Evaluation of Expected Energy Generation in Multi-Area Interconnected Systems with Renewable Energy Generating Units

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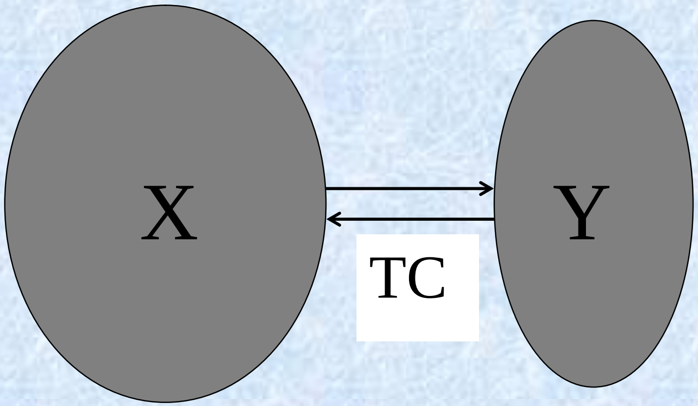
Outline

- Introduction
- Proposed Numerical Model
- Example to Evaluate expected energy generation (EEG) using the Model
- Evaluation of EEG for a Realistic Two Area Interconnected System with Renewable Generating Units
- Conclusion

Two Area Interconnected System



X and Y resembles the two geographically isolated utility systems but electrically interconnected by a tie line with capacity TC. Each system is having a projected hourly load pattern with generating unit (SOU/JOU) to meet its own demand first and then they can export some of the generated energy if they have excess and the other system has demand.

Renewable Energy Sources in the Interconnected System

- Renewable energy sources are driving a great deal of research effort in different dimension in power system. It is primarily due to the minimum cost of energy generation and environmental friendliness.
- Solar, wind, hydro, geothermal, wave are few example of energy sources that are feasible alternative to the conventional fossil fuel burning electric generating unit.
- Inclusion of Photovoltaic (PV) unit to harvest solar energy requires special attention to evaluate expected energy generation (EEG) as its availability is random (depending on the sun).
- Availability of PV units is affected by the seasonal, weather and hourly variation of solar irradiance.

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The evaluation Procedure of the expected energy generated by a unit

1. Evaluate the expected export. Modify the demands of the exporting and the importing systems as well as the tie line capacity
2. Evaluate the expected share transfer from a JOU to the system where the unit is not located. Accordingly modify only the tie line capacity. For conventional unit this step is not necessary.
3. For unit with renewable energy source (solar unit in this case) modify the capacity according to hourly generation data and follow the above two steps used for non renewable units. For the sake of simplicity we consider our solar unit is considered as separately owned.
4. Obtain the expected unserved energy. If the committed unit is a JOU the evaluation of unserved energies of both the systems is required because both of them generate energy.
5. Convolve the unit [4,5].
6. Recalculate the unserved energy after the convolution of the unit.
7. Calculate the EEG of each unit which is the deference of two unserved energies evaluated before and after the convolution.

Export or Import

1) Export Using Tie Line:

A system will export to the other interconnected system to meet their excess demand only when the exporting system has surplus capacity and residual tie line capacity permits the export.

2) Export Without Using Tie Line:

Since the JOU is located in system *Y* the export from the share of system *X* to system *Y* does not require the tie line. The amount of export depends on the expected unserved demand of system *Y* and the portion of share, which has not been transferred to system X, and it may be evaluated as[5]

For unit with renewable energy source (solar unit in this case) modify the capacity according to hourly generation data. Usually the cells are available during daytime and at night they are completely unavailable. Also at daytime their capacities varies according to the solar irradiance.

•Kaisar R Khan, Q. Ahsan and M. R Bhuiyan, “Expected Energy Production Cost of Two Area interconnected Systems with Jointly Owned Units” Electric Power System Research journal (Elseiver),vol. 69, pp. 115-122, April 2004

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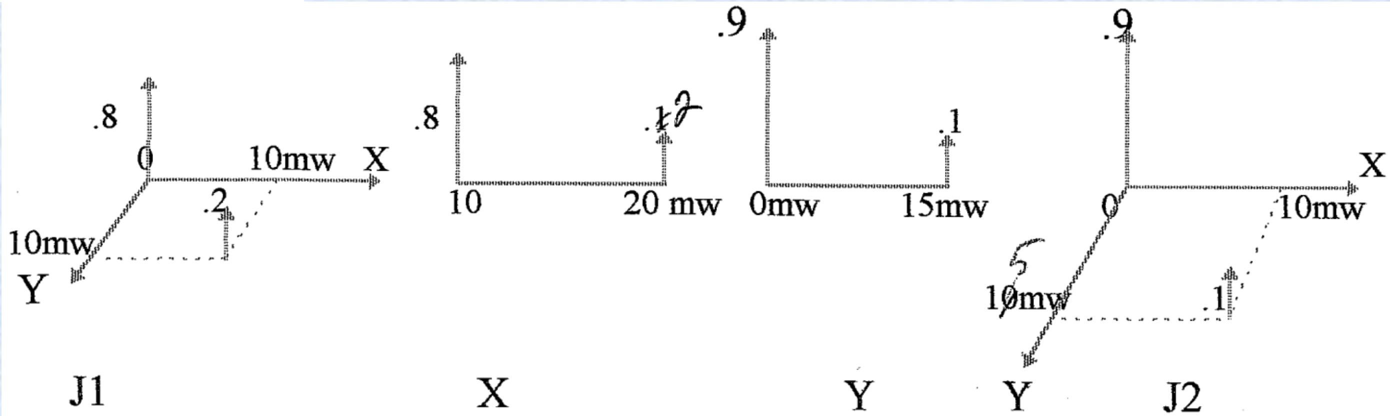
Capacity Model

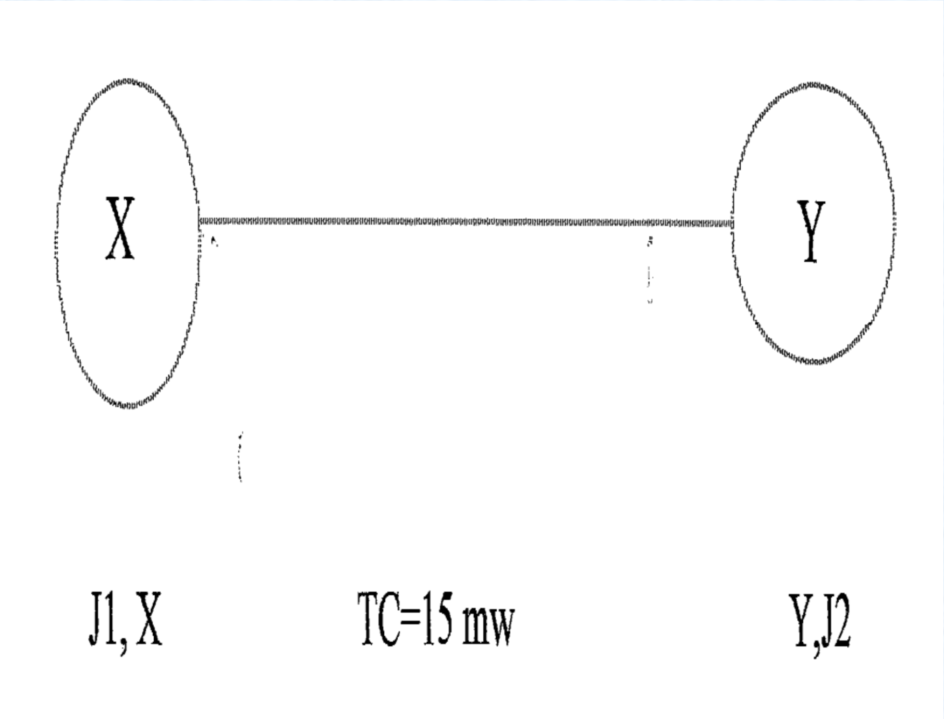
SL NO	CAPACITY MW			Symbol	Ownership	Location	FOR
	X	Y	Global				
1	10	10	20	J1	JOU	X	.2
2	20	0	20	X	SOU	X	.2
3	0	15	15	Y	SOU	Y	.1
4	10	15	25	J2	JOU	Y	.1

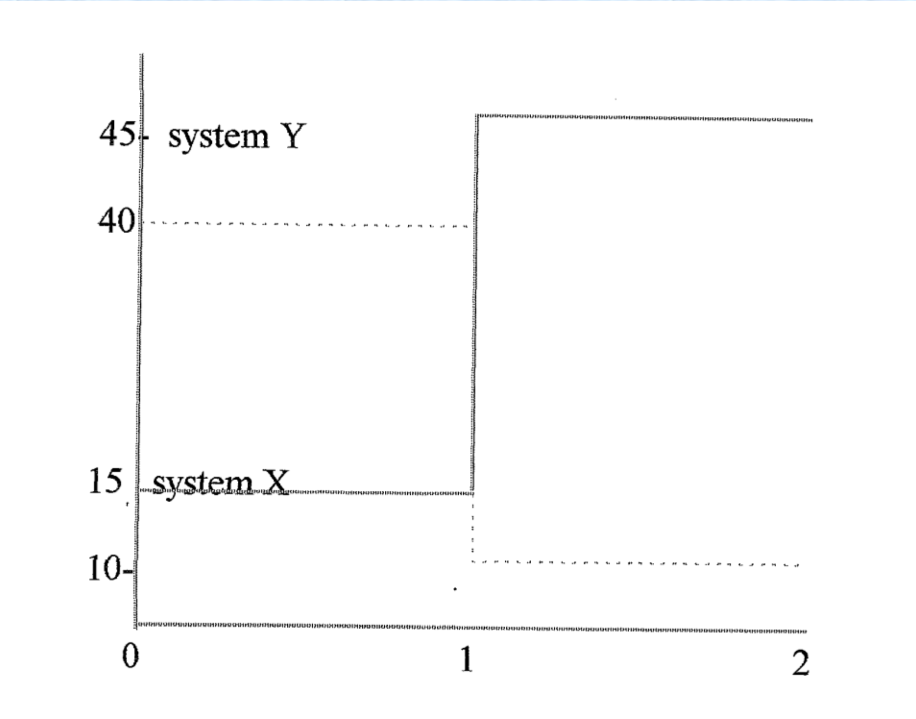
$\lambda_{j1} < \lambda_X < \lambda_Y < \lambda_{j2}$

λ is the average generation cost, therefore the generator j1 should be committed first then x, then y and at last j2.



Load Model





1.K. R. Khan, “An Approach to evaluate the expected Energy Generation of Two Area Interconnected System with Jointly Owned Units located in one of the Areas’’, M.Engg. Thesis, BUET, Dhaka 1997.

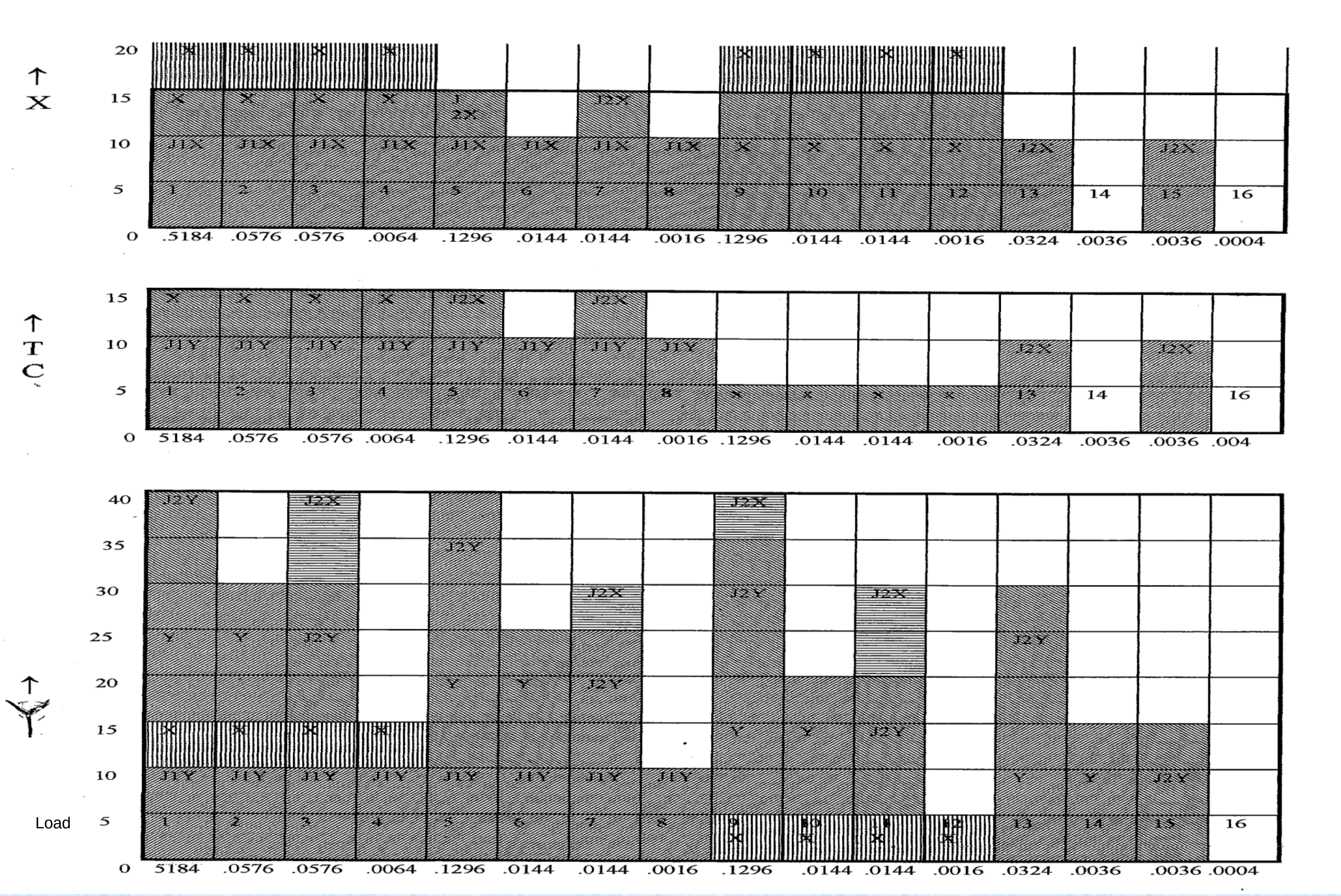
Heuristic Method (I):
Joint Probability of Available Generation

Sl no	States	Joint probability
1	$j1.\ x.\ y.\ j2$	$0.8 \times 0.8 \times 0.9 \times 0.9 = 0.5184$
2	$j1.\ x.\ y.\ \overline{j2}$	$0.8 \times 0.8 \times 0.9 \times 0.1 = 0.0576$
3	$j1.\ x.\ \overline{y}.\ j2$	$0.8 \times 0.8 \times 0.1 \times 0.9 = 0.0576$
4	$j1.\ x.\ \overline{y}.\ \overline{j2}$	$0.8 \times 0.8 \times 0.1 \times 0.1 = 0.0064$
5	$j1.\ \overline{x}.\ y.\ j2$	$0.8 \times 0.2 \times 0.9 \times 0.9 = 0.1296$
6	$j1.\ \overline{x}.\ y.\ \overline{j2}$	$0.8 \times 0.2 \times 0.9 \times 0.1 = 0.0144$
7	$j1.\ \overline{x}.\ \overline{y}.\ j2$	$0.8 \times 0.2 \times 0.1 \times 0.9 = 0.0144$
8	$j1.\ \overline{x}.\ \overline{y}.\ \overline{j2}$	$0.8 \times 0.2 \times 0.1 \times 0.1 = 0.0016$
9	$\overline{j1}.\ x.\ y.\ j2$	$0.2 \times 0.8 \times 0.9 \times 0.9 = 0.1296$
10	$\overline{j1}.\ x.\ y.\ \overline{j2}$	$0.2 \times 0.8 \times 0.9 \times 0.1 = 0.0144$
11	$\overline{j1}.\ x.\ \overline{y}.\ j2$	$0.2 \times 0.8 \times 0.1 \times 0.9 = 0.0144$
12	$\overline{j1}.\ x.\ \overline{y}.\ \overline{j2}$	$0.2 \times 0.8 \times 0.1 \times 0.1 = 0.0016$
13	$\overline{j1}.\ \overline{x}.\ y.\ j2$	$0.2 \times 0.2 \times 0.9 \times 0.9 = 0.0324$
14	$\overline{j1}.\ \overline{x}.\ y.\ \overline{j2}$	$0.2 \times 0.2 \times 0.9 \times 0.1 = 0.0036$
15	$\overline{j1}.\ \overline{x}.\ \overline{y}.\ j2$	$0.2 \times 0.2 \times 0.1 \times 0.9 = 0.0036$
16	$\overline{j1}.\ \overline{x}.\ \overline{y}.\ \overline{j2}$	$0.2 \times 0.2 \times 0.1 \times 0.1 = 0.0004$

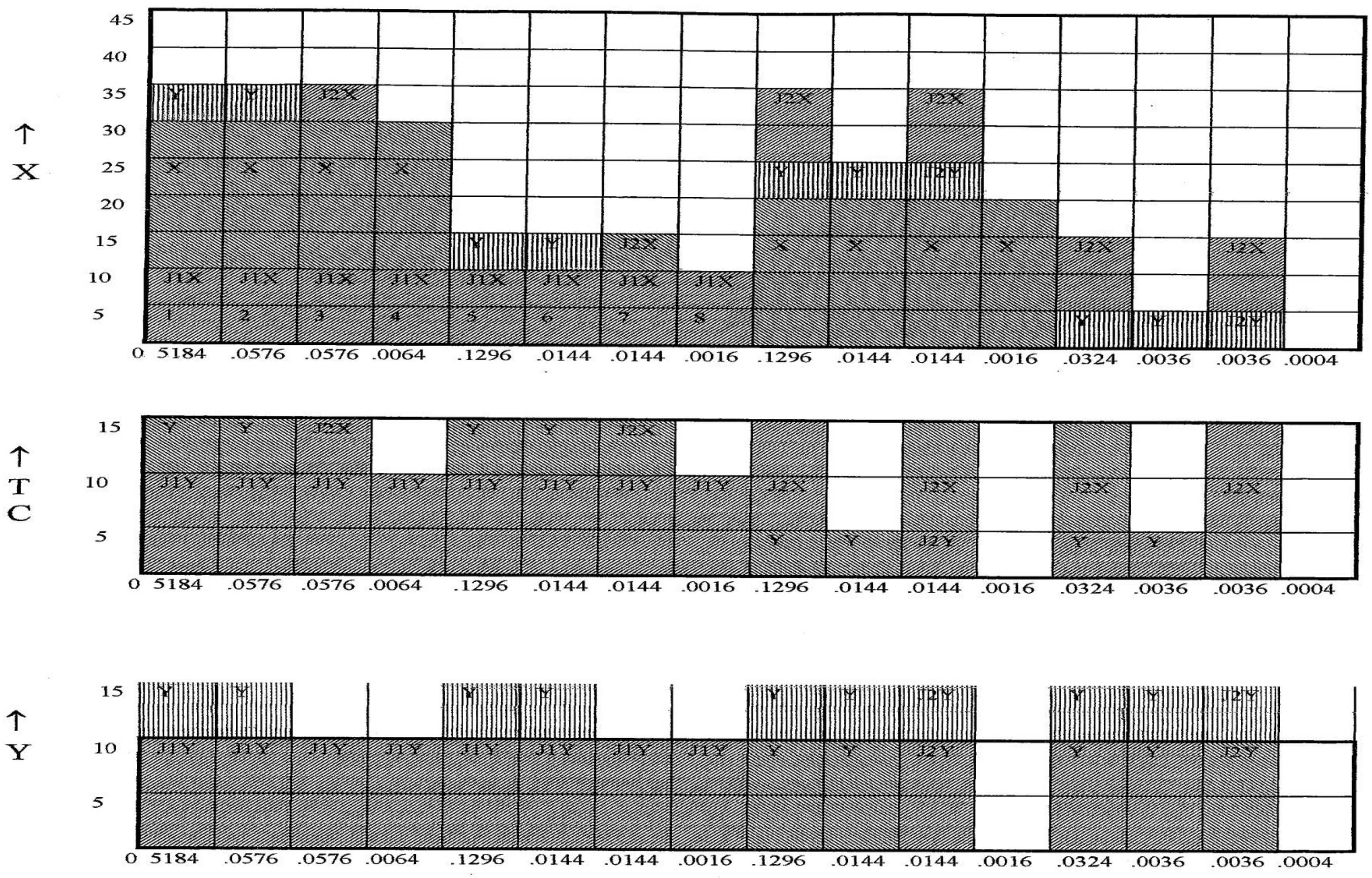
Probability of available generation

The symbol j1, x, y and j2 represents that these generators are available and the symbol $\overline{j1}$, $\overline{x}$, $\overline{y}$ and $\overline{j2}$ represent that these four generators are unavailable.

Joint Probability and Corresponding Available Capacity to Meet the Demand: First Sample , X=15, Y=40, TC=15



Joint Probability and Corresponding Available Capacity to Meet the Demand: Second Sample, X=45, Y=10, TC=15.



EEG Evaluated from Heuristic Method

1. $ESE_{1X} = 10 \times 0.8 + 10 \times 0.8$

$= 8 + 8 = 16$ Mwh

$ESE_{1Y} = 10 \times 0.8 + 10 \times 0.8$

$= 8 + 8 = 16$ Mwh

$ESE_{1} = 16 + 16 = 32$ Mwh

2. $ESE_{2} = (10 \times 0.64 + 20 \times 0.16) + (20 \times 0.64 + 20 \times 0.16)$

$= 6.4 + 3.2 + 12.8 + 3.2 = 25.6$ Mwh

3. $ESE_{3} = (15 \times 0.576 + 15 \times 0.144 + 15 \times 0.144 + 15 \times 0.036) +$

$(5 \times 0.576 + 5 \times 0.144 + 15 \times 0.144 + 15 \times 0.036)$

$= 13.5 + 6.3 = 19.8$ Mwh

4. $ESE_{4X} = (5 \times 0.144 + 10 \times 0.036 + 10 \times 0.0576 + 5 \times 0.144 + 10 \times 0.0144 +$

$5 \times 0.0576 + 5 \times 0.0144 + 10 \times 0.144 + 1 \times 0.36)$

$= 4.68$ Mwh

$ESE_{4Y} = (10 \times 0.5184 + 15 \times 0.0576 + 15 \times 0.144 + 15 \times 0.144 + 15 \times 0.036 +$

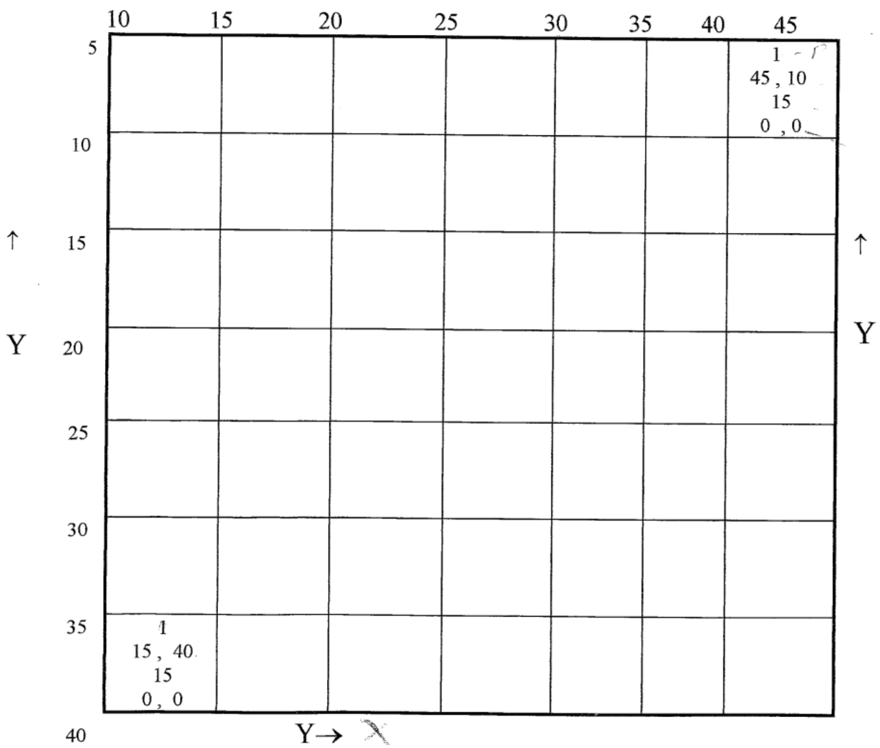
$15 \times 0.144 + 15 \times 0.0036)$

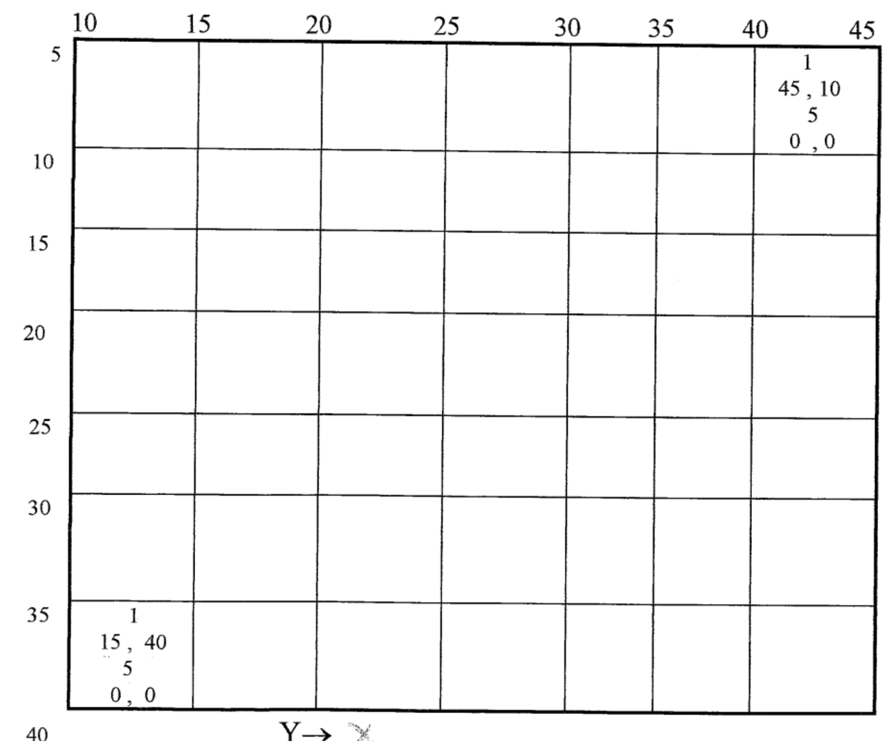
$= 11.178$ Mwh

$ESE_{4} = 4.68 + 11.178 = 15.858$ Mwh

EEG Evaluated from Proposed Method (I):

Discretized parameters (availability, demand, TC and capacity) in grid

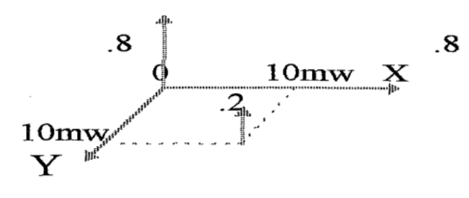




The unserved energy of system X and Y before committing the first unit are

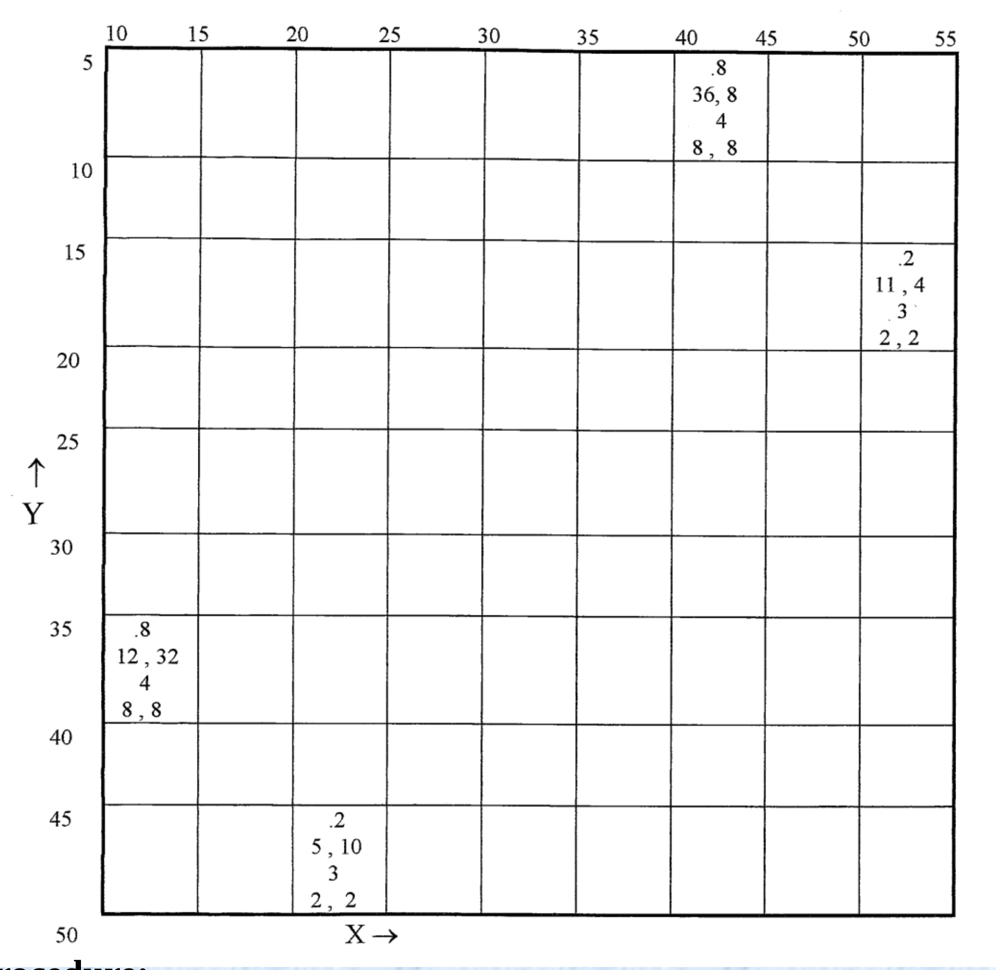
$USE_{1X-} = (45 + 15) - 0 = 60$ Mwh

$USE_{1Y-} = (40 + 10) - 0 = 50$ Mwh



J1

EEG Evaluated from Proposed Method (II): Parameters after committing the first unit



The unserved energy of system X and Y after committing the first generating unit is

$USE_{1X} = 64 - 20 = 44$ Mwh and

$USE_{1Y} = 54 - 20 = 34$ Mwh

The expected energy generated by the share of system X and Y is

$ESE_{1X} = 60 - 44 = 16$ Mwh and

$ESE_{1Y} = 50 - 34 = 16$ Mwh

So the total energy generated by the first unit

$ESE_{1} = 16 + 16 = 32$ Mwh

Process of convolution

In the segmentation method, the process of convolution is simply effected by shifting each segment appropriately as each generating unit, in the loading order, is committed to meet the equivalent load.

For two interconnected systems a two-dimensional approach is necessary, that is, the direction of shift depends on the system to which the generating unit belongs.

Procedure;

- Multiply the segment's parameters, before the generating unit is committed by the unit availability (1-q).
- Multiply the shifted segment's parameters by FOD = q.
- Sum the two previous results for each segment to obtain the final parameters after committing Kth generator unit.

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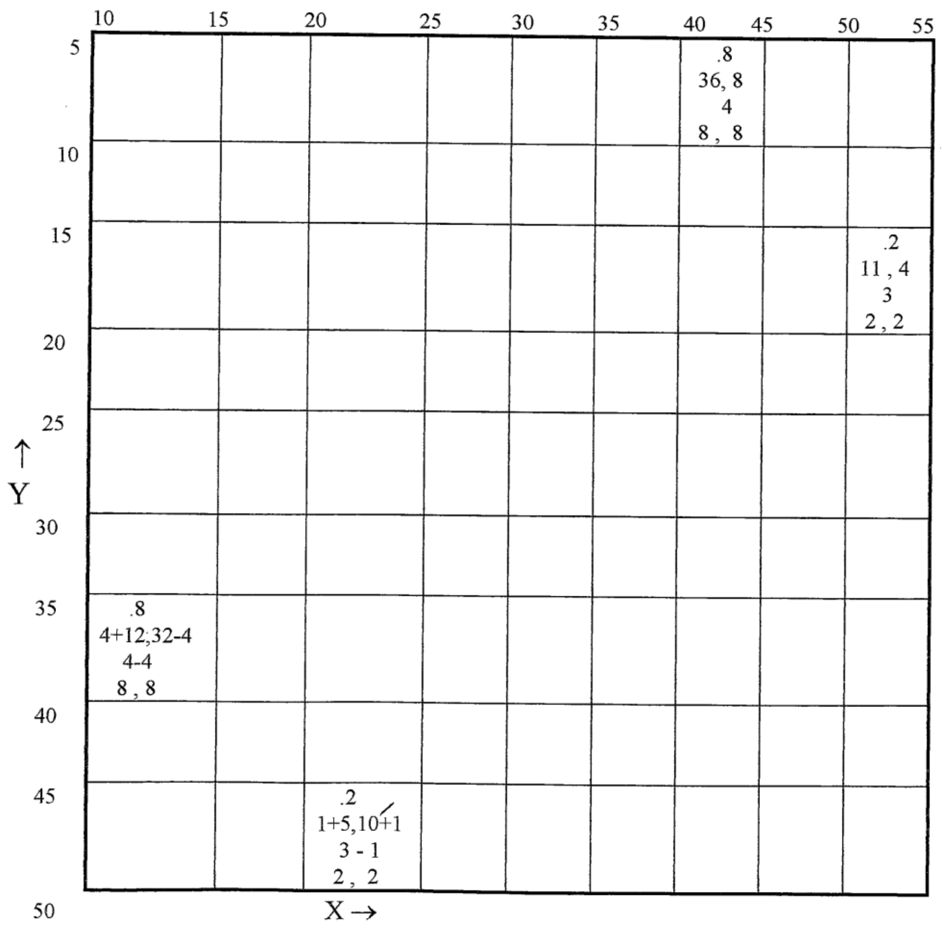
EEG Evaluated from Proposed Method (III): Parameters before committing the second unit



The unserved energy of the system X before committing the second unit

$$USE_{2X^-} = 69 - 20 - 0.2(4+1) = 48 \text{ Mwh}$$

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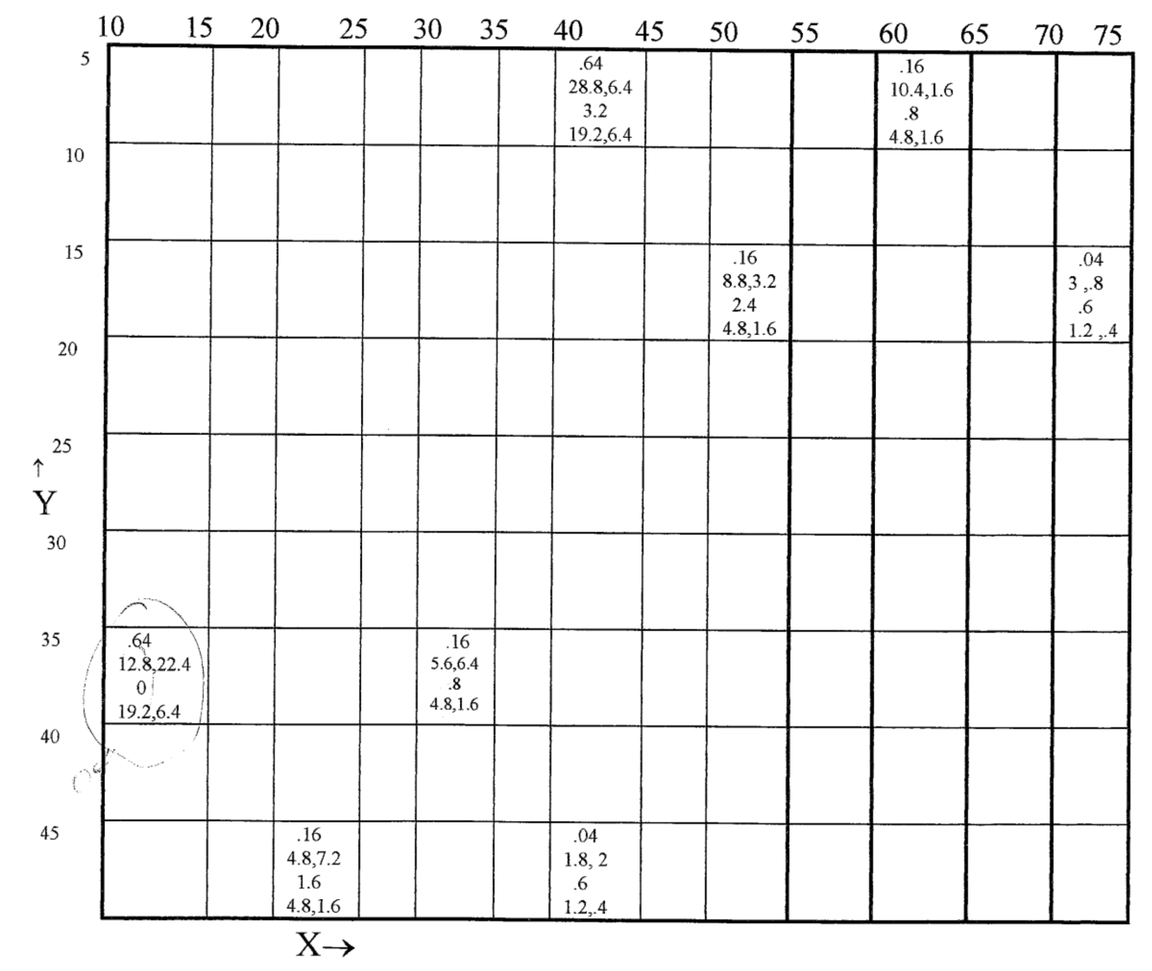
EEG Evaluated from Proposed Method (IV): Parameters after committing the second unit



$USE_{2X} = 63.4 - 40.8 = 22.4$ Mwh

The expected energy generation of the second unit

$ESE_2 = 48 - 22.4 = 25.6$ Mwh

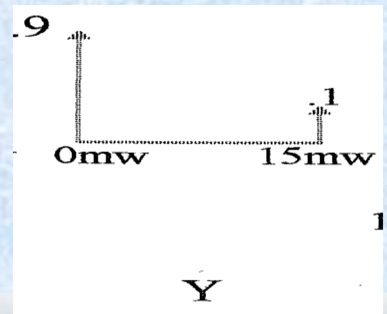
EEG Evaluated from Proposed Method (V): Parameters before committing the third unit

Y ↓ / X →	10–15	15–20	20–25	25–30	30–35	35–40	40–45
35–40	.64 12.8, 22.4 0 19.2, 6.4				.16 5.6 , 6.4 .8 4.8 , 1.6		
40–45							
45–50			.16 4.8 , 7.2 1.6 4.8 , 1.6				.04 1.8 , 2 .6 1.2 , .4
50–55							

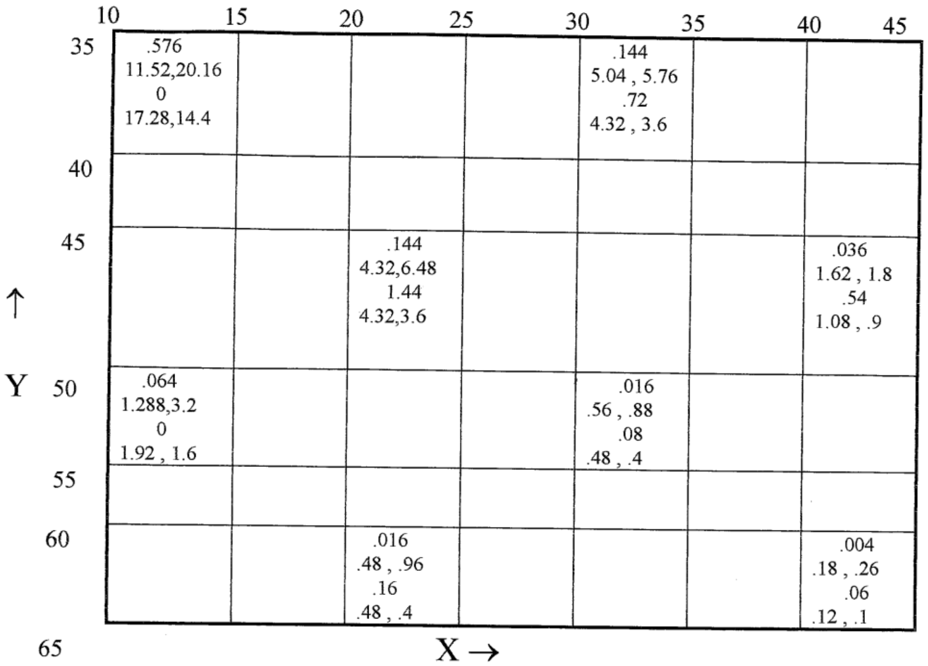
Y ↓ / X →	40–45	45–50	50–55	55–60	60–65	65–70	70–75
5–10	.64 3.2-28.8,8.6+3.2 3.2 - 3.2 19.2, 6.4				.16 .8-10.4,1.6+.8 .8-.8 4.8,1.6		
10–15							
15–20			.16 .8-8.8,3.2+.8 2.4 -.8 4.8 , 1.6				.04 .2-3,.8+.2 0.6-0.2 1.2,0.4
20–25							
25–30							
30–35							

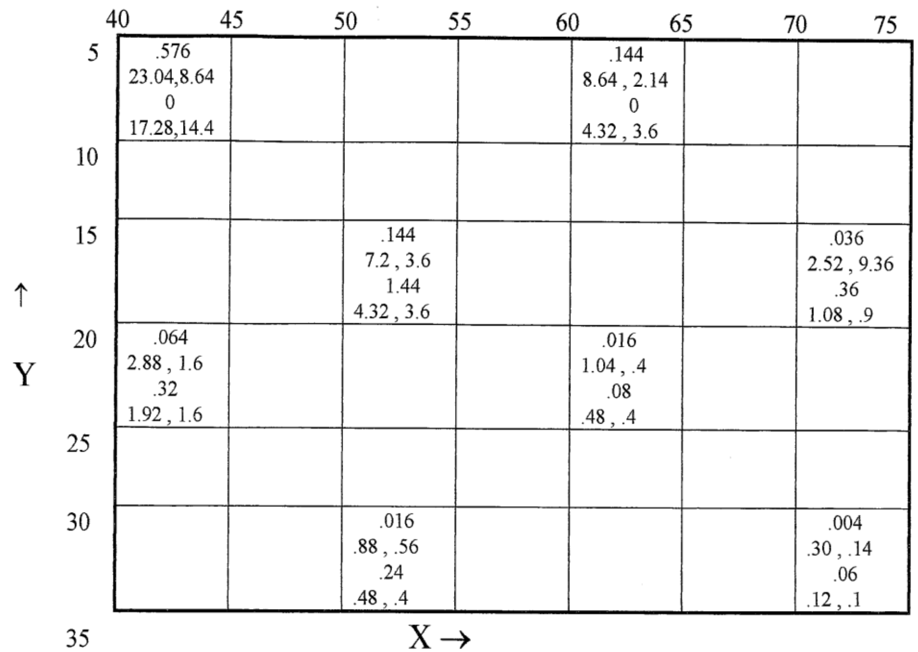
The unserved energy of system Y before convolving the third unit

$USE_{3Y} = 54-20-0.1(3.2+.8+.1+.9) = 33.5$ Mwh



EEG Evaluated from Proposed Method (VI): Parameters after committing the third unit





Unserved energy of the system Y after committing the third unit

$USE_{3Y} = 45.7 - 32 = 13.7$ Mwh

The energy generated by the third unit

$ESE_3 = 33.5 - 13.7 = 19.8$ Mwh

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EEG Evaluated from Proposed Method (VII): Parameters before committing the fourth unit

Y ↓ \ X →	10–15	15–20	20–25	25–30	30–35	35–40	40–45
35–40	.576 11.52,20.16 0 17.28,14.4				.144 5.04,5.76 .72 - .72 4.32 , 3.6		
40–45							
45–50			.144 4.32, 6.48-.72 1.44 4.32,3.6				.036 1.62 , 1.8 .54-.36 1.08 , .9
50–55	.064 1.288,3.2-.64 0 1.92 , 1.6				.016 .56,.88-.08 .08 - .08 .48 , .4		
55–60							
60–65			.016 .48,.96-.16 .16 .48 , .4				.004 .18 , .26 .06-.04 .12 , .1

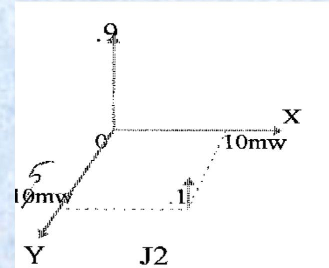
Y ↓ \ X →	40–45	45–50	50–55	55–60	60–65	65–70	70–75
5–10	.576 23.04,8.64 0 17.28,14.4				.144 8.64, 2.17 0 4.32 , 3.6		
10–15							
15–20			.144 7.2 , 3.6 1.44-1.44 4.32 , 3.6				.036 2.52 , .9 .36-.36 1.08 , .9
20–25	.064 2.88 , 1.6 .32-.32 1.92 , 1.6				.016 1.04 , .4 .08-.08 .48 , .4		
25–30							
30–35			.016 .08-.88,.56+.08 .24-.24 .48 , .4				.004 .02-.3 ,.14+.02 .06 -.06 .12 , .1

So the unserved energy of the system X and Y before convoving the Jointly owned fourth generator

$USE_{4X-} = 53.8-36 + .1\times.1 = 17.81$ Mwh

$USE_{4Y-} = 38.7 - 25.5 + .1(.88 + .08 + .64 - .1)$

$= 13.35$ Mwh



EEG Evaluated from Proposed Method (VIII): Parameters after committing the fourth unit

X ↓ \ Y →	10	15	20	25	30	35	40	45	50
35	.5184 10.368,18.144 0 15.552,20.736				.1296 4.536,5.184 0 4.536,5.184				
40									
45			1296 3.88,5.184 1.296 3.88,5.184				.0324 1.458,1.62 .162 1.296,1.296		
50	.0576 1.152,2.304 0 1.1728,2.304		.0576 1.728,2.88 0 2.304,2.304		.0144 .504,.72 0 .504,.576		.0144 .648 ,.792 .072 .576,.576		
55									
60			.0144 .432,.72 .144 .432,.576		.0144 .576,.864 .144 .576,.576		.0036 .162,.234 .018 .144,.144		.0036 .198,.234 .054 .144,.144
65			.0064 .192,.416 0 .192,.256				.0016 .072,.112 .008 .064,.064		
70									
75					.0016 .064,.12 .016 .064,.064				.0004 .022,.032 .006 .016,.016
80									

Y ↓ \ X →	40	45	50	55	60	65	70	75	80 85
5	.5184 20.736,7.776 0 15.552,20.736				.1296 7.776,1.944 0 3.88,5.184				
10									
15			.1296 6.48,3.24 0 5.184,5.184				.0324 2.268,.81 0 1.296,1.296		
20	.0576 2.592,1.44 0 2.016,2.304		.0576 2.88,1.728 0 2.304,2.304		.0144 .936,.36 0 .504,.576		.0144 1.008,.432 0 .576,.576		
25									
30			.0144 .72, .576 0 .576 ,.576		.0144 ..864,.576 0 .576,.576		.0036 .252,.144 0 .144,.144		.0036 .27,.144 0 .144,.144
35			.0064 .352,.256 .032 .256,.256				.0016 .12,.064 .008 .064,.064		
40									
45					.0016 .104,.08 0 .064,.064				.0004 .034,.02 .006 .016.016
50									

Expected energy generation of the system X and Y

$ESE_{4X} = 17.81 - 14.57 + .9(.88 + .08 + .64) = 4.68$ Mwh

$ESE_{4Y} = 13.35 - 2.172 = 11.178$ Mwh

So the expected energy generated by the fourth unit

$ESE_4 = 4.68 + 11.178 = 15.858$ Mwh

Unserved energy of the system X and Y after convolving the fourth unit

$USE_{4X} = 49.97 - 35.4 = 14.57$ Mwh

$USE_{4Y} = 8.84 - 6.672 = 2.172$ Mwh

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EEG Evaluated from Proposed Method (IX)

SL NO	CAPA-CITY IN MW			TYPE	LOCA-TION IN SYSTEM	F.O..R	EEG IN MWH		
	X	Y	GLOBAL				X	Y	GLOBAL
1	10	10	20	JOU	X	0.2	16	16	32
2	20	0	20	SOU	X	0.2	25.6	0	25.6
3	0	15	15	SOU	Y	0.1	0	19.8	19.8
4	10	15	25	JOU	Y	0.1	4.68	11.178	15.858
TOTAL	40	40	80				46.28	46.978	93.258

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Validity Check

- Both heuristic and proposed methodology provide us the same evaluated EEG.
- Computer program was first tuned with bench mark values from heuristic approach and manually calculated EEG using the proposed model with only four generating unit and two load sample mentioned earlier.
- The evaluated EEG was 100% matched.
- The program was later expanded for more generating units including PV units as well as hourly load data for 24 hour.

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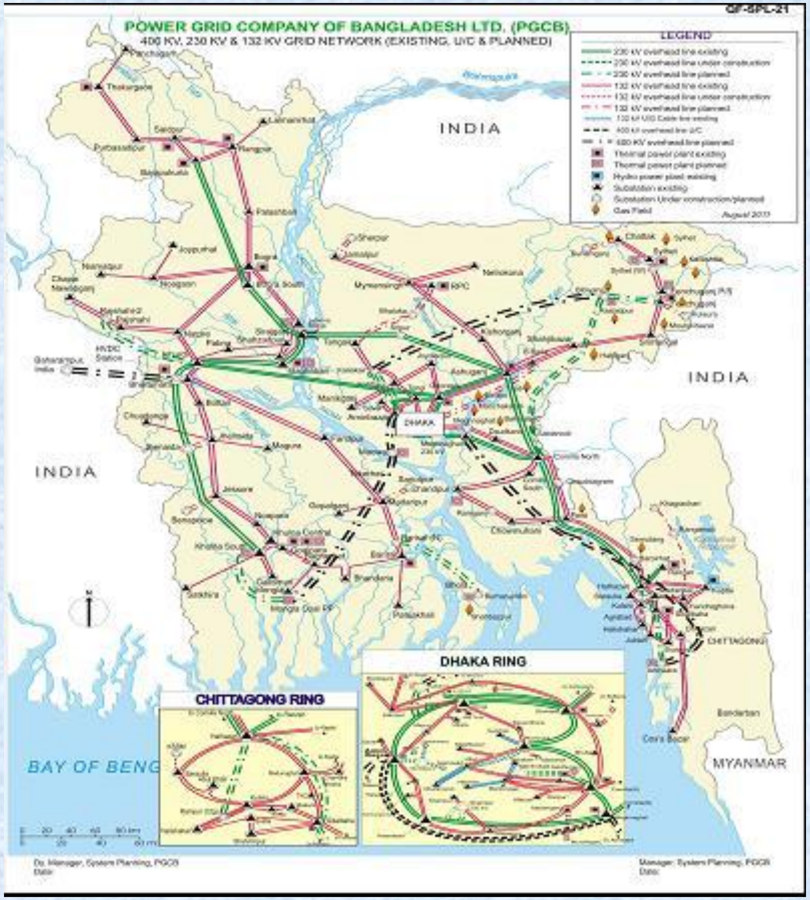
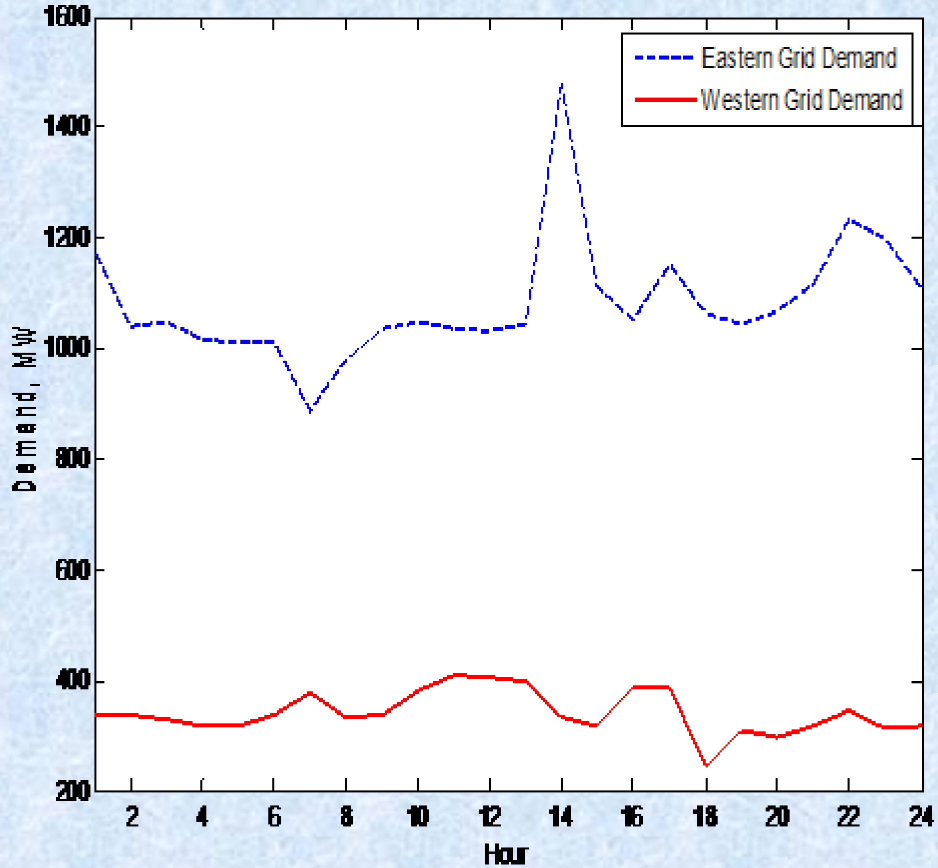
Two Area Interconnected System Example: Power System in Bangladesh



(a)



(b)

EEG for individual unit committed in loading order with a tie line capacity of 450 MW

Loading order	Type of unit	Capacity (MW)	FOR	Location	Ownership	Global expected energy generation (GWh)
1	PV	150	0.03	West	SOU	1.7460
2	Hydro	120	0.032	East	SOU	2.7878
3	Steam Turbine1	720	0.069	East	SOU	16.088
4	Steam Turbine2	806+40	0.097	East	JOU	12.8352
5	Combined Cycle	140	0.15	East	SOU	0.121
6	Gas Turbine	142	0.33	East	SOU	0.211
7	Diesel Engine	9	0.1	West	SOU	0.0118
8	Barge Mounted	18	0.15	West	SOU	0.022
9	Gas Turbine	167	0.27	West	SOU	0.012
	Total	2312	------	-------	----------	33.454

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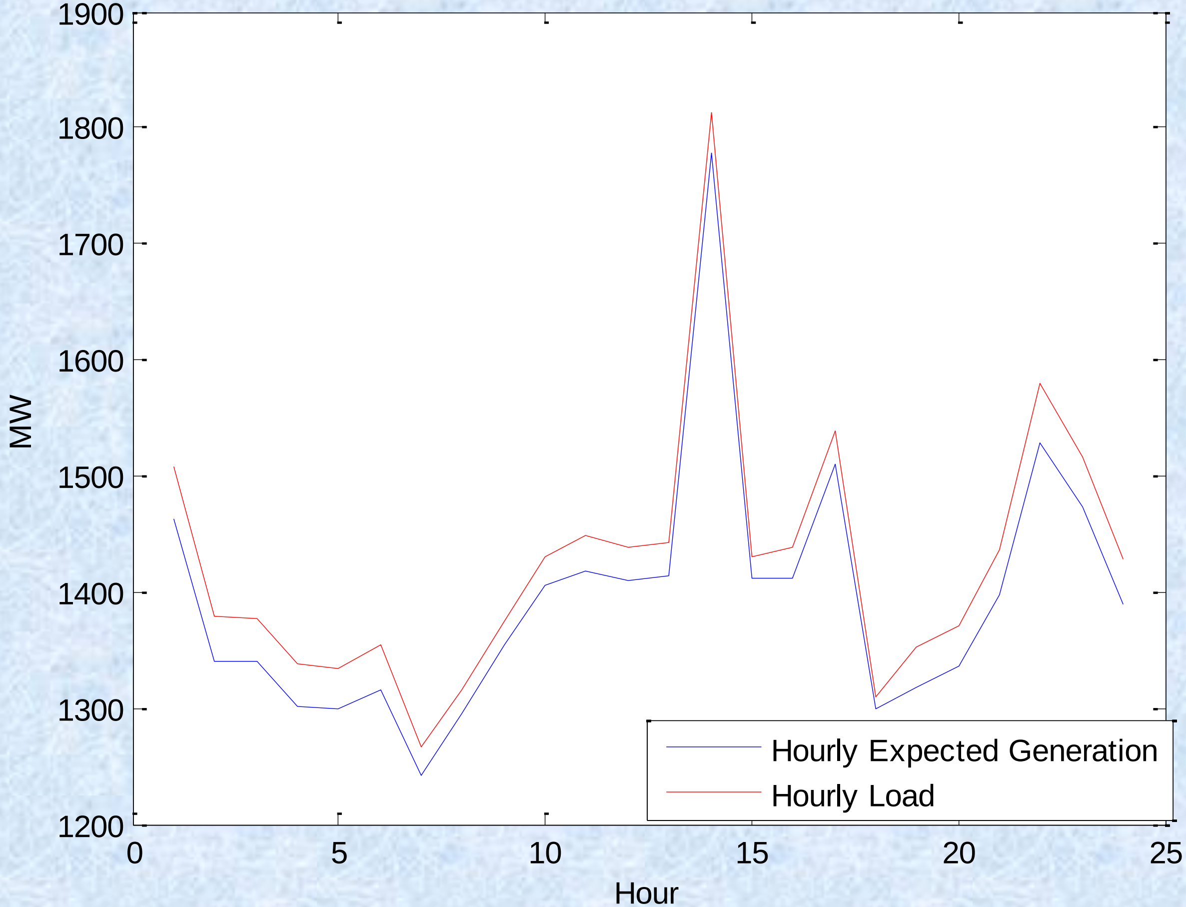
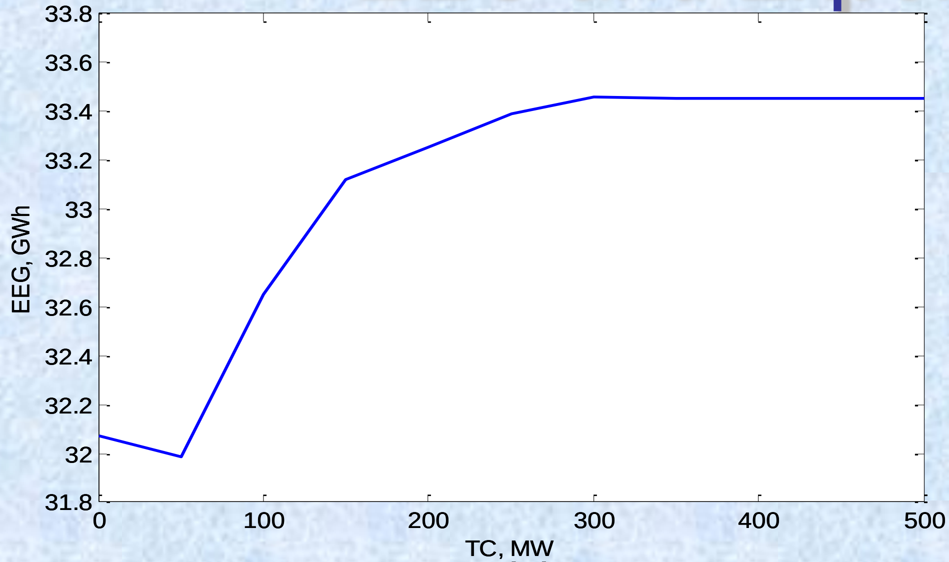
Expected Generation Meeting the Demand

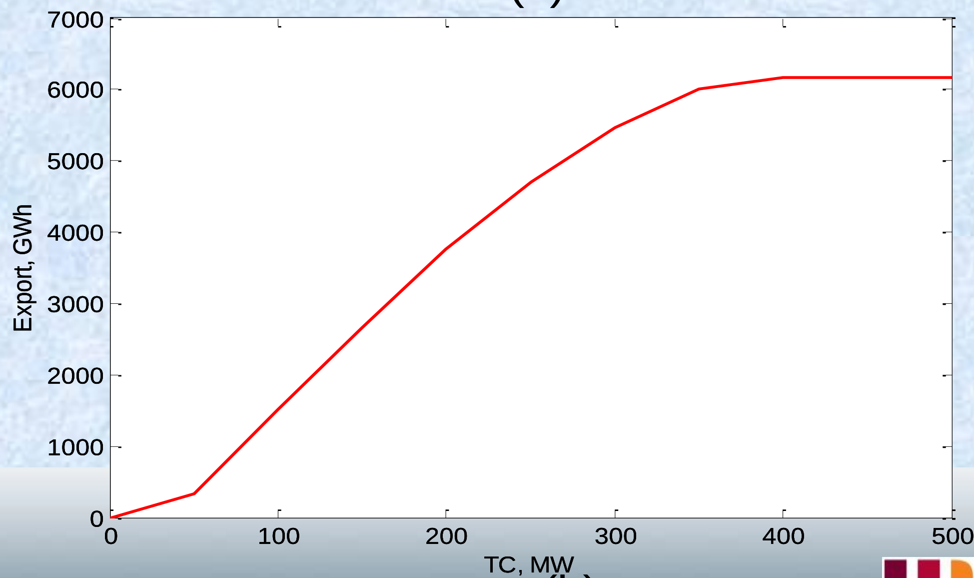


- Always there is lacking of Generation

EEG and Export-Import



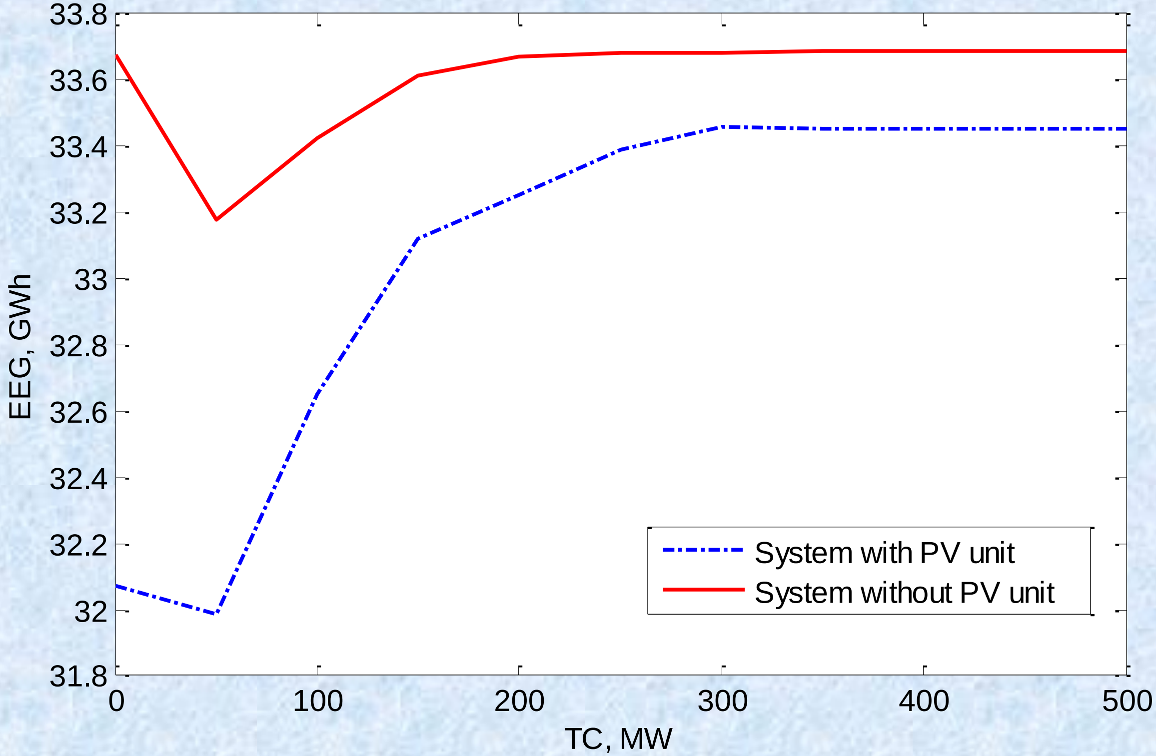
(a)



(b)

Variation of global expected energy generation with tie line capacities (a) EEG for one day (b) global export

Effect of Inclusion of Solar Units



For unit with renewable energy source (solar unit in this case) modify the capacity according to hourly generation data. Usually the cells are available during daytime and at night they are completely unavailable. Also at daytime their capacities varies according to the solar irradiance.

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Conclusions

- An accurate model has been developed to evaluate expected energy generation as well as export.
- The model also can successfully include the behavioral change of PV generating unit. This will give designer a better idea how to include this type of renewable sources for future expansion planning.
- The initial results are encouraging and the similar feature will be done for other type of renewable sources such as wind generation.