Robustness of Trans-European Gas Networks: The Hot Backbone

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Motivation: characterising robustness

- Ukraine alone transits approximately 80% of Russian gas exports to Europe, suggesting the presence of a strong transportation backbone crossing several European countries;
- Historically, critical infrastructure networks have evolved under the pressure to minimize local rather than global failures. However, little is known on how this local optimization impacts network robustness and security of supply on a global scale;
- The absence of historical records on the simultaneous failure of a significant percentage of components in natural gas networks implies that the methods of percolation theory are of little practical relevance in our case.
- Here we adopt the view that a *robust infrastructure network* is one which has evolved to be *error-tolerant to failures of high load links*.

Where do we come in?

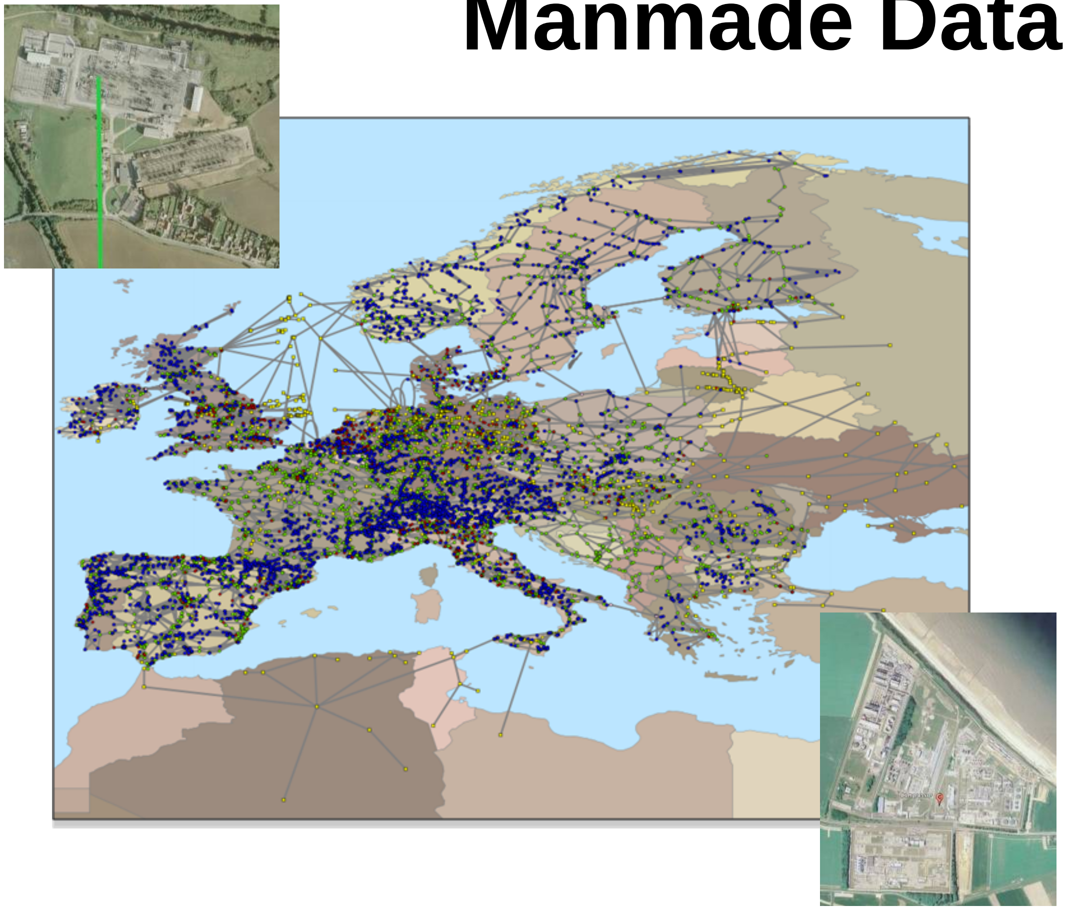
- "What has been co-ordinated remarkably effectively is climate change strategy, with a working emissions trading scheme and a well-developed trading market. EU governments have also agreed on some very ambitious targets for cutting emissions and boosting renewable energy. On the other hand, energy security policy is still a free-for-all, with no common stance on negotiations with Russia and other energy suppliers."

Ed Crooks, FT energy editor

FT, 23/10/2008

If it’s not regulated, it can be modelled with tools of complex systems.

Manmade Data Overview



Electricity network

Nodes (10494) - power stations, power plants;

Links (15413) - power lines;

Node attributes - position, power plant capacity;

Link attributes - voltage level, Length.

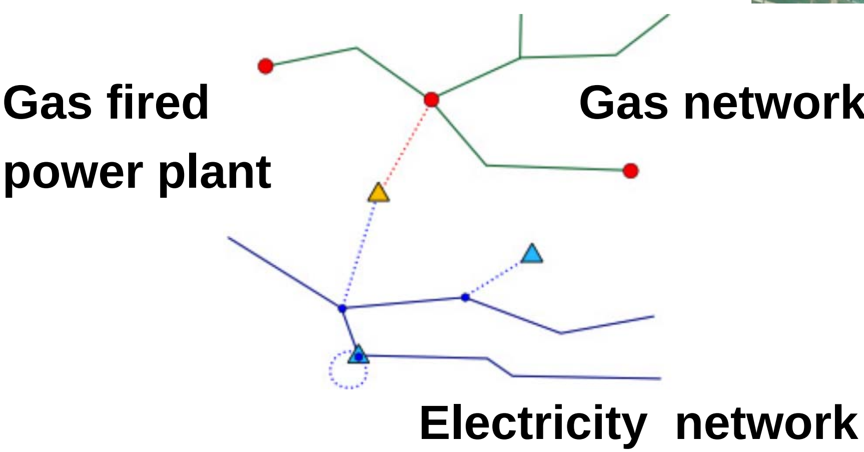
Gas network (transmission)

Nodes (2207) - compressor stations, LNG terminals, city gates, etc.

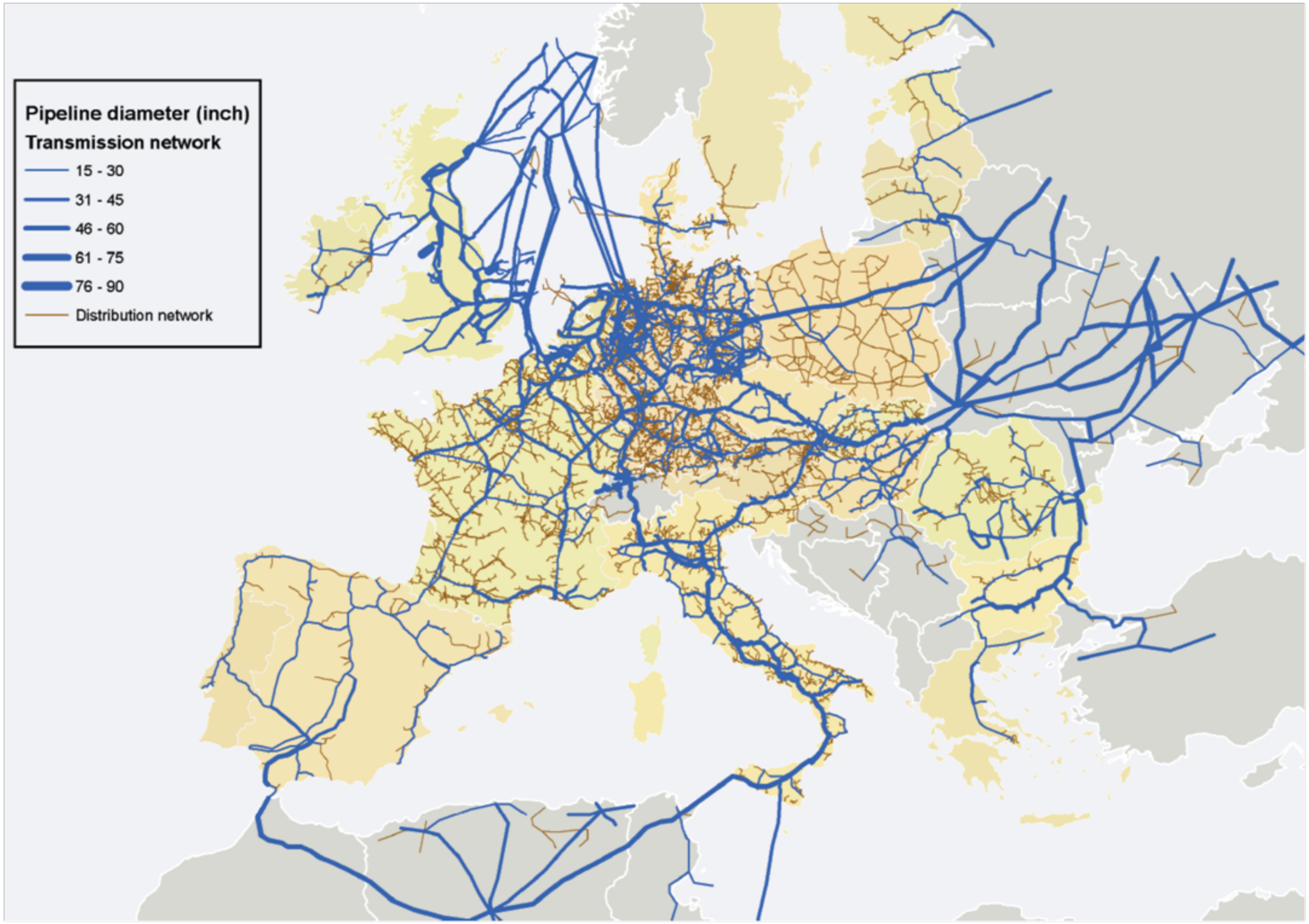
Links (2696) – pipelines;

Node attributes - position, storage and LNG terminal capacities;

Link attributes - length, diameter



Datasets: European gas pipeline network



Transmission network

(d>= 15, + interconnections)

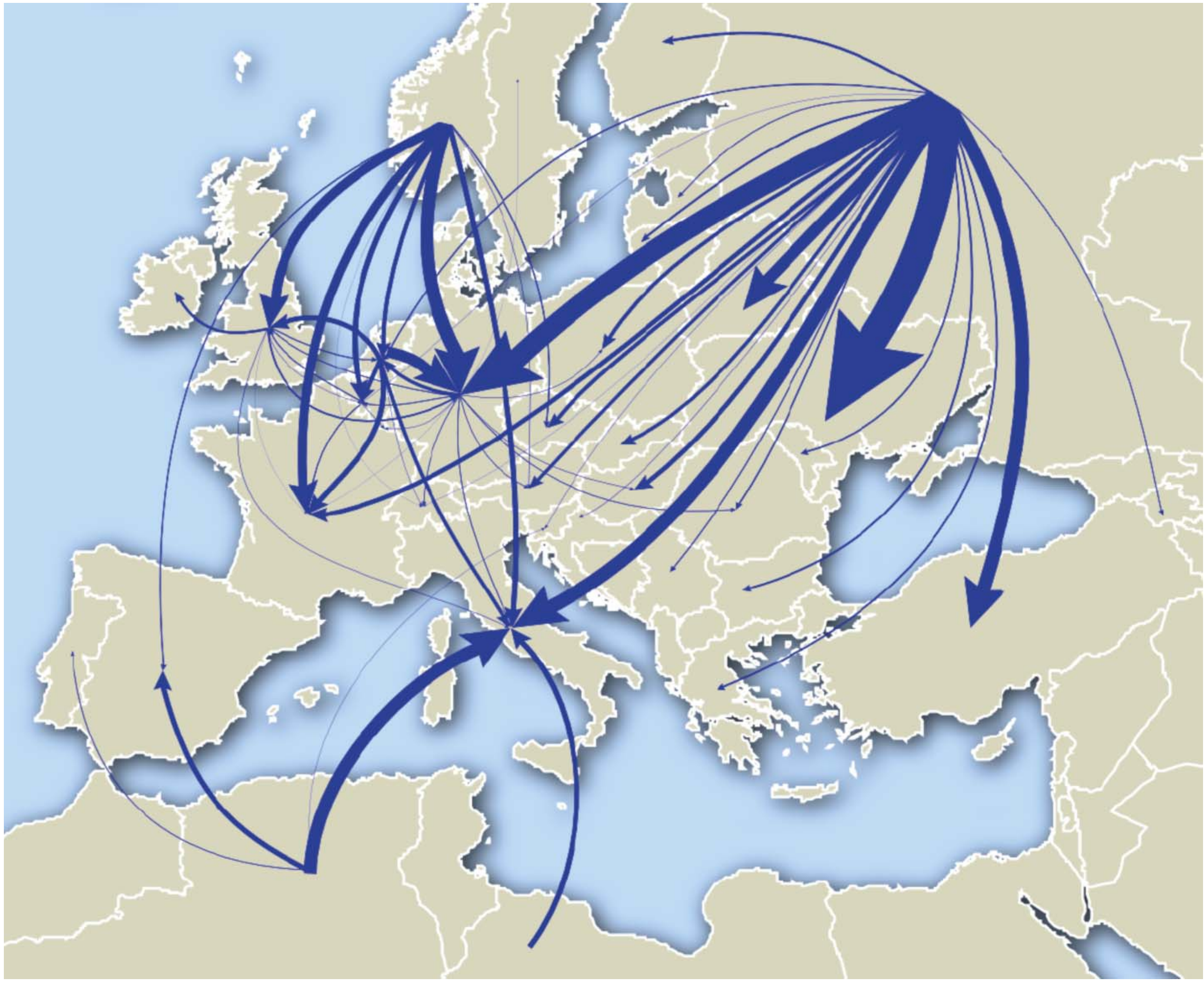
2207 nodes, 2696 links

Complete network

24010 nodes, 25554 links

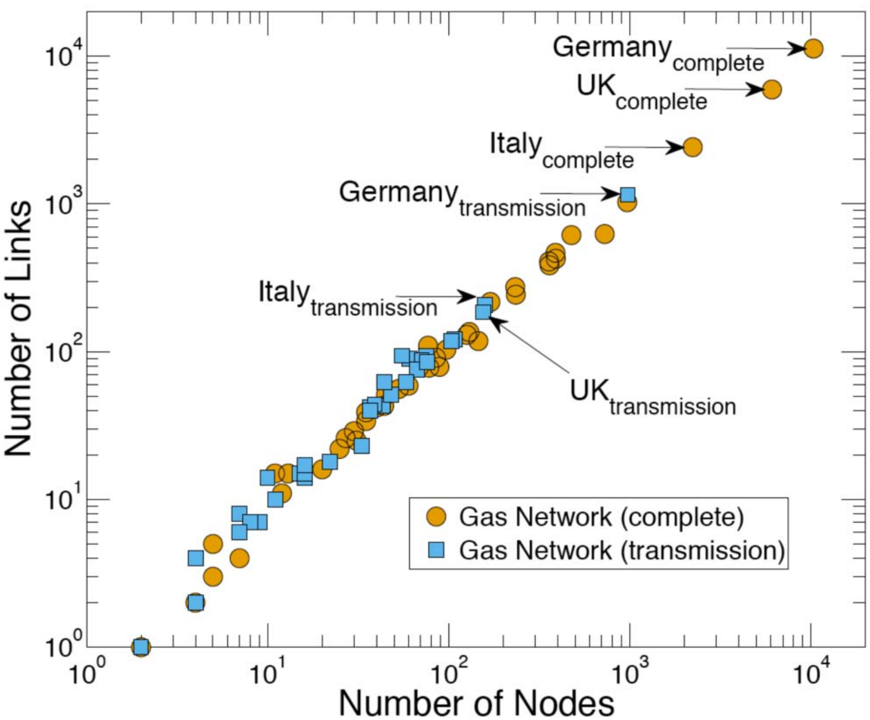
www.platts.com

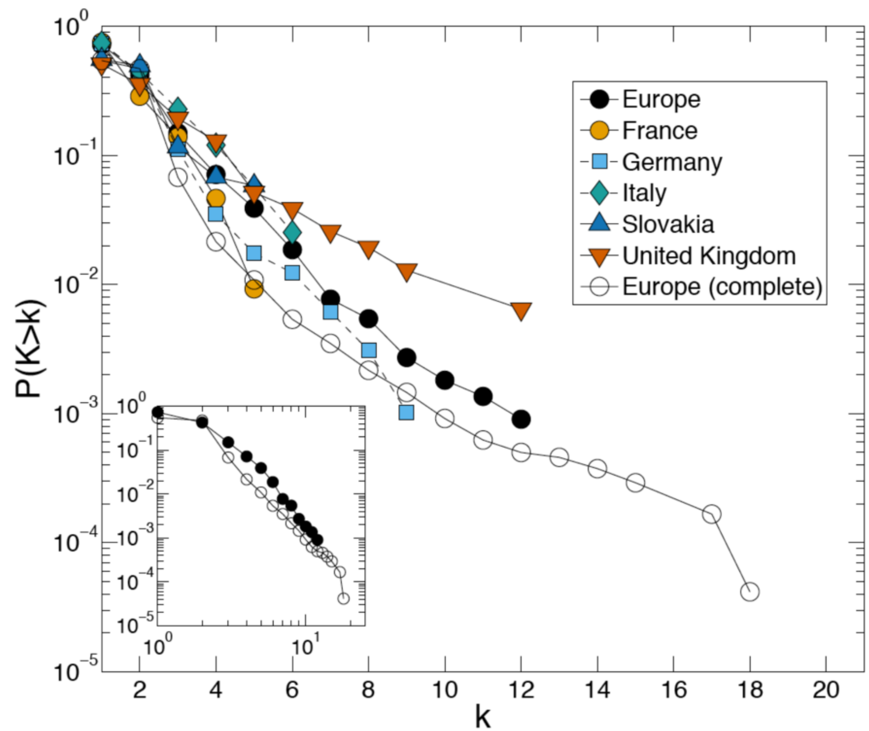
Datasets: Gas trade movements by pipeline



Data collected from:
www.bp.com
www.iea.org

Gas network topology





$\langle k_{\mathrm{transmission}} \rangle = 2.4$

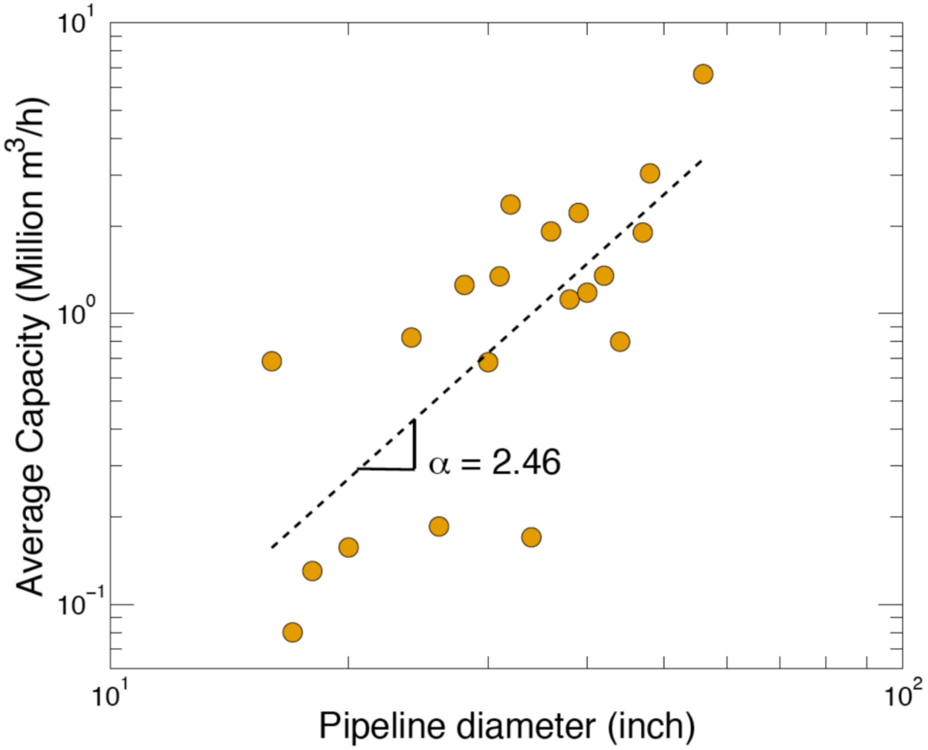
$\langle k_{\mathrm{full}} \rangle = 2.1$

$P(K > k) \approx \exp(-k/\lambda)$, with $\lambda = 1.44$

Pipeline capacity

- (phenomenological) Darcy–Weisbach eq. describes the loss of energy due to friction within the pipeline and is valid in the laminar and turbulent regimes:

$$h_f = \frac{16 f\, l\, (dV/dt)^2}{\pi^2 d^5},$$



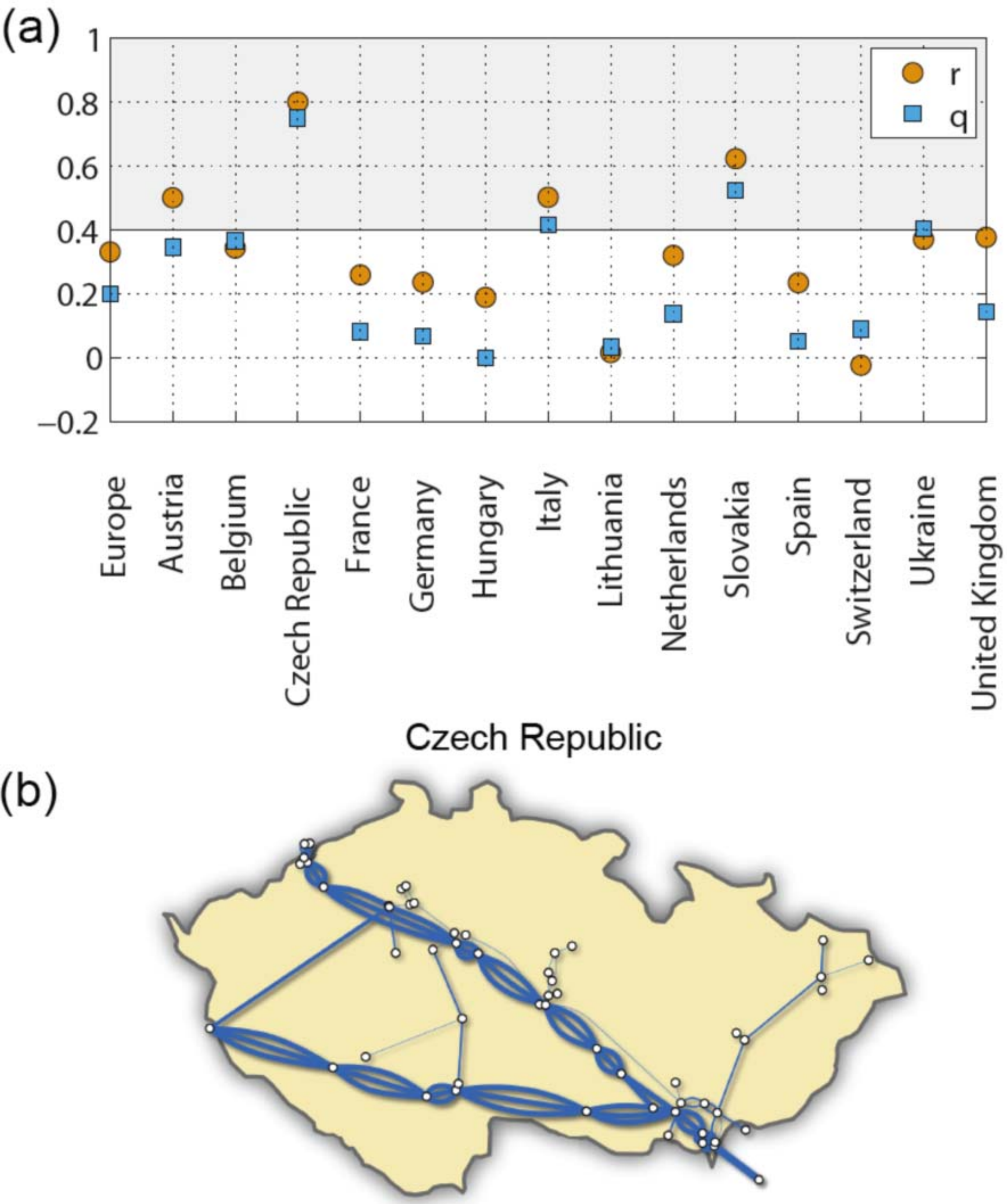
- h_f is the pipeline head loss;
- f is called the Darcy friction factor;
- l is the length of the pipeline;
- dV/dt is the volumetric flow rate (also capacity);
- d is the pipeline diameter.

- In general, the friction factor f and the pipeline loss h_f depend on d, so the capacity of the pipeline is given by $c = dV/dt = \frac{\pi}{4}\left(\frac{h_f}{f\,l}\right)^{1/2} d^{5/2} \sim d^{\gamma}$, where typically $\gamma \simeq 2.6$ for gas pipelines.

$$c \sim d^{2.5}$$

www.gie.eu.com

Do highly connected nodes to link to each other over high capacity pipelines?



$$r = \frac{\sum_{e_{ij}} \left(k_i k_j - \overline{k_i k_j}\right)\left(c_{e_{ij}} - \overline{c_{e_{ij}}}\right)}{\sqrt{\sum_{e_{ij}} \left(k_i k_j - \overline{k_i k_j}\right)^2}\sqrt{\sum_{e_{ij}} \left(c_{e_{ij}} - \overline{c_{e_{ij}}}\right)^2}}.$$

- k_i and k_j are the degrees of the nodes at the ends of pipeline e_{ij};
- $c_{e_{ij}}$ is the capacity of the pipeline;
- Countries with high values of r have a gas pipeline network where degree hubs are interconnected by several parallel pipelines;

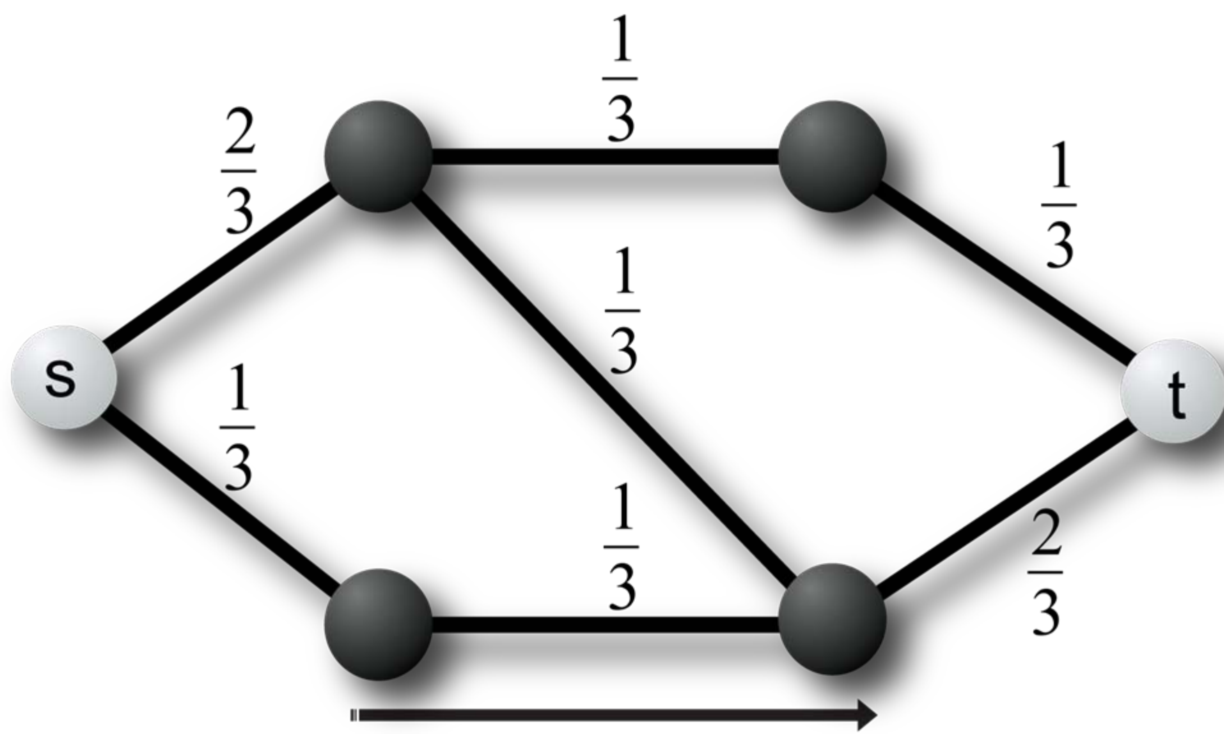
- Further, we plotted the percentage q of capacity on parallel pipelines for each national network. Typically, countries with high values of r also have high values of q.

Betweenness centrality

Consider a substrate network $G_S = (V_S, E_S)$ with node-set V_S and link-set E_S. The betweenness centrality of link $e_{ij} \in E_S$ is defined as the relative number of shortest paths between all pairs of nodes which pass through e_{ij},

$$g(e_{ij}) = \sum_{\substack{s,t \in V_S \\ s \neq t}} \frac{\sigma_{s,t}(e_{ij})}{\sigma_{s,t}} \quad (1)$$

where $\sigma_{s,t}$ is the number of shortest paths from node s to node t and $\sigma_{s,t}(e_{ij})$ is the number of these paths passing through link e_{ij}.

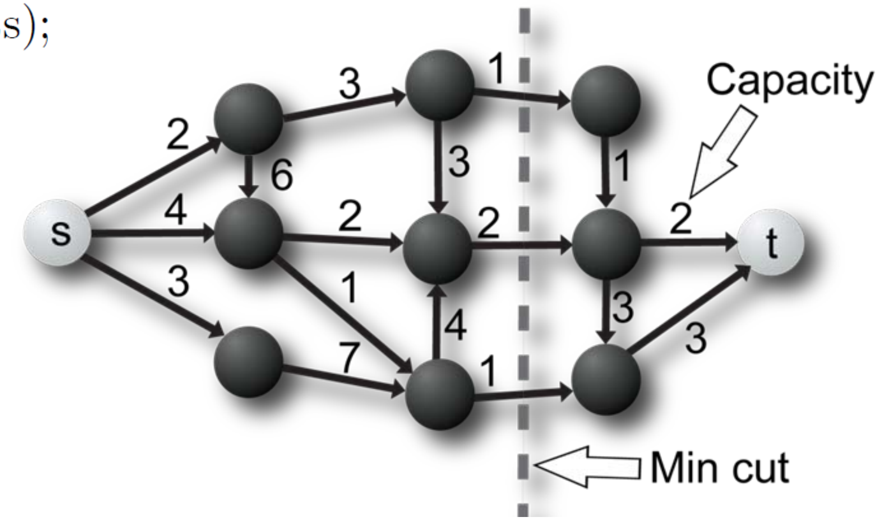


The max-flow problem

The maximum flow problem can be stated as follows: In a network with link capacities, we wish to send as much flow as possible between two particular nodes, a source and a sink, without exceeding the capacity of any link.

Formally, an *s-t flow network* $G_F = (V_F, E_F, s, t, c)$ is a digraph with node-set V_F, link-set E_F, two distinguished nodes, a *source* s and a *sink* t, and a capacity function $c : E_F \rightarrow \mathbb{R}_0^+$. A *feasible flow* is a function $f : E_F \rightarrow \mathbb{R}_0^+$ satisfying the following two conditions:

- $0 \leq f(e_{ij}) \leq c(e_{ij}), \forall e_{ij} \in E_F$ (capacity constraints);
- $\sum_{j:e_{ji} \in E_F} f(e_{ji}) = \sum_{j:e_{ij} \in E_F} f(e_{ij}), \ \forall i \in V \backslash \{s, t\}$ (flow conservation constraints);



The *maximum s-t flow* is defined as the maximum flow into the sink, $f_{st}(G_F) = \max(\sum_{i:e_{it} \in E_F} f(e_{it}))$ subject to the conditions that the flow is feasible.

Generalized betweenness centrality

Create a flow network by partitioning the substrate network, $G_S = (V_S, E_S)$, into a set of disjoint subgraphs $V_F = \{(V_{S_1}, E_{S_1}), \cdots, (V_{S_M}, E_M)\}$. The flow network $G_F = (V_F, E_F)$ is then defined as the directed network of flows among the subgraphs in V_F, where the links E_F are weighted by the value of aggregate flow among the V_F.

The betweenness centrality of link $e_{ij} \in E_S$ is defined as

$$g(e_{ij}) = \sum_{\substack{s,t \in V_S \\ s \neq t}} \frac{\sigma_{s,t}(e_{ij})}{\sigma_{s,t}} \tag{1}$$

The *generalized betweenness centrality* (generalized betweenness) of link $e_{ij} \in E_S$ is defined as follows. Let $T_{K,L}$ be the flow from source subgraph $K = (V_K, E_K) \in V_F$ to sink subgraph $L = (V_L, E_L) \in V_F$. Take each link $e_{KL} \in E_F$ and compute the betweenness centrality from Eq. (1) of $e_{ij} \in E_S$ restricted to source nodes $s \in V_K$ and sink nodes $t \in V_L$. The contribution of that flow network link is then weighted by $T_{K,L}$ and normalized by the number of links in a complete bipartite graph between nodes in V_K and V_L

$$G_{ij} = \sum_{e_{KL} \in E_F} \sum_{s \in V_K, t \in V_L} \frac{T_{K,L}}{|V_K||V_L|} \frac{\sigma_{st}(e_{ij})}{\sigma_{st}}.$$

Generalized max-flow betweenness vitality

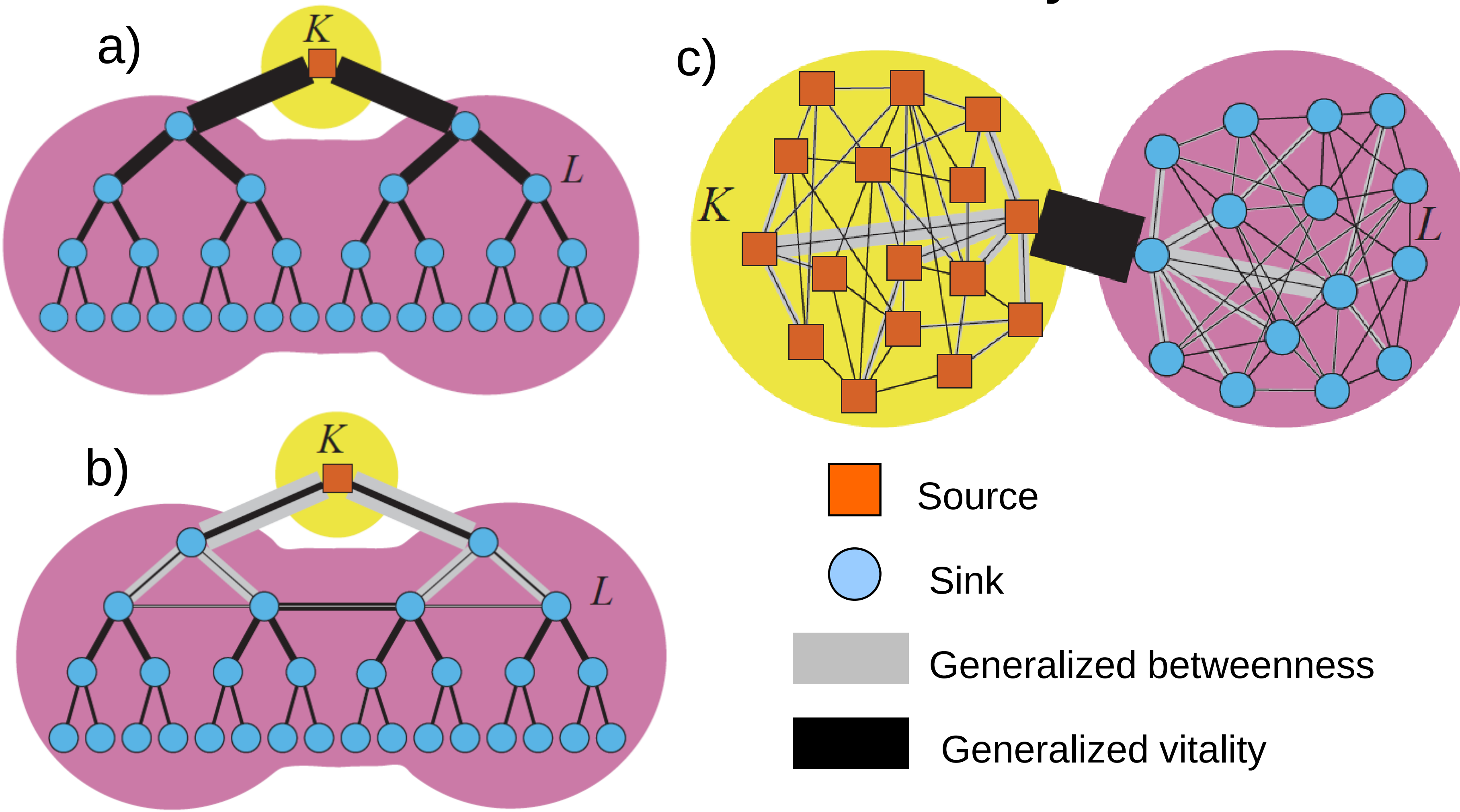
Question: How does the maximum flow between all sources and sinks change, if we remove a link e_{ij} from the network?

In the absence of a detailed flow model, we calculated the flow that is lost when a link e_{ij} becomes non-operational assuming that the network is working at maximum capacity. In agreement with Eq. (2), we define the *generalized max-flow betweenness vitality* (generalized vitality):

$$V_{ij} = \sum_{e_{KL} \in E_F} \sum_{s \in V_K, t \in V_L} \frac{T_{K,L}}{|V_K||V_L|} \frac{\Delta_{st}^{G_F}(e_{ij})}{f_{st}(G_F)}, \tag{3}$$

where the amount of flow which must go through link e_{ij} when the network is operating at maximum capacity is given by the vitality of the link: $\Delta_{st}^{G_F}(e_{ij}) = f_{st}(G_F) - f_{st}(G_F \backslash e_{ij})$, and $f_{st}(G_F)$ is the maximum s-t flow in G_F.

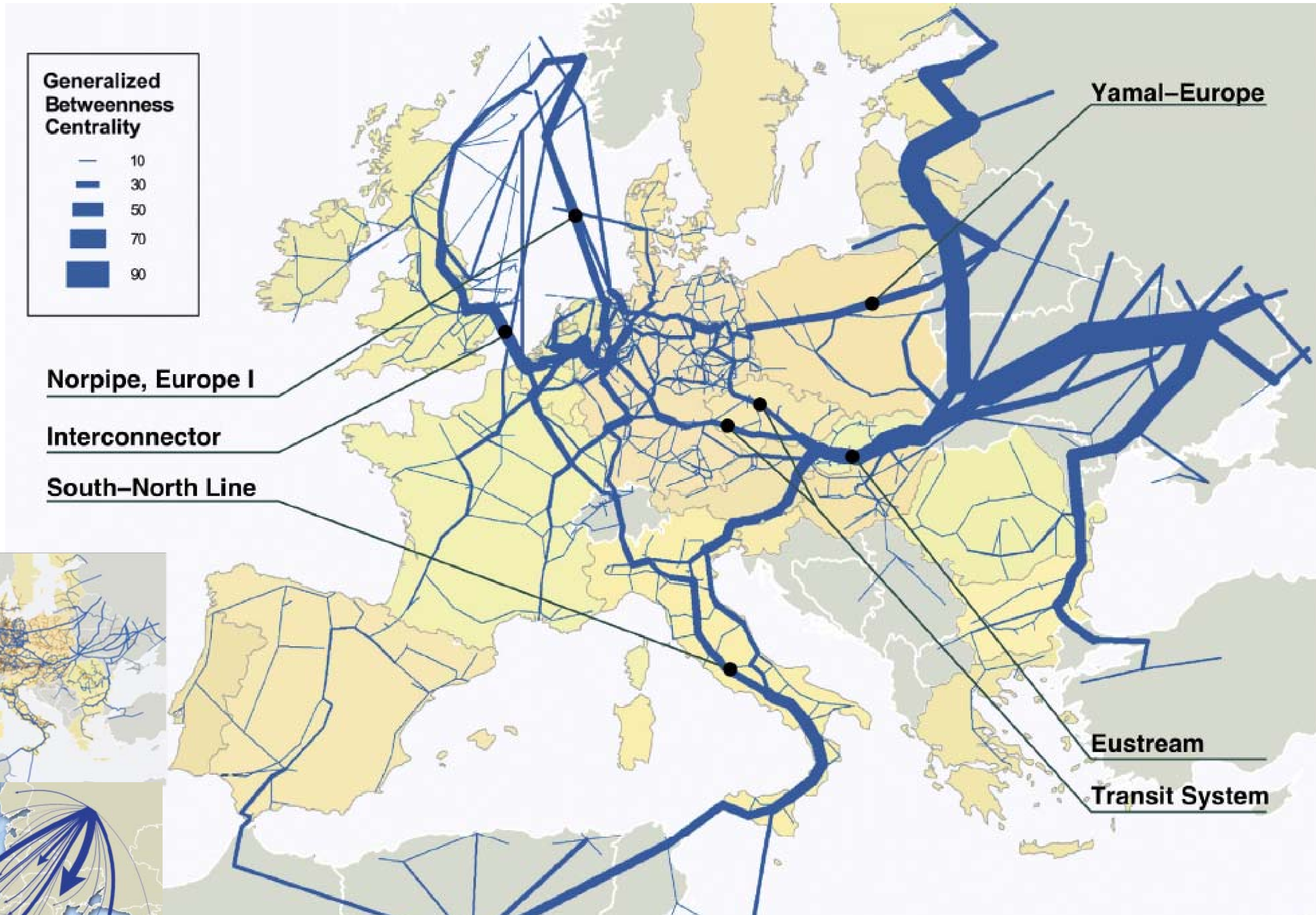
Relation between generalized betweenness and vitality



Generalized betweenness (grey) and vitality (black) measures on: (a) a rooted tree (b) a modified rooted tree with interconnections at a chosen level and (c) two communities connected by one link.

Generalized betweenness applied to gas networks

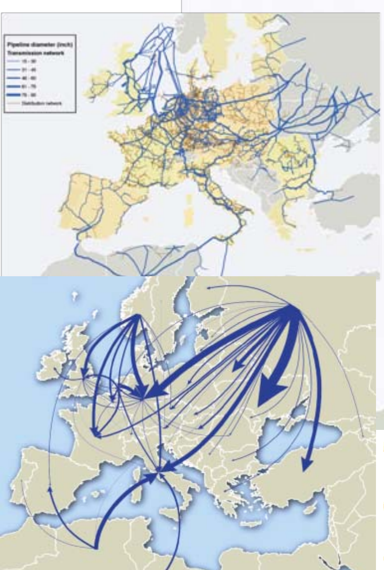
$$G_{ij} = \sum_{e_{KL} \in E_F} \sum_{s \in V_K, t \in V_L} \frac{T_{K,L}}{|V_K||V_L|} \frac{\sigma_{st}(e_{ij})}{\sigma_{st}}.$$



Trans-European natural gas network. Link thickness is proportional to the generalized betweenness centrality, where the sets K and L are countries and the values of $T_{K,L}$ are taken from the data in the flow network.

Generalized vitality applied to gas networks

$$V_{ij} = \sum_{e_{KL} \in E_F} \sum_{s \in V_K, t \in V_L} \frac{T_{K,L}}{|V_K||V_L|} \frac{\Delta_{st}^{G_F}(e_{ij})}{f_{st}(G_F)},$$



Trans-European natural gas network. Link thickness is proportional to the generalized max-flow betweenness vitality, where the sets K and L are countries and the values of $T_{K,L}$ are taken from the data in the flow network.

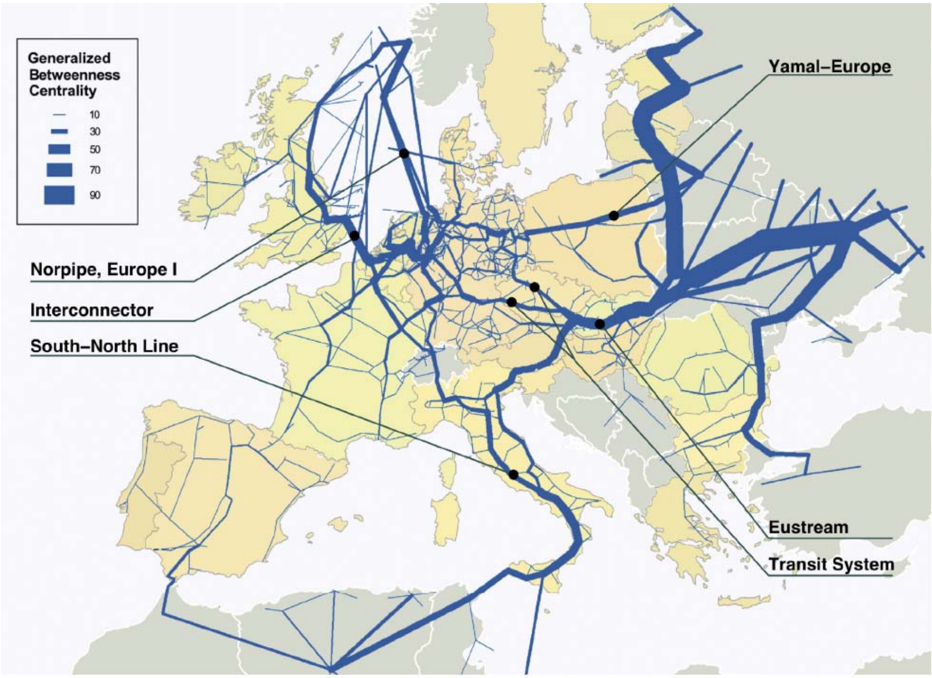
What is the hot backbone?

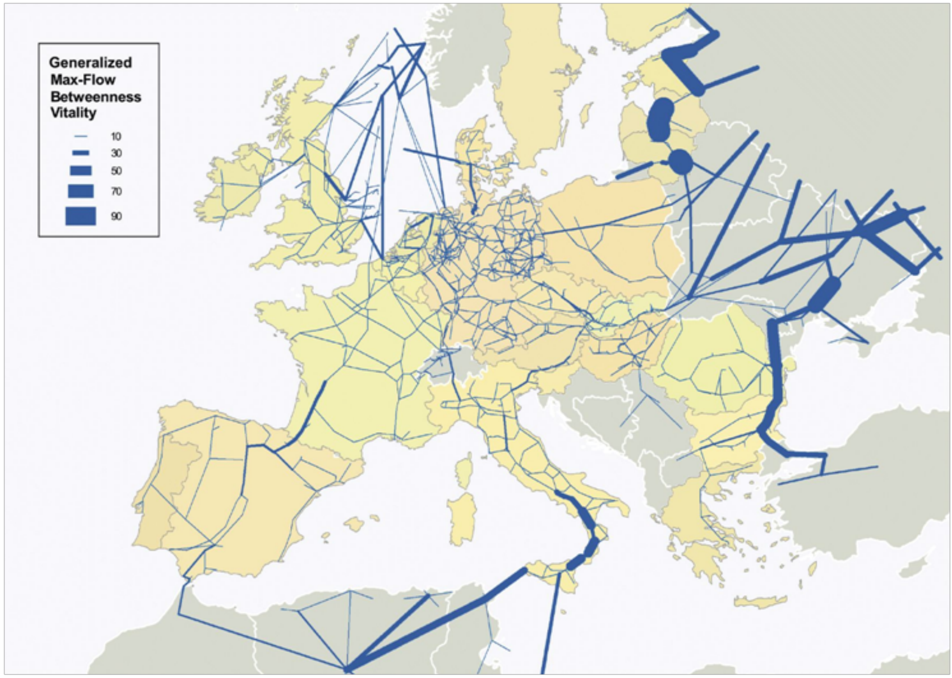
[see Almaas, Kovacs, Vicsek, Oltvai, Barabasi, Nature **247**, 839 (2004)]

- Possible flux structures:
  - A homogeneous local organization; comparable fluxes;
  - The *hot backbone*: local flux organization is heterogeneous; majority of flux carried along few pathways;
- Why ‘hot’?
  - A few active interactions embedded into a web of less active interactions;

Robust infrastructure network: error tolerant to failures of high load links

High Traffic (Hot) Backbone + Error Tolerance = Robustness
(*i.e.* **Good Engineering**)





Summary of conclusions

- Degree of transmission net decays exponentially;
- Degree distribution of the complete (transmission + distribution) net is fat tailed;
- In some transit countries (Austria, Czech Rep, Italy and Slovakia), the main gas pipelines are organized along high capacity corridors with parallel pipelines;
- This implies that the network is error-tolerant because failure of one pipeline causes only a decrease in flow;

- At global scale, there are two competing mechanisms :
    - Cost and efficiency constraints to minimize length of transport routes and maximize transported volumes (backbone of transport efficiency; betweenness);
    - Error-tolerance developed by adding redundant links (backbone of fault tolerance; vitality);
- The two mechanisms make the network robust: error-tolerant to failures of high-load links;

- Further possible directions:
    - Planned and under construction pipelines may change the robustness of the network
    - LNG and storage has the potential to reduce dependency on one single export country such as Russia;
    - The Ukraine-Russia dispute (Jan 2009) has highlighted how the European gas network is robust to engineering failures, yet fragile to geopolitical crises.