An Optimization Model for Sizing Decisions of Grid-Connected Photovoltaic System

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Abstract

The use of fossil fuels to generate energy produces greenhouse gases, which is the main factor in climate change. Solar energy is a clean source of energy that is environmentally friendly. The photovoltaic (PV) system is a well-established technology for converting solar energy into electrical energy. Sizing-decision of the PV system is a strategic decision-making process that has a long-term impact on the project. This work proposes an optimization model for the sizing decisions of the grid-connected PV system. The model considers the financial aspects in terms of minimizing project lifetime costs and the non-financial aspects in terms of reducing CO2 emissions and satisfying the planned service level. The decisions are the number of PV modules, the amount of energy purchased from the main grid, and the amount of energy supplied to the main grid. Besides an auxiliary binary variable for an either-or decision, either purchase-from or supply-to the grid. A case study is provided to clarify the model's practicality based on the residential area at King Fahd University of Petroleum & Minerals (KFUPM). It is found that 1,670 PV modules are required to meet the annual demand at an annual cost of M$1.45 over 25 years.

Keywords
Photovoltaic system, Grid-connected, Sizing decisions, Financial aspects, Non-financial aspects.

1. Introduction
Energy is essential for the economic, social, and industrial growth of any country. Energy demand is expected to be several times higher than currently in the coming years (Jamil et al., 2017). Greenhouse gasses such as CO2 and N2O are by-products of fossil fuels for electricity production. It is known that climate change is triggered by a rise in greenhouse gasses in the Earth's atmosphere (Mohammadi et al., 2018; Panwar et al., 2011). These gasses in the atmosphere have recently contributed to an uptick in world temperatures, ocean acidity, and unusual weather trends. As fossil fuels such as natural gas and crude oil will be exhausted within the next few years, plans have been made to explore green energies as an alternative to fossil fuels.

Sources of renewable energy can be used repeatedly to produce energy,e.g., solar energy, wind energy, biomass energy, geothermal energy, etc. Solar thermal energy is the most abundant source of renewable energy and is available both directly and indirectly. PV is a well-established solar energy system that has become an appealing form of energy supply (Mohammadi et al., 2018). Various experiments have been undertaken to determine PV systems' technological efficiency and economic viability under various circumstances, e.g., temperature and solar radiation (Alam Hossain Mondal and Sadrul Islam, 2011; Allouhi et al., 2016; EL-Shimy, 2009; Khalid and Junaidi, 2013; Türkay and Telli, 2011).

Getting the PV system up and running requires several decisions, some of which have a long-term horizon, while others are more short-term. Dependent on the horizon's duration, decisions can be divided into three groups: strategic, tactical, and operational decisions. Only the optimal size decisions were considered in this work. The PV system's optimum size is a strategic decision, a long-term decision that is potentially costly and directly affects the system's reliability.

PV systems may be built in rural areas to provide electricity or linked to power grids to sell power generated. The system utilizes a hybrid PV-battery network to supply sustained and reliable electricity due to solar energy's erratic existence. Energy storage eliminates the chance of intermittent power supply from PV and often means users can always have what they need. Typically, batteryless PV systems do not need complicated management strategies. The battery contributes to the average life cycle bill. It has a reduced life period of 3 to 5 years, which increases the replacement cost and requires operational and repair costs (García-Triviño et al., 2015; Tsuanyo et al., 2015).

This work attempts to contribute to the literature by proposing a mixed-integer linear program (MILP) model for sizing decisions of a grid-connected PV system. These decisions are strategic planning since the project lifetime is more than 20 years. The proposed model considers the project's financial aspects in terms of minimizing total lifetime cost, i.e., investment cost, operating and maintenance costs, and replacement cost. In addition, the non-financial aspects in terms of system reliability by achieving the planned service level and environmental effect by limiting CO2 emissions as a result of supplied energy from the grid. A case study based on the residential area's monthly demand at KFUPM is provided to clarify the model's practicality.

The organization of this research paper is as follows: the literature review is presented in section 2. Modeling of system components is presented in section 3. Section 4 describes model development explaining cost expressions, decision variables, constraints, and objective function. The case study and results, and discussion are presented in sections 5 and 6. The paper closes with the conclusion and recommendations for future research in Section 7.

2. Literature Review

The reviewed papers were classified into a standalone or grid-connected and subclassified as supported with wind system or not.

The first set of papers reviews the standalone system, i.e., the open-loop system. Soras and Makios (1988) proposed a model based on the monthly average demand to design the tilt angle, PV system area, and the battery's storage capacity. To reduce the battery's effect on the total cost (Phiri and Kusakana, 2016; Wu et al., 2015) designed a small-scale standalone system.

The second set of papers reviews the grid-connected system. Mondol et al. (2009) and Ramli et al. (2015) simulated the system to study the economic feasibility by achieving the maximum profit and minimum cost. Audenaert et al. (2010) studied the viability of using the system for companies in Flanders (Belgium). They found it is a reasonable option based on net present value, discounted payback period, and profitability index. In the same line of study, Firouzjah (2018) studied Iran's viability, and they found that Iran's southern parts have a strong potential for solar energy production. Sulaiman et al. (2011) designed the system with an inverter using the genetic algorithm (GA) by minimizing production over demand ratio. (Al-Maghalseh, 2019) carried a numerical analysis using the Open Distribution Source Simulator (OpenDSS) to reduce over and under energy production.

The third set of papers reviews the standalone hybrid PV/wind system. Yang et al. (2008) considered the system with a battery. Kaabeche et al. (2011) considered system reliability to be the probability of power supply deficiency and economic criterion to be the electricity Levelized cost. They tested the model in a case study on the supply of energy to a residential area. Ferrer-Martí et al. (2013) proposed a model for sizing and location selection problems. The model minimizes the life-cycle cost and selects the generation point location in rural areas.

Lamedica et al. (2018) examined the PV/wind hybrid system's feasibility for industrial plants considering demand variation. They used a stochastic simulation tool and provided a case study in Rome to prove the system's feasibility. Abbes et al. (2014) utilized the multi-objective optimization (MOO) framework to minimize life-cycle cost, system embodied energy, and probability of power supply loss. The Pareto-optima was generated by doing iterations through the integration of Simulink and MATLAB. In the same study line, (Kamjoo et al., 2016) minimized the life-cycle cost and maximized the reliability simultaneously. Reliability was measure as the probability of loss of power supply. They formulated the uncertainties in renewable resources by chance-constrained programming.

The fourth set of papers reviews the grid-connected hybrid PV/wind system. González et al. (2015) and Mousa and Diabat (2011) proposed optimization models for the size of the systems' different components without battery banks. Eventually, this research work proposes a MILP model for sizing decisions of a grid-connected PV system. The model integrates both financial and non-financial aspects of the system. A case study is presented to study the economic viability of supplying power to a residential area.

3. Modeling of system components

This research considered a grid-connected system consists of PV panels, DC/AC inverter, a utility grid, and a residential area, as depicted in Figure 1. The utility grid and the generated load are connected directly to a common coupling point without interfacing power conditioning equipment. The PV panels are used to take in solar energy and convert it to direct current (DC) power, P_{pv}. The inverter takes the DC power and transforms it to an alternating current (AC) power, P_{inv}. In the beginning, PV panels can supply power to satisfy demand, and surplus power can be supplied to the utility grid. If the demand is more than the generated power, the remaining excess demand can be satisfied by the grid, P_{grid}. The mathematical formulation of the different components is defined in the following section.

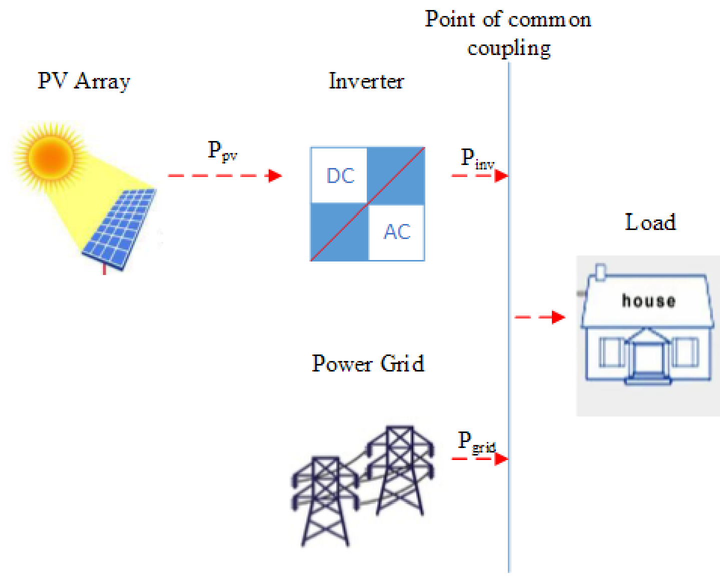

Figure 1. Design of the Grid-connected PV system

3.1. Nomenclature

The following notation is used to formulate the proposed model

- A_P: available area for the project (m^2).
- A_{pv}: area of one PV cell (m^2).
- β: temperature coefficient for cell efficiency (typically 0.004–0.005/°C).
- C_v: investment cost.
- C_{inv}: inverter capital cost per kW.
- $C_{O\&M}$: operating and maintenance cost.
- C_{pv}: PV array capital cost per kW.
- C_r: replacement cost.
- η_{inv}: inverter efficiency.
- η_{pv}: power generation efficiency.
- η_R: PV generator efficiency measured at T_R.
- E_{Excess}: amount of produced energy more than the demand (kWh).
- E_{Grid}: amount of energy purchased from the utility grid (kWh).
- EC_v: equivalent initial investment cost.
- $EC_{O\&M}$: equivalent operating and maintenance cost.
- EC_r: equivalent replacement cost.
- f: inflation rate.
- γ: carbon conversion factor of electricity.
- G_{limit}: limit of CO2 emissions (kg/months).

i: interest rate considering inflation.
i': inflation-free interest rate.
I_B: hourly global irradiation (kWh/m^2).
I_D: hourly diffuse irradiation (kWh/m^2).
I_{pv}: hourly solar irradiation incident on the PV array (kWh/m^2).
I_{pvo}: average solar irradiation on the array under $NOCT$ conditions.
IC_{pv}: PV cell initial cost.
IC_{inv}: inverter initial cost.
K_{inv}: inverter oversize coefficient.
N_{max}: maximum number of PV cells.
N_{min}: minimum number of PV cells.
$NOCT$: normal operating cell temperature.
P_{pv}: PV cell output power (W).
Pr_{inv}: inverter power rated (W).
R_{inv}: number of inverter replacements.
R_B: geometric factor representing the ratio of the actual irradiation on the tilted plane to the standard irradiation on the horizontal plane.
SL: planned service level.
T_{A0}: ambient temperature at NOCT.
T_{C0}: cell temperature at NOCT test conditions.
T_{inv}: lifetime of the inverter (years).
T_p: lifetime of the project (years).
T_R: cell referenced temperature.
X_{Grid}: binary variable; 1 if E_{Grid} exists and 0 otherwise.
X_{Excess}: binary variable; 1 if E_{Excess} exists, and 0 otherwise.
X_{pv}: number of PV arrays.

3.2. PV module

PV cell is a semiconductor surface that produces electricity from sunlight. PV module is a set of cells connected based on a specific configuration to form an array (Bonthagorla and Mikkili, 2020). The output power from an array depends on the cell area, cell efficiency, solar irradiance, and ambient temperature. The produced power from the array can be represented mathematically as follows (Wu et al., 2015):

$$P_{pv}(t) = \eta_{pv} A_{pv} I_{pv} \tag{1}$$

The solar irradiation of the PV array, I_{pv}, depends on many factors such as day time, season, tilt angle, global irradiation, and diffuse irradiation. It can be represented mathematically as follows (Collares-Pereira and Rabl, 1979; Tazvinga et al., 2013):

$$I_{pv} = (I_B + I_D)R_B + I_D \tag{2}$$

The power efficiency, η_{pv}, depends on the hourly irradiation, I_{pv}, and the ambient temperature, T_A. It can be represented mathematically as follows (Tazvinga et al., 2013):

$$\eta_{pv} = \eta_R \left[1 - \frac{0.9\beta I_{pv}(T_{Co} - T_{Ao})}{I_{pvo}} - \beta(T_A - T_R)\right] \tag{3}$$

The number of PV arrays, X_{pv}, depends on the available area, A_P, and can be expressed as the following:

$$N_{min} \leq X_{pv} \leq N_{max} \tag{4}$$

$$N_{max} = \frac{A_p}{A_{pv}} \tag{5}$$

3.3. Inverter module

The inverter module is used as an interface between the PV module and the demand area (Bilal et al., 2012). It converts the DC generated from the PV module to the AC. The output power of the inverter, $P_{inv}(t)$, is expressed as:

$$P_{inv}(t) = P_{pv}(t)\ \eta_{inv} \tag{6}$$

The power rating of the inverter, Pr_{inv}, depends on the output power from the PV module, P_{pv}, number of PV modules, X_{pv}, and the oversize inverter coefficient, K_{inv}, (Bilal et al., 2012). It can be defined as

$$Pr_{inv} = P_{pv}(t)\ X_{pv}\ K_{inv} \tag{7}$$

The lifetime of the inverter, T_{inv}, is shorter than the lifetime of the project, T_p, so the number of replacements, R_{inv}, during the project is formulated as (Ndwali et al., 2020):

$$R_{inv} = \frac{T_p}{T_{inv}} - 1 \tag{8}$$

4. Model development

The sizing problem of PV grid-connected system is a strategic decision making problem that requires the decision-maker to specify the number of PV arrays, X_{pv}. Besides the amount of energy supplied from the grid, E_{Grid}, to satisfy demand if the generated energy is not enough. While, if the generated energy is more than the demand, the decision-maker has to decide on the amount of energy produced over the demand, E_{Excess}, i.e., excess production. The following sections express the different components of the proposed model mathematically.

4.1. Cost expressions

The system's life-cycle cost is the sum of investment cost, C_v, operating and maintenance costs, $C_{O\&M}$, and replacement cost of different components, C_r, (González et al., 2015); can be expressed as follows:

$$TC = C_v + C_{O\&M} + C_r \tag{9}$$

The initial investment includes costs of purchasing and installation of PV arrays, IC_{pv}, and inverter, IC_{inv}. The installation cost is assumed to be 20% of the purchasing cost (Ndwali et al., 2020). It can be expressed as follows:

$$C_v = IC_{pv} + IC_{inv} \tag{10}$$

$$IC_{pv} = 1.2\ X_{pv} C_{pv} P_{pv} \tag{11}$$

$$IC_{inv} = 1.2\ X_{pv} K_{inv} C_{inv} P_{pv} \tag{12}$$

The PV system's lifetime can be split into shorter planning periods, such as monthly or annually. For each planning period, equivalent cost, EC_v, can be determined by translating the sum of initial costs, C_v, into equal amounts over the system's lifetime under an interest rate, i, (Park, 2013). It can be expressed as follows:

$$i = i' + f + i'f \tag{13}$$

$$EC_v = C_v \left[\frac{i\,(1+i)^{T_p}}{(1+i)^{T_p} - 1}\right] \tag{14}$$

The equivalent cost of the operating and maintenance processes, $EC_{O\&M}$, is assumed to be 1% of the initial cost (Kamjoo et al., 2016; Ndwali et al., 2020).

$$EC_{O\&M} = 0.01\, X_{pv} C_{pv} P_{pv} \tag{15}$$

It is assumed that the inverter is the only component that requires replacement during the lifetime. The costs of the initial purchase and the subsequent purchasing during the lifetime are converted to equal payment per planning period over the life-cycle, EC_r, (Park, 2013). The inverter's replacement cost can be calculated as follows:

$$EC_r = IC_{inv}\, [(1+i)^{T_{inv}}] \left[\frac{i\,(1+i)^{T_p}}{(1+i)^{T_p} - 1}\right] \tag{16}$$

4.2. Model formulation

The proposed model considers the financial and non-financial aspects of the PV system. The objective is to minimize the system's total cost of investment, EC_i, operating and maintenance, $EC_{O\&M}$, and replacement, EC_r, expressed in Eq.(17). The constraints are divided into five groups: energy balance, either over-or under-production, service level, the environmental aspect, the restricted number of PV arrays, and the type of decision variables.

Eq. (18) balances the system's energy such that the generated energy, $E_{PV}(t)$, plus the energy from the grid, $E_{Grid}(t)$, minus the over-produced energy, $E_{Excess}(t)$, equal to the demand, $E_{Demand}(t)$. Energy balance equation does not avoid the occurrence of over-and under-production simultaneously, so Eqs. (19-23) are used to avoid this situation. Binary variables are used to take an either-or decision; X_{Grid} takes 1 if E_{Grid} has a value 0 otherwise and X_{Excess} takes 1 if E_{Excess} has a value, 0 otherwise. A supplementary parameter, M, with a high value, is used to complete the either-or formulation.

Eq. (24) is proposed to achieve the planned service level, SL, which represents the proportion of the demand, $E_{Demand}(t)$, satisfied from the generated energy, $E_{PV}(t)$. Eq. (25) limits the amount of CO2 emissions produced as a result of supplied energy from the grid, E_{Grid}. Where γ represents carbon conversion factor of electricity that depends on the fuel composition. Eqs. (26) and (27) restrict the number of PV arrays, X_{pv}, by the available area. Eq. (28) specifies the type of decision variables.

$$Minimize\ Total\ Cost = \min\,(EC_i + EC_{O\&M} + EC_r) \tag{17}$$

$$E_{PV}(t) + E_{Grid}(t) - E_{Excess}(t) = E_{Demand}(t) \tag{18}$$

$$X_{Grid} + X_{Excess} \le 1 \tag{19}$$

$$E_{Grid}(t) \le M\, X_{Grid} \tag{20}$$

$$E_{Grid}(t) \ge M\,(X_{Grid} - 1) \tag{21}$$

$$E_{Excess}(t) \leq M\ X_{Excess} \tag{22}$$

$$E_{Excess}(t) \geq M\ (X_{Excess} - 1) \tag{23}$$

$$E_{PV}(t)\ \geq SL\ \times\ E_{Demand}(t) \tag{24}$$

$$\gamma\ E_{grid}(t) \leq G_{limit} \tag{25}$$

$$X_{pv} \geq N_{min} \tag{26}$$

$$X_{pv} \leq N_{max} \tag{27}$$

$$X_{pv} \in N; \quad X_{Grid}, X_{Excess} \in (0,1); \quad E_{Grid}(t), E_{Excess}(t) \geq 0 \tag{28}$$

5. Case study

A case study based on the residential area at KFUPM was utilized to evaluate the proposed model's practicability. The surplus energy, E_{Excess}, can be used to satisfy part of the demand of the other areas on the KFUPM campus. This selection's logic is to catch solar irradiation, temperature, and demand changes during the different seasons of the year. Figure 2 represents the average monthly demand from the KFUPM housing department. While the monthly average global and diffuse irradiance throughout 2014-2017 provided by King Abdullah City for Atomic and Renewable Energy (K.A.CARE) ("Home | Renewable Resource Atlas," n.d.) based on measurements from the KFUPM station, as shown in Figure 3.

Table 1 and Table 2 summarize the financial and non-financial model parameters, mostly taken from (Ndwali et al., 2020). Saudi Arabia's inflation-free interest rate and inflation rate are announced at the end of the third quarter, August 2020, by Saudi Arabian Monetary Authority ("Saudi Arabian Monetary Authority," n.d.).

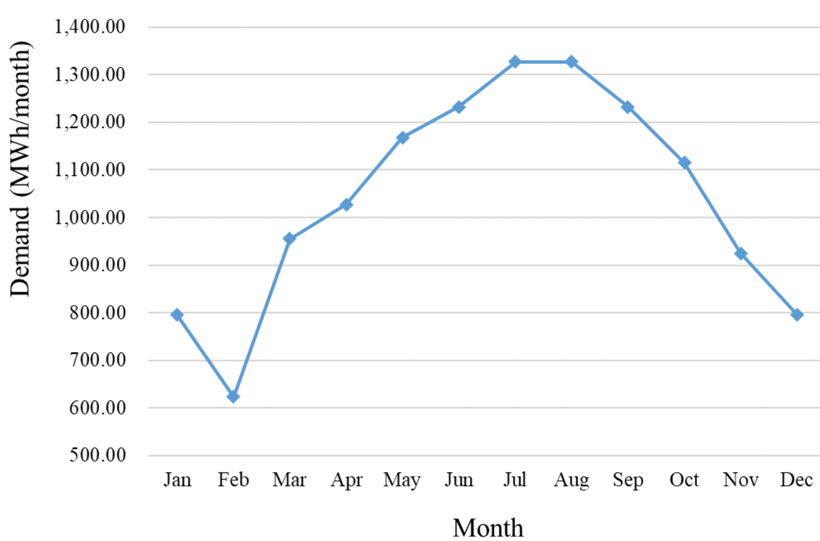

Figure 2. Energy demand of the residential area at KFUPM

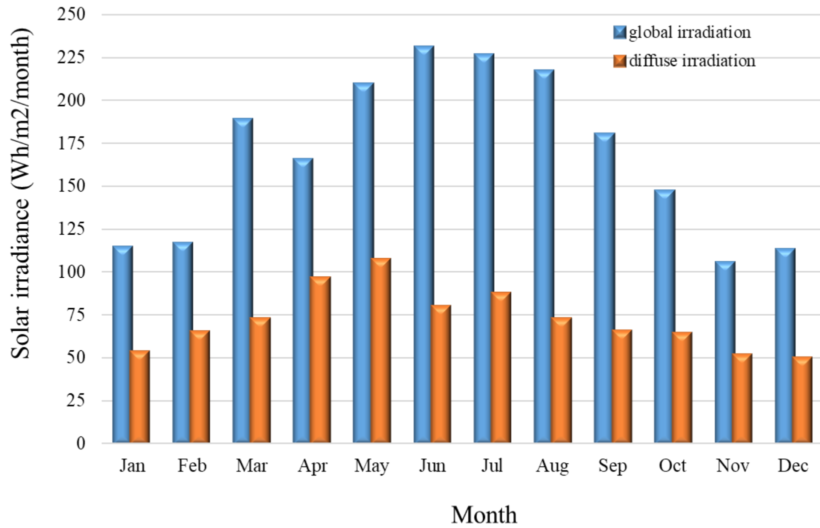

Figure 3. Global and diffuse solar irradiance at KFUPM

Table 1. Model Financial parameters (Ndwali et al., 2020)

Economic parameter	**PV Panel**	**3 Phase Inverter**
Investment cost	281 \$/kW	148 \$/kW
Installation Cost	20%	20%
O&M Cost	1%	
Replacement Cost	0 \$/kW	148 \$/kW
η_r	17.5%	98.5%
Lifetime	25 years	15 years

Table 2. Model Parameters

$\beta =$	0.004°C	$T_p =$	25 years
$T_{A0} =$	20°C	$T_{inv} =$	15 years
$T_{C0} =$	45°C	$\eta_{inv} =$	98.5%
$T_R =$	25 °C	$K_{inv} =$	1.25
$\eta_r =$	17.5%	$t_s =$	1 month
$A_{pv} =$	1.96 m^2	$SL =$	70%
$A_P =$	200,000 m^2	$\gamma =$	0.218
$N_{min} =$	0	$f =$	6.2%
$N_{max} =$	102,040.00	$i' =$	1.0%

6. Results and discussion

In this paper, the optimization is performed by GAMS software using CPLEX solver. The number of PV modules, X_{pv}, is 1,670 to achieve a minimum annual cost of M\$ 1.45/year over the project's lifetime, results summarized in Table 3. Based on the suggested design, 220.13 kg/year of CO2 will be emitted to the environment as a result of consumed energy from the grid, E_{Grid}. Table 4 summarize the performance of the systems of the year.

Table 3. Values of the decision variables

Total cost =	M$ 1.45/year
CO2 emissions =	220.13 kg/year
Number of PV modules =	1,670

Table 4. Values of E_{PV}, E_{Grid}, and E_{Excess} (MWh)

Month	E_{Demand}	E_{PV}	E_{Grid}	E_{Excess}
Jan	796.23	612.33	183.90	0.00
Feb	623.29	603.51	19.78	0.00
Mar	955.48	935.74	19.74	0.00
Apr	1,027.40	1,338.77	0.00	311.37
May	1,167.81	1,539.13	0.00	371.32
Jun	1,232.88	1,228.63	4.25	0.00
Jul	1,327.05	1,411.88	0.00	84.83
Aug	1,327.05	1,246.75	80.30	0.00
Sep	1,232.88	1,098.91	133.97	0.00
Oct	1,114.73	1,002.96	111.77	0.00
Nov	924.66	707.47	217.19	0.00
Dec	796.23	557.36	238.87	0.00
Total	12,525.68	12,283.44	1,009.77	767.52

In this section, we assess the effect of changing the limit of CO2 emissions, G_{limit}, on the PV system performance, e.g., $E_{PV}, E_{Grid}, and\ E_{Excess}$, at the same time ignoring the service level constraint, SL.
Table 5 summarizes the results by incrementing and decrementing the G_{limit} by 10% and 20%. It is observable that by increasing G_{limit} the SL during January, February, November, and December can not be reached, bottleneck months.

In conclusion, it costs KFUPM M$1.20/year to meet the demand entirely from the grid under a $0.096/kWh tariff, which produces 2,730.59kg/year CO2 emissions. In comparison, the proposed PV system would cost M$1.45/year with 220.13kg/year of CO2. Financially, it's not a lucrative investment, and it is cheaper to maintain the status quo. However, this investment is a strategic decision, and it would secure power supply over 25 years under a stable cost. Non-financially, the project would reduce atmospheric pollution. So, it is recommended to switch to the PV systems to avoid the increases in energy tariffs, depleting fossil fuels, and reduce greenhouse gas production.

7. Conclusion

This work proposes an optimization model for the sizing decision of a grid-connected PV system, taking into account the financial and non-financial aspects of the decision-making process. The financial aspect is evaluated by minimizing the project life-cycle costs, e.g., investment cost, operating and maintenance costs, and replacement cost. The non-financial aspects are evaluated by achieving a planned service level and a limit of CO2 emissions. It is assumed that the project lifetime is equivalent to the PV modules' functional life and is split into annual planning intervals to reflect fluctuations in demand during the year, i.e., over the seasons. The study found that for short-term planning, it is more viable to generate energy using fossil fuels. For long-term planning, some financial factors, e.g., energy tariffs and inflation, and non-financial factors, e.g., greenhouse gases, can motivate solar energy utilization. PV system secures power supply. Hopefully, these factors, in addition to government incentives, will make the PV system financially attractive over the grid systems in the future. This work can be extended to consider the uncertainty of demand and the uncertainty in the PV system's energy generation.

Table 5. PV system performance under different limits of CO2 emission

	$1.20\ G_{limit}$		$1.10\ G_{limit}$		$1\ G_{limit}$		$0.90\ G_{limit}$		$0.80\ G_{limit}$	
Month	E_{Grid}	SL	E_{Grid}	SL	E_{Grid}	SL	E_{Grid}	SL	E_{Grid}	SL
Jan	358.85	54.93	271.38	65.92	183.90	76.90	96.43	87.89	8.95	98.88
Feb	241.62	61.23	130.70	79.03	19.78	96.83	0.00	114.62	0.00	132.42
Mar	241.59	74.71	130.67	86.32	19.74	97.93	0.00	109.54	0.00	121.15
Apr	5.09	99.50	0.00	114.91	0.00	130.31	0.00	145.71	0.00	161.11
May	0.00	103.23	0.00	117.51	0.00	131.80	0.00	146.08	0.00	160.36
Jun	230.53	81.30	117.39	90.48	4.25	99.66	0.00	108.83	0.00	118.01
Jul	166.90	87.42	41.04	96.91	0.00	106.39	0.00	115.88	0.00	125.36
Aug	284.85	78.53	182.58	86.24	80.30	93.95	0.00	101.66	0.00	109.36
Sep	323.19	73.79	228.58	81.46	133.97	89.13	39.36	96.81	0.00	104.48
Oct	307.33	72.43	209.55	81.20	111.77	89.97	13.99	98.75	0.00	107.52
Nov	382.63	58.62	299.91	67.56	217.19	76.51	134.47	85.46	51.75	94.40
Dec	398.12	50.00	318.49	60.00	238.87	70.00	159.25	80.00	79.62	90.00
Total Cost (M$/year)	1.04		1.24		1.45		1.66		1.87	
X_{PV}	1,193.00		1,432.00		1,670.00		1,909.00		2,147.00	

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