Impact of Increasing Penetration of Renewables in Insular Grids: Insights from the Case of Andaman and Nicobar Islands

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Indices

g	Individual oil-fired generator
s	Individual solar power plant
t	Individual time index

Variables

P_{gt}	Scheduled generation of oil-fired generator, g, at time, t
R_{gt}^{U}	Spinning up-reserve capacity provided by generator, g, at time t
R_{gt}^{D}	Spinning down-reserve capacity provided by generator, g, at time t
C_{gt}^{SU}	Start-up cost associated with starting of generator, g, at time t
P_{st}^{sch}	Scheduled generation of solar power plant, s, at time t
P_{st}^{cur}	Curtailed generation of solar power plant, s, at time t
P_{t}^{ENS}	Energy not served at time t
U_{gt}	Unit commitment status of generator, g, at time t
$C^{penalty}$	Penalty term that includes penalty associated curtailed solar power and energy not served

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O. H. Gupta et al. (eds.), *Recent Advances in Power Systems*, Lecture Notes in Electrical Engineering 812, https://doi.org/10.1007/978-981-16-6970-5_52

Constants

λ_g	Cost of generation for oil-fired generator, g, at time t
λ_g^{RU}	Cost of up-reserve capacity provided by generator, g, at time t
λ_g^{RD}	Cost of down-reserve capacity provided by generator, g, at time t
$P_{st}^{forecast}$	Predicted quantity of photovoltaic (PV) power for solar plant, s, at time t
λ_{gt}^{su}	Cost of start-up of generator, g at time t
λ_{cur}^{ENS}	Cost (penalty) during energy net served at time t
λ_s^{cur}	Cost of curtailment of photvoltaic (PV) power for solar plant

1 Introduction

Andaman & Nicobar (A&N) Islands is an archipelago of around 572 islands, of which 37 islands are inhabited and electrified. Power grid of these islands, also referred to as insular grids, are heavily dependent on oil-fired generating stations which are expensive and have high levels of greenhouse gas emission. So, in order to reduce the carbon footprint, Government of India (GoI) has initiated several solar power plant projects in A&N Islands. In this work, the authors explore the technical and economic viability of increasing share of renewables in the generation mix of insular grids like A&N Islands.

Insular grids, like A&N Islands, have distinctive peculiarities that make them different from well-interconnected mainland power grids. Insular systems have a smaller number of generators and are not interconnected with neighboring grids [1]. Hence, they have lower inertia which makes them fragile in nature. Renewable energy sources (RES) introduce uncertainty in the grid owing to their intermittency and dynamism. High uncertainty levels of non-dispatchable RES can hamper the fragile structure of insular grids. One approach to address this issue would be to improve the forecast accuracy of non-dispatchable RES such as wind [2] and solar [3]. Another approach would be to formulate generation scheduling problem using stochastic approaches [4] such as recourse method [5] and solving them using methods like bi-linear variant of decomposition technique [6], etc. These approaches have been adopted for generation scheduling problems of insular grids as well [7, 8]. A&N Islands are non-interconnected insular grids with each island grid having its own generation and distribution units [9]. Considerable research has been undertaken on renewable energy forecasting as in [10] wherein a hybrid bVAR-NARX wind power prediction model has been proposed which exploits the correlation between wind power injection into grid for varying load demand conditions under different conjestion conditions. Similarly, a novel machine learning strategy is proposed in [11] to forecast the solar power prediction using a hybrid ensemble averaging technique. Cumulative generation capacity of these islands is around 109.45 MW [12]. Unlike the highly interconnected grid of the mainland portion of India with cheaper thermal generation options, insular grid of A&N Islands has to rely on the expensive oil-fired diesel generators which form 88% of the generation mix. Hence solar power projects took prominence in the agenda of the GoI. The main objective of this work is to formulate a deterministic problem that would help in analyzing the outcome of the gradual transition from a conventional grid to a renewable rich grid. The flow of this work is as follows. Introduction in Sect. 1 is followed by a description of the authors' approach in Sect. 2. Section 3 discusses the results elaborately while Sect. 4 gives the final concluding comments.

2 Methodology

RES are economic and have lower carbon footprint but they increase uncertainties during operational procedures. To deal with this, diesel generators have to provide ancillary services such as up-down ramping, reserve, voltage and frequency regulation, etc. But these services come at the cost of increased greenhouse gas emissions and per unit price of electricity. The present work studies this conundrum from the economic and scheduling aspect. A unit commitment problem is formulated, as explained below, with a set of reserves that include uncertainty associated with RES like solar and wind. The objective function is as shown in Eq. (1a), wherein the first four terms represent cost of generating electricity through the conventional diesel generators, up- reserve cost, down-reserve cost, and start-up cost of diesel generator, respectively. The final term shows the cost that penalizes the objective function when solar power is curtailed or energy is not served. It is expressed by Eq. (1b).

$$\text{minimize} \quad \sum_{t=1}^{Nt} \left[\sum_{g=1}^{Ng} \left\{ \lambda_g P_{gt} + \lambda_g^{RU} R_{gt}^{U} + \lambda_g^{RD} R_{gt}^{D} + C_{gt}^{SU} \right\} + C^{penalty} \right] \tag{1a}$$

subject to

$$\sum_{s=1}^{Ns} \left\{ \lambda_s^{cur} P_{st}^{cur} \right\} + \lambda^{ENS} P^{ENS} = C^{penalty}, \quad \forall t, \tag{1b}$$

$$\sum_{g=1}^{Ng} P_{gt} + \sum_{s=1}^{Ns} P_{st}^{sch} + P^{ENS} = L(t), \quad \forall t, \tag{1c}$$

$$P_{st}^{sch} + P_{st}^{cur} = P_{st}^{forecast}, \quad \forall t, \tag{1d}$$

$$P_g^{min} U_{gt} \leq P_{gt} \leq P_g^{max} U_g t, \quad \forall t, \tag{1e}$$

$$C_{gt}^{SU} \geq \lambda_{gt}^{SU} \left(U_{gt} - U g, t - 1 \right), \quad \forall t, \tag{1f}$$

$$U_{gt} \in \{0, 1\}, \quad \forall g, \forall t, \tag{1g}$$

$$P_{gt}, R_{gt}^{U}, R_{gt}^{D}, C_{gt}^{SU}, P_{st}^{cur}, P^{ENS}, P_{st}^{sch} \in \Re, \quad \forall g, \forall s, \forall t \tag{1h}$$

Load balance constraints are represented by Eqs. (1c) and (1d) while generation limit and start-up constraints are shown by Eqs. (1e) and (1f) respectively. Up-reserve constraints are generally considered based on the largest generating station size or based on load demand depending on the reserve policy adopted by the system operator of that grid. Constraint (1g), represents the binary variables while constraint (1h) represents real variables.

2.1 Proposed Reserve Constraints to Handle Uncertainty Associated with RES

Insular grid is a low inertia grid. And hence further addition of dynamic RES like solar and wind can lead to system instability issues. In order to handle the uncertainty associated with non-dispatchable RES, additional spinning reserve constraints should be provided along with the reserve needed for demand uncertainty. Hence, the system up-reserve constraint, considered in this work, also includes the additional component of up-reserve that needs to be produced if the solar power generated in real time is less than the day-ahead committed value. It is expressed as shown in Eq. (2).

$$\sum_{g=1}^{Ng} R_{gt}^{U} \geq \%L(t) + \%P_{st}^{forecast}, \quad \forall t \tag{2}$$

Spinning reserve provided by a generator is over and above the scheduled generation of the generator. To ensure that up-reserve never violates maximum generation limit technicality, in the event of actual delivery of power in any scenario, Eq. (3) is used as a constraint for the problem at hand. This constraint ensures that unrealistic spinning reserve constraints are not considered which cannot be materialized in the eventuality of an actual reserve requirement.

$$\sum_{g=1}^{Ng} \left(R_{gt}^{U} + P_{gt}\right) \leq P_{g}^{max} U_{gt}, \quad \forall t \tag{3}$$

Similarly, applying the complementary logic for down-reserve, Eq. (4) shows the additional negative capability needed for ensuring that if, in real time, solar power is more than the committed day-ahead value, then adequate spinning down-reserve is provided by the conventional generators (i.e. the oil-fired generators as in case of the insular grid) such that its generation can be reduced in order to accommodate the higher share of solar power in real time.

$$\sum_{g=1}^{Ng} R_{gt}^{D} \geq \%L(t) + \%P_{st}^{forecast}, \quad \forall t \tag{4}$$

Equation (5) is similar to the technicality mentioned in Eq. (3) except for the difference that, here, it talks about the minimum generation limit which should not be violated in real time in the eventuality of actual realization of greater penetration of solar power than committed in the day-ahead market.

$$\sum_{g=1}^{Ng} \left(P_{gt} - R_{gt}^{D}\right) \geq P_{g}^{min} U_{gt}, \quad \forall t \tag{5}$$

All the above constraints from (2) to (5) are included in the original formulation of unit commitment problem discussed above from Eqs. (1a) to (1h).

2.2 Proposed Approach for Analysis

In order to study and analyze the vulnerability of insular grids to a higher share of RES, this work has been divided into three different stages. At each stage, one or more key parameters are kept constant and the sensitivity of the rest of the parameters are studied with respect to the constant parameters. Throughout the work, the demand and all other associated conditions (except the key parameters), are considered to be the same for all the stages. The different stages of the proposed approach are as follows:

1. Reserve constraints shown in Eqs. (2) and (4) have two components—one responsible for load uncertainty and the other responsible for the uncertainty in RES. At the first stage, the additional up and down-reserve components that represent the reserve requirement for uncertainty in RES are made zero. Thereafter, the system details are analyzed for different installed capacity of the solar plant penetration which is increased periodically. Such an increase would result in an overall increase in the solar power forecast for a particular demand at a certain time of the day.
2. At the second stage, the installed capacity of the solar plant is kept constant, while the appropriate up/down-reserve requirement is changed periodically. While in this work, reserve component of Eqs. (2) and (4) are changed with 5% interval, a much shorter interval would give a more clearer picture.
3. At the third and final stage, the limit of solar power curtailment is extracted for different penetration levels for different % reserve capacity.

The proposed approach gives a holistic picture and assists in formulating a proper policy to deal with the situation at hand.

3 Result and Discussions

As mentioned in the introductory paragraph of Sect. 1, A&N Islands are made up of several non-interconnected islands run on oil-fired generators. Of all these islands, the largest installed capacity and highest peak demand is that of the South Andaman Islands. Hence, in this work, the mathematical formulation discussed in Sect. 2 is implemented on the insular grid of South Andaman.

Currently, South Andaman island has 13 diesel generators which range from a size of 12 kW to 5 MW generation capacity. It also has a solar plant of 5 MW and solar rooftop capacity of 1 MW. To this existing range of solar plants, additional solar power projects are proposed by GoI. As discussed in Sect. 2.2, this work analyzes different scenarios pertaining to the realization of these solar power projects and discusses its results. [It is to be noted that the input–output characteristics of diesel generators, start-up costs, energy costs, and other relevant information needed for the system are based on the scaled-down data of [8]. The analytical portion of this work is done using *optim* toolbox of MATLAB.]

Like in well-interconnected systems, it was foreseen that inclusion of PV plants would reduce the cost of generation, based on the argument that increasing share of solar would reduce the net power generated by the expensive diesel generators. This is universally true for any case wherein a cheaper conventional/non-conventional source of energy would displace the more expensive source of energy. In the preliminary stages (stage 1) of this work, the same was evident when solar power was treated as any other cheaper source of power. And hence, stage 1, as explained in Sect. 2.2, was implemented wherein reserve variability due to solar was not considered, i.e., up–down reserve capacity was determined based on (15%) load demand only. As seen in Figs. 1 and 2 and as discussed above, it was found that as the installed capacity of solar power plant increases, the power generated by expensive sources reduces and hence the cost of generation also decreases.

The contradiction in the above analysis was the fact that dynamic RES like solar and wind are non-dispatchable sources of energy and they have uncertainties asso-

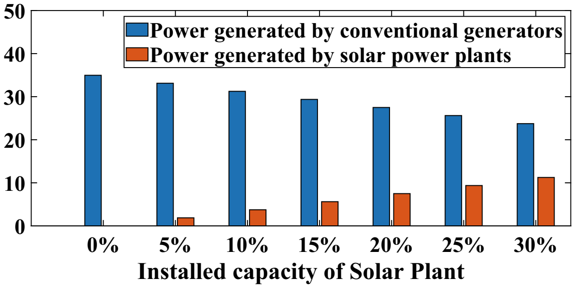


Fig. 1 Decrease in power produced by oil-fired generators as installed capacity of PV plant increases without considering reserve component for solar

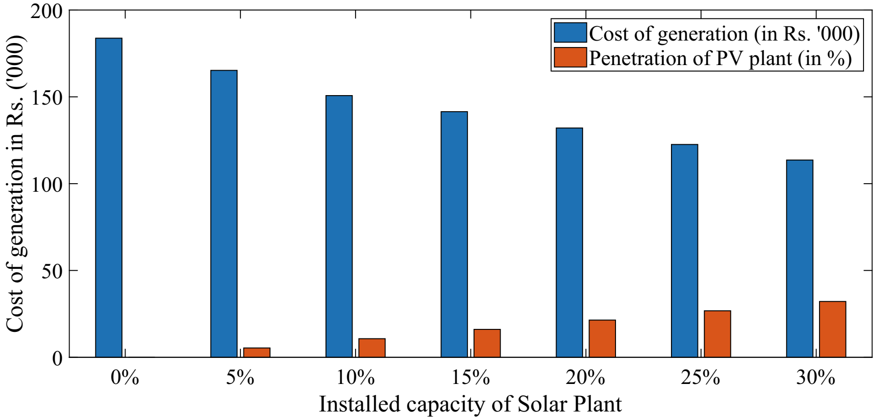


Fig. 2 Decrease in cost of generation as installed capacity of PV plant increases without considering reserve component for solar

Table 1 System details when solar power plant penetration is 35% or different reserve provision

Res. (%)	Cost (Rs.)				Power scheduled		Curtailment
	Generation	Reserve	Start-up	Total	Diesel	Solar	
0	108360	6146.6	3453.8	117960	22.75	12.25	0
5	108540	6867.2	3753.4	119161	22.75	12.25	0
10	110730	7640.3	4164.4	122535	22.75	12.25	0
15	110910	8378.9	4547.2	123836	22.75	12.25	0
20	131270	9822.3	4747	145839	23.9	11.1	1.15

Table 2 System details when solar power plant penetration is 40% for different reserve provision

Res. (%)	Cost (Rs.)				Power scheduled		Curtailment
	Generation	Reserve	Start-up	Total	Diesel	Solar	
0	99705	6109.5	3341.2	109156	21	12.25	0
5	99923	6929.8	3837.5	110690	21	12.25	0
10	115190	8335.5	3931.4	127457	21	12.25	0
15	112050	8705.5	4738.8	125494	22.97	12.03	1.97
20	134380	9727.1	5174.4	149282	26.69	8.31	5.69

ciated with them due to forecast inaccuracies. So, RES like solar, cannot be equated with the operation of other cheaper conventional/non-conventional sources of energy. Therefore, proposed model, explained in Sect. 2.1, was implemented in the manner mentioned in stage 2, explained in Sect. 2.2. Tables 1 and 2 provide results of two scenarios wherein the share of the solar power plant was restricted to 35% and 40%, respectively, and the reserve requirement was changed at an interval of 5%.

Fig. 3 Increase in start-up cost at stage 2

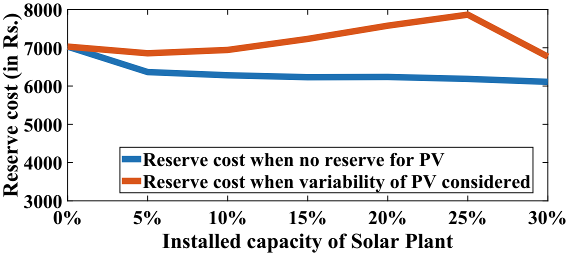
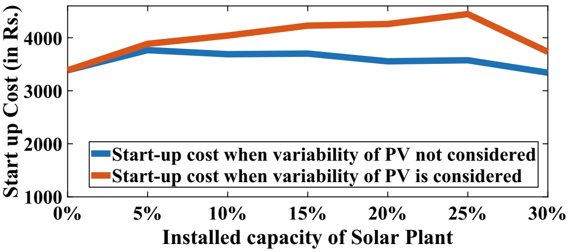


Fig. 4 Increase in reserve cost at stage 3



Tables 1 and 2 look into two separate aspects of generation scheduling. Constraints (2)–(5) cater to up-down system spinning reserve constraints. It has two parts—one portion is based on forecast inaccuracy arising in demand forecasts. The second portion is concerned with the scenario that due to forecasting inaccuracies, actual power produced by solar plant is more/less than the committed value. So by increasing the reserve component representing variability in solar, system instability issues are being reduced as sufficient spinning reserve would be able to adjust the imbalance due to solar prediction errors. On the other hand, if the system stability is prioritized, then it is observed in Tables 1 and 2 that the cost of generation using diesel generators, start-up cost, and reserve costs increases. This is seen in Figs. 3 and 4. Thus, the overall cost of generation increases as the penetration of solar increases.

In stage 3 of the analysis, the reserve component due to variability in solar is restricted 20%, i.e., in order to maintain system stability, a reserve capacity of 20% is to be acquired. It is observed that as the installed capacity of solar is increased, if system stability is prioritized through reserve component then lesser solar power will be scheduled. This is owing to the fact that for higher variability considerations, more conventional generators are needed. Details of parameters analyzed in stage 3 is shown in Table 3 along with Fig. 5.

GoI has taken a bold initiative to address the energy crisis of A&N Islands by increasing the share of renewables in the grid profile. But conscious analysis of the situation needs to be done before aggressively pursuing its renewable targets. Increasing share of dynamic RES increases the need to cater to the uncertainty introduced by forecasting inaccuracies of these non-dispatchable sources. The proposed model makes provision for the same by adding an additional reserve capacity component for the solar power generated. This additional reserve is eventually taken care

Table 3 System details when reserve requirement is restricted to 20% for different solar power plant penetration

Solar share (%)	Cost (Rs.)				Power scheduled		Curtailment
	Generation	Reserve	Start-up	Total	Diesel	Solar	
30	128840	8978.1	4654.6	142472.7	24.5	10.5	0
35	131270	9822.3	4747	145839.3	23.9	11.1	1.15
40	134380	9727.1	5174.4	149281.5	26.69	8.31	5.69
45	151390	10554	5209.4	167153.4	28.06	6.94	8.81

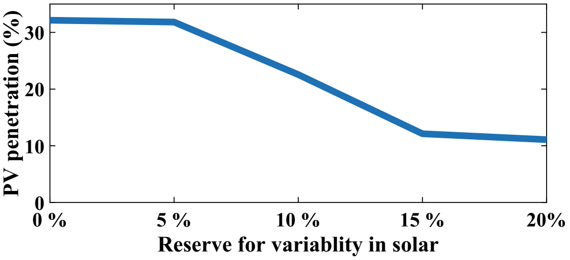


Fig. 5 Reduction in scheduled solar power as the installed capacity of solar is increased

of by the oil-fired generators themselves. So, as the penetration of renewables in insular grids increase, the reserve cost and start-up cost also increase. The overall rise in the total cost may not be much in the initial levels of integration with small reserve variability. But keeping smaller reserve component would mean that forecast inaccuracies observed in real time may not be handled every time leading to system instability when inaccuracies are higher. And smaller renewable integration is against the ultimate goal of integrating renewables.

If the installed capacity of solar is increased and for system stability sake, reserve component for solar is also increased, the overall cost of generation, inclusive of reserve and start-up costs increases. This increase may not be as much as the scenario without renewables, but it is sizeable enough to rethink the extent to which penetration should be increased. It is observed that after a certain point, there is no visible improvement in generation cost. Moreover, if additional conventional generating capacity is not increased then with increasing solar share, curtailment would have to be introduced.

The above mentioned remarks are applicable to other insular grids as well that are heavily reliant on oil-fired generators and are looking forward to increasing its renewable portfolio. Although it looks appealing, there are pitfalls.

4 Conclusion

Insular grids rely on expensive oil-fired generators. Moreover, they are not interconnected with other grids. This makes the cost of electricity generation higher than the mainland grid. Other than this, such generators increase carbon emission levels. Therefore, raising the share of RES in insular grids seems like the ideal solution to the problem. But this solution has pitfalls. The proposed model and approach helps in identifying these pitfalls. Some of them are in terms of increase in start-up and reserve costs of diesel generators. Another pitfall exists in the fact that if solar is left unaccounted for while planning reserve then it will make the grid vulnerable to instability issues while on the other hand if it is included in the reserve planning then the scheduled solar power will stagnate as the installed capacity is kept increasing. This work intends to get the policy makers to rethink their strategy such that a balanced way forward can be planned as opposed to adopting either of the extreme stance.

The current work presented in this paper has looked at the analysis from the deterministic perspective. This work can be further extended into the stochastic domain giving a much more clearer picture. Moreover, the feasibility of storage systems like pumped hydro stations and battery energy storage systems can be explored in both deterministic and stochastic perspective.

References

1. Kaldellis J, Gkikaki A, Kaldelli E, Kapsali M (2012) Investigating the energy autonomy of very small non-interconnected islands. Energy Sustain Dev 16:476–485
2. Heistrene L, Mishra P, Lokhande M (2020) Recourse based stochastic market clearing algorithm. In: Advances in electric power and energy infrastructure, pp 91–101
3. Heistrene L, Mishra P, Lokhande M (2019) Stochastic market clearing with revenue sufficiency constraints. Energy Procedia 158:3840–3845
4. Zhang Y et al (2017) Chance-constrained two stage UC under uncertain load & wind using bilinear BD. IEEE Trans Power Syst 32:3637–3647
5. Asensio M, Contreras J (2016) Stochastic unit commitment in isolated systems with renewable penetration under CvaR. IEEE Trans Smart Grid 7:1356–1367
6. Papadopoulos AM (2020) Renewable energies and storage in small insular systems: potential, perspectives and a case study. Renew Energy 149:103–114
7. Simoglou C et al (2014) An advanced model for the efficient and reliable short-term operation of insular electricity networks with high renewable energy sources penetration. Renew Sustain Energy Rev 38:415–427
8. Psarros G et al (2017) Generation scheduling in non-interconnected islands with high RES penetration. Renew Energy 13:2345–2354
9. Sonamuthu K (2019) Energy crisis in Andaman and Nicobar Islands. I IARJSET 6:29–35
10. Heistrene L, Mishra P, Lokhande M (2018) A hybrid bVAR-NARX wind power forecasting model based on wind and load demand correlation: a case study of ERCOT's system from an ISO's perspective. EPCS 46:1634–1649
11. Nayak A, Heistrene L (2020) Hybrid machine learning model for forecasting solar power generation. In: Proceedings of 7th international conference on SGES, pp 910–915
12. Joint initiative of Govt. of India and Andaman Nicobar. https://powermin.nic.in