

# Incentives for Transmission Investment in Natural Gas and Electricity Networks— Theory and Roadmap

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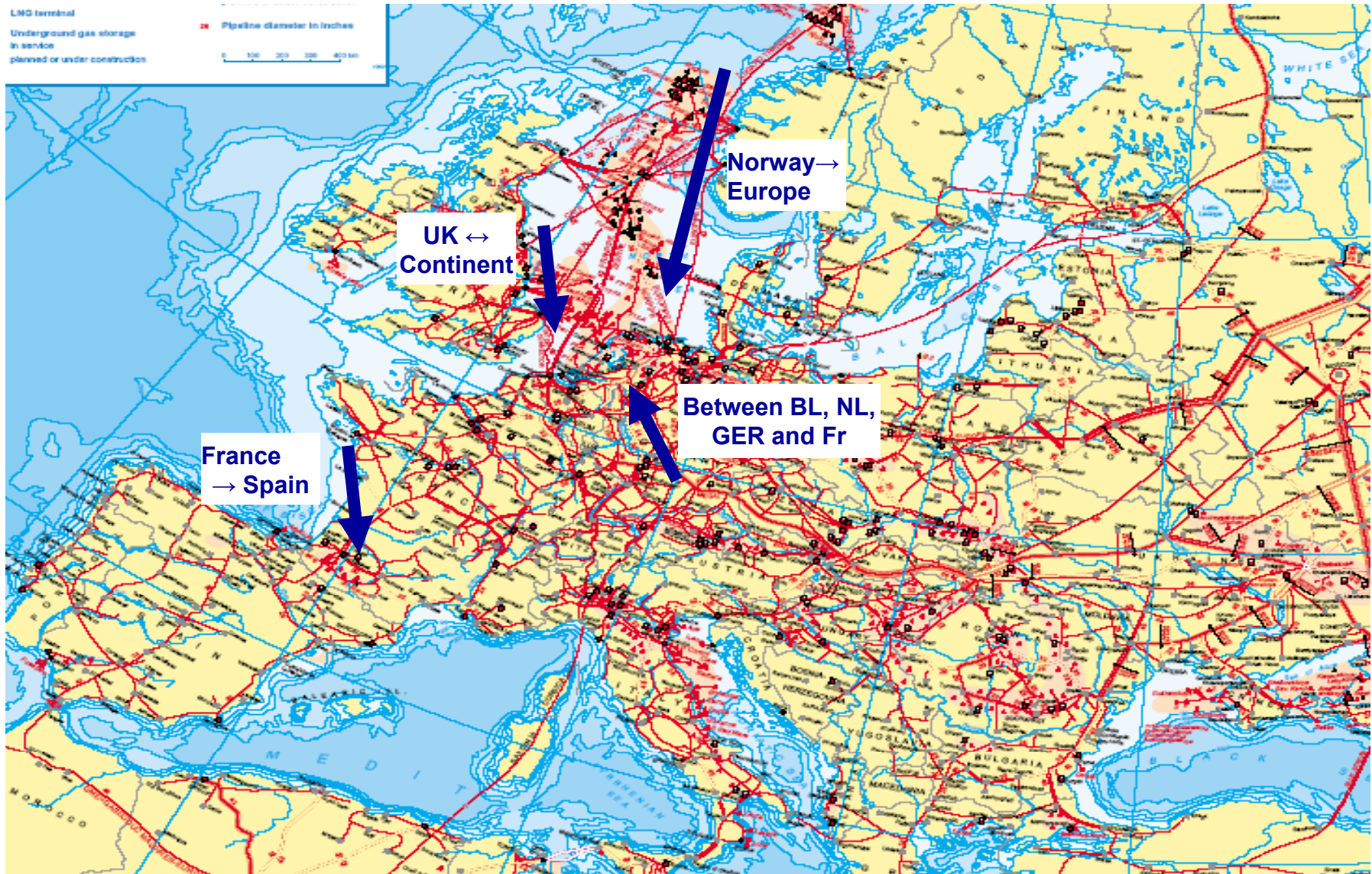
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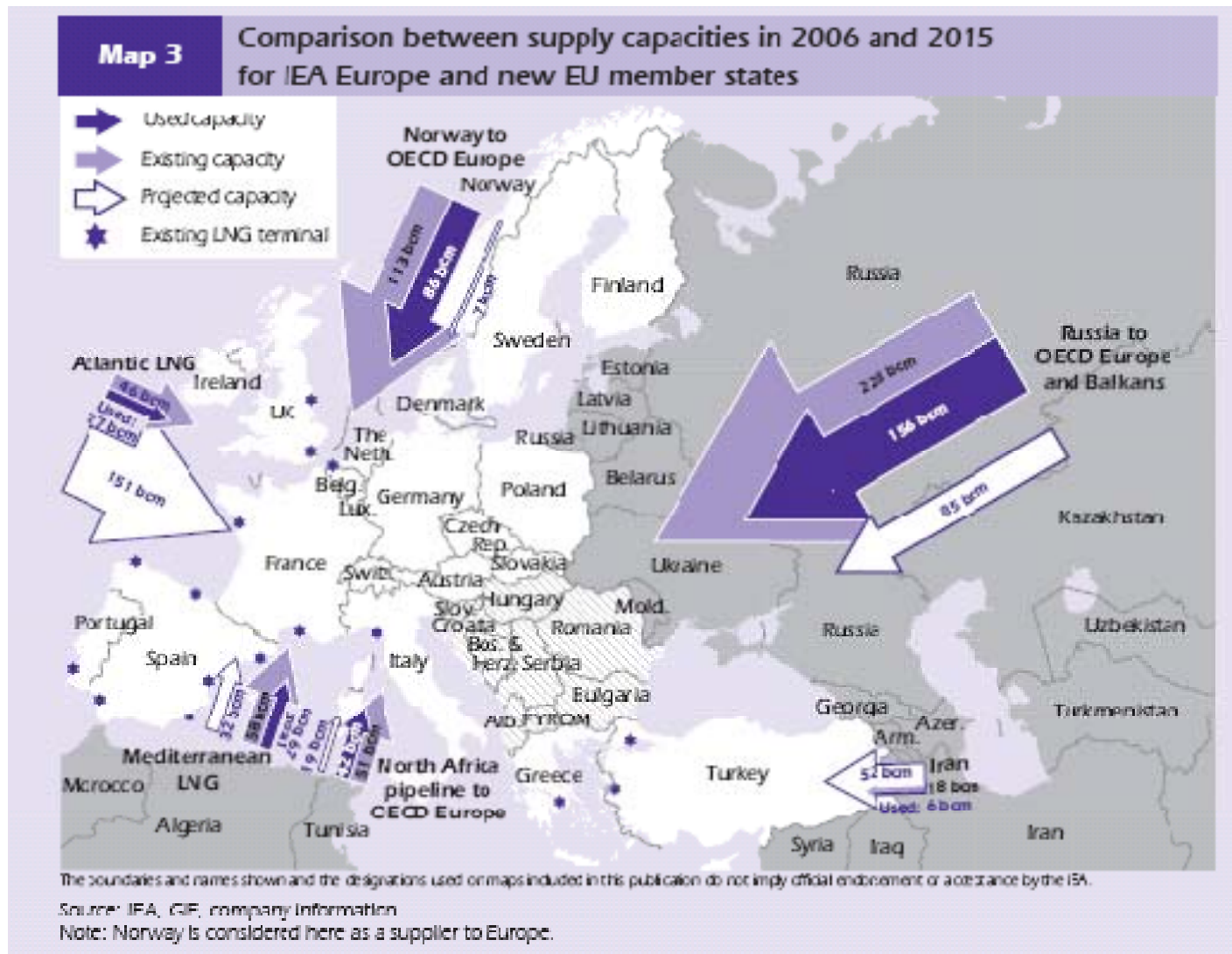
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- Application to Electricity Transmission
- Potential Application to Natural-Gas Networks
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# Introduction

# PIPELINE CAPACITY CONSTRAINTS IN EUROPE



# SUPPLY CAPACITIES 2006 AND 2015

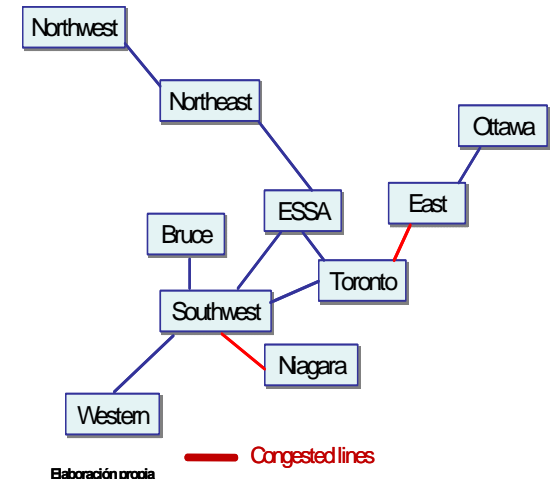
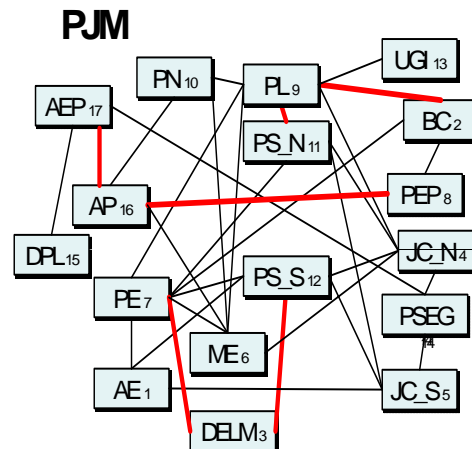
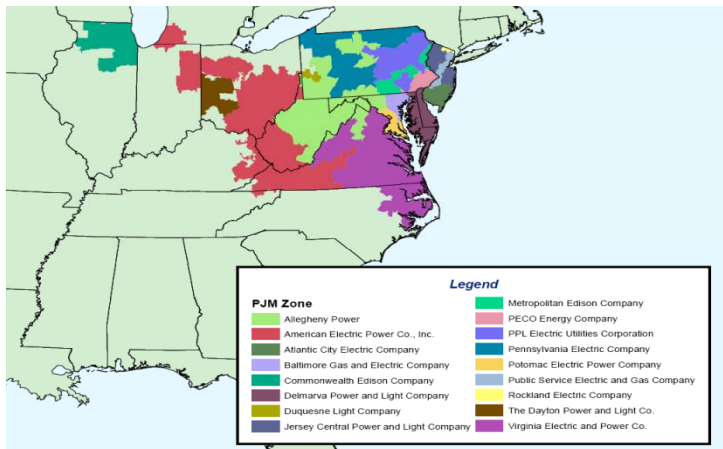
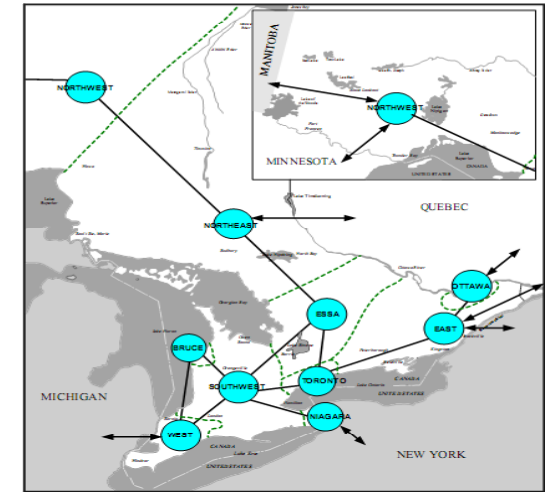
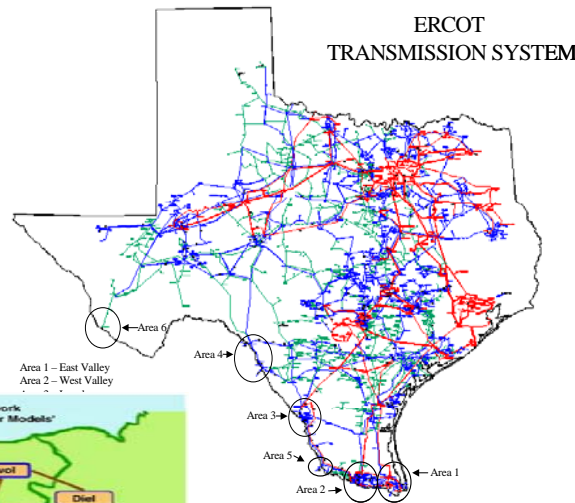


Source: IEA Natural Gas Market Review 2008

# NATURAL GAS MARKET REVIEW 2008, IEA

- EU natural-gas production will decline and imports rise: from 63% of supply in 2010 to 77% of supply in 2020
- “The increasing need to import gas necessitates not only additional supply infrastructure but also greater interconnection between EU countries to enable the large increments of imported gas to be absorbed efficiently within Europe, and to provide access to LNG supplies to countries without seaborne terminals”
- “...few internal network interconnections are being built...new suppliers were not able to enter markets...investment was an issue, especially in cross-border interconnections ...storage”
- Potential pipeline projects: Norway-UK; Russia-Germany; Russia-Bulgaria-Central Europe-Italy; Norway-Sweden-Denmark-Poland
- In 2007, the EU Commission proposed the creation of a **European regulatory agency**

# CONGESTED ELECTRICITY NETWORKS



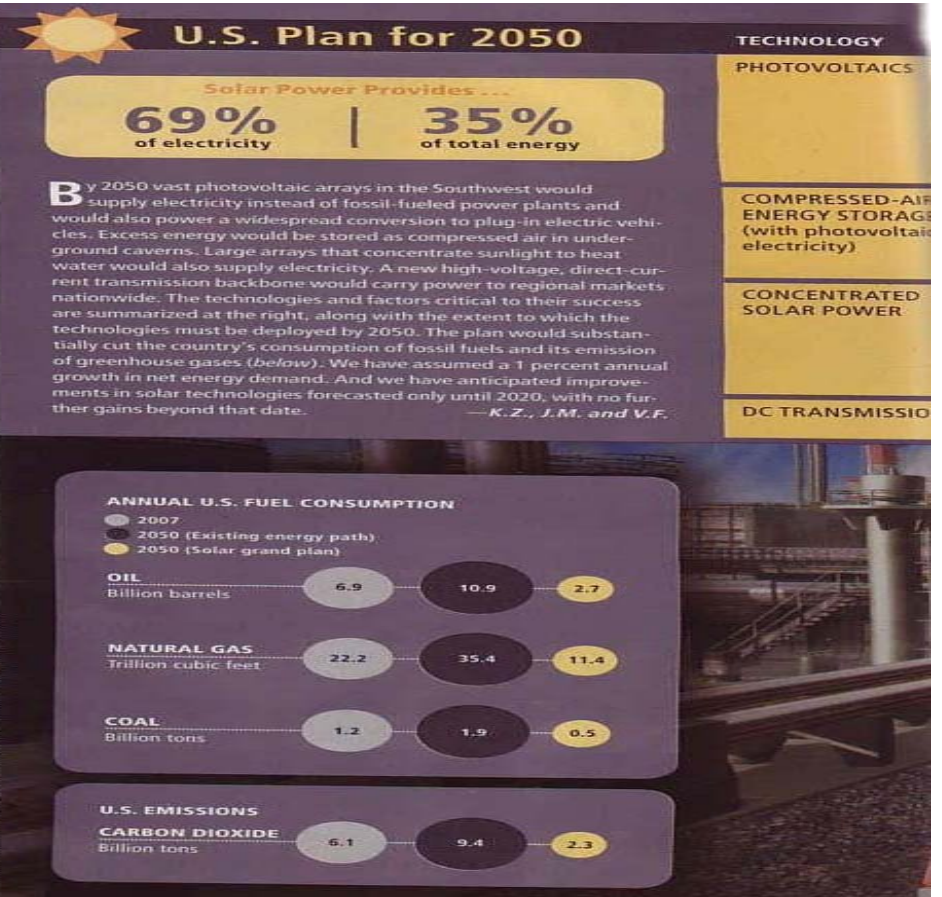
## BIG IDEAS

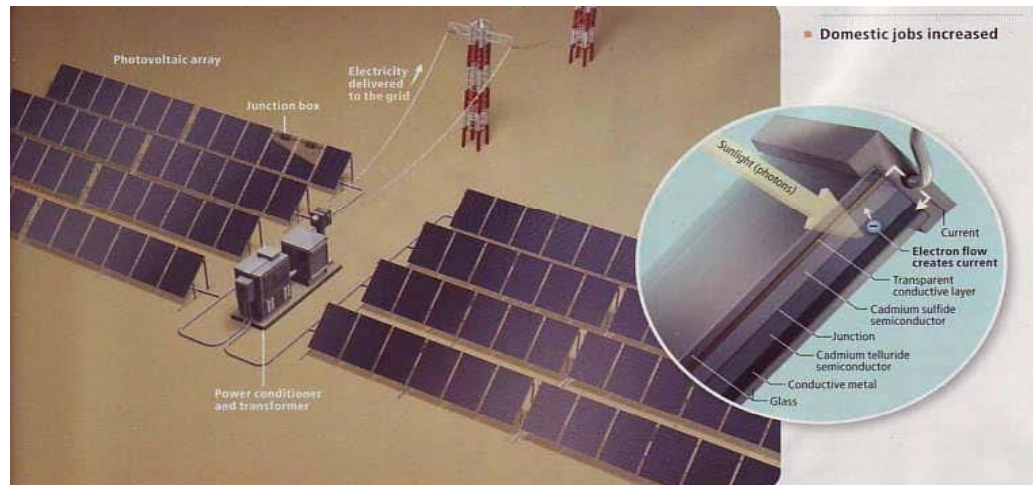
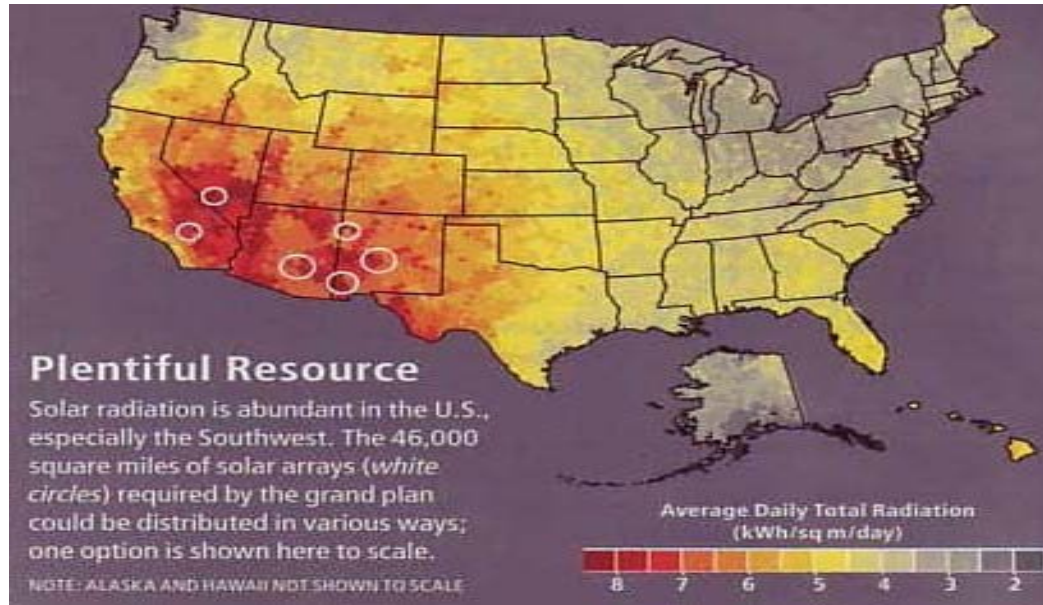
By 2050 solar power could end U.S. dependence on foreign oil and slash greenhouse gas emissions

By Ken Zweibel, James Mason and Vasilis Fthenakis

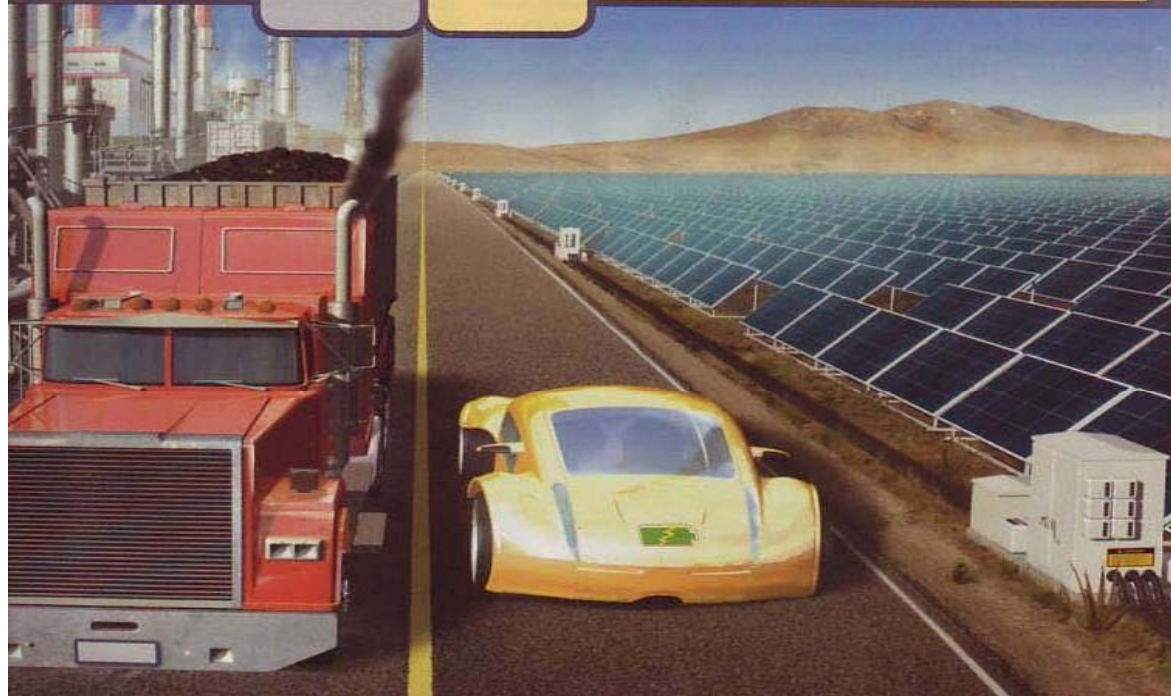


# Solar Grand Plan





| CRITICAL FACTOR              | 2007        | 2050                  | ADVANCES NEEDED   |
|------------------------------|-------------|-----------------------|---|
| Land area                    | 10 sq miles | 30,000 sq miles       | Policies to develop large public land areas   |
| Thin-film module efficiency  | 10%         | 14%                   | More transparent materials to improve light transmission; more densely doped layers to increase voltage; larger modules to reduce inactive area |
| Installed cost               | \$4/W       | \$1.20/W              | Improvements in module efficiency; gains from volume production   |
| Electricity price            | 16¢/kWh     | 5¢/kWh                | Follows from lower installed cost   |
| Total capacity               | 0.5 GW      | 2,940 GW              | National energy plan built around solar power   |
| Volume                       | 0           | 535 billion cu ft     | Coordination of site development with natural gas industry  |
| Installed cost               | \$5.80/W    | \$3.90/W              | Economies of scale; decreasing photovoltaic electricity prices  |
| Electricity price            | 20¢/kWh     | 9¢/kWh                | Follows from lower installed cost   |
| Total capacity               | 0.1 GW      | 558 GW                | National energy plan  |
| Land area                    | 10 sq miles | 16,000 sq miles       | Policies to develop large public land areas   |
| Solar-to-electric efficiency | 13%         | 17%                   | Fluids that transfer heat more effectively  |
| Installed cost               | \$5.30/W    | \$3.70/W              | Single-tank thermal storage systems; economies of scale   |
| Electricity price            | 18¢/kWh     | 9¢/kWh                | Follows from lower installed cost   |
| Total capacity               | 0.5 GW      | 558 GW                | National energy plan  |
| Length                       | 500 miles   | 100,000–500,000 miles | New high-voltage DC grid from Southwest to rest of country  |



- There are capacity shortages/bottlenecks in diverse energy network systems
- Transmission capacity is likewise critically needed along with the fostering of renewable energy (e.g., solar and wind)
- We have an idea on how to approach these problems through a model on transmission expansion that has already worked in electricity networks
- Joint team CIDE-DIW Berlin-EE2 TU Dresden

# The Incentive Model

# THE CONGESTION “TRAP”

- The problem with network providers is that they might find it more profitable not to expand the system because of the high revenues of keeping the pipelines congested
- At the optimum, the per-unit marginal cost of new transportation capacity must be equal to the expected congestion cost of not adding an additional unit of capacity (Crew, M. A., C.S. Fernando, and P. R. Kleindorfer (1995) “The Theory of Peak-Load Pricing: A Survey,” *Journal of Regulatory Economics*, 8: 215-248.)

# PRICE REGULATION

- Price regulation can be used to reverse the congestion trap
- Price-level regulation can also be used to achieve other goals: allocative efficiency, productive efficiency and distributive efficiency
  - Price of firms with increasing returns to scale (natural monopolies, such as pipelines) needs to be regulated
  - Ramsey-Boiteux equilibrium
  - Regulation of price level: long-run distribution of rents and risks between consumers and the firm
  - Alternatives:
    - *Cost-of-service* regulation
    - *Price caps*. Adjustment factors (*RPI*, *X*, etc.)

# PRICE REGULATION

- Regulation of price structure can promote convergence to an “expanding” equilibrium and to the Ramsey-Boiteux equilibrium
  - Regulation of “price structure”: short-run allocation of costs and benefits among distinct types of consumers.
  - Cap set over an index of prices
  - Tariff-basket regulation
    - Fixed weights: Laspeyres, Fixed Laspeyres, Ideal.
    - Under stable cost and demand functions, and myopic profit maximization, the chained Laspeyres index induces convergence to Ramsey prices
  - Average revenue regulation
    - Sets a cap on revenues per unit.
    - Flexible endogenous weights
    - Laxer constraint for tariff rebalancing: good for profit maximization under risk aversion and uncertainty.
    - Assuming stable cost and demand functions, and myopic profit maximization, average revenue regulation causes divergence from Ramsey prices
    - In a dynamic setting with changing cost and demand functions --and/or non-myopic profit maximization-- the chained Laspeyres index generates prices that may diverge from the Ramsey structure
- Regulation of the structure of the price might be used to promote the intertemporal expansion of networks

$$I(p) = \sum_{i=1}^h w_i p_i \leq \bar{P}$$

# SEMINAL MODEL

*Vogelsang, I. (2001), "Price Regulation for Independent Transmission Companies," Journal of Regulatory Economics, 20(2): 141-165, September*

- The Transco is a monopolist maximizing the flow of profits subject to regulation of its two-part tariff
- Explicitly studies cost and demand functions of transmission, relies on a "linear" definition of output (or throughput), and isolates the monopolistic nature of a for-profit Transco
- The intertemporal model:
  - Price cap (RPI-X) –regulatory lagged– regulation is the best price-level option
  - Price structure regulation: two-part tariff regulatory model with variable (or usage) charges, and fixed (or capacity) charges
  - The variable (usage) charge can also be understood as a nodal (congestion) price
  - The fixed (capacity) charge recovers fixed capital costs
  - **Expansion of the network reached by the intertemporal rebalancing of the fixed charge and the variable charge**
  - Transmitted volumes are weights
  - In equilibrium, optimal rebalancing of the fixed and variable charges depends on the ratio between the output weight, and the number of consumers

$$\max \Pi^t = p^t q^t + F^t N - c(q^t, K^t)$$

subject to

$$F^t \leq F^{t-1} + (p^{t-1} - p^t) q^w / N$$

$$q^t \leq K^t$$

Cost function:

$$C(q^t, K^{t-1}) = C(q^{t-1}, K^{t-1}), \forall q^t, q^{t-1} \leq K^{t-1}$$

$$C(q^t, K^t) = C(q^t, K^{t-1}) + f(K^{t-1}, I^t) \text{ for } q^t > K^{t-1}$$

$$I^t = K^t - K^{t-1}$$

Optimal conditions:

$$\left( \frac{\partial q^t}{\partial p^t} \right) \left( p^t - \frac{\partial C}{\partial q^t} \right) = q^w - q^t$$

$$L^t = -[1 - \frac{q^w}{q^t}] / \varepsilon^t$$

# THE UPGRADED MODEL

*Hogan, W., J. Rosellón and I. Vogelsang (2009), "A Combined Merchant-Regulatory Mechanism for Electricity Transmission Expansion," Revise and Resubmit, Journal of Regulatory Economics*

$$c^*(q, K^{t-1}, H^{t-1}) = \underset{K^t \in \mathbf{K}, H^t \in \mathbf{H}}{\text{Min}} \left\{ c(K^t, K^{t-1}, H^t, H^{t-1}) \mid H^t q \leq K^t \right\}.$$

$q_t$  = the net injections in period  $t$  (FTRs are derived from  $q_t$ )

$K_t$  = available transmission capacity in period  $t$

$H_t$  = transfer admittance matrix at period  $t$

$$\underset{\tau^t, F^t}{\text{Max}} \pi^t = \tau^t (q(\tau^t) - q^{t-1}) + F^t N^t - c^*(q(\tau^t), K^{t-1}, H^{t-1})$$

subject to

$$\tau^t Q^w + F^t N^t \leq \tau^{t-1} Q^w + F^{t-1} N^t$$

$t^t$  = vector of transmission prices between locations in period  $t$

$F^t$  = fixed fee in period  $t$

$N^t$  = number of consumers in period  $t$

$$Q^w = (q^t - q^{t-1})^w$$

$w$  = type of weight.

- The upgraded model emphasizes the need to combine the incentive model with a power-flow type of model where dispatch is carried out by an ISO. It provides optimal flows and nodal prices
- Sequence of actions:
  - Given an existing grid with historic market price information the regulator sets up the two-part pricing constraint
  - Based on the available market information (demand, generation, network topology, etc.) the Transco identifies the lines to expand
  - The Transco auctions the available transmission capacity
  - The ISO manages actual dispatch. According to locational marginal prices it collects the payoffs from loads and pays the generators. The difference of both values represents the congestion rent of the system that is redistributed to the property-right holders.
  - The Transco can also set the fixed fee according to the regulatory price cap.

# A combined merchant-regulatory mechanism (algorithm)

- Profit maximizing Transco:

$$\max_{k, F} \pi = \sum_t \left[ \sum_i (p_i^t d_i^t - p_i^t g_i^t) + F^t N^t - \sum_{i,j} c(k_{ij}^t) \right]$$

s.t.

$$\frac{\sum_i (p_i^t d_i^w - p_i^t g_i^w) + F^t N^t}{\sum_i (p_i^{t-1} d_i^w - p_i^{t-1} g_i^w) + F^{t-1} N^t} \leq 1 + RPI + X$$

**Regulatory constraint**

## Lower level problem:

### Welfare maximization:

s.t.

Line capacity restriction

Energy balance

Plant capacity restriction

$$\max_{d, g} W = \sum_{i,t} \left( \int_0^{d_i^t} p(d_i^t) dd_i^t \right) - \sum_{i,t} mc_i g_i^t$$

$$|pf_{ij}^t| \leq k_{ij}^t \quad \forall ij$$

$$g_i^t + q_i^t = d_i^t \quad \forall i,t$$

$$g_i^t \leq g_i^{t, \max} \quad \forall i,t$$

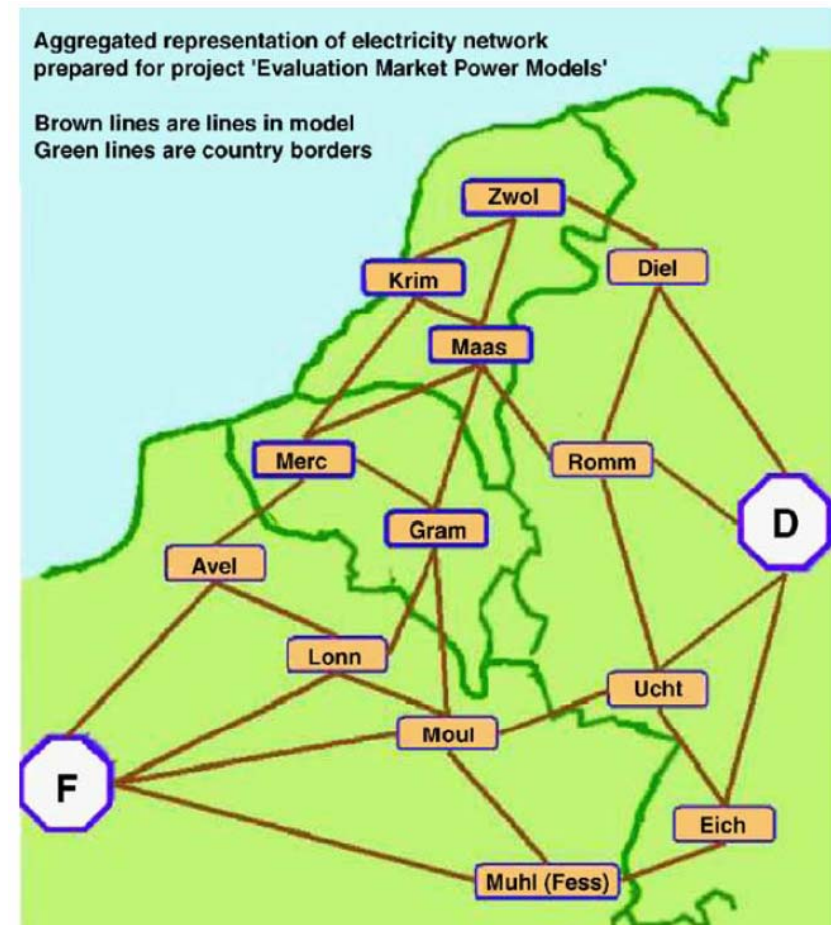
# Application to Electricity Transmission

# APPLICATION OF HOGAN, ROSELLÓN AND VOGELSANG (2009)

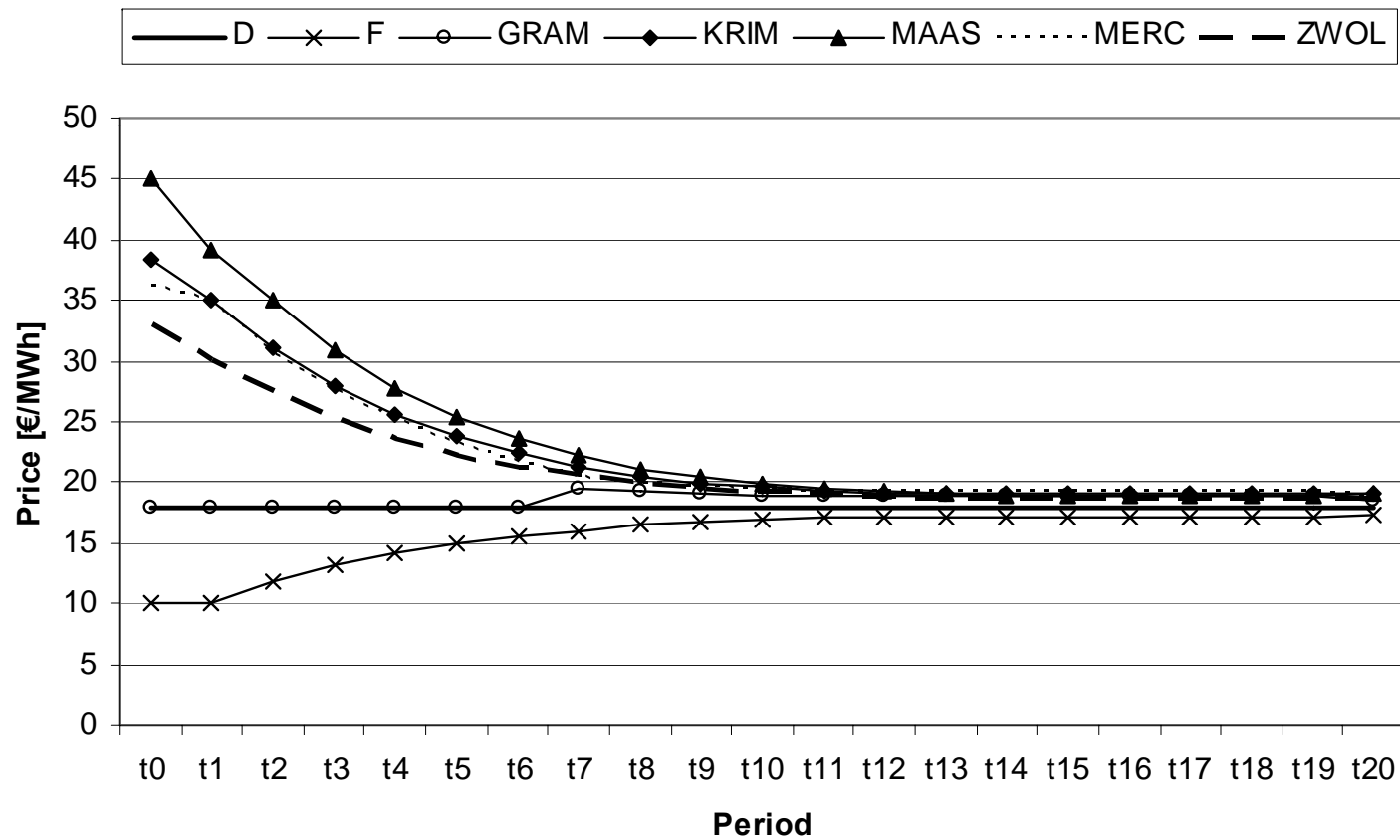
*Rosellón, J. and H. Weigt (2009), "A Dynamic Incentive Mechanism for Transmission Expansion in Electricity Networks – Theory, Modeling and Application," submitted to the Energy Journal (winner of the Reimut Jochimsen Prize)*

Simplified model of the BENELUX:

- Implementation of the HRV model to meshed electricity networks.
- Covering 15 nodes and 28 lines.
- Including 8 plant types (nuclear, lignite, coal, CCGT, gas/oil, hydro, pump) with fixed marginal costs.
- Initial congestion between Belgium and France, and Germany and the Netherlands.
- Neglecting wind capacities.
- 20 periods, 8% interest rate.
- Only network upgrades possible at linear extension costs of 100 € per km per MW capacity.



# Extension schedule leads to price convergence at the marginal generation level



Total transmission capacity is significantly increased, the Transco's profits are augmented, and there is convergence towards the welfare optimum.

**Table 1: Comparison of regulatory approach with welfare maximization (values refer to the last period)**

|                            | No grid extension | Regulatory Approach | Welfare Maximization |
|----------------------------|-------------------|---------------------|----------------------|
| Consumer rent [Mio€h]      | 10.37             | 10.31               | 10.30                |
| Producer rent [Mio€h]      | 0.65              | 0.99                | 1.02                 |
| Congestion rent [T€h]      | 107.8             | 20.20               | 7.13                 |
| Total welfare [Mio€h]      | 11.13             | 11.32               | 11.33                |
| Total extension sum [Mio€] | -                 | 285.27              | 305.26               |
| Total grid capacity [GW]   | 33.4              | 60.9                | 62.64                |
| Average price [€/MWh]      | 28,4              | 18,5                | 18,1                 |

# PRELIMINARY RESULTS FOR OTHER NETWORKS

|   | No grid extension |              |              |                         | Regulatory Approach |              |              |             | Welfare Maximization |              |              |              |
|---|-------------------|--------------|--------------|-------------------------|---------------------|--------------|--------------|-------------|----------------------|--------------|--------------|--------------|
|   | PJM               | ONTARIO      | MEXICO       | NWE                     | PJM                 | ONTARIO      | MEXICO       | NWE         | PJM                  | ONTARIO      | MEXICO       | NWE          |
| Total grid capacity<br>[GW <sup>1</sup> ] | <b>26.91</b>      | <b>15.35</b> | <b>11.04</b> | <b>33.4</b>             | <b>49.88</b>        | <b>28.54</b> | <b>21.74</b> | <b>60.9</b> | <b>52.63</b>         | <b>31.74</b> | <b>24.87</b> | <b>62.64</b> |
| Average price<br>[Usd/MWh]                | <b>72.0</b>       | <b>14.59</b> | <b>20.4</b>  | <b>28.4<sup>2</sup></b> | <b>46.63</b>        | <b>11.78</b> | <b>13.54</b> | <b>18.5</b> | <b>46.21</b>         | <b>11.72</b> | <b>13.50</b> | <b>18.1</b>  |

Data set: PJM 2006, Ontario 2006, Mexico 2004, NWE 2005.

<sup>1</sup> Excluding auxiliary lines.

<sup>2</sup> €/MWh.

# Potential Applications to Natural Gas Networks

# MODEL FORMULATION

*Neumann, A., N. Viehrig, and H. Weigt (2009), "InTraGas-A Stylized Model of the European Natural Gas Network," Mimeo.*

- “**Lower level**” program for natural gas transportation. Simple representation of the main natural gas infrastructure in Europe
- It provides optimal loads, nodal prices, and transportation bottlenecks through a simple linear programming approach that maximizes welfare given technical and capacity constraints (similar to the power flow model in electricity)
- These results can later be used to test the proposed incentive regulatory model which removes existing cross-border bottlenecks in the European long-distance natural gas pipeline system
- One operator is responsible for the long-distance natural gas transportation network across Europe

$$\begin{aligned} \max W = & \sum_{n,t} \int_0^{d_{n,t}^*} p(d_n) dd_{n,t} - \sum_{n,t} c_{n,t} g_{n,t} \\ & - \sum_{n,m,t} tc_{n,m} flow_{n,m,t} - \sum_{n,m,t} LNGtc_{n,m} LNGflow_{n,m,t} \end{aligned} \quad (1)$$

**s.t.**

$$g_{n,t} \leq g_n^{\max} \quad \text{production constraint} \quad (2)$$

$$flow_{n,m,t} \leq flow_{n,m}^{\max} \quad \text{Pipeline constraint} \quad (3)$$

$$LNGflow_{n,m,t} \leq LNGflow_{n,m}^{\max} \quad \text{LNG route constraint} \quad (4)$$

$$\sum_m LNGflow_{n,m,t} \leq Liquefaction_{n,t}^{\max} \quad \text{Liquefaction constraint} \quad (5)$$

$$\sum_m LNGflow_{m,n,t} \leq Regasification_{n,t}^{\max} \quad \text{Regasification constraint} \quad (6)$$

$$store_{n,t} = store_{n,t-1} + s_{n,t-1}^{in} - s_{n,t-1}^{out} \quad \text{Storage balance} \quad (7)$$

$$store_{n,t} \leq store_n^{\max} \quad \text{Storage constraint} \quad (8)$$

$$\begin{aligned} & g_{n,t} - d_{n,t} - s_{n,t-1}^{in} + s_{n,t-1}^{out} \\ & + \sum_m flow_{m,n,t} - \sum_m flow_{n,m,t} \\ & + \sum_m LNGflow_{m,n,t} - \sum_m LNGflow_{n,m,t} \geq 0 \end{aligned} \quad \text{Energy balance} \quad (9)$$

| Parameter               | Explanation  |
|-------------------------|--|
| <b>Production</b>       |  |
| gmax(n,t)               | Maximum production capacity at node n in period t            |
| c(n)                    | Natural gas production / extraction costs at node n          |
| <b>Demand</b>           |  |
| d_ref(n,t)              | Reference demand at node n in period t                       |
| <b>Pipeline Network</b> |  |
| flowmax(n,m)            | Maximum pipeline capacity between nodes                      |
| dis(n,m)                | Distance between two nodes n and m in pipeline network in km |
| tc(n,m)                 | Pipeline transportation cost ratio                           |
| <b>Storage</b>          |  |
| storemax(n)             | Maximum storage capacity at each node                        |
| sinmax(n)               | Maximum storage injection capacity at each node              |
| soutmax(n)              | Maximum storage withdrawal capacity at each node             |
| <b>LNG</b>              |  |
| Liquefactionmax(n)      | Maximum liquefaction capacity at each node                   |
| Regasificationmax(n)    | Maximum regasification capacity at each node                 |
| LNGflowmax(n,m)         | Maximum LNG transportation capacity from node to node        |
| LNGtc(n,m)              | LNG transportation costs from node to node                   |

# IMPLEMENTATION OF THE INCENTIVE HRV MODEL TO THE EUROPEAN PIPELINE SYSTEM

## Data:

- ✓ Number of nodes
- ✓ Number of producers associated to each node and their type of technology
- ✓ Marginal production cost
- ✓ Maximum production
- ✓ Demand at each node (peak and non-peak demand)
- ✓ Capacities of transmission pipelines.

## Results:

- ✓ Nodal prices
- ✓ Optimal loads
- ✓ Congested pipelines

Table: Country coverage

| Country         | Node | Country        | Node | Country      | Node |
|-----------------|------|----------------|------|--------------|------|
| Germany         | n1   | Austria        | n14  | Iran         | n27  |
| Denmark         | n2   | Italy          | n15  | Turkmenistan | n28  |
| Norway          | n3   | Czech Republic | n16  | Azerbaijan   | n29  |
| Sweden          | n4   | Slovakia       | n17  | Qatar        | n30  |
| Finland         | n5   | Poland         | n18  | Egypt        | n31  |
| The Netherlands | n6   | Estonia        | n19  | Libya        | n32  |
| Belgium         | n7   | Latvia         | n20  | Algeria      | n33  |
| France          | n8   | Lithuania      | n21  | T&T          | n34  |
| UK              | n9   | Belarus        | n22  | Nigeria      | n35  |
| Ireland         | n10  | Ukraine        | n23  | Russia       | n36  |
| Spain           | n11  | Romania        | n24  | Turkey       | n37  |
| Portugal        | n12  | Hungary        | n25  |              |      |
| Switzerland     | n13  | Slovenia       | n26  |              |      |

# Conclusions

- Incentive regulation for firms to expand networks
- Decisions on price regulation should consider reaching equilibrium in at least two trade-offs:
  1. Risk management vs. Incentives
  2. Investment attraction vs. Consumer-surplus maximization
- Our studies on electricity and natural gas transmission are just first steps in a research agenda that should evolve into various modeling exercises as well as simulations and applications

- One (“super”) ISO responsible for the long-distance energy transmission networks
- Different institutions within regions: e.g. Europe and North America. Scope of their attributions. Would a real-world application of the HRV model make sense? Would it help to expand border capacities?
- The application of the incentive mechanism would at least provide a welfare efficient “benchmark” even if the institutional constraints cannot be solved
- The application of the model would at least provide a measure of the implied welfare losses of not solving the bottlenecks