

## Netload-constrained Unit Commitment Considering Increasing Renewable Energy Penetration Levels: Impact of Generation Schedules and Operational Cost

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### ABSTRACT

In the context of low carbon power systems, the penetration levels of renewable energy sources (RES) are expected to increase dramatically. In this regard, this paper investigates the maximum RES penetration level constrained by net load while considering an inflexible unit commitment (UC) model. To solve the UC problem, an enhanced priority list (EPL) based method is developed. In the proposed method, the plants were activated sequentially based on the operational price. The system constraint violations were repeatedly corrected until all system constraints (such as net load and spinning reserves) were satisfied. The proposed EPL method was efficient to achieve a near optimal solution under high shares of RES. Furthermore, the research work investigates three different scenarios representing penetration levels of 10% solar-only, 14.5% wind-only and 27.5% mixture of both solar and wind. The impact of each penetration level on the system scheduling and operational cost were analyzed in detail. The analysis presented shows that a potential operational cost savings of 21.6 \$/MW, 20 \$/MW and 11.1 \$/MW is feasible under each of the represented scenarios, respectively.

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## 1. INTRODUCTION

The climate change mitigation and security of energy supply has stimulated national energy policies towards higher integration of renewable energy sources (RES) [1]. Unlike conventional power sources, variable RES has a maximum available generation limit that changes with time (variability), and this limit is not known to be in perfect accuracy (uncertainty) [2]. The adoption of high penetration levels has significantly intensified the degree of variability and uncertainty involved in the short-term operation and long term planning. Furthermore, RES integration has become a challenging task due to the nonlinear and random nature of RES which involves definite constraints and nonlinear objective functions [3]. Different levels of RES generation penetration have different impacts on system generation scheduling. The uncertain and volatile nature of RES may pose many challenges to the power system such as imbalance between load and generated power, transient and voltage stability [4].

The wind and solar power generation sources are the most popular RES that can be considered as the most essential and sustainable energy resources [5-6]. As a must-taken energy, RES generation acts purely as load-shaving, leading to the concept of net load (or sometimes known as residual load). It is defined as the difference between the load and output of solar and/or wind output generation [7]. Therefore, in the perspective of the power system, the UC is an important optimization problem for daily operation and economic planning. It is the process of determining the optimal schedule of generating units over a set of

study period subject to device and system operating constraints. In line with high RES penetration, the UC problem is used to investigate the impact of high penetration on system schedules. To achieve this, a suitable UC optimization tool that is able to cope with variable and low net load profiles in an efficient way should be developed.

A wide range of techniques has been proposed and developed over the years to solve the UC problem, such as dynamic programming, a novel heuristic approach using PSO [8], De-commitment method [9], modified differential evolution algorithm [10], Lagrangian Relaxation [11] and other optimization techniques including metaheuristic methods [3], [12], [13]. The main focus of the existing methods is to improve the computational speed and solution quality. However, in recent times, prominent methods fail to address the computational difficulty that arises as a result of low values of net loads, resulting from high RES penetration levels [14].

On the other hand, recent literature indicates that priority list (PL) could be investigated further due to its ability to give a near-optimal solution in a reduced computational time [15]. The method has undergone important developments. For example, the PL method has been adapted in the management of power systems with ESS [16]. In addition, the combination of an improved PL and an Augmented Hopfield Lagrange (AHL) neural network was proposed [17]. Subsequently, an improved pre-prepared power demand was combined with the Muller method [18]. There are other priority list methods such as ranking units based on the full-load average production cost of each unit [19] and on the incremental cost rate of each unit [20] or on the maximum load production cost as well [21]. However, the issue of increasing computational effort for systems with low residual demand has not been effectively addressed so far.

This paper focuses on the PL technique as it is able to carry out fast computation with low net load conditions within the network. Hence, a new enhanced priority-list (EPL)-based method is developed specifically for low net load demand settings. The method is based on the principle of satisfying the system constraints followed by satisfying the load and minimizing the system fuel costs within those committed units. In comparison with the conventional priority list method, the EPL method has satisfied the following constraints; spinning reserve, minimum up time and minimum down time constraints which are not taken into account in the conventional priority list method. In addition, the study carries out three main investigations:

- a. The maximum penetration levels constrained by net load
- b. The impact of high RES penetrations on system schedules and
- c. The overall achievable cost saving under high RES penetrations.

## 2. UNIT COMMITMENT PROBLEM FORMULATION

In electric power systems, the UC problem formulation is mainly divided into two sub-solutions, namely unit commitment decision and economic load dispatch by determining the optimal generated power for each committed unit. Furthermore, this would satisfy generating units and system constraints over the scheduling period.

### 2.1 Unit commitment objective function

The on-off states of the generation units or the “commitment decision” contribute to the first step towards the optimal solution. It is the discrete variables that determine the state of on or off of a particular unit at any particular time.  $U_n^t$ , the unit  $n$  at hour  $t$ , is 1, if the unit is “on line” and 0 if the unit is “off line” and is represented by (1) [22].

$$U_n^t \in \{0,1\} \quad (1)$$

Thus, the principal objective in UC is to prepare the on/off schedule of the generating units in every sub-period (typically 1 hour) of the given planning period (typically 1 day or 1 week) in order to serve the load demand and spinning reserve at minimum total production cost (fuel cost, start-up cost, shut down cost), while meeting all unit and system constraints. In this study, the main objective is to efficiently minimize the total operation cost ( $TOC$ ) over the scheduling period. The  $TOC$  is subject to the fuel cost, start-up cost and shut down cost. The UC problem can be formulated as a mixed integer constrained, in which the overall objective function of the UC problem is described by (2).

$$\min TOC = \sum_{t=1}^T \sum_{n=1}^N \left( U_n^t \cdot F_n^t(P_n^t) + U_n^t \cdot S_n^t + \sum_{n=1}^M oc(w_{nt}) + \sum_{n=1}^S oc(pv_{nt}) \right) \quad (2)$$

Where  $TOC$  is the total operating cost,  $N$  is the total generating units,  $M$  is the wind farm,  $S$  is the  $PV$  power plant,  $T$  is the time horizon which is 24 hours in this case study,  $oc(w_{nt})$  is the operating cost of the wind farm and  $oc(pv_{nt})$  is the operating cost of the  $PV$  power plant. The fuel cost of  $n$ -th thermal unit with the generating output  $p$ -th power at  $t$ -th hour  $F_n^t(P_n^t)$  is expressed as a second order (parabolic) function of every unit output as follows.

$$F_n^t(P_n^t) = a_n(P_n^t)^2 + b_n P_n^t + c_n \quad (3)$$

The  $a_n, b_n, c_n$  are the fuel cost coefficient of  $n$ -th unit. The generator start-up cost  $s_n^t$  for restarting a de-committed thermal unit, which is related to the temperature of the boiler is included in this model. The  $s_n^t$  depends on the duration the unit has been turned off prior to start-up. By changing the on/off status of the units, the number of start-up and shut down and the type of units (hot or cold) will also change accordingly [23]. The start-up cost can vary from a maximum “cold-start” value to a much smaller value if the unit is only turned off recently and remains relatively close to the operating temperature [19], as presented by (4).

$$s_n^t = \begin{cases} HSC_n, & \text{if } MDT_n < T_{off,n} \leq MDT_n + T_{cc} \\ CSC_n, & \text{if } T_{down} > MDT_n + T_{cold,n} \end{cases} \quad (4)$$

Where  $HSC_n$  and  $CSC_n$  are the hot and cold start-up costs of unit  $n$ , respectively. The start-up cost and shut down cost values are usually identical and are predefined constant values for each unit [24]. The shutdown cost is usually neglected and has been taken as equal to 0 for all units and is excluded from the objective function.

The second step of the UC solution is the economic dispatch solution. For each UC decision achieved, its economic power generation output  $P_n^t$  is visualized as a  $(H \times N)$  matrix with the real values of dispatch as shown in (5).

$$P_n^t = \begin{matrix} P_1^1 & P_1^2 & \dots & P_1^N \\ P_2^1 & P_2^2 & \dots & P_2^N \\ \vdots & \vdots & \ddots & \vdots \\ P_H^1 & P_H^2 & \dots & P_H^N \end{matrix} \quad (5)$$

## 2.2. System constrains

In minimizing the objective function, the problem solution must respect both generator physical constraints and system operational constraints. These constraints include one or more of the following:

### 2.2.1. Generating unit limit constraint

The active power output of the generating unit must satisfy the minimum and maximum limits of the unit as given in (6).

$$P_n^t(\min) < P_n^t < P_n^t(\max) \quad (6)$$

where  $P_n^t(\min)$ ,  $P_n^t(\max)$  are the minimum and maximum real power output, respectively.

### 2.2.2. Power balance constraint

The actual power output of the online committed units must be sufficient to satisfy the customers load demand for each hour and is given by (7).

$$\sum_{n=1}^N P_{n(\max)}(t) \cdot U_n(t) = D_t \quad (7)$$

where  $D_t$  is the total demand at  $t$ -th hour.

### 2.2.3. Minimum up-time constraint

Minimum up-time is the minimum number of hours of operation at or above the minimum generation capacity. In other words, once the unit is committed to be online, it cannot be turned off for a specific number of hours.

$$T_n^{on} > MUT_n \quad (8)$$

Where  $T_n^{on}$  and  $MUT_n$  are the total up-time and the minimum up-time of  $n$ -th unit  $n$ , respectively.

### 2.2.4. Minimum down-time constraint

Minimum down time is the minimum number of hours once the generator is shut down before it is re-committed again to generate power.

$$T_n^{off} > MDT_n \quad (9)$$

where  $T_n^{off}$  and  $MDT_n$  are the total down time and the minimum down time of  $n$ -th unit, respectively.

### 2.2.5. Ramp rate up/down constraint

The change of the generating unit power output does not increase or decrease instantaneously. The change of this power output is restricted by ramp rate limits. These constraints are formulated based as on the following conditions.

$$P_{n,t} - P_{n,t-1} \leq UR_n \text{ ,if generation increases} \quad (10)$$

$$P_{n,t-1} - P_{n,t} \leq DR_n \text{ ,if generation decreases} \quad (11)$$

where  $UR_n$  and  $DR_n$  are the ramping up and ramping down of  $n$ -th unit, respectively.

### 2.2.6. Spinning reserves constraint

Spinning reserve (SR) is an indicator of the percentage or amount of power that is required to fulfill the percentage of forecasted peak demand. It is also capable to make up the loss of the most heavily loaded unit in a given period of time.  $D_t$  is the power demand at hour  $t$ . The formulation for SR can be seen in (12).

$$\sum_n^N (U_n^t \cdot P_n^t) \geq (D_t + SR_t), 1 \leq t \leq T \quad (12)$$

where  $SR_t$  is the spinning reserve at  $t$ -th hour.

### 2.2.7. Must run unit

The must run unit is specified by the system operator to be committed on line for a particular interval of operation to address operating reliability considerations and voltage support on the transmission network or commercial considerations. The solar and wind are considered as must run units for better economic system operation.

### 2.2.8. Transmission constraint

Transmission constraint is the limitation of the transfer capability of transmission systems, such as thermal rating of individual transmission line and contingency constraint.

### 2.2.9. Capacity limit

The capacity limits of thermal units may change frequently due to maintenance or unscheduled outages of different types of equipment in the plant. This must also be taken into account in unit commitment.

## 3. PROPOSED IMPROVED PRIORITY LIST METHOD

The proposed improved PL method is composed of several processes and sub-problems which jointly lead to a feasible and cost-effective solution to the UC problem [23], [25]. The sub-problems involved are UC decision, minimum up/down time repairing, spinning reserve repairing and shut-down excess of power generation.

In this approach, the commitment order of each generator is based on its maximum production cost and heat rate. The solution obtained must satisfy the minimum up/down time constraints. The correction for this constraint satisfaction may lead to reduced total generated capacity. As a consequence, an extra generation capacity could be needed. The process of minimum up/down time repairing and spinning reserve repairing may lead to extra power generated at certain hours which will lead to the increase of generation cost. In order to obtain optimized generation and cost effective scheduling, shutdown of excess generated power must be carried out. Figure 1 represents the flowchart for the proposed improved PL method to clarify the system constraint satisfaction and optimization process.

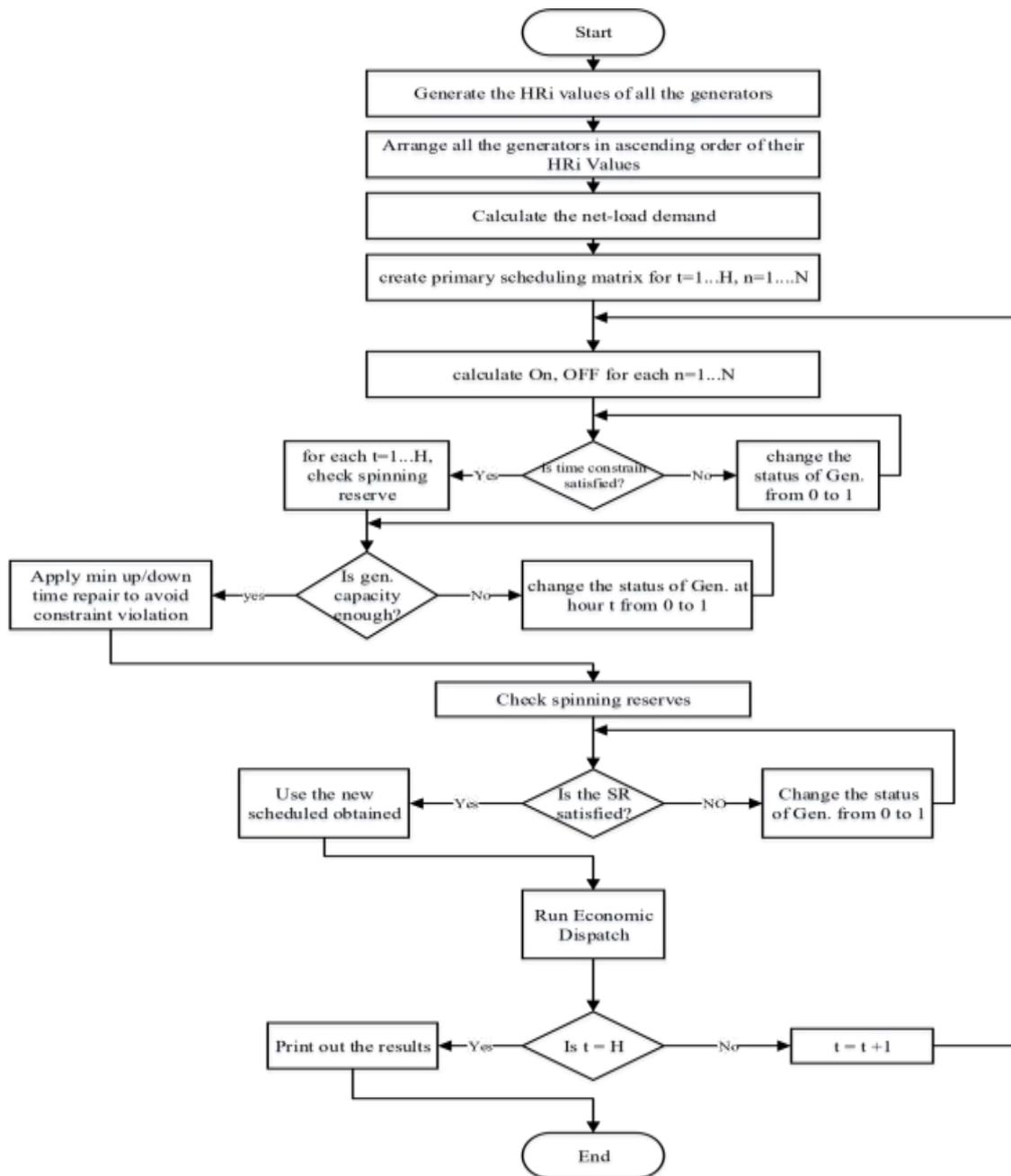


Figure 1. A proposed improved priority list flowchart

## 4. CASE STUDY SCENARIOS AND SIMULATION RESULTS

### 4.1. Data set specification/data description

A ten unit system used in this research is to investigate the effect of solar and wind power output into the power system generation scheduling. The data from the generators and the 24-hour load demand profile are presented in Table 1 and 2 respectively [20]. The load profile is assumed to be similar throughout the year. The load consumption is observed to be high during day time. The initial status of the generator prior to the time frame is considered in the optimization. The negative number indicates down-time while the positive number indicates up-time. The start-up cost is modeled as a stepwise cost function with two steps. The first step is the hot start-up cost and the other step is the cold start-up cost. The reserve requirement is equal to 10% of the hourly load demand.

Table 1. Generator Data of 10 Units System

	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10
Pmax(MW)	455	455	130	130	162	80	85	55	55	55
Pmin(MW)	150	150	20	20	25	20	25	10	10	10
a(\$/h)	1000	970	700	680	450	370	480	660	665	670
b(\$/MWh)	16.19	17.26	16.6	16.5	19.7	22.26	27.74	25.92	27.27	27.79
c(\$/MW <sup>2</sup> h)	0.00048	0.00031	0.002	0.00211	0.00398	0.00712	0.00079	0.00413	0.00222	0.00173
MUT(h)	8	8	5	5	6	3	3	1	1	1
MDT(h)	8	8	5	5	6	3	3	1	1	1
HSC(\$)	4500	5000	550	560	900	170	260	30	30	30
CSC(\$)	9000	10000	1100	1120	1800	340	520	60	60	60
CS(h)	5	5	4	4	4	2	2	0	0	0
IS(h)	8	8	-5	-5	-6	-3	-3	-1	-1	-1

Table 2. Hourly Electricity Load Profile for 24 Hours

Hour	1	2	3	4	5	6	7	8	9	10	11	12
Load (MW)	700	750	850	950	1000	1100	1150	1200	1300	1400	1450	1500
Hour	13	14	15	16	17	18	19	20	21	22	23	24
Load (MW)	1400	1300	1200	1050	1000	100	1200	1400	1300	1100	900	800

### 4.2 Solar radiation and wind speed data

A multiplying scale factor is used to model the wind and solar farms. By using this scale, the power production level or the penetration level of a single PV module and wind turbine is received. The power output of each PV cell and turbine is proportional to the resource potential in terms of solar radiation and wind speed respectively. The scale factors are generated separately for wind and PV for each penetration level/ scenario.

In this research, the actual solar radiation and wind speed data are collected at Kuala Terengganu, Malaysia [26]. The wind power output,  $P_{WTG}$  generated from the wind turbine can be presented as:

$$P_{WTG} = \begin{cases} 0 & V < V_{ci} \\ a \times V^3 - b \times P_r & V_{ci} \leq V \leq V_r \\ P_r & V_r \leq V \leq V_{co} \end{cases} \quad (13)$$

where  $P_r$  is the wind turbines rated power;  $V_{ci}$  is the cut-in wind speed;  $V_r$  is the rated wind speed;  $V_{co}$  is the cut-out wind speed. a and b are defined as:

$$a = \frac{P_r}{V_r^3 - V_{ci}^3} \quad (14)$$

$$b = \frac{V_{ci}^3}{V_r^3 - V_{ci}^3} \quad (15)$$

On the other hand, solar radiation in Malaysia is relatively high in comparison with the world standards. It is estimated that the solar power in Malaysia is four times higher than the world fossil fuel resources [27]. The highest amount of solar radiation with an average of more than 3 kWh/m<sup>2</sup> throughout the year can be found in Malaysia. From this solar irradiation profile, the output power,  $P_{pv}$  generated from the PV array can be calculated using (16).

$$P_{pv} = G \times A_{pv} \times \eta_{pv} \quad (16)$$

where  $G$  is the solar radiation ( $KW/m^2$ );  $A_{pv}$  is the PV area ( $m^2$ );  $P_{pv}$  is the PV module efficiency and is equal to 16% in this case study. The penetration level is defined as:

$$\text{Penetration Level} = \frac{\sum_{t=1}^{t=24} P_{wind}(t) + \sum_{t=1}^{t=24} P_{pv}(t)}{\sum_{t=1}^{t=24} D} \quad (17)$$

#### 4.3 Scenario descriptions

In this study, four different scenarios are created to achieve the three main objectives of the work which are:

- Scenario 1: 0% RES penetration.
- Scenario 2: 14.5% solar-power penetration.
- Scenario 3: 27.5% wind-power penetration.
- Scenario 4: mixture of 10% solar-power and 10% wind-power penetration.

The maximum feasible penetration level in scenario II and III were determined as 14.5% and 27.5% for this case study before the total generation exceeds the amount of load at certain hours.

##### 4.3.1 Scenario 1: 0% RES penetration

This scenario acts as the benchmark scenario. There is no RES consideration. Therefore, in this case, the net load is the same as the typical load demand of the system. Table 3 shows the results of the UC analysis for the ten thermal units. The results show that the load is satisfied along the scheduling time horizon. All system constraints are satisfied and the optimal generation cost is also obtained. The committed units are represented by their real value of dispatch (power output) while the de-committed units are represented by 0 (off).

Table 3. An Improved Priority List Solution for Ten Units System (Thermal)

	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	HOC(\$)	SUC(\$)	TOC(\$)
H1	455	245	0	0	0	0	0	0	0	0	13683	0	13683
H2	455	295	0	0	0	0	0	0	0	0	14554	0	14554
H3	455	370	0	0	25	0	0	0	0	0	16809	900	17709
H4	455	455	0	0	40	0	0	0	0	0	18598	0	18598
H5	455	390	0	130	25	0	0	0	0	0	20020	560	20580
H6	455	360	130	130	25	0	0	0	0	0	22387	1100	23487
H7	455	410	130	130	25	0	0	0	0	0	23262	0	23262
H8	455	455	130	130	30	0	0	0	0	0	24150	0	24150
H9	455	455	130	130	85	20	25	0	0	0	27225	860	28085
H10	455	455	130	130	162	33	25	10	0	0	30062	60	30122
H11	455	455	130	130	162	73	25	10	10	0	31921	60	31981
H12	455	455	130	130	162	80	25	43	10	10	33895	60	33955
H13	455	455	130	130	162	33	25	10	0	0	30062	0	30062
H14	455	455	130	130	85	20	25	0	0	0	27255	0	27255
H15	455	455	130	130	30	0	0	0	0	0	24150	0	24150
H16	455	310	130	130	25	0	0	0	0	0	21514	0	21514
H17	455	260	130	130	25	0	0	0	0	0	20642	0	20642
H18	455	360	130	130	25	0	0	0	0	0	22387	0	22387
H19	455	455	130	130	30	0	0	0	0	0	24150	0	24150
H20	455	455	130	130	162	33	25	10	0	0	30062	490	30552
H21	455	455	130	130	85	20	25	0	0	0	27255	0	27255
H22	455	455	0	0	145	20	25	0	0	0	22740	0	22740
H23	455	420	0	0	25	0	0	0	0	0	17685	0	17685
H24	455	345	0	0	0	0	0	0	0	0	15427	0	15427
	Total cost (\$)										559895	4090	563985

\*HOC: hourly operating cost. SUC: start up cost. TOC: total operating cost

Figure 2 shows the total daily demand of this scenario which is satisfied through the thermal power generation. It is observed that at 15 to 18 hours, the generated power is considerably more than the load in order to satisfy the system constraints. This difference in generation is optimally solved through the economic dispatch technique.

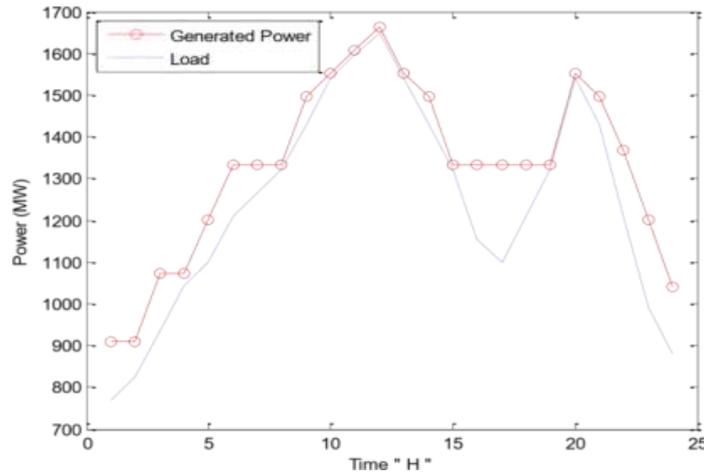


Figure 2. Daily load demand and thermal scheduled generation

**4.3.2 Scenario 2: solar-only**

Based on the comparison to full load thermal generation cost, 14.5 % of solar penetration, which is equal to 3929.5 MW can save \$85009. The shaded cells in Table 4 represent the solar penetration effect on the generation scheduling where the value of each unit output at a certain hour has been affected. Throughout the time horizon schedule, the scheduling hours at 13 and 14 hours are most affected by the solar power integration. At these hours, the generation scheduling is affected from the cheapest units (U1 and U2) to the most expensive units. This effect is clear where the output of some units is reduced while some other units are kept off.

Table 4. Optimal Generation Scheduling Under the Share of Solar Power

	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	Must Run	HOC(\$)	SUC(\$)	TOC(\$)
H1	455	245	0	0	0	0	0	0	0	0	0	13683	0	13683
H2	455	295	0	0	0	0	0	0	0	0	0	14554	0	14554
H3	455	370	0	0	25	0	0	0	0	0	0	16809	900	17709
H4	455	455	0	0	40	0	0	0	0	0	0	18598	0	18598
H5	455	390	0	130	25	0	0	0	0	0	0	20020	560	20580
H6	455	360	130	130	25	0	0	0	0	0	0	22387	1100	23487
H7	455	393.3	130	130	25	0	0	0	0	0	16.69	22970	0	22970
H8	455	383.2	130	130	25	0	0	0	0	0	76.78	22793	0	22793
H9	455	419.8	130	130	25	0	0	0	0	0	140.2	23434	0	23434
H10	455	322.8	130	130	25	0	0	0	0	0	337.2	21738	0	21738
H11	455	455	130	130	31.34	0	25	0	0	0	223.7	25355	520	25875
H12	455	455	130	130	98.06	20	25	0	0	0	186.9	27522	340	27862
H13	388.8	150	0	0	25	20	25	0	0	0	791.2	13875	0	13875
H14	180.3	150	0	0	25	20	0	0	0	0	924.7	9264	0	9264
H15	384.1	150	0	0	25	0	0	0	0	0	640.9	11800	0	11800
H16	424.3	150	0	0	25	0	0	0	0	0	450.7	12467	0	12467
H17	455	386.5	0	0	25	0	0	0	0	0	133.5	17098	0	17098
H18	455	353.3	130	130	25	0	0	0	0	0	6.676	22270	1110	23380
H19	455	455	130	130	30	0	0	0	0	0	0	24150	0	24150
H20	455	455	130	130	162	33	25	10	0	0	0	30062	490	30552
H21	455	455	130	130	85	20	25	0	0	0	0	27255	0	27255
H22	455	315	130	130	25	20	25	0	0	0	0	22740	0	22740
H23	455	420	0	0	25	0	0	0	0	0	0	17685	0	17685
H24	455	345	0	0	0	0	0	0	0	0	0	15427	0	15427
	Total cost (\$)											473956	5020	478976

\*HOC: hourly operating cost. SUC: start up cost. TOC: total operating cost

Figure 3 represents the net load ramp under the share of 14.5% generated solar power. Based on the results, the difference between the load consumption with power produced by solar can be generated by the thermal units. Notably, the solar power output shows maximum solar power generation of 924.7 MW around

2 pm in the afternoon. During the same time, the load demand is 1300MW. A 375.3 MW is generated from 6 units, satisfying the load demand and power system constraints as shown in Table 4.

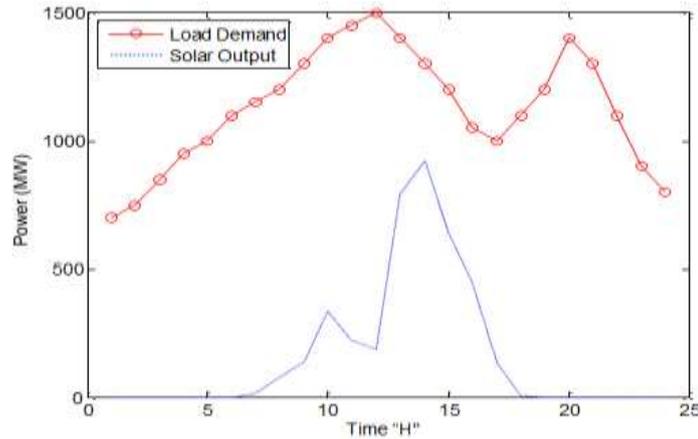


Figure 3. Netload ramp with the share of 14.5% of solar power

**4.3.3 Scenario 3: wind-only**

By comparison to the full load thermal generation cost, the total cost saving achieved is equal to \$149050 for wind power generation of 7452.5 MW at 27.5% wind penetration. It can be observed from Table 5 that the cheaper units of U1 and U2 remain ON continuously to share the major portion of load demand. The expensive units of U6 to U10 are OFF for the total operation hours as compared to the base case. Furthermore, it is noticed that the minimum thermal power output occurs during 14 hours with 5 units ON due to the highest generation of wind power at that time. Some units are kept within their minimum generation capacity at peak load hours to fulfill reserve requirement and generation constraints. The shaded cells in the following Table represent the wind penetration effect on the generation scheduling where the value of each unit output at that certain hour has been affected.

Table 5. Optimal Generation Scheduling Under the Share of Wind Power

	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	Must Run	HOC(\$)	SUC(\$)	TOC(\$)
H1	455	180.5	0	0	0	0	0	0	0	0	64.46	12562	0	12562
H2	455	286	0	0	0	0	0	0	0	0	9.039	14397	0	14397
H3	455	368.3	0	0	25	0	0	0	0	0	1.679	16780	900	17680
H4	455	455	0	0	30.96	0	0	0	0	0	9.039	18417	0	18417
H5	455	367.7	0	130	25	0	0	0	0	0	22.32	19630	560	20190
H6	455	358.3	130	130	25	0	0	0	0	0	1.679	22358	1100	23233
H7	455	408.3	130	130	25	0	0	0	0	0	1.679	23233	0	23233
H8	455	246.4	130	130	25	0	0	0	0	0	213.6	20405	0	20405
H9	455	150	112.6	130	25	0	0	0	0	0	427.4	18432	0	18432
H10	455	339.3	130	130	25	0	0	0	0	0	320.7	22026	0	22026
H11	455	311.2	130	130	25	0	0	0	0	0	398.8	21534	0	21534
H12	455	150	92.95	111.8	25	0	0	0	0	0	665.3	17788	0	17788
H13	455	150	38.66	60.34	25	0	0	0	0	0	671	16005	0	16005
H14	455	150	28.79	50.98	25	0	0	0	0	0	590.2	15683	0	15683
H15	378	150	0	20	25	0	0	0	0	0	627	12710	0	12710
H16	189.7	150	0	20	25	0	0	0	0	0	665.3	9611	0	9611
H17	316.6	150	0	20	25	0	0	0	0	0	488.4	11695	0	11695
H18	455	327.9	0	130	25	0	0	0	0	0	162.1	18934	0	18934
H19	455	293	0	130	25	0	0	0	0	0	297	18325	0	18325
H20	455	427.2	130	130	25	0	0	0	0	0	232.8	23563	560	24123
H21	455	413.1	130	130	25	0	0	0	0	0	146.9	23317	0	23317
H22	396.6	150	20	20	25	0	0	0	0	0	488.4	14051	0	14051
H23	227.8	150	20	20	25	0	0	0	0	0	457.2	11267	0	11267
H24	152.8	150	20	20	0	0	0	0	0	0	457.2	9094	0	9094
											Total cost (\$)	411817	3120	414937

\*HOC : hourly operating cost. SUC: start up cost. TOC: total operating cost

**4.3.4 Scenario 4: mixture of 10% solar and 10% wind penetration**

In this scenario, a mixed generation of solar and wind power resources is presented. A feasible penetration level of 10% for each resource is hybridized. The optimal scheduling of this scenario is given in Table 6. The 3 units that are most expensive and satisfied the load demand and the system constraints are kept off. The shaded cells in the following table represent the effect of mixed generation on the generation scheduling compared to base case system. From the analysis, the total cost obtained in this case is \$503830 for 5420 MW power generated from both solar and wind. This combination is able to reduce \$670 in total SUC.

Table 6 and Figure 4 show that the hourly load demand minus the summation of solar and wind power output for each hour is supported by the thermal units. The minimum mix power generated is about 0.61 MW at the 6<sup>th</sup> hour. The thermal power output is considered to be the highest and generated from the first 5 cheapest units (U1 to U5). The highest RES output is observed at the 14<sup>th</sup> hour with 852.34 MW. The net load is fulfilled through U1 to U5 satisfying the load, reserves and systems constraints with the lowest price.

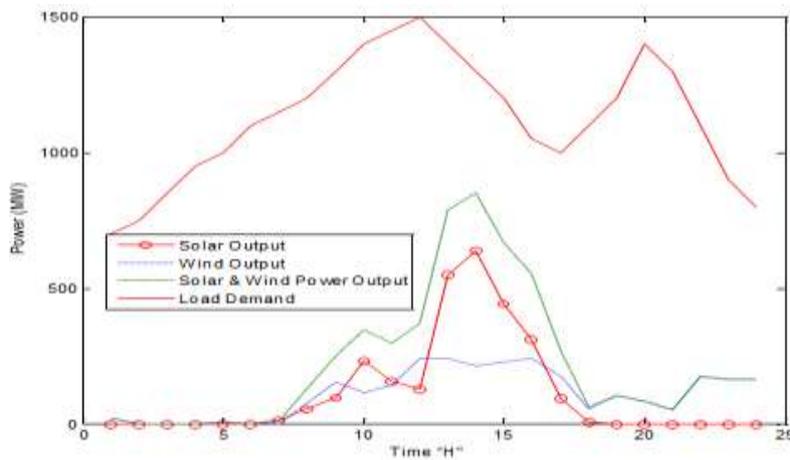


Figure 4. Netload ramp with mixed generation of 10% solar and 10% wind penetration

Table 6. Optimal Generation Scheduling Under the Share of Mixed Solar and Wind Power

	U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	10% Solar	10% Wind	Total RES (MW)	HOC(\$)	SUC (\$)	ΓOC(\$)
H1	455	221.6	0	0	0	0	0	0	0	0	0	23.44	23.44	13275	0	13275
H2	455	291.7	0	0	0	0	0	0	0	0	0	3.287	3.287	14497	0	14497
H3	455	369.4	0	0	25	0	0	0	0	0	0	0.61	0.61	16799	900	17699
H4	455	455	0	0	36.71	0	0	0	0	0	0	3.287	3.287	18532	0	18532
H5	455	381.9	0	130	25	0	0	0	0	0	0	8.117	8.117	19878	560	20438
H6	455	359.4	130	130	25	0	0	0	0	0	0	0.61	0.61	22376	1100	23467
H7	455	409.4	130	130	25	0	0	0	0	0	11.51	0.61	12.12	23251	0	23251
H8	455	382.3	130	130	25	0	0	0	0	0	52.95	77.68	130.6	22777	0	22777
H9	455	404.6	130	130	25	0	0	0	0	0	96.69	155.4	252.1	23167	0	23167
H10	455	455	130	130	113.4	0	0	0	0	0	232.5	116.6	349.1	25841	0	25841
H11	455	455	130	130	135	0	0	0	0	0	154.2	145	299.3	26287	0	26287
H12	455	455	130	130	88.09	0	0	0	0	0	128.9	241.9	370.8	25322	0	25322
H13	455	416	130	130	25	0	0	0	0	0	545.6	244	789.6	23367	0	23367
H14	455	345.4	130	130	25	0	0	0	0	0	637.7	214.6	852.3	22131	0	22131
H15	455	232	130	130	25	0	0	0	0	0	442	228	670	20154	0	20154
H16	455	150	79.2 6	98.8 3	25	0	0	0	0	0	310.8	241.9	552.7	17336	0	17336
H17	455	150	86.6	105. 8	25	0	0	0	0	0	92.09	177.6	269.7	17578	0	17578
H18	455	301.1	130	130	25	0	0	0	0	0	4.604	58.95	63.55	21358	0	21358
H19	455	352	130	130	25	0	0	0	0	0	0	108	108	22247	0	22247
H20	455	455	130	130	100.3	20	25	0	0	0	0	84.67	84.67	27569	860	28429
H21	455	455	130	130	31.59	20	25	0	0	0	0	53.41	53.41	26179	0	26179
H22	455	150	117. 4	130	25	20	25	0	0	0	0	177.6	177.6	20510	0	20510
H23	455	150	78.7 3	0	25	0	25	0	0	0	0	166.3	166.3	16175	0	16175

H24	433.7	150	0	0	25	0	25	0	0	0	0	166.3	166.3	13802	0	13802
												Total cost(\$)	500408	3420	503828	

\*HOC : Hourly operating cost. SUC: Start up cost. TOC: Total operating cost

#### 4.3.5 The impact of high variable res on overall operation cost

The variability associated with the wind and solar power outputs has a significant effect on the power system generation scheduling. According to Table 7, the lowest TOC is obtained in the case of 27.5% of wind penetration. Among all the cases, the wind power implementation in the modern power system offers lower generation cost. Table 7 confirms that wind generation is cheaper because of its availability throughout 24 hours and requires minimum installation area compared to the same daily output of solar system. The minimum SUC is with a higher percentage of wind.

Table 7. Impact of Renewable Integration on Operation Cost

Penetration Level	HOC (\$)	SUC (\$)	TOC (\$)	RES MW Output	Max No. of thermal units ON	Saving (\$/MW)	Minimum Output (MW)	Maximum output (MW)
0% RES	559895	4090	563985	0	10	0	10	455
14.5 % Solar	473956	5020	478976	3929.5	8	21.6	0	924.7
27.5 % Wind	411817	3120	414937	7452.5	5	20	1.67	671
Mix (10% Solar & 10 % Wind)	500408	3420	503828	5420	7	11.1	0.61	852.3

\*HOC : Hourly Operating Cost. SUC: Start Up Cost. TOC: Total Operating Cost

## 5. CONCLUSION

In this paper, an improved method based on priority list is presented to deal with net load specifically. The improved method satisfies all the system technical constraints for optimal economic power system operation. The most crucial task of generation scheduling with stochastic RES power generation is more challenging. Hence, an efficient EPL algorithm is executed to achieve the optimal solution. The combined effects of these two RES on UC significantly reduce the total cost and enhance the net load profile. Furthermore, the maximum variability results in the least penetration levels in the case of solar power penetration scenarios. On the other hand, compared to solar, wind penetration levels which show less difference cause a reduction in the number of committed thermal units which lead to reduction in start-up cost.

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