Software Design of Photovoltaic Grid-Connected Power Plants

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Abstract: It is aimed to construct software to aid the design of photovoltaic grid-connected (PVGC) power plants at suitable locations in Saudi Arabia with high solar radiation that are not in the area of sand dunes or shifting sands. These power plants should cover 15% of the expected load by 2020 and support conventional power generation during peak loads. PVGC software was built with Microsoft Visual Basic to assist in the design. The results show that adding 11273.25 MW of solar energy in the Saudi Arabia grid would save 3581151 ton of CO_2, 62869 ton of SO_2, and 42375 ton of NO_x emissions. The tariff of PVGC power plants in this design varied between 0.45 and 0.72 Saudi riyal/kWh. Solar radiation is the most significant factor in the design of PVGC plants. Accordingly, Saudi Arabia should be ready to add PVGC to its network by 2020 to support conventional generation and meet increasing power demands.
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1. Introduction

The construction of photovoltaic (PV) power plants for generating electricity chiefly depends on issues such as finance, environment and health, geography, and meteorology. All these factors must be taken into account when designing a PV grid-connected (PVGC) system.

In a grid-connected system, the PV system is connected to the utility grid. This means that during the daytime, the electricity generated by the PV system can either be used directly or transferred to the utility network. The PVGC power plant reduces the power taken from the utility power grid during the daytime and integrates the power demand of the load. At nighttime, the PVGC power plant is unable to provide the electricity required, and therefore during this time, the power is generated from conventional power plants. The PVGC system is able to use the utility grid as a store because the system does not require storage batteries. By 2010, transmission networks in Saudi Arabia were almost completely connected, and therefore installing PVGC would help to feed the loads to customers connected to the national grid.

The use of PVGC has been growing internationally since 2000 [1] and has a large advantage over PV stand-alone systems in that initial costs are reduced by approximately 40% [2]. The initial capital costs of a PV power plant are 2000–4000 $/kW [3], and these costs are falling with new developments coming onto the market.

2. Grid-Connected Systems

The PV generator is a number of strings connected in parallel, and a string is a number of series-connected PV modules. This configuration of parallel/series connections determines the current and voltage of the system. The PV generator is connected to the utility grid through inverters in the case of the grid-connected system. These inverters convert the DC power from the PV arrays into AC power at a voltage and frequency that can be accepted by the utility grid. PVGC systems may have a centralized inverter layout (plant-oriented), string inverter layout (module-oriented), or individual inverter layout (module-integrated) (summarized in Table1)[4].

Table 1. Comparison of PVGC Layouts

Plant-oriented	Module-oriented	Module-integrated
Connection in parallel and/or in series on DC side	Several modules connected in series on DC side, and parallel connection on AC side	Connection in parallel and/or in series on AC side
One inverter for the entire PV power plant	One inverter for each string	Individual inverter per PV module
Nominal inverter power of up to several MW	Inverter power of up to 2 kW	Inverter power of 50–400 W

3. Sizing of PVGC Power Plants

Normally, for PVGC, the installed power is not of great importance [5], and an array size is suggested by the designer. Accordingly, in the present paper, the suggested sizing of PVGC power plants is based on a fraction of the total electrical loads. The suggested DC/AC inverter power is equal to the nominal array power. In grid-connected plants, the inverters reproduce the exact network voltage. The sizing of power transformers depends on the PV plant peak power [6]. These transformers are required to boost the inverter output voltage to the voltage of the utility network.

Simple calculations are normally conducted to determine the number of PV solar panels needed to meet the required demand. The number of series PV modules per string, M_s, can be determined via Eq.1. The total required number of PV modules, M, is given by Eq.2, and the number of strings of modules in the PV array, M_p, can be calculated via Eq.3. The number of modules M_s is determined by the selected voltage, and M_p is given by the current required from the plant. The current I_m and voltage V_m at the maximum power point (MPP) are needed to calculate the number of panels required to cover a given load. Operational MPP can be considered in the design via Eq.6. The values of PV parameters change for other conditions of irradiance and temperature, and for this a sizing factor is introduced to oversize the amount of current available from the array according to Eq.4 [7].

$$\mathbf{M_s} = \frac{V_{in}}{V_m} \qquad (1)$$

where V_{in} is the required input voltage.

$$\mathbf{M} = \frac{\text{Nominal capacity of PV power plant}}{MPP} \qquad (2)$$

$$\mathbf{M_p} = \frac{M}{M_s} \qquad (3)$$

$$I^A = \frac{\text{Nominal capacity of PV power plant}}{V^A} \qquad (4)$$

where I^A is the total current of the PV array, and V^A is the output voltage of the PV array.

The land area required for the PV power plant can be calculated according to solar radiation h, nominal capacity of the PV plant, and efficiency of the solar module [5], as shown in Eq.7. This equation can be derived via Eq.2 and Eq.6.

$$\mathbf{A} = \mathbf{M} \times \mathbf{A_{module}} \qquad (5)$$

$$\mathbf{MPP} = \eta_{PV} \times h \times A_{module} \qquad (6)$$

By substituting Eq.6 and Eq.2 into Eq.5,

$$\mathbf{A} = \frac{\text{Nominal capacity of PV power plant}}{\eta_{PV} \times h} \qquad (7)$$

The yearly energy delivery E_y in kWh/year is defined as the following [3]:

$$\mathbf{E_y} = H_y . K_p . P_{max} \qquad (8)$$

where K_p is the performance ratio of the system, indicating loss accumulation; H_y is yearly solar radiation in kWh/m^2/year divided by 1000 W/m^2 [8]; and P_{max} is the installed peak power under STC.

Typical values of K_p for well-designed grid-connected systems are 0.7 to 0.8 [3]. For sizing a PVGC system, a safety (sizing) factor must be considered as well as factors such as reduction of module efficiency due to dust accumulation on the solar modules, changes to the load profile, and variations in weather conditions.

The fill factor FF is a measure of sharpness of the knee in an I-V curve [9] and indicates the quality of the PV module. The I-V curve indicates the electrical characteristics of the PV cell. Typical values of FF are between 0.7 and 0.8, with the maximum value of 1. It can be represented by the following formula:

$$\mathbf{FF} = \frac{I_m \times V_m}{V_{oc} \times I_{sc}} \qquad (9)$$

where I_{sc} and V_{oc} are the short-circuit current and the open-circuit voltage of the PV module, respectively, and I_m and V_m are maximum current and maximum voltage of the PV module, respectively. The short-circuit current is the higher value of the current generated by the PV and is obtained under short-circuit conditions. The open-circuit voltage is the PV voltage during the nighttime.

A PV module would attain maximum efficiency if the angle of incidence of solar radiation was always 90° [10]. Most PV modules are supported at fixed positions. The advantages of this design are simplicity, no moving parts, and low cost. The tilt angle ( ) of the PV array is usually set at the annual optimum tilt angle. The annual optimum tilt angle depends mainly on the latitude of the location [11], and the array faces due south for the northern hemisphere or due north for the southern hemisphere in order to face the sun [12]. Sun-tracker systems increase the solar energy collected by up to 40% [3, 7] compared with fixed-tilt systems, but the disadvantages of sun-tracker systems include complexity and high cost because of the maintenance required. Tracking systems are important and recommended only when concentrated PV cells are used. As discussed above, the optimum fixed orientation is usually suggested to be south-facing in the northern hemisphere, and thus a fixed-tilt angle toward the south with flat panels is used for PVGC systems in Saudi Arabia (Figure 1) according to the latitude of the selected location.

Figure.1 Tilt Angle of Photovoltaic Module

4. Design Procedures

To design PVGC power plants, many elements must be specified, which include, but are not limited to, specifications of the

- Grid
- Solar PV power plant
- Inverter
- Transformer
- PV module

The design of a PVGC power plant requires the following steps, which must be input into suitable computer software for calculation:

1 Determination of overall forecasted electrical loads

2 Determination of the required percentage and the equivalent value in MW to be covered by solar power plants during peak load period

3 Determination of PVGC location with associated average solar irradiance in W/m^2

4 Determination of PV module specifications

5 Determination of capacity for each solar power plant

6 Determination of essential land area in m^2 to construct the PV system

7 Determination of number of PV modules to provide the required power

8 Determination of parallel and series branches for PV arrays to obtain suitable values of voltage and current

9 Selection of tilt angle for the PV array according to the latitude of the power plant location

10 Selection of suitable inverter to convert the DC output of the solar array to AC system

11 Selection of appropriate power transformers to boost output voltage from the inverter

12 Calculation of total cost for each solar power plant

13 Calculation of the reduction in greenhouse gas emissions

5. PVGC Software Analysis

We constructed a PVGC program via Microsoft Visual Basic 2010. This visual PVGC software is intended to be a tool for designing solar PVGC power plants according to user-input data and required specifications. The results are displayed in specific windows of the PVGC software and can be printed at the end as a report form. The PVGC software consists of a Home window, Project Information, Introduction window, Main window, Design Parameters, Conditioning System, Tilt Angle, Cost of PVGC Plants, Reduction of GHG (greenhouse gas) Emissions, and Report.

PVGC power plant design in Saudi Arabia is expected to be implemented via PVGC software. PV-generated electricity in Saudi Arabia should be ready for action by 2020 [13]. The proposed design of PV power plants in Saudi Arabia should cover 15% of the expected load by 2020, which is estimated to be 75155 MW. Consequently, the capacity of PVGC power plants will be approximately 11273.25 MW. The first step to designing PV power plants via PVGC software is to register the project's information. The Project Information window contains five icons (Figure 2).

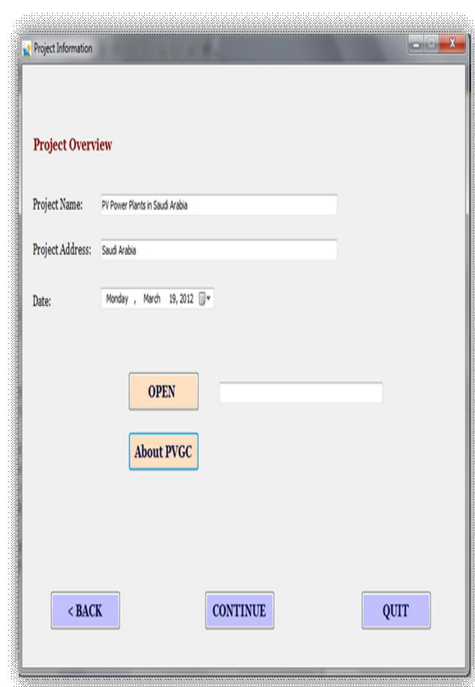

Figure.2 Project Information Window

The Introduction window (Figure 3) contains the main parameters of the network and PV power plants. Total expected load by 2020 in Saudi Arabia (75155 MW) and percentage required from solar power (15%) were input as system parameters. The parameters of PV power plants, required modules, and suitable location were selected at the same stage. A monocrystalline module with a maximum power of 300 W and efficiency of 15.4% was chosen in the design for all PV power plants. The ambient temperature was set to the nominal value of 25°C. The pollution factor is required as a percentage, and its default value in the program is 0% because until now there was no representation of the effect of pollution, e.g., dust as a ready value to be deducted from the efficiency of the PV module. Many practical studies are needed to measure the effect of pollutants on the efficiency of PV modules.

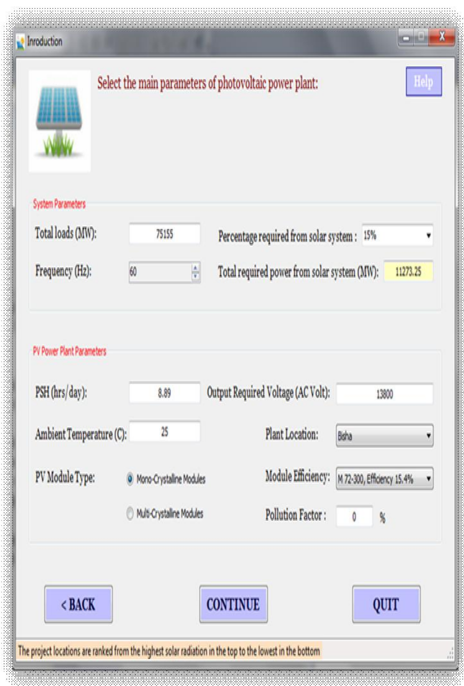

Figure.3 Main Parameters of Photovoltaic Power Plants

The plant locations are ranked according to solar radiation, with the highest solar radiation at the top. The PVGC program is sufficiently flexible to enable a new location to be added by selecting "other" from a dropdown list by *Plant Location*; the user is then asked to enter location name, solar radiation, latitude, and longitude of this new location (Figure 4).

The same applies when the user needs to change the PV module data: Selecting "other" from the dropdown list by *Module Efficiency* brings up a dialog box (Figure 5) for the user to enter the necessary data on the new PV module.

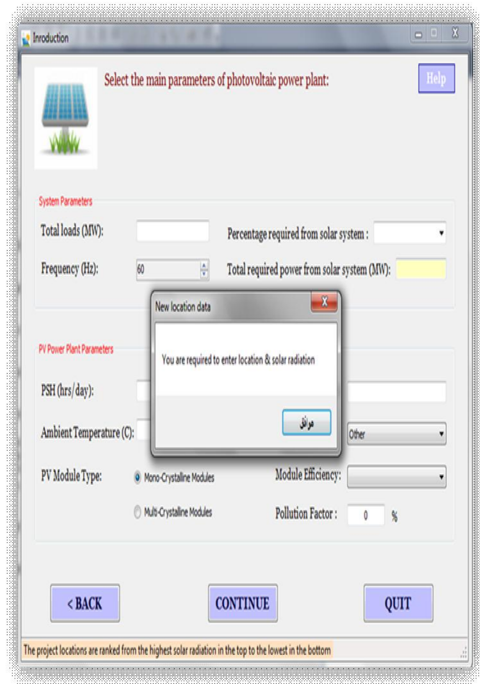

Figure.4 New Location Data

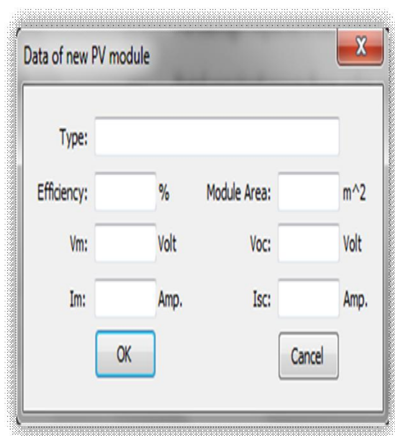

Figure.5 Data of New Photovoltaic Module Dialog Box

In the Main window, the user is required to enter the capacity of the PV power plant or to determine the land area in m^2. A sizing factor of 0%, 5%, or 10% may be chosen according to the design requirements of the user. The results (Figure 6) comprise location, module type, solar radiation, PV plant capacity, latitude, longitude, required area, and the fill factor of the PV module.

The Design Parameters window displays the number of series modules, number of parallel modules, total number of modules, array current, array DC voltage, and MPP of PV modules at the ambient temperature (Figure 7).

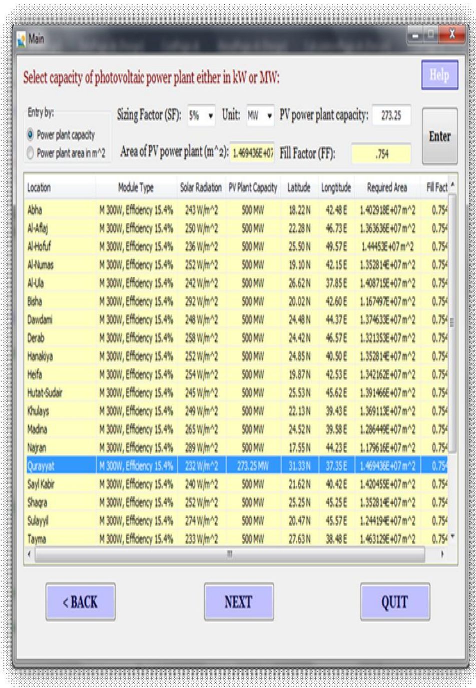

Figure.6 Main Data of Photovoltaic Power Plants

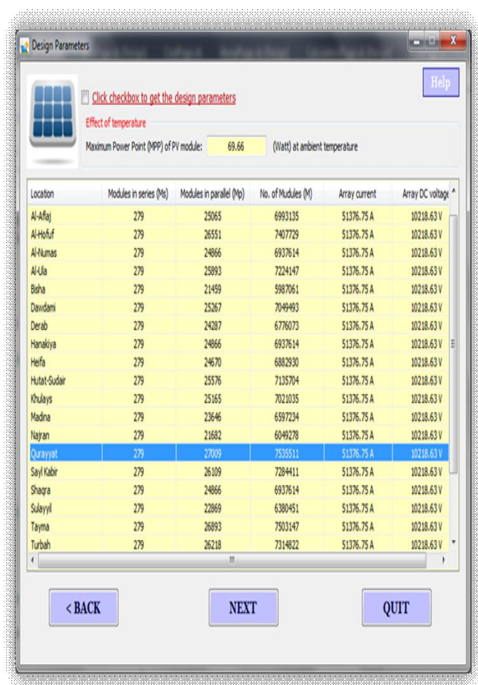

Figure.7 Design Parameters of Photovoltaic Power Plants

In this step, the power conditioning system is considered, such as using inverters to convert the system from DC to AC and power transformers to boost the output voltage of the solar power system. The rating of step-up transformers may be changed to any value as per the user's requirements. The same applies for determining the efficiency of the inverter. The inverter input voltage, output voltage, rating, and type, and the number of transformers, power transformer rating, and transformer ratio may be determined by selecting one of the listed PV plant layouts (Figure 8).

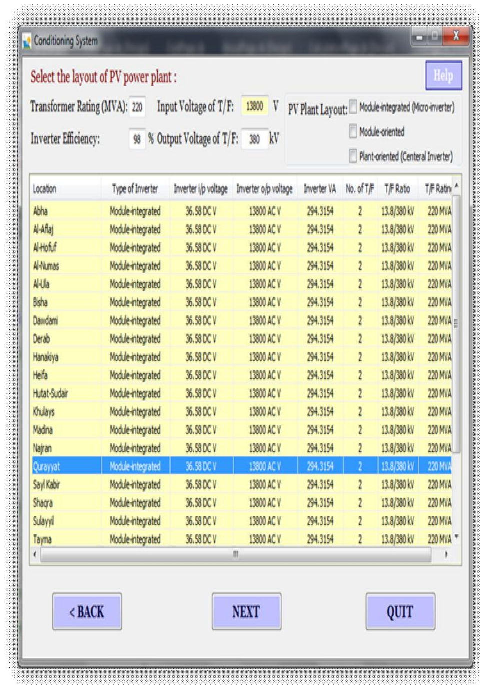

Figure.8 Conditioning Systems of Photovoltaic Power Plants

The tilt angle of the PV module is determined in this step according to the latitude of the selected location. The PV modules are mounted in the design at a fixed angle from the horizontal. In addition, the suggested direction of the PV module is described for each location (Figure 9).

Costs of PV power plants are categorized as cost of PV modules, cost of inverters, cost of transformers, and total cost of the plant. Three questions are asked at this stage if cost changing of the PV module, solar inverter, or power transformer is required (Figure 10 and Figure 11), otherwise programmable costs are used. The user can obtain these costs for each plant in either US$ or Saudi riyals (Figure 12). The tariff of solar energy for a specific PV power plant also is also calculated.

The final step is related to reducing greenhouse gases, which is given in terms of annual reductions in the amounts of CO_2, SO_2, and NO_x emissions. To calculate these reductions, the amount of annual energy in MWh from each PVGC power plant is calculated via Eq.8. Accordingly, CO_2 reduction, SO_2 reduction, and NO_x reduction values are obtained for each PVGC plant (Figure 13). The total reduction in greenhouse gases for all required PVGC power plants is calculated via Eqs.10–12 [13].

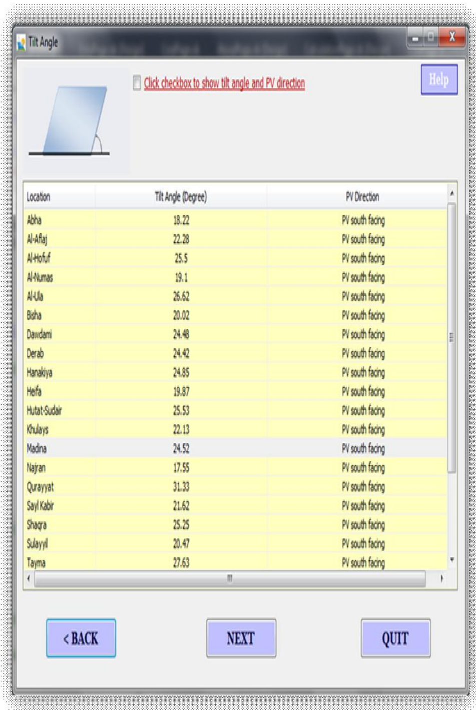

Figure.9 Tilt Angles of Photovoltaic Power Plants

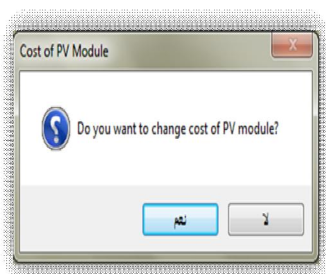

Figure.10 Dialog Box for Cost of Photovoltaic Module

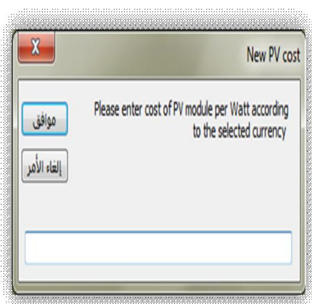

Figure.11 Dialog Box for New Photovoltaic Module Cost

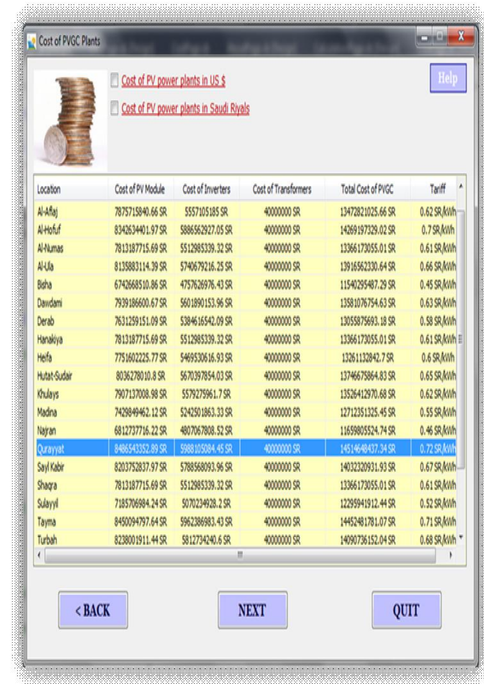

Figure.12 Costs of Photovoltaic Power Plants

CO_2 reduction = CO_2 emission (180 g/kWh) $\times$ Ey (10)

SO_2 reduction = SO_2 emission (3.16 g/kWh) $\times$ Ey (11)

NO_x reduction = NO_x emission (2.13 g/kWh) $\times$ Ey (12)

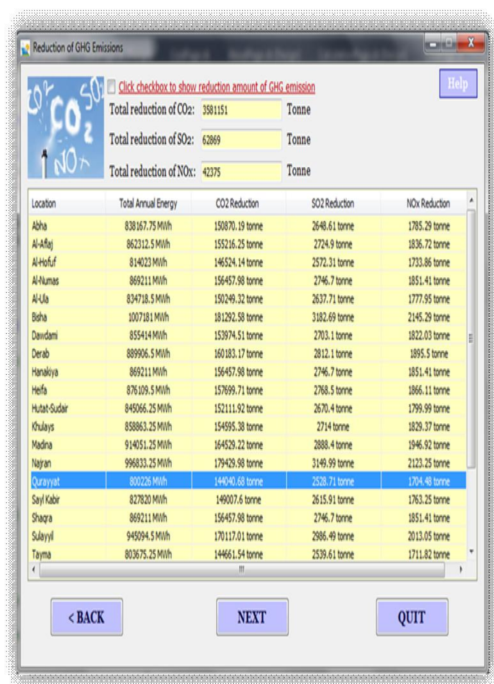

Figure.13 Reduction of Greenhouse Gases by Photovoltaic Power Plants

The Help window (Figure 14) offers a guide to using the PVGC software. It can be accessed from any window from the Introduction window to the Reduction of GHG Emissions window.

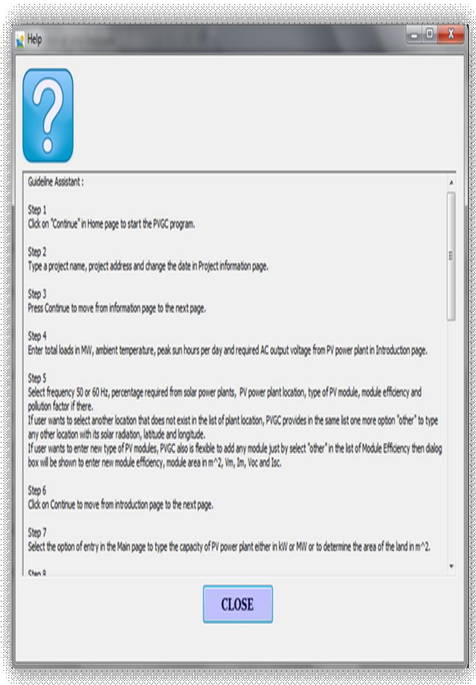

Figure.14 Help Window

Finally, all data inputs and results are shown as a simple report. This report can be printed by selecting *Report* (Figure 15), and each page of the report may be printed individually upon the user's request. The full project can be saved by selecting *Save*.

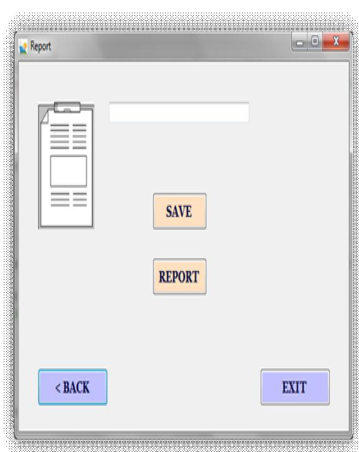

Figure.15 Report and Printout Window

6. Conclusion

The total size of PVGC power plants in Saudi Arabia is based on the fraction of the expected total electrical loads in 2020. This fraction is considered to be 15% of total loads, which is approximately 11273 MW. This would reduce environmental pollution and save emissions of 3581151 ton of CO_2, 62869 ton of SO_2, and 42375 ton of NO_x, as shown in the results obtained from the PVGC software. The tariff cost of PVGC power plants in this design varies between 0.45 and 0.72 Saudi riyal/kWh, and the average tariff cost is 0.62 Saudi riyal/kWh.

The nominal capacity of individual PVGC power plants was set to 500 MW to match that of projects currently under construction around the world. The PV modules are 300 W monocrystalline type because these are of suitable efficiency compared with other types. The major parameter for sizing PV arrays is solar radiation, where locations with the highest solar radiation should have the lowest number of PV modules. The values of PV parameters should be changed according to variation in solar radiation and ambient temperature, and accordingly, a sizing factor should be introduced.

Our analysis of PVGC software shows that the most significant factor in the design of PVGC power plants is solar radiation. The total number of PV modules, land area of PVGC power plants, cost of PVGC power plants, and tariff are inversely proportional to the intensity of solar radiation at the same capacity, whereas MPP, total annual amount of energy, and reduction of greenhouse gases are directly proportional to solar radiation. It was found that the efficiency of PV modules changes inversely with ambient temperature, and that the performance of PV modules is affected by the accumulation of dust on PV module surfaces.

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