Unit Commitment with Respect to Both Cost and Emission Based on a Day Load Demand in an Integrated Solar and Wind Power System

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Abstract. Emission control has become a critical global challenge due to increasing greenhouse gas (GHG) concentrations, primarily resulting from fossil-fuel-based power generation. In India, the growing electricity demand has intensified dependence on thermal power plants, leading to higher carbon dioxide emissions and associated environmental concerns. This paper addresses the dual objectives of reducing electricity generation cost and minimizing emissions by integrating renewable energy sources with conventional thermal units. Solar photovoltaic (PV) and wind power are incorporated into the generation mix. The problem formulation employs Unit Commitment (UC) to determine the optimal hourly scheduling of generating units and Economic Load Dispatch (ELD) to allocate generation economically among committed units. A 24-hour UC problem for a system of four thermal units is solved using Dynamic Programming. The results demonstrate that coordinating renewable energy with thermal generation significantly decreases operating costs and carbon emissions. The findings highlight the potential of renewable–thermal integration as a viable approach for sustainable and cost-efficient power system operation.

Keywords: Dynamic Programming, Day Load Demand, Emission, Optimization, Unit Commitment

1. Introduction

India's electricity demand is growing rapidly due to urbanization, economic development, and population expansion, creating significant pressure on the power system to deliver reliable and affordable energy. [1] Historically, this demand has been met largely through fossil-fuel-based thermal power plants, which are major contributors to greenhouse gas (GHG) emissions and environmental degradation. To address these challenges, the Government of India has adopted ambitious renewable energy targets, aiming to achieve 500 GW of non-fossil fuel installed capacity by 2030, with substantial contributions from solar and wind energy. As of mid-2025, India's total renewable capacity has exceeded 220 GW, and non-fossil sources account for over 50 % of the country's installed generation capacity, milestones achieved ahead of schedule toward the 2030 goals. [2]

Unit Commitment (UC) is an essential optimization problem in short-term power system operation that schedules generating units over a planning horizon—typically 24 hours—to minimize total operating cost while satisfying technical constraints. Traditional UC formulations focus primarily on thermal generation, but the rising penetration of wind and solar resources necessitates new models. In the Indian context, large hourly load variations and high peak demands further complicate this problem. [3, 4]

Wind and solar photovoltaic energy have emerged as cornerstone resources in India's renewable strategy due to their significant installed capacity growth and declining generation costs. However, their intermittent nature introduces operational challenges for system reliability and economic dispatch. Effective integration of these resources into UC framework is hence critical for reducing thermal generation, overall cost and emissions. [5, 6]

This paper investigates a UC framework that integrates wind and solar PV generation with conventional thermal units to achieve cost-effective and low-emission power system operation. The proposed approach incorporates renewable generation into the UC and Economic Load Dispatch process while satisfying all operational constraints. Case studies demonstrate that coordinated scheduling of thermal and renewable resources significantly reduces both operating costs and carbon emissions, highlighting the relevance of renewable-integrated UC for the future Indian power system. This paper addresses the Unit Commitment and Economic Load Dispatch problems using a Dynamic Programming approach while satisfying all operational constraints of thermal generating units. Two different case studies are conducted, and the results are comparatively analysed.

This paper is structured as follows: Sec-1 introduces the issue under study. Sec-2 presents the motivation due to research gaps, and objectives for study. Sec-3 describes the UC formulation and emission function, along with the Dynamic Programming–based solution approach. In Sec-4, the proposed technique is implemented to a test system and results so obtained are discussed. At last, Sec-5 gives the conclusion of the paper.

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2. Motivation & Objectives

Although renewable energy capacity has grown significantly, coal-based thermal power plants continue to supply a major share of electricity and remain the primary source of energy. Despite extensive research on UC and renewable integration, several gaps remain. Many studies rely on benchmark systems and do not reflect Indian grid characteristics [7, 8]. Emission reduction is often not explicitly integrated into UC framework [9], and the use of Dynamic Programming for renewable-integrated UC with emission considerations has received limited attention [7, 10]. Many studies do not provide clear comparative analyses between thermal-only and renewable-integrated UC scenarios, making it difficult to quantify the actual benefits of renewable integration [11, 12]. Motivated by these gaps, this paper develops a Dynamic Programming-based UC framework integrating wind and solar generation to achieve economical and environmentally sustainable operation.

The objectives of this paper are:

- To determine the Economic Load Dispatch (ELD) for all feasible unit commitment combinations across 24 scheduling stages, corresponding to a 24-hour horizon with a one-hour time interval, while satisfying system and unit operational constraints and meeting load demand at each stage.
- To evaluate the total generation cost, including operating fuel cost as well as start-up and shutdown costs, and to quantify the corresponding carbon dioxide emissions for each feasible unit combination obtained from the Economic Load Dispatch.
- To integrate renewable energy sources, namely solar photovoltaic and wind power, into the system and evaluate their impact on total system operating cost and carbon dioxide emissions.
- To determine and compare the optimal ON/OFF scheduling of generating units over a 24-hour scheduling horizon for both cases, with and without renewable energy integration, to minimize total generation cost and CO_2 emissions while satisfying all system and unit constraints.

Based on the above objectives, work is carried out in this paper.

3. Methodology

Based on the objectives mentioned above, the studies were carried out for 2 systems:

(i) *4-unit Thermal power system.* The unit commitment problem is addressed through appropriate problem formulation, followed by the minimization of total production cost and carbon dioxide emissions using a Dynamic Programming approach.

(ii) *4-unit Thermal power system with Solar and Wind integrated.* The steps involved for this system are nearly the same as in system (i). But now the additional inputs are received from Solar and Wind units for carrying out the minimization of production cost and carbon dioxide emissions.

Formulation of UC Problem, Emission function, and Backward DP are explained thereby.

3.1 Formulation of Unit Commitment Problem

The UC objective is to achieve minimum production cost and carbon dioxide emissions over the scheduled 24-hour horizon while adhering to generator operational constraints.

The objective function to be minimized is

$$F(P_i^t, U_{i,t}) = \sum_{t=1}^{T} \sum_{i=1}^{N} [\, F_i\,(P_i^t) \;+\; ST_{i,t}(1 - U_{i,t-1})\,]U_{i,t} \tag{1}$$

Subject to following constraints:

(a) Constraints linked with Power Balance

$$P_{load}^t - \sum_{i=1}^{N} P_i^t \, U_{i,t} = 0 \tag{2}$$

(b) Constraints linked with Generation Limits

$$P_{i,min}U_{i,t} \;\leq\; P_i^t \;\leq\; P_{i,max}U_{i,t} \quad \text{for } i = 1,2, \ldots \text{N} \tag{3}$$

Where,

$F_i(P_i^t)$ – Cost function for i^{th} unit with generated power output P_i^t, at time 't' hour (in \$/h).

Usually, it's a quadratic equation with coefficients a_i, b_i & c_i as mentioned:

$$F_i(P_i^t) = \frac{a_i}{2}(P_i^t)^2 + b_i P_i^t + c_i \tag{4}$$

Unit of a_i is in $\frac{\$}{(MW)^2 h}$

Unit of b_i is in \$/MWh

Unit of c_i is in \$/h

N − Number of units

T − Number of hours

P_i^t − Generated power output for i[th] unit at time 't' hour (in MW)

$U_{i,t}$ − Status ON or OFF for i[th] unit at time 't' hour

$U_{i,t} = 0$ if OFF

$U_{i,t} = 1$ if ON

P_{load}^t − Power Demand at time 't' hour (in MW)

$P_{i,max}$ − Max. real power that can be generated for unit 'i' (in MW)

$P_{i,min}$ − Min. real power that can be generated for unit 'i' (in MW)

In this paper, minimum up/down time constraints for unit startup and shutdown, as well as spinning reserve constraints, are neglected.

3.2 Emission Function

Emission of Carbon dioxide is directly related to the fuel consumed [13]. In this paper, a second order emission function is used. Emission of carbon dioxide pollutant is only considered.

Here, the Emission function is written mathematically as

$$E_{i,t} = e_{f,i}\,(k_{0i} + k_{1i}P_i^t + k_{2i}(P_i^t)^2)U_{i,t} \tag{5}$$

Where,

$e_{f,i}$ − Carbon dioxide emission factor from i[th] unit

Emission factor i.e. $e_{f,i}$ depends on following things:

- Design parameters of the plant
- Quality of fuel
- Considered type of Emission

According to [13],

$$e_{f,i} = 9.4 * 10^{-2} \text{ kg/MWh (for coal conventional units)}$$

k_{0i}, k_{1i} and k_{2i} are the polynomial heat rate coefficients of the i[th] generating unit

$$k_{0i} = c_i/\emptyset_i \text{ (in MW)} \tag{6}$$

$$k_{1i} = b_i/\emptyset_i \text{ (unitless)} \tag{7}$$

$$k_{2i} = a_i/2\emptyset_i \text{ (in MW}^{-1}\text{)} \tag{8}$$

$\emptyset_i$ − Average fuel cost

$$\emptyset_i = F_i(P_i^t)/P_i^t \text{ (in \$/MWh)} \tag{9}$$

Here, emissions due to startup and shutdown have been neglected.

3.3 Dynamic Programming (DP) Approach

The DP approach is an efficient optimization technique used to solve multi-stage decision-making problems involving many possible decisions. In this approach, each decision at a given stage is associated with a specific cost, which may depend on the decisions made in preceding stages. Additionally, a transition cost may be encountered when moving from a decision at one stage to a decision at the subsequent stage. The sequence of decisions connecting successive stages is referred to be a transition path. Primary aim of Dynamic Programming is to identify the optimal decision at each stage such that the cumulative cost over all stages is minimized. The overall DP algorithm employed in this paper is illustrated using a flowchart in Fig. 1.

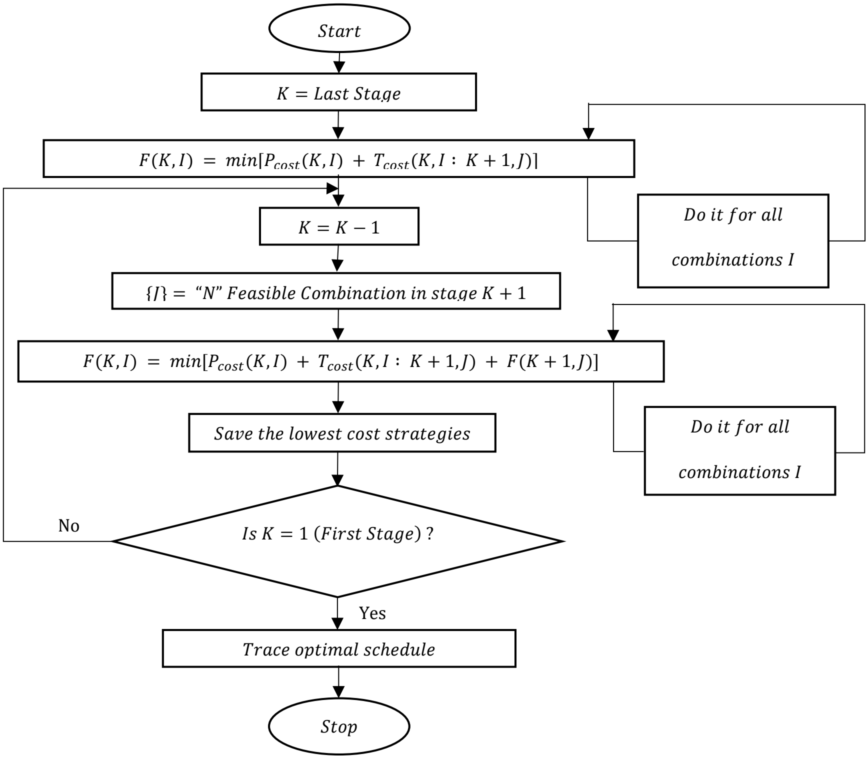

Fig. 1. DP Approach to Solve Unit Commitment

4. Results and Discussion

The procedure described in the previous section is employed to obtain the results. Fig. 2 and Table 1 present the hourly load demand for the 24-hour period used for Backward Dynamic Programming. Table 2 lists the characteristics of the four generating units, including their minimum and maximum generation limits and fuel cost coefficients.

Table 1. A Sample Day Load Demand on Hourly Basis [14]

Hour	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Demand (MW)	237.5	175	113	112	112	137.5	212.5	375
Hour	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*

Demand (MW)	612.5	900	1062.5	956.25	850	775	725	787.5
Hour	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*
Demand (MW)	987.5	1475	1812.5	1712.5	1462.5	1100	700	362.5

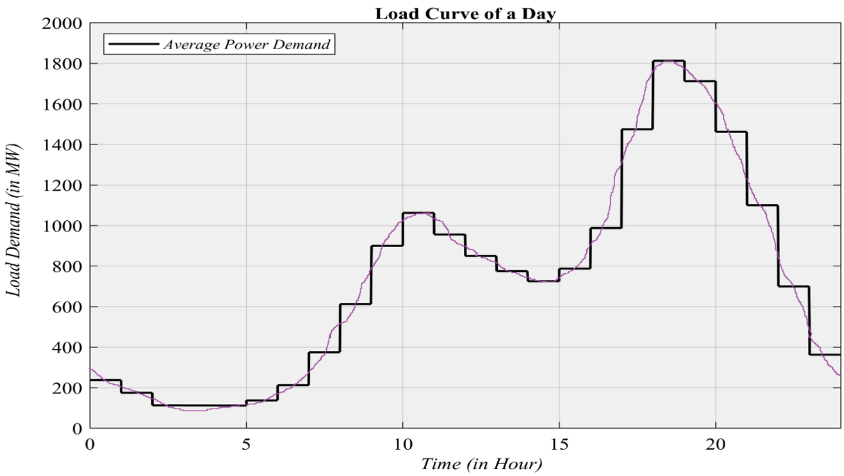

Fig. 2. A Sample Load Curve of a Day [14]

Table 2. Unit Characteristics of all 4 Thermal Units [15]

Units	*Maximum Limit (in MW)*	*Minimum Limit (in MW)*	*Cost Parameters of the Fuel*		
			a_i (in $\frac{\$}{(MW)^2h}$)	b_i *(in \$/MWh)*	c_i *(in \$/h)*
Unit-1	625	75	0.0080	8.0	500
Unit-2	625	100	0.0096	6.4	400
Unit-3	600	100	0.0100	7.9	600
Unit-4	500	75	0.0110	7.5	400

Table 3 lists the feasible unit commitment combinations for meeting the system load demand. Since the system load is nonzero throughout the daily load cycle, at least one generating unit must always remain online. Accordingly, Unit-1 is designated as a must-run unit in this study. For the four-unit system, there can be a total of 15 possible combinations; however, with Unit-1 enforced as a must-run unit, the number of feasible combinations is reduced to eight.

Table 3. Various Possible combinations considered for the solving the UC Problem *(Unit-1 is a Must-Run Unit)* [15]

Units	*Combinations*							
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8
Unit-1	1	1	1	1	1	1	1	1
Unit-2	0	0	0	0	1	1	1	1
Unit-3	0	0	1	1	0	0	1	1
Unit-4	0	1	0	1	0	1	0	1

Case – I: *Only Thermal Units considered*

In the first case where only thermal units are considered, Dynamic Programming approach has been performed to get the production costs and carbon dioxide emissions for every hour of study in 24-hour horizon. Minimum up/down time constraints are neglected, while fixed startup and shutdown costs of $3000 and $1500, respectively, are modelled as transition costs [15]. The resulting optimal schedule, along with hourly production cost and carbon dioxide emissions, is presented in Table 4.

Table 4. UC and ELD of the Units by Backward Dynamic Programming (without integrating renewable sources)

Hour	*Combination*	*ELD Generation Schedule (MW)*				*Production Cost ($)*	CO_2 *Emission (kg)*
		Unit-1	*Unit-2*	*Unit-3*	*Unit-4*		
1	x_1	237.5	0	0	0	2626	674
2	x_1	175	0	0	0	2023	622
3	x_1	113	0	0	0	1455	571
4	x_1	112	0	0	0	1446	570
5	x_1	112	0	0	0	1446	570
6	x_1	137.5	0	0	0	1676	591
7	x_5	75	137.5	0	0	2521	1029
8	x_6	75	219.675	0	80.325	4067	1529
9	x_6	156.361	296.967	0	159.172	6306	1730
10	x_6	268.639	390.533	0	240.828	9094	1950
11	x_8	250.068	375.056	210.054	227.322	11096	2657
12	x_8	218.451	348.71	184.761	204.328	10045	2575
13	x_8	186.835	322.362	159.468	181.335	9024	2493
14	x_8	164.518	303.764	141.614	165.104	8318	2433
15	x_8	149.639	291.366	129.711	154.284	7856	2393
16	x_8	168.237	306.864	144.59	167.809	8435	2443
17	x_8	227.75	356.459	192.2	211.091	10351	2599
18	x_8	372.813	477.344	308.251	316.592	15423	2960
19	x_8	473.242	561.035	388.593	389.63	19265	3191
20	x_6	615.902	625	0	471.598	18745	2517
21	x_6	488.314	573.595	0	400.591	15297	2340
22	x_5	509.091	590.909	0	0	11467	1675
23	x_5	290.909	409.091	0	0	6987	1405
24	x_5	106.818	255.682	0	0	3750	1147
Total		**5684.587**	**6841.912**	**1859.242**	**3370.009**	**188719**	**42664**

From Table 4 only thermal units are sufficient to produce the required amount of power. But these thermal units also cost huge amount of capitals as well as it releases lot of CO_2. To produce power for a whole day, these units cost a total amount of $194055 (including the transition costs) and a total amount of carbon dioxide emission of 42664 kg. This is a very big reason of concern now-a-days. Therefore, we should also look forward to other alternatives to produce power like renewable sources of energy.

Case – II: *Thermal Units integrated with Solar and Wind Power*

In Case II, thermal units are integrated with solar and wind power. All available renewable generation is fully utilized due to its zero-fuel cost and emission-free nature, thereby reducing the load to be supplied by thermal units. The reduced hourly net load is then used for Dynamic Programming, while all other system parameters remain unchanged from Case I. This integration results in different production cost and carbon dioxide emissions compared to the thermal-only case.

Table 5. A Sample Wind Power Generation Data for 24 Hours [6]

Hour	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Wind Power (MW)	21.45	19.8	26.4	27.06	33	23.1	16.5	28.05	33	36.3	34.98	31.35
Hour	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*
Wind Power (MW)	26.4	33	29.04	33	35.2	20.68	26.07	15.18	28.05	21.78	18.48	17.16

Table 6. A Sample Solar PV Power Production Data for 24 Hours [16]

Hour	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
Solar Power (kW)	0	0	0	0	0	2.94	10.59	17.06	23.82	28.82	32.35	32.65
Hour	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*	*24*
Solar Power (kW)	30.59	28.82	25.29	18.53	11.18	3.24	0	0	0	0	0	0

Table 5 gives data for wind power generation taken from [6] which dealt with the historical data from Mendota Hills wind farm in Lee County of Illinois state in USA. Table 6 gives data for solar PV power production, taken from [16], studied on the buildings of the Golden city of Colorado state in USA. It can be noticed that solar power is fetched when the Sun is available. After considering the power from renewable sources like Solar PV and Wind Power, once again Dynamic Programming was performed, and the result is given in Table 7.

Table 7. UC and ELD of the Units by Backward Dynamic Programming (with integrating renewable sources)

Hour	*Combination*	*ELD Generation Schedule (MW)*				*Production Cost ($)*	*CO_2 Emission (kg)*
		Unit-1	*Unit-2*	*Unit-3*	*Unit-4*		
1	x_1	216.05	0	0	0	2415	656
2	x_1	155.2	0	0	0	1838	606
3	x_1	86.6	0	0	0	1223	549
4	x_1	84.94	0	0	0	1208	548
5	x_1	79	0	0	0	1157	543
6	x_1	114.397	0	0	0	1468	572
7	x_5	75	120.989	0	0	2368	1016
8	x_6	75	196.933	0	75	3890	1512
9	x_6	143.464	286.22	0	149.792	6002	1703
10	x_6	254.451	378.71	0	230.51	8728	1923
11	x_6	318.427	432.023	0	277.038	10414	2043
12	x_8	209.113	340.927	177.29	197.537	9742	2551

13	x_8	178.97	315.808	153.176	175.615	8774	2471
14	x_8	154.689	295.575	133.751	157.956	8012	2408
15	x_8	140.991	284.159	122.792	147.993	7588	2371
16	x_8	158.412	298.677	136.729	160.663	8129	2417
17	x_8	217.273	347.727	183.818	203.471	10008	2571
18	x_8	366.659	472.216	303.327	312.115	15197	2946
19	x_8	465.484	554.571	382.387	383.988	18959	3173
20	x_6	605.034	625	0	467.286	18505	2505
21	x_6	477.359	564.466	0	392.625	14965	2322
22	x_5	497.211	581.009	0	0	11206	1662
23	x_5	280.829	400.691	0	0	6797	1392
24	x_5	97.458	247.882	0	0	3599	1133
Total		**5452.011**	**6743.583**	**1593.27**	**3331.589**	**182192**	**41593**

From Table 7, total cost of power production over 24 hours is \$187349 (including transition costs) which is \$6706 less than the previous case study i.e. UC without integrating the renewable sources. Also, in terms of carbon dioxide emission, Table 6 results show less than Table 4. After involving renewable sources, total amount of emission over 24 hours reduced to 41593 kg, which was 42664 kg earlier i.e. 1071 kg less carbon dioxide emission.

5. Conclusions

Thermal generation remains necessary to meet growing electricity demand; however, increasing renewable penetration can significantly reduce operating cost and emissions. This paper applies a Backward Dynamic Programming–based Unit Commitment approach to a four-unit system under two scenarios: thermal-only and renewable-integrated (solar PV and wind). The results show that renewable integration substantially reduces production cost and carbon dioxide emissions, while the Unit Commitment schedule and transition costs remain nearly unchanged. Reduced thermal generation in the renewable-integrated case directly leads to lower electricity cost and emissions.

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