Energy Economics and Environment

Lecture 4

EVROPSKÁ UNIE
Evropské strukturální a investiční fondy
Operační program Výzkum, vývoj a vzdělávání

MINISTERSTVO ŠKOLSTVÍ,
MLÁDEŽE A TĚLOVÝCHOVY

- Transmission pricing (Nodal versus Zonal)
  - Peak-load pricing
  - Nodal and zonal dispatch in meshed networks

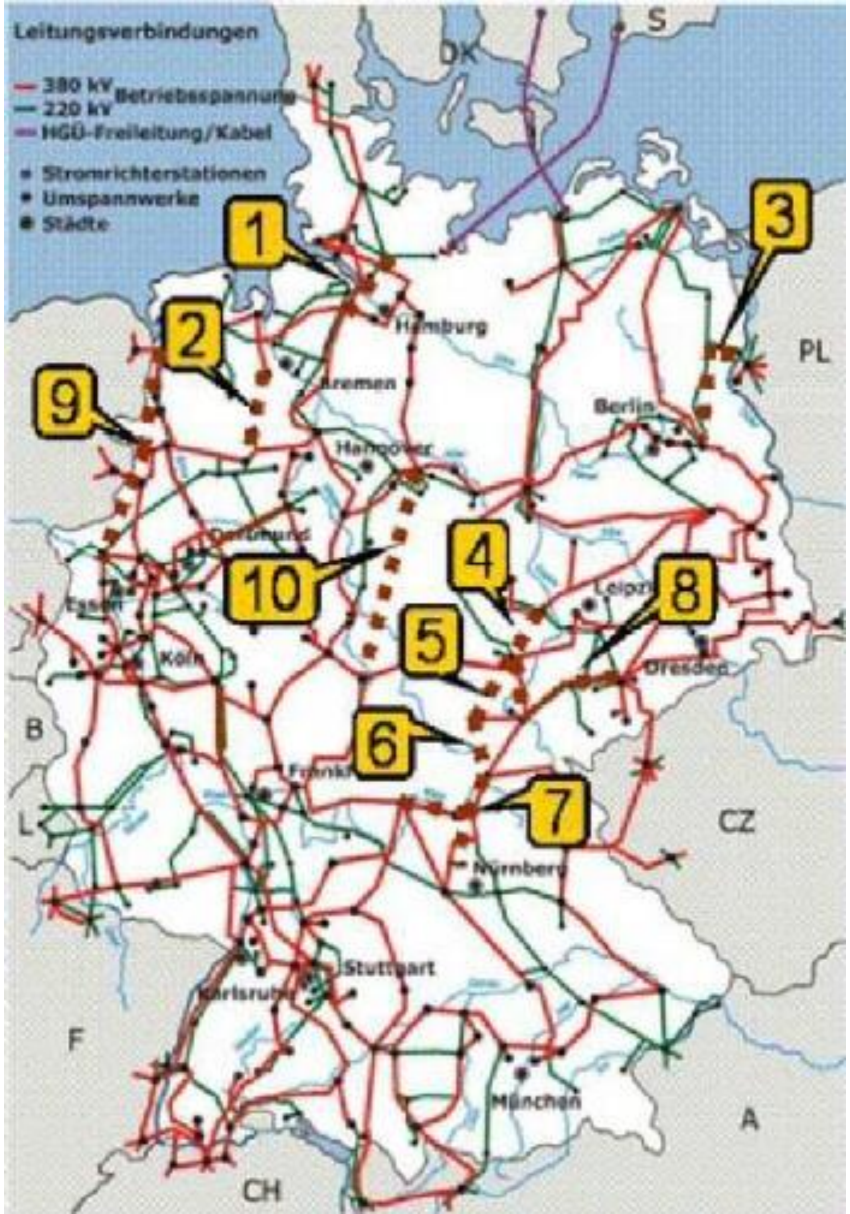
- Peak-load pricing
- Nodal & Zonal

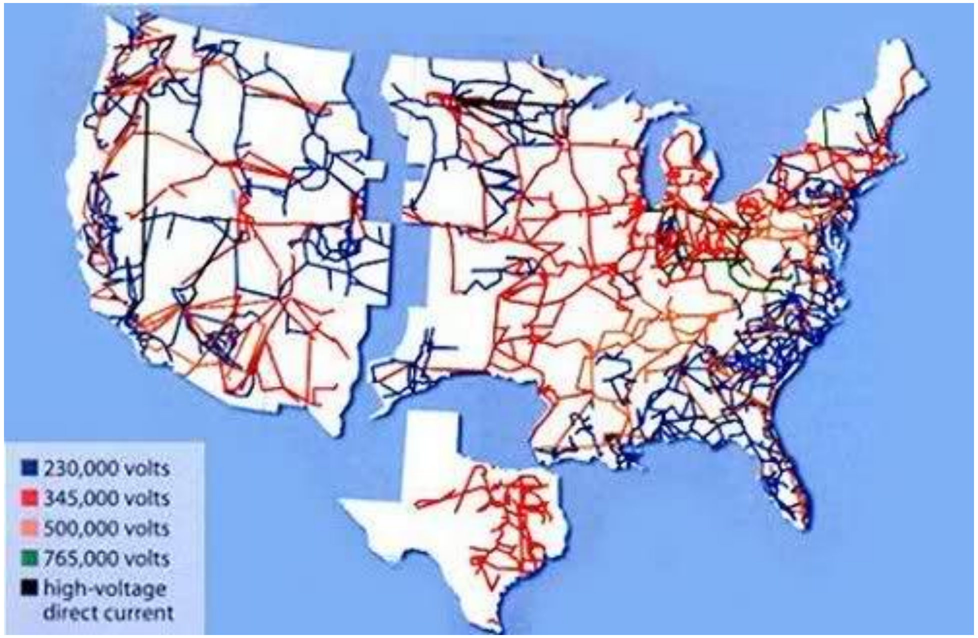
Zonal pricing -> averaging

(EU)

Nodal pricing (also Locational Marginal Pricing) -> peak-load pricing

(USA)





- Nodal pricing is a generalization of peak-load pricing

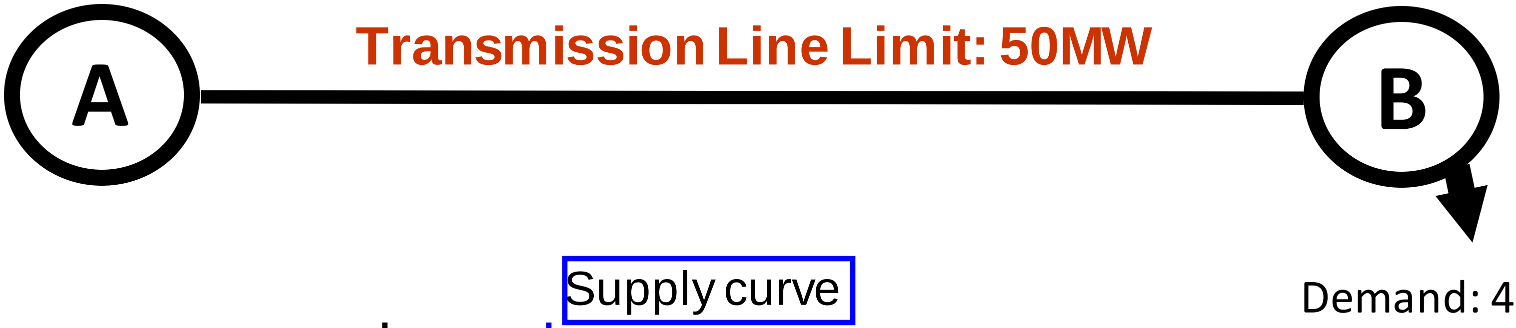
2 node network

- Biggar Chap 7.1-7.3

Perfect competition both on seller (power producers) and buyers (power retailers) side

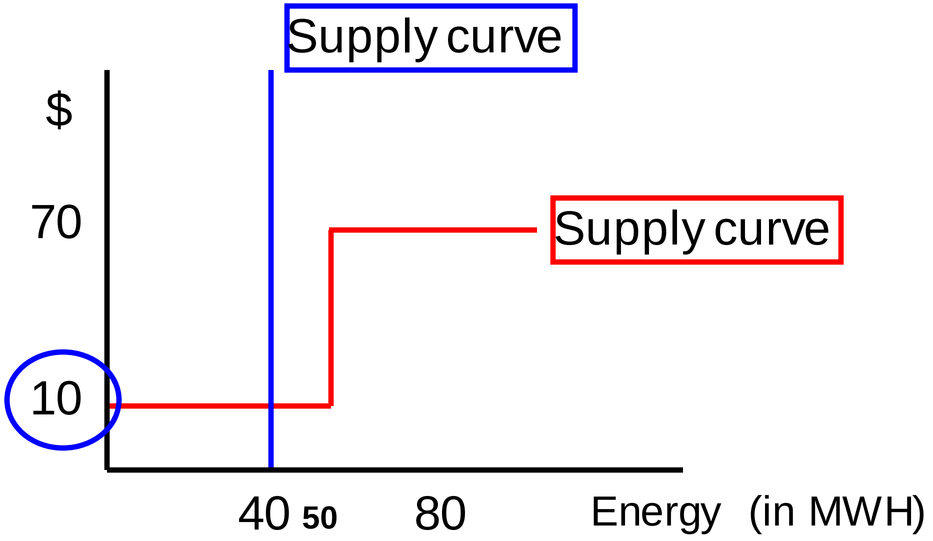
Production cost (MC): $10/MWH

Production cost (MC): $70/MWH



Price electricity at A: $10/MWH

Price electricity at B: $10/MWH

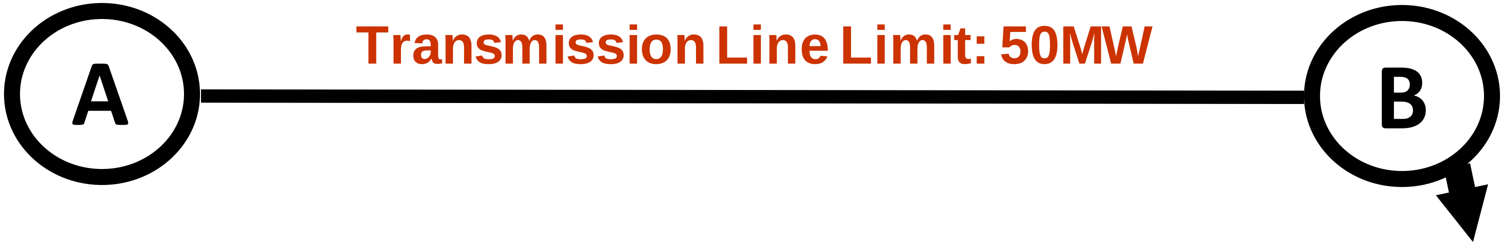


Perfect competition both on seller (power producers) and buyers (power retailers) side

Production cost (MC): $10/MWH

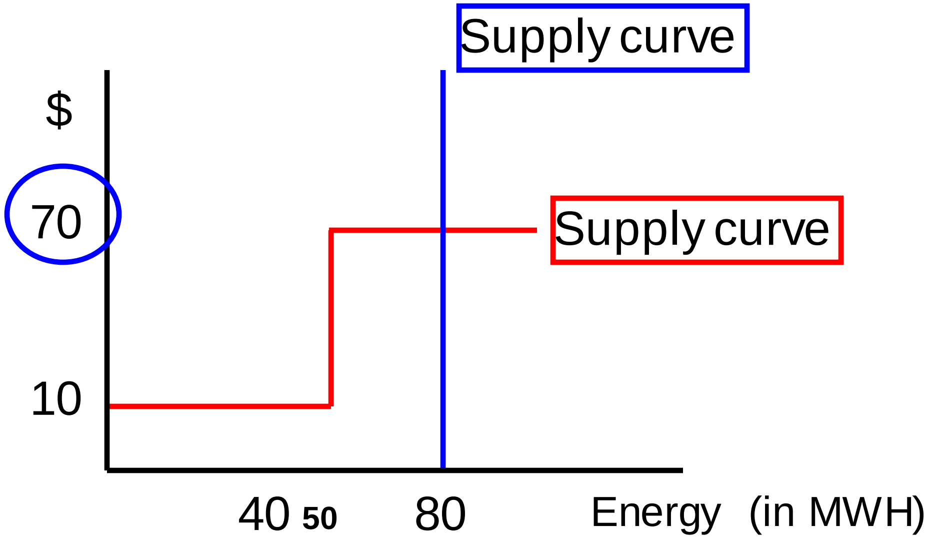
Price of the line? <u>$60/MWH!</u>

Production cost (MC): $70/MWH



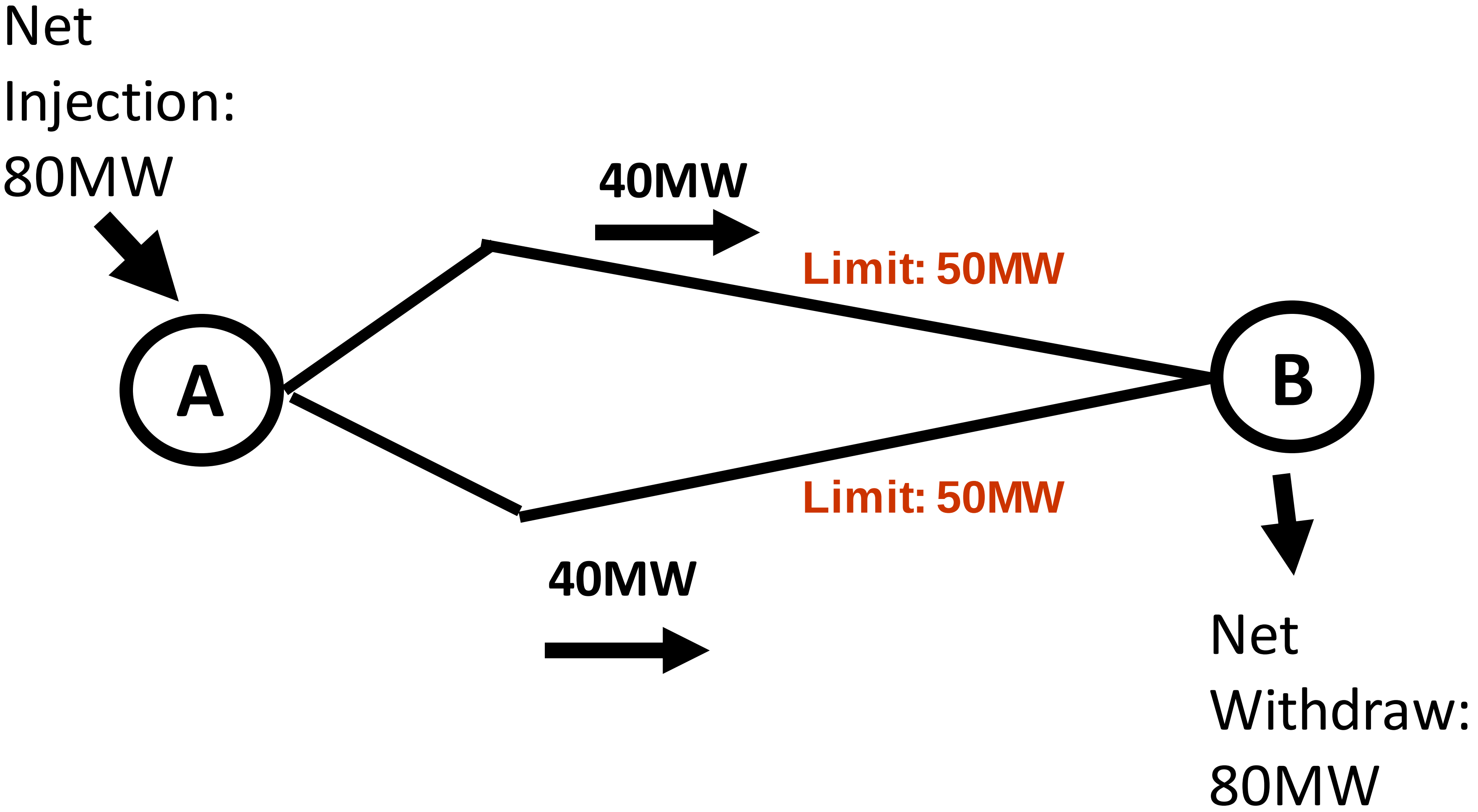
Transmission Line Limit: 50MW

Demand: 80MW



Price electricity at A: $10/MWH

Price electricity at B: <u>$70/MWH!</u>



Net
Injection:
80MW

A

40MW

Limit: 50MW

B

Limit: 50MW

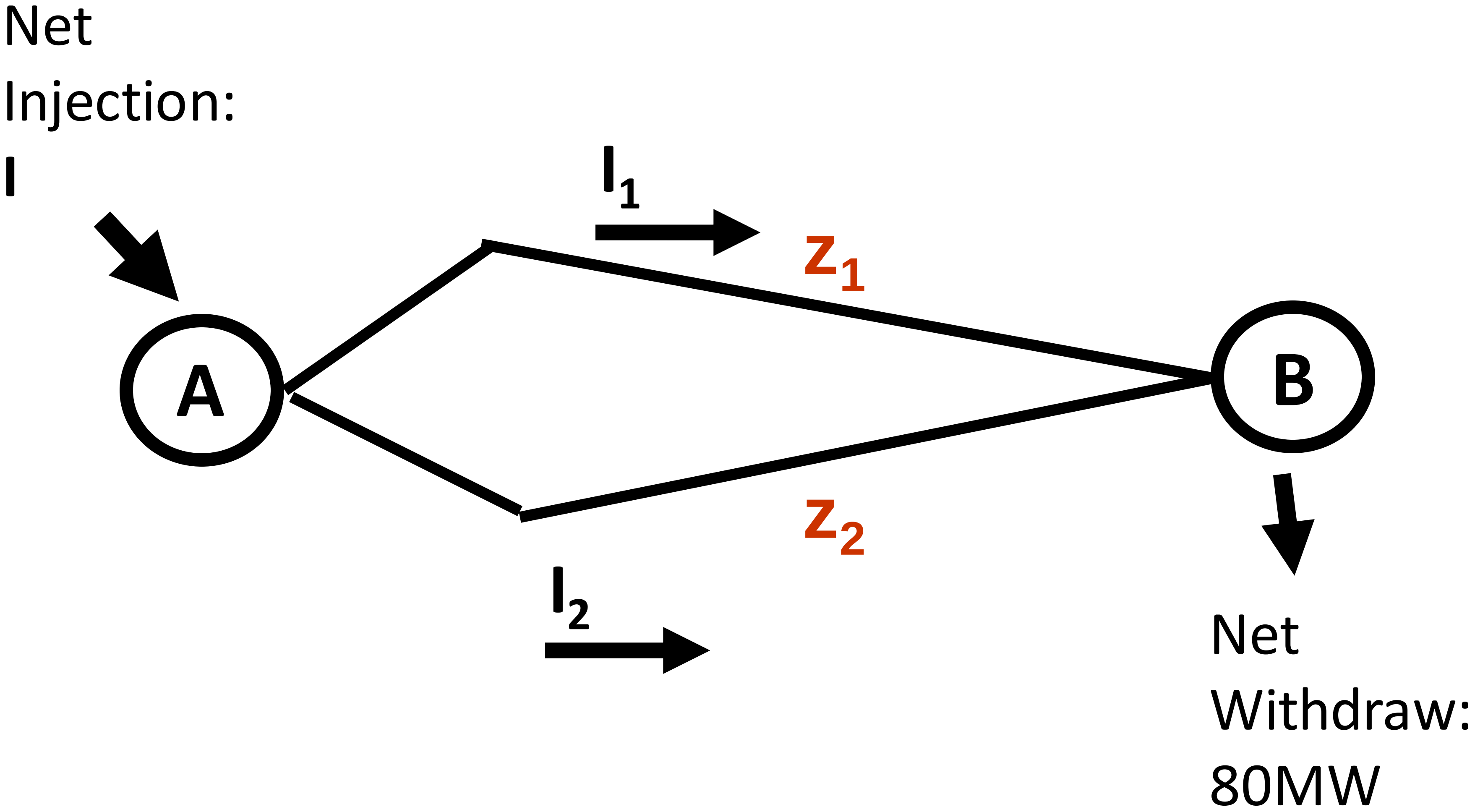
40MW

Net
Withdraw:
80MW

- **WIKI:**
- **Electrical impedance** is the measure of the opposition that a circuit presents to a current when a voltage is applied.
- In quantitative terms, it is the complex ratio of the voltage to the current in an alternating current (AC) circuit. Impedance extends the concept of resistance to AC circuits, and possesses both magnitude and phase, unlike resistance, which has only magnitude. When a circuit is driven with direct current (DC), there is no distinction between impedance and resistance; the latter can be thought of as impedance with zero phase angle.

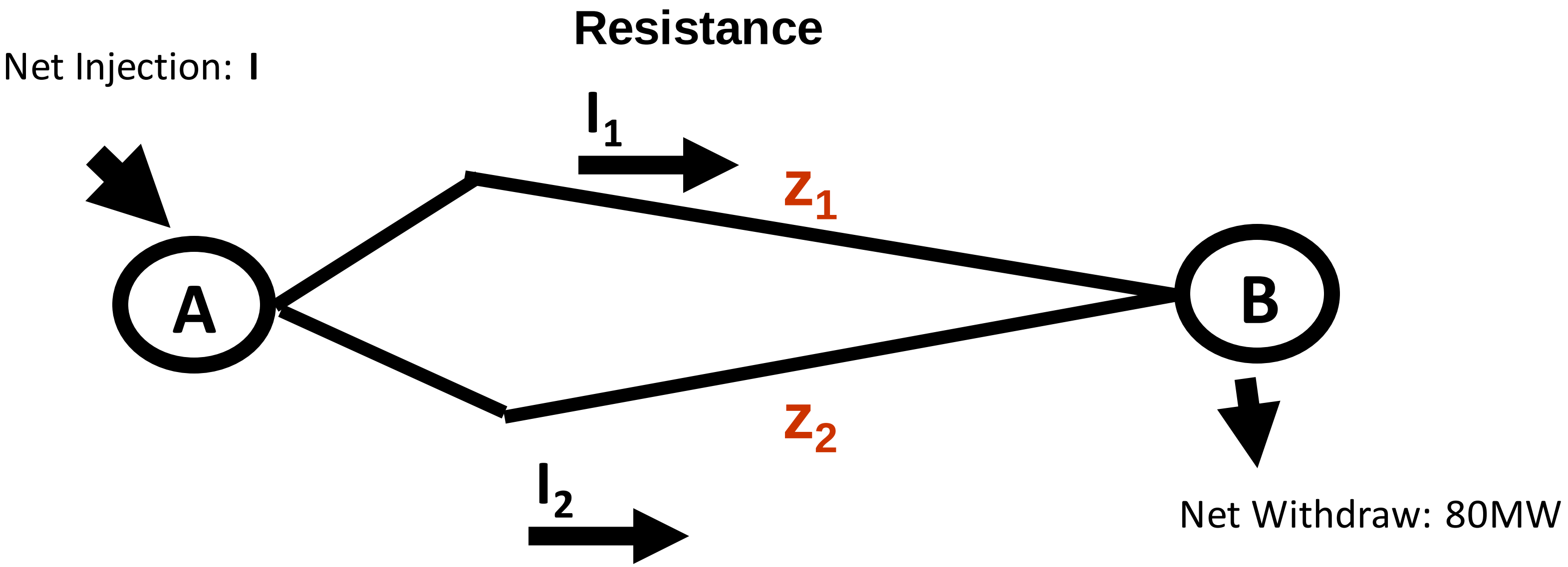
- **Reactance** is the opposition of a circuit element to a change of electric current or voltage, due to that element's inductance or capacitance. A built-up electric field resists the change of voltage on the element, while a magnetic field resists the change of current. The notion of reactance is similar to electrical resistance, but they differ in several respects.

Resistance



Net
Injection:
I

Net
Withdraw:
80MW



$$I = I_1 + I_2$$

$$I_1 z_1 = I_2 z_2$$

Kirchen, 2004, p.143

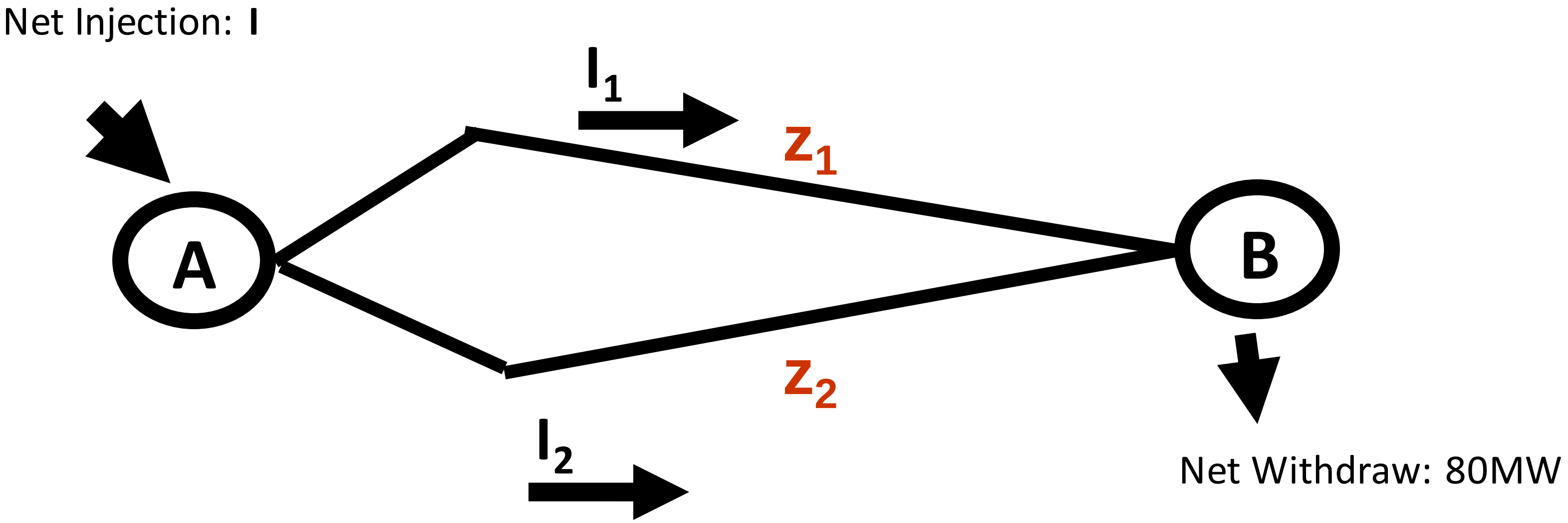
$$I_2 = \frac{I_1 z_1}{z_2}$$

$$I_1 = I - I_2 = I - \frac{I_1 z_1}{z_2}$$

$$I_1 \left(1 + \frac{z_1}{z_2}\right) = I$$

$$I_1 = I \frac{1}{1 + \frac{z_1}{z_2}} = I \frac{z_2}{z_2 + z_1}$$

Resistance



What is the resistance going from A to B?

$$\frac{1}{Z} = \frac{1}{z_1} + \frac{1}{z_2}$$

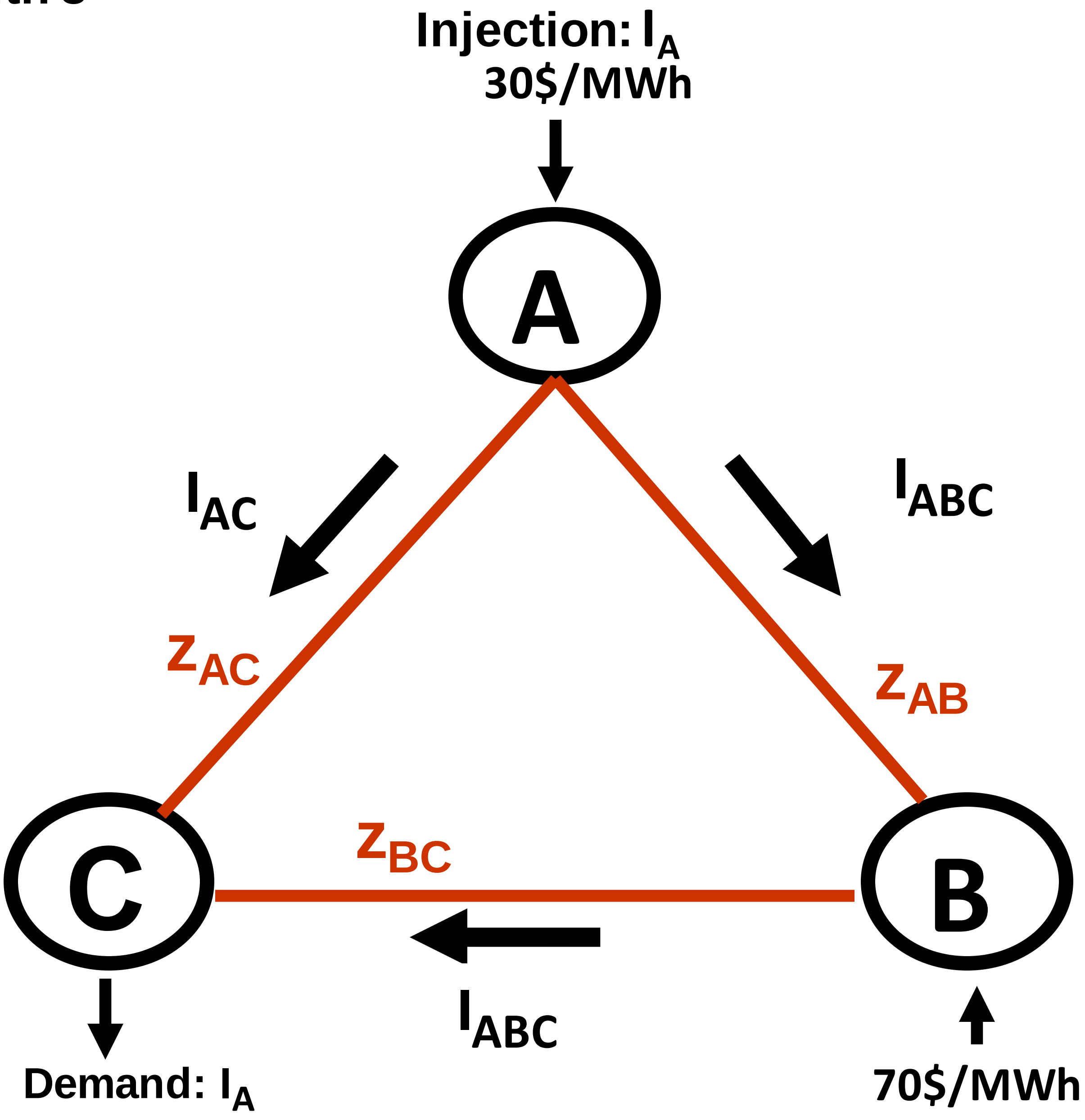
Say $z_1 = z_2 = 1$

$$\frac{1}{Z} = 2 \Leftrightarrow Z = \tfrac{1}{2}$$

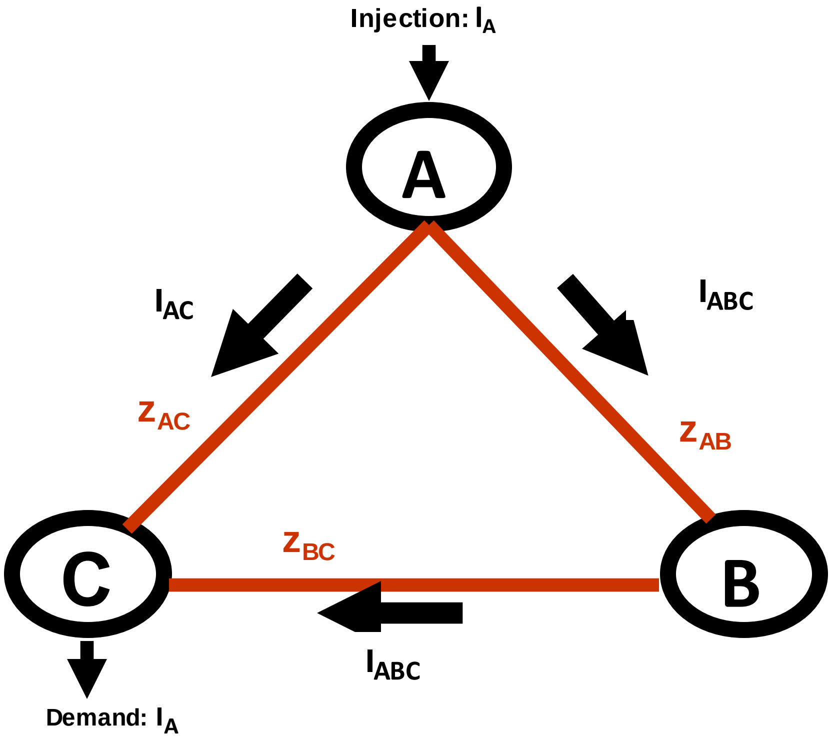
3 node network

- Kirschen Ch.6 (ignore losses)
- Biggar Chap 6, 7.4-7.8

Dispatch with 3 nodes



Dispatch with 3 nodes



$$I = I_{AC} + I_{ABC}$$

$$I_{AC} z_{AC} = I_{ABC} (z_{AB} + z_{BC})$$

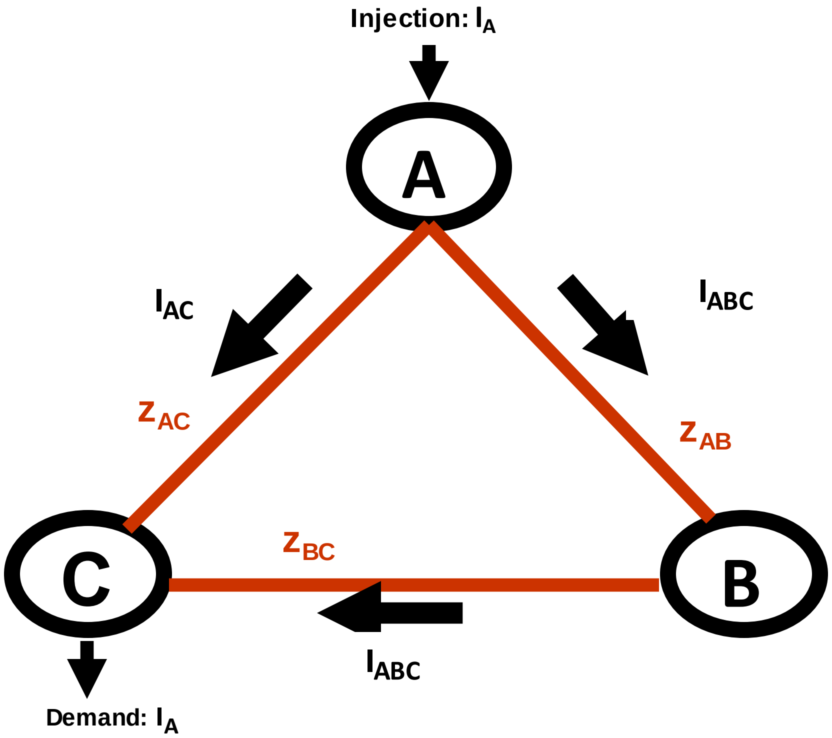
$$I_{ABC} = \frac{I_{AC} z_{AC}}{z_{AB} + z_{BC}}$$

$$I_{AC} \left(1 + \frac{z_{AC}}{z_{AB} + z_{BC}}\right) = I$$

$$I_{AC} = I \frac{1}{1 + \frac{z_{AC}}{z_{AB} + z_{BC}}}$$

$$= I \frac{z_{AB} + z_{BC}}{z_{AB} + z_{BC} + z_{AC}}$$

Dispatch with 3 nodes



$$I_{AC} = I\frac{z_{AB} + z_{BC}}{z_{AB} + z_{BC} + z_{AC}}$$

$$I_{ABC} = I\frac{z_{AC}}{z_{AB} + z_{BC} + z_{AC}}$$

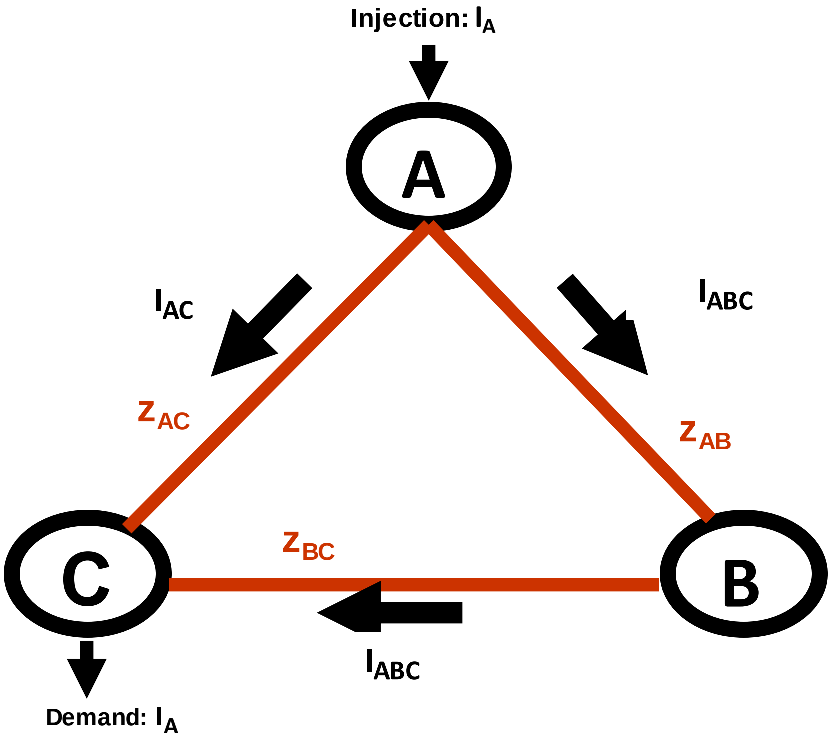
For a simple example, take the simplest possible numbers

$$z_{AC} = z_{AB} = z_{BC} = 1$$

$$I_{AC} = \tfrac{2}{3} I$$

$$I_{ABC} = \tfrac{1}{3} I$$

Dispatch with 3 nodes



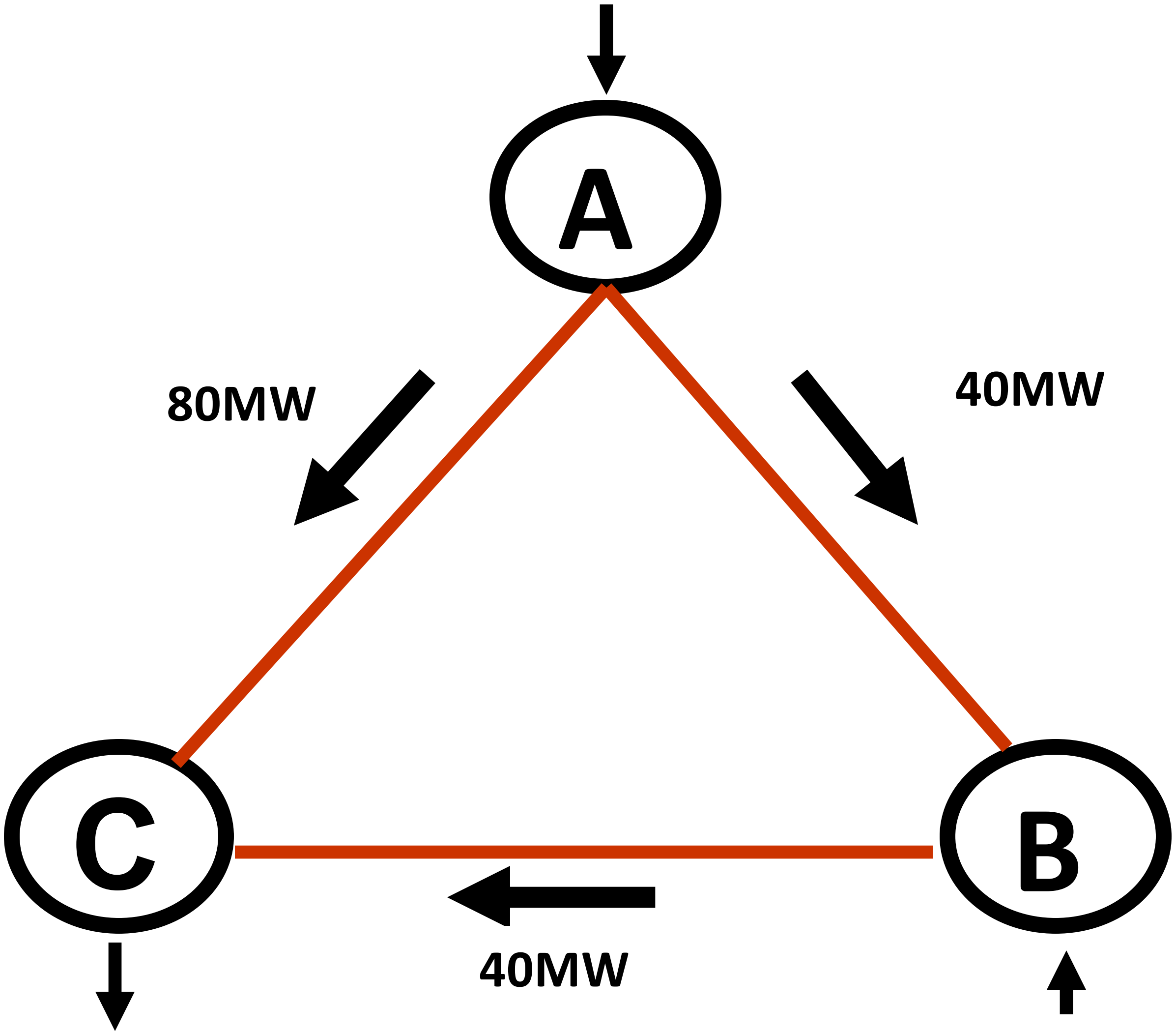
What is the resistance going from A to B?

$$\frac{1}{Z} = \frac{1}{z_1} + \frac{1}{z_2 + z_3}$$

And we assumed $z_1 = z_2 = z_3 = 1$

$$\frac{1}{Z} = \frac{1}{1} + \frac{1}{2} \Leftrightarrow Z = \tfrac{2}{3}$$

Dispatch with 3 nodes



Injection: 120MW

30$/MWh

80MW

40MW

40MW

70$/MWh

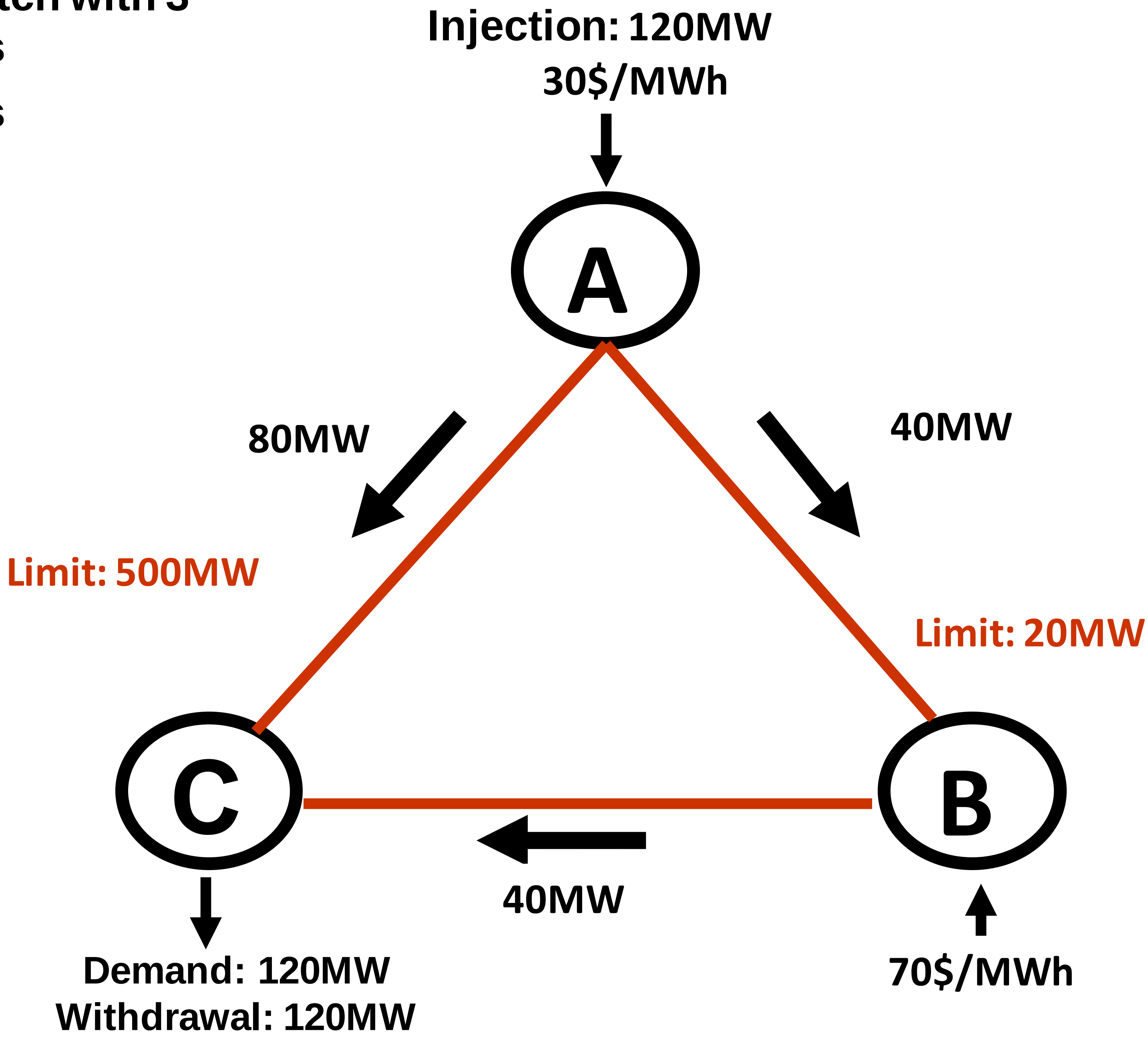
Demand: 120MW

Withdrawal: 120MW

Marginal Cost? 30$/MWh

Dispatch with 3 nodes

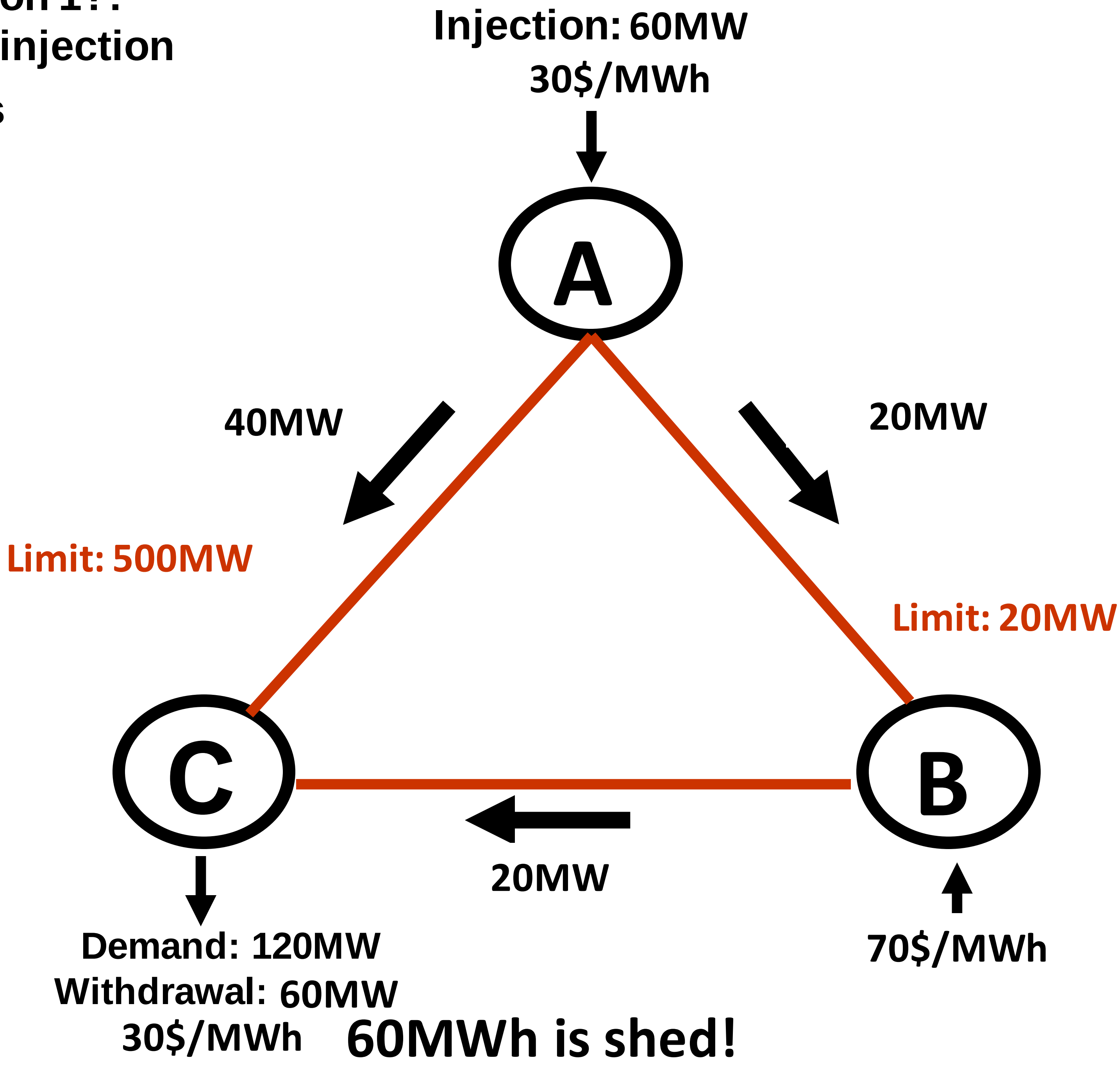
Limits



- **Line AB: limit violated!**

Solution 1?: lower injection

Limits



Injection: 60MW
30$/MWh

40MW

20MW

Limit: 500MW

Limit: 20MW

20MW

70$/MWh

Demand: 120MW
Withdrawal: 60MW
30$/MWh

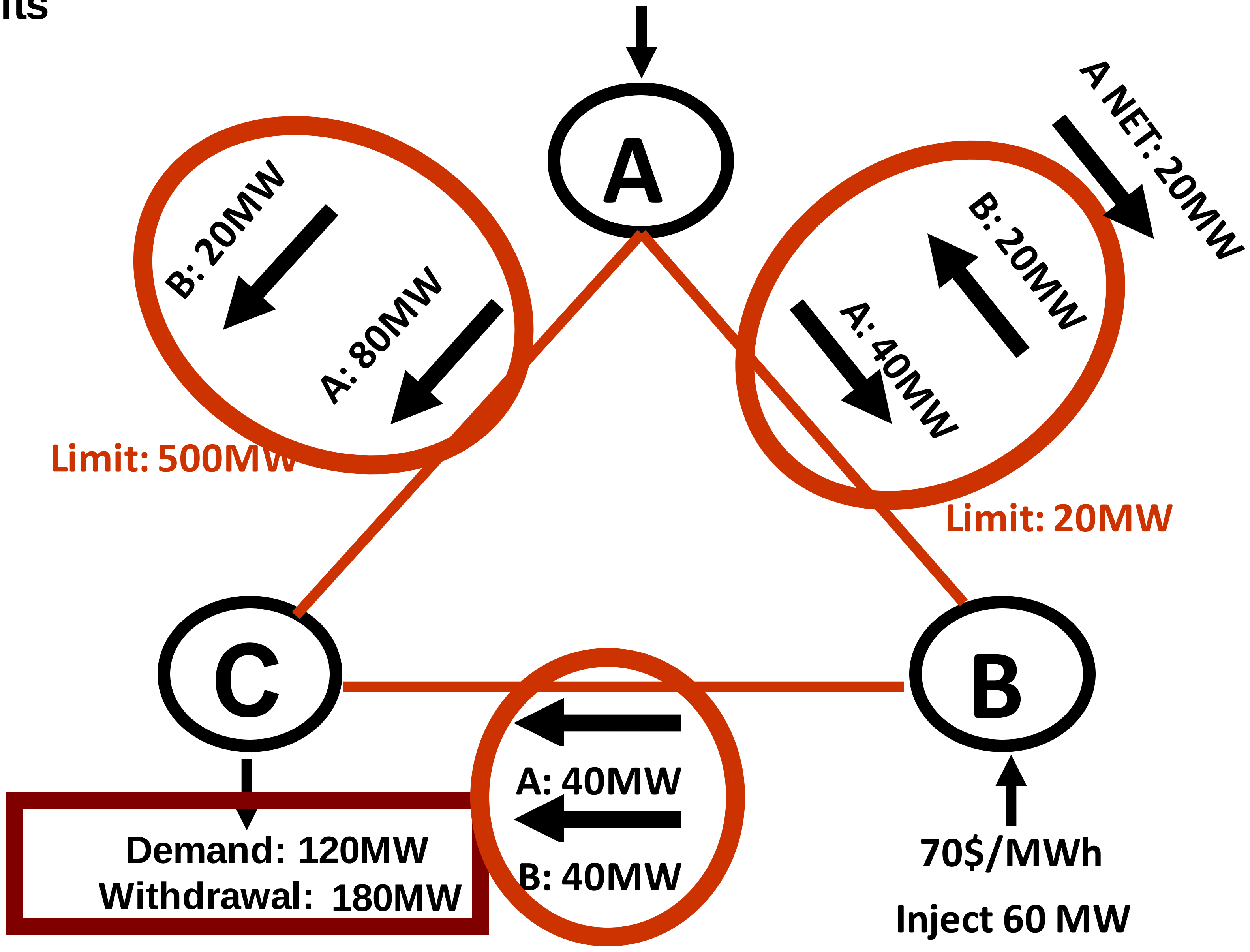
60MWh is shed!

- **Too little electricity to C!**

Solution 2?: Add counter flow

Limits

Injection: 120MW
30$/MWh



A NET: 20MW

B: 20MW

A: 80MW

Limit: 500MW

B: 20MW

A: 40MW

Limit: 20MW

A: 40MW

B: 40MW

Demand: 120MW
Withdrawal: 180MW

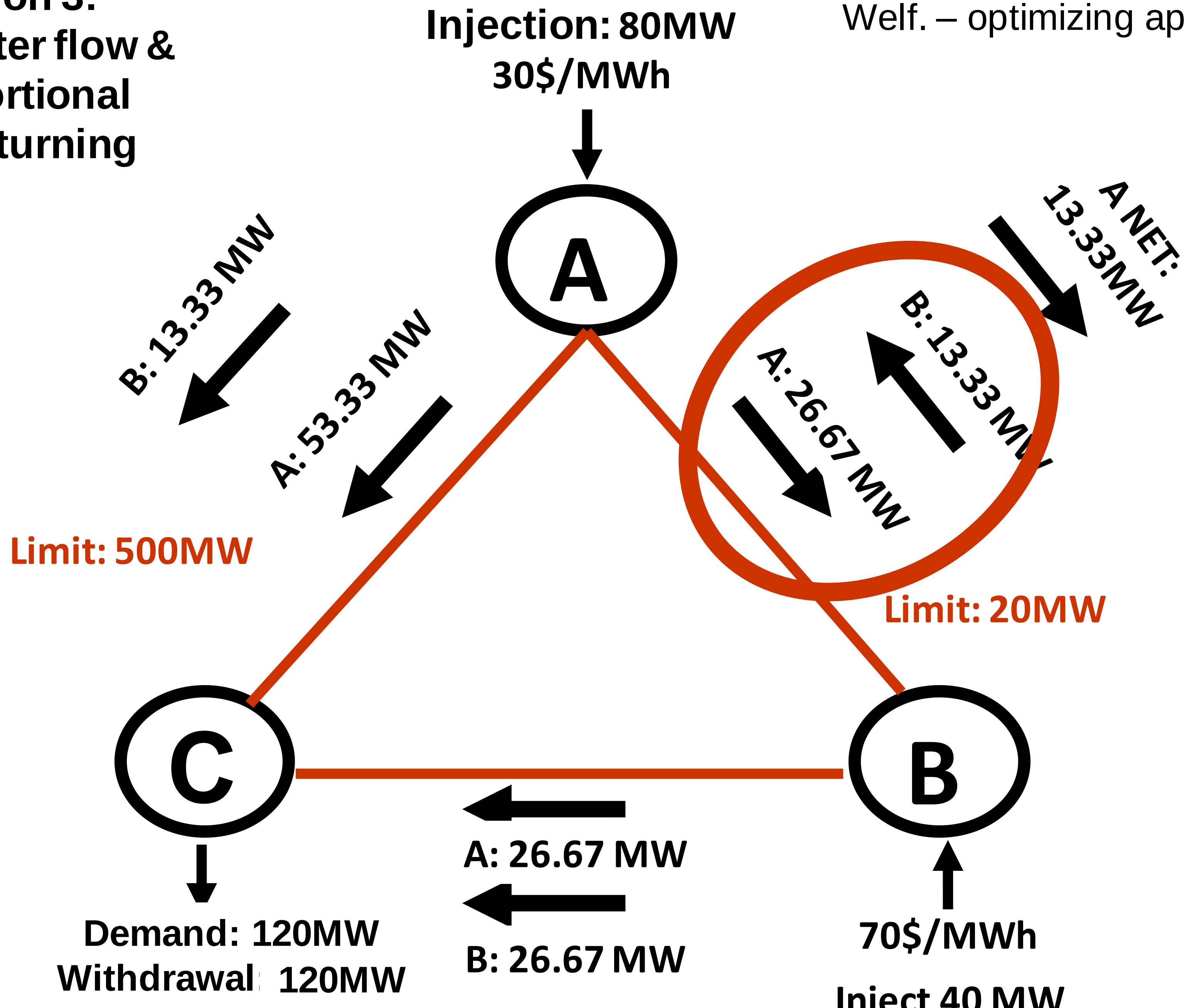
70$/MWh

Inject 60 MW

- **Too much electricity to C!**

Solution 3: Counter flow & proportional downturning

Welf. – optimizing approach



Injection: 80MW

30$/MWh

B: 13.33 MW

A: 53.33 MW

Limit: 500MW

A NET: 13.33MW

B: 13.33 MW

A: 26.67 MW

Limit: 20MW

A: 26.67 MW

B: 26.67 MW

Demand: 120MW

Withdrawal: 120MW

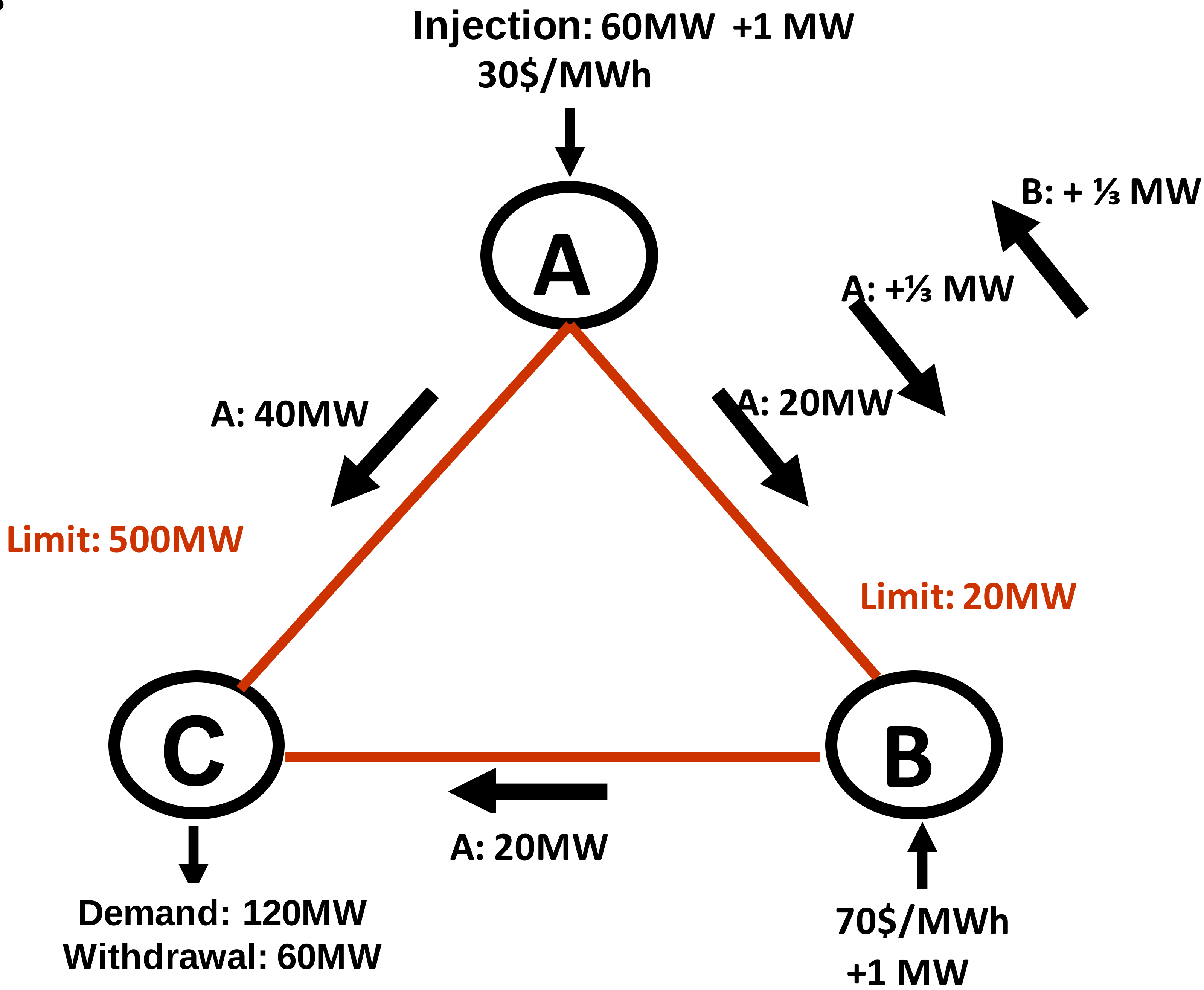
70$/MWh

Inject 40 MW

- **Inefficient solution**
  - **Line AB is not fully used**
    - **some generation at B can be replaced by A**

- Start from scratch
- Notice:
  - Up till 60MW from A no problem

Limits



Injection: 60MW +1 MW

30$/MWh

B: + ⅓ MW

A: +⅓ MW

A: 40MW

A: 20MW

Limit: 500MW

Limit: 20MW

A: 20MW

Demand: 120MW

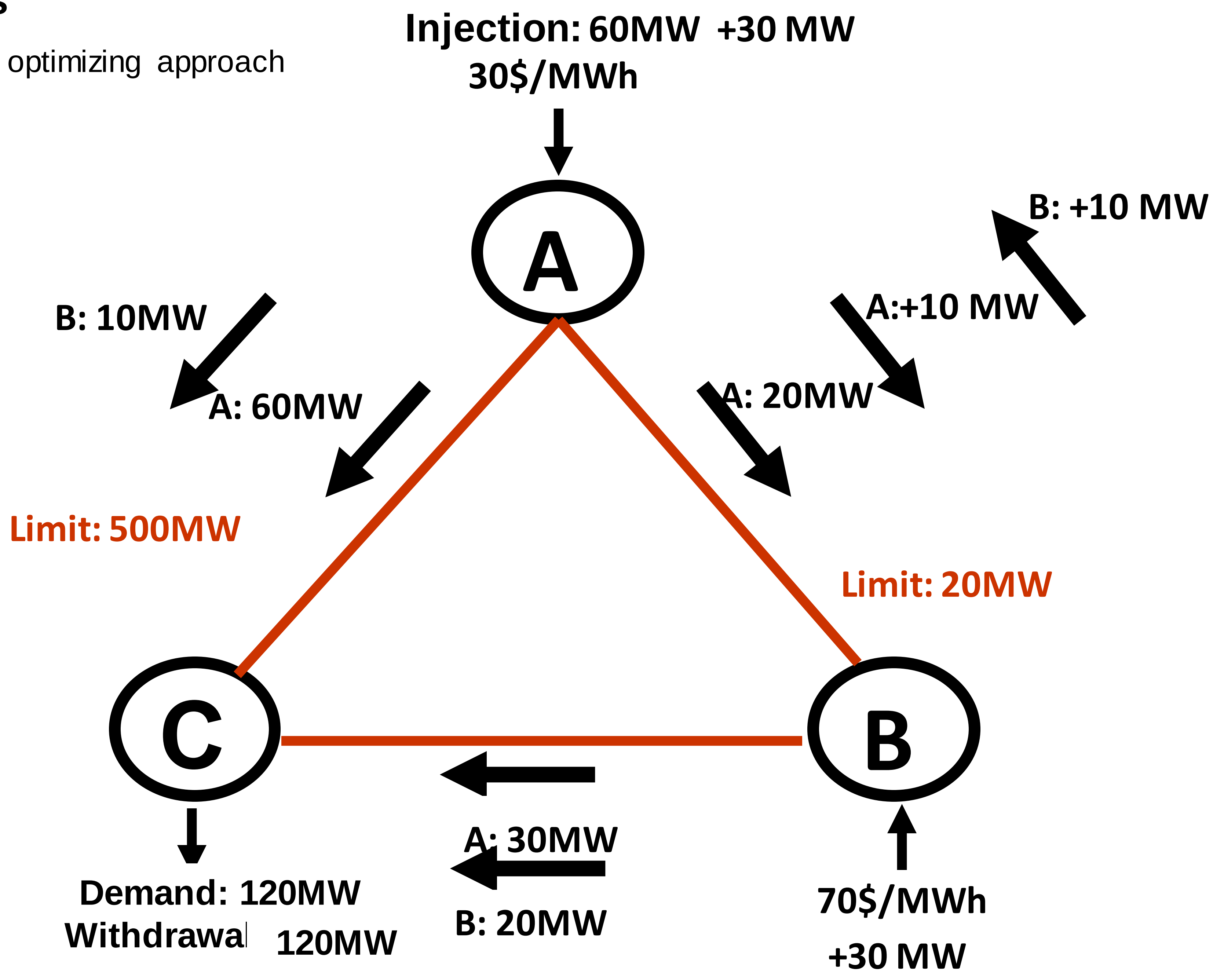
Withdrawal: 60MW

70$/MWh

+1 MW

Limits

Welf. – optimizing approach



Injection: 60MW +30 MW

30$/MWh

B: +10 MW

A:+10 MW

B: 10MW

A: 60MW

A: 20MW

Limit: 500MW

Limit: 20MW

A: 30MW

B: 20MW

Demand: 120MW

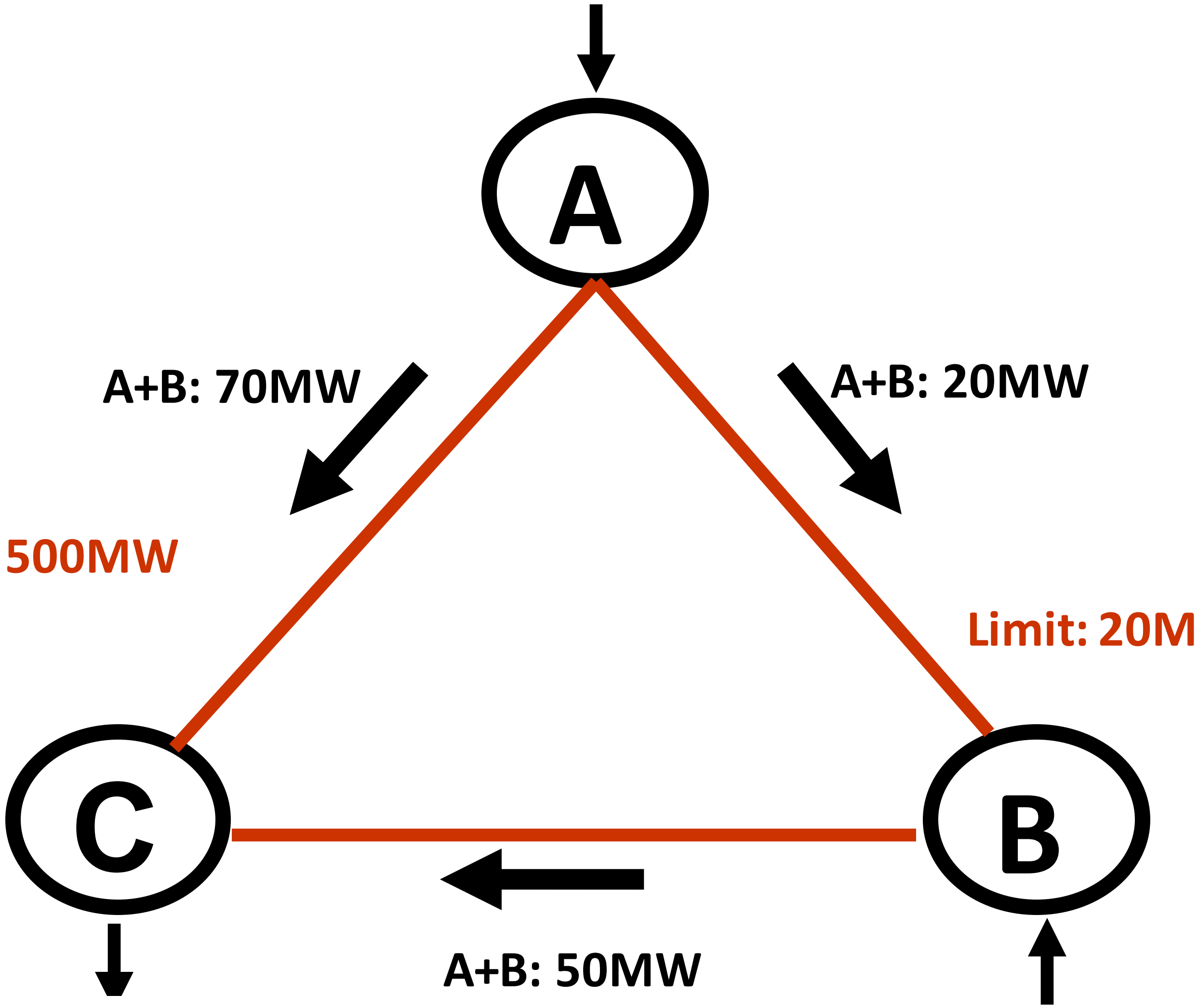
Withdrawal 120MW

70$/MWh

+30 MW

Limits

Welf. – optimizing approach



Injection: 60MW +30 MW
30$/MWh

A

A+B: 70MW

Limit: 500MW

A+B: 20MW

Limit: 20MW

C

B

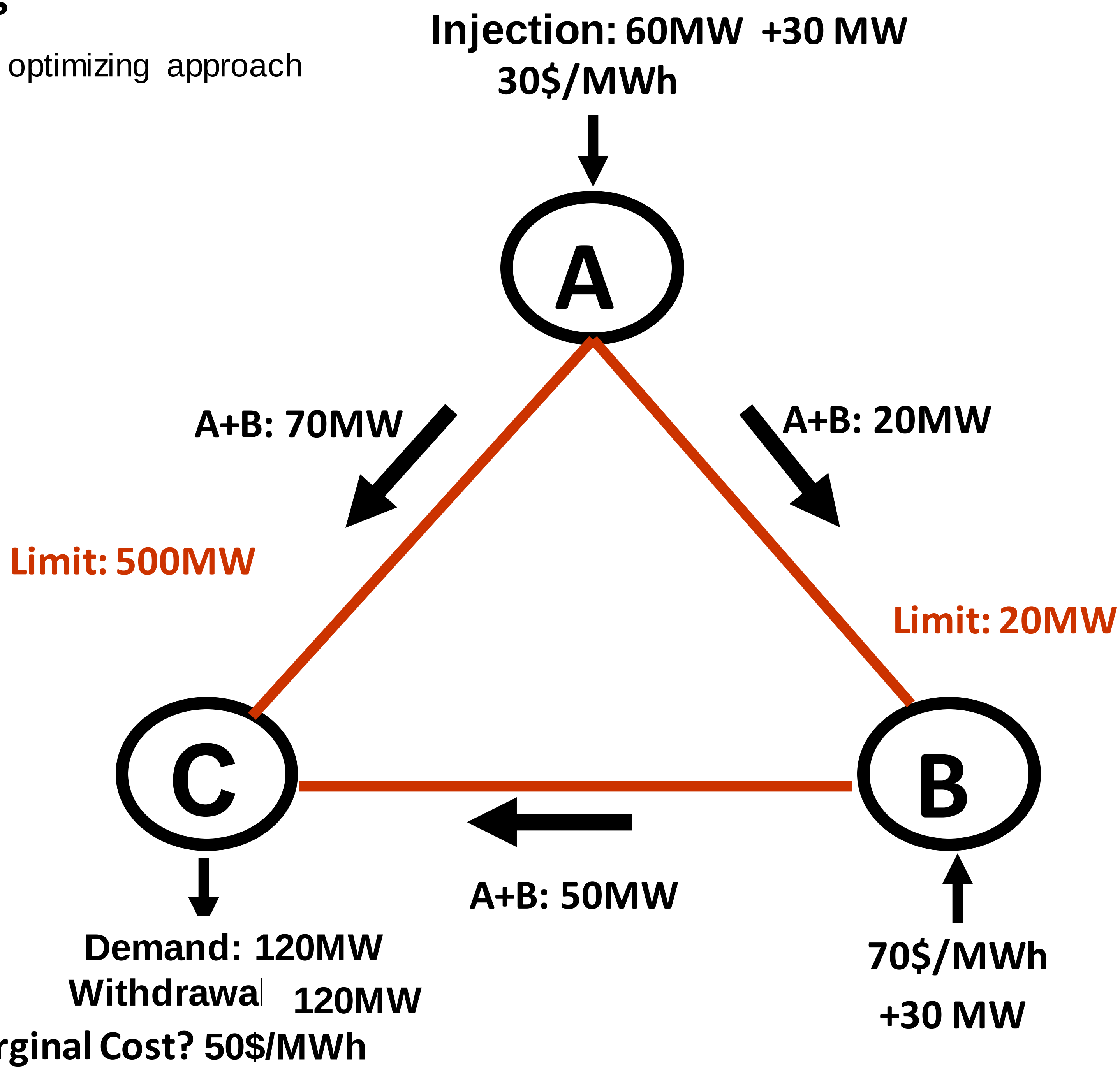
A+B: 50MW

Demand: 120MW
Withdrawal 120MW

70$/MWh
+30 MW

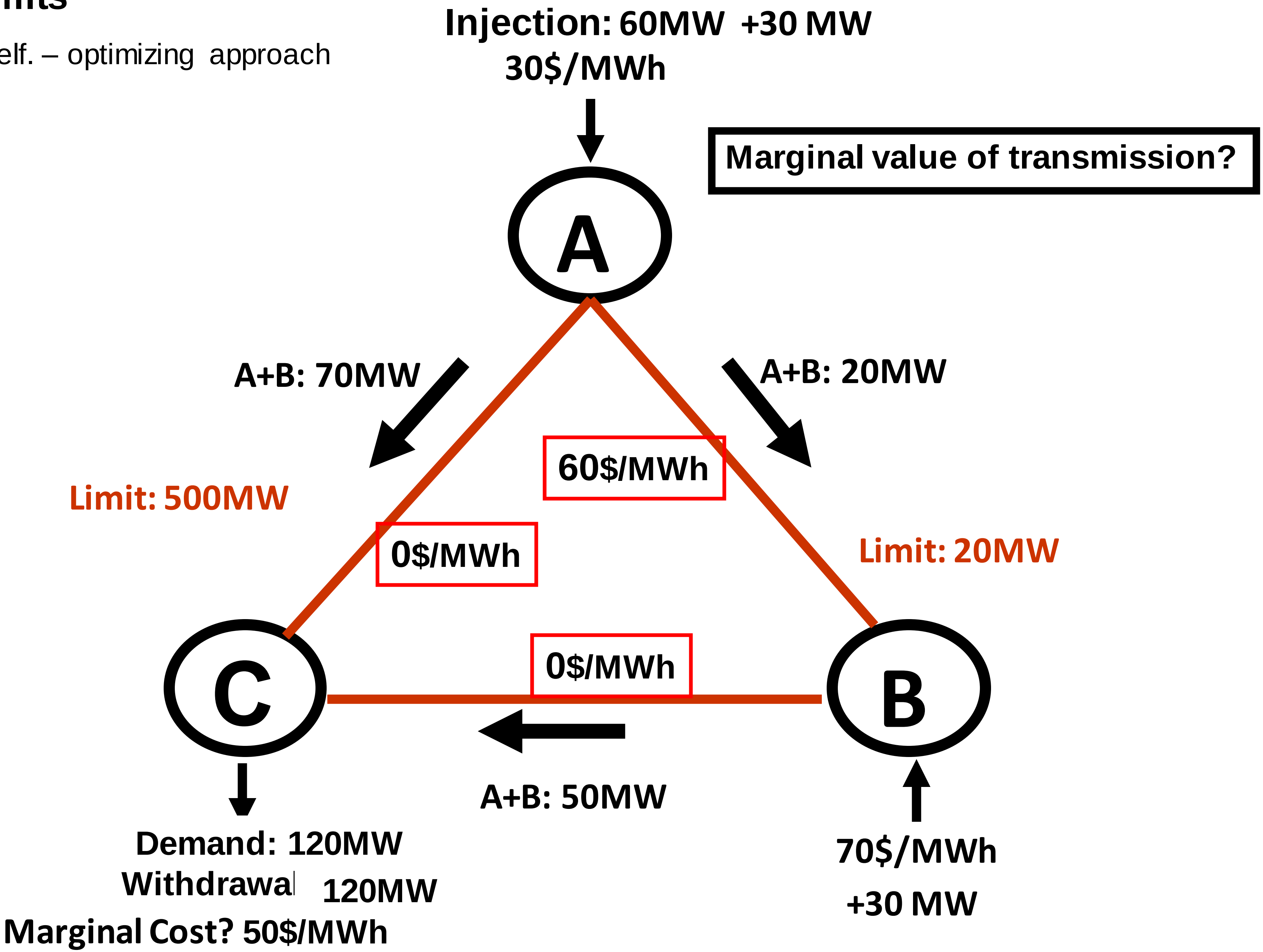
Limits

Welf. – optimizing approach



Limits

Welf. – optimizing approach



Injection: 60MW +30 MW
30$/MWh

Marginal value of transmission?

A+B: 70MW

A+B: 20MW

60$/MWh

Limit: 500MW

0$/MWh

Limit: 20MW

0$/MWh

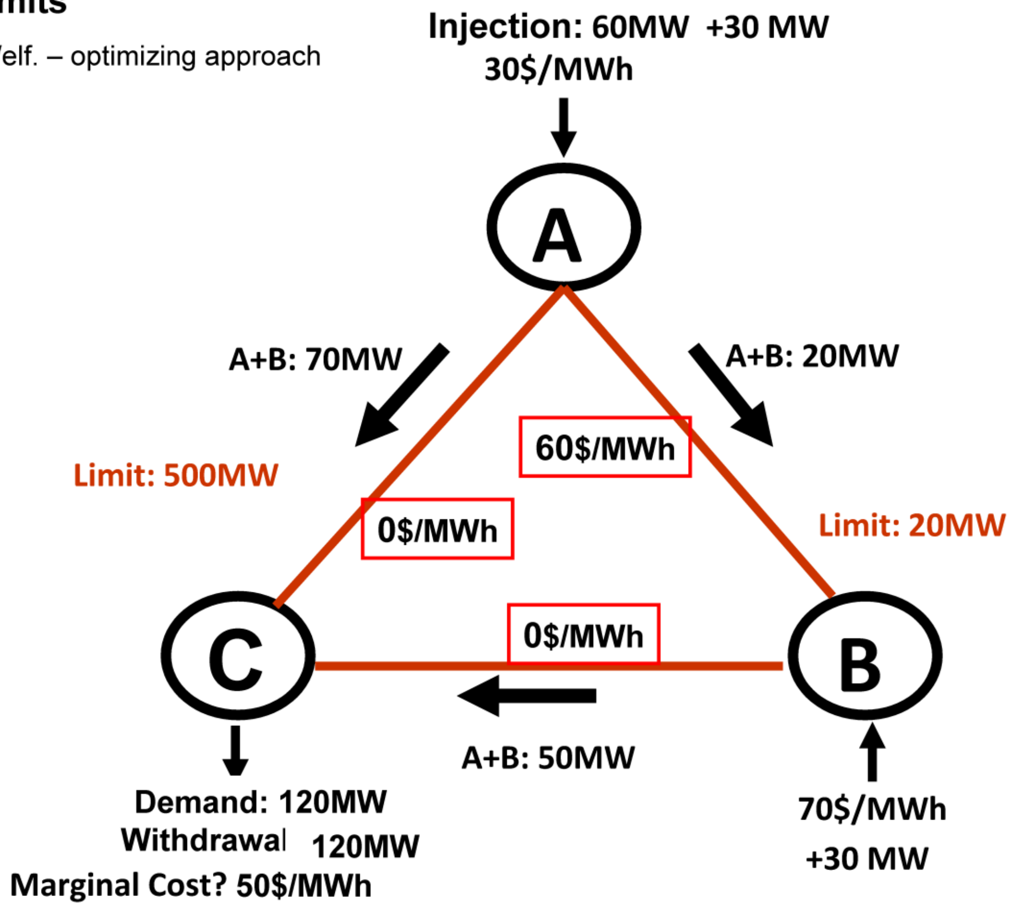
A+B: 50MW

Demand: 120MW
Withdrawal 120MW
Marginal Cost? 50$/MWh

70$/MWh
+30 MW

Limits

Welf. – optimizing approach



Earnings

- What do generators at A earn?
- What do generators at B earn?
- What do transmission owners earn?

Switch to CE–approach

Earning from production

- A: 90 * $20 = $1800
- B: 30 * -$20 = -$600

???

Payments for transmission

- A: 30 * $60 = $1800
- B: 10 * -$60 = -$600

- Formal formulation

$$\mathrm{Min}_{A,B}\ 30\,\mathrm{A}+70\,\mathrm{B}\ \mathrm{s.t.:}$$

$$\tfrac{1}{3}A-\tfrac{1}{3}B\leq 20$$

$$120\leq(A+B)$$

plant cost-minimizing input bundle. Each plant then has a cost function derived in the usual way. In the two-plant problem the plant cost function is

$$C_i = C_i(y^i) \qquad (i = 1, 2)$$

where C_i is total cost in plant i, y^i is the output in plant i (y^1 and y^2 are the same goods but produced in different plants) and the input prices have been omitted from the cost functions. C_i may be the short- or long-run cost function depending on the constraints on the adjustment of inputs. The second stage of the problem is

$$\min_{y_1, y_2} C = C_1(y^1) + C_2(y^2) \quad \text{s.t. (i)} \; y^1 + y^2 \geqslant y^0$$
$$\text{(ii)} \; y^i \geqslant 0 \qquad (i = 1, 2) \qquad \text{[D.1]}$$

The marginal cost in plant i is $C_i'(y^i)$ and we assume that the cost functions are strictly convex in y^i so that marginal cost is increasing with output: $C_i''(y^i) > 0$, $y^i \geqslant 0$. This means that $C_1 + C_2$ is convex in the output levels and thus the Kuhn–Tucker conditions are sufficient as well as necessary. The Lagrangean is

$$L = C_1(y^1) + C_2(y^2) + \lambda(y^0 - y^1 - y^2) \qquad \text{[D.2]}$$

and the Kuhn–Tucker conditions are

$$L_i = C_i'(y^i) - \lambda \geqslant 0, \qquad y^i \geqslant 0, \qquad y^i[C_i'(y^i) - \lambda] = 0, \qquad i = 1, 2 \qquad \text{[D.3]}$$

$$L_\lambda = y^0 - y^1 - y^2 \leqslant 0, \qquad \lambda \geqslant 0, \qquad \lambda(y^0 - y^1 - y^2) = 0 \qquad \text{[D.4]}$$

Gravelle & Rees, 2004, Microeconomics, 3rd edition, p.135

- Formal formulation

$$L[A,B,\lambda,\mu]=30\,\mathrm{A}+70\,\mathrm{B}+\lambda(\tfrac{1}{3}A-\tfrac{1}{3}B-20)+\mu\big(120-(A+B)\big)$$

$$\boxed{\begin{array}{l}(1)\quad 0=L_A\Leftrightarrow 30+\tfrac{1}{3}\lambda-\mu\geq 0\\ \&\quad A(30+\tfrac{1}{3}\lambda-\mu)=0\quad \&\quad A\geq 0\end{array}}$$

$$\boxed{\begin{array}{l}(2)\quad 0=L_B\Leftrightarrow 70-\tfrac{1}{3}\lambda-\mu\geq 0\\ \&\quad B(70-\tfrac{1}{3}\lambda-\mu)=0\quad \&\quad B\geq 0\end{array}}$$

$$\boxed{\begin{array}{l}(3)\quad 0=L_\lambda\Leftrightarrow \tfrac{1}{3}A-\tfrac{1}{3}B-20\leq 0\\ \&\quad \lambda(\tfrac{1}{3}A-\tfrac{1}{3}B-20)=0\end{array}}$$

$$\boxed{\begin{array}{l}(4)\quad 0=L_\mu\Leftrightarrow 120-(A+B)\leq 0\\ \&\quad \mu\big(120-(A+B)\big)=0\end{array}}$$

- Suppose A>0, B=0

$$\boxed{(3)\quad \tfrac{1}{3}A-\tfrac{1}{3}B-20\leq 0\ \text{violated!}}$$

- Formal formulation

$$L[A,B,\lambda,\mu] = 30\,\mathrm{A} + 70\,\mathrm{B} + \lambda(\tfrac{1}{3}A - \tfrac{1}{3}B - 20) + \mu\big(120 - (A+B)\big)$$

$$\boxed{\begin{array}{l}(1)\quad 0 = L_A \Leftrightarrow 30 + \tfrac{1}{3}\lambda - \mu \geq 0 \\ \&\quad A(30 + \tfrac{1}{3}\lambda - \mu) = 0 \quad \& \quad A \geq 0\end{array}}$$

$$\boxed{\begin{array}{l}(2)\quad 0 = L_B \Leftrightarrow 70 - \tfrac{1}{3}\lambda - \mu \geq 0 \\ \&\quad B(70 - \tfrac{1}{3}\lambda - \mu) = 0 \quad \& \quad B \geq 0\end{array}}$$

$$\boxed{\begin{array}{l}(3)\quad 0 = L_\lambda \Leftrightarrow \tfrac{1}{3}A - \tfrac{1}{3}B - 20 \leq 0 \\ \&\quad \lambda(\tfrac{1}{3}A - \tfrac{1}{3}B - 20) = 0\end{array}}$$

$$\boxed{\begin{array}{l}(4)\quad 0 = L_\mu \Leftrightarrow 120 - (A+B) \leq 0 \\ \&\quad \mu\big(120 - (A+B)\big) = 0\end{array}}$$

- Suppose A>0, B>0

$$\left.\begin{array}{l}(1)\quad 30 + \tfrac{1}{3}\lambda - \mu = 0 \\ (2)\quad 70 - \tfrac{1}{3}\lambda - \mu = 0\end{array}\right\} \quad 100 - 2\mu = 0 \;\Leftrightarrow\; \mu = 50$$

Marginal cost of production for node c
The nodal price at c!

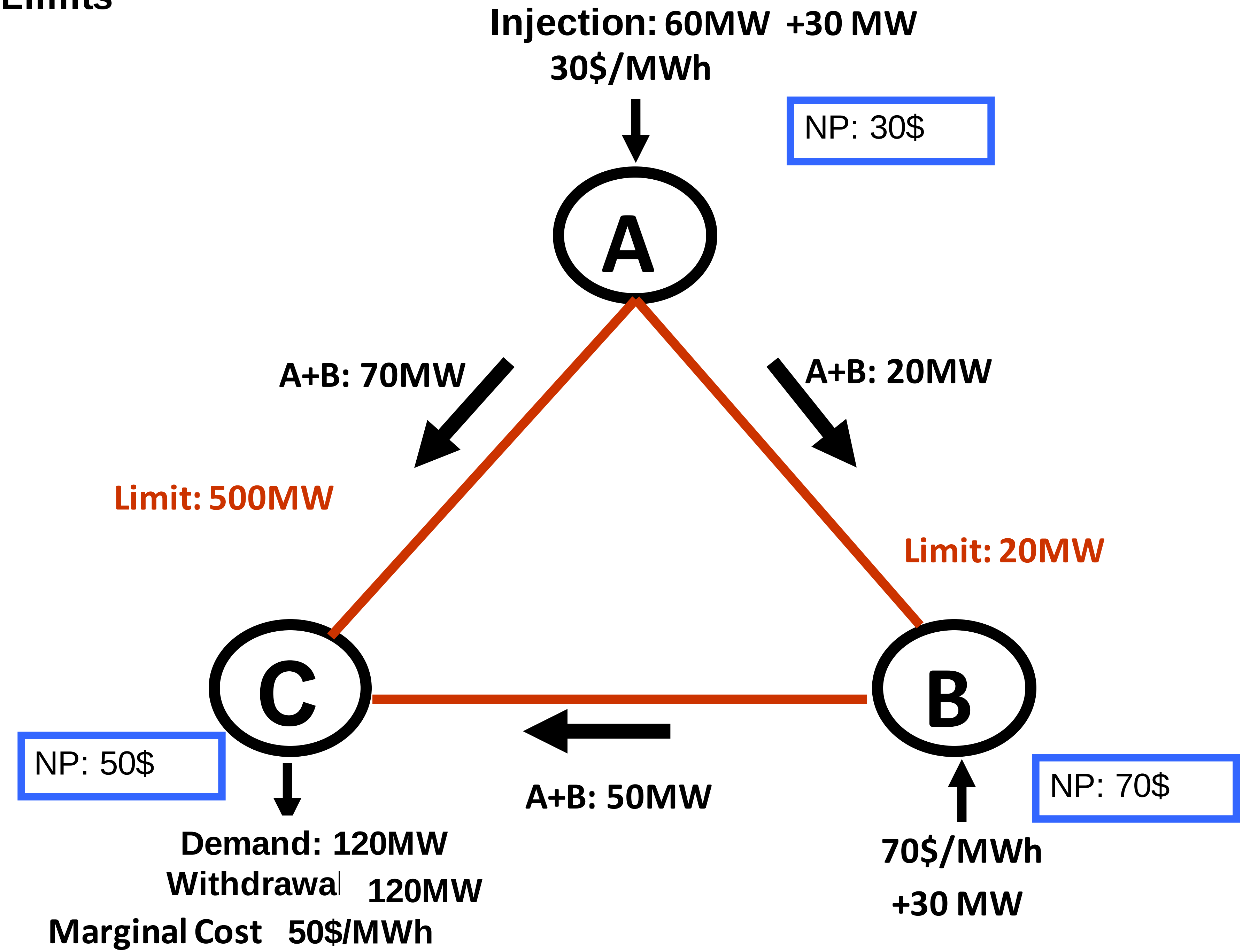
$$(1)\quad 30 + \tfrac{1}{3}\lambda - 50 = 0 \;\Leftrightarrow\; \tfrac{1}{3}\lambda = 50 - 30 = 20 \Leftrightarrow \lambda = 60$$

What is the economic interpretation of λ?

Theoretical work

- Léautier, T. 2001. Transmission constraints and imperfect power markets, the Journal of Regulatory Economics.
- Léautier, T. 2001. Auctions in power markets, the Journal of Economics and Management Strategy 3.
- Léautier, T. 2000. Regulation of a power transmission company, the Energy Journal 21(4).
- Léautier, T. 1999. The hidden value of transmission assets, The Electricity Journal, p. 69-78.

Limits



Injection: 60MW +30 MW
30$/MWh

NP: 30$

A+B: 70MW

A+B: 20MW

Limit: 500MW

Limit: 20MW

NP: 50$

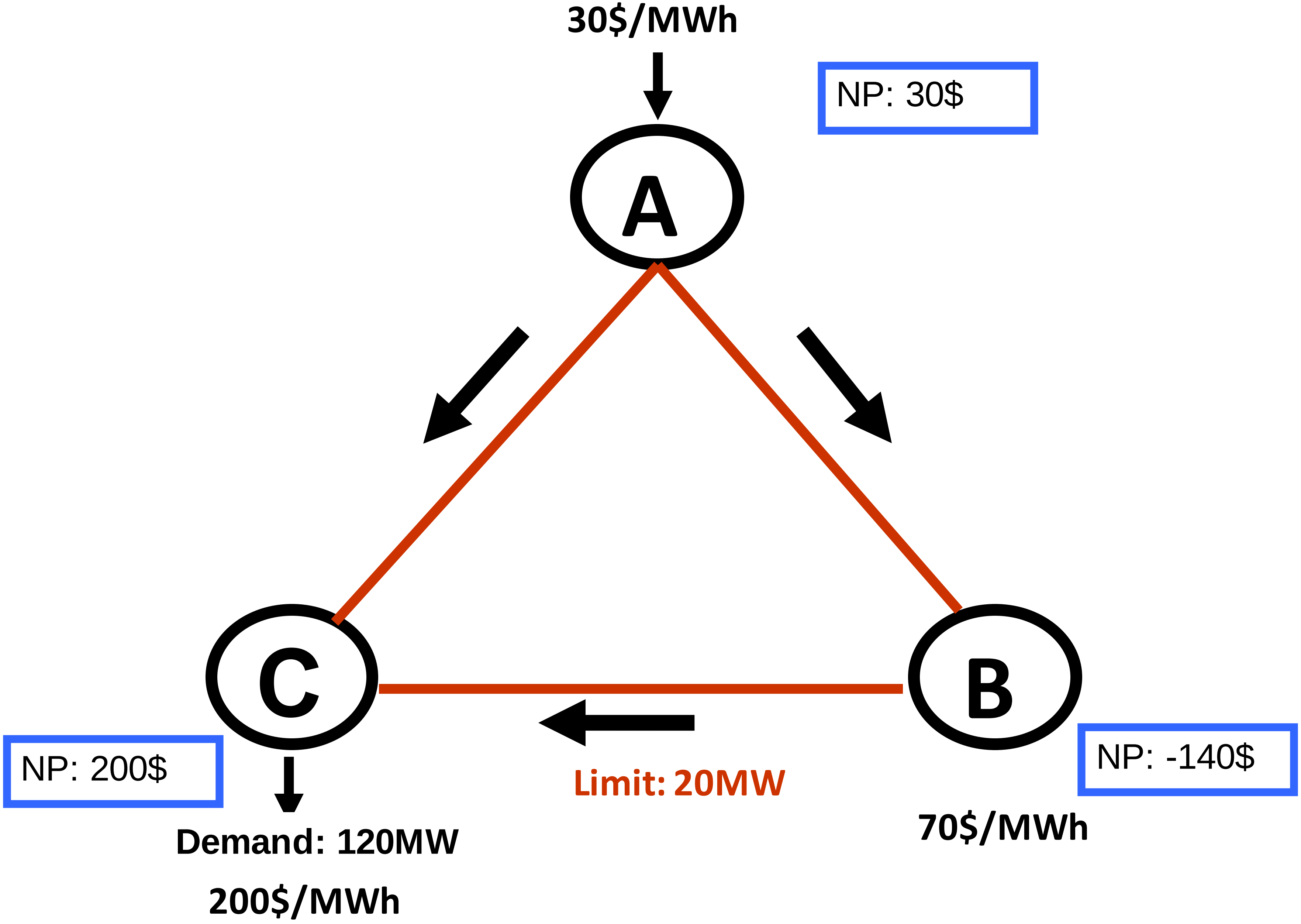
A+B: 50MW

NP: 70$

Demand: 120MW
Withdrawal 120MW
Marginal Cost 50$/MWh

70$/MWh
+30 MW

Limits



30$/MWh

NP: 30$

A

B

C

NP: 200$

NP: -140$

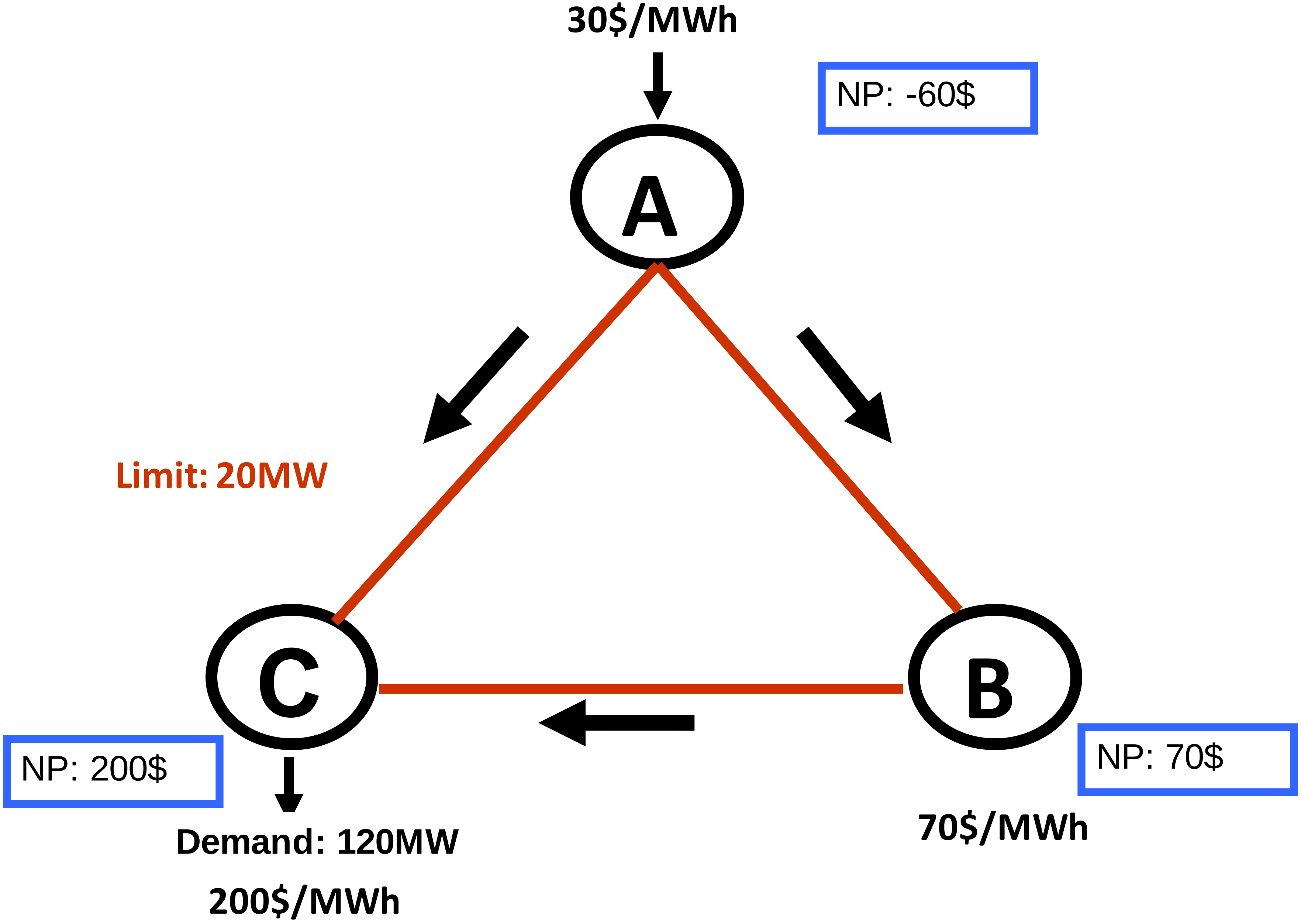
Limit: 20MW

Demand: 120MW

200$/MWh

70$/MWh

Limits



30$/MWh

NP: -60$

A

Limit: 20MW

C

B

NP: 200$

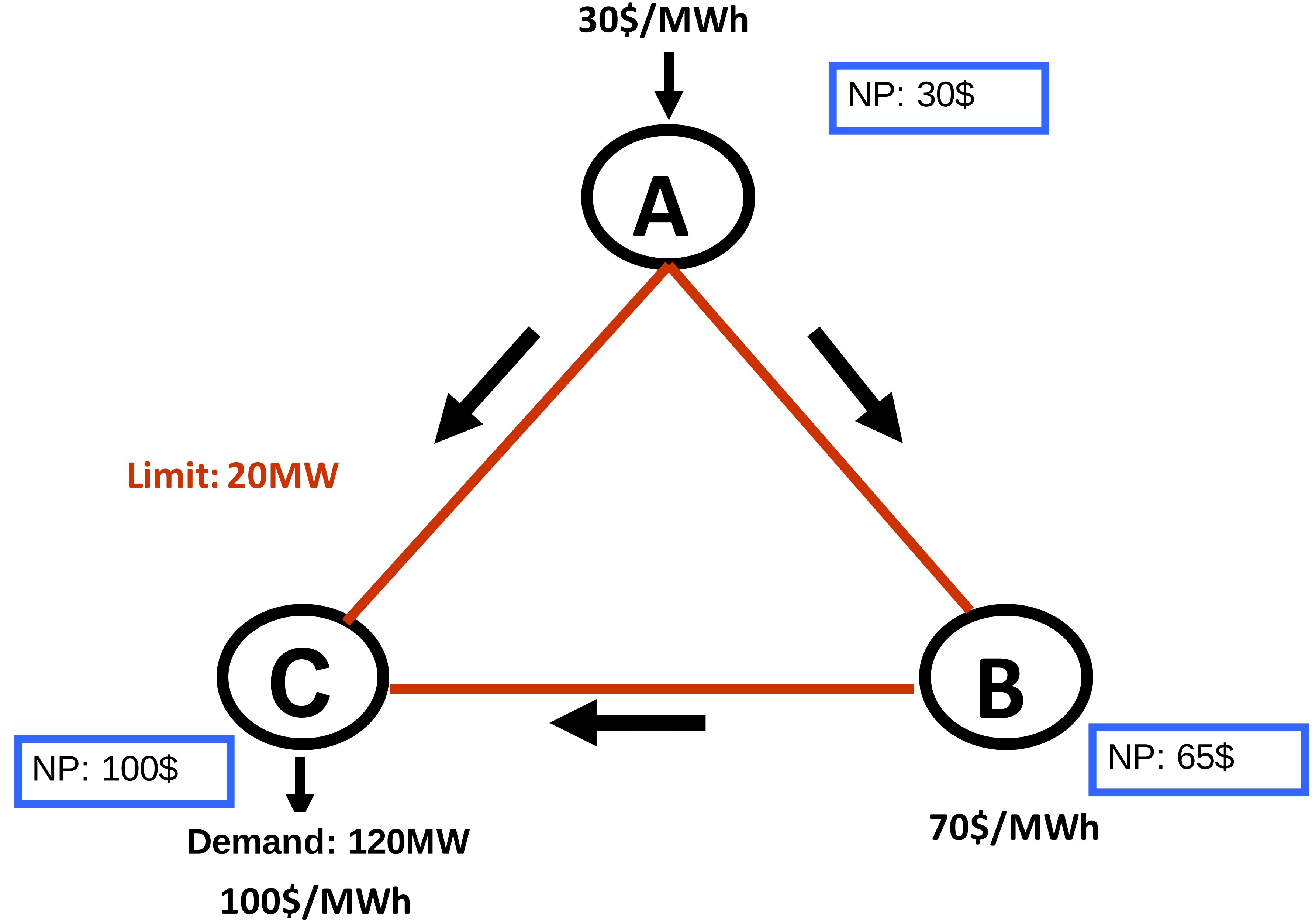
NP: 70$

Demand: 120MW

200$/MWh

70$/MWh

Limits



30$/MWh

NP: 30$

Limit: 20MW

NP: 100$

NP: 65$

Demand: 120MW

100$/MWh

70$/MWh

Simulation work I

- *Alguacil, N.; Motto, A. L. & Conejo, A. J. (2003): Transmission Expansion Planning: A Mixed-Integer LP Approach. IEEE Transactions on Power Systems, 18, 1070-1077.*
- *Arroyo, J. M., & Conejo, A. J. (2000): Optimal response of a thermal unit to an electricity spot market. IEEE Transactions on Power Systems, 15(3), 1098-1104.*
- *Baldick, R. (1995). The generalized unit commitment problem. Power Systems, IEEE Transactions on, 10(1), 465-475.*
- *Brunekreeft, G.; Neuhoff, K. & Newbery, D. (2005): Electricity transmission: An overview of the current debate, Utilities Policy, 13, 73-93.*
- *Ehrenmann, A., & Smeers, Y. (2005): Inefficiencies in European congestion management proposals. Utilities policy, 13(2), 135-152.*
- *Göransson, L., Goop, J., Unger, T., Odenberger, M. & Johnsson, F. (2014): Linkages between demandside management and congestion in the European electricity transmission system, Energy, 69, 860-872*
- *Hobbs, B. F. (2001): Linear Complementarity Models of Nash-Cournot Competition in Bilateral and POOLCO Power Markets. IEEE Transactions on Power Systems, 16.*
- *Kunz, F (2013): Improving Congestion Management - How to Facilitate the Integration of Renewable Generation in Germany. Energy Journal, 34(4).*
- *Kunz, F. & Zerrahn, A. (2013): The Benefit of Coordinating Congestion Management in Germany. DIW Discussion Paper 1298.*
- *Leuthold, F. U., Weigt, H., & von Hirschhausen, C. (2012). A large-scale spatial optimization model of the European electricity market. Networks and spatial economics, 12(1), 75-107.*
- *Morales-España, G., Latorre, J. M., & Ramos, A. (2013): Tight and compact MILP formulation for the thermal unit commitment problem. IEEE Transactions on Power Systems.*

Simulation work

- *Oggioni, G.; Smeers, Y.; Allevi, E. & Schaible, S. (2012): A Generalized Nash Equilibrium Model of Market Coupling in the European Power System. Networks and Spatial Economics, 12, 503-560.*
- *Stigler, H., & Todem, C. (2005). Optimization of the Austrian electricity sector (control zone of*
- *VERBUND APG) under the constraints of network capacities by nodal pricing. Central European Journal of Operations Research, 13(2), 105-125.*
- *Ventosa, M., Baíllo, Á., Ramos, R. & Rivier, R. (2005): Electricity market modeling trends. Energy Policy, 33, 897-913.*

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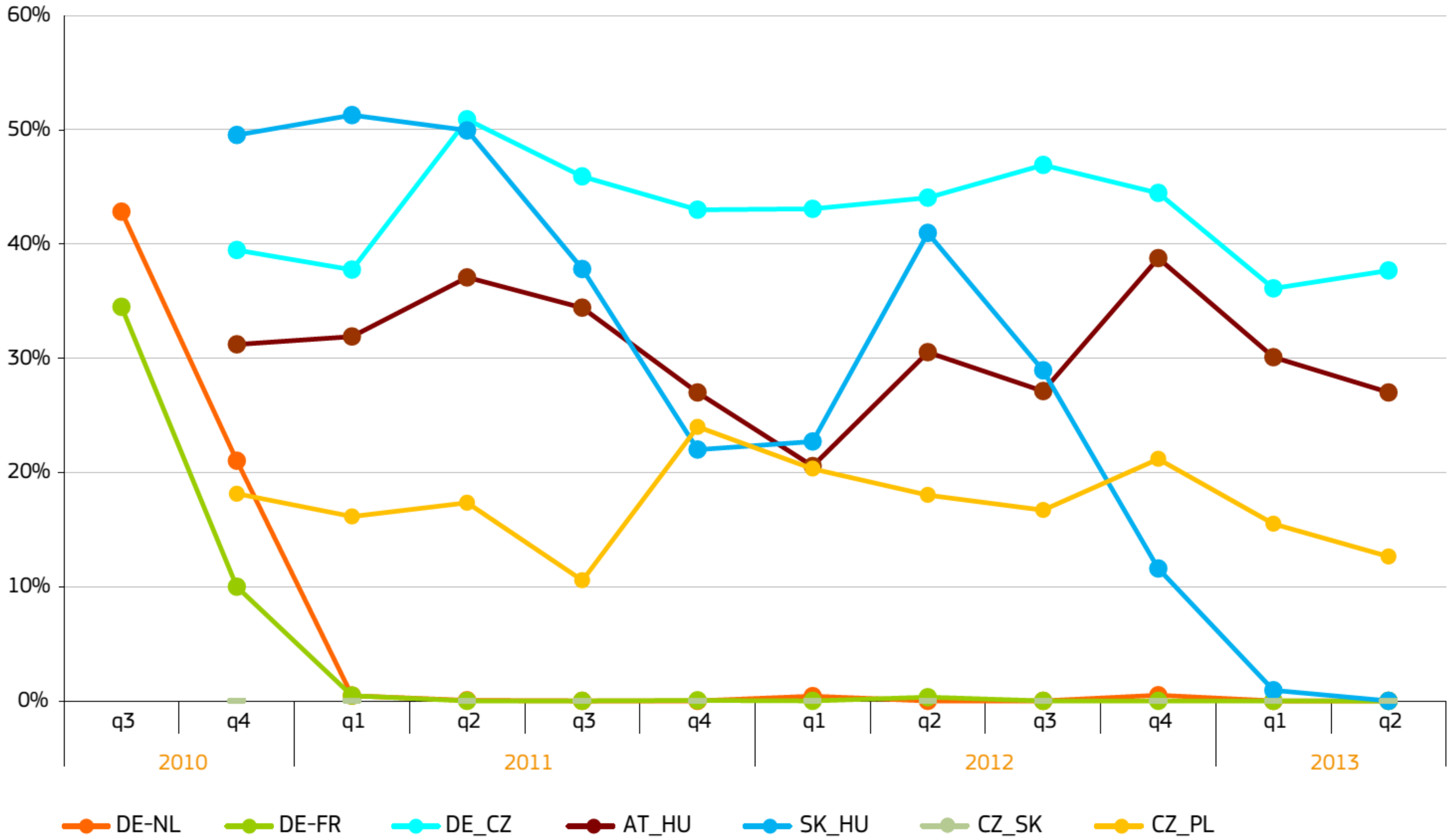
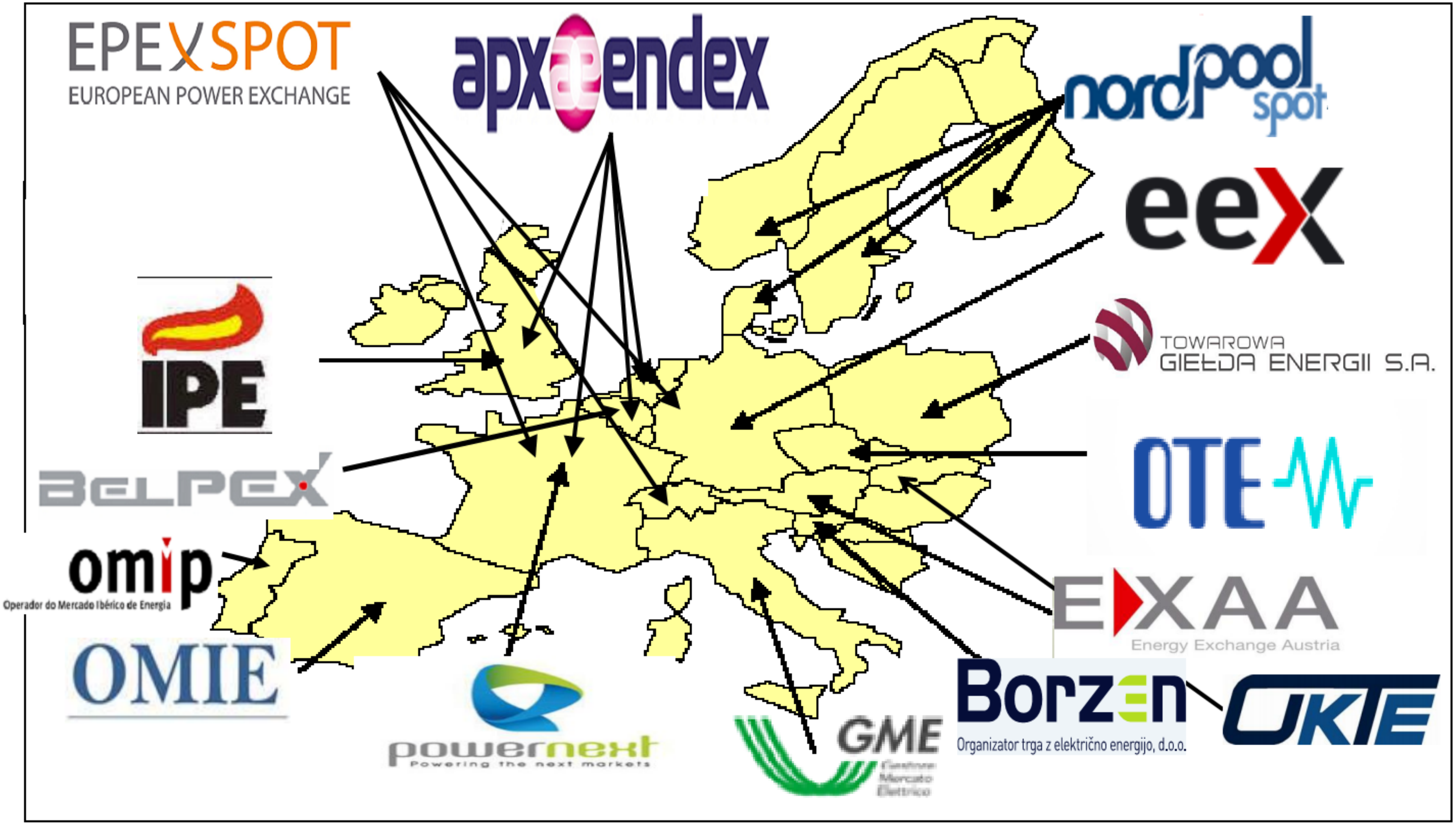
- Zonal versus nodal pricing

- Zonal price = more or less an average price over the pricing zone.
- Area of pricing zone is often the whole country
  - Sweden is an exception as it has 4 pricing zones.

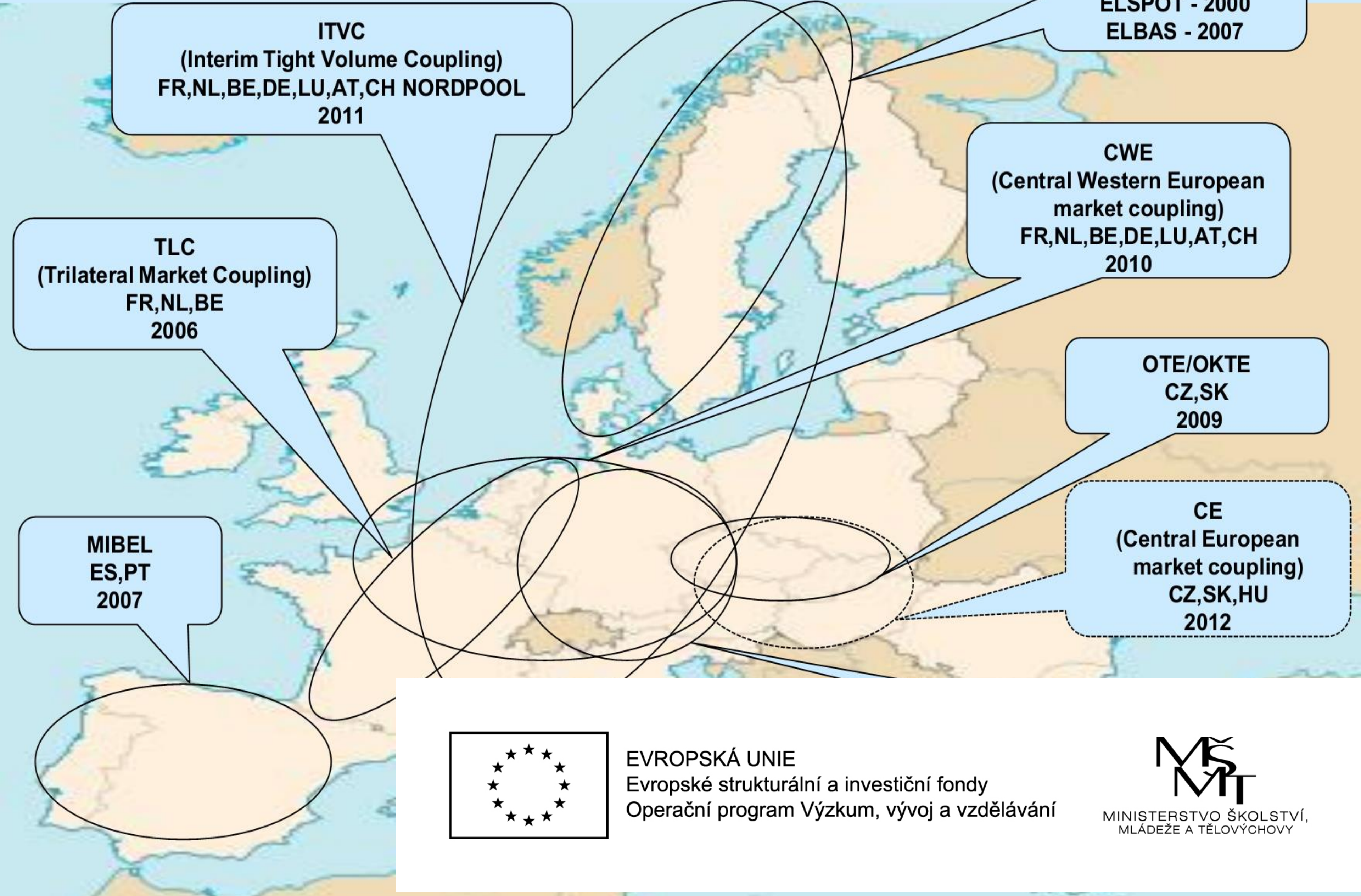
FIGURE 21 – EVOLUTION OF ADVERSE POWER FLOW RATIOS IN THE CENTRAL WESTERN AND CENTRAL EASTERN EUROPEAN REGIONS



Adverse flows


EPEX SPOT
EUROPEAN POWER EXCHANGE
apx endex
nord pool spot
eex
TOWAROWA GIEŁDA ENERGII S.A.
IPE
OTE
BELPEX
omip
Operador do Mercado Ibérico de Energia
EXAA
Energy Exchange Austria
OMIE
powernext
Powering the next markets
GME
Gestore Mercato Elettrico
Borzen
Organizator trga z električno energijo, d.o.o.
OKTE

Coupled markets



NORDPOOL
NO,SE,FI,DK
ELSPOT - 2000
ELBAS - 2007

ITVC
(Interim Tight Volume Coupling)
FR,NL,BE,DE,LU,AT,CH NORDPOOL
2011

TLC
(Trilateral Market Coupling)
FR,NL,BE
2006

CWE
(Central Western European market coupling)
FR,NL,BE,DE,LU,AT,CH
2010

OTE/OKTE
CZ,SK
2009

MIBEL
ES,PT
2007

CE
(Central European market coupling)
CZ,SK,HU
2012

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