Cumulative Capacity Credit Estimation for Renewable Energy Projects

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Abstract—This paper presents a novel method for accurately estimating the cumulative capacity credit (CCC) of renewable energy (RE) projects. Leveraging data from the main interconnected system (MIS) of Oman for 2028, where a substantial increase in RE generation is anticipated, our novel method is introduced alongside the traditional effective load carrying capability (ELCC) method. To ensure its robustness, we compare CCC results with ELCC calculations using two distinct standards of reliability criteria: loss of load hours (LOLH) at 24 hour/year and 2.4 hour/year. Our method consistently gives accurate results, emphasizing its exceptional accuracy, efficiency, and simplicity. A notable feature of our method is its independence from loss of load probability (LOLP) calculations and the iterative procedures associated with analytic-based reliability methods. Instead, it relies solely on readily available data such as annual hourly load profiles and hourly generation data from integrated RE plants. This innovation is of particular significance to prospective independent power producers (IPPs) in the RE sector, offering them a valuable tool for estimating capacity credits without the need for sensitive generating unit forced outage rate data, often restricted by privacy concerns.

Index Terms—Effective load carrying capability, renewable energy resource, capacity credit, generation system reliability, loss of load probability.

I. INTRODUCTION

DUE to the continuous depletion of fossil fuels and increasing atmospheric pollution, it is being realized that fossil fuel-based generation is not feasible in the long term to match the increasing power demand. In that regard, governments worldwide have made plans to incentivize companies in the electricity sector to rely more on renewable energy systems (RESs) [1], [2]. Although renewables are sustainable and environmentally friendly, their output varies from hour to hour according to weather conditions [3]. Unlike renewables, fossil fuel-based generators have the liberty of control, where operators in those utilities generate power ac-

cording to the prices on the spot market. Therefore, a critical balance between fossil fuel-based and renewable power plants must be maintained to achieve the desired reliability. Since the output of renewables varies according to the availability of the resource, there is a need to estimate the capacity value or capacity credit (CC) of the RES. The CC is the percentage of a power plant's installed capacity that is reliable at a specific moment in time (often amid system stress). It is frequently represented as a percentage of the nameplate capacity [4]. In the case of solar, the CC can be maximized by using the appropriate tilt angle and array tracking systems to get an optimal output [5]. In addition to that, some advanced solar technologies such as concentrated solar power (CSP) technology can yield better CC values than traditional photovoltaic (PV) technology [6]. The accurate determination of the CC of renewables is very important in resource planning. If RESs are given a small CC, they will be considered an infeasible option for future generation expansion. If given high CCs, there will be a higher risk of outages. CC mostly depends on the availability of generators during peak load periods [7]. On that note, CC brings another concept, which is effective load carrying capability (ELCC) [8], and it is defined as the additional load-carrying capacity of a newly added generator without affecting the reliability level of the previous power system [9], as shown in Fig. 1, where A is the original (acceptable) operating point; B is the operating point with an increase in load (unacceptable); C is the operating point after the addition of a new unit; and DE is the ELCC of the new unit, which is measured at the defined criterion of loss of load expectation (LOLE).
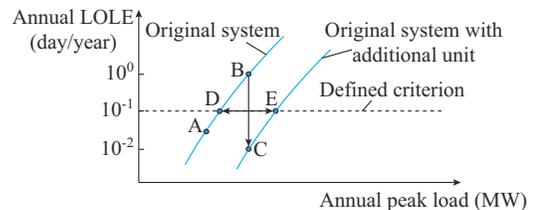

Fig. 1. ELCC.

Many indices are used to determine the reliability of the power system, mainly including loss of load probability (LOLP), loss of load hours (LOLH), LOLE, and expected energy not served (EENS). To understand these indices and their calculations, a tutorial in [10] can be consulted. In [11], LOLE was used to estimate the ELCC of a PV plant using

the empirical method. In [12], an empirical approach was used to investigate and compare the different properties of four typical CC definitions. From the empirical study, the author concluded that the choice of definitions influences the results of CC. The study recommends using equivalent firm capacity or equivalent load-carrying capacity for the calculation of CC. In [13], the PV plants were integrated into conventional power generation in two scenarios: with and without a battery energy storage system, and the impact of that on the CC values was investigated using ELCC based on LOLE. In [14], three reliability indices, LOLH, LOLE, and expected unserved energy (EUE), were used by applying the ELCC method to evaluate CC. In [15], a study was performed on a system consisting of wind turbines (WTs) combined with multiple energy storage systems to determine the effect of increasing WT penetration on the ELCC using the LOLE. A similar study was conducted in [16] to investigate the vulnerability of power systems caused by the interconnection of renewables with high penetration levels. Those studies expanded to cover the effect of renewables' penetration on nuclear power plants, as in [17], where nuclear power was replaced with wind power and then the system reliability was calculated using LOLE. The conclusion was that the system reliability drops when replacing nuclear power with wind power with five times the capacity. Reference [18] conducted a study to determine the minimum data required to investigate the reliability. The study was conducted in the context of wind farms in Ireland, where wind power capacity data were collected for ten years at seventy-four stations. It was concluded that 4-5 years of data are sufficient to present wind power generation. Moreover, the study attributed the reliability issues of wind farms to the correlation between the failure rates of WTs and wind speed. LOLE was evaluated based on the mean capacity outage by utilizing the analytical procedure in [19]. Then, the CC of wind power was obtained using the trial-and-error method. Due to the tremendous trial effort, particle swarm optimization (PSO) was used as described in [20]. In order to find the capacity value of the system, both the interpolation technique and the genetic algorithm were used in [21].

The primary contribution of this paper is to offer a simple and effective method for calculating the CC of RES projects using an ascending load order method without requiring an iterative procedure. The significance of this paper is enhanced by applying the method to a real-world case study of the Omani power system.

In Oman, the main sources of power are fossil fuel-based natural gas plants, which are supplied by the Ministry of Oil and Gas (MOG). The production of natural gas increased during the period from 2005 to 2014 by 51% [22], which is considerably high. Despite the massive production, the consumption of natural gas is also increasing. In light of that, a mandate to have a minimum of 10% renewable energy (RE) contribution to the total supply mix by 2025 was issued by the Council on Financial Affairs and Energy Resources (CFAER). Solar and wind energy have immense potential in Oman due to the sunny weather and tropical winds in the coastal areas. To reach the desired RE contribution, an Ibri

solar project with a capacity of 500 MW was commissioned in 2021, and some other independent power producer (IPP) projects are planned to be commissioned in the next five years [23].

The evaluation of system reliability in the case of increased penetration of renewables is particularly important in the context of Oman, as Oman seeks to become a carbon-neutral country by 2050 [24]. This paper describes a novel method to investigate the CC of the main interconnected system (MIS) of Oman for 2028, when several renewable projects are envisaged to come online. The method is compared with the standard ELCC method used to find the CC of renewable plants.

The remainder of this paper is organized as follows: Section II presents the important generation reliability indices used for CC calculations. Section III describes the CC calculation with the ELCC method and the proposed ascending load order method. The CC evaluation results for renewables in MIS are presented with both methods in Section IV, and the results are discussed in Section V. Section VI draws the conclusions.

II. GENERATION RELIABILITY INDICES USED FOR CC CALCULATIONS

A generation system is considered fully reliable when it is capable of meeting an annual demand, that is to say, when the power generation is not lower than the load. However, due to the random occurrence of outages in generating units, there is always a possibility that, for a fraction of a period, some demand will not be met. This reliability could be expressed in percentages using some reliability indices that vary from one electric utility to another. The two important reliability indices that are used to calculate the CC of an RE unit are described below [25].

A. LOLE

The LOLE is the number of days per year where the power generation cannot meet the demand. The most common standardized value of LOLE for generating systems used in North America is 0.1 day/year. LOLE can be mathematically expressed as:

$$LOLE = \sum_{i=1}^{N} P[G(i) < L(i)] \qquad (1)$$

where N is the number of days in a year (365 or 366); and $P[G(i) < L(i)]$ is the probability function when the daily peak demand $L(i)$ exceeds the available generation capacity $G(i)$.

B. LOLH

The LOLH refers to the number of hours of outage per year (8760 hours or 8784 hours for a leap year). The mathematical representation of LOLH is as follows:

$$LOLH = \sum_{t=1}^{T} P[G(t) < L(t)] = T \cdot LOLP \qquad (2)$$

where T is the number of hours in a year; and $P[G(t) < L(t)]$ is the LOLP, i.e, the probability function when the hourly load demand $L(t)$ exceeds the available generation capacity $G(t)$. The LOLH in generation expansion planning reliability

criteria used in Oman is 24 hour/year.

III. CC CALCULATION WITH ELCC AND ASCENDING LOAD ORDER METHODS

As defined earlier, CC is a metric that quantifies the extent to which an existing generator can be substituted with another generator without compromising the overall system reliability. The new generator in this case is powered by solar and wind energy, both of which have variable characteristics. Several methods are used to evaluate the CC, which are classified into two categories. The first category is reliability-based methods, which include equivalent conventional power (ECP), ELCC, and equivalent firm capacity (EFC). The other category is the approximation methods, including the capacity factor (CF) method, Graver's method, Graver's multi-state method, and Z-method [26].

The reliability-based methods use power system reliability evaluation techniques based on LOLP and LOLE. Essentially, the three reliability-based methods are very similar and differ only in how the CC of RES is measured. If the CC of RES is measured against a conventional generating unit that can be replaced while maintaining the same system reliability level, it is called the ECP. If the CC of RES is measured against the amount by which the system loads can increase (when the RES generator is added to the system) while maintaining the same system reliability level, it is called the ELCC. If the CC of RES is measured against a fully reliable generating unit (i.e., a unit with a forced outage rate of 0%) that can be replaced while maintaining the same system reliability level, it is called the EFC. We will discuss the ELCC method in detail and use this method as a standard to verify the results obtained by our new method for calculating the CC.

A. ELCC Method for Calculating CC

The flowchart for calculating the CC of RE plants based on the ELCC method is shown in Fig. 2, and the corresponding steps are as follows.

Step 1: for a given set of conventional generating units and an hourly load for a specified year, the LOLH of the system without the RE plant is calculated using (2). If the LOLH is not the same as the defined criterion, i.e., 24 hour/year, then a constant load is either added or subtracted and the LOLH is recalculated. For example, if the LOLH calculated is less than 24 hour/year, a constant load is added to the original load dataset; if the LOLH is larger than 24 hour/year, a constant load is subtracted from the original load dataset. The process is repeated iteratively until the desired LOLH is found. The new hourly load $L(t)$ can be called base load data, and the LOLH thus obtained is $LOLH_{Base}$.

Step 2: the time series for the output of the RE plant is treated as a negative load time series and is subtracted from the base load time series, resulting in a load time series net of RE. The LOLH of the jth RE plant, $LOLH_{REj}$, is then calculated as:

$$LOLH_{REj} = P\left[G(t) < L(t) - \sum_{j=1}^{r} C_j(t)\right] \quad (3)$$

where r is the total number of RE plants; and C_j is the output of the jth RE plant in hour t. $LOLE_{REj}$ is now less (and therefore better) than the target $LOLH_{Base}$ obtained in *Step 1* and will continue to be less each time when an RE plant is integrated into the system.
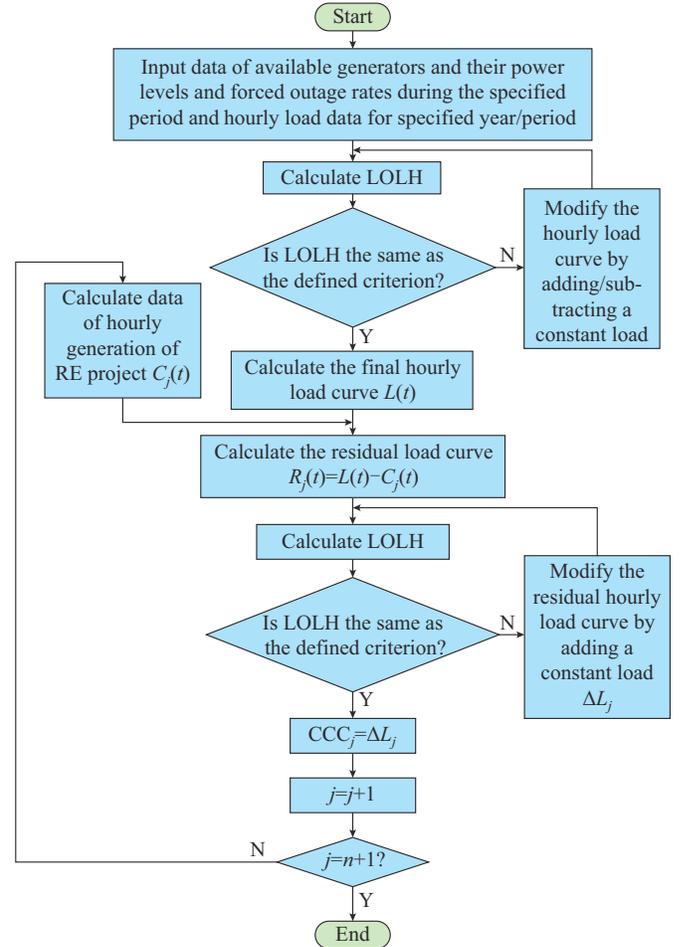

Fig. 2. Flowchart for calculating CC of RE plants based on ELCC method.

Step 3: the load data are then increased by a constant load ΔL_j across all hours using an iterative process, and the LOLH of ΔL_j (i.e., $LOLH_{\Delta L_j}$) is recalculated at each step until the target $LOLH_{Base}$ is reached. $LOLH_{\Delta L_j}$ is expressed as:

$$LOLH_{\Delta L_j} = P\left[G(t) < L(t) - \sum_{j=1}^{r} C_j(t) + \Delta L_j\right] \quad (4)$$

$$LOLH_{\Delta L_j} \approx LOLH_{Base} \quad (5)$$

The increase in load ΔL_j that achieves the reliability target is the cumulative capacity credit (CCC) CCC_j of the RE plants.

$$CCC_j = \Delta L_j \quad (6)$$

B. Ascending Load Order Method for Calculating CC

This is a very simple method that has given very accurate results with the Omani power system without even calculating LOLH. The flowchart for calculating the CC of RE plants based on the ascending load order method is shown in Fig. 3, and the corresponding steps are as follows.
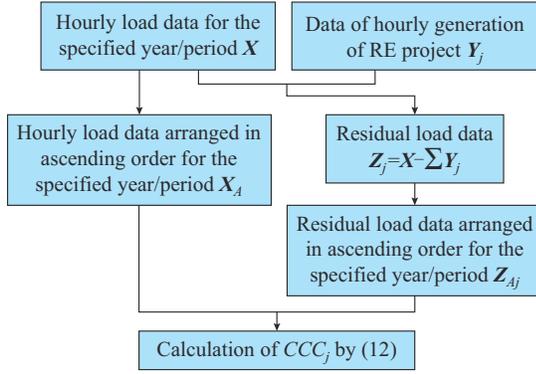
Fig. 3. Flowchart for calculating CC of RE plants based on ascending load order method.

Step 1: let vector X be the annual hourly load data and vector Y_j be the annual hourly generation of the jth RE plant, $j = 1, 2, \ldots, r$. They can be mathematically expressed as:

$$X = [X_1, X_2, \ldots, X_n] \tag{7}$$

$$Y_j = [Y_1, Y_2, \ldots, Y_n]_j \tag{8}$$

where X_i $(i = 1, 2, \ldots, n)$ is the hourly load, and n is the number of loads; and Y_i $(i = 1, 2, \ldots, n)$ is the hourly power generation of a RE plant. *Step 1* is to take the difference between the hourly load and hourly power generation of a RE plant and find the residual hourly load data as follows:

$$Z_j = X - \sum_{j=1}^{r} Y_j \quad j = 1, 2, \ldots, r \tag{9}$$

Step 2: the original hourly load data of (7) and the residual hourly load data of (9) are then rearranged in ascending order, such that:

$$X_A = [X_{A1}, X_{A2}, \ldots, X_{An}] \tag{10}$$

$$Z_{Aj} = [Z_{A1}, Z_{A2}, \ldots, Z_{An}]_j \tag{11}$$

where $X_{A1} \leq X_{A2} \leq \ldots \leq X_{An}$; and $Z_{A1} \leq Z_{A2} \leq \ldots \leq Z_{An}$.

Step 3: the CCC is an average of the difference between hourly ascending load data and the residual ascending load data after each RE plant is integrated into the system for the last few peak hours from N_L to N_H as follows:

$$CCC_j = \sum_{i=N_L}^{N_H} \frac{X_{Ai} - Z_{Aij}}{N_H - N_L + 1} \quad j = 1, 2, \ldots, r \tag{12}$$

It is discovered that the average difference between hourly ascending base load data and residual ascending load data for the last one hundred peak hours provides a very accurate result for $LOLH = 24$ hour/year, and the average difference between hourly ascending load data and residual ascending load data for the last 65 peak hours provides a very accurate result for $LOLH = 2.4$ hour/year.

IV. CC Evaluation Results for Renewables in MIS

In order to investigate the response of the system reliability to the integration of renewables in MIS, this study applied estimated generation and load data for the year 2028, when all planned RE plants will have been commissioned. The CCs of RE plants are calculated both by the ELCC method and the proposed new method of ascending load order.

A. Generation and Load Data of MIS for 2028

Table I and Table II show the data of conventional and renewable generating units of MIS in 2028, respectively [23].

TABLE I
Data of Conventional Generating Units of MIS in 2028

Unit name	Unit type	$C_{\max}$ (MW)	FOR (%)	Unit name	Unit type	$C_{\max}$ (MW)	FOR (%)
Barka1_GT1	CC (GT)	89	2	Sohar2_ST	CC (ST)	247	5
Barka1_GT2	CC (GT)	89	2	Sur1_GT1A	GT	242	2
Barka1_ST	CC (ST)	181	5	Sur1_GT1B	GT	242	2
Barka2_GT1	CC (GT)	123	2	Sur1_GT1C	GT	308	2
Barka2_GT2	CC (GT)	123	2	Sur1_GT2A	GT	242	2
Barka2_GT3	CC (GT)	123	2	Sur1_GT2B	GT	242	2
Barka2_ST1	CC (ST)	160	5	Sur1_ST1A	CC (ST)	308	5
Barka2_ST2	CC (ST)	160	5	Sur1_ST1B	CC (ST)	242	5
Barka3_GT1	CC (GT)	254	2	Sur1_ST1C	CC (ST)	155	5
Barka3_GT2	CC (GT)	254	2	Ibri IPP_GT1	CC (GT)	242	3
Barka3_ST	CC (ST)	247	5	Ibri IPP_GT2	CC (GT)	242	3
Manah_GT2A	GT	91	2	Ibri IPP_ST1	CC (ST)	282	3
Manah_GT2B	GT	91	2	Ibri IPP_GT3	CC (GT)	242	3
Rusail_GT7	GT	96	2	Ibri IPP_GT4	CC (GT)	242	3
Rusail_GT8	GT	95	2	Ibri IPP_ST2	CC (ST)	282	3
Sohar1_GT1	GT	126	2	Sohar3_GT1	CC (GT)	273	3
Sohar1_GT2	GT	126	2	Sohar3_GT2	CC (GT)	273	3
Sohar1_GT3	GT	126	2	Sohar3_ST1	CC (ST)	326	3
Sohar1_ST	CC (ST)	220	5	Sohar3_GT3	CC (GT)	273	3
Sohar2_GT1	GT	254	2	Sohar3_GT4	CC (GT)	273	3
Sohar2_GT2	GT	254	2	Sohar3_ST2	CC (ST)	326	3

TABLE II
DATA OF RENEWABLE GENERATING UNITS OF MIS IN 2028

Unit name	Index	Unit type	C_{max} (MW)
Ibri II Solar IPP (existing)	A	PV	500
Manah I Solar IPP 2025	B	PV	500
Manah II Solar IPP 2025	C	PV	500
Adam Solar IPP 2025	D	PV	500
Jalan Bani Bu Ali Wind IPP 2025	E	WT	100
Duqm Wind IPP 2025	F	WT	200
Total capacity			2800

In Table I, GT and ST represent the gas turbine and steam turbine units of a combined cycle (CC) plant, C_{max} is the maximum generation capacity of a unit, and FOR is the forced outage rate of a unit. The total generation capacity of the conventional generating units will be 8786 MW, and that of renewable generating units will be 2300 MW. According to the MIS load forecast, the peak load in 2028 will be 8546 MW. The hourly demand is estimated by multiplying 8546 MW with the normalized hourly demand in 2020, assuming the load pattern does not change over time. Figure 4 shows the estimated hourly power generation of RE plants in 2028, and Fig. 5 shows the estimated hourly load of MIS with and without RE plants. RE generation is considered as negative load.
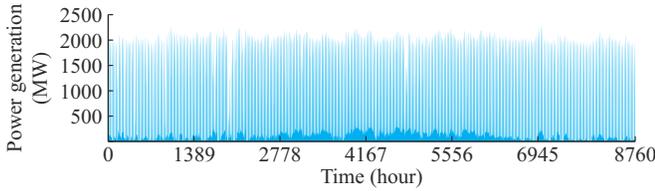

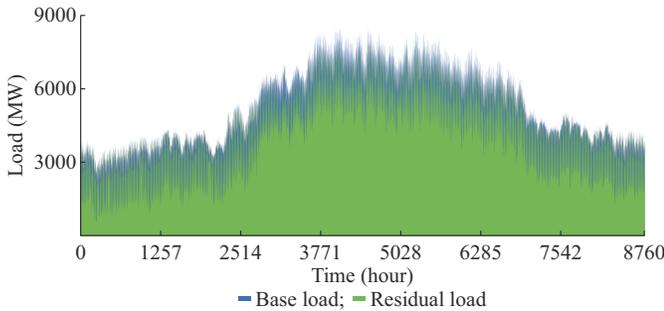Fig. 4. Estimated hourly power generation of RE plants in 2028.

Fig. 5. Estimated hourly load of MIS with and without RE plants.

B. Load Adjustment for ELCC Method

A MATLAB code was developed to calculate LOLP and LOLE from the data in Tables I and II. It was found that with hourly load data and a system peak load of 8546 MW and a conventional power generation of 8786 MW, the LOLH is 8.9139 hour/year, which is below the defined criterion of 24 hour/year. Therefore, a constant load is added iteratively to the hourly load data for 2028 to bring the LOLH close to 24 hour/year. It was found that an addition of 200 MW of constant load to the hourly load data for 2028 brings

the LOLH to 23.97 hour/year. A further addition of 1 MW brings the LOLH to 24.0706 hour/year, which is above the defined criteria. Therefore, a constant load of 200 MW is added to the hourly load data for 2028 to make LOLH close to the standard. Figure 6 shows the variation in risk against the system peak load. It may be noted that LOLH equals 23.97 hour/year when the system peak load equals 8746 MW, and the LOLP has a logarithmic scale. At the peak load of 8786 MW, the LOLP reaches 1.0, which is also the total conventional power generation that is available. If the peak load increases further from 8786 MW, the LOLP remains at 1.0. It should be emphasized that LOLH is the total of all hourly LOLPs over the duration, while LOLP is the likelihood of loss of load at any given hour.
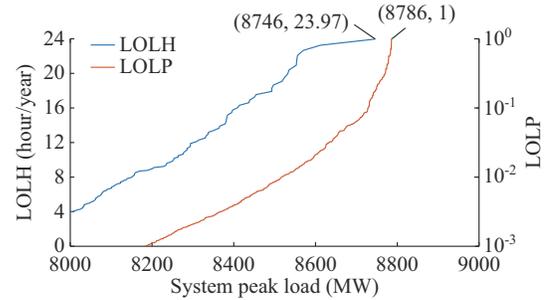

Fig. 6. Variation in risk against system peak load.

C. Results of CCC with ELCC and Ascending Load Order Methods for LOLH = 24 hour/year

Table III shows the CCC estimated both with ELCC and ascending load order methods for $LOLH = 24$ hour/year, where CCC_1 and CCC_2 are the CCC estimated with ELCC and ascending load order methods, respectively.

TABLE III
CCC WITH ELCC AND ASCENDING LOAD ORDER METHODS FOR
$LOLH = 24$ HOUR/YEAR

Sequence of addition of RE plants	Cumulative capacity (MW)	$LOLH_{REj}$	$LOLH_{\Delta L_j}$	CCC_1 (MW)	CCC_2 (MW)
A	500	5.4452	23.8984	261	279
A + B	1000	3.7767	23.8975	325	336
A + B + C	1500	3.5940	23.9836	340	340
A + B + C + D	2000	3.5735	23.9443	342	340
A + B + C + D + E	2100	2.8852	23.9004	377	374
A + B + C + D + E + F	2300	1.3729	23.9504	492	492

Figure 7 shows the CCC with ELCC and ascending load order methods after the addition of RE plants for $LOLH = 24$ hour/year. It may be noted that for the ascending load order method, there is no need for load adjustment to make $LOLH = 24$ hour/year; even there is no need to calculate the LOLH. Figure 7 also shows the variation of LOLH as the RE plants are added to the system. It can be observed from Fig. 7 and Table III that after the addition of the first PV plant, the CCC does not change much for the addition of the second, third, and fourth PV plants until the WT plant is added. This also shows that the individual CC of a PV plant is

not important when several PV plants are in the generation system. Figure 8 shows the percentage of CCC with respect to cummulative capacity of RE plants for $LOLH=24$ hour/year. As can be observed, both methods give very similar results. Figure 9 shows the last one hundred peak hours of base load and residual load after the addition of RE plants to estimate CCC for $LOLH=24$ hour/year. Note that the average difference of the last one hundred peak hours of base load with respect to residual load after the addition of RE plants is used to calculate CCC at $LOLH=24$ hour/year. It may be further noted that CCC is estimated at the actual base load without a constant hourly load addition of 200 MW.
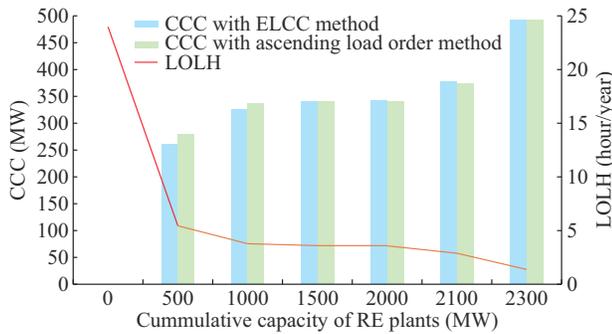

Fig. 7.   CCC with ELCC and ascending load order methods for $LOLH=24$ hour/year and LOLH as RE plants are added to system.
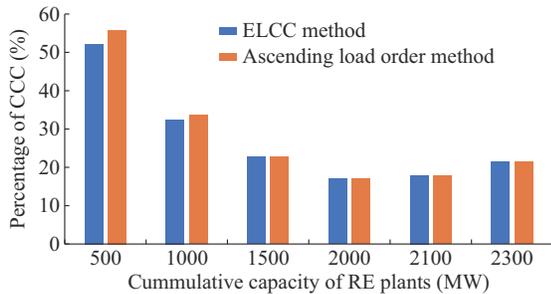

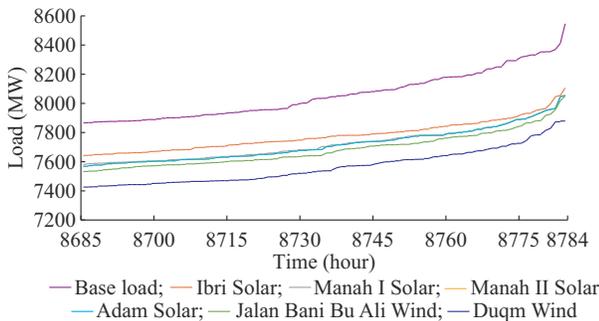Fig. 8.   Percentage of CCC with respect to cummulative capacity of RE plants for $LOLH=24$ hour/year.

Fig. 9.   Last one hundred peak hours of base load and residual loads after addition of RE plants to estimate CCC for $LOLH=24$ hour/year.

D. Results of CCC with ELCC and Ascending Load Order Methods for LOLH = 2.4 hour/year

As mentioned earlier, with a peak load of 8546 MW and a conventional power generation of 8786 MW, the LOLH is 8.9139 hour/year, which in this case is above the defined cri-

terion of 2.4 hour/year. Therefore, a constant load is subtracted iteratively from the hourly load data for 2028 to bring the LOLH close to 2.4 hour/year. It was found that a subtraction of 229 MW of constant load in the hourly load data of 2028 brings the LOLH to 2.3916 hour/year. A further increase of 1 MW brings the LOLH to 2.4035 hour/year, which is above the defined criterion.

Therefore, a constant load of 229 MW is subtracted from the hourly load data for 2028 to make LOLH close to the standard. Table IV shows the CCC estimated both with the ELCC and ascending load order methods for $LOLH=2.4$ hour/year.

TABLE IV
CCC WITH ELCC AND ASCENDING LOAD ORDER METHODS FOR
$LOLH=2.4$ HOUR/YEAR

Sequence of addition of RE plants	Cumulative capacity (MW)	$LOLH_{REj}$	$LOLH_{\Delta L_j}$	CCC_1 (MW)	CCC_2 (MW)
A	500	0.29538	2.3947	300	310
A+B	1000	0.19967	2.3970	357	361
A+B+C	1500	0.19253	2.3896	364	364
A+B+C+D	2000	0.19196	2.3928	365	364
A+B+C+D+E	2100	0.14964	2.3984	400	400
A+B+C+D+E+F	2300	0.06067	2.3944	516	516

Figure 10 shows the variation of CCC with ELCC and ascending load order methods after the addition of RE plants for $LOLH=2.4$ hour/year. It may be noted again that for the ascending load order method, there is no need to calculate LOLH for load adjustment to make $LOLH=2.4$ hour/year. Figure 10 also shows the variation of LOLH as the RE plants are added to the system. It may be noted again from Fig. 10 and Table IV that after the addition of the first PV plant, the CCC does not change much with the addition of the second, third, and fourth PV plants until the addition of the WT plant. Figure 11 shows the percentage of CCC with respect to cummulative capacity of RE plants for $LOLH=2.4$ hour/year. As can be observed again, both methods give very similar results. Figure 12 shows the last sixty-five peak hours of base load and residual load after the addition of RE plants to estimate CCC for $LOLH=2.4$ hour/year. Note that the average difference of the last sixty-five peak hours of base load with respect to residual load after the addition of RE plants is used to calculate CCC at $LOLH=2.4$ hour/year.
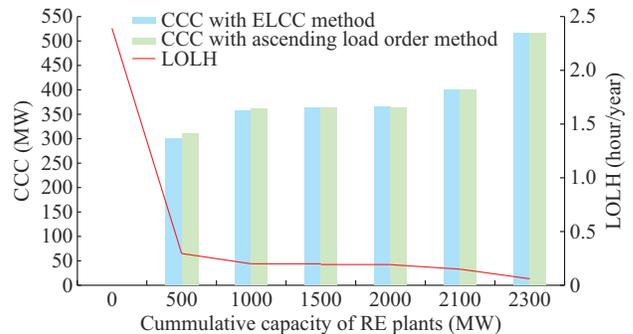

Fig. 10.   CCC with ELCC and ascending load order methods for $LOLH=2.4$ hour/year and LOLH as RE plants are added to system.
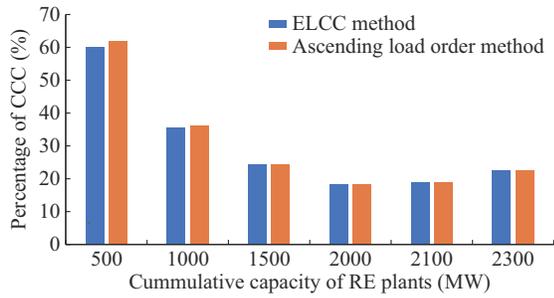
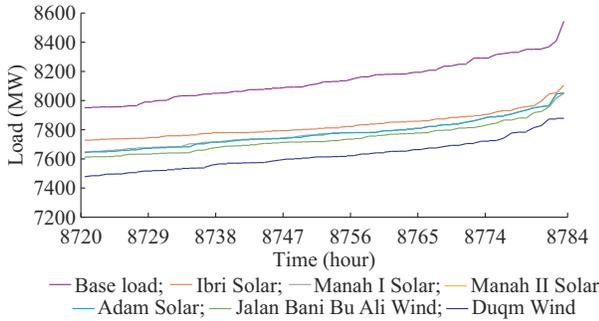Fig. 11. Percentage of CCC with respect to cummulative capacity of RE plants for *LOLH* = 2.4 hour/year.

Fig. 12. Last sixty-five peak hours of base load and residual loads after addition of RE plants to estimate CCC for *LOLH* = 2.4 hour/year.

E. Results of CCC with ELCC and Ascending Load Order Methods by Reversing Sequence of Addition of RE Plants for LOLH = 24 hour/year

Table V shows the CCC estimated both with ELCC and ascending load order methods by reversing the sequence of addition of RE plants for *LOLH* = 24 hour/year. Figure 13 shows the CCC with ELCC and ascending load order methods after adding the RE plants in reverse sequence. Figure 13 also shows the variation of LOLH as the RE plants are added to the system in reverse sequence.

TABLE V
CCC WITH ELCC AND ASCENDING LOAD ORDER METHODS BY REVERSING SEQUENCE OF ADDITION OF RE PLANTS FOR *LOLH* = 24 HOUR/YEAR

Sequence of addition of RE plants	Cumulative capacity (MW)	$LOLH_{REj}$	$LOLH_{\Delta L_j}$	CCC_1 (MW)	CCC_2 (MW)
F	200	13.6652	23.9261	117	114
F + E	300	11.8422	23.9707	149	144
F + E + D	800	2.1634	23.9295	410	423
F + E + D + C	1300	1.4509	23.9928	476	487
F + E + D + C + B	1800	1.3801	23.9916	490	492
F + E + D + C + B + A	2300	1.3729	23.9504	492	492

Again, it can be observed from Fig. 13 and Table V that after the addition of the first PV plant, the CCC does not change much for the addition of the second, third, and fourth PV plants. Figure 14 shows the percentage of CCC with respect to cummulative capacity of RE plants when the sequence of addition of RE plants is reversed for *LOLH* = 24 hour/year. Again, it can be observed that both methods give very similar results. Figure 15 shows the last one hundred

peak hours of base load and residual load after adding the RE plants in reverse sequence to estimate CCC for *LOLH* = 24 hour/year.
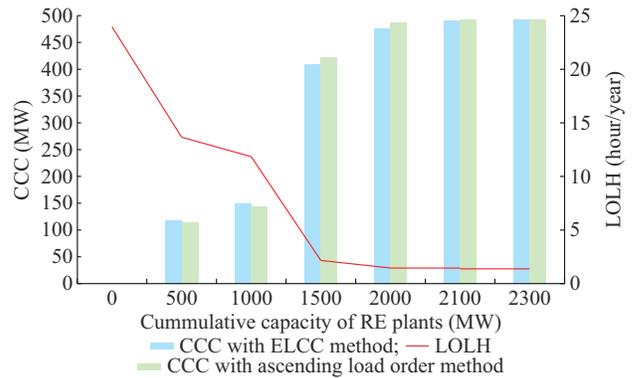

Fig. 13. CCC with ELCC and ascending load order methods for *LOLH* = 24 hour/year and LOLH when sequence of addition of RE plants is reversed.
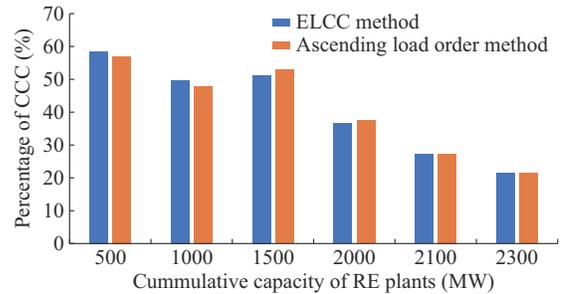

Fig. 14. Percentage of CCC with respect to cummulative capacity of RE plants when sequence of addition of RE plants is reversed for *LOLH* = 24 hour/year.
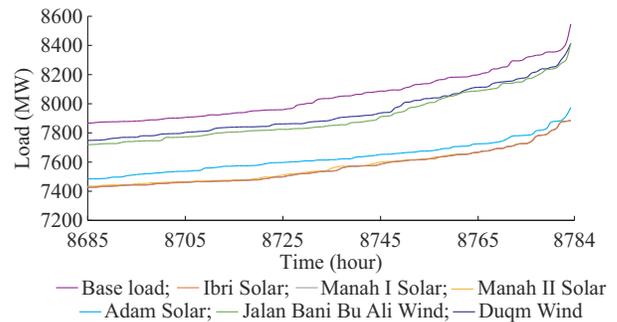

Fig. 15. Last one hundred peak hours of base load and residual loads after adding RE plants in reverse sequence to estimate CCC for *LOLH* = 24 hour/year.

F. Results of CCC with ELCC and Ascending Load Order Methods by Reversing Sequence of Addition of RE Plants for LOLH = 2.4 hour/year

Table VI shows the CCC estimated both with ELCC and ascending load order methods by reversing the sequence of addition of RE plants for *LOLH* = 2.4 hour/year.

Figure 16 shows the CCC with ELCC and ascending load order methods after adding the RE plants in reverse sequence for *LOLH* = 2.4 hour/year. Figure 16 also shows the variation of LOLH as the RE plants are added to the system in revese sequence. Figure 17 shows the percentage of CCC

with respect to cummulative capacity of RE plants when the sequence of the addition of RE plants is reversed. Again, it can be observed that both methods give very similar results. Figure 18 shows the last sixty-five peak hours of base load and residual load after adding the RE plants in reverse sequence to estimate CCC for $LOLH = 2.4$ hour/year.

TABLE VI
CCC with ELCC and Ascending Load Order Methods by Reversing Sequence of Addition of RE Plants for $LOLH = 2.4$ hour/year

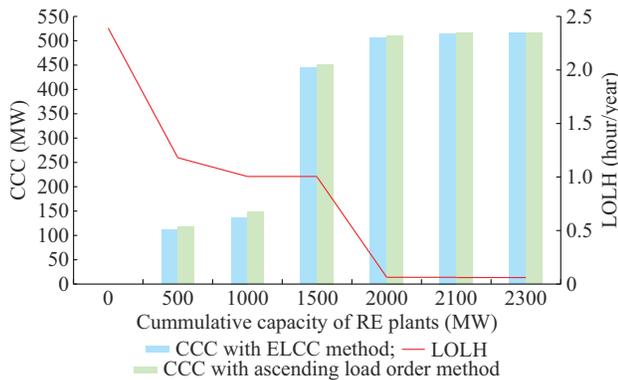| Sequence of addition of RE plants	Cumulative capacity (MW)	$LOLH_{REj}$	$LOLH_{\Delta L_j}$	CCC_1 (MW)	CCC_2 (MW)
F	200	1.18030	2.3899	112	118
F + E	300	1.00510	2.3880	137	148
F + E + D	800	0.10012	2.3974	445	452
F + E + D + C	1300	0.06329	2.3890	506	511
F + E + D + C + B	1800	0.06084	2.3946	515	516
F + E + D + C + B + A	2300	0.06067	2.3944	516	516

Fig. 16. CCC with ELCC and ascending load order methods for $LOLH = 2.4$ hour/year and LOLH when sequence of addition of RE plants is reversed.
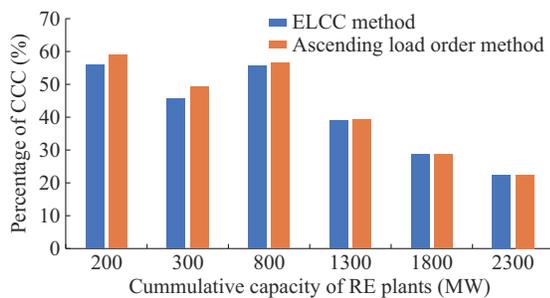

Fig. 17. Percentage of CCC with respect to cummulative capacity of RE plants when sequence of addition of RE plants is reversed for $LOLH = 2.4$ hour/year.

V. Discussion of Results

The results of the CCC of RE plants for $LOLH = 24$ hour/year and $LOLH = 2.4$ hour/year reveal that the ascending load order method provides very accurate results compared with the standard ELCC method. The only difference in the calculation of CCC with the ascending load order method between LOLH of 24 hour/year and 2.4 hour/year is the number of peak hours used to get the average difference between base load and residual load due to RE generation.
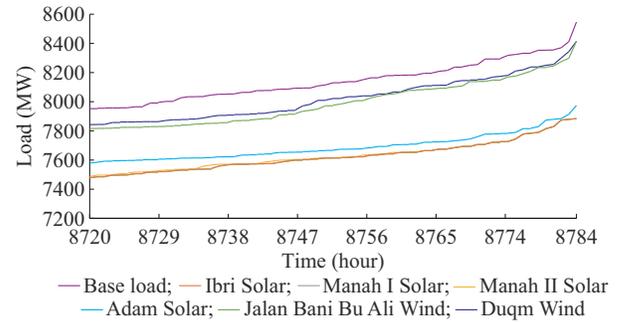

Fig. 18. Last sixty-five peak hours of base load and residual loads after adding RE plants in reverse sequence to estimate CCC for $LOLH = 2.4$ hour/year.

For LOLH of 24 hour/year, the average of the last one hundred peak hours is used, whereas for LOLH of 2.4 hour/year, the average of the last sixty-five peak hours is used to get the capacity contribution from RE plants.

To gain confidence in the method, we checked if the results would be any different if we reversed the sequence of addition of RE plants in the system. We found that the ascending load order method shows consistency in the results. Now the question could be asked: how does this simple method work? The answer is that at these defined reliability criteria, only the last few dozen peak hours are important in the LOLH calculation. For example, at off-peak hours, supposing the hours where load is around 7000 MW, the LOLPs in those hours are in the order of 10^{-5}, which are almost negligible and have no significant contribution towards LOLH. It is only the last few dozen hours that are important in contributing to the overall LOLH. Therefore, it was observed that the capacity contributions of subsequent PV plants exhibited a notable decline following the addition of the first PV plant. This decline was so pronounced that the CC of the fourth PV plants of 500 MW added to the system had a CC of only 2 MW (refer to column 5 of Table III, 342 MW − 340 MW = 2 MW). This is because PV plants operate during daylight, and after the addition of the first three PV plants, the daylight hours become off-peak hours for the fourth PV plant, which thus has no contribution during the peak hours. Hence, the contribution of the fourth PV plant towards LOLH improvement is negligible, resulting in a very low CCC. Therefore, the novel method is effective when the capacity contribution of RE plants during the last few dozen hours is considered. For the LOLH criterion of 2.4 hour/year, the number of peak hours required to estimate CCC is even less than the number of hours required for the LOLH criterion of 24 hour/year. This is because, for more strict criteria, the reserve margin between the total capacity and the peak demand is increased, and hence the off-peak hours become even more irrelevant in the calculation of LOLH.

VI. Conclusion

A novel, precise, and straightforward method is proposed for determining the CCC of RE facilities based on an ascending load order method. To validate the efficacy of this method, it is applied to data from the MIS of Oman in the year

2028, during a period of significant RE integration into the system. This method is then compared with the conventional ELCC method commonly used for assessing the CCs of RE installations.

In order to assess the reliability of our method, we examine its results in comparison with the ELCC method when considering two distinct standards of reliability criteria: LOLH of both 24 hour/year and 2.4 hour/year. We also evaluate the accuracy of our method under these two reliability criteria, considering scenarios where the addition of RE plants to the system is reversed. Remarkably, our method consistently yields robust and reliable results across all these scenarios.

The efficiency of our method lies in its ability to obviate the need for calculating LOLP and eliminate the necessity for iterative CC calculations often required by traditional analytical-based reliability assessments. Moreover, the simplicity of our method is evident in the minimal data requirements, which only involve annual hourly load data and hourly generation data from the RE plants in the power system.

This method holds particular value for prospective IPPs in the RE sector, as it empowers them to estimate their RE CCs without the challenges of acquiring confidential data regarding the forced outage rates of generating units, which may not be readily accessible due to privacy constraints.

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