Investment in Infrastructure in Electricity Markets

Examining the effect on social welfare

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Outline

- Assumptions / Simplifications
- Market Models
- Counter-Intuitive Examples
- Conclusions

Assumptions / Simplifications

Generation & Demand / Transmission Grid

Generators The electricity markets consist of a number of generators located at different locations.

We will assume that there exists a generator at each node, who injects a quantity of electricity. Each has the following properties:

- Capacity: Maximum injection quantity.
- Marginal Cost: Marginal cost of electricity based on the fuel costs.

Demand At each node there is a linear demand curve:

$$p_i = a_i - b_i\, y_i$$

We approximate the grid using a DC power flow model, consisting of nodes and lines.

Nodes Each generator is located at a GIP and each source of demand is located at a GXP; these are combined into nodes.

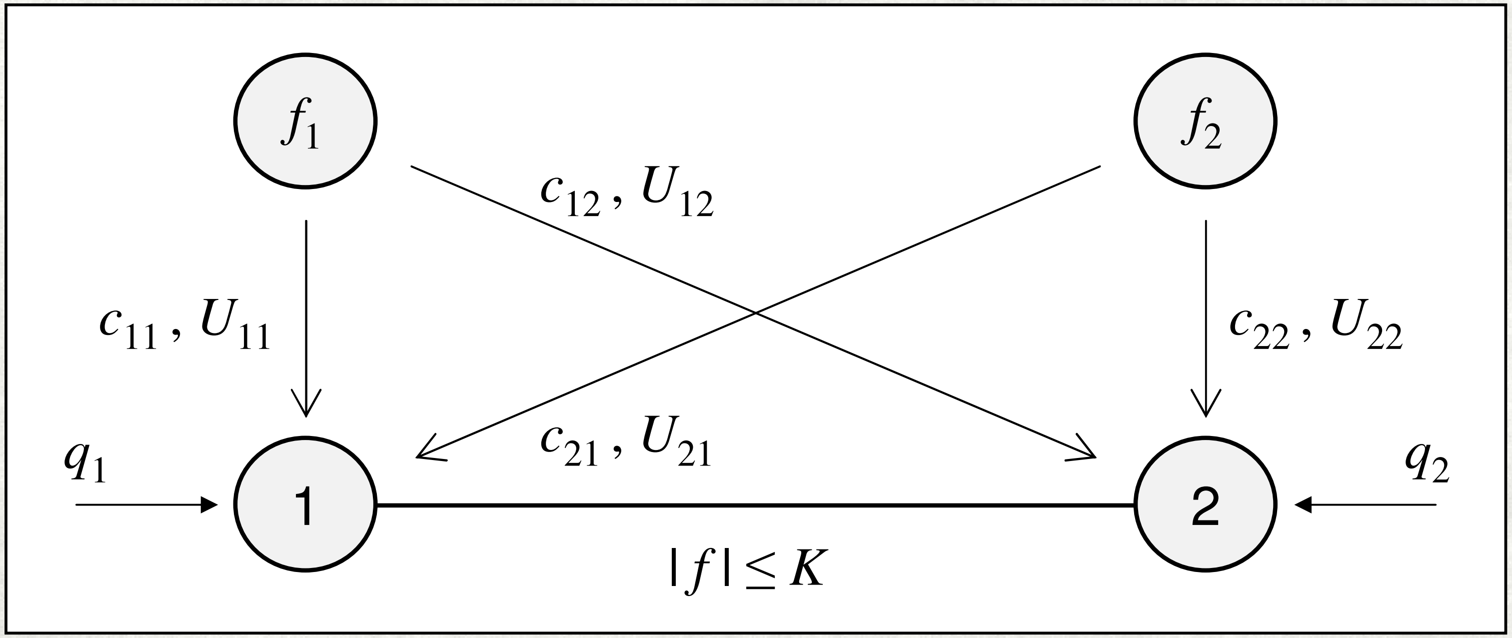
Lines The lines connect the nodes and have the following properties:

- Capacity: Maximum allowable flow.
- Reactance: Affects the flow around loops.

Fuel Network

Fuel Suppliers Fuel is supplied by a number of suppliers. Each supplier is able to send fuel to a number of generators. There can also be a capacity on the total fuel supply of a supplier.

Fuel Network Fuel is sent from suppliers to generators via a transportation network, each line in the network has a cost and capacity.

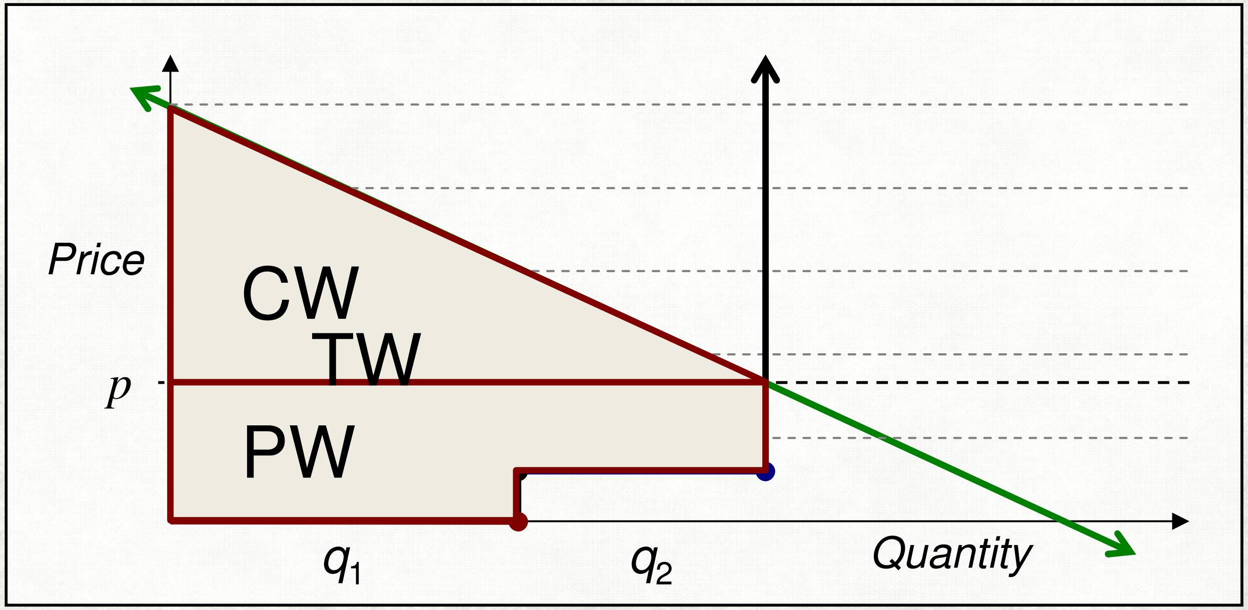


Aggregating Offers

Suppose that there are two strategic generators at a node,

- there is demand curve with slope –0.5 and intercept 1,
- the generators offer a quantities, q_1 and q_2,
- the price at the node is p.

We get the following dispatch:



Pricing & Dispatch – Radial Network

Simplified Dispatch Model

- f_{ij} is the MW sent directly from node *i* to node *j*.
- q_i is the MW of electricity injected by the generator *i*.
- y_i is the demand served at node *i*.
- a_i is the intercept of the demand curve at node *i*.
- b_i is the slope of the demand curve at node *i*.
- K_{ij} is the capacity of line *ij*.

$$\max \quad \sum_{i\in N}\left(a_i y_i - \tfrac{1}{2} b_i y_i^{\,2}\right) - \sum_{i\in N} C_i(q_i)$$

$$s.t. \quad q_i - \sum_{j,ij\in L} f_{ij} + \sum_{j,ji\in L} f_{ji} = y_i \qquad \forall i\in N \quad \text{(Energy Balance)}$$

$$\left|f_{ij}\right| \le K_{ij} \qquad \forall ij\in L \quad \text{(Line Capacities)}$$

Definitions

Players

The players in the game are the generators, the ISO and the fuel dispatcher. Each player has a decision which affects the payoffs of the game.

Players	**Decision**	**Payoff**
Generators	Electricity Injected	Profit
ISO	Prices / Price Premia	Total Welfare
Fuel Dispatch	Marginal Cost of Fuel	–Total Fuel Cost

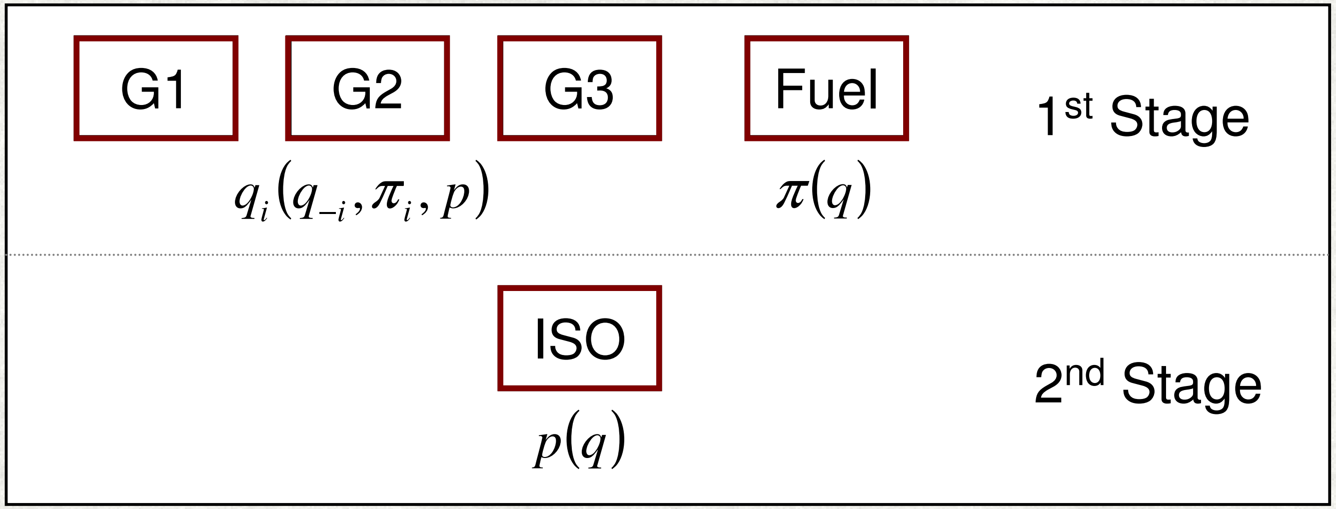
Nash Equilibrium

A Nash equilibrium is a point in a game's decision space where no player can improve their payoff by altering their decision.

Market Models

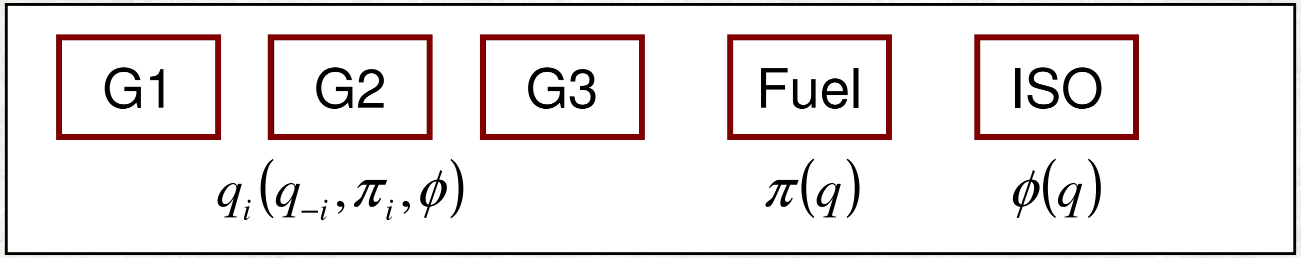
Rationality of Players

Full Rationality



This is arguably the more realistic model, however a pure strategy Nash equilibrium is not guaranteed to exist, this makes this model difficult to analyse.

Partial Rationality

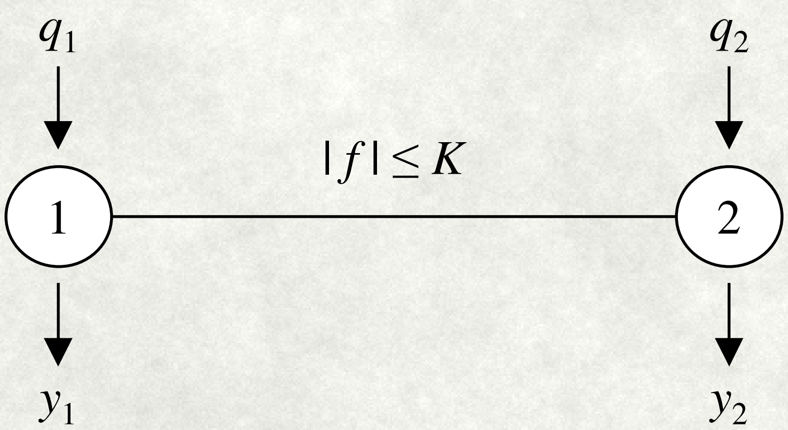


A pure strategy Nash equilibrium is guaranteed to exist in this game, however, the generators will not take advantage of potential congestion in the network.

Comparing Rationality Models

In the context of a symmetric two node, one line example we can see how these two models can give different results.

If the size of the line is very large, then both models will give a duopoly solution, however if the line had capacity 0, then the full rationality model would now give a monopolist outcome, whereas the partial rationality model would still give the duopoly solution.



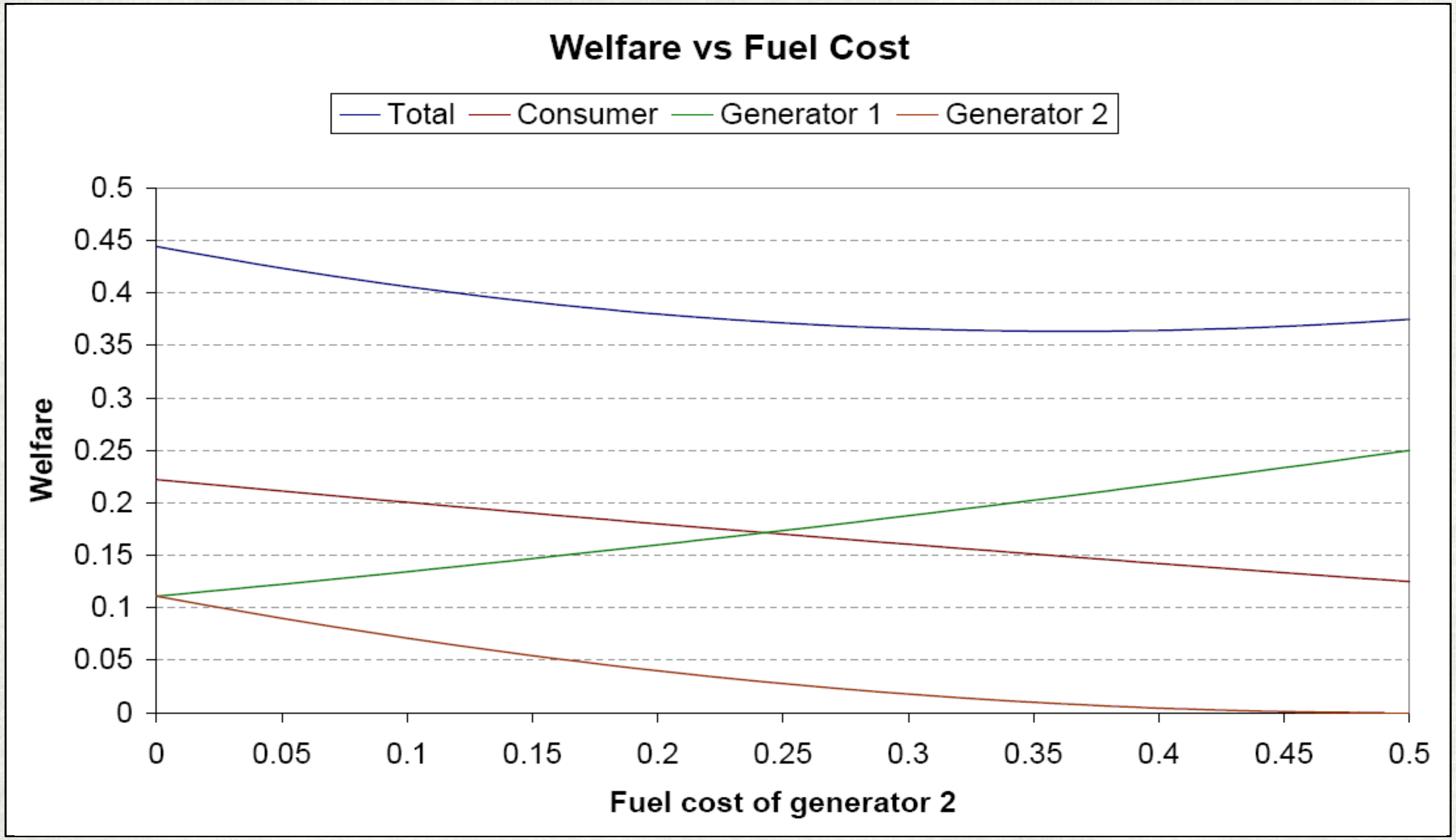
	Full Rationality	**Partial Rationality**
$K = 0$	Local Monopolies	Duopoly
$K = \infty$	Duopoly	Duopoly

Yao, Oren, Adler

Single Node Equilibrium

Effect of increasing the cost of an expensive generator

In the context of a single node, it is possible to get some counter-intuitive results we dealing with fuel costs of generators.

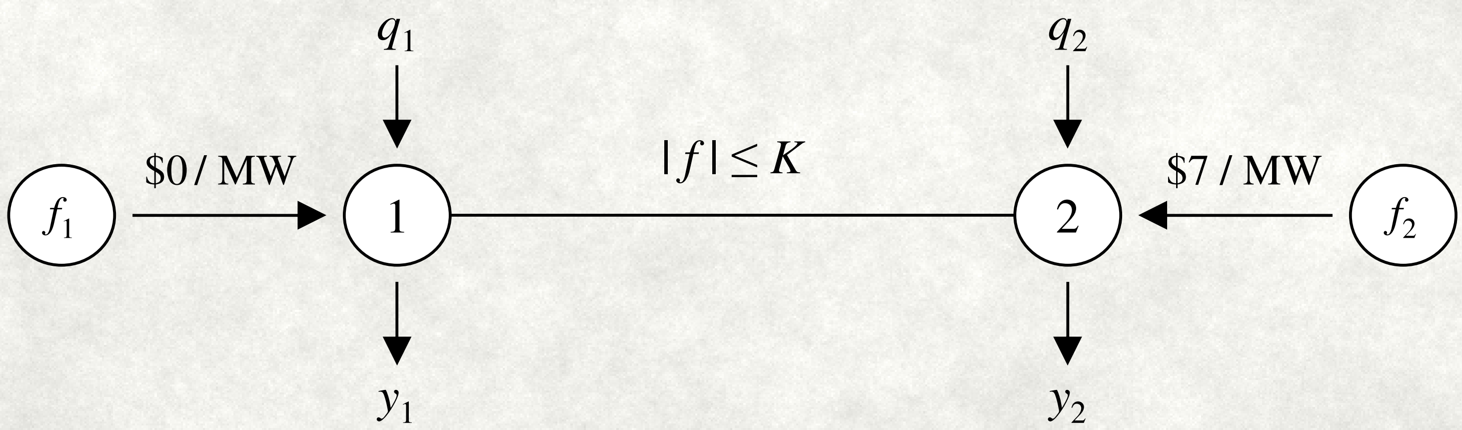


Transmission Line Capacity

Effect of increasing the capacity of transmission line

The result from the single node example can easily be reproduced in a multi-node setting. In this setting, however, it is also possible to get counter-intuitive results when expanding the size of transmission lines.

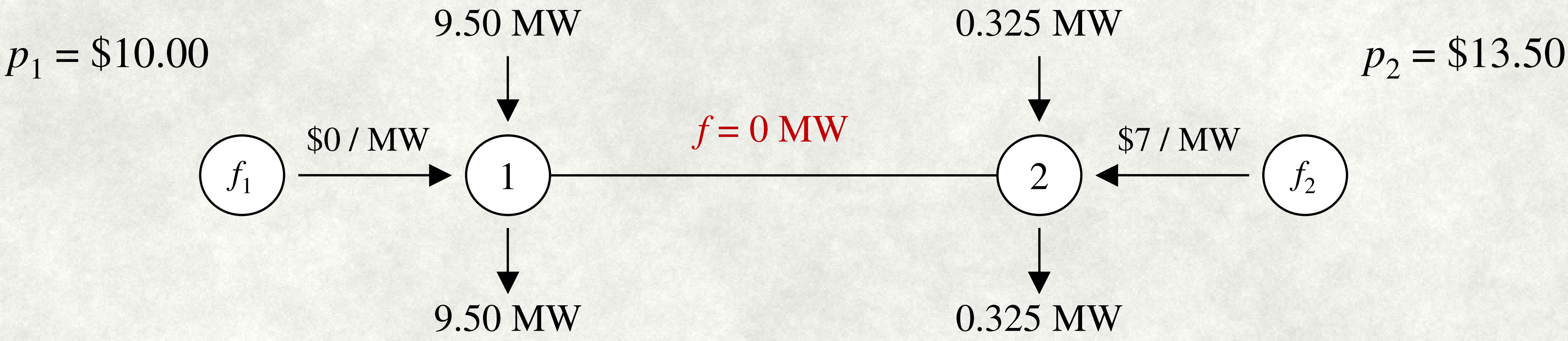
Demand curves: $p_1 = 20 - {}^{20}/_{19}\, y_1$ and $p_2 = 20 - 20\, y_2$



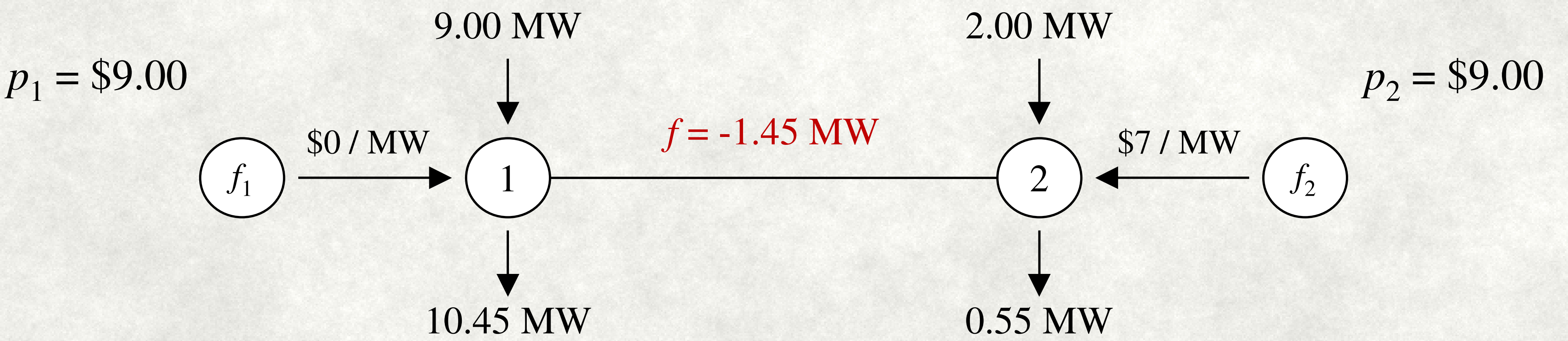
Examples

Transmission Line Capacity

Zero Line Capacity



Infinite Line Capacity



Examples

Transmission Line Capacity

Welfare Comparisons

When we compare the total welfare for the different costs for the two models, we get similar results.

Full Rationality	$K = 0$	$K = \infty$	
Total Welfare	145.67	145.50	← Higher capacity has lower welfare
Producer Welfare	97.11	85.00	← Producer welfare decreases
Consumer Welfare	48.56	60.50	← Consumer welfare increases
Congestion Rents	0.00	0.00	← No congestion rents

Partial Rationality	$K = 0$	$K = \infty$	
Total Welfare	149.12	145.50	← Higher capacity has lower welfare
Producer Welfare	95.32	85.00	← Producer welfare decreases
Consumer Welfare	53.80	60.50	← Consumer welfare increases
Congestion Rents	0.00	0.00	← No congestion rents

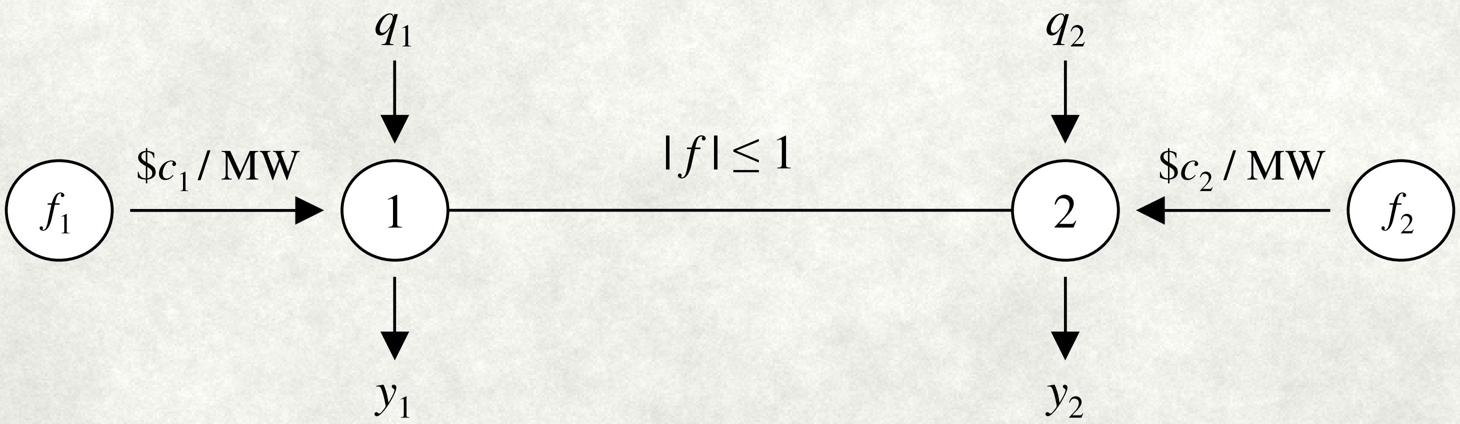
Decreasing Fuel Costs – Two Nodes

Effect of decreasing the cost of fuel

When we are dealing with a multi-node situation with transmission capacities, we need to be careful about the assumptions we make.

If we assume partial rationality, we can get very different results than the full rationality situation.

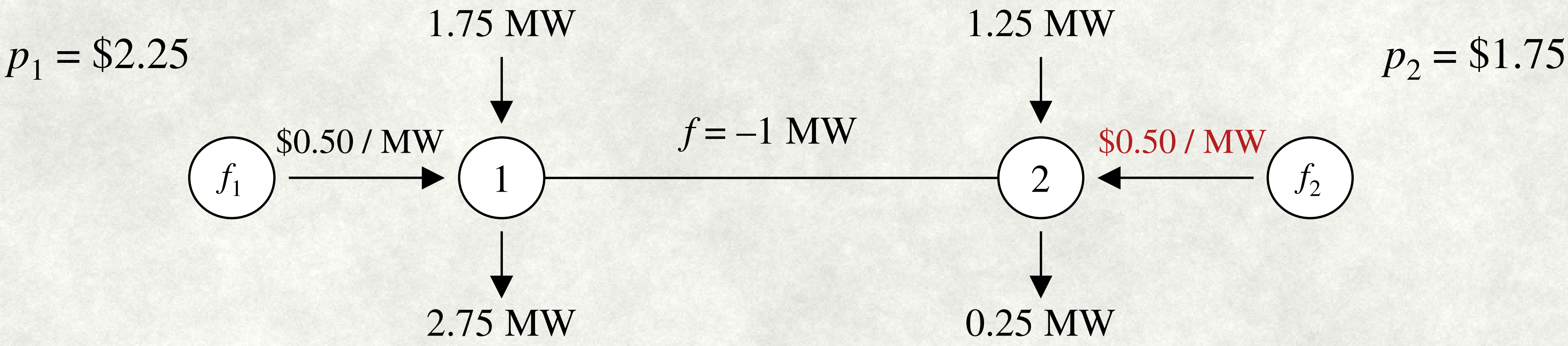
Demand curves: $p_1 = 5 - y_1$ and $p_2 = 2 - y_2$



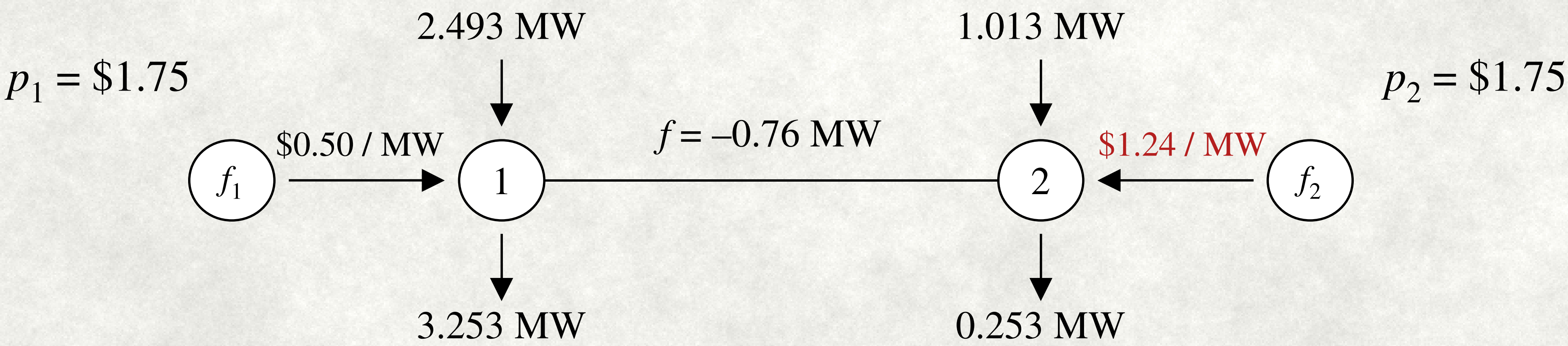
Examples

Decreasing Fuel Costs – Two Nodes

Low Fuel Costs



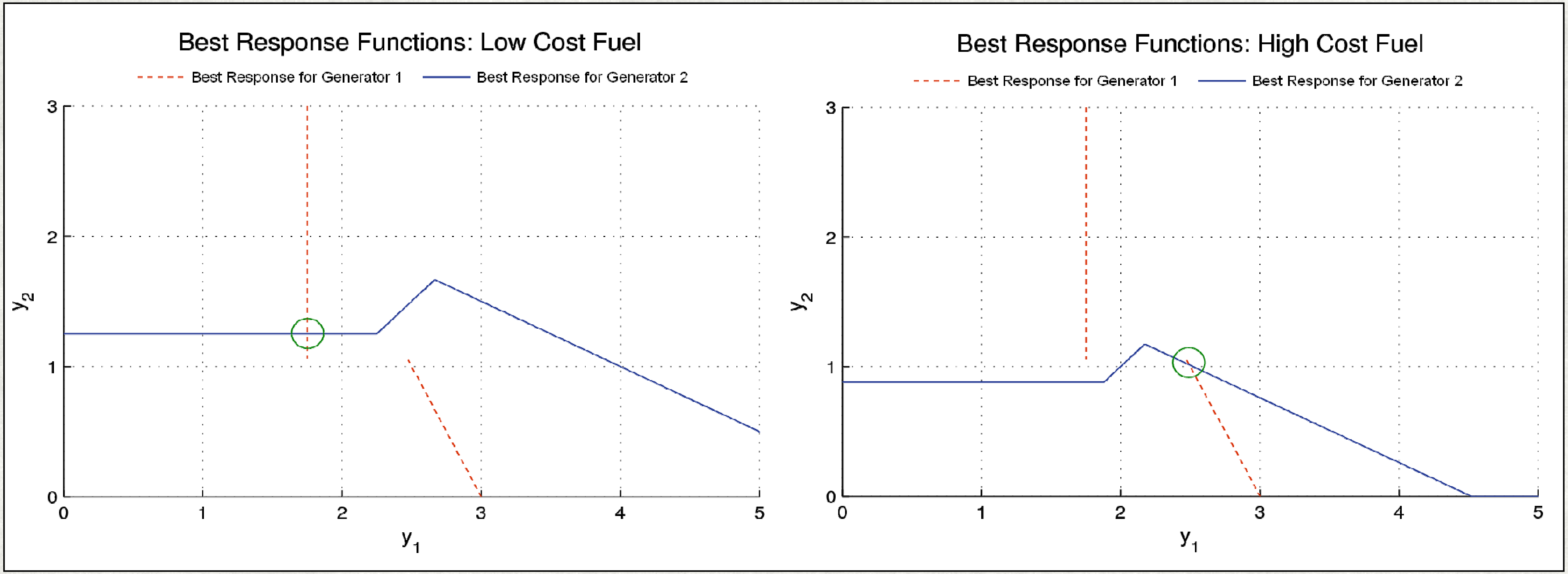
High Fuel Costs



Decreasing Fuel Costs – Two Nodes

Best Response Curves

The plots below show the best response functions for each player, under the full rationality assumption. The Nash Equilibrium is shown in the green circle.



Decreasing Fuel Costs – Two Nodes

Welfare Comparisons

When we compare the total welfare for the different costs for the two models, we get different results.

Full Rationality	$c_2 = 0.50$	$c_2 = 1.24$	
Total Welfare	8.937	8.946	← Higher cost has higher welfare
Producer Welfare	4.625	3.622	← Producer welfare decreases
Consumer Welfare	3.812	5.324	← Consumer welfare increases
Congestion Rents	0.500	0.000	← Congestion is relieved

Partial Rationality	$c_2 = 0.50$	$c_2 = 1.24$	
Total Welfare	10.222	8.946	← Higher cost has lower welfare
Producer Welfare	4.111	3.622	← Producer welfare decreases
Consumer Welfare	5.778	5.324	← Consumer welfare decreases
Congestion Rents	0.333	0.000	← Congestion is relieved

Conclusions

We have developed a model which, for any network structure, can find a Cournot equilibrium in a partial rationality framework. This model was formulated in GAMS and solved using PATH.

This model has weaknesses, especially when dealing with a congested transmission network.

We found that one must be cautious when expanding transmission and fuel network capacities as it may in fact have a negative impact on total welfare, without even taking into account the cost of the investment.

Thank You

Any Questions?