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Capacity Credit of Solar PV Projects – Oman's Main Interconnected System Case Study

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Abstract

Due to high growth in electricity demand, it is important to add more dispatchable generation capacity in power systems to maintain demand-supply balance in real time. In many power systems, fossil fuel-based units such as gas or coal power plants are used to maintain high-reliability standards during peak demand hours. Although intermittent renewable energy generation facilities such as solar PV systems are used as a fuel saver, they can offset part of the load during peak hours. Capacity credit measures the contribution of a power plant to reliably meet demand. Estimating capacity credit of solar PV systems is important to ensure the adequacy and security of electricity supply. In this article, the capacity credit of solar PV power plants in the Main Interconnected System (MIS) of Oman is modelled. Oman's MIS considered in this study has 6,372 MW gas-based generation capacity, a negligible solar PV capacity, and 5,712 MW peak load. The results revealed that the capacity credit of solar PV plants is high at low solar PV penetration levels. However, it decreases drastically as solar PV capacity increases. For example, the first 500MW plant has a capacity credit of about 120 MW. When the cumulative installed solar PV capacity is 2000MW, the next 500MW plant has a capacity credit of only 26 MW.

Keywords

Renewable Energy; Solar PV; Capacity Credit; Main Interconnected System.

1. Introduction

Power generation from renewable resources solar power varies from hour to hour according to prevailing weather conditions. This is different to fossil-fuel generators, which can normally be dispatched according to their operators' preferences. In a competitive market, they can choose to generate when spot prices are sufficiently high. As the penetration of variable renewable generation technologies increases, the variable nature of their output will become a more important feature of power systems. In particular, it will have an impact on the amount of capacity required to be installed to meet peak system demand, and on the operating patterns of other generators [1].

Capacity credit or value or sometime called effective capacity is defined as the amount of additional load that can be served due to the addition of the generating unit, while maintaining the existing levels of reliability [2]. Alternatively, the amount of conventional generation the alternate energy source would replace without appreciable change in system performance [3]. Yet another definition is the amount of power (as an average output of the plant) which Transmission System Operator (TSO) expects. The Organization for Economic Cooperation & Development (OECD) and the International Energy Agency (IEA) define the capacity credit as the amount of variable renewable energy power that can reliably be expected at the times when demand for electricity is highest. The National Renewable Energy Laboratory (NREL) defines the capacity credit as the contribution of a power plant to reliably meet demand. According to the European Wind Energy Association (EWEA), the capacity credit of renewable energy is measured against the outage probabilities of conventional power plants. In special cases, PJM interconnection and New York Independent System Operator (NYISO) define capacity credit as the capacity factor during the daily peak load hours of the peak load months. Capacity credit is measured in term of kW, MW or GW. On other hand, capacity factor is the measurement of the average production of generation unit over a period as a percentage from its installed capacity [4]. It is important to determine the capacity value of generation resource to ensure that the system reliability met during power generation planning [5].

Reference [6] provides a review of solar capacity evaluation whereas [7] is an updated survey of methods and implementation of capacity value of wind. Authors of [8] presents practical experience in evaluating the adequacy of generating capacity by different regions in the Western interconnection. This includes an analysis of uncertainties associated with load, intermittent energy sources, and forced and maintenance outages on generating units and transmission facilities. Reference [9] provides a framework for capacity credit assessment of electrical energy storage and demand response. The impact of battery storage and solar PV installation on capacity credit improvement is investigated in [10]. This paper presents an approximate method of capacity factor to evaluate the capacity credit of committed solar PV plant of 500 MW in Main Interconnected System (MIS) of Oman.

In the MIS of Oman, power plants are supplied with natural gas by the Ministry of Oil and Gas (MOG). During the period from 2005 to 2014, natural gas production increased by 51% [11]. However, because of the substantial increase in natural gas consumption in energy-intensive industries, liquefied natural gas (LNG) exports decreased by 12% [11]. Although the contribution of renewable energy in the electricity supply mix is very small, several published studies have emphasized the potential of solar and wind resources in Oman.

Due to the fact that natural gas resources are tight and committed, policy maker in Oman are seeking to diversify electricity supply mix. In 2017, Council of Financial Affairs and Energy Resources (CFAER) approved a new national energy policy that mandates to have 10% minimum contribution of renewable energy in electricity supply mix by 2025. To reach this objective, the Authority for Electricity Regulation (AER) in Oman announced Sahim roof-top solar PV program in 2017. In 2018, the National Program for Enhancing Economic Diversification mandated that 11% of the country's electricity requirements through renewable energy sources by 2023. Oman Power and Water Procurement Company (OPWP) floated a tender in 2018 for a 500MW solar PV plant in Ibri. This solar plant is to be operational by 2021 [12-13]. Similar solar IPP projects are planned to be commissioned in 2022, 2023, and 2024.

Estimating capacity credit (value) of solar PV power is very important to ensure supply adequacy and security. The objective of this paper is to estimate capacity credit of committed and candidate Solar PV projects in Oman's Main Interconnected System.

2. Capacity Credit Evaluation Methods

There are several methods that can be used for estimating the capacity credit of a renewable energy project. In general, both generation and load models are required. The evaluation of capacity credit starts with forming the generation and load curves for knowing the capacity of generation system against the changes of load profile. The overall reliability of the system is then computed. After getting the system reliability at different operating points, the output of intermittent resource is used to calculate net load and the reliability of the power system is assessed again. The capacity credit of intermittent resource is obtained by comparing the system reliability with and without the intermittent renewable energy resource.

Methods for evaluating the capacity credit of renewable resources are often classified into two major categories as shown in Fig. 1. These categories differ in terms of process complexity and data requirements. The first category is reliability-based methods and includes Equivalent Conventional Power (ECP), Effective Load Carrying Capability (ELCC), and Equivalent Firm Capacity (EFC). These methods use power system reliability evaluation techniques, that include Loss of Load Probability (LOLP) and Loss of Load Expectation (LOLE) calculations. LOLP is the likelihood of a loss of load event during which the system load is larger than the available generating capacity throughout a given period. LOLP is usually computed in one-hour increments. The LOLE is the sum of the LOLPs throughout a planning period, typically one year. LOLE offers the expected range of time periods within which a loss of load event happens. Power system planners usually aims to maintain a pre-specified LOLE value, for example 0.1 days/year [14].

The second category uses approximations and are less complicated but varies in accuracy. These methods include Garver's ELCC approximation, Z-method, and capacity factor-based methods. These methods involve modeling conventional generator outages using an Equivalent Forced Outage Rate (EFOR). EFOR is the probability that a selected generator will experience a failure at any given time. Once renewables are added to a system, the system reliability models should also capture the variability of real-time resource availability. To do this, renewable resource availability is usually anticipated using historical information or by simulating such information [14].

Capacity factor approximation method considers the capacity factor of a generator over of a part of period while the system is facing a high risk of an outage events. This method was applied due to its simplicity and accuracy. There are three different approximation methods that differ based on the set of hours examined. The first one uses the average capacity factor during the peak-load hours. The second one uses the capacity factor during the peak-LOLP hours. The third one uses the highest-load hours and normalizes the capacity factors using LOLPs in order to give more weight for the contribution during hours with high LOLPs [14]. Due to its accuracy, the third method is used in this study. The authors of [14] suggest the 10-30% of hours yield sufficient accuracy. In this study, all hours are used and capacity factors are normalized using LOLPs to improve accuracy.

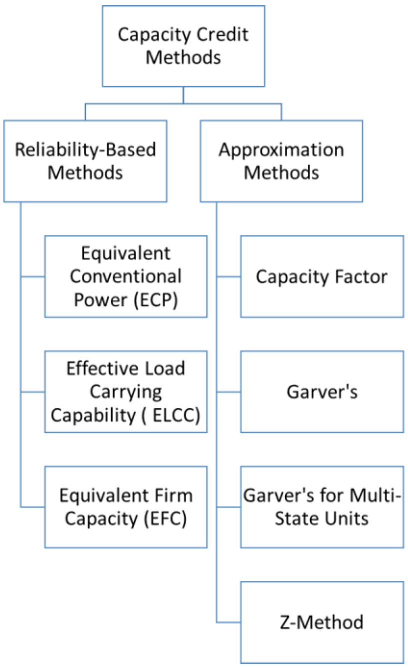

Fig. 1. Classification of capacity credit calculation methods

3. Capacity Factor Approximation Method – Simple Example

To highlight the calculation steps, a simple 3-unit test system is considered as shown in table 1.

- Step#1: Outage State Estimation

This method starts with calculating units' availabilities from Forced Outage Rates data (FOR) of the generation system.

$$Availability = 1 - FOR \qquad (1)$$

Table 1 Generating System of 3 Units

Units	*Max. Net Available Power MW*	*FOR*	*Availability*
A	100	0.03	0.97
B	200	0.05	0.95
C	300	0.07	0.93
Total	600		

The probability of the units to be in service or on outage at different loading conditions are calculated as shown in Table 2.

Table 2 Outage State Estimation

On Outage	*X MW on Outage*	*In service*	*Probability*	*Probability of X MW or More on Outage*
None	0	A,B,C	0.857000	1.000000
A	100	B,C	0.026505	0.143005
B	200	A,C	0.045105	0.116500
C	300	A,B	0.064505	0.071395
A,B	300	C	0.001395	0.006890
A,C	400	B	0.001995	0.005495
B,C	500	A	0.003395	0.003500
A,B,C	600	None	0.000105	0.000105
Total			1.00000	

The probability of a given outage configuration is obtained by multiplying the availability of the units in service and FOR of the units on outage. The Probability of X MW or more on outage is calculated as following. First row is the sum of all probabilities second row is the previous cell minus the first probability and so on.

- Step # 2: LOLP calculation without PV power

Table 3 shows the daily peak of one-week load profile. The capacity or more on outage (column 3 of table 3) is obtained by subtracting each daily peak load from the available system generation capacity of 600 MW. The LOLP in column 4 of table 3 is obtained by inspecting columns 2 and 5 of Table 2. For example, LOLP of 0.0035 (column 4 in Table 3) of 480MW or more on outage corresponds to the probability of X MW or more on outage of 500 MW from Table 2.

Table 3 Index of LOLP

Day	*Daily Peak Load (MW)*	*Capacity or More on Outage (MW) (600 – Daily Peak Load)*	*Probability of not Meeting Load (LOLP)*
Sunday	120	480	0.003500
Monday	170	430	0.003500
Tuesday	250	350	0.005495
Wednesday	330	270	0.006890
Thursday	390	210	0.006890
Friday	440	160	0.116500
Saturday	490	110	0.116500
		Total	**0.259275**

- Step # 3: LOLP with PV system

Table 4 assumes that the solar PV system produces power between 88.598 and 96.876 MW during daily peak time (column 2). This production is considered as a negative load as it will reduce the net load seen by the generation system. Therefore, it is expected that capacity credit of this PV system is between 88.598 and 96.876 MW.

The new net daily peak load become less by the PV system output compared with the load before adding the solar PV system. The probability of not meeting the load or $LOLP$ is calculated again for the system as follows. The capacity or more on outage will be the whole system power (600 MW) minus the net load after adding solar PV power. The $LOLP$ with the PV system is obtained from columns 2 and 5 in Table 2. For example, if the capacity or more on outage equal to 570.123 MW (column 4 of table 4), take the probability of X MW or more on outage of 600 MW from Table 2 and fill it on column 5 of Table 4. From Tables 3 and 4, it is clear that the $LOLP$ after adding PV system is less than the previous $LOLP$.

Table 4 Index of $LOLP$ with PV

Day	*PV Output (MW)*	*Net Daily Peak Load (MW) (with PV output)*	*Capacity or More on Outage (MW)*	*Probability of not Meeting Load (LOLP with PV)*
Sunday	90.123	29.877	570.123	0.000105
Monday	93.786	76.214	523.786	0.000105
Tuesday	91.772	158.228	441.772	0.0035
Wednesday	88.598	241.402	358.598	0.005495
Thursday	94.546	295.454	304.546	0.005495
Friday	96.876	343.124	256.876	0.071395
Saturday	95.112	394.888	205.112	0.071395
			Total	**0.15749**

- Step # 4: Calculate the Capacity Credit

Table 5 shows the capacity credit CC which is calculated using the following equations:

$$w_i = \frac{LOLP_i}{\sum_{j=1}^{T} LOLP_j} \quad (2)$$

Where w_i is the weight in hours i, $LOLP_i$ is the $LOLP$ in hours i and T is the number of hours in the research. The average weighted generation, β_i, of the PV plant in the highest load-hours is calculated from pervious weights and PV output (PV_i) during those hours as follows:

Table 5 Capacity Credit Calculation example

Day	*Sum LOLP*	w_i	β_i
Sunday	0.15749	0.000667	0.060085815
Monday		0.000667	0.06252797
Tuesday		0.022224	2.03950727
Wednesday		0.034891	3.09128205
Thursday		0.034891	3.298814337
Friday		0.45333	43.91683294
Saturday		0.45333	43.11715817
		$\boldsymbol{CC}$	***95.59***

$$\beta_i = w_i PV_i \quad (3)$$

$$CC = \sum_{i=1}^{T'} \beta_i \quad (4)$$

Where T' is the number of hours used in approximation and β_i is the weighted generation of the PV plant during the high-load hours [13].

4. Capacity Credit of PV Solar Projects in MIS

MATLAB simulation package was used to build a capacity credit model of different solar PV capacities in MIS including the first 500 MW Solar IPP Plant in Ibri. Below is the system data used in this study.

4.1 MIS Generation Units

Table 6 represents MIS power plants data. MIS system was represented by an equivalent 21-unit system.

Table 6 Generation Units in MIS

Unit Name	*Unit Type*	*Max Net Available Power*	*FOR*
		MW	%
AlKamilGT	GT	271.299	2.0
Barka1_GT	CC (GT)	249.000	2.0
Barka1_ST	CC (ST)	180.970	5.0
Barka2_GT	CC (GT)	396.000	2.0
Barka2_ST	CC (ST)	279.587	5.0
Barka3_GT	CC (GT)	475.828	2.0
Barka3_ST	CC (ST)	268.880	5.0
ManahGT1	GT	82.791	2.0
ManahGT2	GT	179.742	2.0
RusailGT1	GT	234.108	5.0
RusailGT4	GT	241.119	5.0
RusailGT7	GT	92.174	5.0
RusailGT8	GT	90.948	5.0
Sohar1_GT1	CC (GT)	415.698	2.0
Sohar1_ST	CC (ST)	169.302	5.0
Sohar2_1st GT	CC (GT)	475.828	2.0
Sohar2_ST	CC (ST)	268.880	5.0
Sur GT1	CC (GT)	1,222.000	2.0
SurA_ST	CC (ST)	308.013	5.0
SurB_ST	CC (ST)	311.997	5.0
SurC_ST	CC (ST)	157.990	5.0
Total		6,372.154	

4.2 MIS Load PV Data

The hourly MIS load data for 2015 is shown in Fig. 2. To have more accurate results, all hours were used. The estimated output of a 500MW$_p$ solar PV plant is described in Fig. 4. The PV output data are based on solar irradiation data provided by the OPWP for the year 2015 [2]. The data of the lowest load and peak load weeks are presented in Fig. 4.

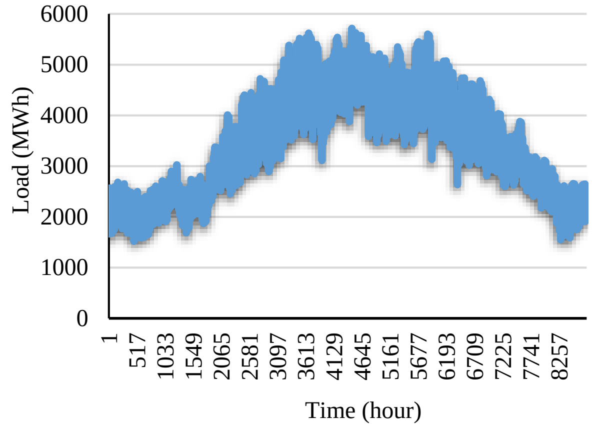

Fig. 2. Hourly MIS load data for 2015

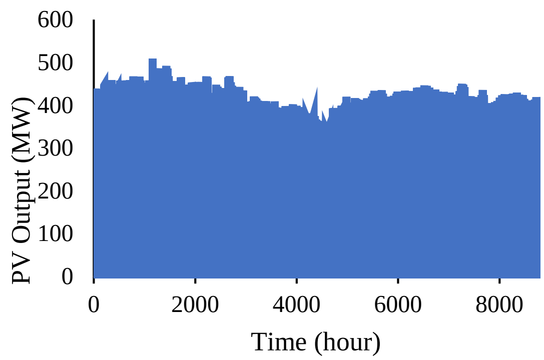

Fig. 3. Hourly PV output based on for 2015 data

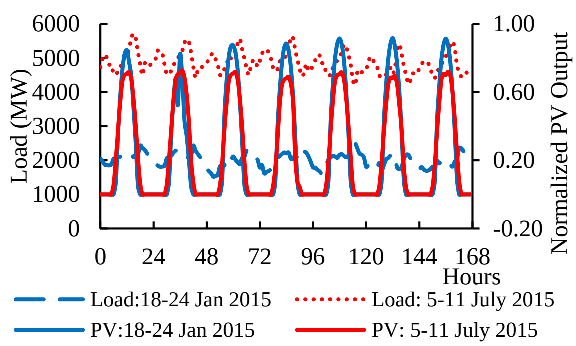

Fig. 4 Hourly load and PV output data for the weeks of the minimum and maximum load.

4.3 Results

The capacity of solar PV system increases by 500 MW for each new project as shown in the Table 7. Fig. 5, shows the capacity credit versus the solar capacity in the system. At the beginning, the capacity credit increases proportionally with the solar capacity. However, with higher capacities, the difference between peak load and peak PV output become smaller. This fact results in smaller incremental capacity credit values as the cumulative installed capacity increases. The capacity credit of the first project is 20% of nameplate capacity while it is only 5% for the fourth project.

Table 7 Capacity Credit of Different Solar IPP for Different Years.

Solar IPP Projects	*Cumulative Capacity (MW)*	*Total CC (MW)*	*Plant CC (MW)*	*Plant CC (%)*
Ibri II (2021)	500	119.36	119.36	24
500MW (2022)	1000	221.40	102.03	20
500MW (2023)	1500	295.33	73.92	15
500MW (2024)	2000	343.71	48.38	10
500MW (2025)	2500	369.36	25.65	5
500MW (2026)	3000	370.35	1.00	0

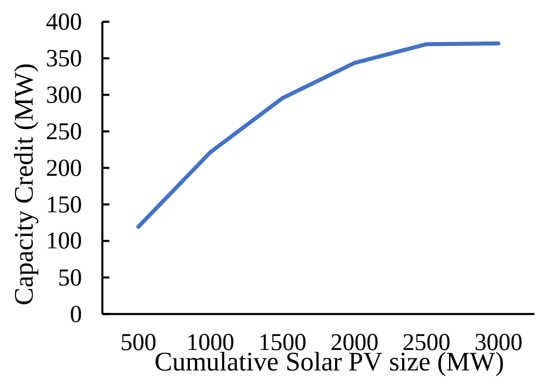

Fig. 5. Capacity Credit of Different PV Sizes

5. Conclusions

Capacity credit is defined as amount of additional load that can be served due to the addition of the generating unit, while maintaining the existing levels of reliability. Capacity credit calculations help policy makers in planning renewable energy capacity as well as fossil fuel-based generation capacity. There exist several methods for capacity credit calculation. These methods are classified into reliability and approximation methods. In this research, capacity factor approximation method is used for solar PV system. The study considered 21 generation units representing Oman's main interconnected system generation capacity. One-year hourly load and PV data are used. The calculation was based on comparing the loss of load probability with and without the solar PV system using MATLAB. Simulation results show that the first 500MW Solar IPP in Ibri has a capacity credit of 119.3MW. The second 500MW IPP project, which expected to be commissioned in 2022, has a capacity credit of 102.1MW. The third 500MW IPP project, expected to be commissioned in 2023, has a capacity credit of 73.9MW. The fourth 500MW IPP project, expected to be commissioned in 2024, has a capacity credit of 48.4MW only. It is worth noting that as cumulative solar PV capacity increases, the capacity credit of new projects diminishes.

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