Design, feasibility study and environmental analysis of a grid connected PV system in Cambodia

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Abstract

Cambodia's economy is growing rapidly as its CO_2 emissions. The low quality of the electricity from the grid, its high price and the country high insolation make Cambodia favorable for the development of solar energy. The thesis aims to analyze performance indicators of the expected production of a medium-scale PV system connected to a MV grid. A garment factory in Cambodia has been analyzed, with PVsyst software, as case study. The influence of the recently approved new solar regulation was added to the traditional energetic, technological, economic and environmental performance indicators. The project design together with the shading analysis of the system for the garment factory have been developed. With PVsyst software, the solution that maximizes the performance ratio has been found to be 707 kWp, with JKM340PP-72 polycrystalline modules from Jinko Solar coupled with SUN2000-36KTL Huawei inverters. The result has been guided by the regulation restrictions of no grid export and PV system size limited to less than half the contracted size. From the economic assessment of the project has emerged how the investments are affected by the regulation. The pay-back time of the system goes from around 4 years with the old regulation to more than 65 years with the new regulation. Both the NPV and net cash-flow, which were positive with the old regulation, are now resulting in extremely negative values. Nevertheless, from the carbon balance of the project has emerged that the installation can save up to 11200 tCO_2 during its lifetime.

1. Introduction

Cambodia, located in the tropical area of Southeast Asia in the Lower Mekong region, has an extremely bad Environmental Performance Index (EPI) with a rank of 150 out of 180 countries. Several years of war (1979-91) have critically damaged Cambodia's power and communication sectors putting an already fragile economy in crisis. After the restoration of order in the country, the Government has followed a program focused on rehabilitation and development of the basic infrastructure, with the aim of improving the socio-economic conditions. Without energy, promoting economic growth, overcoming poverty, and supporting human development are impossible [1].

Indeed, sustainable energy is the 7th of the 17 UN Sustainable Development Goals to ensure access to affordable, reliable, sustainable, and modern energy for all by 2030. Despite Cambodia now is one of the fastest growing economies in Asia with an average GDP growth rate around 6 percent over the last decade [2], there are many factors that prevent the agriculture in favor of garment, textiles, and tourism sectors. These sectors are expanding, bringing increased foreign investment and international trade but the development is facing many difficulties. Cambodia ranked 183 out of 190 countries in the 2017 World Bank Doing Business report [3] to start a business and 137 to get electricity. Solar power has a critical role to play to meet the United Nations Sustainable Development Goals and to facilitate the business development in the country.

2. Cambodia State of Art

Cambodia have three major institutions of electricity industry: the Minister of Mines and Energy (MME), which is the primary policy making and planning entity, Electricity Authority of Cambodia (EAC), which is an autonomous agency established under Cambodia's Electricity Law that has its own budget funded from license fees, and Electricité du Cambodge (EDC), which is the state-owned electricity supplier with responsibility for the generation, purchase, transmission and distribution of electricity throughout the country. EDC is the only entity licensed to conduct activities across the full electricity supply chain. Nevertheless, Cambodia has always been heavily dependent on the private sector to generate electricity and sell it to EDC due to financial constraints. Those private third parties are called Independent Power Producers (IPPs). IPPs were formalized following the creation of EAC which licensed them and brought them under regulatory control. In more recent years, third party entities have also entered the transmission and sub-transmission sectors.

The electric grid has expanded rapidly, with the electrification rate greatly increasing, from the initial percentage of 9.3% in 1997 to 34.4% in 2009 and to 56.1% in 2014 [4]. At the present time in Cambodia, 100% of the urban population have access to electricity while only 36.5% of rural population have it [5]. The first problem of Cambodia's electricity system is the generation capacity that is lower than the total consumption. With the establishment of the connection with Thailand in 2007 and with Vietnam in 2009, the imports have replaced the internal generation, reaching in 2011 about two third of the country needs. Big step forwards have been made after 2013 with the growth of hydropower and coal to make the electricity system more independent from the neighboring countries [6]. The imports are still high, with almost 19% of imports from other countries in 2017, but the trend is decreasing. Heavy investment in the extension of the transmission grid has significantly increased the proportion of people with access to electricity and aims to have a wider coverage of the territory. In fact, multiple generation projects are in the pipeline in order to increase the energy generation to become more energy independent and cover energy demands when access to electricity increases. These projects comprehend two 135 MW coal fired plant, one 400 MW hydroelectric power plant and two small projects for a 10 MW solar farm and 8 MW biomass project.

Another challenge to the electrification of the country, and in particular to the development of businesses such as big garment or textiles factories, is the high price of electricity. The average price of electricity in Cambodia for a LV consumer is between 800 and 1000 Riels/kWh (0.20-0.25 USD/kWh), the highest price of all other Southeast Asian countries. What makes the price even more inadequate is the quality of the service. While in the capital city power cut-offs are quite isolated, in the provinces they occur almost every day and they can last for multiple hours.

Solar power in Cambodia is currently a very small industry that is trying to emerge with different results depending on the context, but it could be the solution for many challenges that the energy sector is facing. It can decrease the dependency on fossil fuels and on imports from other countries, it can cut the electricity costs thanks also to the Power Purchase Agreements (PPA) and, with batteries or generator as a backup option, can be the solution for the unstable grid.

On the 26th of January 2018, EAC approved a new regulation, "On General Conditions For Connecting Solar Generation Sources To The Electricity Supply System Of National Grid Or To Electrical System Of A Consumer Connected To The Electricity Supply System Of National Grid" [7].

The key points of the new solar regulation are:

- The regulation affects only grid connected solar system. Off-grid solar installations are not affected by the new regulation.
- No electricity can be injected into the grid, only EDC has the right.
- The maximum capacity of solar cannot exceed the 50% of contracted power.
- Only Big Consumers (MV) and Bulk Consumers (HV) are allowed to connect and synchronize the PV systems with the grid.
- MV and HV consumers that want to install solar and synchronize to the grid will have to apply to EDC for a license to install solar.
- MV and HV customers that install solar will be moved to a new tariff structure called "the tariff for consumers with the solar PV system"

The new tariff has been split into a fixed contracted load charge and a consumption charge. The prices per kWh will be 50% lower in average than the previous ones but the fixed load charge based on the transformer size (or on the contracted size if no transformer is present) are extremely high. Solar installations would have now to compete with really low price of energy, comparable with the current PPA contracts, and a high fixed charge that will make the solar investment hardly favorable. Moreover, the regulation presents lots of uncertainties and is not clearly defined. For instance, it is not clear if the contracted size can be varied to meet the real consumption since EDC tends to oversize the transformers meaning higher expenses with the new regulation. As result, most investors have put their projects on hold until further information are released or until someone else "try and see what happen".

3. Garment Factory Case Study

A garment factory in the suburb of Phnom Penh has been analysed both to see the solar potential in Cambodia and the impact of the new solar regulation on the economics of a solar project.

The garment factory is a MV consumer, connected from a MV (22kV) distribution network, it has two different transformers, namely T1 and T2, both of 1000 KVA, that are under the same contract. The electricity bill amounts to more than 20,000 USD/month and thus solar installation would be evaluated to reduce electricity costs and ease the business.

The first site visit has been done in order to establish whether the building was suitable to install a solar system and to measure the load profile. The garment factory presents a normal metal roof, typic of Cambodian environment, it is quite robust and permits to install the rail structures for the solar panels or to mount them directly on its surface. The available area is huge and free from any shading obstacle, thus perfect for the PV installation. The load profile measurement has been done with two different power analyzers connected to the two different transformers of the factory. Even if the ideal time for a load measurement would be one year in order to perfectly model the consumption profile, due to practical limitations the power analyzers have been connected slightly more than one week. The typical weekly load profile of T1 and T2 have been then computed in Excel to create a file to upload in PVsyst for the user needs simulation. From the weekly profile, a yearly consumption profile has been created taking into account the average load during working days and on holiday days. The load profile created considers also the holidays during the year and presents a difference of 0.57% from the actual electricity bill and has thus been considerate adequate for the simulation. The consumption pattern has been then used for the PVsyst simulation to compare the possible solar production with respect to the internal consumption.

The solar system must be smaller than half the size of the transformers with a correction factor of 0.9 from KVA to KW and the energy exported to the grid should be minimized to avoid losses due to the zero export to the grid imposed by the regulation. Both transformers of the factory have been found oversized. While both transformers are 1000 KVA, T1 peak load is slightly lower than 500 kW while T2 does not reach 200 kW.

After the site visit and the load profile measurement, a preliminary design has been done. The 3D model of the buildings has been created with SketchUp and Skelion plugin has been used to simulate the possible PV system size. The fast shading simulation with respect to the 3D area designed has also been performed with the software and have shown no near obstacles for the PV field. The roofs resulted oriented with an azimuth of -4° and a tilt of 8° and thus almost in the perfect condition for Cambodia. Two solar system has been designed: one to be connected with T1 and the other one with T2. They would be independent and mounted on two different roofs (with same azimuth and tilt). Each system is 30 m far from the electrical rooms where the respective inverters must be placed.

4. System Design with PVsyst

To design the solar system, to model the losses and to predict the energy output of the PV arrays, PVsyst software has been used. Meteonorm 7.2 database integrated in the program has been used as source for the horizontal global and diffuse irradiation, temperature, wind speed and Linke turbidity. PVsyst considers the orientation of the PV system (tilt angle and azimuth), its location on the Earth's surface (latitude and longitude), the available global solar radiation and the time when this energy is available to predict the PVsystem production. From the horizontal irradiation data present in the meteo file, the program can use two different transposition methods to transform them into the tilted ones: the Hay model and the Perez-Ineichen model.

Hay's model to compute the total radiation on a tilted surface (I_T) is an improvement of the isotropic model that tended to underestimate I_T. It assumes that all diffuse radiation can be presented by two parts: the isotropic and the circumsolar. The Perez-Ineichen model is a more "sophisticated model" and is based on a more detailed analysis of the three components of the diffuse radiation. Hay's model, the simpler one, has been used in this study. This method presents average values 2% lower than the Perez-Ineichen model regarding the yearly yield of a PV system and would thus results in a more conservative option [8]. It has also been found that it is more suitable for modules oriented close to 0° azimuth and at latitude close to the equator where the critical radiation levels are significant. Because of these reasons it has been set in PVsyst as transposition model for the simulations.

The reference temperatures of the system for the correct modules/inverter sizing have bee set with regards to the local environment. Equation 1 has been used to compute the cell temperatures with respect to the extreme conditions of Cambodia's environment (winter and summer).

$$T_{cell} = T_{amb} + \left(\frac{NOCT - 20}{800}\right) G \qquad (1)$$

T_{cell} is the cell temperature, T_{amb} is the ambient temperature, NOCT is the normal operating cell temperature as referred by the panel manufacturer under an irradiance of 800 W/m^2 and G is the effective solar irradiance. The temperature set in the program are listed in Table 1.

Table 1 - Reference temperatures for modules/inverters sizing.

Site dependent design parameters	
Low temperature absolute limit	12°C
Winter operating temperature for VmppMax design	20°C
Usual operating Temperature under 1000 W/m^2	62°C
Summer operating temperature for VmppMin design	80°C

The PV arrays and the inverters need to match in three areas: power, voltage and current. First, the input power of the inverter limits the maximum number of panels that can be connected to it, the inverter should be in the range of $0.8P_{PV} < P_{INV,DC} < 1.2P_{PV}$ where P_{PV} is the peak power of the PV system and $P_{INV,DC}$ is the maximum input power of the inverter. Second, the voltage range of the array should be within the MPPT voltage range of the inverter. Finally, the current of the strings connected in parallel cannot exceed the maximum input current of the inverter. In PVsyst, the inverter sizing is based on an acceptable overload loss during operation, and therefore involves estimations or simulations in the real conditions of the system (meteo, orientation, losses). Considering these constrains three different modules and two different inverters have been simulated with the program to understand which system combination would perform better. JKM 340PP-72-V polycrystalline modules from Jinko Solar (340 Wp and 17.52% efficiency), CS6U-335P polycrystalline modules from Canadian Solar (335 Wp and 17.23% efficiency) and AS P72 320 polycrystalline modules from Antaris (320 Wp and 16.49% efficiency) have been simulated with SunnyBoy Tripower 25000TL JP-30 with a peak power of 25 kW from SMA and SUN2000 36KTL with a peak power of 36 kW from Huawei. The systems have been compared looking at the higher performance ratio (PR) achieved. In order to compare the PR of the systems, all the array losses have been modelled with PVsyst. Defining the PR as the ratio between the available energy at the output of the array and the ideal array yield at STC, all the following losses that can reduce the ideal yield have been analyzed:

- Shading losses and electrical effect
- Incident Angle Modifier (IAM)
- Irradiance losses
- Thermal behavior
- Real performance losses
- Mismatch losses
- Soiling losses

- Ohmic losses

Shading losses are the losses consequent to shaded area on the PV field. PVsyst distinguishes between far shading as an horizon line below the one the sun is not visible and near shading that are caused by objects near to the modules. In order to calculate the shading factor at any time as a function of the position of the sun, a full 3D representation of the field and its surroundings have been done in PVsyst and the detailed calculation of the impacts have been performed. The detailed calculation is based on the exact positions and connections of the modules and has thus been performed after the complete module layout definition.

IAM losses, meaning the decrease in the irradiance that effectively reaches the cells' surfaces due to the incidence angle, has been analyzed in this study using Fresnel's law.

Thermal losses, caused by the higher working temperature of the panels in comparison to the STC, have been computed considering the modules as semi-integrated and defining the consequent field thermal loss factor.

Real performance losses, meaning the difference between the performances stated by the manufacturers and the real ones have not been considered.

Mismatch losses are due to the fact that in a string of modules the lowest current drives the current of the whole string. In a real installation, the characteristics of the modules, also if they are of the same model, will slightly differ one from the other and has thus been considered in this study as well as the degradation caused by the ageing of the panels.

Soiling losses, the losses caused by dust on the panels, can be of primary importance in Cambodia because of the dirt roads and the chimneys often positioned on the factories roofs. However, for this study they have been considered equal to the normal city value of 2% since no chimneys were present on the garment factory roofs and because of a person working for the factory will be trained to clean the panels.

Finally, ohmic losses due to the global wiring resistance have been taken into account considering the effective cables length and cross section. This computation has been performed after the detailed module layout design in order to have better results.

To determine the best solution the PR of the different options have been evaluated. For T1 the maximum size allowed by the regulation of 450 kWp has been found adequate and all the options have been designed to meet the power target. T2 has been found highly oversized with respect to the peak load of the factory section connected to it. The system size has thus been defined taking into account an acceptable overall loss due to the export to the grid. Being energy injection into the grid not permitted, all the energy in excess will be prevented to be produced and thus wasted.

The combination that leads to the highest PR has been found to be the solution with Jinko Solar modules coupled with Huawei inverters.

The first system, connected to T1, has 63 strings of 21 panels each. Each string is connected to one of the 8 inputs of each inverter. 11 inverters will be connected to the system with a total of 88 different inputs available. The performance ratio of 80.13% is achieved. The system would produce 703.4 MWh/y of energy with a solar fraction of 42%. The specific production of 1566 kWh/kWp/y has been predicted from the simulation.

The second system has been sized to stay below the 20% export to the grid. This value has been set considering that an optimal solution covering 100%

of the weekly load would have led to an overproduction of more the 17%. The reasons are the working days of the garment factory and the lunch brakes that lower the peak load during the highest production hour of the solar system. The final layout has 36 string of 21 modules connected to 6 inverters (same type of panels and inverters of T1). The peak power of 257 kWp has been achieved with a yearly production of 403.4 MWh and a solar fraction of 60%. The system results in a high PR of 80.31%.

5. Economics and Environment

In order to determine whether the project is feasible, both from the economic and environmental point of view, an economic assessment on the project and a carbon balance analysis have been performed. In the economic assessment of the project, the prices of the balance of system (BoS), meaning all components of a PV system, have been computed together with the installation and engineer costs. Moreover, an analysis of the impacts of the new solar regulation has been done to show the consequences of such measure on the economics of a project in Cambodia. Furthermore, an environmental analysis has been performed with the help of PVsyst software to address the CO_2 emission reduction potential of a big PV installation in Cambodia. In **Errore. L'origine riferimento non è stata trovata.** are shown the economic costs of the project for the garment factory case study.

The modules cost accounts for almost 50% on the total cost including VAT and 56% of the total cost of the BoS, representing the most expensive part of the project. Inverters represent the 15% on the total price while the DC cables the 9% of the total and 10% of the entire BoS. It is important to notice that for big system this can represent an important part of the expenses, especially when is not possible to mount the inverters directly on the roof or closely to the strings. A correct disposition of the modules can make the difference for this part of the expenses. Without the leapfrog connection method used in this project for instance, the DC cables length (and thus cost) could have been up to 26% higher. Decrease the DC cables length decreases the ohmic losses and consequently the energy waste and the cost of the system. The final investment cost for this installation can be considered good for Cambodia. Installations prices for big systems normally range between 800 USD/kWp and 900 USD/kWp. Being this system cost equal to 825 USD/kWp means the design and the components have been carefully selected.

Table 2 - Investment cost and maintenance cost for the installation at the garment factory (707 kWp in total).

	Jinko & Huawei	*Unit*
Module	390.00	USD/kWp
Inverter	135.69	USD/kWp
Inverter manager	1,200.00	USD/piece
Mounting structure	9.20	USD/m
DC cables	3.65	USD/m
Shipping	56.50	USD/kWp
Total BoS	***692.11***	***USD/kWp***
Installation and Engineering	58.00	USD/kWp
Total incl. VAT (10%)	***825.12***	***USD/kWp***
Maintenance	1,000.00	USD/y

To analyze the profitability of the project, three different scenarios have been studied. The first scenario (1) analyzes the profitability of the project if the regulation would not have been approved. It thus represents the situation of PV projects before

January 2018. The second scenario (2) examines the project's profitability with the new regulation. It is of common habit in Cambodia to oversize the transformer for MV and HV consumer and the consequent contract type. Before the new regulation was approved this measure had no major impacts except for a higher initial installation cost. After the approval of the new regulation, and only in case of solar installations, with the contracted load charge split from the consumption charge, the impact of the transformers oversizing is significant. The third scenario (3) has thus been computed taking into account a possible modification in the electricity contract, considering possible a re-sizing of the transformers. In the case study of the garment factory where two different transformers were present, only the second transformer has been considered to be changed. Indeed, T2 is much more oversized with respect to the peak load in comparison to T1.

In order to evaluate the profitability of the project for the three scenarios, the yearly savings, the Pay Back Time (PBT), the Net Present Value (NPV) and the Return on Investment (ROI) have been computed for a lifetime of the project of 25 years. The LCOE of the electricity produced has also been computed to compare it with the grid electricity cost and with the PPAs rate. Table 3 summarizes the findings.

Table 3 - Economic indexes of the project for the three different scenarios.

Scenarios	*1*	*2*	*3*
Yearly Savings [USD/y]	**151773**	**-41419**	**9940**
Simple PBT [years]	***3.87***	***-***	***65.25***
NPV [USD]	**36429072**	**-1985563**	**-4892436**
ROI	**1.85**	**-2.01**	**-0.98**
LCOE [USD/MWh]	**67.82**	**67.82**	**67.82**

It can be noticed that the yearly savings decreases from more than 150,000 USD/y to less than 10,000 USD/y for the best-case scenario of the new regulation while without transformer re-sizing the savings would not be present. On the opposite, there will be losses. The PBT was less than 4 years for the old regulation scenarios while the third scenario have a PBT of more than 65 year, longer than the expected lifetime of the system, and the PBT of the scenario 2 can never be achieved. Also, looking at the NPV it can be seen how the regulation badly affects the solar projects. In case of the old regulation scenario the NPV would have been highly positive meaning the investment is recovered, the minimum rate of return of capital is achieved, a surplus is obtained and thus the project is feasible. For both new scenarios, NPV is highly negative, meaning the project is not profitable since the minimum rate of return is not achieved.

The net cash flow of the project has been plotted in Figure 3 to show the regulation impacts on the project finance. Green lines are referred to scenario

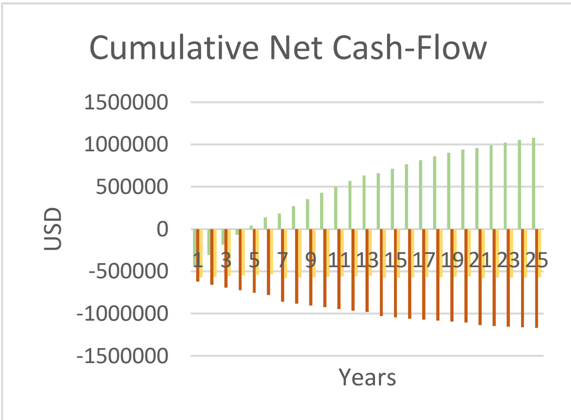

Figure 1 - Net cash flow for the three different scenarios.

1 while yellow and red are scenario 3 and 2 respectively. It can be seen that the net cash flow for the new regulation scenarios is deeply negative while with the old regulation would have been highly positive. Moreover, from the return on investment (ROI) can be seen the difference between old regulation and new regulation scenarios. ROI is a performance measure to evaluate the efficiency of an investment. It measures the amount of return on an investment, relative to the investment's cost. As can be seen from Table 3 while for scenario 1 ROI is positive and bigger than one, for scenario 2 and 3 it is negative, respectively -2.01 and -0.98, meaning there is no return on the investment but losses.

LCOE has been computed and results equal to 0.067 USD/kWh. This price is less than half the price of electricity with the old regulation and only 30% lower than the tariff of the new solar regulation.

The carbon balance of the system has also been computed with the help of PVsyst software to address the possible savings of the systems in terms of emissions reduction.

The total carbon balance depends on many factors:

- The system production, or energy yield
- The system lifetime
- The LCE of the electricity produced by the grid
- The LCE of the electricity produced by the PV system

The hardest part in calculating the carbon balance of a system is to compute the life cycle cost (LCE) of the electricity both from the grid and from the solar installation. Taking into account the energy mix of the country and the PV system specification for what concern the items shipping and the replacements during the expected lifetime of the project (25 years), the carbon balance have been computed. The values inserted into the program to compute the equivalent kgCO_2 emissions are based on a LCE study published by the International Panel on Climate Change (IPCC). They are not specific of Cambodia but can be considered a good average for an estimation of the global savings of the system.

From the computations have been found that the total system for the garment factory (T1+T2) can save up to 11296.549 tCO_2 during its lifetime meaning 451.9 tCO_2/y.

6. Conclusion

The analysis carried out for the garment factory has shown the high potential of solar energy in Cambodia while the economic assessment has proved how the new solar regulation prevents investment in this sector. Even with a low cost per kWp for the installation, because of the new regulation the investment results not profitable. The high fixed tariff prevents all the savings and the low electricity tariff limits the margin with respect to the LCOE of the system. In case of PPA, the investors that own the system, have to compete with a consumption charge that is less than half the price of the preview regulation one. The new consumption tariff is lower than the usual charge of PPA contract in Cambodia. With an LCOE of almost 7 cent/kWh the margin is minimum if a PPA tariff of 8-9 cent/kWh is applied and would not be capable of recovering the costs in the lifetime of the project. Moreover, the customer will not save money, on the contrary he would lose money due to the fixed tariff.

Without a revision of the reform about grid connected solar, the private investments would not be directed anymore towards renewable sector, solar in particular, and the CO_2 emissions will be hardly lowered in the country. Moreover, the economic sector that is growing rapidly in the country, will slow down due to the high costs and poor quality of the electricity from the grid.

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