Carnegie Mellon

Electric Energy Systems Group

Electrical & Computer ENGINEERING

Designing Incentives for Flexibility in the Transmission Sector

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10th CMU Electricity Conference
Pre-conference Workshop
March 30, 2015

Why Flexibility in the Transmission Sector?

- Increasing short-run and long-run uncertainties in the electricity industry

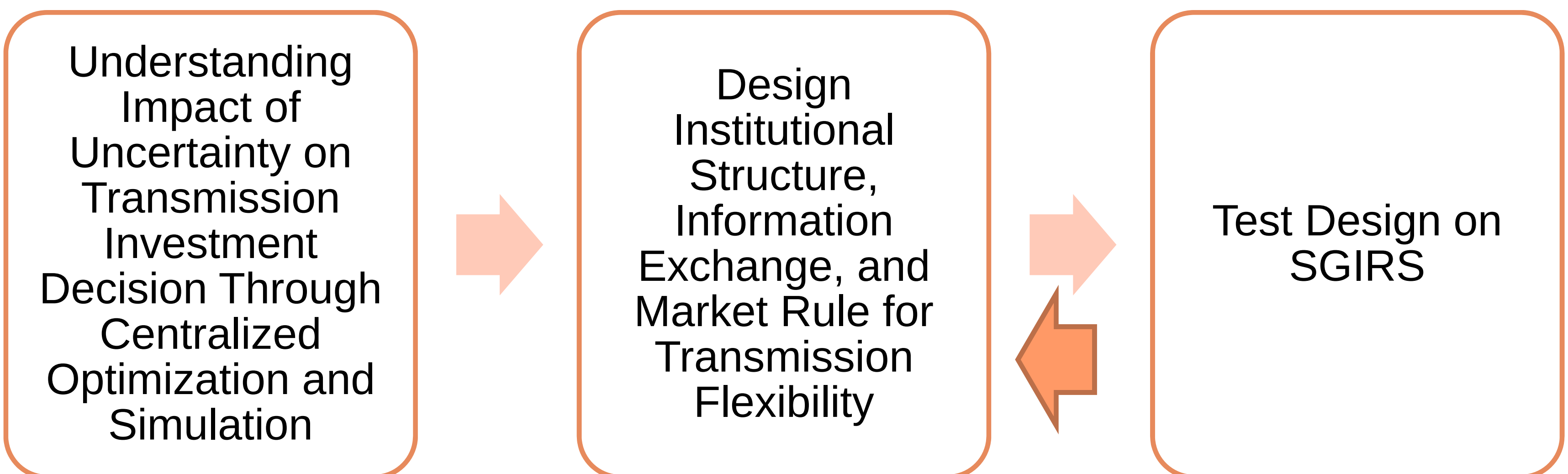
- Large-variety of smart control, communication, and sensing available to more efficiently and reliably operate the electric power system

- Changing economies of scale of transmission technologies – Big is no longer necessarily more efficient

- Need operational, investment, and institutional flexibility to enable these technologies and better manage uncertainties

Institutional Flexibility: Some Institutional Framework are More Conducive for Flexibility

- Key Question: What kind of institutional design and market rules are needed to provide incentives for flexibility in the transmission sector?



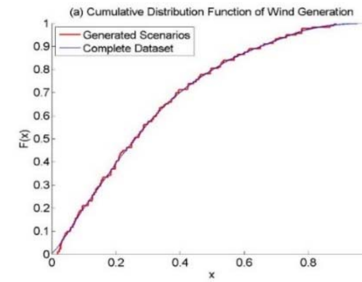
Why do we need testbeds and simulators for policy/regulatory design?

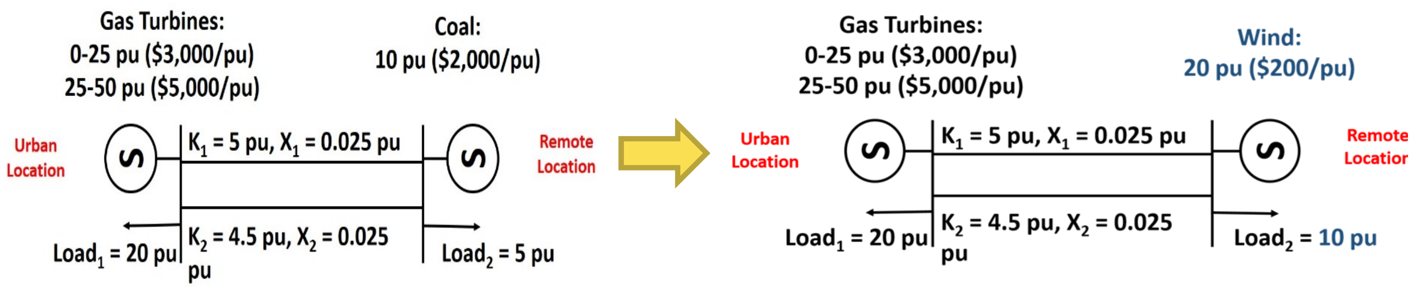
- Traditional economic and regulatory theory based on assumption that there is perfect information. In reality – no such thing as perfect information

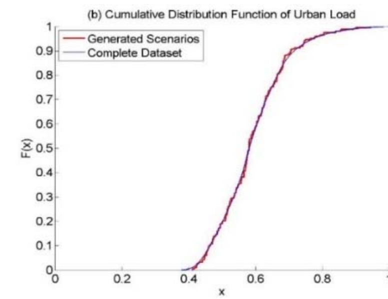
- Centralized social welfare optimization can guide policy/institutional design but does not fully reflect how a certain policy will work in the real world

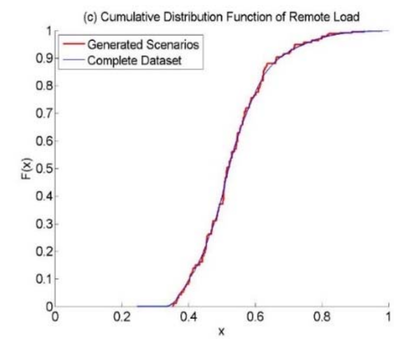
- Testbeds and simulators allow us to understand how policy/institutional design works under:
  - Imperfect information
  - Private incentives
  - Different market rules

Insight 1: Operational and Market Rules have a Significant Impact on Incentives for Flexibility







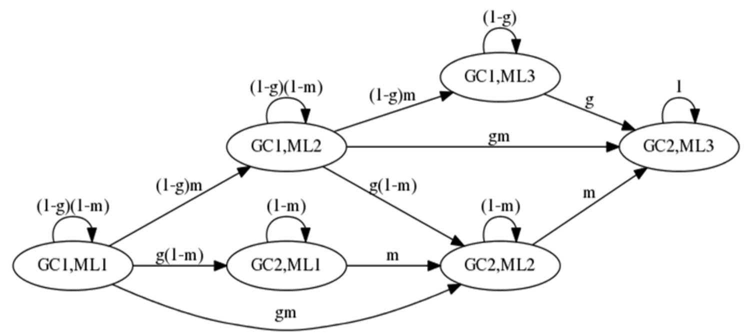


Operational Framework	Investment Decision	Operational and Annualized Investment Cost
Economic Dispatch	FRD Line 1 (0.0025 pu)	$0.303 Billion
Preventive N-1	Line (450MW)	$0.314 Billion
Corrective N-1	Line (353MW),FRD Both Line (0.0053 pu)	$0.311 Billion
Corrective N-1 with Dispatchable Load	FRD Line 1(0.0025pu)	$0.307 Billion

Insight 2: Load Participation in Markets and Well-Designed Long Term Markets Needed to Promote Information and Risk Sharing

$$GC \in \left\{ \begin{matrix} Coal\ Remains, No\ Wind\ (GC1/Base) \\ 2000\ MW\ Wind\ Generation\ (GC2) \end{matrix} \right\}$$

$$ML \in \left\{ \begin{matrix} No\ Increase\ in\ Load\ (ML1/Base) \\ Load\ Level\ Increase\ to\ 1000MW\ (ML2) \\ Load\ Level\ Increase\ to\ 1500\ MW\ (ML3) \end{matrix} \right\}$$



gi	m	Load Elastic?	Investment Decision
1	1	No	Invest in 0.0025 pu of flexible reactance in line 1 during Year 1 and invest in the 450MW new line in Year 9.
0.5	0.5	No	Build the 450 MW new line in Year 1. The flexible reactance device will be built in Year 5 or Year 9 only if the demand increased from the base case.
0.5	0.5	Yes	Invest in 0.0025 pu of flexible reactance in line 1 during Year 1 .The new line will only be built in Year 5 or Year 9 if the load increased to 1500MW and the wind farm is built.

Different Institutional Frameworks have Different Design Questions and Information Needs

Rate-of-Return Regulation | Performance-based Regulation | Merchant Transmission Investment

Rate-of-Return Regulation / Performance-based Regulation:

- Combined vs. Separate Ownership and Operation of Transmission System
- Used and Useful/ Performance Metrics
- Information Availability to Regulators

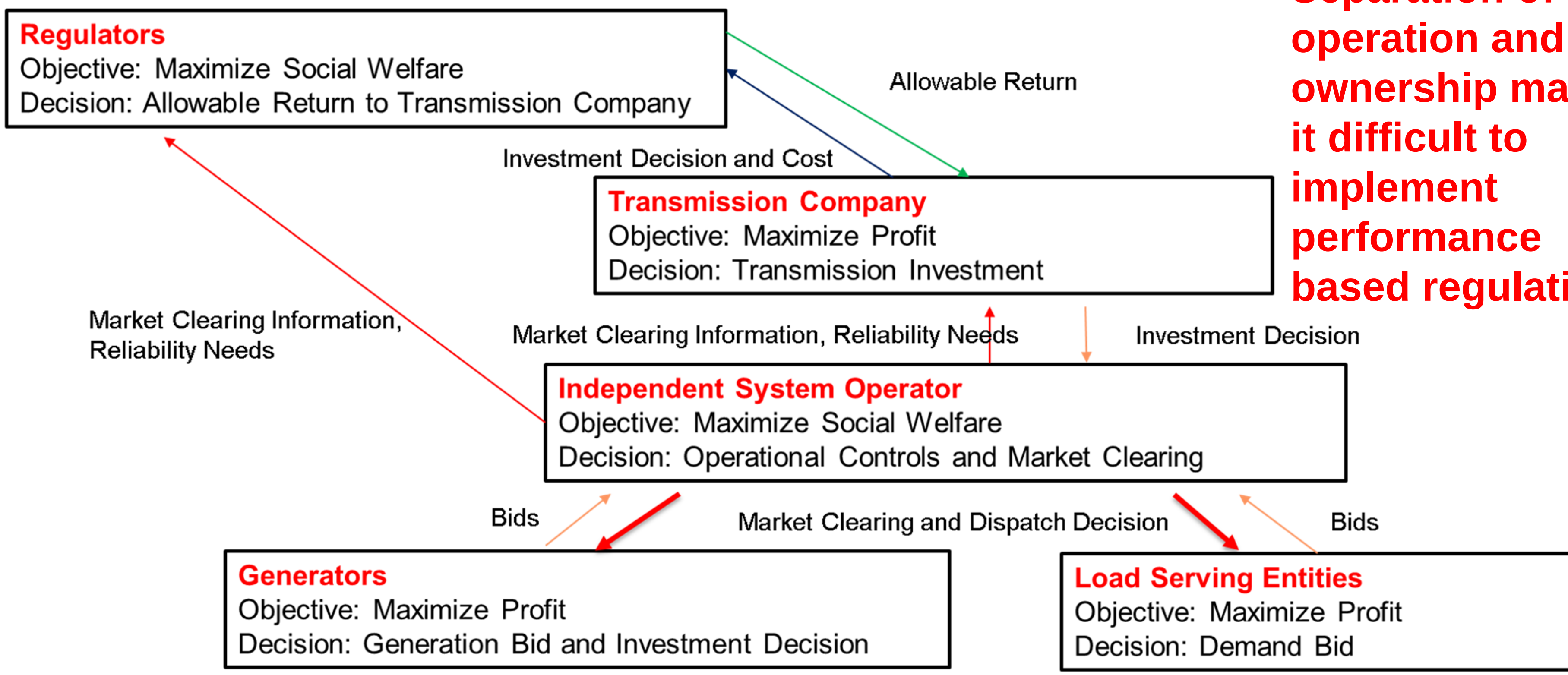
Merchant Transmission Investment:

- Design of long-term transmission rights

All frameworks:

- Design of market rules and mechanisms
- Risk sharing considerations
- Reliability/Policy Investments vs. Economic Investments

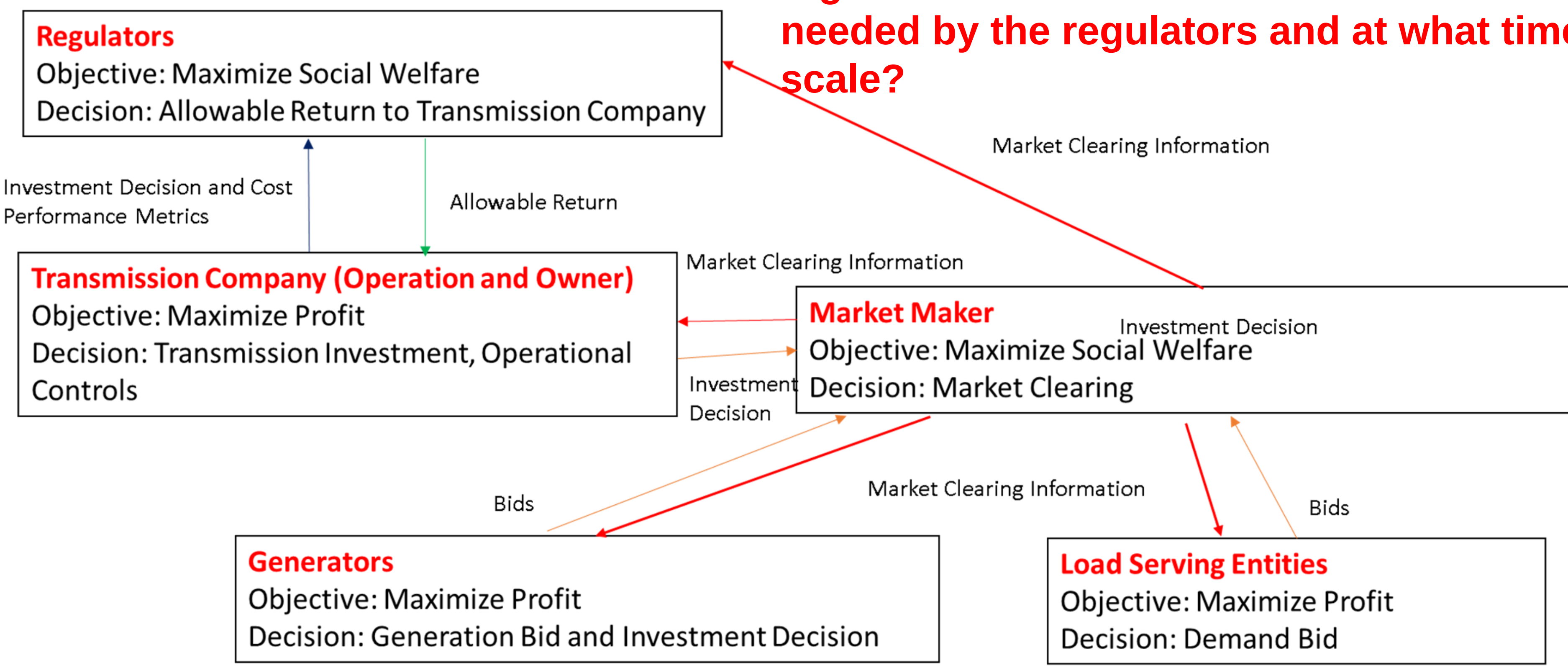
Separate Ownership and Operation of Transmission System



Separation of operation and ownership makes it difficult to implement performance based regulation.

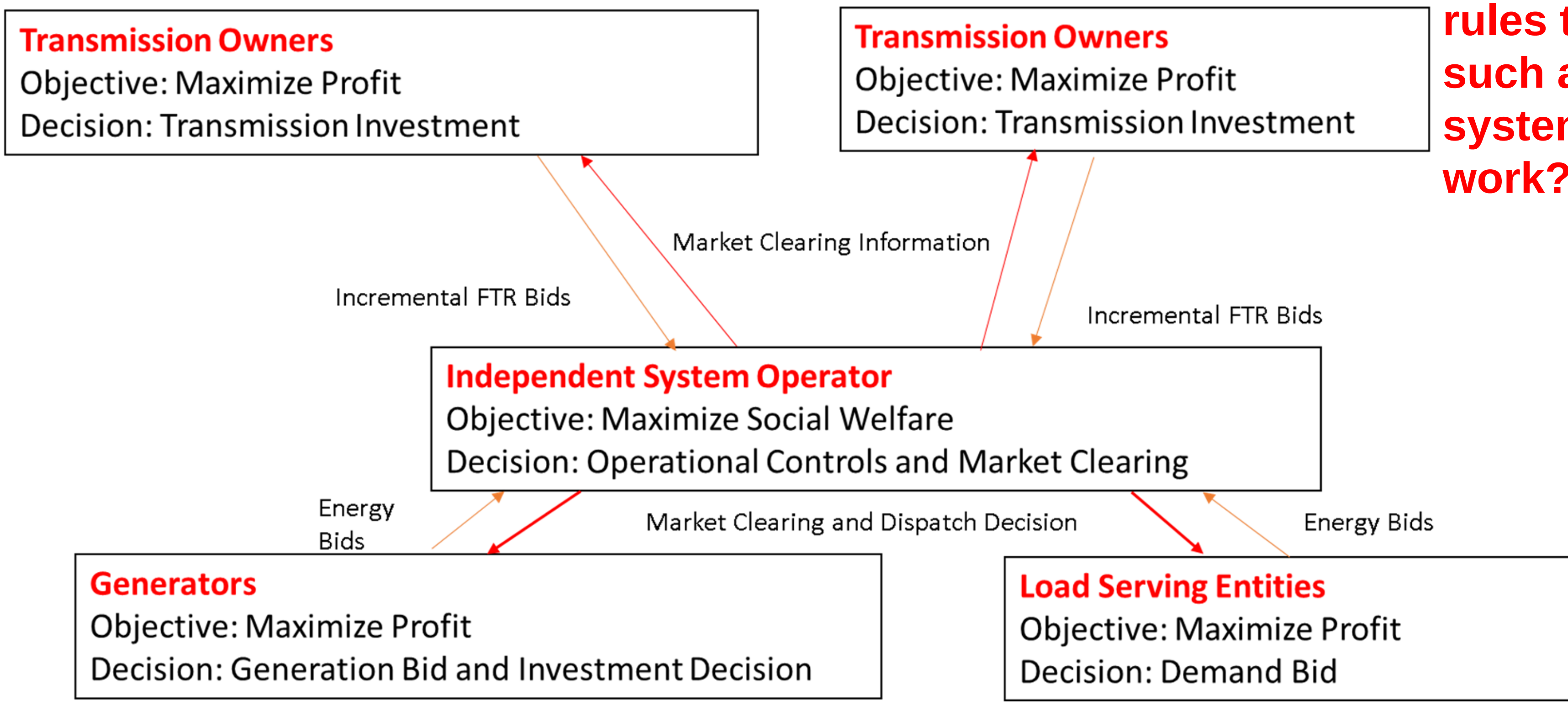
Combined Ownership and Operation of Transmission System

Easier to implement performance based regulation. What kind of information is needed by the regulators and at what time scale?

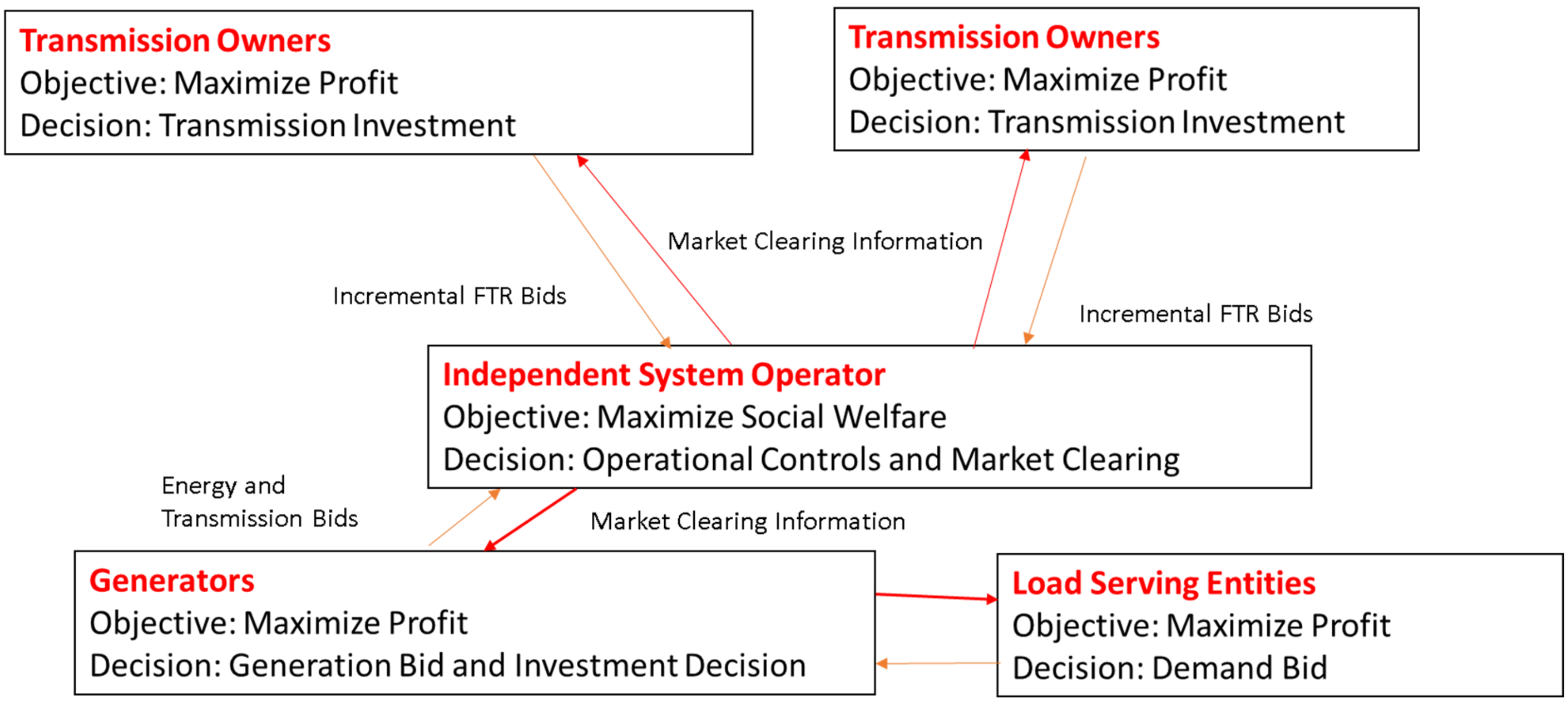


Merchant Transmission (Centralized Market)

Fully market-based system. How do we design the market rules to make such a system work?



Merchant Transmission(Bilateral Contracting)



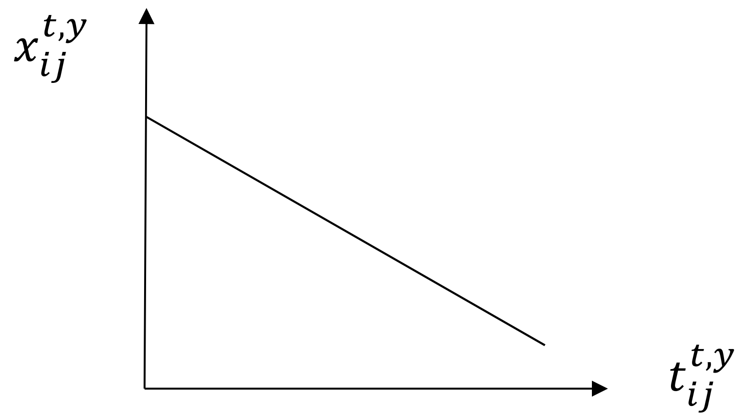
Merchant Transmission Example – Transmission Demand Function

- Assume bilateral contracting, load submits demand function to generator, generator problem (Adapted from [1]):

$$\min_{x_{ij}^{t,y}} \sum_{y=1}^{Y} \sum_{t=1}^{T} \left[C_i \left(\sum_{j=1}^{n} x_{ij}^{t,y} \right) - \sum_{j=1}^{n} D_{ij}\left(x_{ij}^{t,y}\right) + \sum_{j=1}^{n} t_{ij}^{t,y} x_{ij}^{t,y} \right]$$

$$subject\ to \quad x_{ij}^{t,y} \geq 0$$

- Sufficient condition gives demand function(total energy transaction as a function of transmission charge) for transmission which is submitted to the ISO.



[1] Wang, H.; Ilic, M.; Vogelsang, I., "Multilayered unbundled delivery of electricity service to customers under normal conditions," *Power Engineering Society General Meeting, 2004. IEEE* , vol., no., pp.2257,2265 Vol.2, 10-10 June 2004

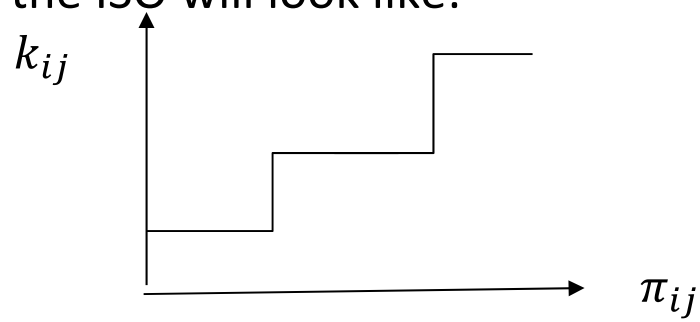
Merchant Transmission Example – Transmission Supply Function

- Assume transmission owner compensated based on the marginal value of capacity + reactance [2,3], the transmission owner problem for line ij becomes:

$$\min_{k_{ij},b_{ij}(k_{ij})} \overbrace{\sum_{y=1}^{Y}\sum_{t=1}^{T}\left[\left(\mu_{ij}^{t,y,+}+\mu_{ij}^{t,y,-}\right)k_{ij}+\sum_{l=1}^{N_l}\left(-\mu_{ij}^{t,y,+}+\mu_{ij}^{t,y,-}\right)\frac{\partial f_l^{t,y}}{\partial b_{ij}}b_{ij}\right]}^{\pi_{ij}} - C_k\left(k_{ij}\right)$$

$$subject\ to\quad k_{ij} \geq 0$$

- Given that transmission investment is lumpy, the resulting supply function for transmission submitted to the ISO will look like:



[2] Gribik, Paul R.; Shirmohammadi, D.; Graves, J.S.; Kritikson, J.G., "Transmission rights and transmission expansions," *Power Systems, IEEE Transactions on* , vol.20, no.4, pp.1728,1737, Nov. 2005

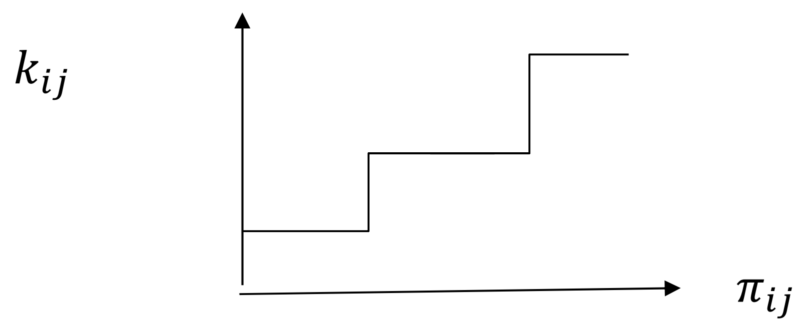
[3] Chin Yen Tee; Ilic, M., "Optimal investment decisions in transmission expansion," *North American Power Symposium (NAPS), 2012* , vol., no., pp.1,6, 9-11 Sept. 2012

Merchant Transmission Example – ISO Clearing

- Extending TSP/ISO problem given in [1]:

$$\max_{\boldsymbol{\mu}^{t,y},\boldsymbol{K}_l} \sum_{i=1}^{n} \left\{ \frac{1}{2} \boldsymbol{\mu}^{t,y\,\prime} \boldsymbol{A}_i \boldsymbol{Q}_i \boldsymbol{\mu}^{t,y} + \boldsymbol{\mu}^{t,y\,\prime} \boldsymbol{A}_i \boldsymbol{h}_i \right\} - \boldsymbol{\mu}^{t,y} \boldsymbol{K}_l$$

$$subject\ to: transmission\ supply\ function$$



- Transmission demand function included in objective function

Conclusion

- Testbeds and simulators are needed to guide future policy and institutional design for Smart Grids
- Different institutional frameworks lead to different model design question and information exchange
- SGIRS allow us to compare different institutional framework and market rules

Future work:

- Mathematically define the private objective and information exchange for the different stakeholders.
- Test out different institutional design and market rules on SGIRS and evaluate the incentives for flexibility