ASSESSMENT OF TRANSMISSION CONGESTION IMPACTS ON ELECTRICITY MARKETS

presentation by

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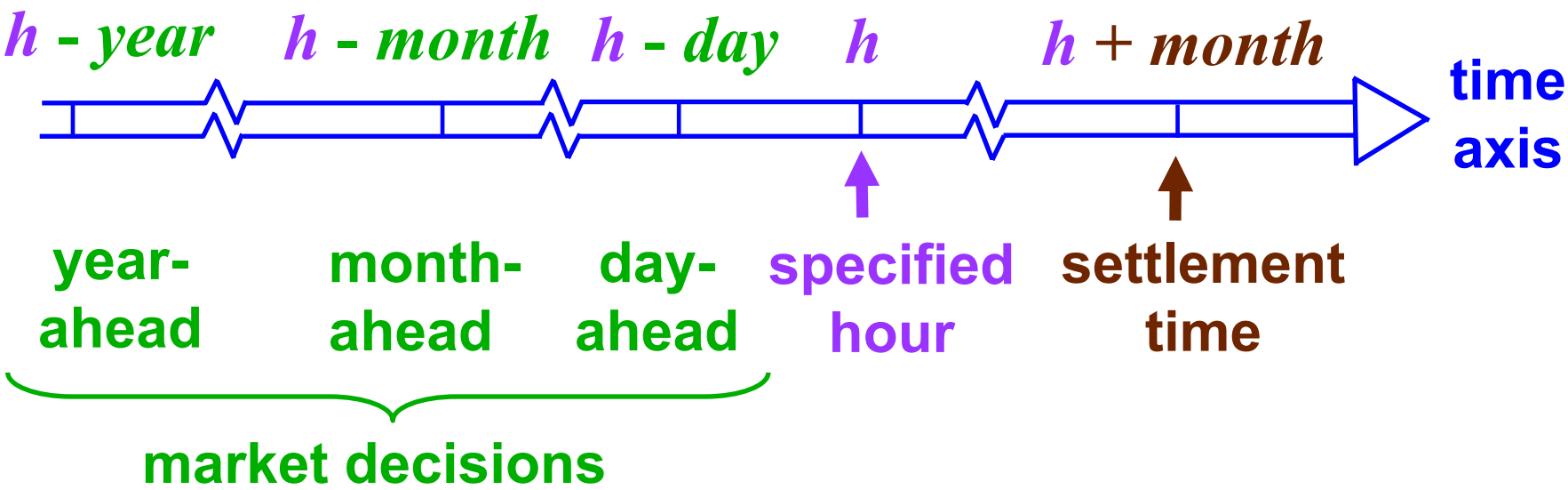
OUTLINE

- Transmission-unconstrained markets
- Transmission-constrained markets
- Market performance metrics
- Measures of congestion impacts
- Congestion and local market power
- Congestion impact evaluation examples in various systems

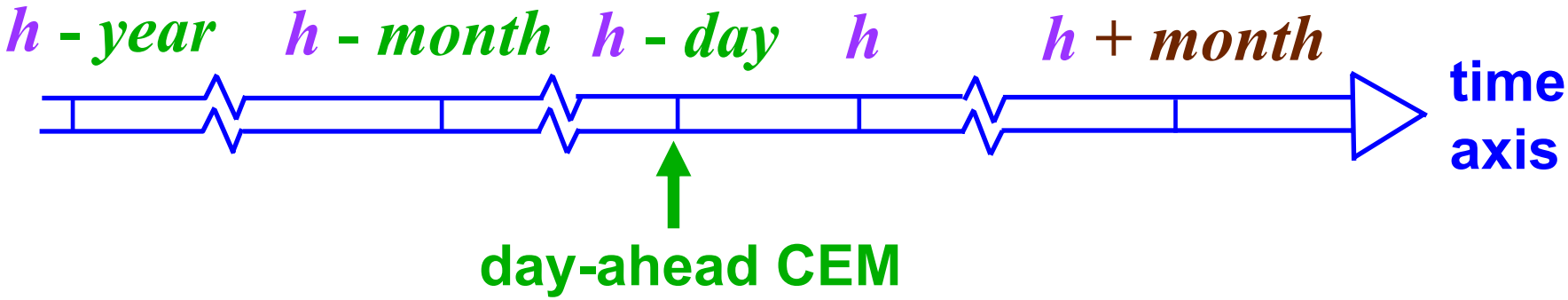
THE TIME FRAME FOR MARKETS

- We define one hour as the smallest indecomposable unit of time and focus on a specified hour *h*
- We discuss the market decisions for that specified hour

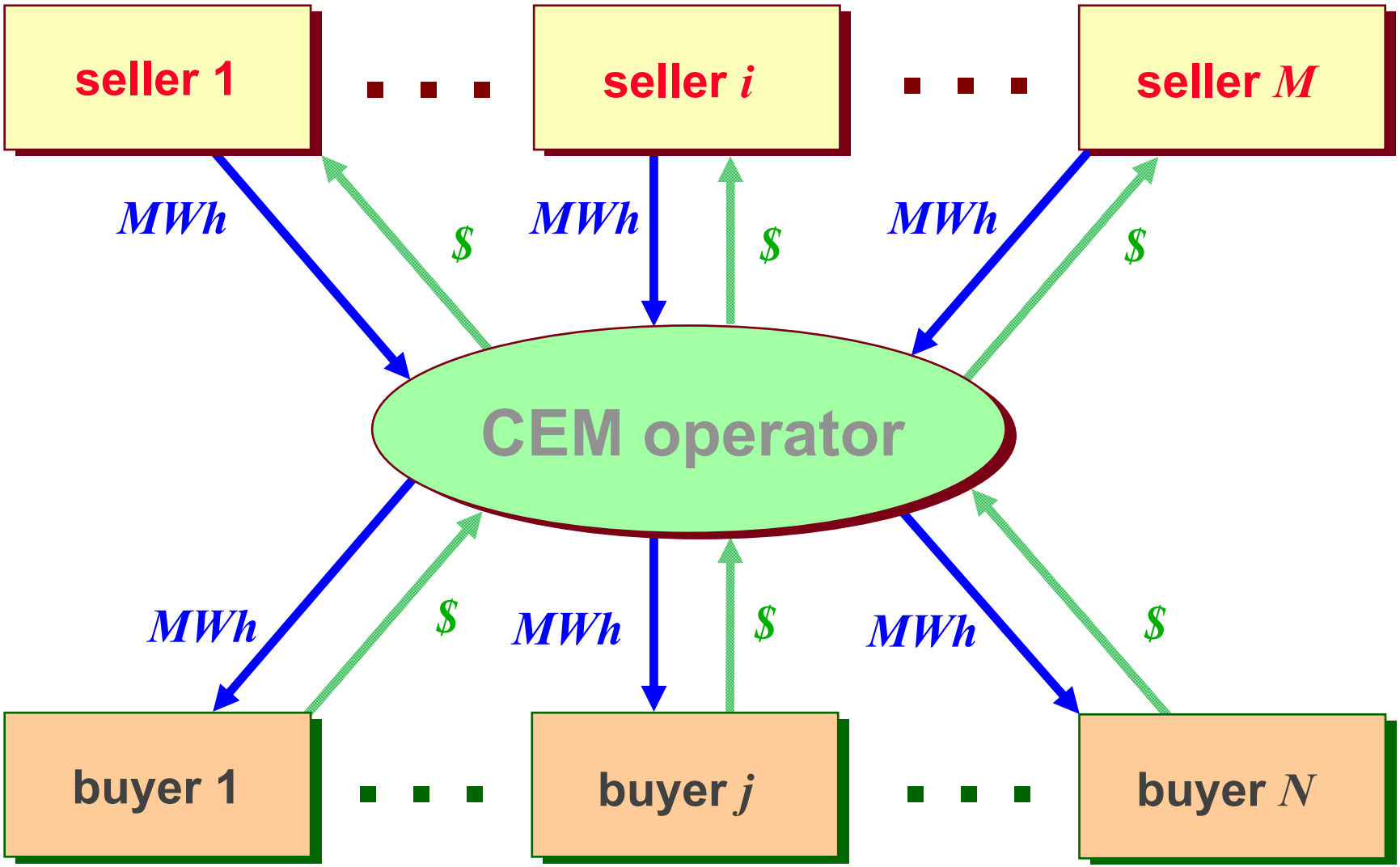


THE CENTRALIZED ELECTRICITY MARKET (CEM)

- We discuss the structure of the forward market by examining the day-ahead centralized electricity market
- In fact, the day-ahead market is a collection of 24 separate commodity markets, one for each hour of the day; we focus on the market corresponding to the specified hour h and suppress the hour h in our notation



CEM STRUCTURE



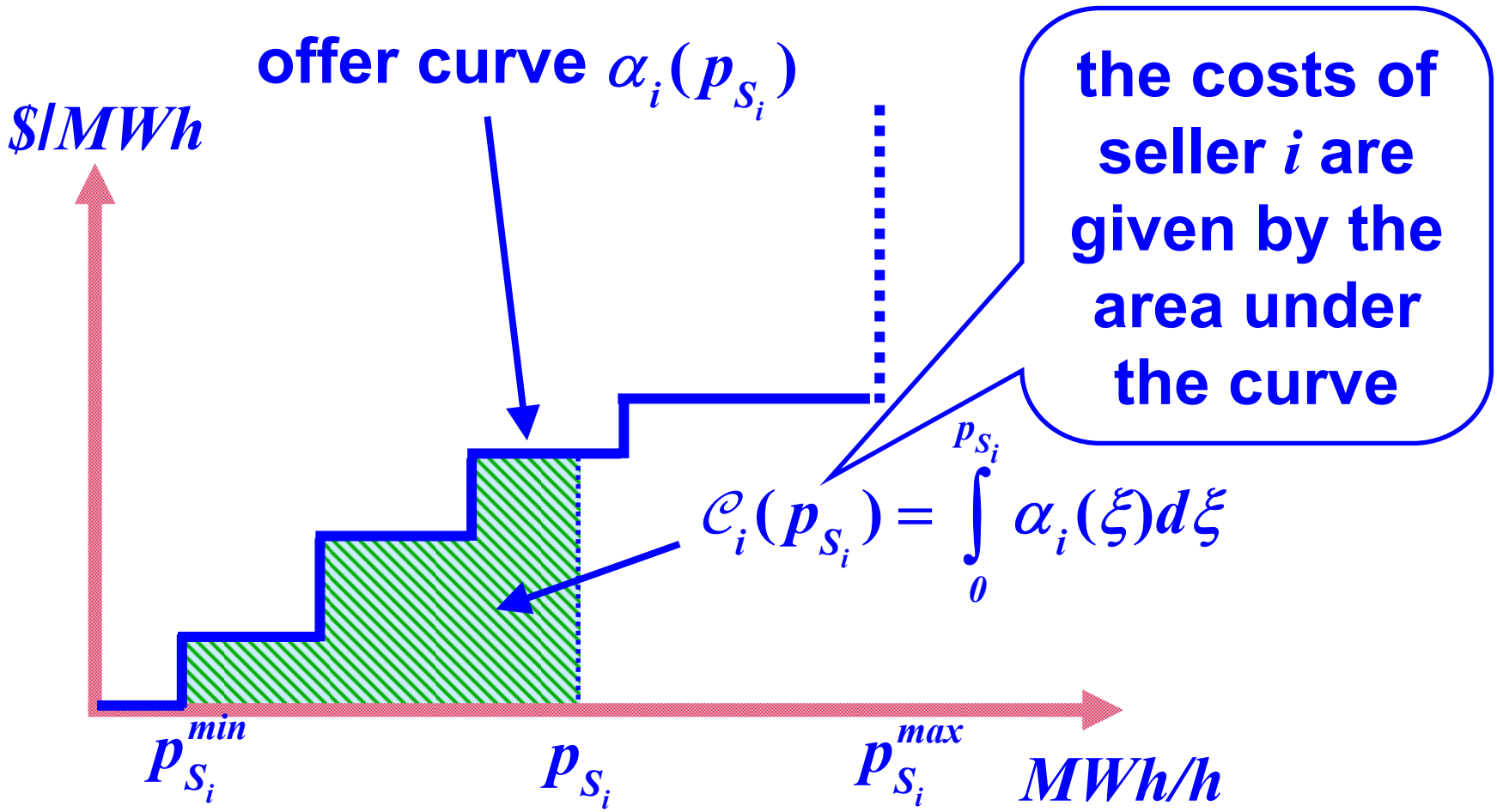
CEM PARTICIPANTS

- The CEM *operator* is in charge of this market and uses auctions to determine the prices and quantities bought and sold for each hour
- Sellers are generation entities and brokers/ marketers
- Buyers are consumers, brokers/marketers, distribution entities and generation entities

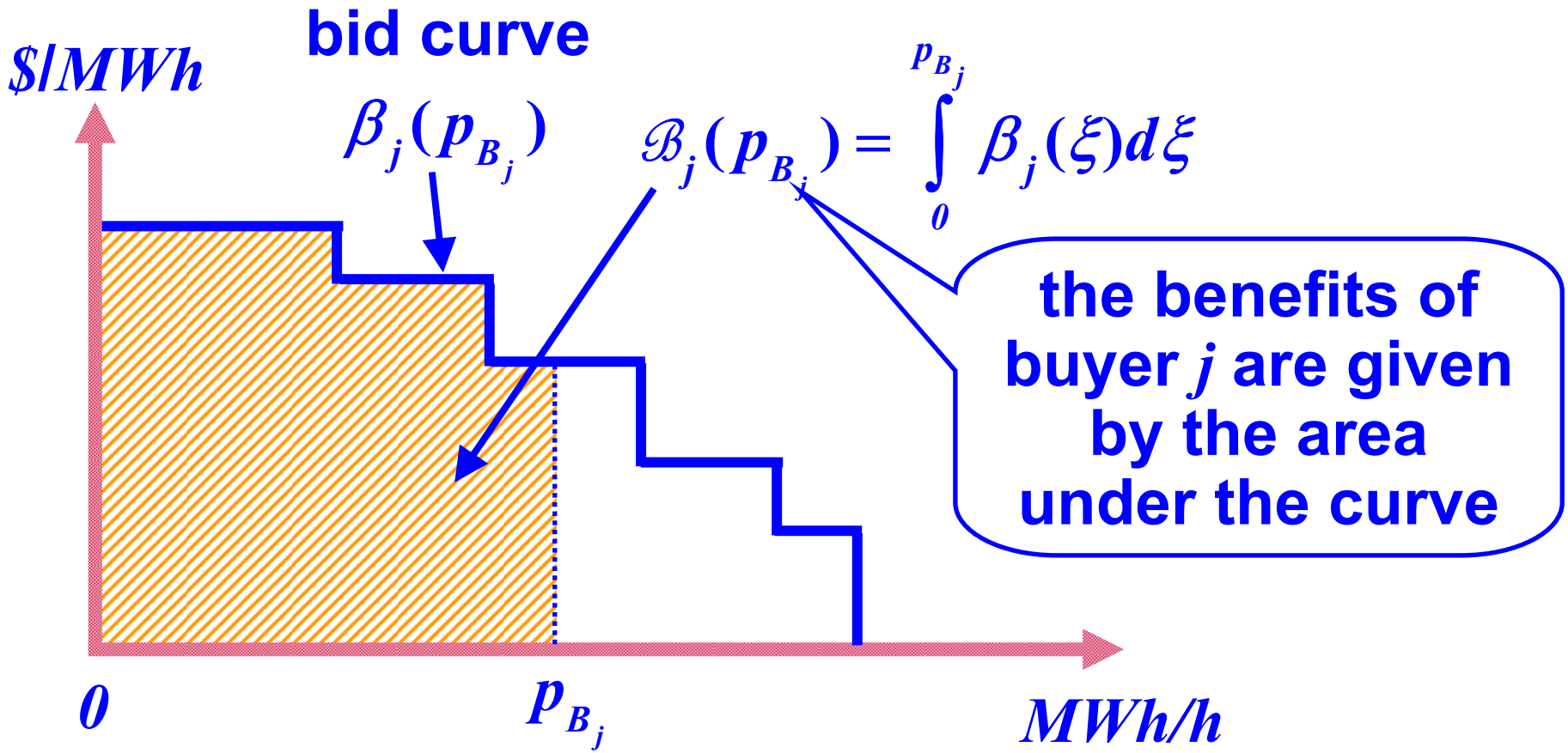
THE COMPETITIVE ELECTRICITY MARKET

- Sellers and buyers in the market submit sealed offers and bids, respectively, describing the price and quantity at which they are willing to sell/buy energy
- The CEM operator determines the successful offers and bids and the market clearing price by maximizing the social surplus
- The auction results determine the unit commitment and dispatch of the physical units

SELLER *i* OFFER AND COSTS

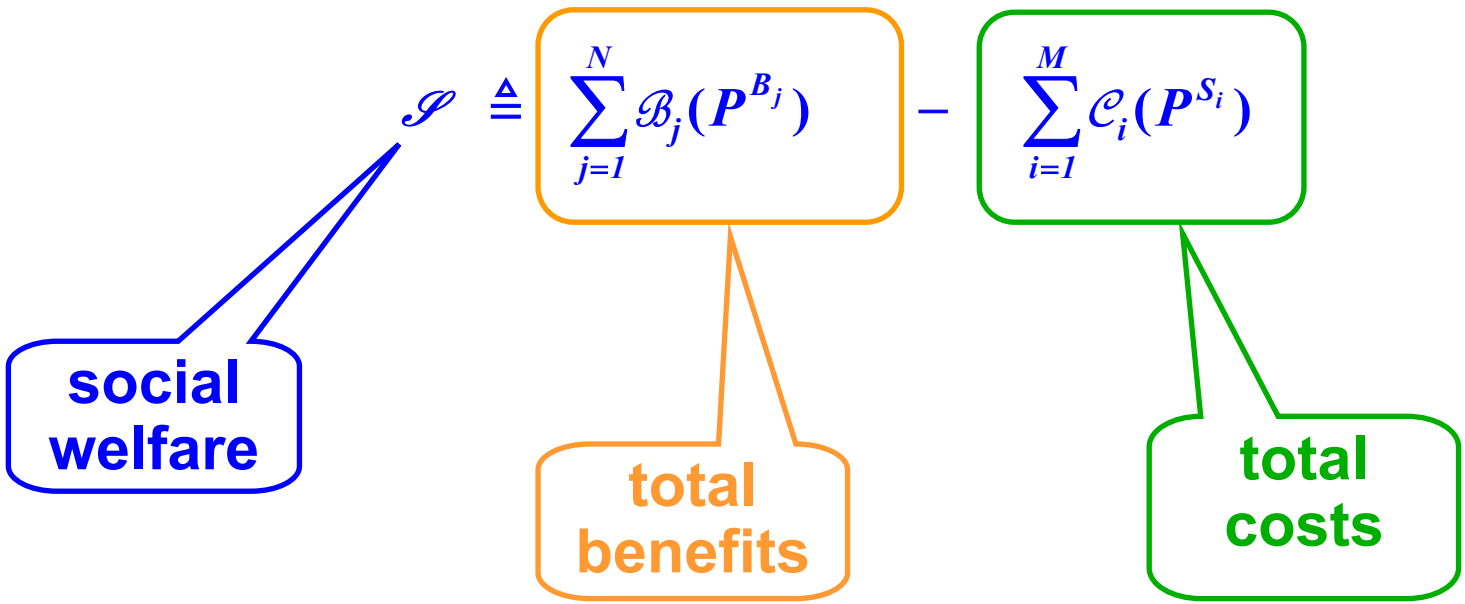


BUYER j BID AND BENEFITS



THE SOCIAL WELFARE

The social welfare is defined as the total benefits of the buyers minus the total costs of the sellers:



MAXIMIZATION OF THE SOCIAL WELFARE

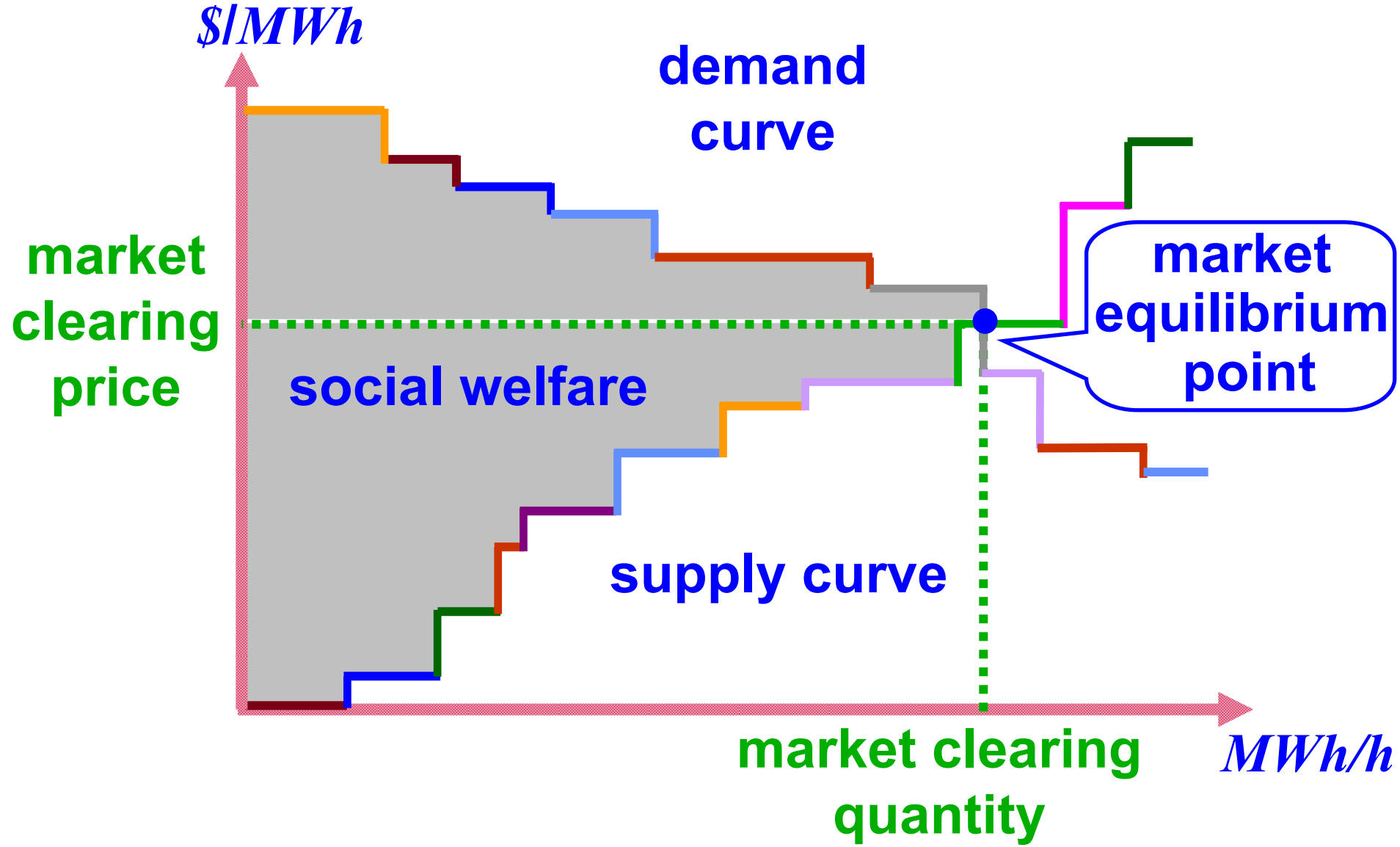
- The objective in markets is to maximize the social welfare, so as to determine the maximum net benefits for society
- We neglect the transmission network constraints
- The CEM *operator* solves the resulting optimization problem to determine the successful offers and bids

$$\max \quad \mathcal{S} = \sum_{j=1}^{N} \mathcal{B}_j(p_{B_j}) - \sum_{i=1}^{M} \mathcal{C}_i(p_{S_i})$$

$$s.t.$$

$$\sum_{j=1}^{N} p_{B_j} = \sum_{i=1}^{M} p_{S_i} \quad \text{supply-demand balance}$$

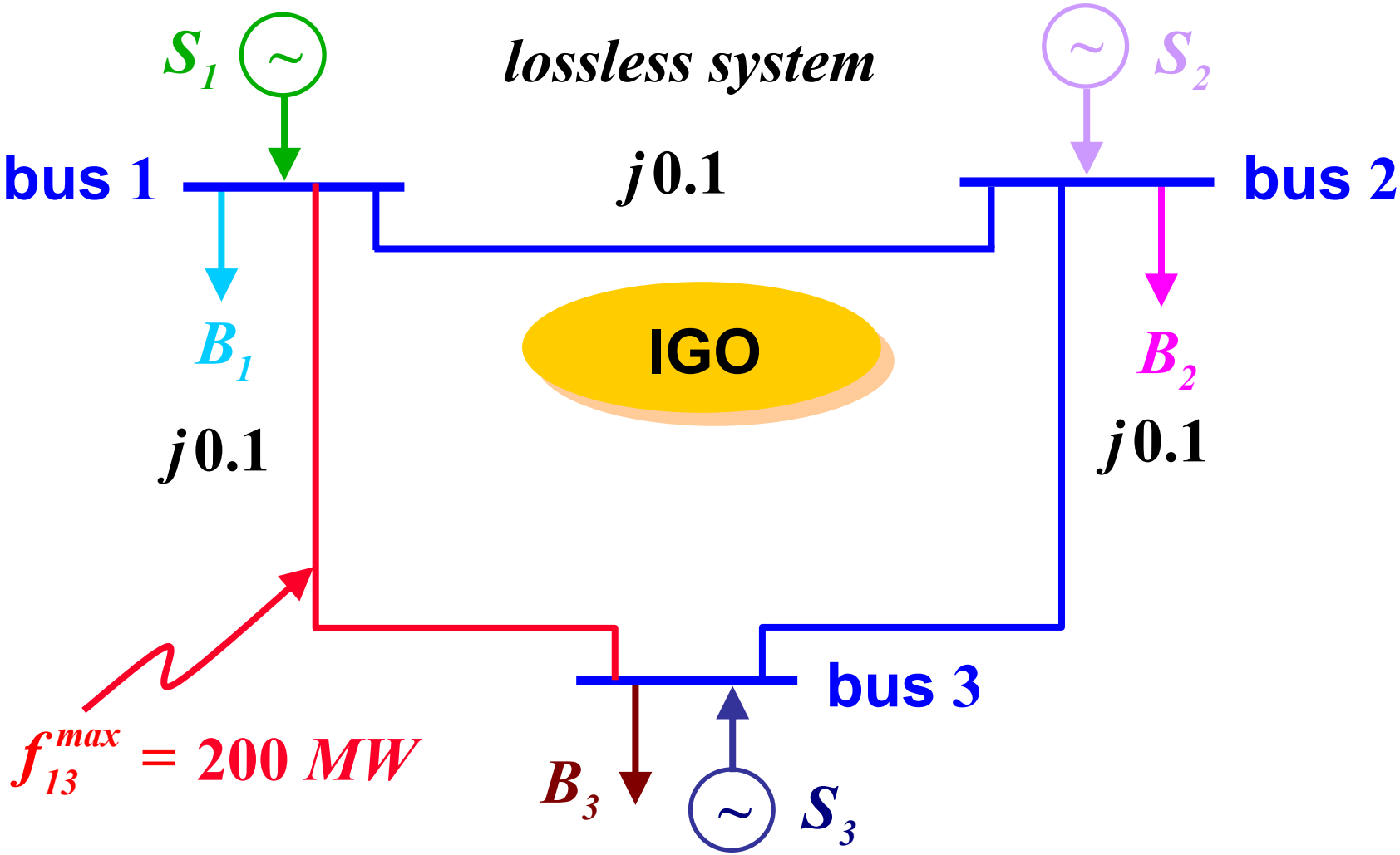
MAXIMIZATION OF THE SOCIAL WELFARE



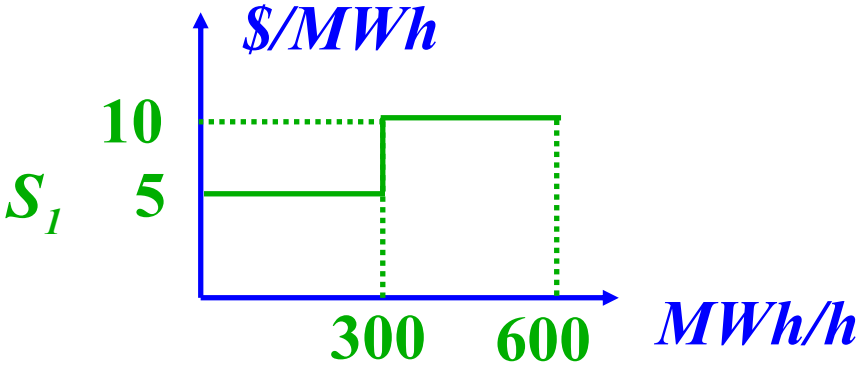
MARKET CLEARING PRICE

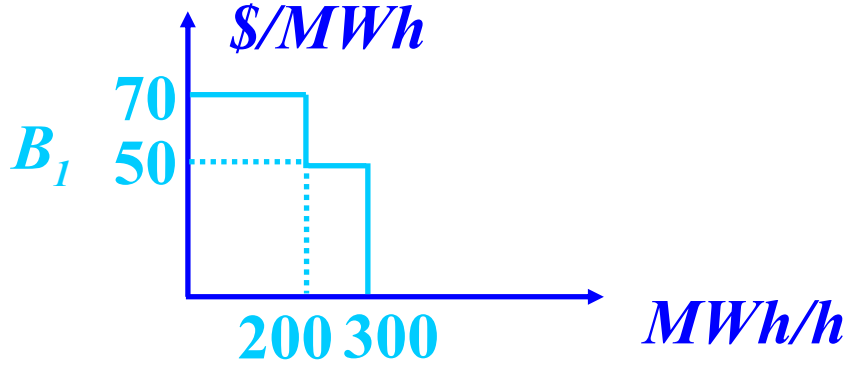
- The market clearing price ρ^* (system marginal price) is the change in the social welfare for a unit change in the market clearing quantity
- Each seller receives ρ^* from the CEM operator for each *MWh* sold
- Each buyer pays ρ^* to the CEM for each *MWh* bought
- The market clearing price is different from the offer/bid price of *nearly* every player

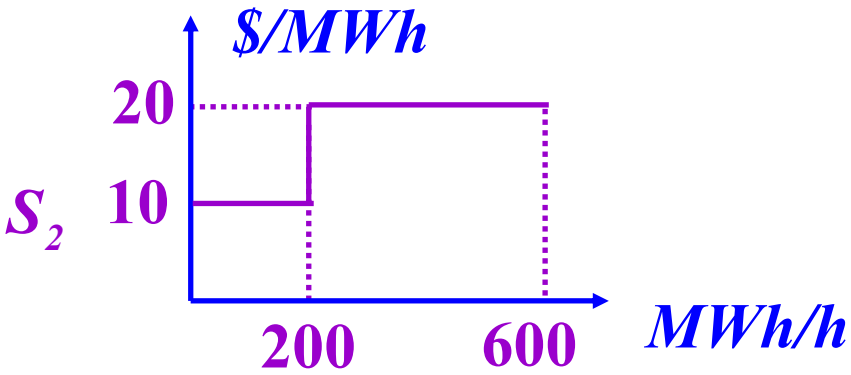
THE THREE-BUS SYSTEM EXAMPLE

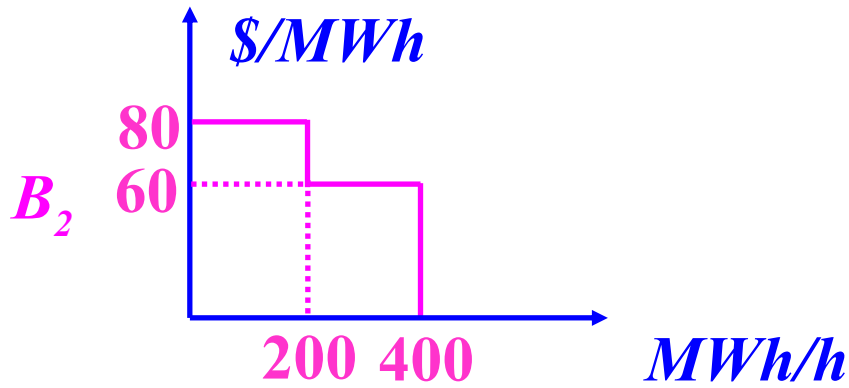


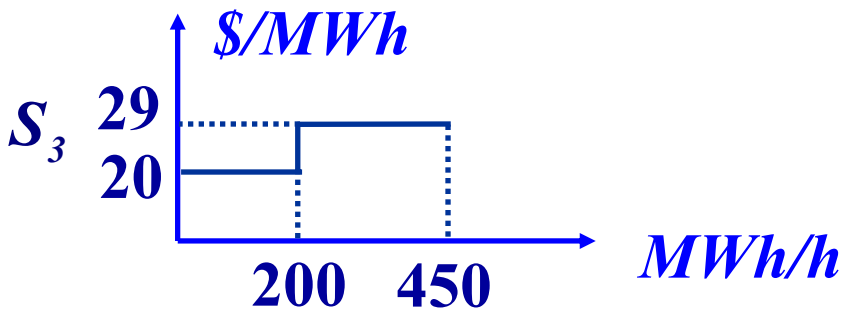
THREE-BUS SYSTEM: OFFERS AND BIDS

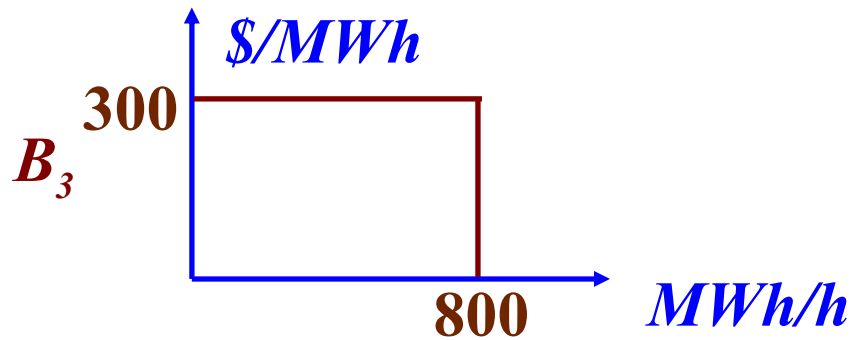




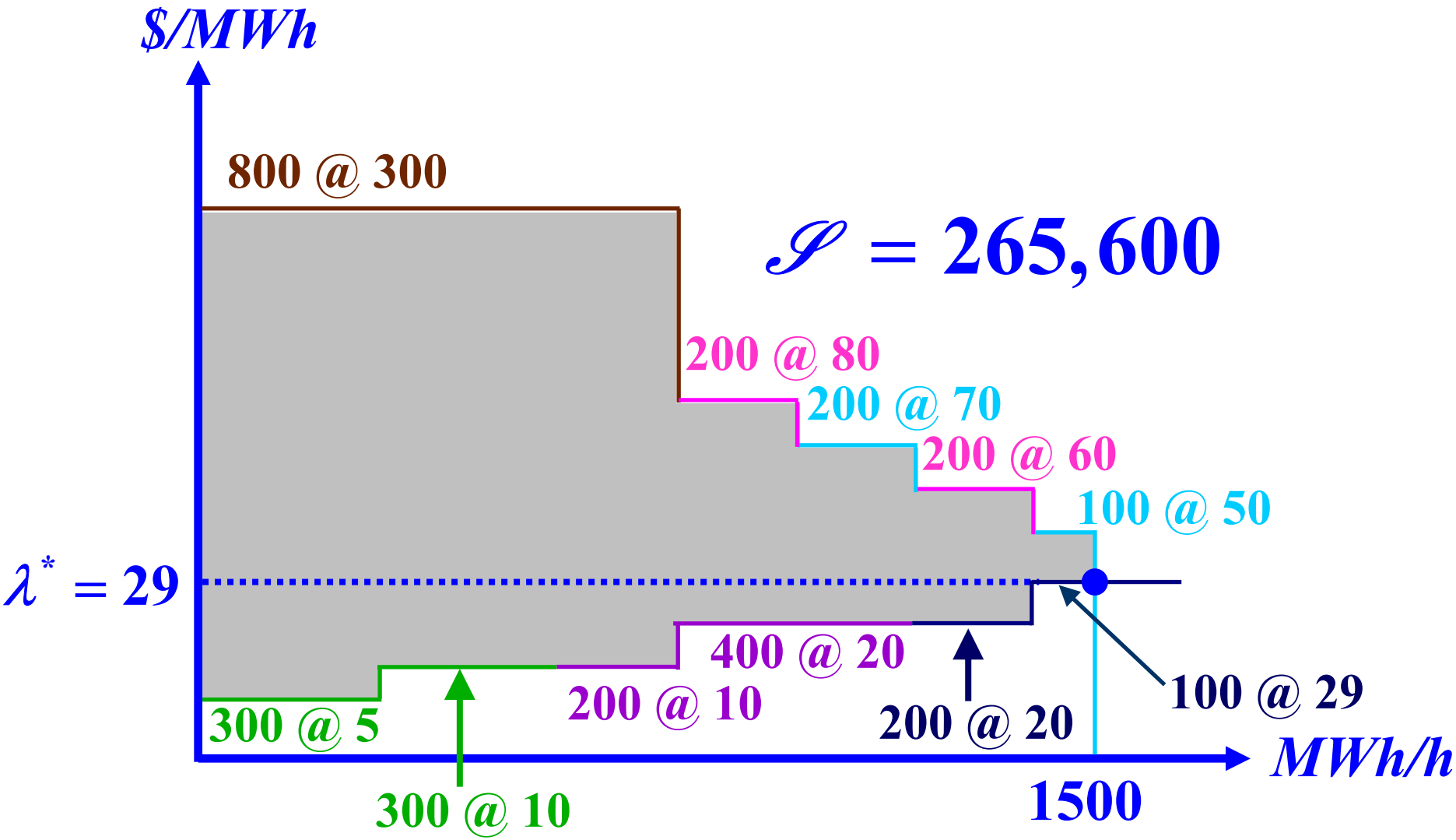








THREE-BUS SYSTEM: TRANSMISSION UNCONSTRAINED EQUILIBRIUM



UNCONSTRAINED SYSTEM REVENUES AND PAYMENTS

participant	quantity [*MWh*]	price [*$/MWh*]	revenue [*$*]	payments [*$*]
*S*1	600	29	17400	-
*S*2	600	29	17400	-
*S*3	300	29	8700	-
*B*1	300	29	-	8700
*B*2	400	29	-	11600
*B*3	800	29	-	23200
total	1500	29	43500	43500

MARKET PERFORMANCE BASIC MEASURES

- The social welfare is a measure of the performance of the market as a whole but it does not provide insights about the performance of the individual players
- We define two components of social welfare
  - producer surplus
  - consumer surplus

PRODUCER SURPLUS

- For a seller i, the *individual producer surplus* measures the difference between the revenues received for the sale at the *market clearing price* and those that would be received at the offer price

$$\mathcal{I}_i^S = \underbrace{\rho^* \cdot p_{S_i}}_{\text{revenues under } \rho^*} - \underbrace{\mathcal{C}_i(p_{S_i})}_{\text{revenues under offer}} \quad i = 1, \ldots, M$$

- The total *producer surplus* is

$$\mathcal{I}^S = \sum_{i=1}^{M} \mathcal{I}_i^S$$

CONSUMER SURPLUS

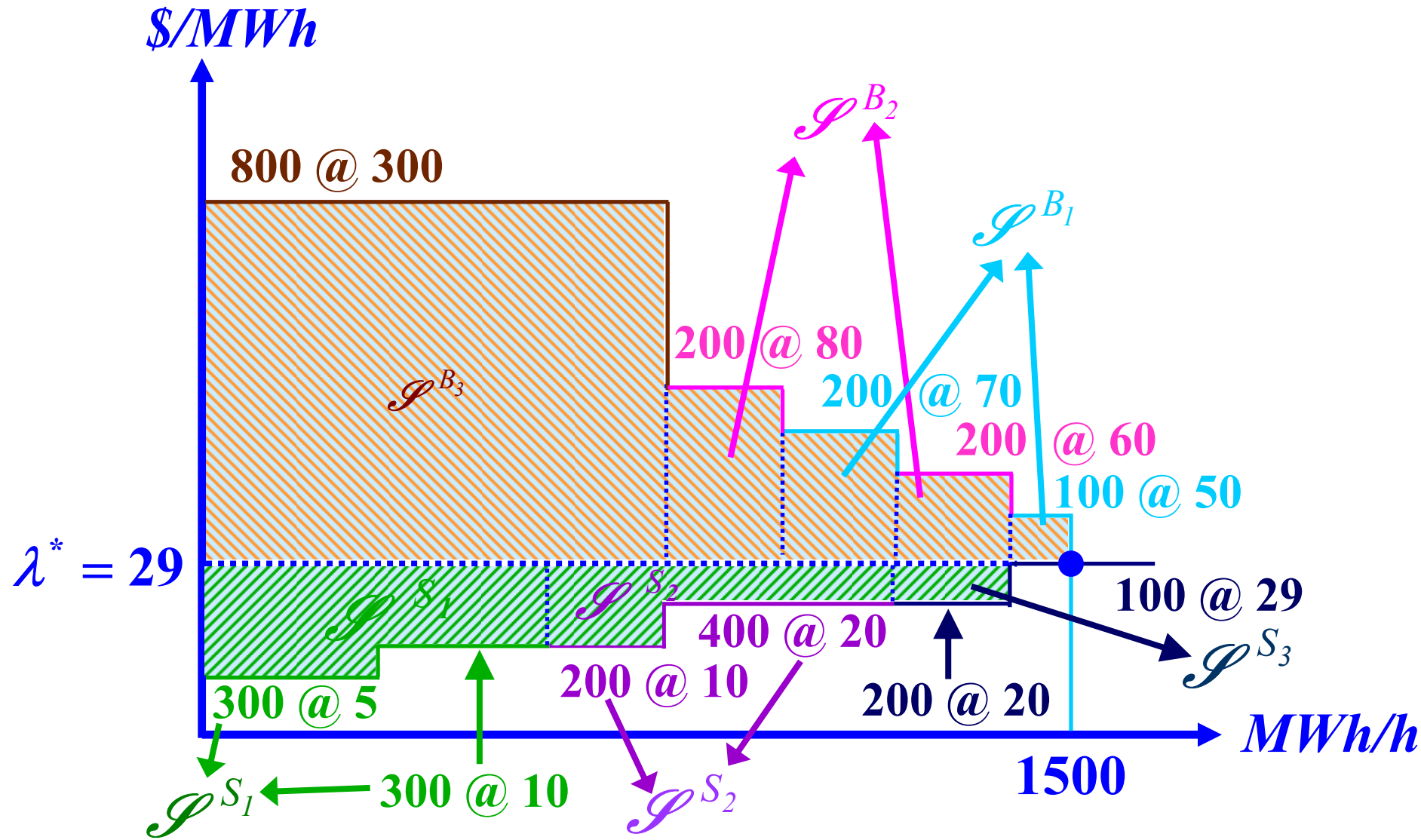
- For each buyer *j*, the ***individual consumer surplus*** measures the difference between the payments for the commodity at the bid prices of the buyer and those at the ***market clearing price***

$$\mathscr{S}_j^B = \underbrace{\mathscr{B}_j(p_{B_j})}_{\text{actual benefits}} - \underbrace{\rho^* \cdot p_{B_j}}_{\text{payments with } \rho^*} \qquad j = 1, \ldots, N$$

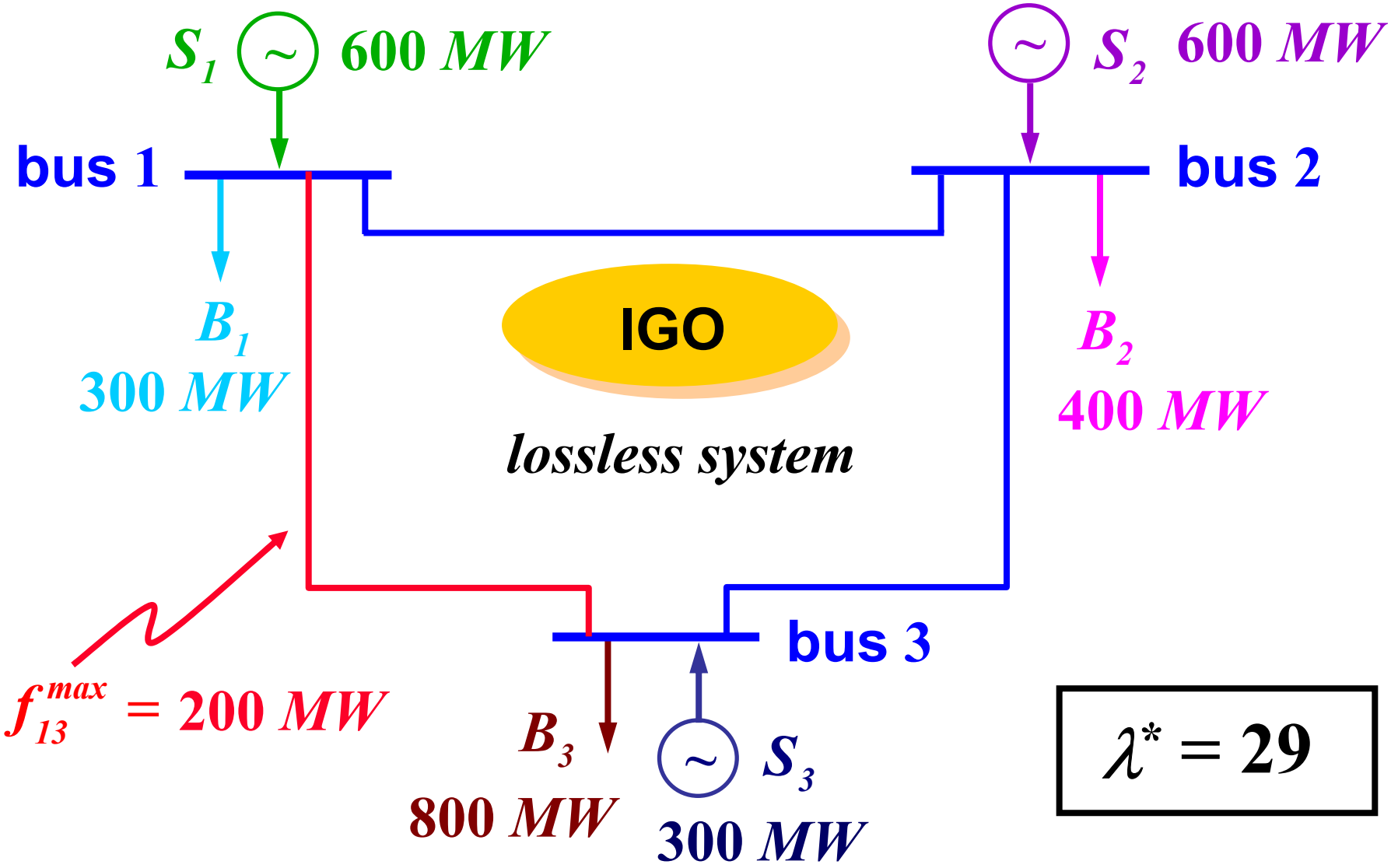
- The total ***consumer surplus*** is

$$\mathscr{S}^B = \sum_{j=1}^{N} \mathscr{S}_j^B$$

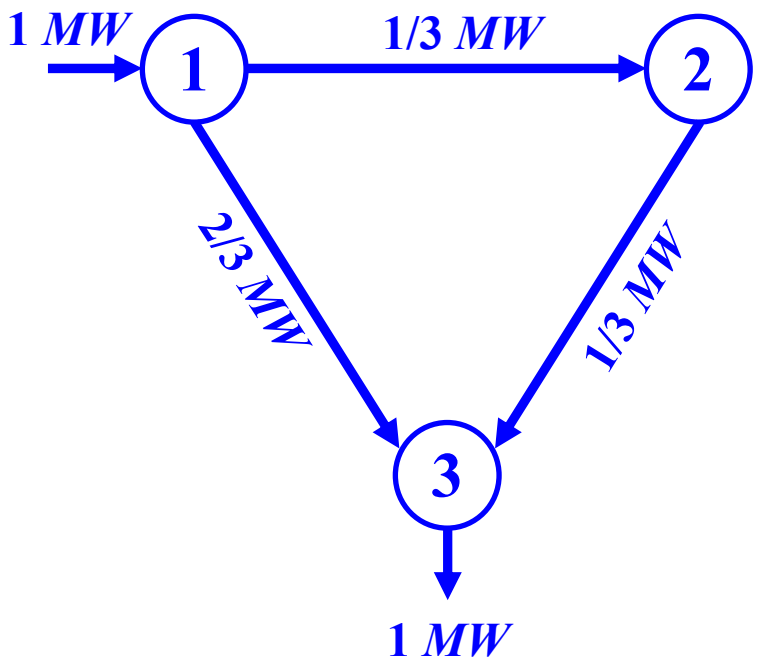
THREE-BUS SYSTEM: TRANSMISSION UNCONSTRAINED EQUILIBRIUM

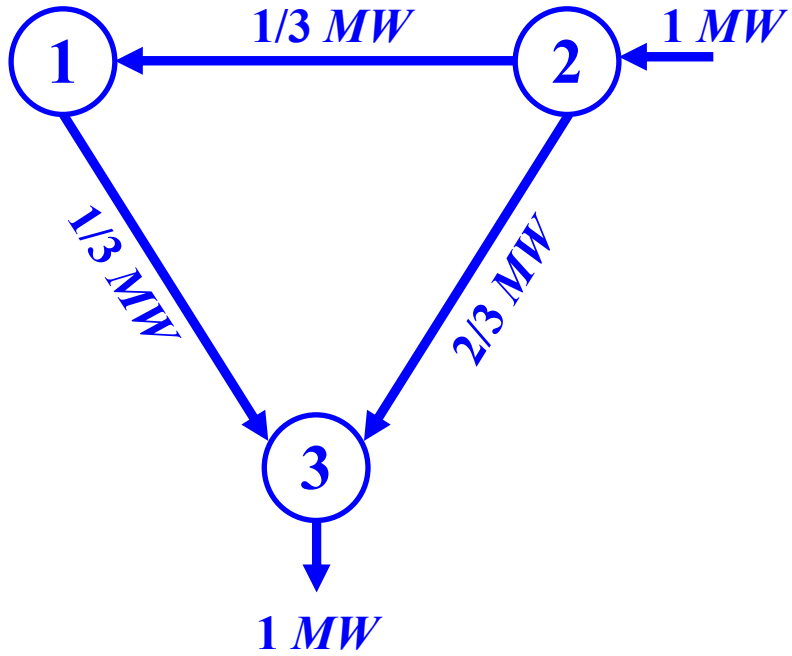


THREE-BUS SYSTEM: TRANSMISSION UNCONSTRAINED DISPATCH

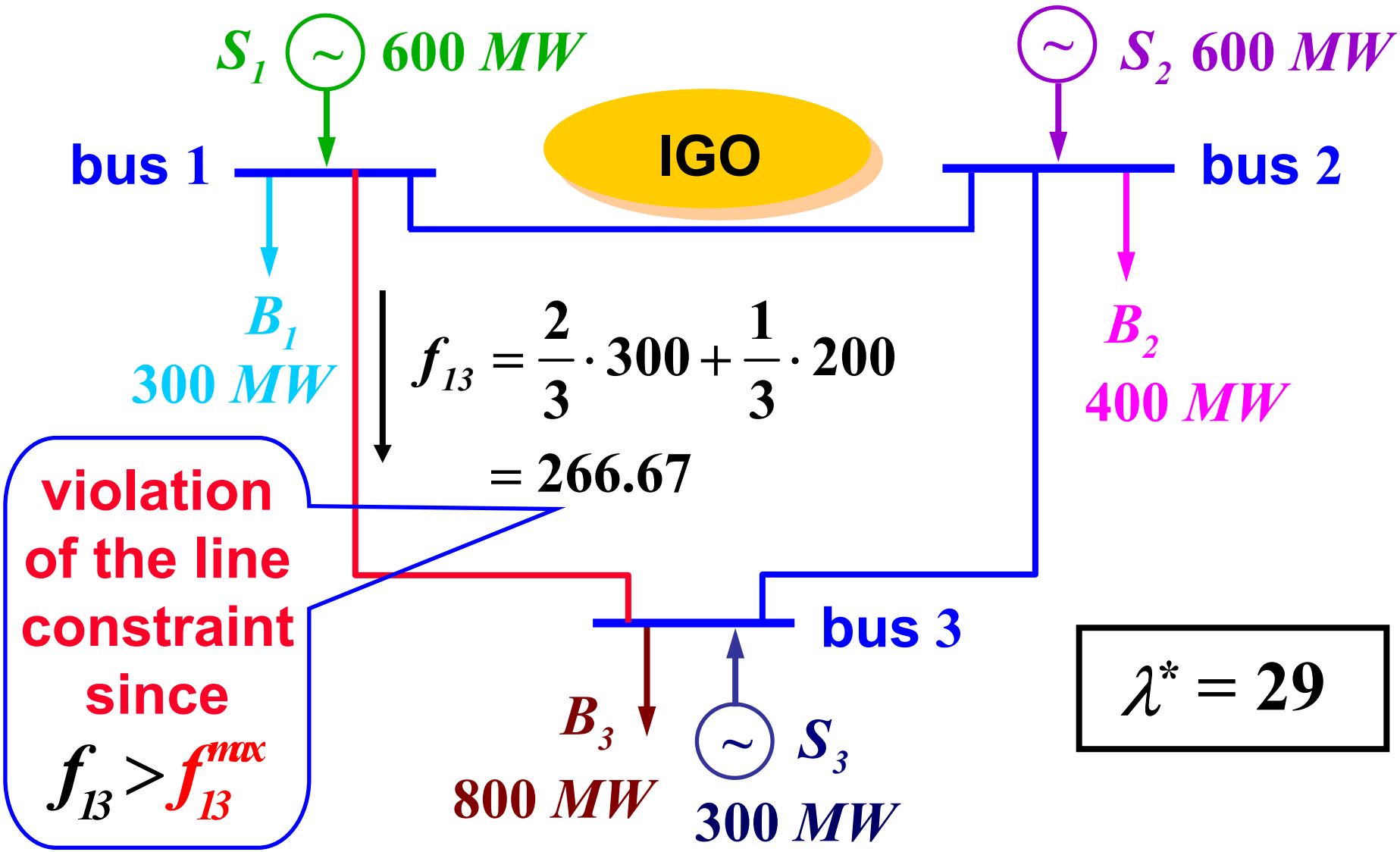


THREE-BUS SYSTEM: PTDFs





THREE-BUS SYSTEM: TRANSMISSION UNCONSTRAINED DISPATCH



THREE-BUS SYSTEM: TRANSMISSION UNCONSTRAINED DISPATCH

- The transmission unconstrained dispatch is infeasible because the line flow f_{13} violates limit f_{13}^{max}
- The net injections at buses 1 and 2 have to be modified to drive the network to feasibility
- The only choice of buyer B_3 is to bid sufficiently high to induce seller S_3 to provide supply to meet his load

SOCIAL WELFARE MAXIMIZATION UNDER TRANSMISSION CONSTRAINTS

$$max \quad \mathscr{S} = \sum_{j=1}^{N} \mathscr{B}_j(p_{B_j}) - \sum_{i=1}^{M} \mathscr{C}_i(p_{S_i})$$

s.t.

$$g_n(p_{S_1},\cdots,p_{S_M};p_{B_1},\cdots,p_{B_N}) = 0 \qquad \forall \text{ node } n$$

} set of power flow equations

$$f_\ell(p_{S_1},\cdots,p_{S_M};p_{B_1},\cdots,p_{B_N}) \le f_\ell^{max} \quad \forall \text{ line } \ell$$

} real power line flow limits

CONGESTED LINE AND SYSTEM

- We call a transmission line ℓ *congested* if the real power line flow violates the line limit, i.e., the corresponding inequality constraint becomes binding :

$$f_\ell(p_{S_1},\cdots,p_{S_M};p_{B_1},\cdots,p_{B_N}) = f_\ell^{max}$$

- We call the transmission system *congested* if there are one or more *congested* lines in the network

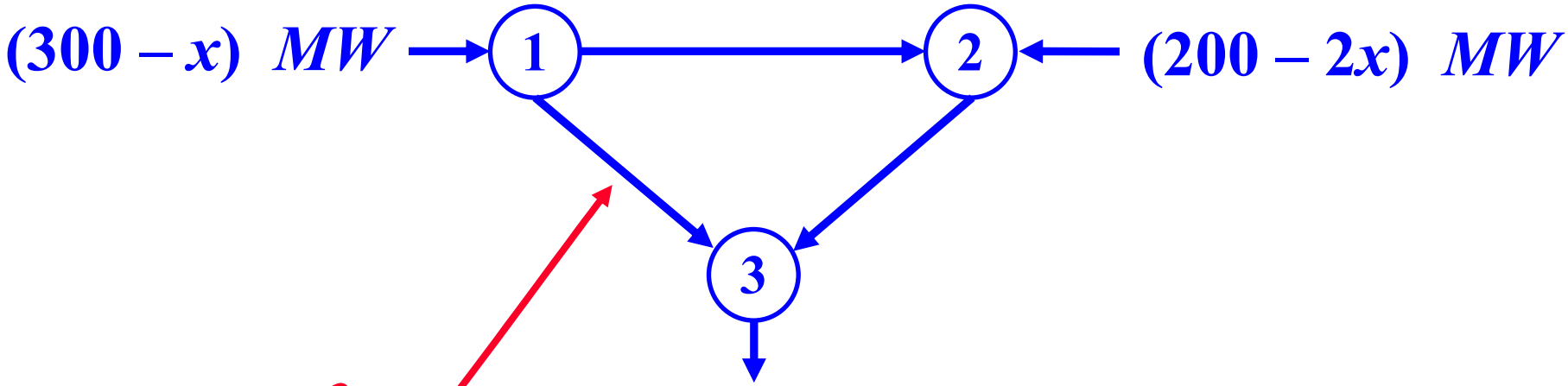
CONGESTION

- Power system reliability considerations require secure operations not only under base case conditions but also under the set of postulated contingency cases
- Congestion occurs if one or more limit violations are detected either under the base case or in any of the contingency cases
- The incorporation of transmission considerations requires the representation of the base case ***and*** all the postulated contingency cases

THREE-BUS SYSTEM: TRANSMISSION UNCONSTRAINED DISPATCH

- The transmission unconstrained dispatch is infeasible because the line flow f_{13} violates limit f_{13}^{max}
- The net injections at buses 1 and 2 have to be modified to drive the network to feasibility
- The only choice of buyer B_3 is to bid sufficiently high to induce seller S_3 to provide supply to meet his load

THREE-BUS SYSTEM: ENSURING TRANSMISSION FEASIBILITY



$$\frac{2}{3}\cdot(300-x) \;+\; \frac{1}{3}\cdot(200-2x) \;=\; 200\ MW \;\rightarrow\; f_{13}^{max}$$

THREE-BUS SYSTEM: REDISPATCH OF SUPPLY

- x is the amount of redispatch due to the impacts of the f_{13}^{max} constraint on seller S_1
- $2x$ is the amount of redispatch due to the impacts of the f_{13}^{max} constraint on seller S_2
- Redispatch calculation:

$$\frac{2}{3}\cdot(300-x)+\frac{1}{3}\cdot(200-2x)=200\ MW$$

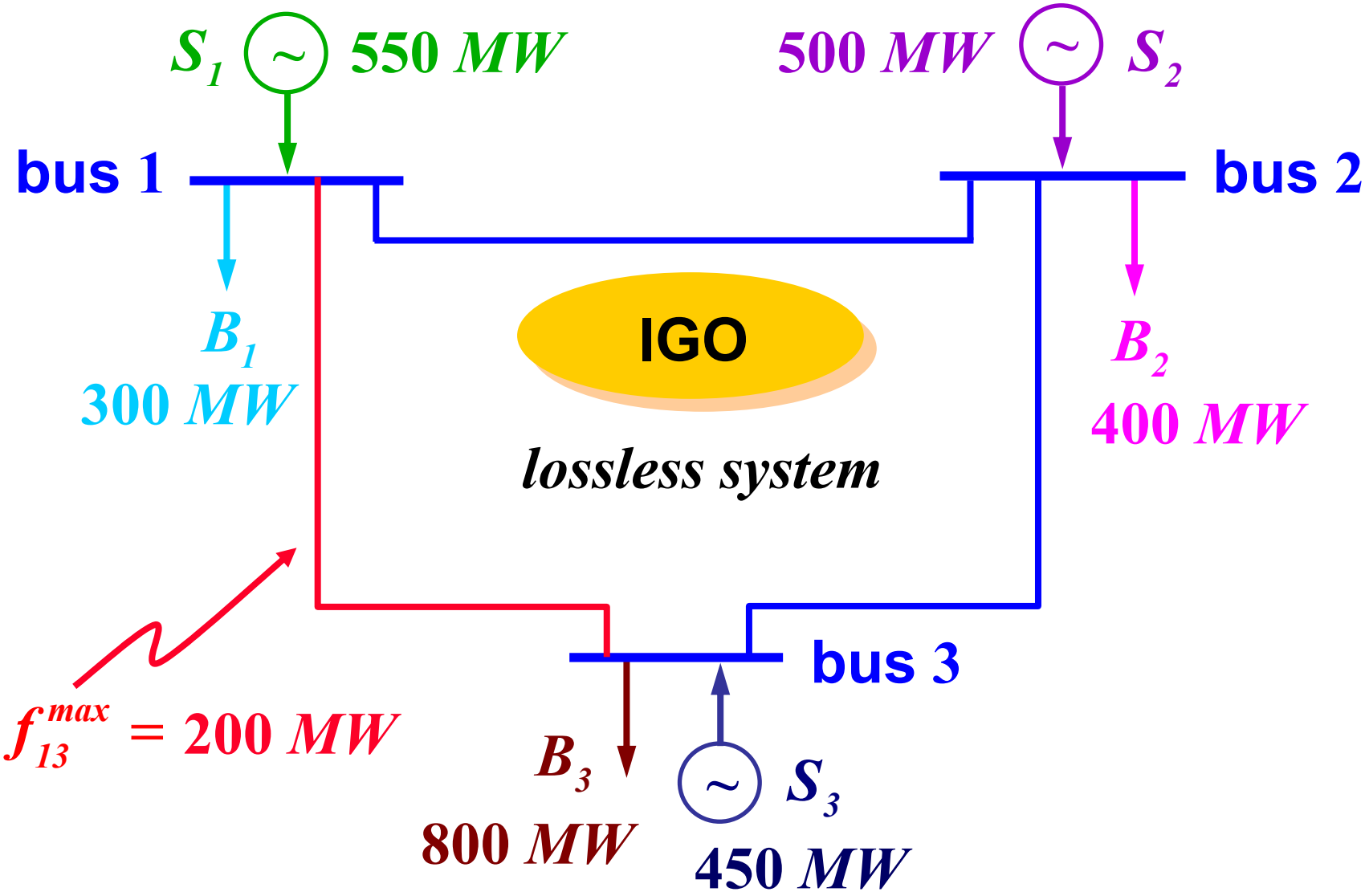
so that

$$x=50\ MW$$

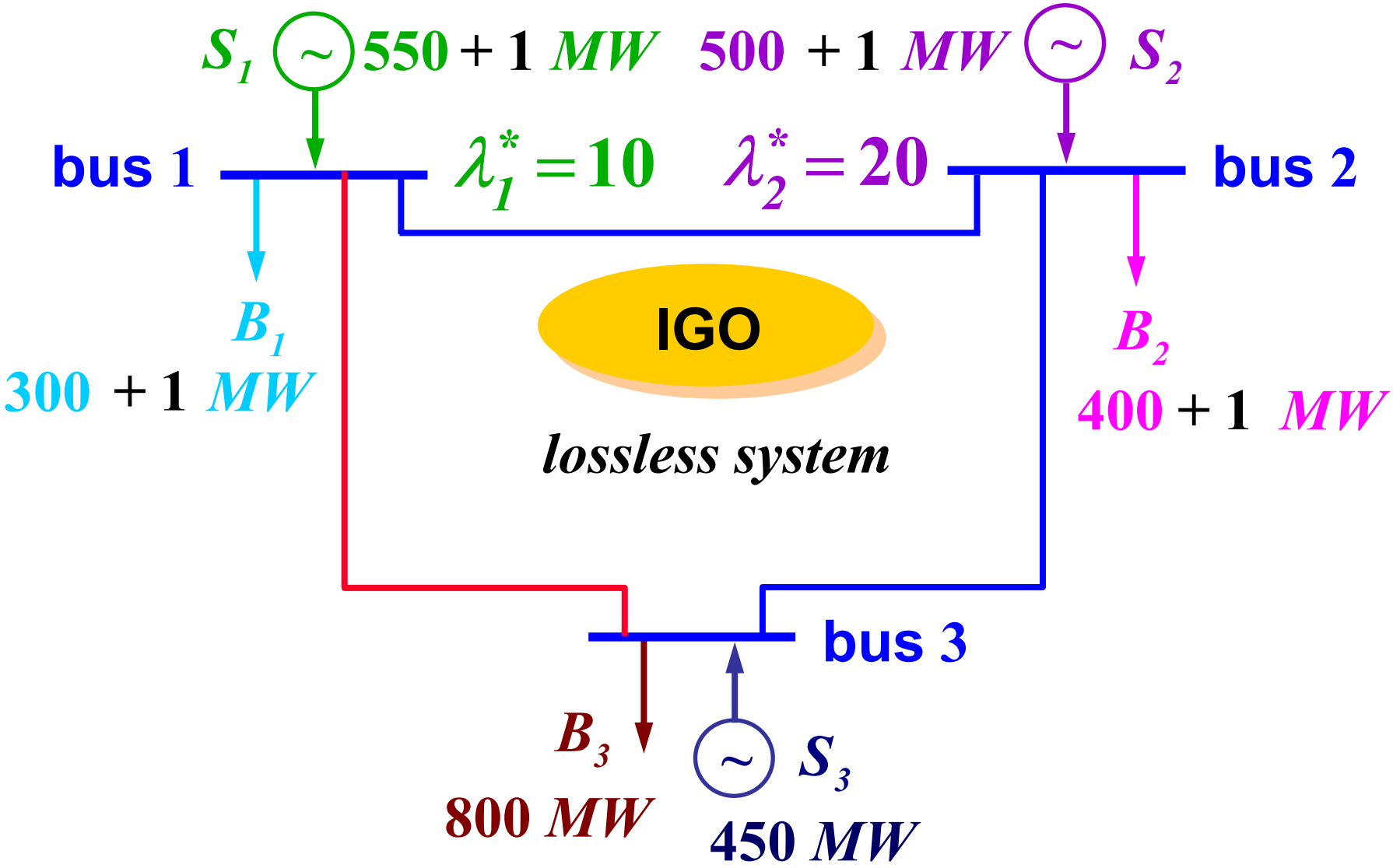
THREE-BUS SYSTEM: REDISPATCH OF SUPPLY

- Then, the IGO reduces the output of seller S_1 by $50\ MW$ and that of seller S_2 by $100\ MW$
- Since there is a willingness to pay by the buyer B_3, the IGO increases the output of seller S_3 by $150\ MW$
- The constrained dispatch changes the output of each seller and may impact the load supplied to buyer B_3

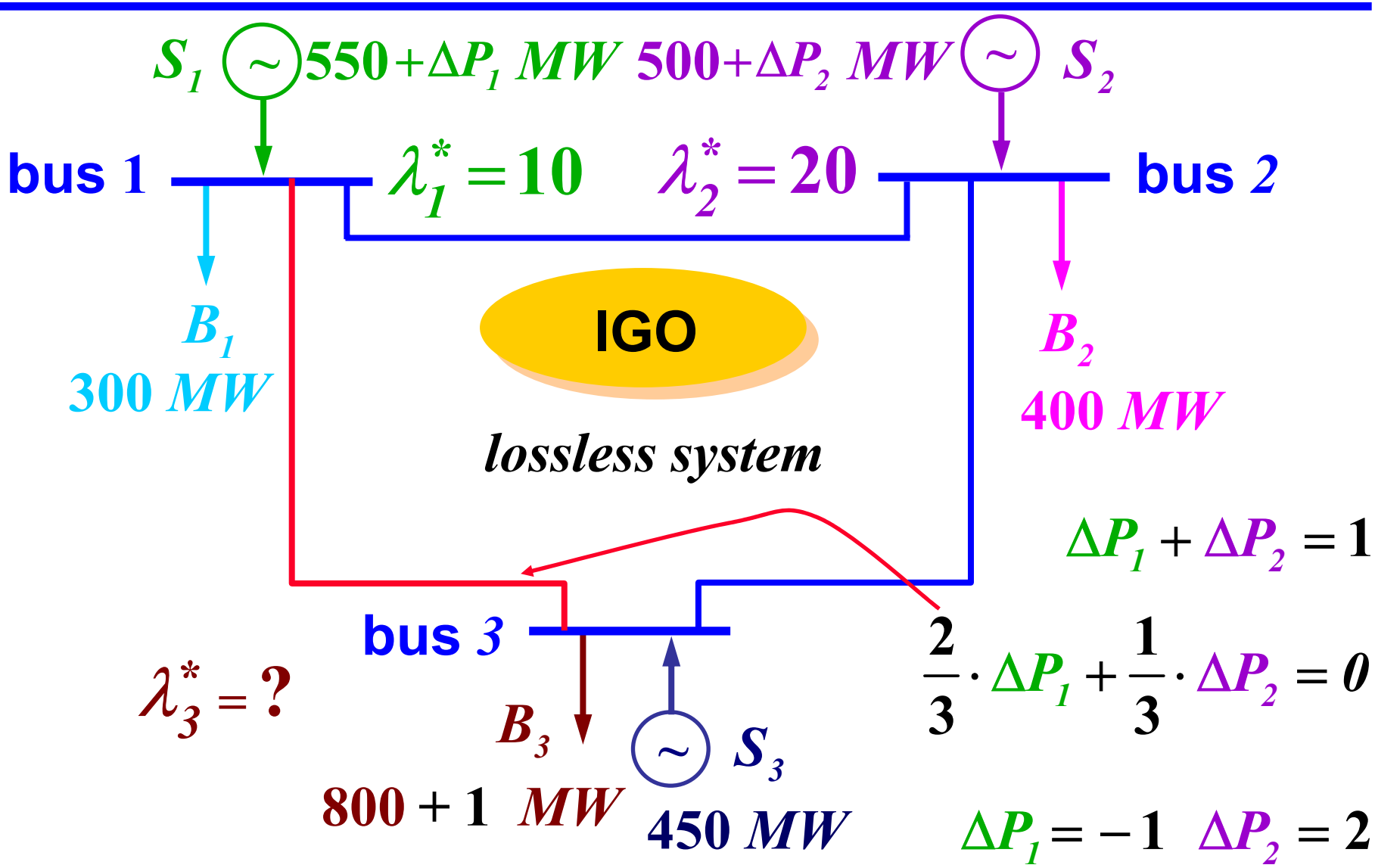
THREE-BUS SYSTEM: TRANSMISSION CONSTRAINED DISPATCH



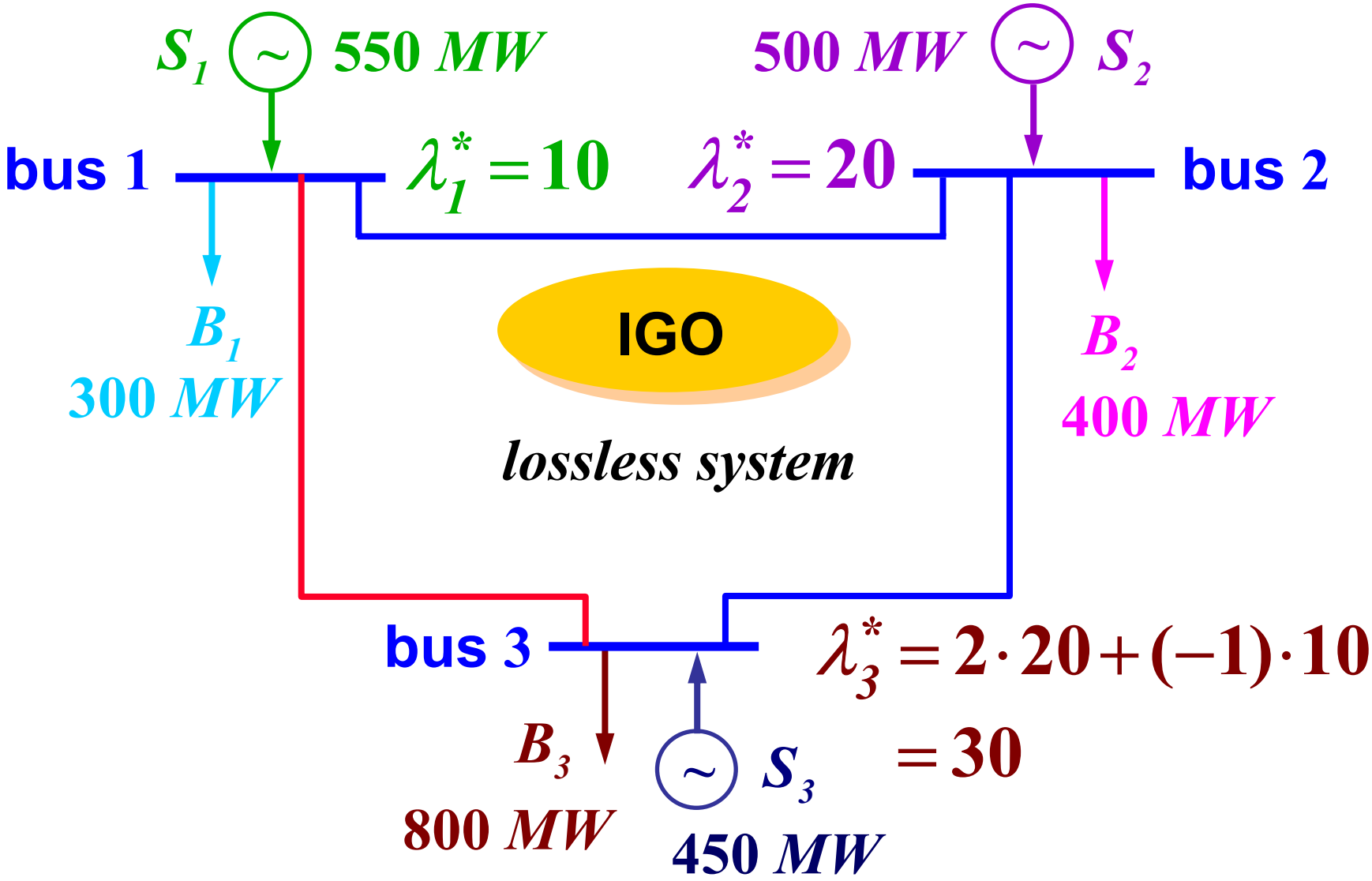
THREE-BUS SYSTEM: *LMPs*



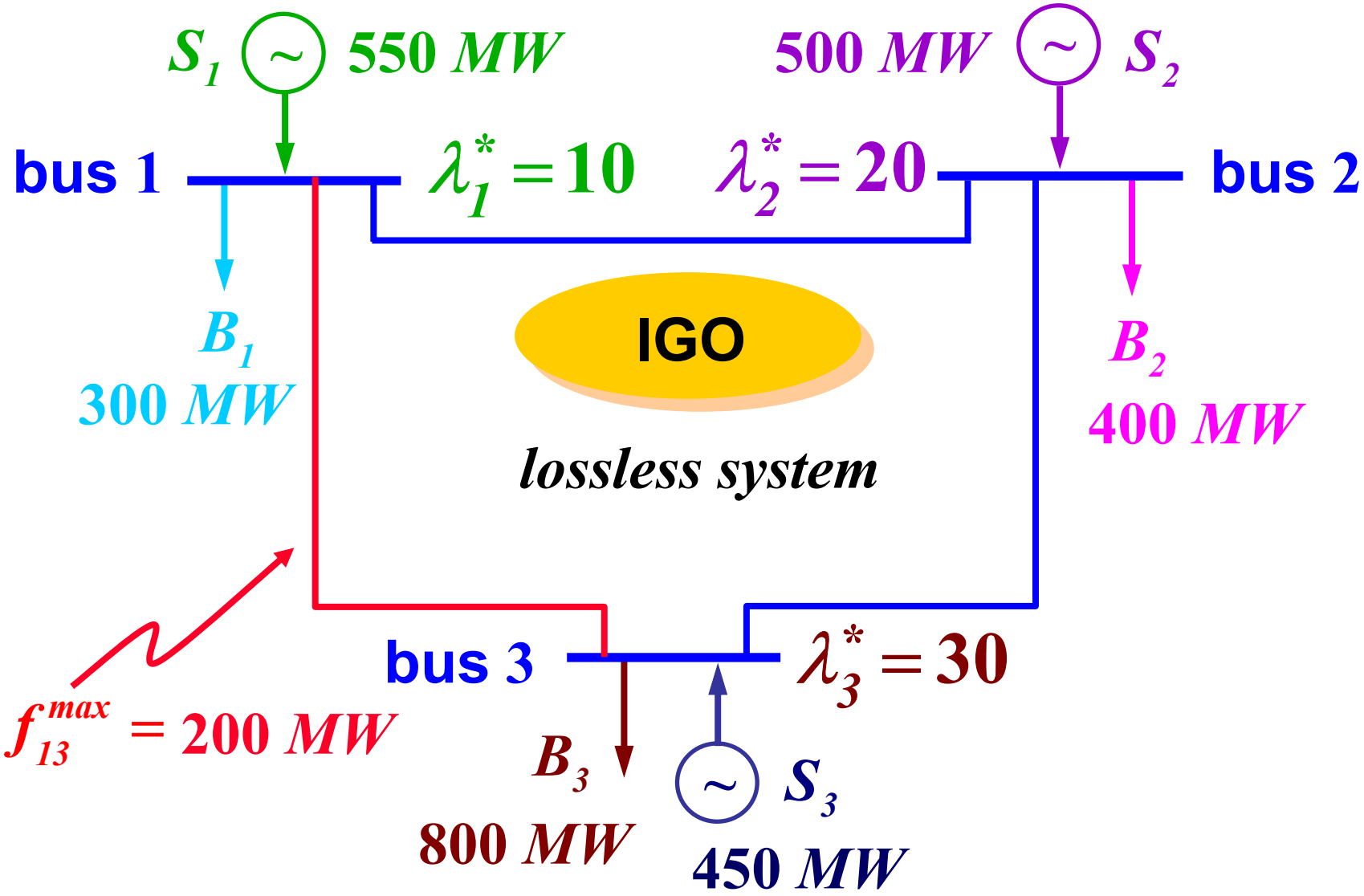
THREE-BUS SYSTEM: *LMPs*



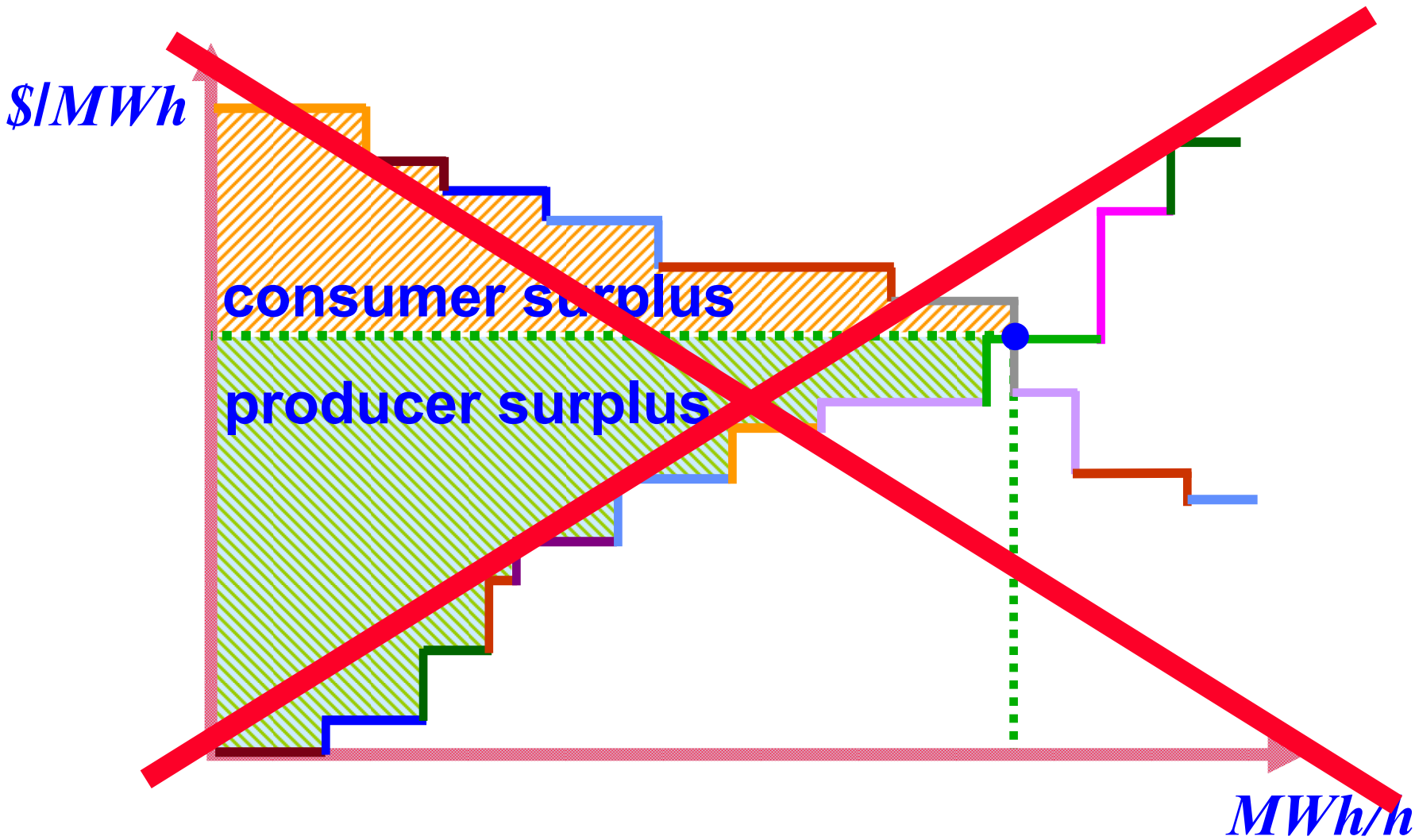
THREE-BUS SYSTEM: *LMPs*



THREE-BUS SYSTEM: *LMPs*



SOCIAL WELFARE AND SURPLUSES



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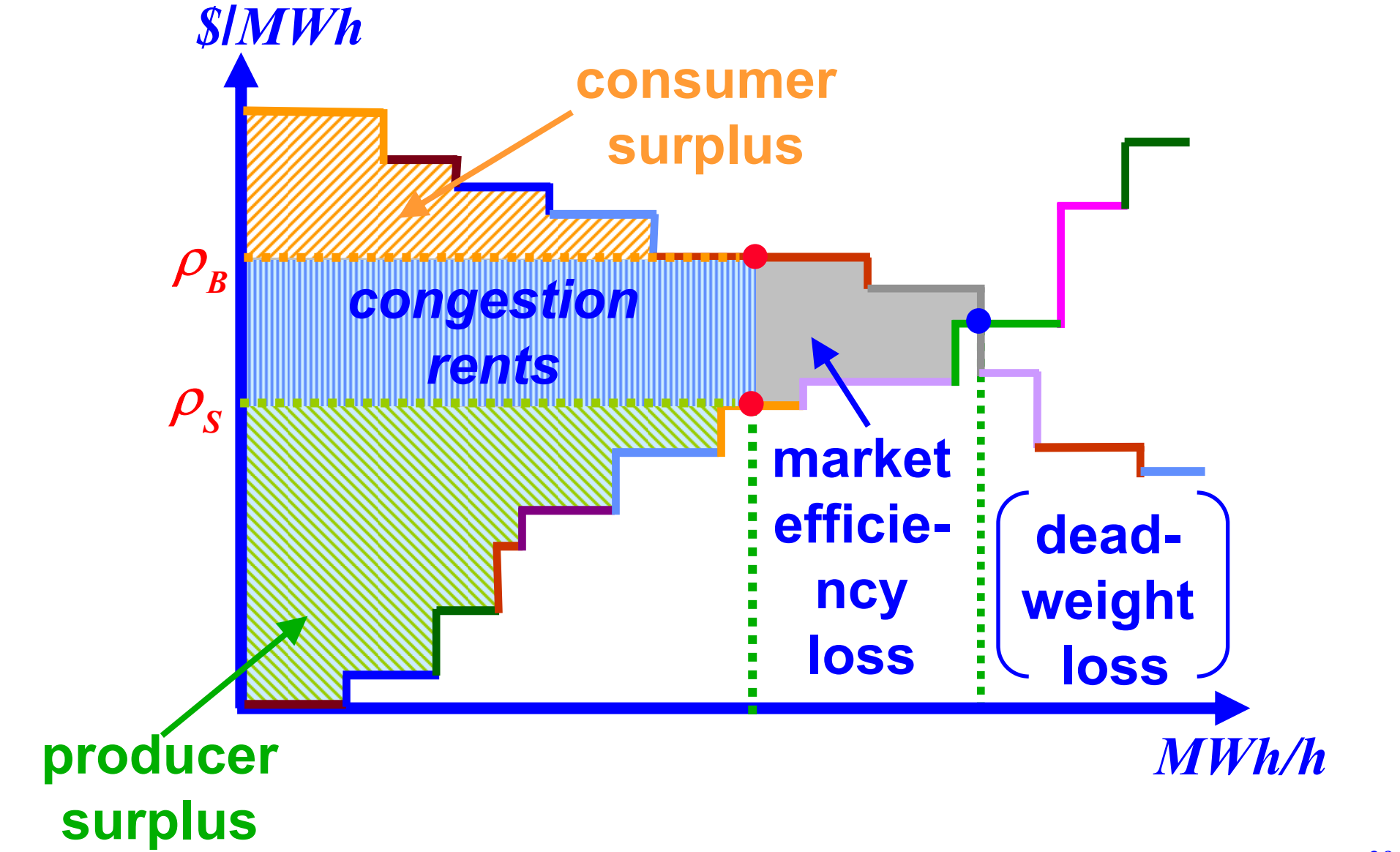


IMPACTS OF CONGESTION

- Congestion in the system leads to a change from the single market equilibrium point to different nodal equilibrium points
- Change in the preferred schedule for the required generation – demand balance may lead to possible curtailment in production or consumption
- The individual surpluses of the players change from the unconstrained market values to those in the markets at each bus under constrained conditions

CONGESTION MEASURES

- The impacts of congestion may be measured in terms of the energy that needs to be redispatched and/or the financial costs on the various players
- Measures of congestion impacts in *$*
  - redispatch costs
  - *congestion rents*
  - market efficiency loss

CONGESTION RENTS

- In the constrained case we have different prices at the different zones, so the players may face different clearing prices depending on their locations
- The social welfare in this case is given by

$$\hat{\mathscr{S}} = \hat{\mathscr{S}}^{S} + \hat{\mathscr{S}}^{B} + \sum_{j=1}^{N} \rho_j \cdot p_{B_j} - \sum_{i=1}^{M} \rho_i \cdot p_{S_i}$$

congestion rents κ

CONGESTION RENTS

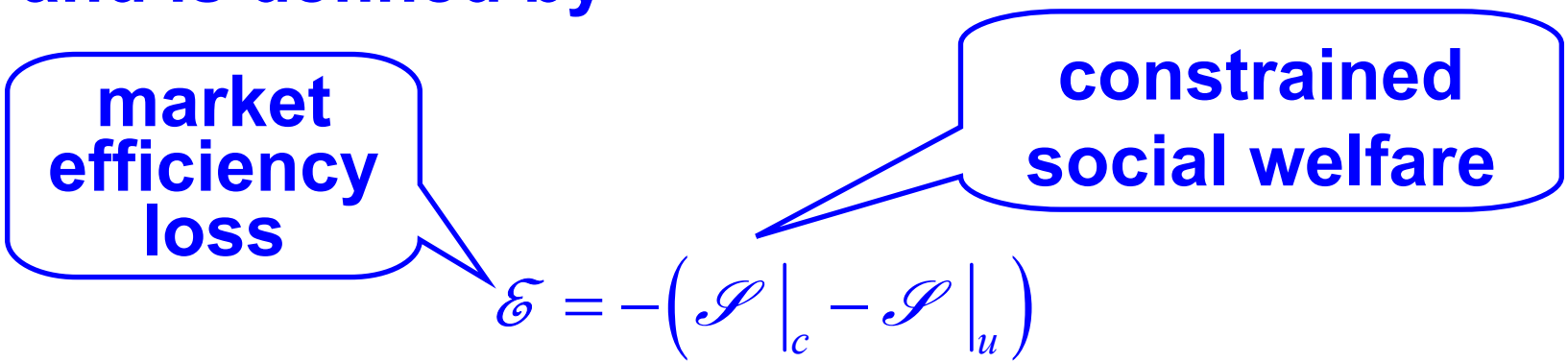
- In the constrained case, the *congestion rents* are part of the social welfare

$$\hat{\mathscr{S}} = \hat{\mathscr{S}}^{B} + \hat{\mathscr{S}}^{S} + \mathcal{K}$$

- The *congestion rents* are also known as *merchandising surplus* and correspond to the difference between the amounts paid by buyers and the amounts received by sellers; the *congestion rents* are collected by the IGO

MARKET EFFICIENCY LOSS

- Congestion may produce a reduction in the social welfare of the market due to the physical network constraints
- This reduction is called *market efficiency loss* and is defined by



- In economics, the *market efficiency loss* is also known as *deadweight loss*

THREE - BUS SYSTEM: MARKET EFFICIENCY LOSS

- For the unconstrained case we have

$$\mathscr{S}\Big|_u = 265,600$$

- For the constrained case we have

$$\mathscr{S}\Big|_c = 263,750$$

- The *market efficiency loss* is

$$\mathscr{E} = -\left(\mathscr{S}\Big|_c - \mathscr{S}\Big|_u\right) = 1,850$$

THREE – BUS SYSTEM: CONSTRAINED CASE

seller	surplus ($)
S_1	1,500
S_2	2,000
S_3	2,250
total	5,750

buyer	surplus ($)
B_1	16,000
B_2	20,000
B_3	216,000
total	252,000

congestion rents ($)	6,000
social welfare ($)	263,750

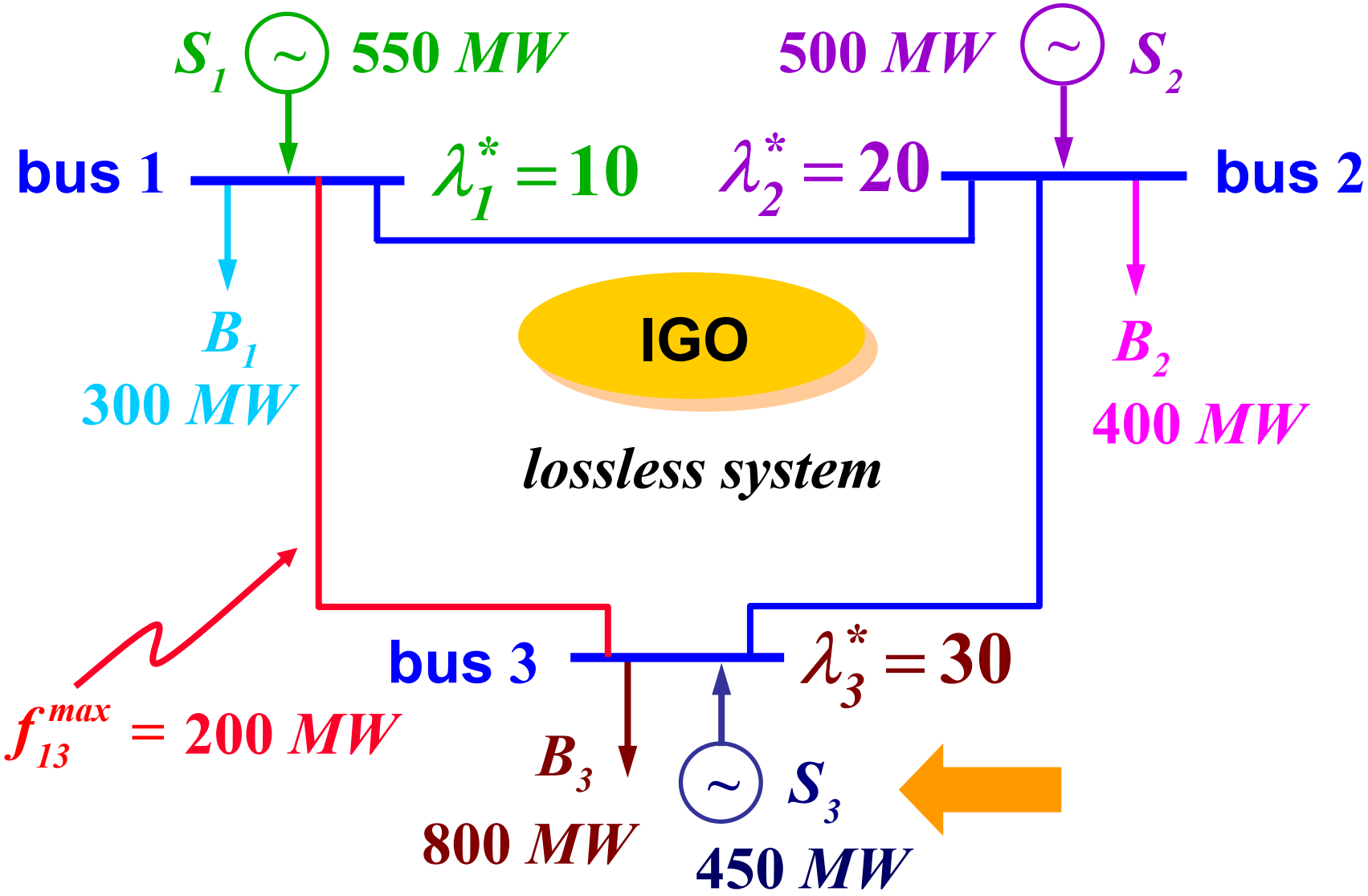
CAUSES OF SOCIAL WELFARE REDUCTION

- The redispatch of higher-priced units to replace the output of the lower-priced generation
- The decrease in market efficiency
- The decrease in the producer surplus of some sellers
- The decrease in the consumer surplus of some buyers
- The needs for ancillary services provided by sellers charging higher prices
- The creation of situations that may lead to the exercise of market power

ADDITIONAL CONGESTION IMPACTS

- Increase of costs for delayed connection of new generation
- Reduction in reliability
- Pollution from older and less efficient plants that must be operated only for reliability purposes

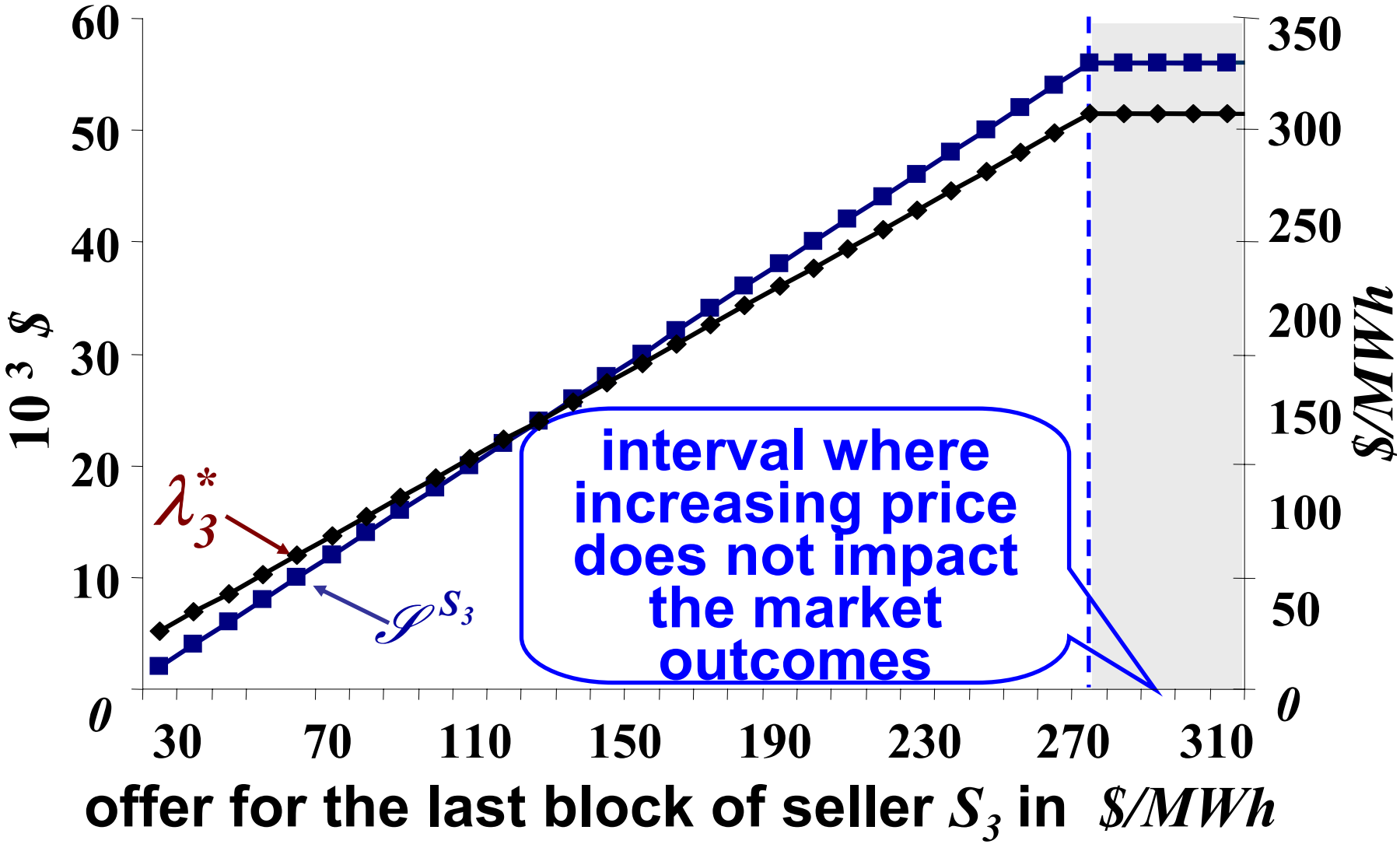
THREE-BUS SYSTEM: *LMPs*



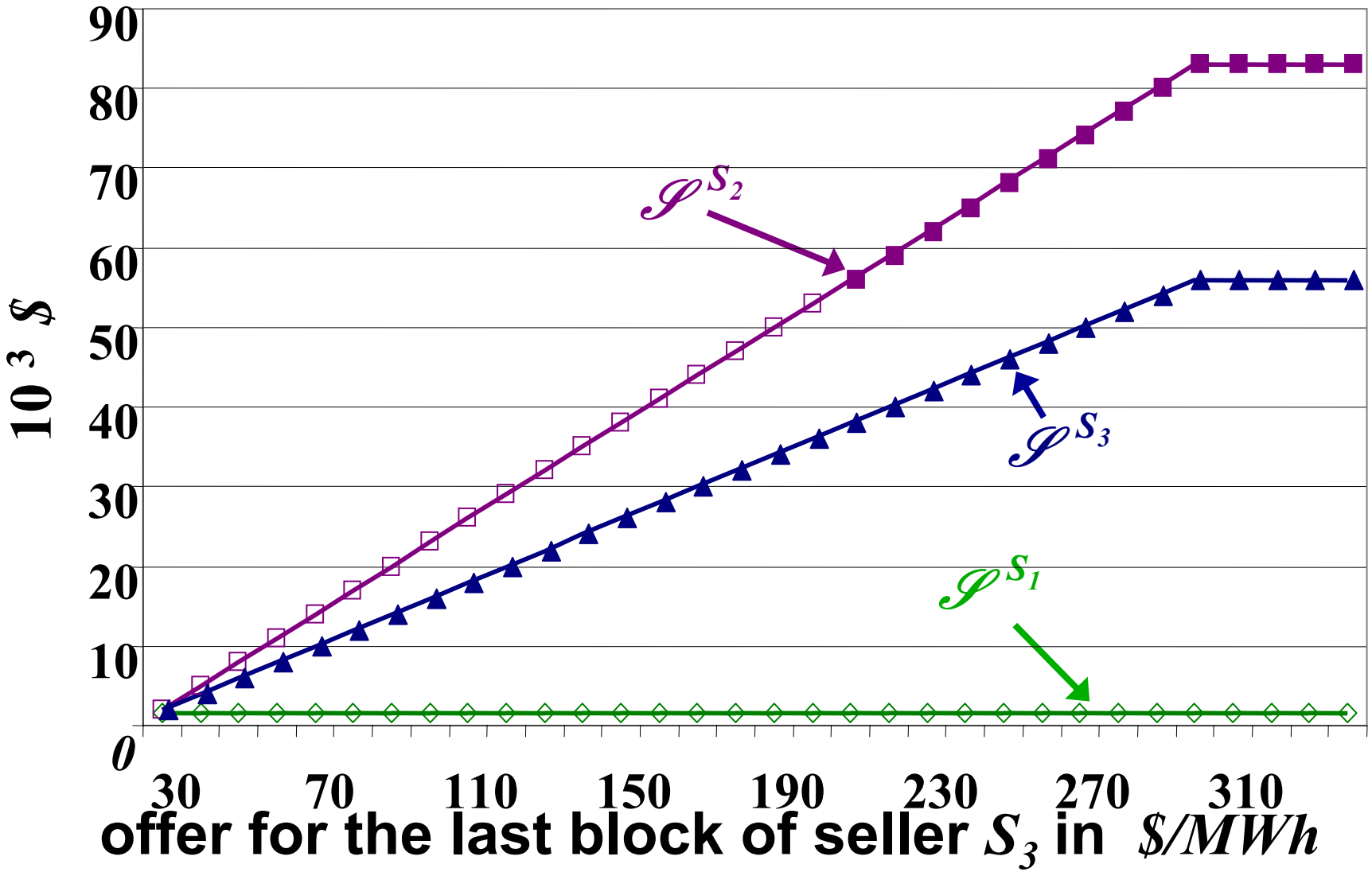
SENSITIVITY STUDY IN THE THREE - BUS SYSTEM

- We investigate the impacts of changing the offer of seller S_3 for his second block by varying the offer price from 29 to 330 $/MWh; the other offers/bids remain unchanged
- We evaluate the resulting surpluses for the various values of the offers submitted

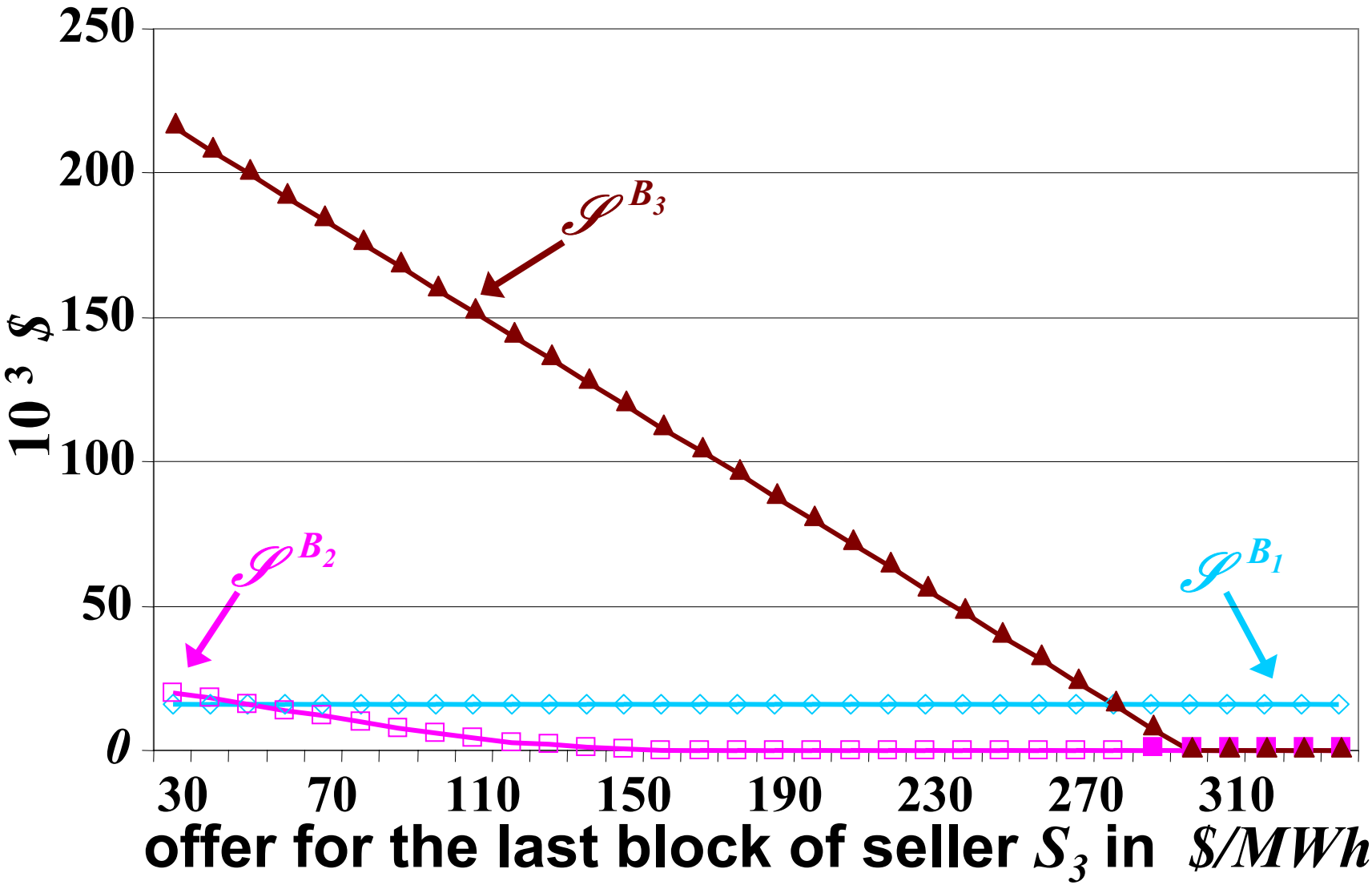
THREE-BUS SYSTEM: λ_3^* AND $\mathcal{J}^{S_3}$



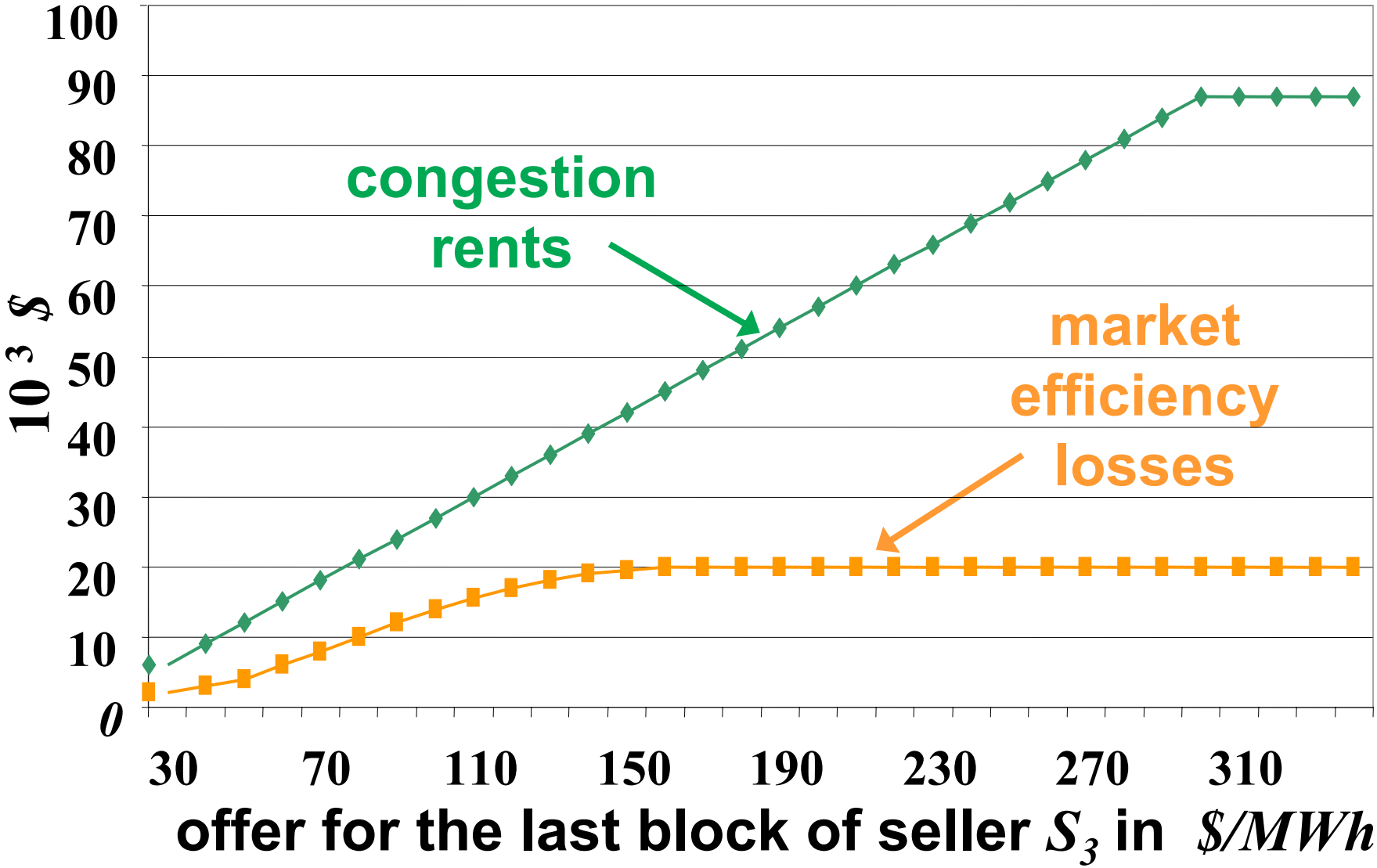
THREE-BUS SYSTEM: PRODUCER SURPLUS



THREE-BUS SYSTEM: CONSUMER SURPLUS



THREE-BUS SYSTEM: MARKET PERFORMANCE MEASURES



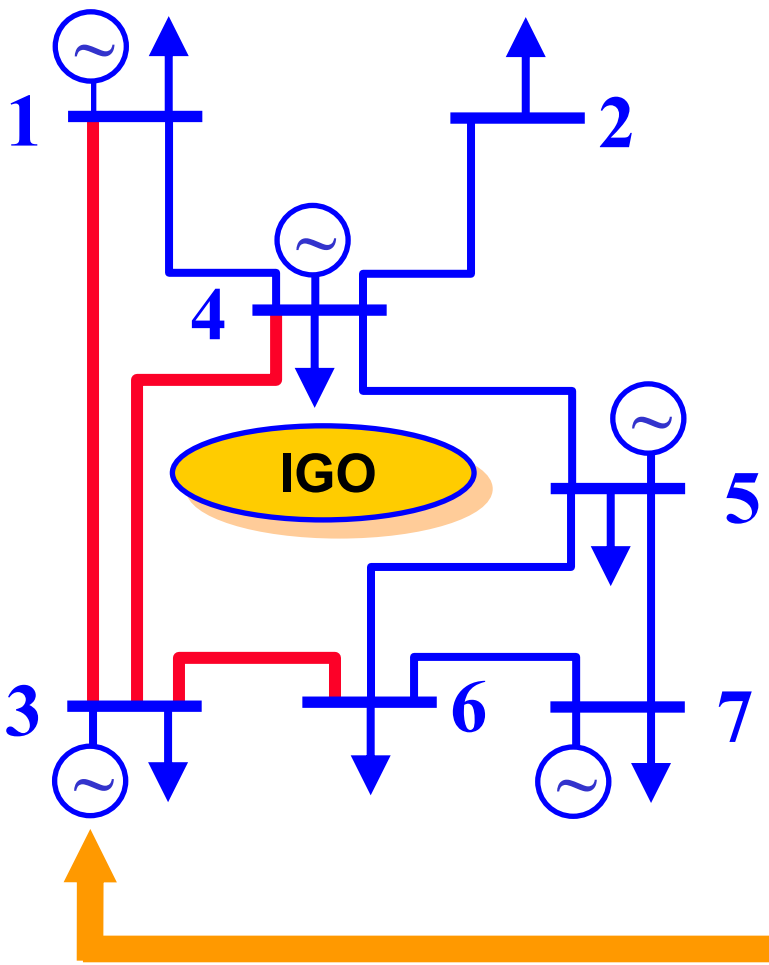
LOCAL MARKET POWER

- Market power is the ability of a firm to profitably raise the price of a product
- The exercise of market power may be carried out by:
  - the physical withholding of units
  - the financial withholding of units
- Transmission constraints may create locational market power since they may set up area markets with limited importing capability

SIMULATION STUDIES

- A seller changes his offer prices by varying the offer price for the last block offered
- We study the resulting variations of the producer surplus, consumer surplus, *congestion rents* and *market efficiency loss*
- The simulations performed on different systems of various sizes are reported

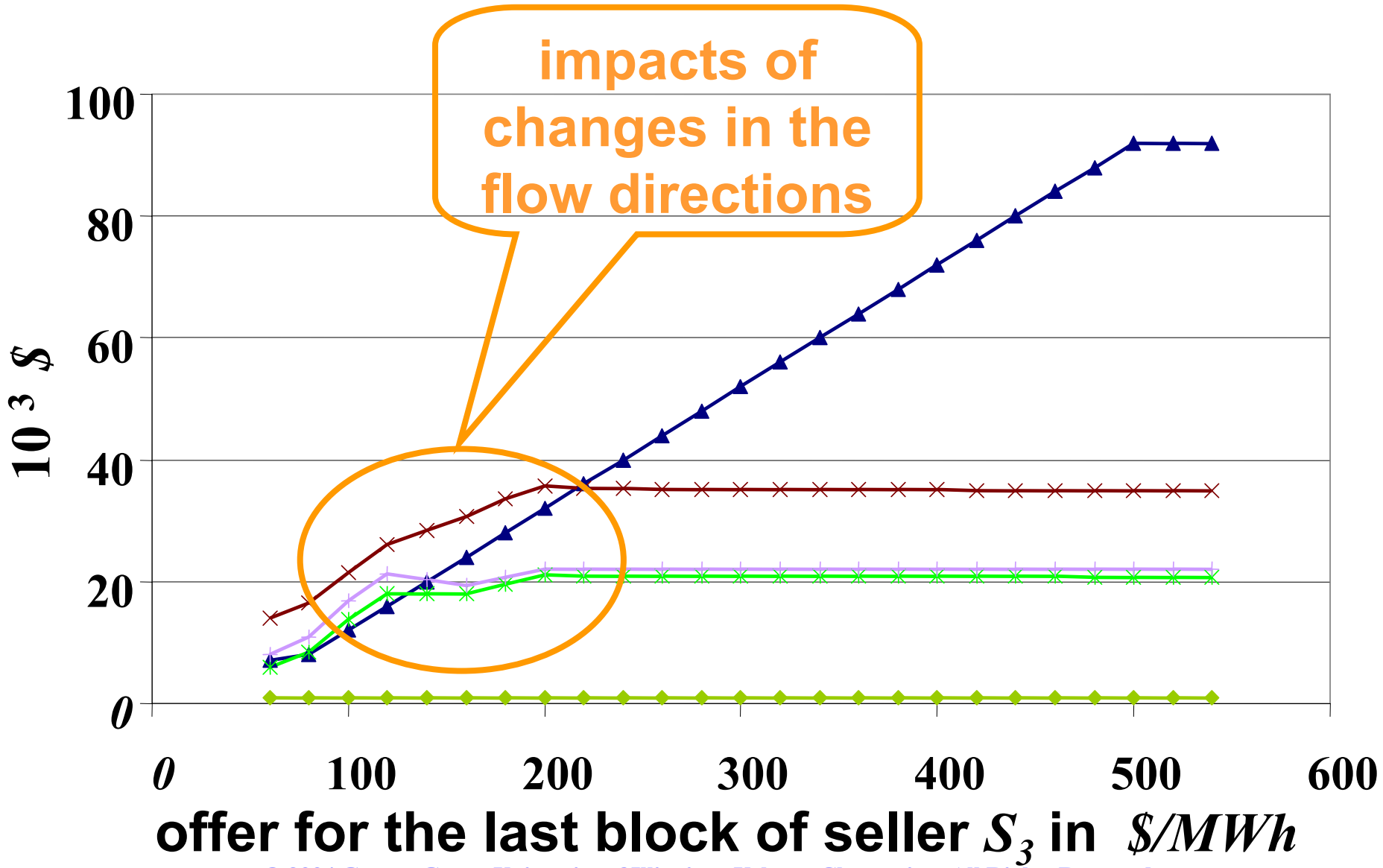
THE SEVEN-BUS SYSTEM EXAMPLE



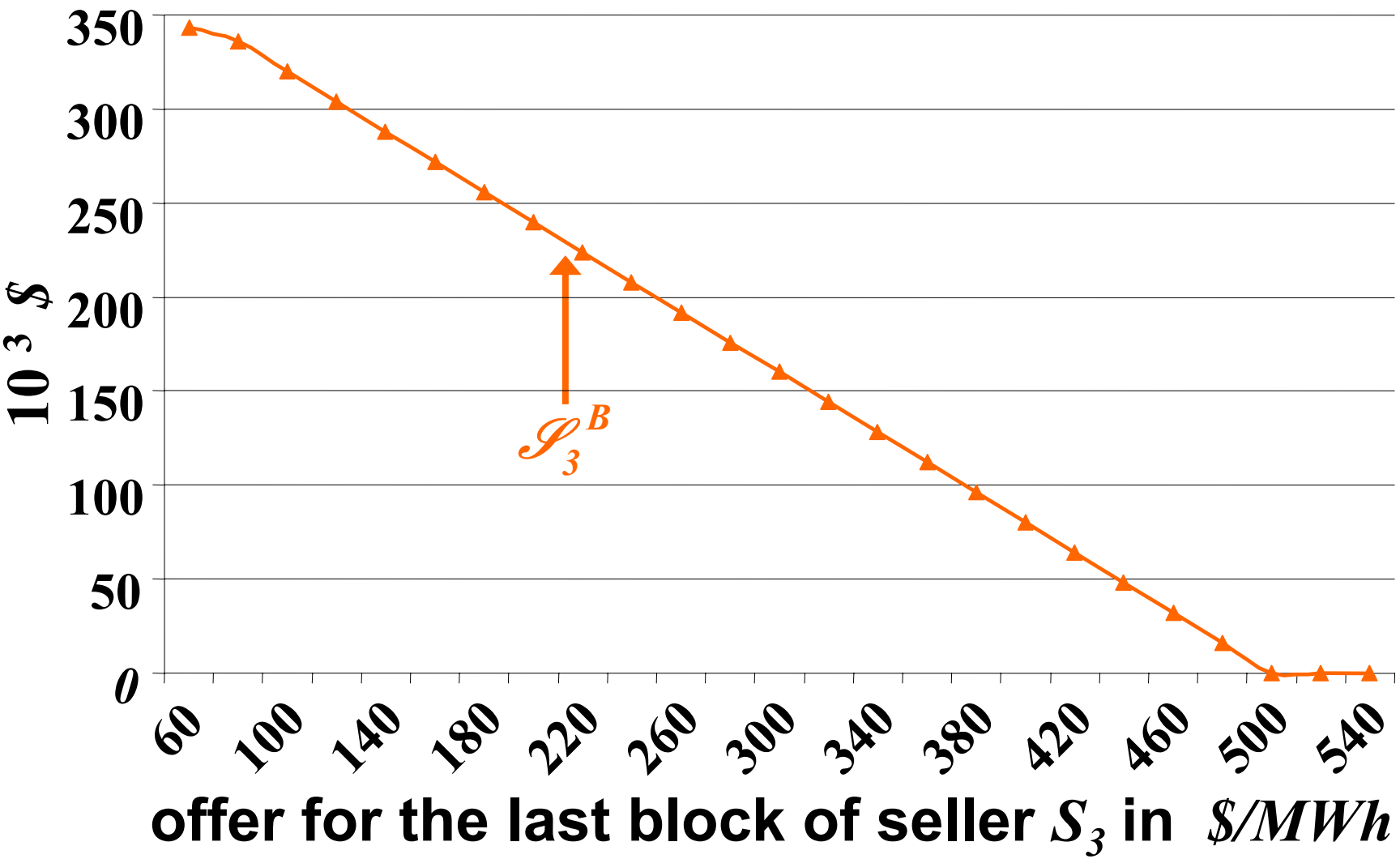
offers		
S_1	200@5	600@10
S_3	200@40	100@60
S_4	200@10	300@15
S_5	100@20	300@40
S_7	200@30	200@40

bids		
B_1	100@80	100@50
B_2	200@100	-
B_3	800@500	-
B_4	200@140	200@120
B_5	100@80	200@50
B_6	200@120	200@110
B_7	100@90	100@50

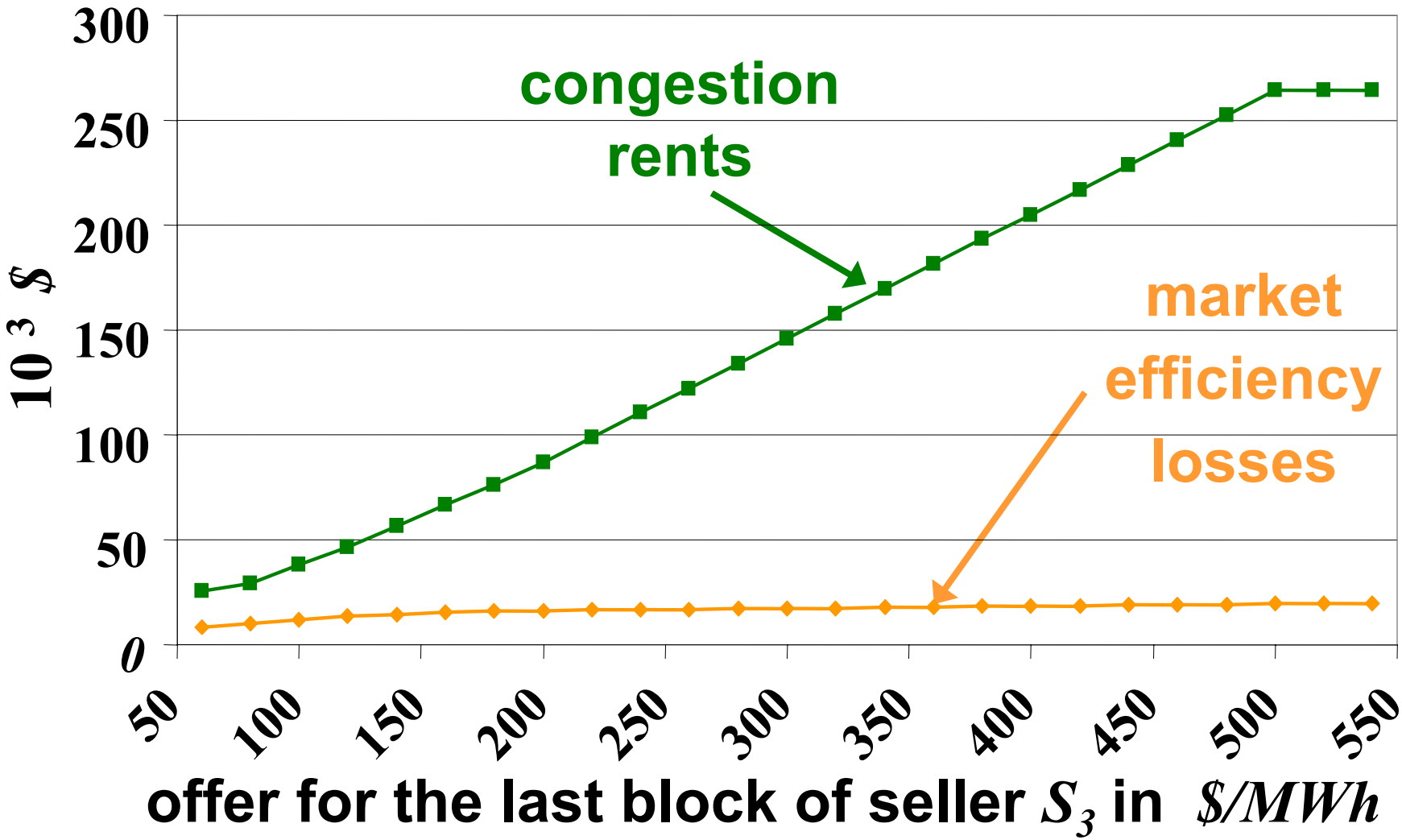
SEVEN-BUS SYSTEM: PRODUCER SURPLUS



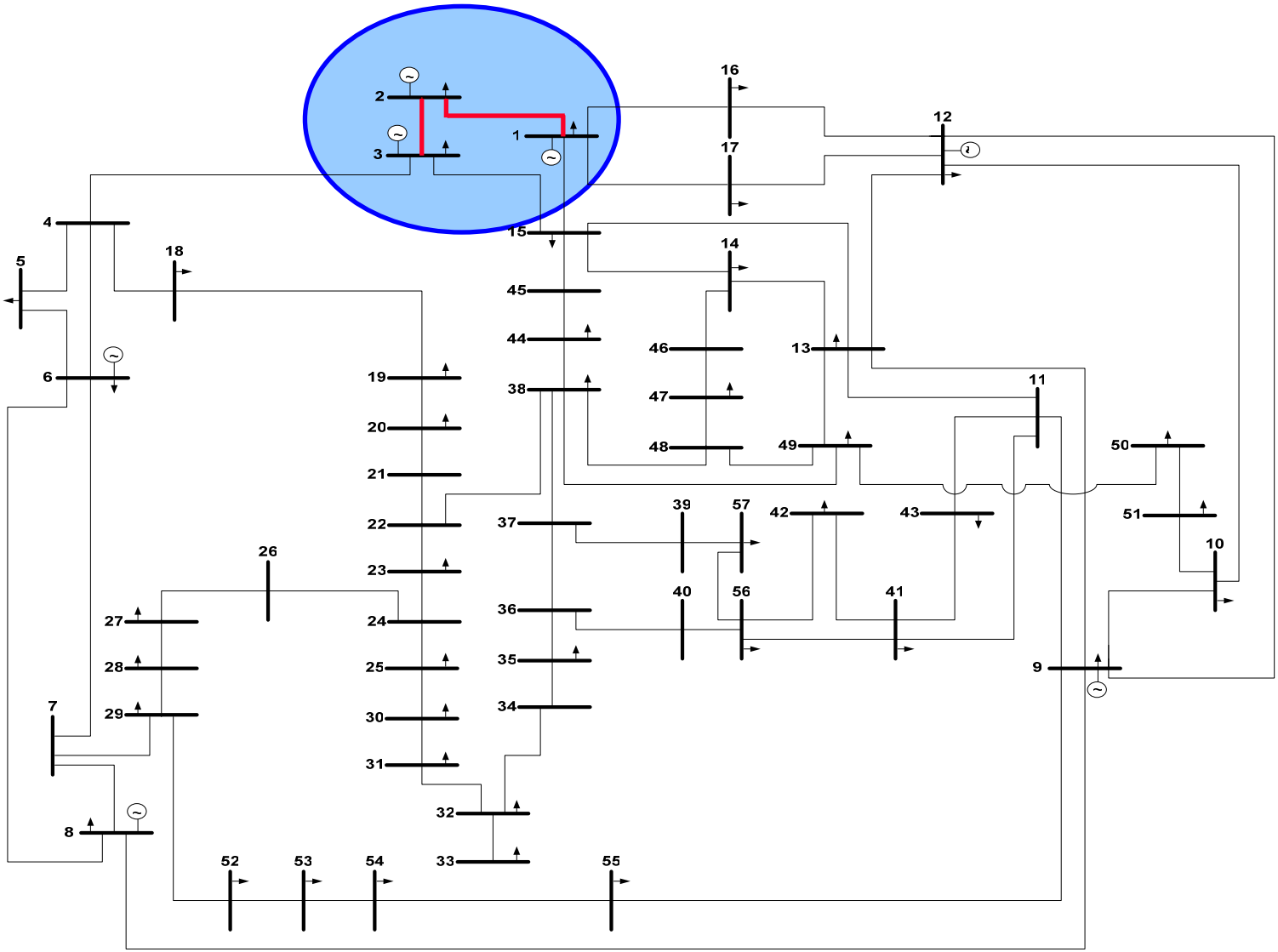
SEVEN-BUS SYSTEM: CONSUMER SURPLUS



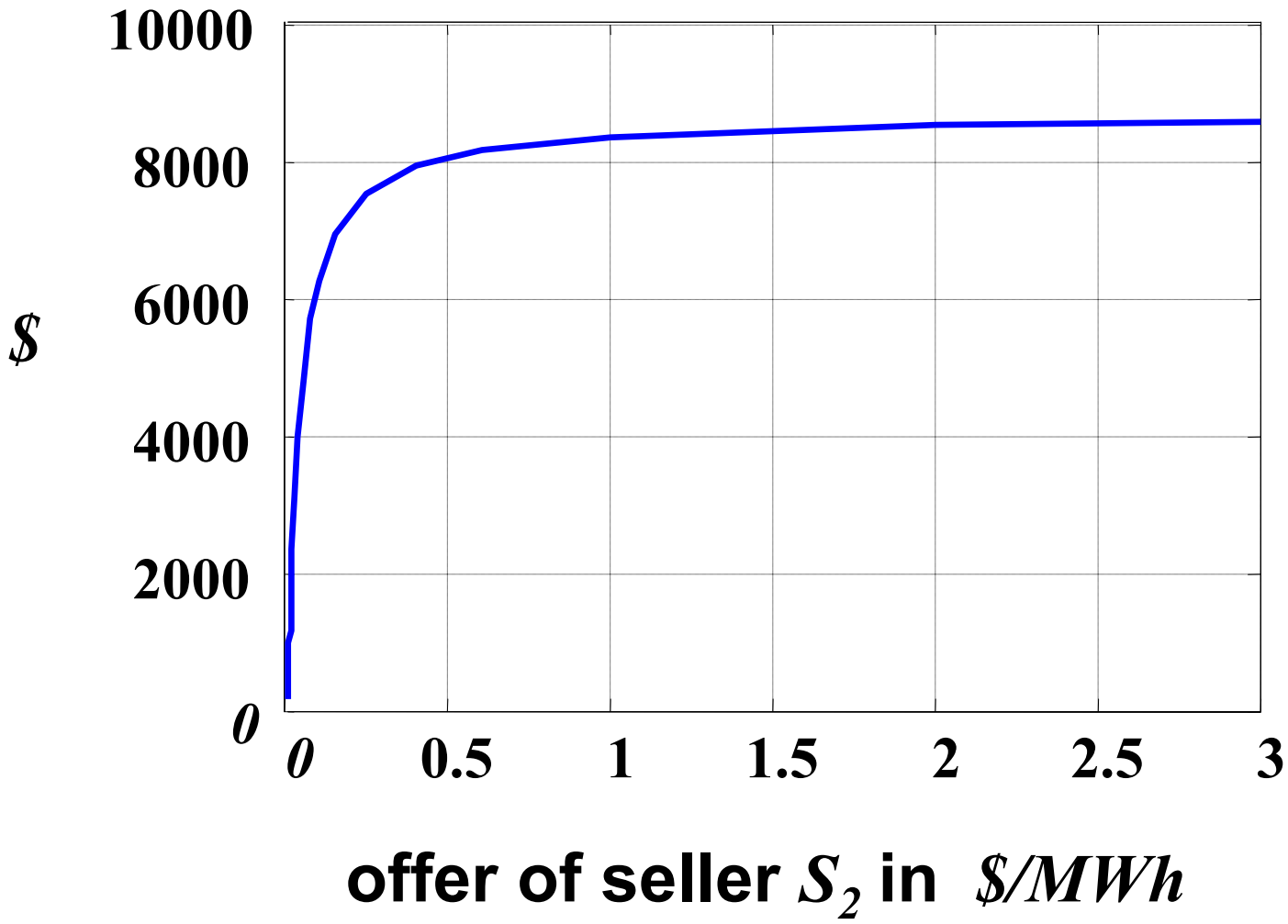
SEVEN-BUS SYSTEM SENSITIVITY



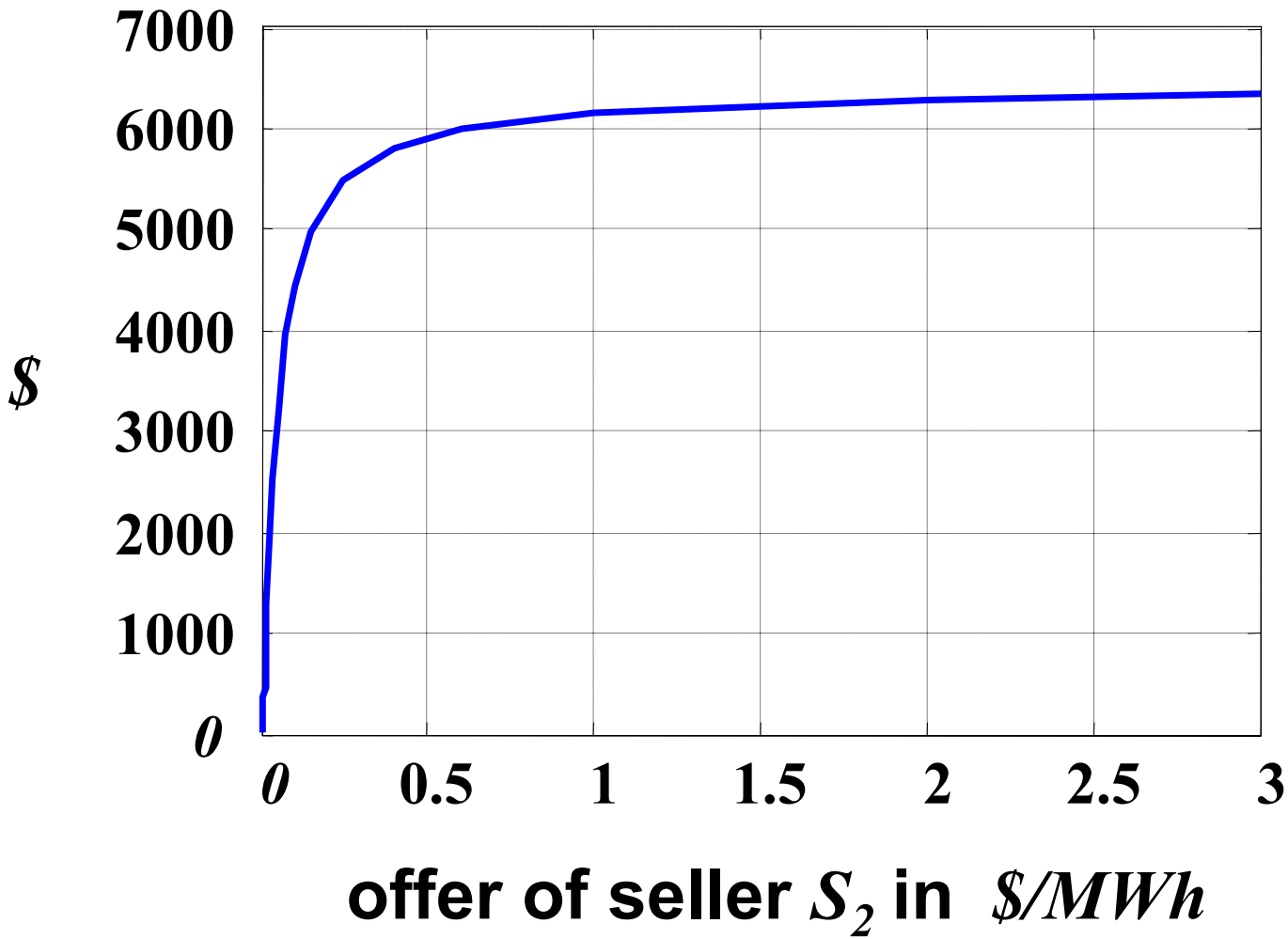
THE 57-BUS SYSTEM



THE 57-BUS SYSTEM: CONGESTION RENTS



THE 57-BUS SYSTEM: MARKET EFFICIENCY LOSS



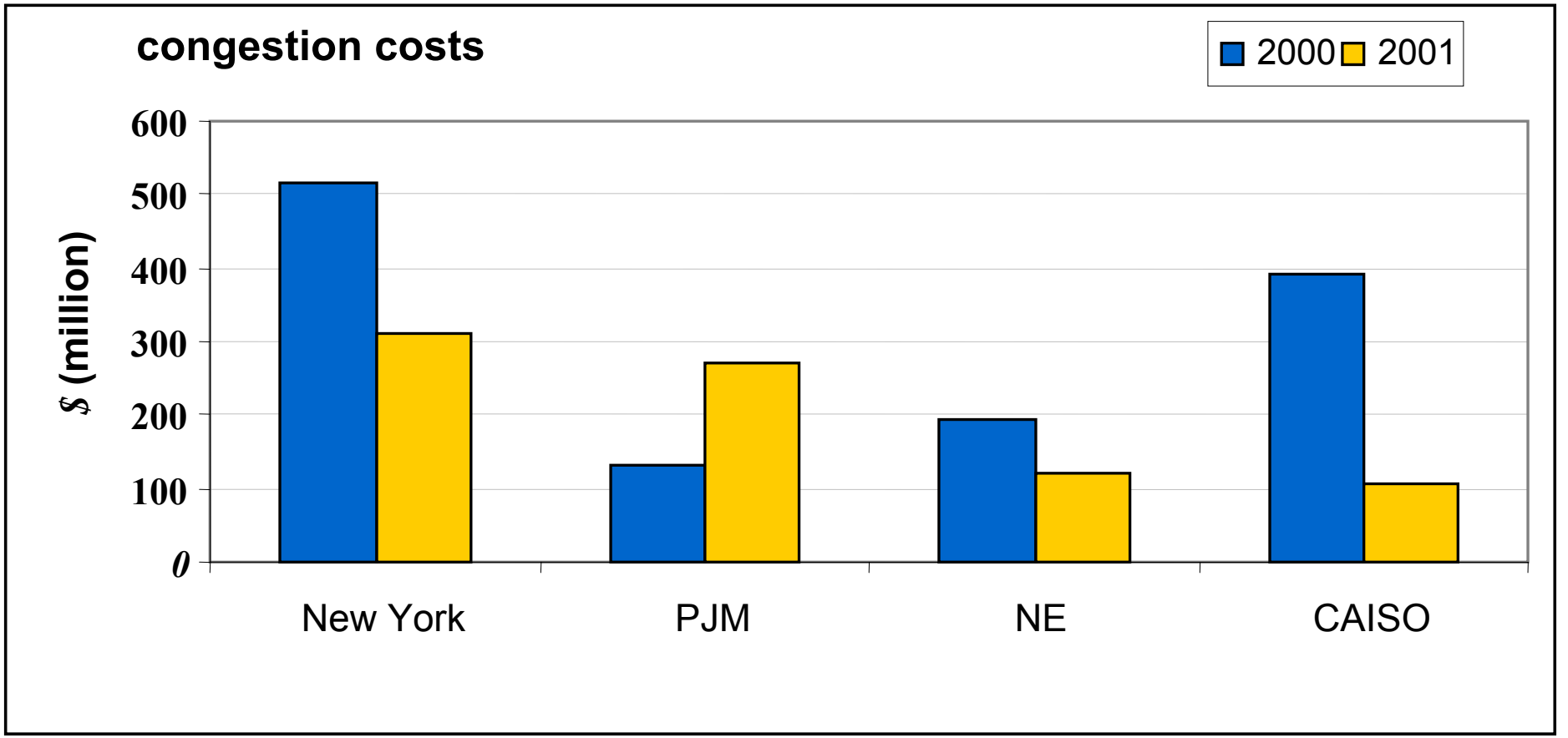
SIMULATION RESULTS

- Congestion situations produce, typically, changes in the consumer and social surpluses, the additional *congestion rents* component of the *social welfare*, and the market efficiency loss with respect to the unconstrained case
- Congestion creates situations which are conducive to the exercise of market power
- Under price-responsive demand, when a particular seller increases his offer prices, the impacts of congestion on the individual players and the entire market are bounded due to the asymptotic nature of the outcomes

SIMULATION RESULTS

- We observe the existence of *free-riders* in the market on both the supply- and demand-sides
- There are also players that are negatively impacted by the exercise of market power
- The simulations underline the critical role of the network topology and the relative location of the market players in determining who are the losers and the gainers as a result in such a market power exercise attempt

RTO CONGESTION COSTS



CAISO data excludes intra-zonal congestion ISO-NE data represents mitigated congestion costs

FUTURE WORK

- Modeling
  - incorporation of real power losses
  - detailed representation of additional constraints
  - incorporation of contingency case analysis
- Parametric analysis
  - demand-side variation
  - multiple players variation of offer/bid prices
- Study of the *market efficiency loss* composition

AN ALTERNATE VIEW OF CONGESTION