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Electric Power Planning for a Transmission Network Under Demand Volatility

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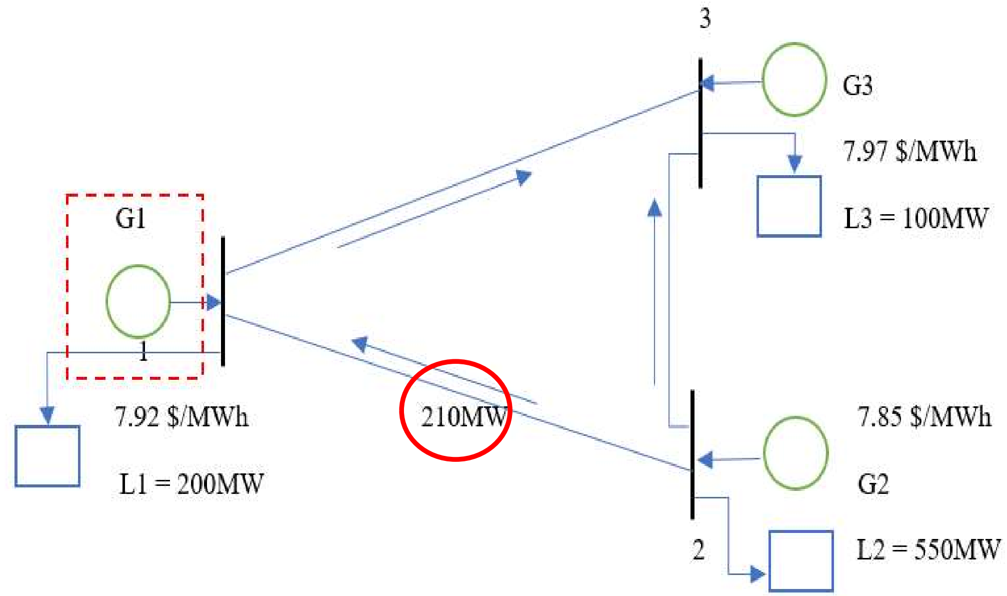
Objective

- Evaluating the option value of expanding the existing transmission line using Real Options approach
  - DCOPF is calculated to obtain LMP values for all buses
  - Binomial Lattice is constructed to map the uncertain demand
  - In part one, a new generator will be added to the network
  - In second part the option value of adding a new transmission line is evaluated as an alternative to a new generator

Adding A New Generator to the Network

Optimal Power Flow (OPF)

- There are 2 generators in bus 2 and 3. The generator at bus 1 is not available currently
- We will discuss the consequence of adding one generator at bus 1



Three bus network model

Optimal Power Flow (OPF)

- **Case 1:** Bus 1 will have no generator and the demand at this node will be satisfied by generators 2 and/or 3
- **Case 2:** We will add a generator at bus 1 and the total demand will be met by the combination of all three generators

Optimal Power Flow (OPF) (Case 1)

Susceptance Matrix

$[B_x]$ = $\begin{pmatrix} (1/x_{12}+1/x_{13}) & -1/x_{12} & -1/x_{13} \\ -1/x_{12} & (1/x_{12}+1/x_{23}) & -1/x_{23} \\ -1/x_{13} & -1/x_{23} & (1/x_{13}+1/x_{23}) \end{pmatrix}$

Minimize (7.85*G2 + 7.97*G3)

$1800 \times t_1 \ - 1000 \times t_2 - 800 \times t_3 + \ 200 = 0$

$-1000 \times t_1 + \ 1500 \times t_2 - 500 \times t_3 - G_2 + 550 = 0$

$-800 \times t_1 - 500 \times t_2 + \ 1300 \times t_3 - G_2 + 100 = 0$

$t_1 \ = 0$

$1000 \times t_1 - 1000 \times t_2 <= 210; \ 1000 \times t_2 - 1000 \times t_1 <= 210$

G_i = generation quantity at node i ; t_i = phase angle for node i

OPF - Solving and Finding LMP values (case 1)

Output for case 1:

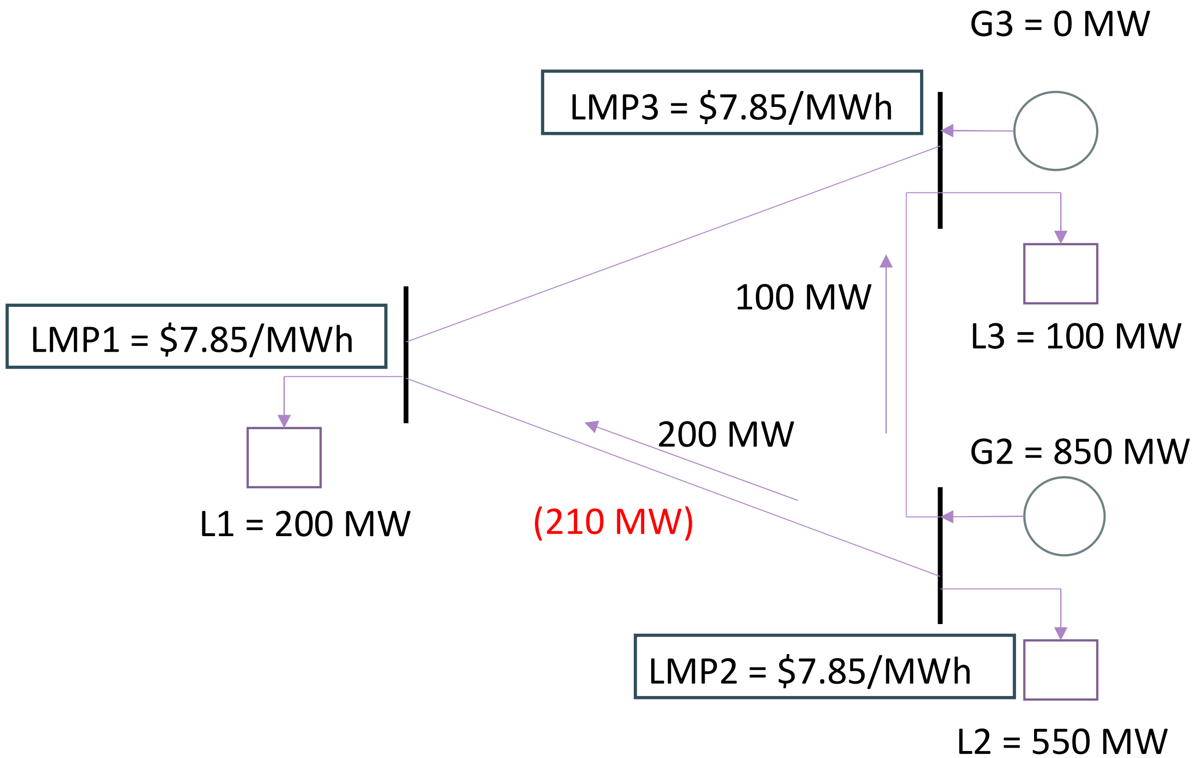
value of G_2 = 850 MW

value of G_3 = 0 MW

value of t_1 = 0 MW

value of t_2 = 0.2

value of t_3 = 0



Optimal Power Flow (OPF) (Case 2)

Minimize (7.92*G1 + 7.85*G2 + 7.97*G3)

$$1800 \times t_1 \; - 1000 \times t_2 - 800 \times t_3 - G_1 + \; 200 = 0$$
$$-1000 \times t_1 + \; 1500 \times t_2 - 500 \times t_3 - G_2 + 550 = 0$$
$$-800 \times t_1 - 500 \times t_2 + \; 1300 \times t_3 - G_2 + 100 = 0$$

$$t_1 = 0$$

$$1000 \times t_1 - 1000 \times t_2 <= 210;$$
$$1000 \times t_2 - 1000 \times t_1 <= 210$$

OPF - Solving and Finding LMP values (case 2)

Output for case 2:

value of G_1 = 0 MW

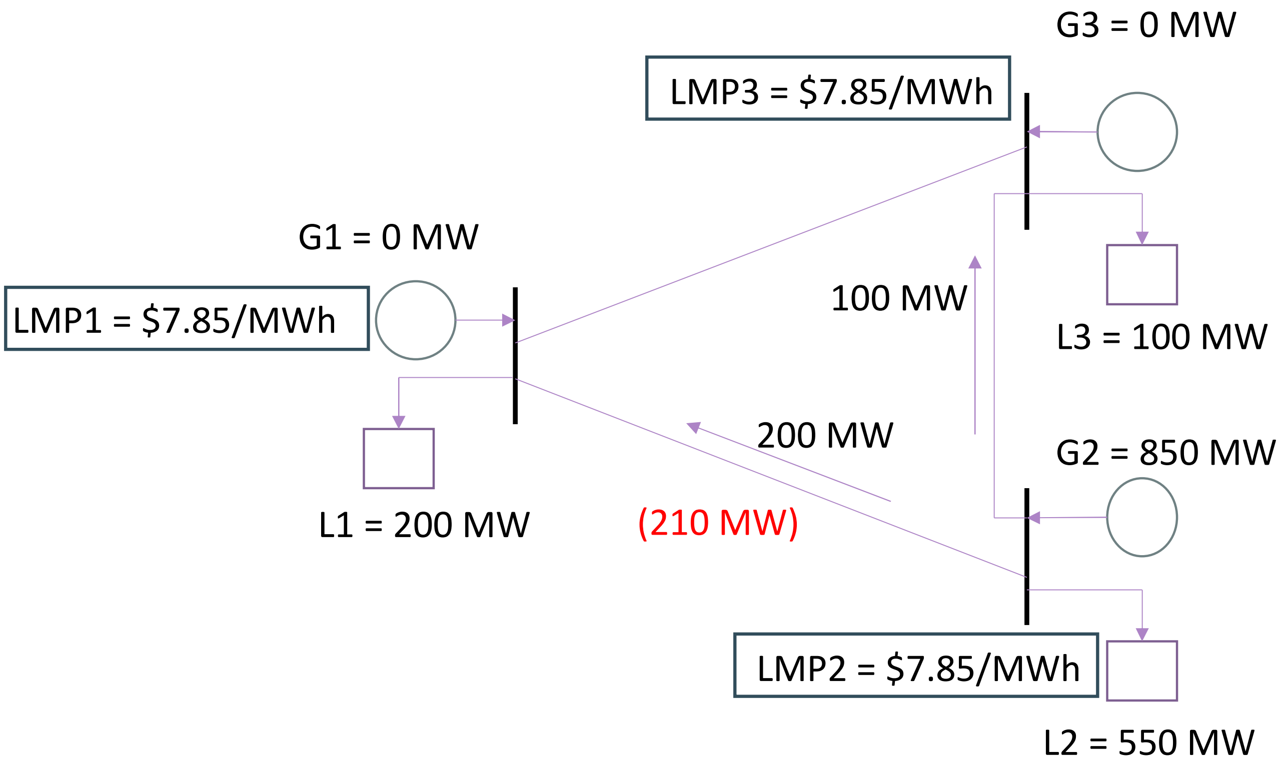
value of G_2 = 850 MW

value of G_3 = 0 MW

value of t_1 = 0 MW

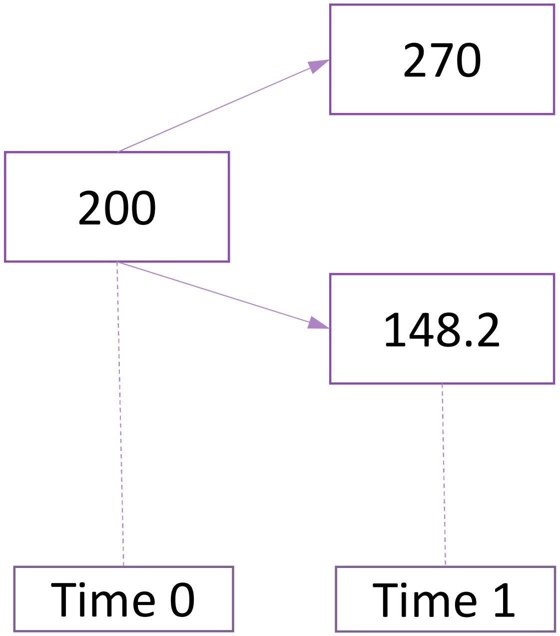
value of t_2 = 0.2

value of t_3 = 0



Demand Evolution at bus 1 for one time step

- Risk free discount rate (r_f)= 4.879% per annum compounded continuously
- Volatility (σ) = 30%/year
- Time step (Δt) = 1 year; Total time frame = 1 year
- Up-factor (u) = $e^{\sigma \Delta t}$ =1.35
- Down factor (d) = 1/u = 0.741
- Initial demand at bus 1 (D)= 200 MW
- Up demand = $u \times D$; Down demand = $d \times D$
- Risk-neutral probability, $q = (e^{rf} - d)/(u-d)$ = 0.5074



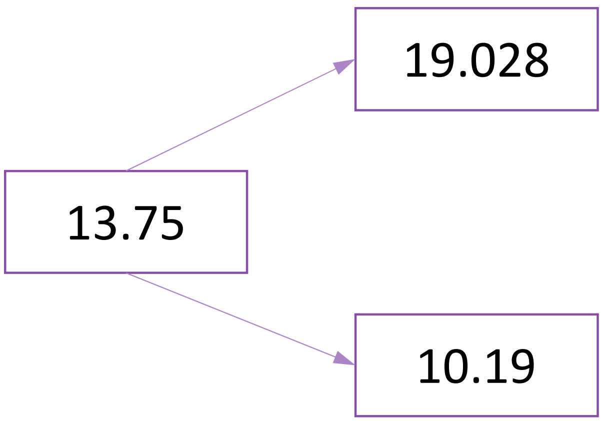
Demand lattice (in MW)

OPF - Solving and Finding LMP values

Case 1: Without generator 1	**Load at bus 1 (MW)**	**LMP at bus 1 ($/MWh)**	**LMP at bus 2 ($/MWh)**	**LMP at bus 3 ($/MWh)**
	200	7.85	7.85	7.85
	270	**8.045**	7.85	7.97
	148.2	7.85	7.85	7.85
Case 2: With generator 1	**Load at bus 1 (MW)**	**LMP at bus 1 ($/MWh)**	**LMP at bus 2 ($/MWh)**	**LMP at bus 3 ($/MWh)**
	200	7.85	7.85	7.85
	270	**7.92**	7.85	7.893
	148.2	7.85	7.85	7.85

Cost paid by the community at bus 1 (Case 1)

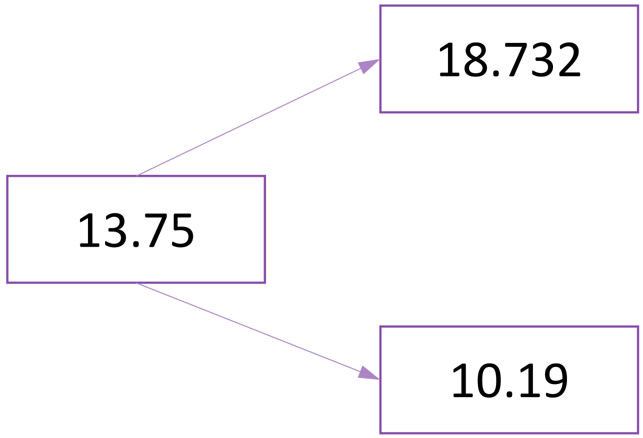
- When the demand at bus 1 is 270 MW, locational marginal price at bus 1 is $8.045
- For other nodes, the locational marginal price is $7.85
- Cost= LMP x load at bus 1 x 8760



Cost lattice for case 1 (in $ millions)

Cost paid by the community at bus 1 (Case 2)

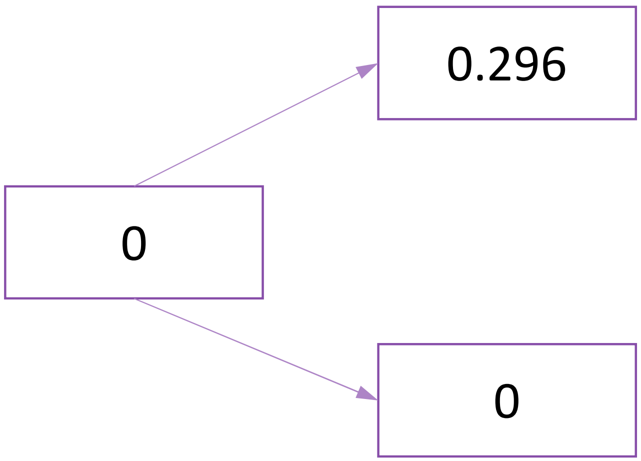
- When the demand at bus 1 is 270 MW, locational marginal price at bus 1 is $7.92
- For other nodes, the locational marginal price is $7.85
- Cost= LMP x load at bus 1 x 8760



Cost lattice for case 2 (in $ millions)

Net benefit

- We can calculate the net benefit by subtracting the two costs mentioned in previous two slides
- That is the amount of monetary benefit we get for adding a generator



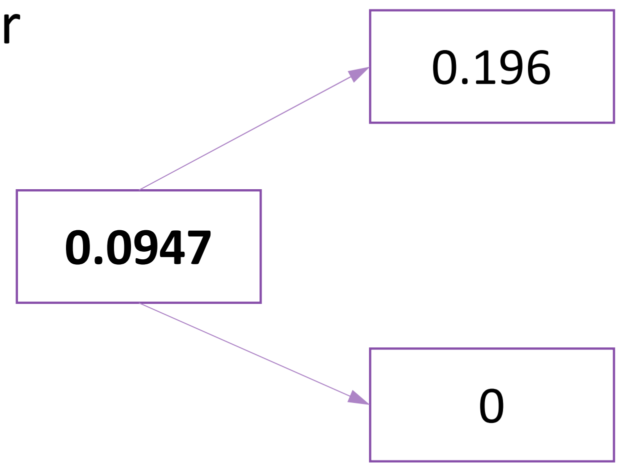
Net benefit lattice (in $ millions)

Option value tree

- The generator is added to the network after one year after knowing the demand at time 1
- The call option is European
- The option value:

$$(0.196 \times 0.5074 \ + \ 0 \times 0.4926) \times e^{-0.04879}$$

= $0.0947 million



Option value tree (in $ millions)

Results & Discussion

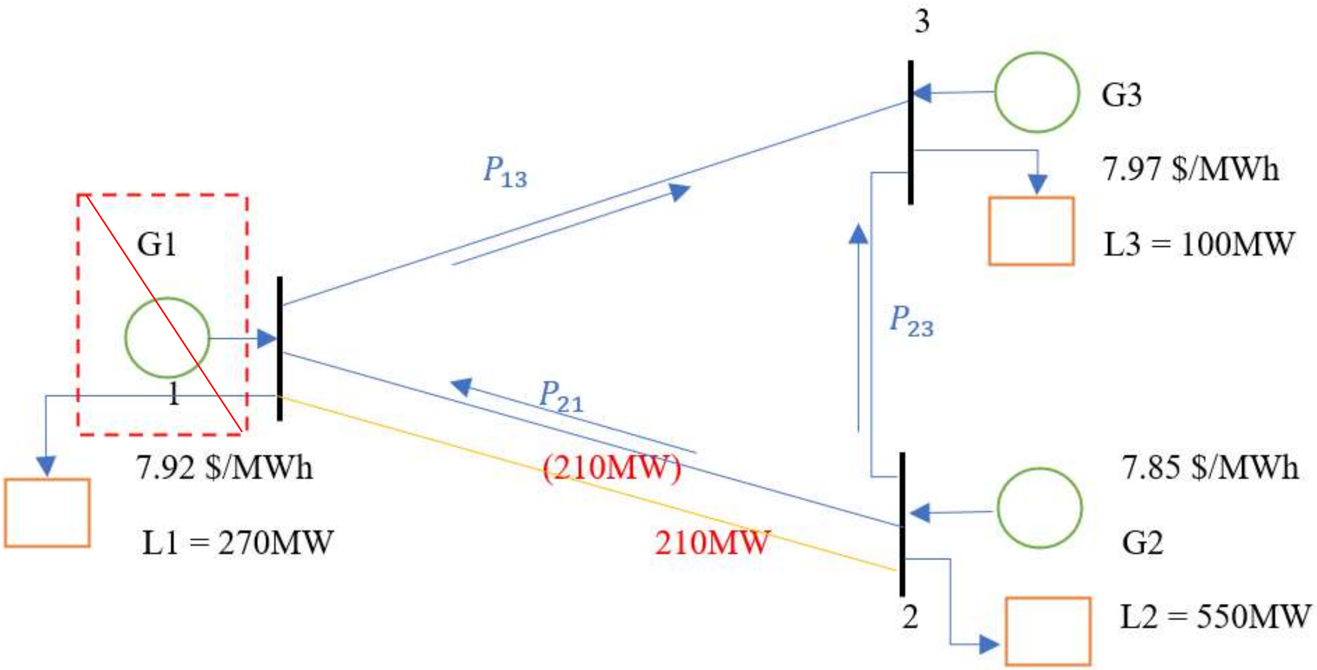
- The value of adding a new generator is $94,700
- Exercising this option is beneficial only when the demand is 270 MW in our case
- Another alternative to adding a generator is adding a transmission line to the network
- Future research includes comparison of these two options

Adding A New Transmission Line Parallel to Line 1-2

The Process to Derive the Option Value

- The susceptance matrix $[B_x]$ is recalculated
- The LMP values are obtained from the new DCOPF
- The net benefit lattice is constructed using the binomial lattice structure
- The option value is calculated using risk neutral probability

Network Model



Reactance –

Line 1-2 = 0.1 PU

Line 1’-2’ = 0.1 PU

Line 2-3 = 0.2 PU

Line 1-3 = 0.125 PU

Susceptance matrix

- The susceptance matrix $[B_x]$ will be changed as follows –
- $[B_x]$ = $$\begin{pmatrix} (1/x_{12}+1/x_{13}) & -1/x_{12} & -1/x_{13} \\ -1/x_{12} & (1/x_{12}+1/x_{23}) & -1/x_{23} \\ -1/x_{13} & -1/x_{23} & (1/x_{13}+1/x_{23}) \end{pmatrix}$$
- x_{12}= 0.1 PU when there is single transmission line
- But x_{12} = 0.2 PU for two parallel transmission lines by assuming 1-2 and 1’-2’ as a single equivalent line

Case 1

Without a new transmission line 1'-2'

- The DCOPF problem is programmed on Excel Solver
- The sensitivity report of the solution gives the LMP values

Variable Cells

Cell	Name	Final Value	Reduced Gradient
C17	Generator 2: Power= P_gen_i (MW)	827.5	0
C18	Generator 3: Power= P_gen_i (MW)	92.5	0
C19	theta_1: Power= P_gen_i (MW)	0	0
C20	theta_2: Power= P_gen_i (MW)	0.21	0
C21	theta_3: Power= P_gen_i (MW)	0.075	0

Constraints

Cell	Name	Final Value	Lagrange Multiplier
C12	Planned delivery (MW): Cost($/h)	920	0
C37	Bus_1 DC power flow formulation	270	8.044999719
C38	Bus_2 DC power flow formulation	550	7.849999905
C39	Bus_3 DC power flow formulation	100	7.96999979
C43	P_flow_12 (MW)	-210	0
C44	P_flow_21 (MW)	210	-0.254999757

Case 2

With a new transmission line 1'-2'

- The LMP values change and are same for all the buses

Variable Cells

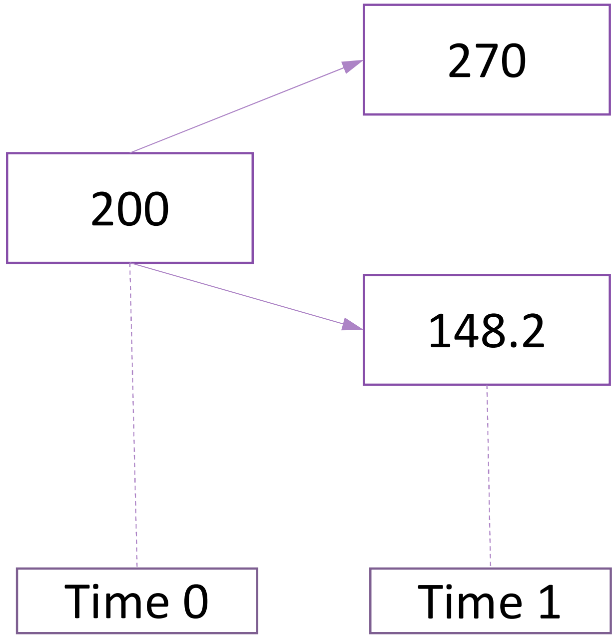
Cell	Name	Final Value	Reduced Gradient
C17	Generator 2: Power= P_gen_i (MW)	920	0
C18	Generator 3: Power= P_gen_i (MW)	0	0.120000362
C19	theta_1: Power= P_gen_i (MW)	0	0
C20	theta_2: Power= P_gen_i (MW)	0.253529412	0
C21	theta_3: Power= P_gen_i (MW)	0.020588235	0

Constraints

Cell	Name	Final Value	Lagrange Multiplier
C12	Planned delivery (MW): Cost($/h)	920	0
C37	Bus_1 DC power flow formulation	270	7.849999905
C38	Bus_2 DC power flow formulation	550	7.849999905
C39	Bus_3 DC power flow formulation	100	7.849999905
C43	P_flow_12 (MW)	-126.7647059	0
C44	P_flow_21 (MW)	126.7647059	0

Demand Evolution at Bus 1

- We construct binomial lattice model to forecast the demand for one time step (1 year)
- We assume that electricity demand follows GBM
- Demand is 200 MW at node 1 at time = 0 and it can rise to 270 MW or drop to 148.2 MW at time = 1

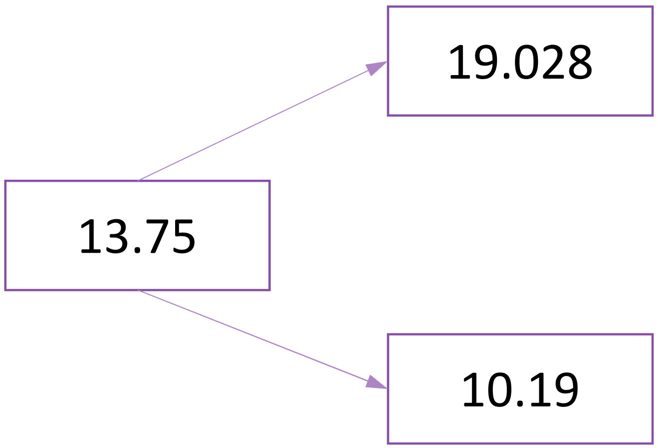


Demand lattice (in MW)

Economic Consequence – Case 1

- When the load = 270 MW at bus 1, LMP is 8.045 \$/MWh
- Bus 1 community pays \$19.028 million in a year when load = 270 MW

$$8.045\,\frac{\$}{MWh} \times 8760\ hrs \times 270\ MW \;= \$19{,}028{,}034$$

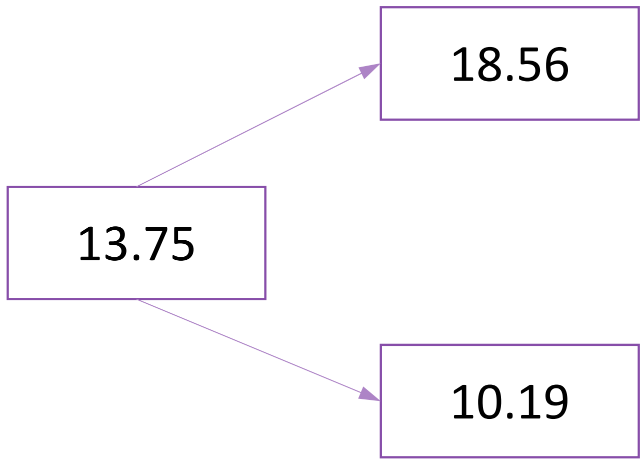


Cost lattice for case 1 (in \$ millions)

Economic Consequence – Case 2

- When the load = 270 MW at bus 1, LMP is 7.85 \$/MWh
- Bus 1 community pays \$18.56 million in a year when load = 270 MW

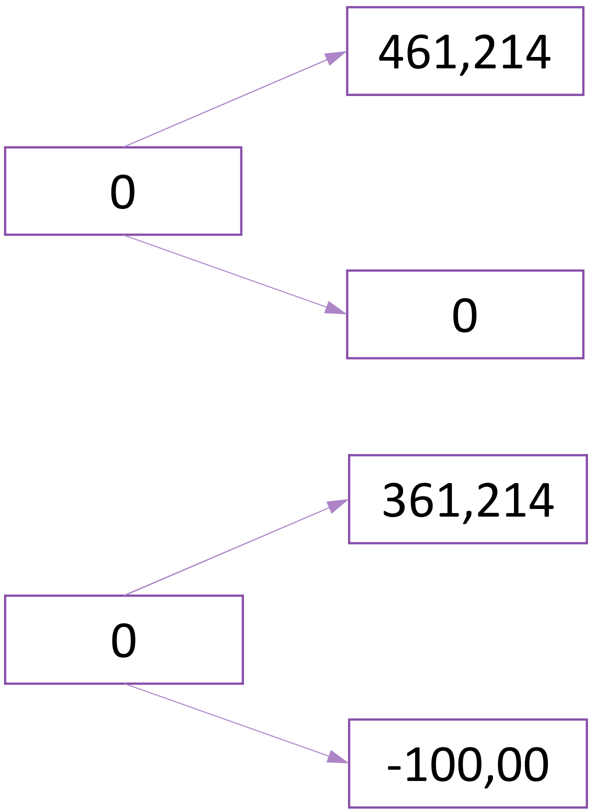
$$7.85\,\frac{\$}{MWh} \times 8760\;hrs \times 270\;MW \;=\; \$18{,}566{,}820$$



Cost lattice for case 2 (in \$ millions)

Net Benefit Lattice

- The net benefit for any time point is the difference between the costs which is $461,214
- We assume that the total construction cost of a transmission line 1’-2’ is $100,000
- The “net benefit lattice after paying the total construction cost” can be attained by simply subtracting the total construction cost from the net benefit
- The decision to build a transmission line is taken before knowing the future demand

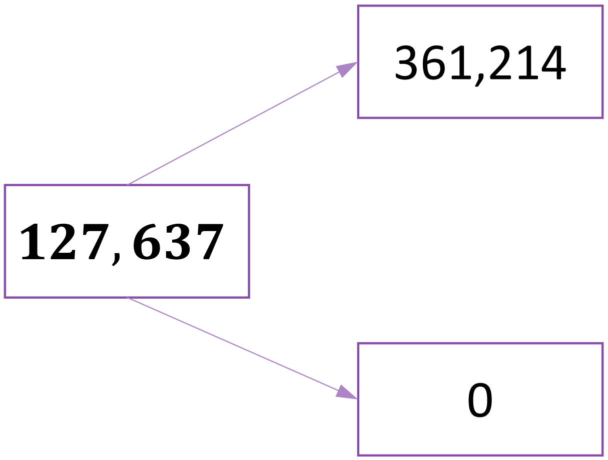


Net benefit lattice (in $)

Option value tree

- A new transmission line is added to the network after one year after knowing the demand at time 1
- The call option is European
- The option value is:

$(361{,}214 \times 0.5074 - 100000 \times 0.4926) \times e^{-0.04879}$ = $\mathbf{\$\,127{,}637.16}$



Option value tree (in $)

Results & Discussion

(Recall back to slide 16)

- The value of the option of adding a new transmission line is superior to adding a new generator to bus 1
- The option value of adding a new generator is $94,700
- The benefit for the whole grid is higher than that for the bus 1 community only
- This is due to reduced LMP at bus 3

Future Research

- Including the power losses in the OPF calculation will increase the practicality of the model
- Considering the accurate cost of transmission line, O&M costs, and the length of the line in the calculation will make the option value more appropriate
- To improve the accuracy of the model, the binomial lattice model can be increased up to 20 years

Thank You!