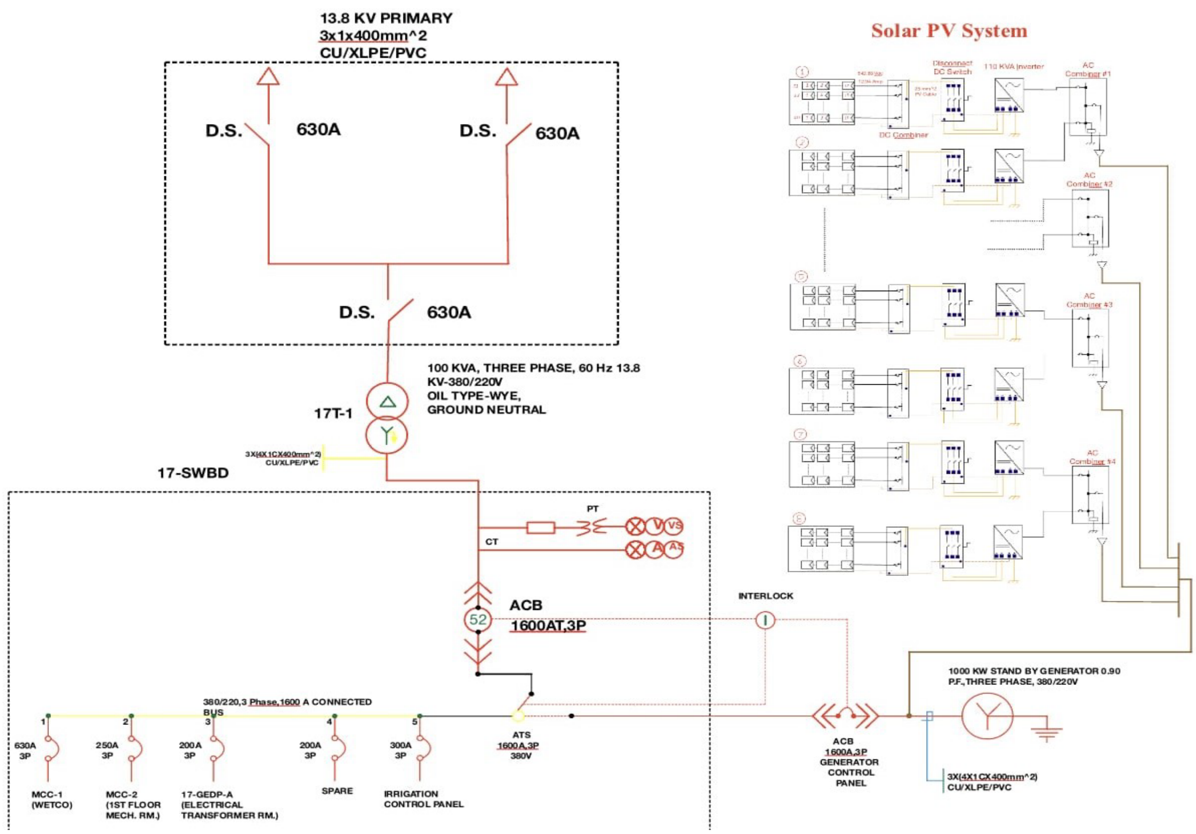

Figure 8. The final Single line diagram of the solar PV system connected to the WTP

In this study, the economic analysis is carried out using the following model described by equations (1) through (5) [16].

The total cost of the PV array can be calculated by using the following equation:

$$C_{pv} = Unit\ Cos\ of\ PV \times No.of\ Modules \times Peak\ Module\ Power \quad (1)$$

The present worth of maintenance cost (C_m), is estimated using the equation [16]:

$$C_m = M_{\frac{c}{yr}} \times \left(\frac{1+i}{1+d}\right) \times \left[\frac{1-\left(\frac{1+i}{1+d}\right)^N}{1-\left(\frac{1+i}{1+d}\right)}\right] \quad (2)$$

Where Mc is used to represent the annual maintenance cost and N is the Lifetime of the system. Life Cycle Cost (LCC) is computed as follows [16]:

$$LCC = C_{PV} + C_{inv} + C_{AC.\,com} + C_{DC.\,com} + C_{inst} + C_m + \cdots \quad (3)$$

The Annualized Life Cycle Cost (ALCC) can be calculated using the following equation [16]:

$$ALCC = LCC\left[\frac{1-\left(\frac{1+i}{1+d}\right)}{1-\left(\frac{1+i}{1+d}\right)^N}\right] \quad (4)$$

The unit electrical cost can be calculated using the equation below [16]:

$$UC_{el} = \frac{ALCC}{365 \times E_{load}} \quad (5)$$

Where E_{Load} is the necessary amount of daily energy in kWh/day.

Table 4. Energy cost for the four scenarios

Scenario	1	2	3	4
Solar Panels Cost (SAR)	576,243	2,352,760	576,243	576,243
Inverters Cost (SAR)	153,073	153,073	153,073	145,899
DC/AC String Boxes Cost(SAR)	15,040	15,040	18,800	15,040
Switch Disconnects Cost (SAR)	1,263	1,263	1,639	1,263
Cable Cost (SAR)	112,800	112,800	150,400	112,800
Installation Cost (SAR)	57,626	57,626	57,626	86,435
Inflation Rate (%)	7	7	6	7
O&M Cost Rate (%)	3	3	3	5
Annual O&M Cost (SAR)	34,224	87,522	34,637	11,977
ALCC (SAR)	270,175	707,594	437,871	347,044
WTP Energy Consumption (kWh)	1,752,000	1,752,000	1,752,000	1,752,000
Energy Cost (SAR)	560,640	560,640	560,640	560,640
PV Energy (kWh)	1,186,250	1,186,250	1,186,250	1,186,250
Energy Purchased from SEC (SAR)	565,750	565,750	565,750	565,750
Energy Purchased Cost (SAR)	181,040	181,040	181,040	181,040
Total Cost (SAR)	451,215	888,634	618,911	528,084
Cost Savings (SAR)	109,425	-327,994	-58,271	32,556
Cost of Energy (SAR/kWh)	0.258	0.507	0.353	0.301

The results in Table 4 are obtained by considering alternative component cost and O&M cost ratio. From Table 4, the first scenario is considered to be optimal since it provides the highest profits of all four cases. The profits are estimated at 109,425 SAR. Moreover, 67% of the WTP energy is provided by the designed solar PV system. The final design economic parameters are listed in Table 5.

In addition to the energy cost savings, environmental benefits occur because of the design PV system. Table 6 displays the annual savings in oil consumption and CO_2 tax savings.

Table 5. Final design size and component cost

Component	Size	Number of items	Unit Cost
PV Panels	540 W	1200	480 SAR/unit
Inverters	110 kW	8	19,130 SAR/unit
DC Combiners	160 A /1500 V	8	1,200 SAR/unit
AC Combiners	400 A / 1000V	4	1,350 SAR/unit
Disconnect DC Switches	250 A	8	160 SAR/unit
Cables	1000 V	-	30,000 SAR
Installation Cost Rate	-	-	10%-20%
O&M/year Rate	-	-	10%

Table 6. Oil Production and CO_2 tax savings

	PV System Life Cycle Energy (MWh)	29,656
Life Cycle Results	Life Cycle Oil Saving (Barrels)	17,445
	Life Cycle Oil Savings (Million SAR)	6.673
	Life Cycle CO_2 Savings (ton)	23,725
	Life Cycle CO_2 Tax Savings (Million SAR)	6.673
Economic Assumptions	Barrel Energy content (kWh)	1,700
	Oil Price ($/Barrel)	102
	CO_2/kWh (kg)	0.8
	CO_2 Tax ($/ton) [17]	75

Conclusion

To meet KSA 2030 Vision which aims to produce electricity from clean energy resources and reduce carbon emissions that cause harm to the environment, and because of the high solar PV resources in Saudi Arabia, the authors recommend designing a solar PV power system for the 1 MW water treatment plant at KFU. This system is an on-grid solar PV system which gives an advantage to KFU in that if there is any excess of the generated electricity from the PV system, it is sold to the electricity company. One important fact about this project is that the authors have taken into consideration the environmental and societal impacts of this project.

For the optimal scenario, the total operation cost using the 650 kW PV system is estimated to be 451,215 SAR with savings of 109,425 compared to the grid alone scenario. This translated to 0.254 SAR/kWh.

In terms of oil and pollution and oil savings, the optimal results for adding the 650 kW PV system yield he life cylce cost anaylsis yield savings of more than 17,000 oil barrels and more than 23 thousand tons of CO_2. The corresponding monetary revenues are about 13.4 million SAR.

And finally found that the proposed design saves the earth's planet from 23,750 tons of CO_2 in the next 25 years.

Acknowledgment

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