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Research paper

Opportunities vis-à-vis threat to thermal generation due to rising renewable energy penetration

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Abstract

An effort has been made to access what happens to prevailing thermal generation plants if the generation from renewable energy resources is increased above 20% of total generation. A test case has been taken where generation system comprising of ten thermal generating units is in conjunction with a 500 MW Wind Energy generation plant, and a 500 MW Solar Energy generation plant. It has been found that on one hand the cost of generation gets significantly reduced whereas, on the other hand few thermal generators are compelled to remain with no generation at all. The study reveals the peak load shaving and the economy achieved in overall generation system versus the threat to individual thermal generating plant due to inclusion of nearly 23% generation from renewable resources.

Keywords: *Hybrid Generation Unit Commitment Problem (HGUCP); Priority List Method (PLM); Particle Swarm Optimization with Time Varying Acceleration Coefficients (PSO_TVAC); Renewable Energy Resources (RER).*

1. Introduction

The optimum generation scheduling plan in order to reduce the operational cost of generation for thermal generators has always proved to be a tall order assignment for researchers. The Unit Commitment Problem (UCP) is a complex, non-linear and constrains based optimization problem, where generation is optimally scheduled 24 hours to 168 hours ahead in order to optimally satisfy the prevailing forecasted load demand while simultaneously abiding by various constraints [1].Today when climate changes are forcing the policy makers to think about inclusion of Renewable Energy Resources (RER) as alternatives [2], [3], the inclusion of RER throws hands full of challenges in front of existing thermal generating units. The economic viability of thermal generating units becomes questionable under the scenario where the generation from RER reaches above 20% of total generation. In this paper the share in generation from RER is taken as 23.42% of total generation. Two cases have been considered in this paper. In the first case, the load demand is satisfied by only ten thermal generating units while in the second case load demand is satisfied by ten thermal generating units in conjunction with a 500 MW Wind Energy Resource (WER) and a 500 MW Solar Energy Resource (SER).

2. Problem formulation

The cost function CF which is to be minimized is given by Equation 1 [4-6].

$$C_F = \sum_{i=1}^{N} [FC_i(P_{ih}) + S_tC_i(1-U_{i(h-1)})]U_{ih} \quad (1)$$

FC is fuel cost function which is quadratic polynomial with coefficients ai, bi and ci given by Equation 2.

$$FC_i(P_{ih}) = a_i + b_iP_{ih} + c_iP^2_{ih} \quad (2)$$

SC_i is the start-up cost of i[th] unit taken according to the minimum down time (MD_i) of respective unit. It is represented by Equation 3.

$$SC_i = \begin{cases} HSc_i: & X_i^{off} \le (MD_i + Cs_i)hrs \\ CSc_i: & X_i^{off} > (MD_i + Cs_i)hrs \end{cases} \quad (3)$$

H_{sc} is the hot start-up cost, C_{sc} is cold start-up cost. C_{sihrs} is cold start-up hours, X_i^{off} is the duration in which i[th] unit is continuously OFF.
The total cost C_{FH} for 24 hours is given by Equation 4.

$$C_{FH} = \sum_{h=1}^{H}\sum_{i=1}^{N} [FC_i(P_{ih}) + SC_i(1-U_{i(h-1)})]U_{ih} \quad (4)$$

U_{ih} is the ON/OFF status of the i[th] unit at h[th] hour. The color red indicates the OFF status of units whereas green indicates the ON status.
The constraints of HGUCP considered here are as follows:

a) Power Balance Constraint

$$\sum_{i=1}^{N} [P_i(t)]U_{ih} + P_{wind}(t) + P_{solar}(t) = LD_h \quad (5)$$

$P_i(t)$, $P_{wind}(t)$ and $P_{solar}(t)$ are the MW output of thermal, wind and solar generation plants respectively.

b) Spinning Reserve Constraint for Thermal Plants

$P_{i\,(max)}$ is the maximal generation in MW of i^{th} unit and SR_h is the spinning reserve at h^{th} hour. The spinning reserve is taken as 5% of total load [4].

$$\sum_{i=1}^{N} P_{i(\max)} U_{ih} \geq LD_h + SR_h \tag{6}$$

c) Generation Limit Constraints

$$P_{i(\min)} \leq P_{ih} \leq P_{i(\max)} \tag{7}$$

d) Minimum Up Time Constraints

$$X_i^{on}(t) \geq MU_i \tag{8}$$

e) Minimum Down Time Constraint

$$X_i^{off}(t) \geq MD_i \tag{9}$$

f) Initial Status

It is the initial down time status that is required to be considered in the first hour of scheduling of a particular unit.

g) Wind Generation Constraints

The wind power generation model is explained in Equations (10-15) [7-9].

$$P_{wind}(t) = 0; v_w(t) \leq v_1 or v_w(t) \geq v_3 \tag{10}$$

$$P_{wind}(t) = \xi(v_w(t)); v_1 \leq v_w(t) \leq v_2 \tag{11}$$

$$P_{wind}(t) = P_{wn}; v_2 \leq v_w(t) \leq v_3 \tag{12}$$

$$\xi(v_w(t)) = k_o + k_1 v_w(t)^2 \tag{13}$$

$$k_o = \frac{P_{wn} * v_1^2}{v_1^2 - v_2^2} \tag{14}$$

$$k_1 = \frac{P_{wn}}{v_2^2 - v_1^2} \tag{15}$$

Where, $v_w(t)$ is forecasted wind speed at hour t, $\xi(v_w(t))$ is function of conversion for energy, P_{wn} is proportionate output power of wind (rated) taken as 500MW. v_1, v_2, v_3 are cut-in, rated and cut-out wind speeds in m/s respectively [8]. The details about hourly wind speeds and v_1, v_2, v_3 are given in Appendix III.

h) Solar Generation Constraints

The hourly solar power generation is calculated by using Equations (16-17) [7-9].

$$P_{solar}(s(t)) = P_{sn} * \frac{s(t)}{S_{stand.} * R_s}; 0 \leq s(t) \leq R_s \tag{16}$$

$$P_{solar}(s(t)) = P_{sn} * \frac{s(t)^2}{s_{stand.}}; s(t) \geq R_s \tag{17}$$

Where, s (t) is solar radiation in accordance to forecast at hour t, S_{stand} denotes solar radiation taken as 1000 W/m^2 for standard environment, R_s denotes the radiation point (cut-in) taken as 150W/m^2 [8], P_{sn} is maximum generation capability of solar system taken as 500 MW.
The data regarding hourly solar radiation is provided in Appendix III.

3. Proposed method

A Three Stage Solution Methodology has been developed for Hybrid Generation Unit Commitment Problem (HGUCP). The prospective method is elaborated in Fig.1.
When the load demand is solely satisfied by thermal generation then there is no requirement of Stage One process as the generation from RER will be considered as zero.

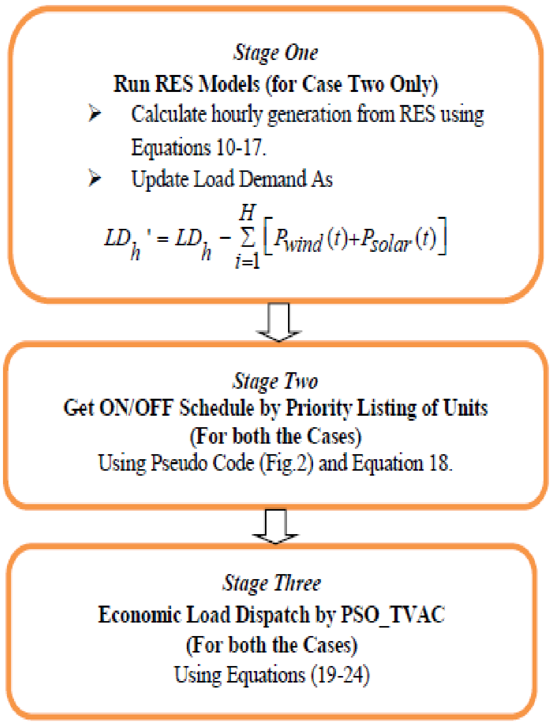

Fig. 1: Solution Methodology for HGUCP.

3.1. Stage two- priority listing of units

The ON/OFF schedule for thermal generating units is obtained by Priority List Method (PLM). First a priority vector containing essential information about thermal units is obtained by using following Equation 19 [4], [5].

$$priorityvector = \left[\frac{P_{(\max),vec}}{\max.\{P_{(\max),vec}\}} + \frac{MD_{vec}}{\max.\{MD_{vec}\}} \right] \tag{18}$$

This priority vector is updated with the help of the pseudo code given in Fig.2 in order to obtain final ON/OFF schedule.

```
% H:    hour (1 to 24)
% hrs:  time frame of one day (1to 24)
% i_hrs: initial status vector (changes every hour)
% MD:   minimum down time vector
% MU:   minimum up time vector
% dem:  demand vector

 for H=1:hrs
commit units with (0<i_hrs_MU)

while sum(capacity of Committed generating units)<1.1* dem (H)
   commit all generating units with (i_hrs>MU)in accordance to
priority vector
end

while sum(capacity of Committed generating units)<1.1*dem(H)
   commit all generating units with (i_hrs<=-MD) in accordance to
priority vector
end

for unchanged units thus far obtain reverse order of priority vector

   if i_hrs(generating unit)>=MU(generating unit)
      if sum(capacity of Committed generating units)> = 1.1dem(H)
&(20-H>MD(generating unit)
         put the generating unit OFF
      else
         put the generating unit ON
      end

   elseif i_hrs(generating unit)<=-MU(generating unit)
      if sum(capacity of Committed generating units)>=1.1dem(H)
         put the generating unit OFF
      else
         put the generating unit ON
      end

   elseif i_hrs(generating unit)<0

      put the generating unit OFF

 end %i_hrs

end %unchanged units

end %for H
```

Fig. 2: Pseudo Code for Priority Listing of Thermal Units.

3.2. Stage three- economic load dispatch (ELD)

The economic allocation of load among conventional thermal generating units has been solved by PSO_ TVAC. The equations used are given as (19-24) [10], [11].

$$v_{id}^{(k+1)} = \begin{bmatrix} W*v_{id}^{k} + c_1*Rand_1()*\left(P_{bestid} - x_{id}^{k}\right) + \\ c_2*Rand_2()*\left(G_{best\ gd} - x_{id}^{k}\right) \end{bmatrix} \quad (19)$$

$$x_{id}^{(k+1)} = x_{id}^{k} + v_{id}^{k+1} \quad (20)$$

Where, 'W' is the inertia weight parameter. The linearly varying 'W' is given in Equation (22).

$$w = w_{max} - \left(\frac{w_{max} - w_{min}}{iter_{max}}\right) * iter \quad (21)$$

'c_1' and 'c_2' are acceleration coefficients, dealing with the high non-linear nature of problem some modifications are done in classical PSO algorithm, in this paper PSO_TVAC is used [10, 12], the values of 'c_1' and 'c_2' can be obtained by Equations (22) and (23).

$$c_1 = \left(c_{1f} - c_{1i}\right) * \frac{iter.}{iter_{max}} * c_{1i} \quad (22)$$

$$c_2 = \left(c_{2f} - c_{2i}\right) * \frac{iter.}{iter_{max}} * c_{2i} \quad (23)$$

$$c_{1f} = 0.5,\ c_{1i} = 2.5, c_{2f} = 2.5,\ c_{2i} = 0.5$$

The bounds for velocity are set to make sure that the solution does not fly away [12].

4. Simulation and results

Two generation systems are considered for analysis. In the first case the forecasted load for 24 hours gets satisfied with ten thermal generating units only. While in the other case the forecasted load gets satisfied by ten thermal generating units in conjunction with one 500 MW WER and one 500 MW SER. The details about thermal plants, load profile, solar radiation and wind speeds are given in Appendices I, II and III respectively.

4.1. Case one-thermal generation unit commitment problem

The Stage One process is not required as there is zero generation considered from RER in Case One .The ON/OFF schedule obtained from Stage Two (Priority Listing of Units) is given in Table 1.The economic allocation of load among thermal generating units obtained from Stage Three (PSO_TVAC) is given in Table 2. The operating cost including fuel cost and start-up cost for all individual generators during 24 hour time period is given in Table 3.

Table 1: On/Off Schedule (Case One)

Unit No.	TG1	TG2	TG3	TG4	TG5	TG6	TG7	TG8	TG9	TG10
Hr.1	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
Hr.2										
Hr.3										
Hr.4					ON					
Hr.5										
Hr.6				ON						
Hr.7			ON							
Hr.8										
Hr.9						ON				
Hr.10							ON			
Hr.11								ON		
Hr.12									ON	
Hr.13								OFF	OFF	
Hr.14							OFF			
Hr.15						OFF				
Hr.16										
Hr.17										
Hr.18										
Hr.19										
Hr.20						ON	ON			
Hr.21			OFF							
Hr.22				OFF						
Hr.23					OFF		OFF			
Hr.24						OFF				

Table 2: Economic Load Dispatch for Case One

Hrs	Unit No. Thermal Generators (TGs)										Tot. Gen. (MWh)
	TG1	TG2	TG3	TG4	TG5	TG6	TG7	TG8	TG9	TG10	
Hr.1	455	245	0	0	0	0	0	0	0	0	700
Hr.2		295									750
Hr.3		395									850
Hr.4		455			40						950
Hr.5					90						1000
Hr.6				130	60						1100
Hr.7		410	130		25						1150
Hr.8		455			30						1200
Hr.9					110	20					1300
Hr.10					162	43	25				1400
Hr.11						80		13			1450
Hr.12								53	10		1500
Hr.13						43		0	0		1400
Hr.14					110	20	0				1300
Hr.15					30	0					1200
Hr.16		310			25						1050
Hr.17		260									1000
Hr.18		360									1100
Hr.19		455			30						1200
Hr.20					162	43	25				1400
Hr.21			0			73					1300
Hr.22				0	145	20					1100
Hr.23		425			0		0				900
Hr.24		345				0					800

Table 3: Operating Cost for Individual Generators for 24 Hours-Case One

Unit No.	Gen. (MWh)	Fuel Cost ($)	Start-up Cost($)
TG1	10920	203179.7	0
TG2	9870	194928.7	0
TG3	1820	40485.2	1100
TG4	2080	45770.54	1120
TG5	1717	43255.23	900
TG6	442	13718.89	510
TG7	175	8249.063	1040
TG8	66	3043.019	60
TG9	10	937.922	60
TG10	0	0	0
Total	27100	553568.3	4790

The total operating cost for Case One is 558358.3$. The convergence obtained from the proposed method is shown in Fig.3. It shows that the convergence is achieved in less than ten iterations.

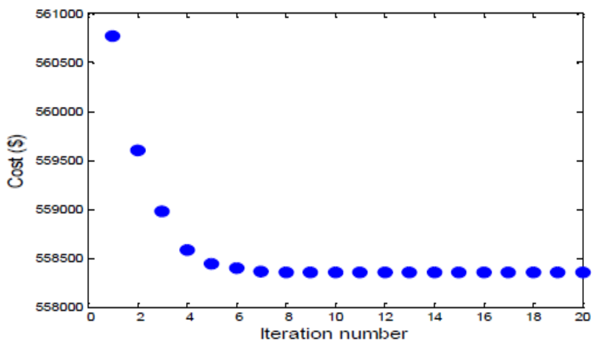

Fig. 3: Convergence for Case One.

4.2. Case Two-Hybrid Generation Unit Commitment

In Stage One the load demand is updated as stated in Fig.1. The method for obtaining the new Priority List and Economic Load Dispatch (Stage Two and Three respectively) stages for updated load demand remains the same. The hourly generation from RES and updated load demand is given in Table 4. The data regarding Wind speeds and solar radiation is given in Appendix III.

Table 4: Hourly Generation From RES and Updated Load Demand

Hrs.	P solar (MW)	P wind (MW)	P tot. (MW)	Updated Load Demand (MW)
Hr.1		12	12	688
Hr.2		14	14	736
Hr.3				850
Hr.4				950
Hr.5				1000
Hr.6	0		0	1100
Hr.7	41		41	1109
Hr.8	155	0	155	1045
Hr.9	187	20	207	1093
Hr.10	251	17	268	1132
Hr.11	308		308	1142
Hr.12	343		343	1157
Hr.13	351	0	351	1049
Hr.14	368	228	596	704
Hr.15	293	329	622	578
Hr.16	212	344	556	494
Hr.17	145	315	460	540
Hr.18	24	280	304	796
Hr.19		308	308	892
Hr.20		337	337	1063
Hr.21		337	337	963
Hr.22		300	300	800
Hr.23		329	329	571
Hr.24	0	500	500	300
Total	2678	3670	6348	20752

The individual generation from SER and WER are shown in Fig.4 and Fig.5 respectively.

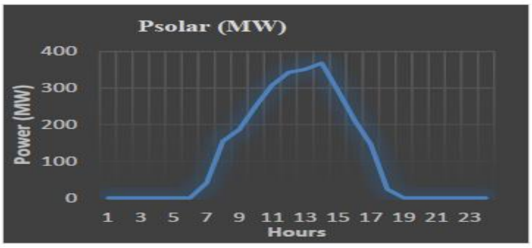

Fig. 4: Hourly Generation from SER.

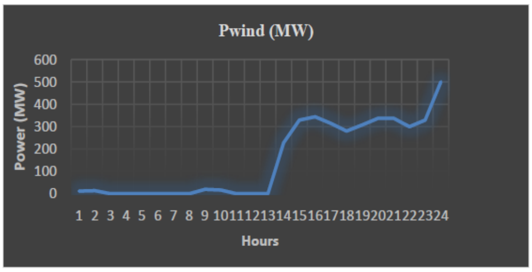

Fig. 5: Hourly Generation from WER.

The ON/OFF schedule from Stage Two for Case Two obtained by Priority Listing of generating units is given in Table 5. The economic allocation of generation among thermal generating units for updated load demand is obtained by PSO_TVAC is given in Table 6. The cumulative fuel cost, start-up cost and generation from individual thermal generators for 24 hours are given in Table 7.

Table 5: On/Off Schedule (Case Two)

Hrs	Unit No.									
	TG1	TG2	TG3	TG4	TG5	TG6	TG7	TG8	TG9	TG10
Hr.1										
Hr.2										
Hr.3					OFF					
Hr.4				OFF						
Hr.5										
Hr.6										
Hr.7										
Hr.8										
Hr.9										
Hr.10										
Hr.11								OFF		
Hr.12								ON		
Hr.13				ON	ON					
Hr.14										
Hr.15										
Hr.16										
Hr.17										
Hr.18								OFF		
Hr.19					OFF					
Hr.20								ON		
Hr.21										
Hr.22		ON								
Hr.23										
Hr.24	ON	OFF	OFF	OFF	ON	OFF	OFF	OFF	OFF	OFF

Table 6: Economic Load Dispatch (Case Two)

Hrs.	Unit No. Thermal Generators (TGs)										Tot. Gen. (MWh)
	TG1	TG2	TG3	TG4	TG5	TG6	TG7	TG8	TG9	TG10	
Hr.1		233									688
Hr.2		281		0	0						736
Hr.3		395									850
Hr.4		455			40						950
Hr.5		390			25						1000
Hr.6		455			60			0			1100
Hr.7					69						1109
Hr.8	455	435			25						1045
Hr.9				130	53						1093
Hr.10		455			92						1132
Hr.11					102						1142
Hr.12					107			10			1157
Hr.13		439	0		25	0	0		0	0	1049
Hr.14		249									704
Hr.15	428										578
Hr.16	344	150						0			494
Hr.17	390				0						540
Hr.18		341									796
Hr.19		427		0				10			892
Hr.20	455	455			143						1063
Hr.21					53						963
Hr.22		320			25			0			800
Hr.23		0			116						571
Hr.24	275				25						300

Table 7: Operating Cost for Individual Generator (Case Two)

Unit No.	Gen. (MWh)	Fuel Cost ($)	Start-up Cost ($)
TG1	10537	196835.5	0
TG2	8055	161366.6	0
TG3	0	0	0
TG4	1170	25745.93	560
TG5	960	25992.05	1800
TG6	0	0	0
TG7	0	0	0
TG8	30	2578.839	120
TG9	0	0	0
TG10	0	0	0
Total	20752	412518.92	2480

The comparison between Case One and Case Two is given in Table 8.

Table 8: Comparison between Case One and Case Two

Unit No.	Reduction in Gen. (MWh)	Reduction in Fuel Cost ($)	Reduction in Start-up Cost ($)
TG1	383	6344.2	0
TG2	1815	33562.1	0
TG3	1820	40485.2	1100
TG4	910	20024.61	560
TG5	757	17263.18	-900
TG6	442	13718.89	510
TG7	175	8249.063	1040
TG8	36	464.18	-60
TG9	10	937.922	60
TG10	0	0	0
Total	6348	141049.3	2310

The convergence of the proposed method for HGUCP is shown in Fig.6. It is observed that the convergence is within ten iterations. Thus it is concluded that the proposed method for solution of non-linear UCP is equally effective after inclusion of additional RES constraints. The overall operating cost of generation gets reduced from 558358.3$ to 414998.92$ as shown in Table 3 and Table 7 respectively. The cumulative reduction in thermal generation, fuel cost and start-up cost of individual thermal generator for 24 hours is given in Table 8. It is interesting to note that the start-up cost for Unit No. 5 and 8 gets increased. This can be attributed to change in their ON/OFF status associated with corresponding hot/cold start-up costs.

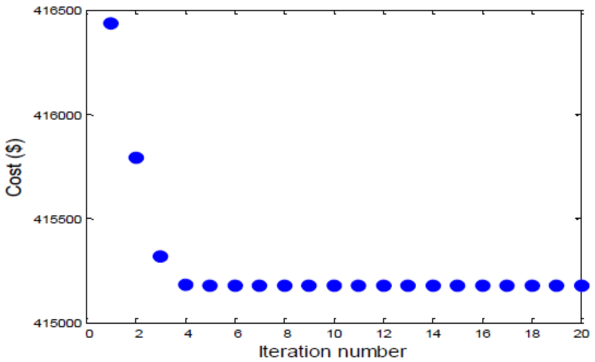

Fig. 6: Convergence for Case Two (HGUCP).

The overall generation scenario for Case Two is shown in Fig.7. It can be seen from Fig. 7 that the summation of all the three generating resources is equal to the load demand for 24 hours. The peak load during day time is reduced by SER and in evening WER is contributing in reduction of peak load. This clearly indicates the peak shaving done by RER.

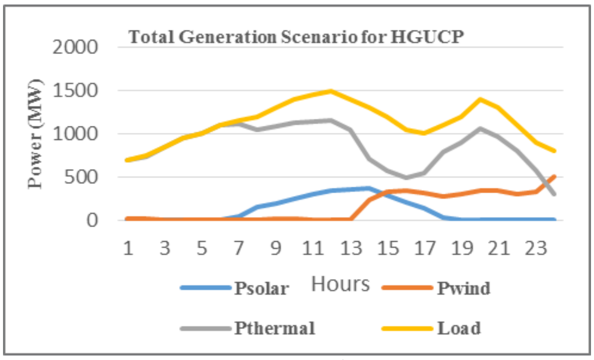

Fig. 7: Total Generation Scenario for Case Two (HGUCP).

5. Conclusion

It can be concluded from this case study that the overall operating cost for generation gets reduced by 143359.3$ due to inclusion of RER. Also the grid gets relieved during peak load hours. At the same time as the significant penetration of generation from RER is included there is a clear threat to the economic viability of existent thermal generating units. Further it is found that on inclusion of 23.42% generation from RER, half of the thermal generating units become redundant. Hence, in the developing countries like India there is an urgent need to develop a policy where the future of thermal generating plants can be secured. It can also be concluded that the hybridization of PLM method with PSO_TVAC is a robust optimization approach that provides reliable results for non-linear, complex optimization problem like UCP.

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Appendices

Appendix I: Thermal Generating Units Detail [4], [5]

Unit No.	1	2	3	4	5
P_{max}	455	455	130	130	162
P_{min}	150	150	20	20	25
a($/h)	1000	970	700	680	450
b($ / MWh)	16.19	17.26	16.6	16.5	19.7
c($/MW^{2}h)	0.0005	0.0003	0.002	0.0021	0.004
MD(h)	8	8	5	5	6
MU(h)	8	8	5	5	6
HSc ($/h)	4500	5000	550	560	900
CSc ($/h)	9000	10000	1100	1120	1800
Cs(h)	5	5	4	4	4
Initial Status	8	8	-5	-5	-6
Unit No.	**6**	**7**	**8**	**9**	**10**
P_{max}	80	85	55	55	55
P_{min}	20	25	10	10	10
a($/h)	370	480	660	665	670
b($/MWh)	22.26	27.74	25.92	27.27	27.79
c($/MW^{2}h)	0.0072	0.0008	0.0041	0.0022	0.0017
MD(h)	3	3	1	1	1
MU(h)	3	3	1	1	1
HSc ($/h)	170	260	30	30	30
CSc ($/h)	340	520	60	60	60
Cs(h)	2	2	0	0	0
Initial Status	-3	-3	-1	-1	-1

Appendix II: 24 Hour Load Demand [4], [5]

Hr.1	700	**Hr.7**	1150	**Hr.13**	1400	**Hr.19**	1200
Hr.2	750	**Hr.8**	1200	**Hr.14**	1300	**Hr.20**	1400
Hr.3	850	**Hr.9**	1300	**Hr.15**	1200	**Hr.21**	1300
Hr.4	950	**Hr.10**	1400	**Hr.16**	1050	**Hr.22**	1100
Hr.5	1000	**Hr.11**	1450	**Hr.17**	1000	**Hr.23**	900
Hr.6	1100	**Hr.12**	1500	**Hr18**	1100	**Hr.24**	800

Appendix III: Data for Hourly Solar Radiation and Wind Speed [7-8]

Hrs.	**1**	**2**	**3**	**4**	**5**	**6**
SR(W/m²)	0	0	0	0	0	0
WS(m/s)	3.5	3.6	1.5	1.4	0.1	1.8
Hrs.	**7**	**8**	**9**	**10**	**11**	**12**
SR(W/m²)	111	311	375	503	617	686
WS(m/s)	1.3	2.2	3.8	3.7	2	0.6
Hrs.	**13**	**14**	**15**	**16**	**17**	**18**
SR(W/m²)	703	736	586	425	291	86
WS(m/s)	0.4	8.4	9.9	10	9.7	9.2
Hrs.	**19**	**20**	**21**	**22**	**23**	**24**
SR(W/m²)	0	0	0	0	0	0
WS(m/s)	9.6	10	10	9.5	9.9	13
Cut-in Speed (m/s)	**3**	**Cut-out Speed (m/s)**		**Rated Speed(m/s)**	**12**	

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