Engineering, Economics & Regulation of the Electric Power Sector

ESD.934, 6.974

Session 13
Module E.1

Electricity transmission: Introduction

Prof. Ignacio J. Pérez-Arriaga

Study material

- Florence School of Regulation (FSR), "Electricity transmission" <Tutorial text with basic material for the complete module, not just this introduction>
- I.J. Pérez-Arriaga et al., "Marginal pricing of transmission services: An analysis of cost recovery", IEEE Transactions on Power Systems, 1995 *<the basic theory behind transmission regulation>*
- P. Joskow, "Transmission policy in the US" (2004) & "Patterns of transmission investment" (2005) <excellent critical evaluation of transmission regulation in the US>

"Material for this transparency has been borrowed from Bernard Tenenbaum, from FERC in the USA.

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Readings

- M.Rivier & I.J. Pérez-Arriaga, "Computation and decomposition of spot prices for transmission pricing", 1993. *<for those who really want to know the mathematical underpinnings & some useful properties of spot prices>*

The problem to be addressed

- Producers & consumers in a **national** market have the right to buy & sell electricity freely ...
  - How much to charge for the use of the network?
  - Who pays for network losses?
  - What to do if the network is congested?
  - Who upgrades the network when needed?

  and, how to address these same issues in a **regional** market?

… & it becomes more complex in a regional *(supranational)* context

Additional difficulties

- Technical
  - Complexity of the regional network & its operation
  - Lack of harmonization in the network charges
  - Management of the network constraints at regonal level
  - Need to develop the network infrastructure
- Institutional
  - Need of a legal framework for regulatory harmonization

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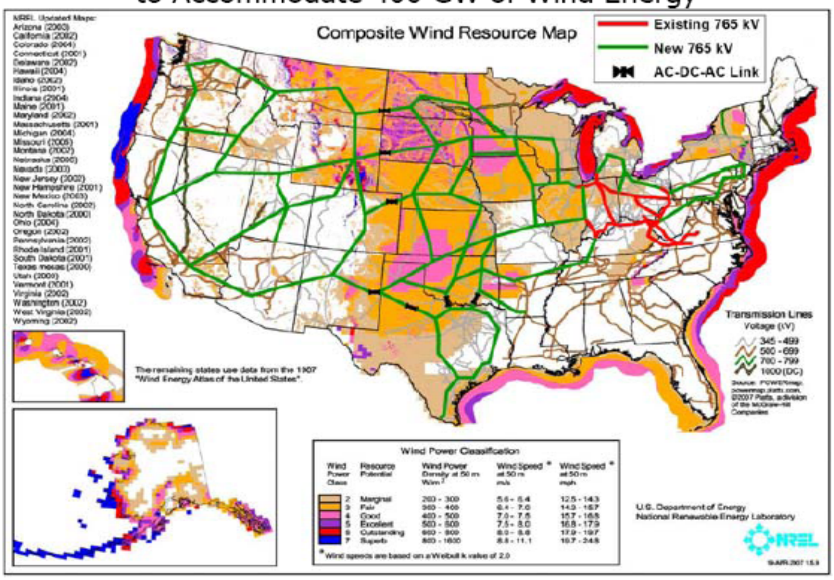
Technically Feasible, Conceptual Extra High-Voltage Transmission Plan to Accommodate 400 GW of Wind Energy



Source: U.S. DOE 20% Wind Report, May 2008, page 12, showing conceptual transmission plan prepared by AEP Transmission and AWEA.

Transmission services

- **Definition:** Activities with some economic value that are performed with the transmission network for the benefit of its users
  - **Primary service:** The transport of electricity from input nodes to output nodes
  - **Secondary services** (jointly with generation)**:**
    - voltage control
    - system security

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Outline

- **Background**
  - **nodal pricing**
  - regulatory characterization of transmission
- The relevant regulatory topics
  - Investment
  - Access *(to be included in next set of slides: module E.2)*
  - Pricing *(to be included in next set of slides: module E.2)*

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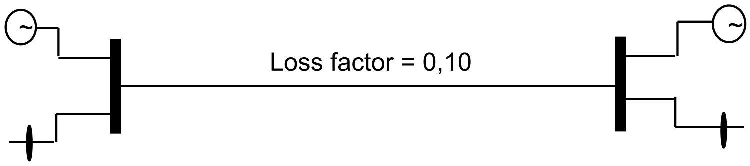
The effects of the transmission network
Losses

GENERATOR 1:
200 MW
cost: 5 cents/kWh

GENERATOR 2:
200 MW
cost: 7 cents/kWh



DEMAND 1:
50MW

DEMAND 2:
50MW

Effect of losses on prices:

1MW D1 => 1MW G1 => price p_1=5

1MW D2 => (1+0.1)MW G1 => price p_2=5.5

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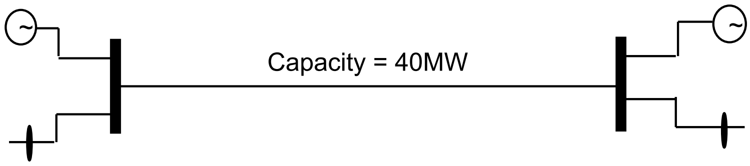
The effects of the transmission network
Congestion

GENERATOR 1:
200 MW
cost: 5 cents/kWh

GENERATOR 2:
200 MW
cost: 7 cents/kWh



DEMAND 1:
50MW

DEMAND 2:
50MW

Effect of congestion on prices:

1MW D1 => 1MW G1 => price p_1=5

1MW D2 => 1MW G2 => price p_2=7

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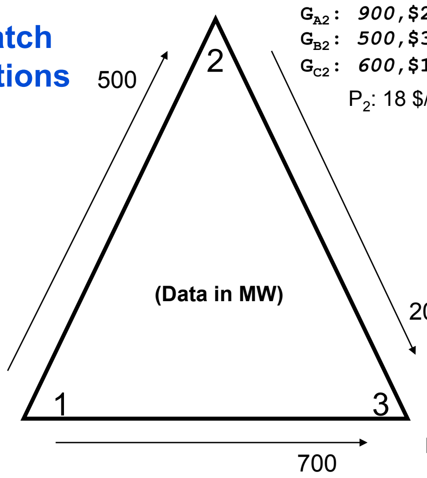
Congestions

Economic dispatch without congestions

	DATA	SOLUTION
G_{A2}:	*900*,$25	0
G_{B2}:	*500*,$30	0
G_{C2}:	*600*,$16	600

P_2: 18 \$/MWh



	DATA	SOLUTION
G_{A1}:	*1000*,$12	1000
G_{B1}:	*900* ,$15	900
G_{C1}:	*600* ,$18	200

P_1: 18 \$/MWh

P_3: 18 \$/MWh

Same demand of 900 MW in the 3 nodes

Same impedance in the three lines

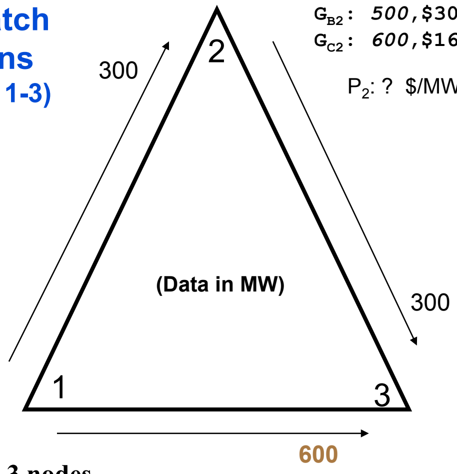
[L Kirsch, Power Utilities Fortnightly Feb. 2000]

Congestions

Economic dispatch with congestions (600 MW in the line 1-3)

	DATA	SOLUTION
G_{A2}:	*900*,$25	?
G_{B2}:	*500*,$30	?
G_{C2}:	*600*,$16	?

P_2: ? \$/MWh



	DATA	SOLUTION
G_{A1}:	*1000*,$12	?
G_{B1}:	*900* ,$15	?
G_{C1}:	*600* ,$18	?

P_1: ? \$/MWh

P_3: ? \$/MWh

Same demand of 900 MW in the 3 nodes

Same impedance in the three lines

[L Kirsch, Power Utilities Fortnightly Feb. 2000]

Nodal prices

- Nodal prices are short-term marginal costs of energy with locational differentiation so that they internalize the network effects (losses & congestions)

"The nodal price at a node k is the increment in the operating cost of the system when the demand at node k increases by one unit"

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Spot prices
The underlying theory

- Definition of spot price: Short term marginal cost of electricity production, with spatial and time discrimination

$$\rho k = \frac{\partial(\text{operation costs})}{\partial(\text{demand at node k})}$$

- The value of r_k depends on
  - available generation and transmission equipment
  - operating conditions
    - load level
    - generation outputs
    - network losses
    - active network constraints
  - marginal cost of generating units

Short-term marginal cost of active power

$$\rho k = \gamma\left(1+\frac{\partial L}{\partial D_k}\right)+\mu\frac{\partial N}{\partial D_k}$$

k node where the price is computed
g generation short run marginal cost
L network ohmic losses
D_k active power demand at node k
N set of network constraints
μ shadow prices of network constraints

The complete value of ρ_k can be directly computed from operation models

Example

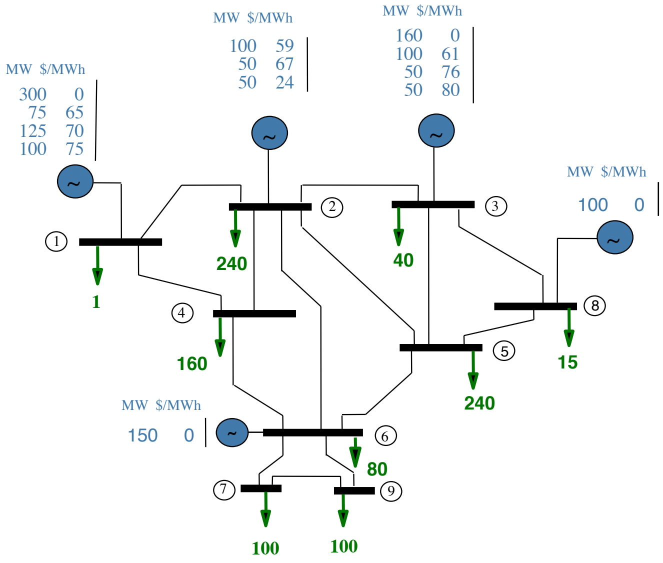
System configuration

System data

Cases:

- Case 1: ohmic losses ignored
- Case 2: ohmic losses
- Case 3: line at its capacity limit

Example
System configuration



Example
System data (i)

Bus	Hydro generation (MW)	Thermal generation						Load	
		Unit 1		Unit 2		Unit 3		Demand	Unserved
		(MW)	(Cost)	(MW)	(Cost)	(MW)	(Cost)	(MW)	(Cost)
1	300	75	65	125	70	100	75	1	1500
2	-	100	59	50	67	50	74	240	1500
3	160	100	61	50	76	50	80	40	1500
4	-							160	1500
5	-							240	1500
6	200							80	1500
7	-							100	1500
8	100							15	1500
9	-							100	1500

ALL COSTS IN €/MWh

Example

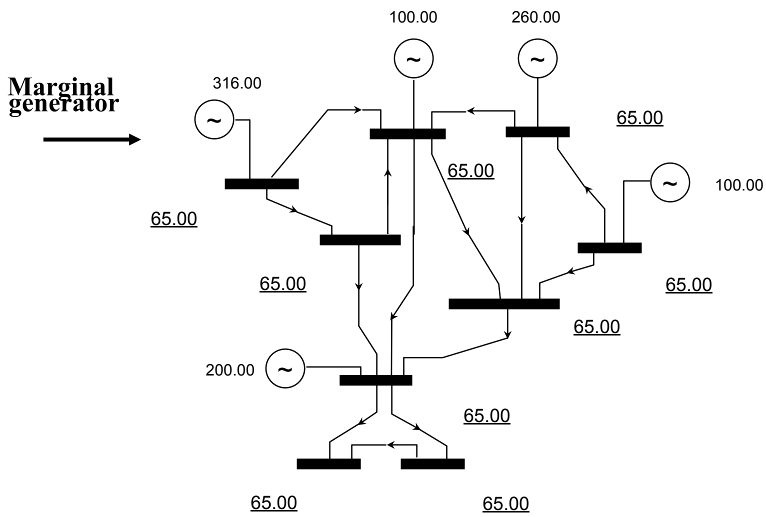
System data (ii)

LINE From	LINE To	Reactance (P.U.)	Resistance (P.U.)	Capacity Limit (MW)
1	2	0'0029	0'0008	500
1	4	0'0020	0'0005	500
2	3	0'0017	0'0004	500
2	4	0'004	0'001	500
2	5	0'002	0'0005	500
2	6	0'004	0'001	500
3	5	0'001	0'0002	500
3	8	0'004	0'001	500
4	6	0'006	0'0015	500
5	6	0'002	0'0005	500
5	8	0'004	0'001	500
6	7	0'006	0'0015	500
6	9	0'002	0'0005	500
7	9	0'002	0'0005	500

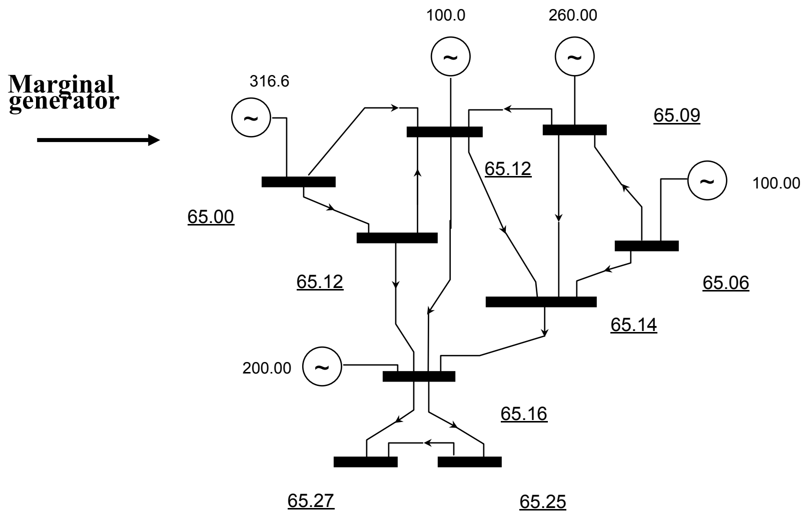
Non realistic values of line parameters

Example

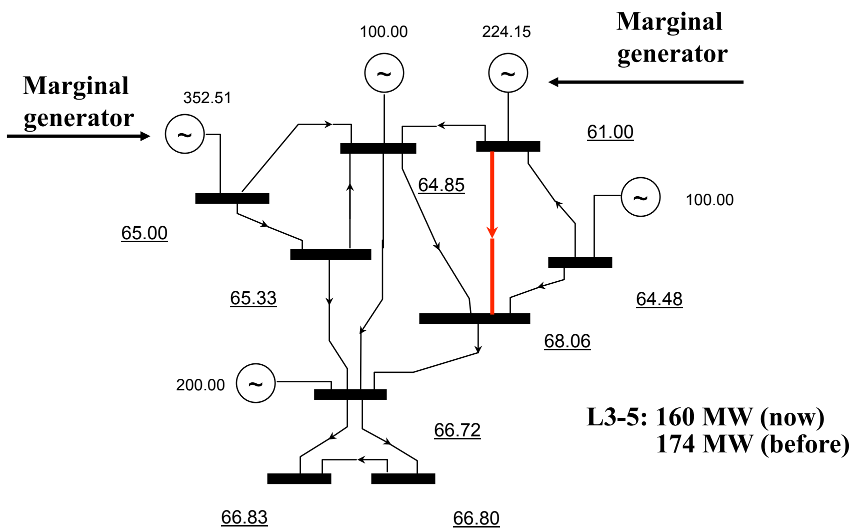
Case 1: Losses are ignored



Example
Case 2: With losses



Example
Case 3: Congestion in line (3-5)



How to compute nodal prices?
Formulation

- Problem formulation with explicit generation-demand balances for each node.

$min \quad Z$	Minimise costs
$\sum_i \varphi_{ik} + g_k - \frac{1}{2}\sum_i L_{ik} = d_k$	**generation-demand balance**
$\phi_{ik} = \frac{1}{Y_{ik}}(\theta_k - \theta_i)$	line flow definition
$L_{ik} = L(\varphi_{ik})$	losses definition
$g \leq \overline{g}$	generator capacity limit
$\varphi \leq \overline{\varphi}$	line capacity limit

Φ_{ik}: active power flow in line ik

θ_k: voltage angle at node k

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How to compute nodal prices?
Formulation

- Now, the only element in the Lagrangian function related with d_k is in the constraint associated to the generation-demand balance for node k.
- Therefore: $$\rho_k = \frac{\partial Z}{\partial d_k} = \pi 1_k$$

The spot price for node k is the shadow price of the balance constraint for that node.

Simple to calculate & widely used.

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On the use of nodal prices

- Motives (founded or not) that are sometimes employed to justify why not to use nodal prices
  - they are volatile or difficult to compute
  - in well developed networks the differences between nodal prices at different nodes are irrelevant most of the time
  - zonal prices are enough for location differentiation
  - they are not compatible with uniform tariffs (if this is the case)
  - There are alternative procedures to apply efficient short-term location signals while maintaining a single energy price for the entire system

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Nodal prices
Regulatory implications (i)

- Nodal prices are **optimal short-term economic signals** for consumers & generators
  - Nodal prices internalize all network effects in the economic dispatch / wholesale market of generation & demand
- Note that **nodal prices** are **energy prices**, to be applied to energy bought & sold by consumers & generators, respectively &, in principle, they are not meant to cover the costs of the transmission activity. However, the application of nodal prices results in an economic surplus, whose meaning will be examined next

Nodal prices
Regulatory implications (ii)

- Application of nodal prices can be interpreted as if the transmission network company "buys" electricity at the input end of each line *(typically at a lower nodal price)* & sells electricity *(different amount, because of losses)* at the output end of each line *(typically at a higher nodal price)*
- This results in a total net surplus

$$\sum_{l} \rho_{l,\,out} \cdot P_{l,\,out} - \rho_{l,\,in} \cdot P_{l,\,in}$$

Nodal prices
Regulatory implications (iii)

- Alternatively, application of nodal prices, when considering the entire transmission network altogether, can be viewed as if the transmission network "buys" electricity at the nodes where generation injects electricity to the network and "sells" electricity at the nodes where load is withdrawn from the network

$$\sum_{k} \rho_k \left(d_k - g_k\right)$$

- It can be easily verified that both expressions are identical

Nodal prices
Regulatory implications (iv)

- Then, when nodal prices are applied to all network users:
  - All of them will receive correct short-term economic signals that fully internalize network losses & constraints
  - In well developed transmission networks the application of nodal prices results in a net income that typically recovers a small fraction of the total network costs (about 15% to 25% typically)
  - However, it can be proved that a "perfectly adapted transmission network" would completely recover its network costs with nodal prices

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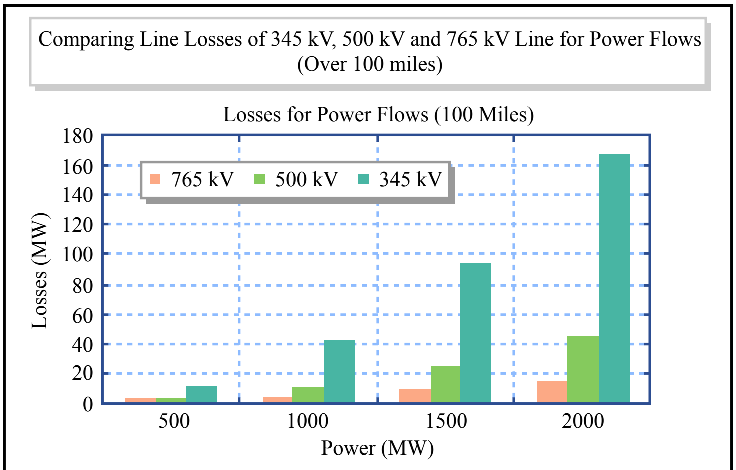
Nodal prices
Regulatory implications (v)

- The reason for the net surplus to be typically short of the required revenues is that the condition of "perfect adaptation" of a transmission network is not possible in practice, since
  - Actual investment options are discrete
  - There are strong economies of scale
  - Network expansion is subject to reliability constraints that may not have a sound economic justification
  - Other constraints: financial, environmental
  - "Mistakes" in network planning

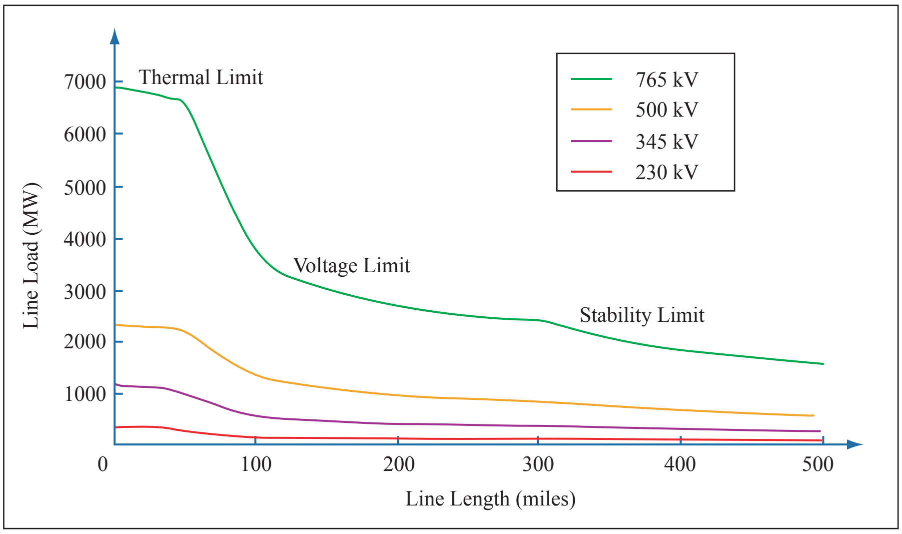
  even if the network design is the "optimal" one *(although subject to the mentioned constraints)*

Economies of scale in transmission



Source: Evan Wilcox, "765 kV Transmission system Facts for the Southwest Power Pool (SPP) Cost Allocation Working Group," May 28, 2008, page 17.

Image by MIT OpenCourseWare.



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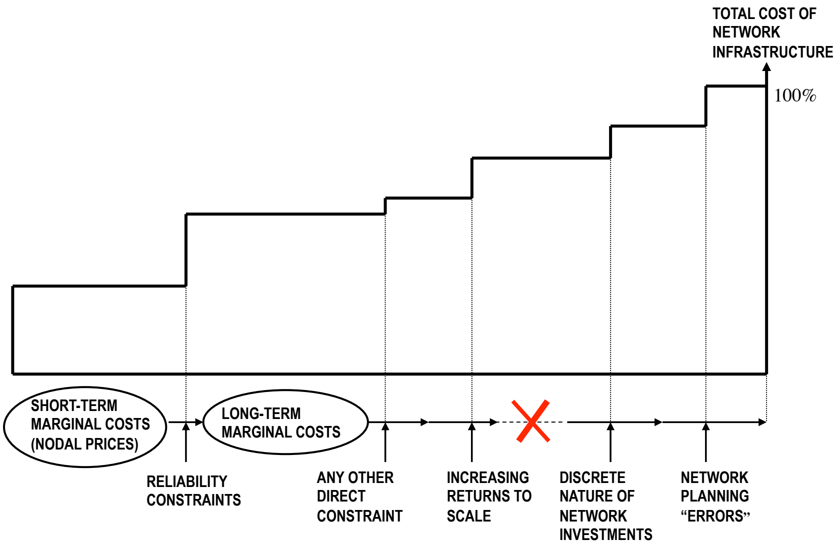
Theoretical results on cost recovery of transmission networks



Regulatory implications

- The "complementary charge":
  - both the theoretical reasons and the practical experiences indicate that *variable network charges fell short of covering the total network costs*
  - network revenues must be regulated to be *independent of variable network charges,* in order to avoid perverse incentives for the network entity
  - therefore a complementary charge is needed to fill the gap:

required network revenues =
= network variable charges +
+ complementary charge

Outline

- **Background**
  - nodal pricing
  - **regulatory characterization of transmission**
- The relevant regulatory topics
  - Investment
  - Access
  - Pricing

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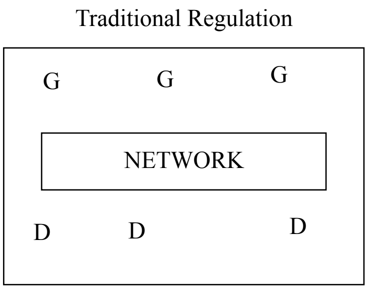
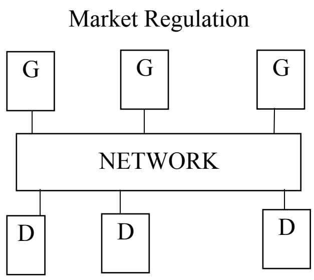
The new role of transmission

Transmission as a meeting point for the market





Secondary attention

Critical importance

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Transmission
Regulatory characterization

- Transmission is a natural monopoly
  - Large economies of scale
  - The entire network is operated as a whole
  - Enormous difficulties in duplicating the network
  - Competition appears to be possible in very limited cases (e.g. merchant lines in very congested areas)
  - Unregulated transmission ownership would provide much market power
- Transmission effects: losses, congestions, costs

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Implications

- A well developed network *(as those that exist in America & Europe, in most cases)* will never be the outcome of "merchant" investment exclusively *(whose only income comes from congestion rents)*
  - The role of "merchant lines" is limited to
    - Large generation projects that need the line
    - Zones with systematic congestions that do not go away with the considered network investment
    - Special investments where the private investor & the centralized planner have a different risk perception

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Single vs. multi-system case

- The "single system paradigm" in transmission regulation
  - investment, access, pricing
- What is different in the multi-system case?
  - Different control areas & system operators
  - Political borders & different regulations
- Economic efficiency requires extending the "single system paradigm" to the multi-system case as much as possible

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A typical legal norm on transmission regulation (1)

- General dispositions
  - Objectives
  - Definitions
    - Nature of the transmission activities & facilities
    - Agents
    - Terminology
  - Procedures to introduce modifications

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A typical legal norm on transmission regulation (2)

- Rights & obligations of the different parties involved
  - Transmission companies
  - System Operator
  - Network users

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A typical legal norm on transmission regulation (3)

- Access to the network
  - Priority rules
    - Consumers
    - Generators
    - Imports/exports
  - International interconnections
  - Connection procedures
    - Application
    - Evaluation
    - Entry in operation

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A typical legal norm on transmission regulation (4)

- Expansion
  - Alternative schemes
  - Responsibilities
  - Procedures
  - Implementation
  - International interconnections

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A typical legal norm on transmission regulation (5)

- Remuneration y network charges
  - Regulated remuneration
    - Principles
    - Responsibilities
    - Scope
    - Indexing
  - Charges
    - Connection
    - Usage
  - Existing/New investments
  - International interconnections

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A typical legal norm on transmission regulation (6)

- Treatment of losses
  - Measures
  - Economic signals / Cost allocation
- Network constraints
  - Identification & classification
  - Network constraint management
  - Economic signals / Cost allocation

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A typical legal norm on transmission regulation (7)

- Quality of service
  - Principles
  - Allocation of responsibilities
  - Penalties/Incentives
  - Reference values (targets)

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A typical legal norm on transmission regulation (8)

- Use of public & private land
  - Authorization procedures
  - Registries
  - Use of public & private land
  - Rights-of-way

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A typical legal norm on transmission regulation (9)

- Technical norms
  - Data
  - Technical description of the projects
    - Connection
    - Planning
  - Security criteria
  - Tests & audits
  - Usage agreements
  - Performance indices

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Outline

- Background
  - regulatory characterization of transmission
  - nodal pricing
- **The relevant regulatory topics**
  - Investment
  - Access
  - Pricing

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What should a sound transmission regulation provide?

- Promote economic efficiency
  - in the short-term (optimal operation)
  - in the long-term (optimal generation / demand investments)

  for the network users
- Ensure economic viability of the transmission activity
- Promote optimal operation performance of the transmission network (O&M)
- Promote optimal transmission investment

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