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Robustness of Trans-European Gas Networks: The Hot Backbone

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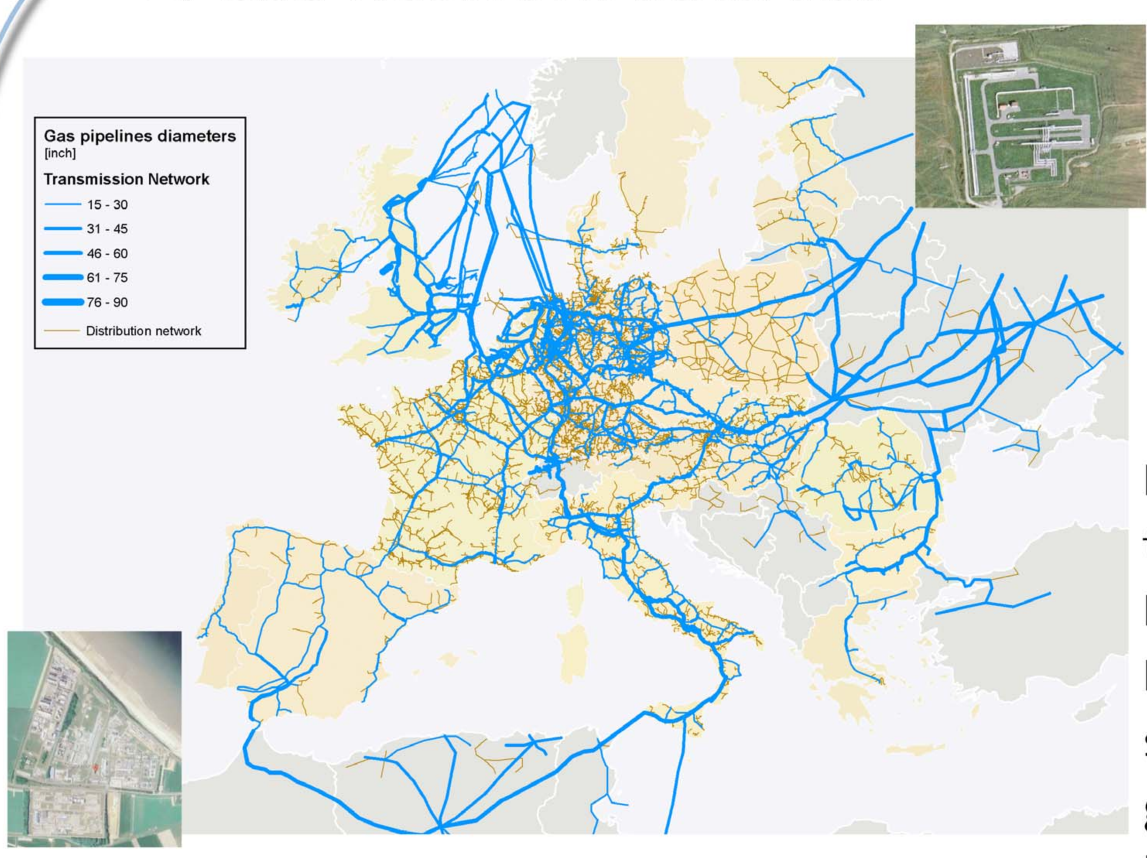
1. Abstract

Here we uncover the load and vulnerability backbones of the Trans-European gas pipeline network. Combining topological data with information on inter-country flows, we estimate the global load of the network and its vulnerability to failures. To do this, we apply two complementary methods generalized from the betweenness centrality and the maximum flow. We find that the gas pipeline network has grown to satisfy a dual-purpose: on one hand, the major pipelines are crossed by a large number of shortest paths thereby increasing the efficiency of the network; on the other hand, a non-operational pipeline causes only a minimal impact on network capacity, implying that the network is error-tolerant. These findings suggest that the Trans-European gas pipeline network is robust, i.e. error-tolerant to failures of high load links.

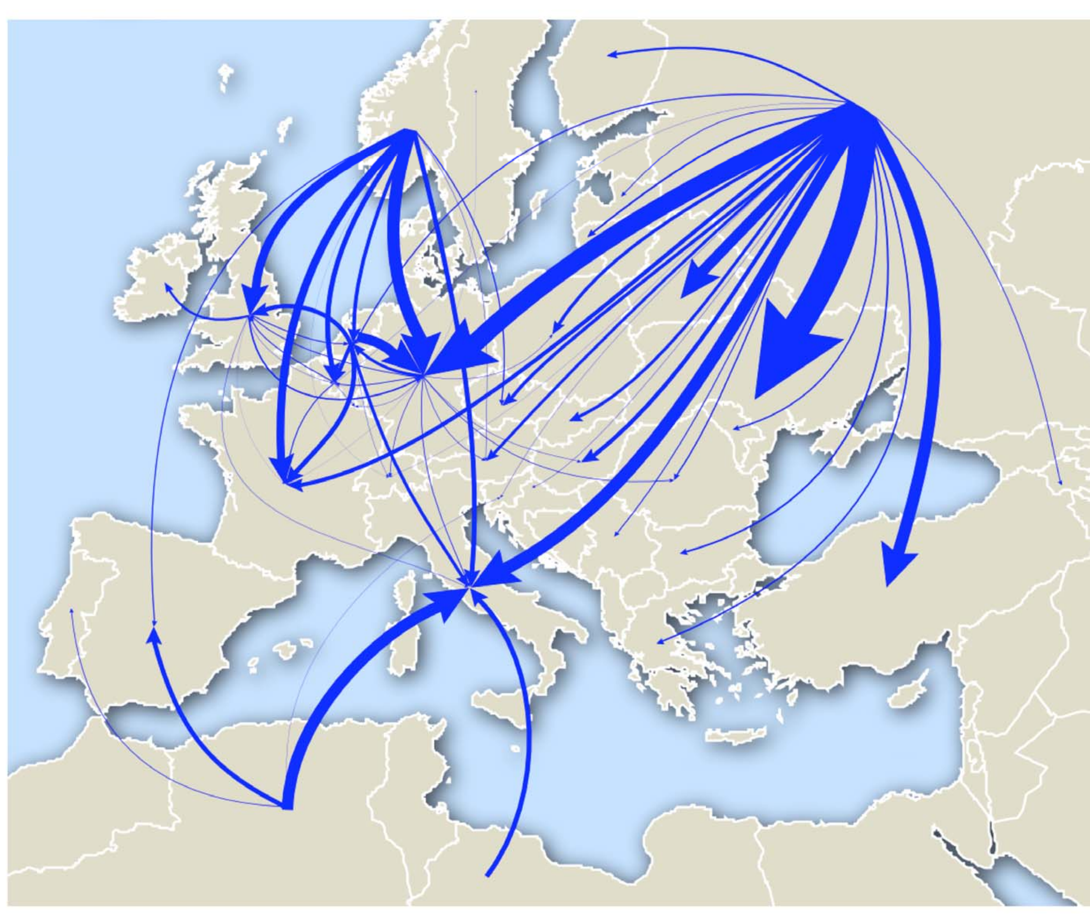
2. Gas network data set



European gas network extracted from GIS data (www.platts.com)

Transmission network:
($d \geq 15$ + interconnections)
2207 nodes, 2696 links
Complete network:
24010 nodes, 25554 links

Nodes: compressor stations, terminals, city gates, …
Links -pipelines
Node attributes: compressor, storage and LNG terminals, geographical coordinates, …
Link attributes: length, diameter



Natural gas trade movements by pipeline for 2007 (www.bp.com, www.iea.org)

88% of natural gas imported in Europe comes from three countries: Russia, Norway and Algeria.

Assumption regarding pipeline capacities:

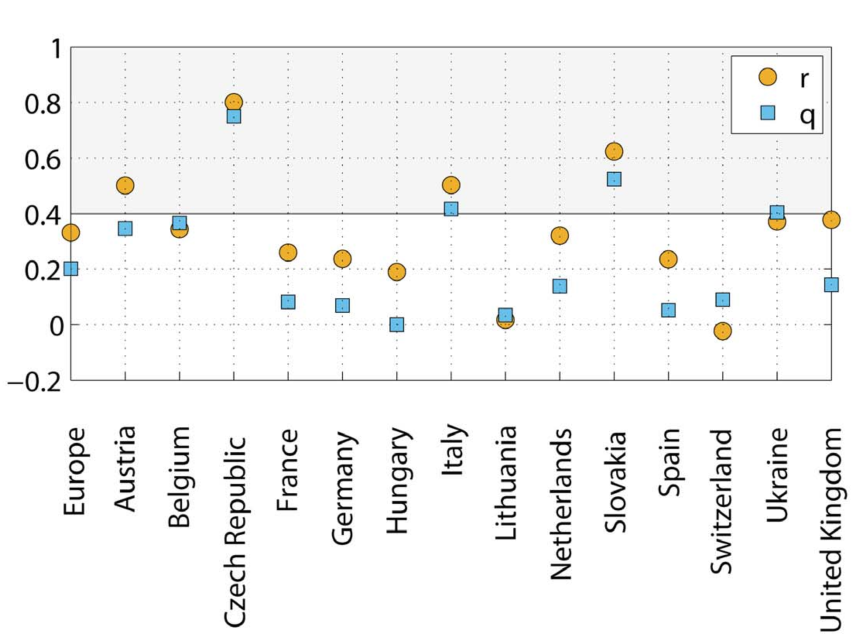
$$c \sim d^{2.5}$$

(www.gtie.eu.com)

3. Basic topological properties

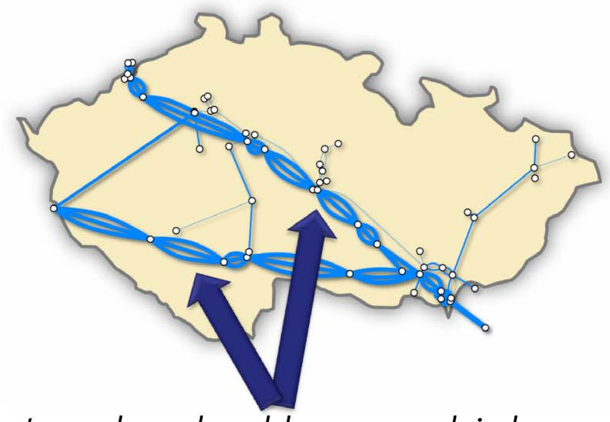
- National gas networks have approximately the same average degree, $\langle k_{transmission}\rangle = 2.4$, $\langle k_{complete}\rangle = 2.1$.
- The complementary cumulative degree distribution of the transmission network decays exponentially as $P(K > k) \approx \exp(-k/\lambda)$, with $\lambda = 1.44$.

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



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

q – proportion of capacity on parallel pipelines



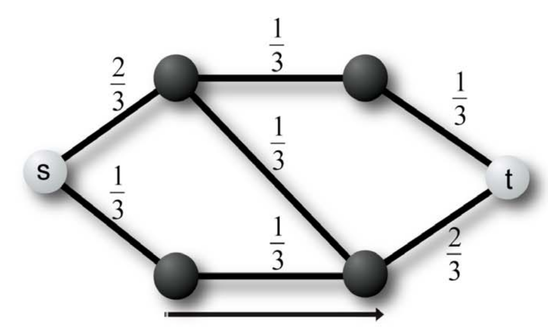
Network backbone: high node degrees and high capacity links.

k_i and k_j - node degree of nodes i and j, respectively,

$c_{e_{ij}}$ – overall capacity of pipelines connecting nodes i and j

4. Analysis of the network load and error tolerance with incomplete information

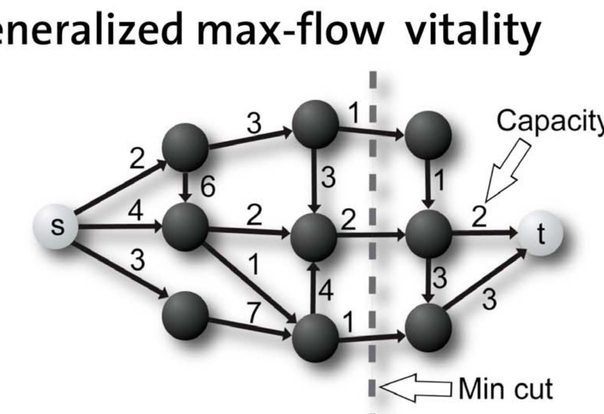
A. Generalized betweenness centrality



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

We assume that the transport of natural gas occurs along the shortest path in geographical space. We generalized betweenness centrality by weighting estimated gas flows per pipeline.

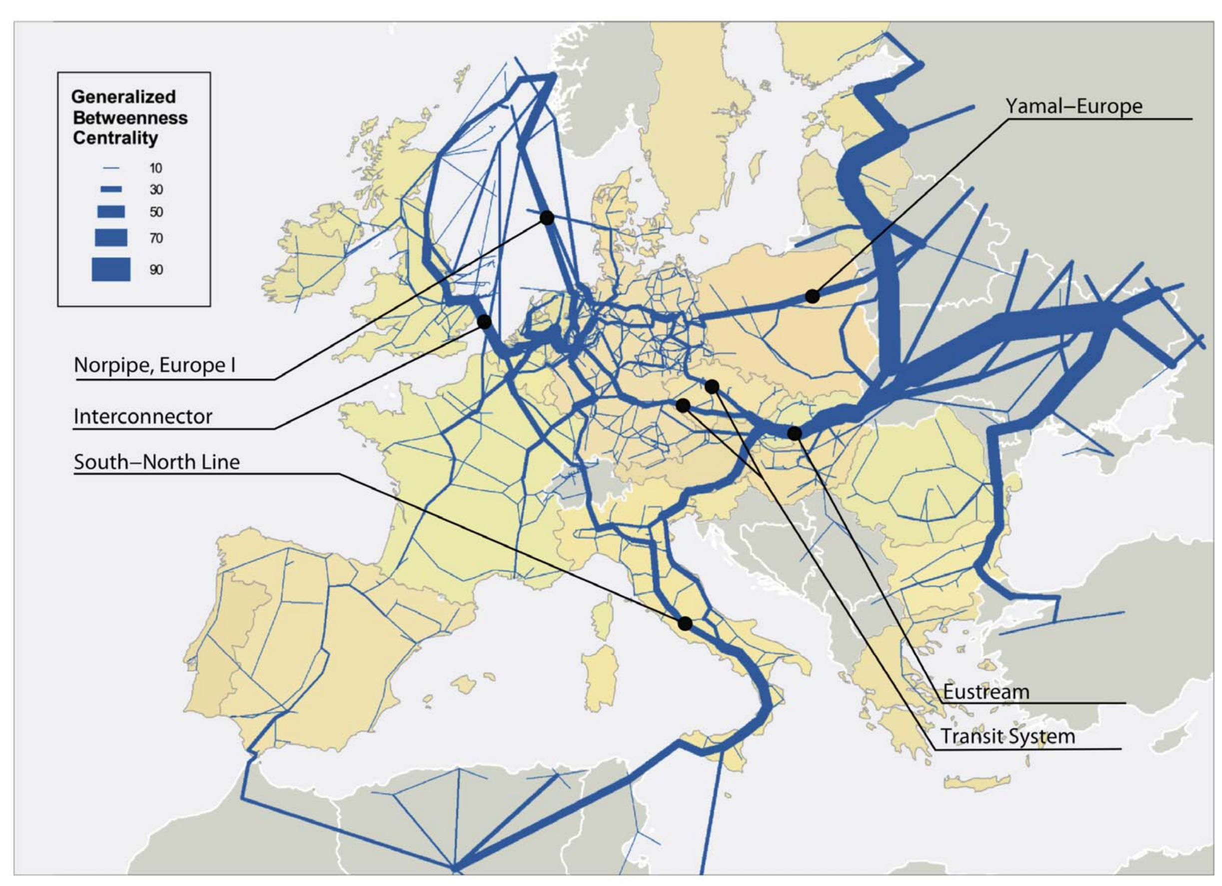
B. Generalized max-flow vitality



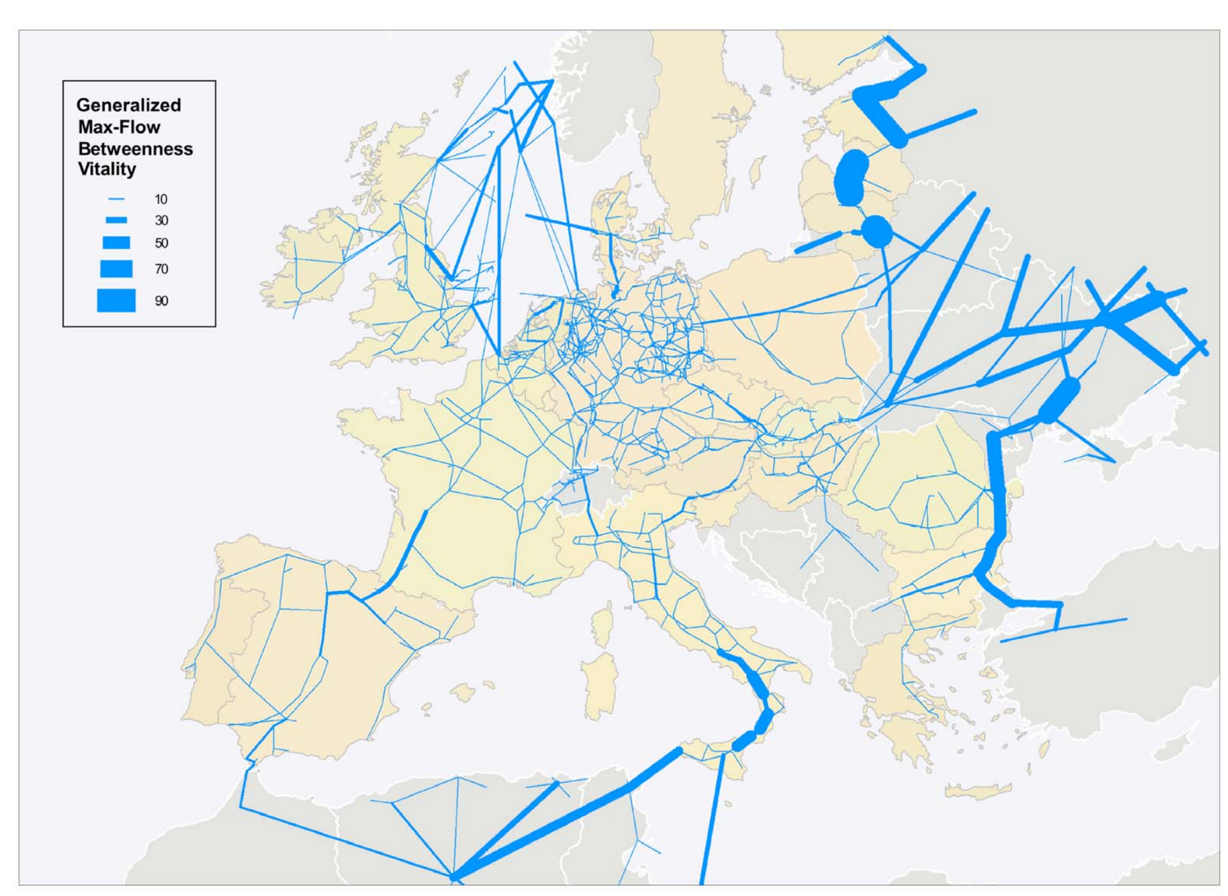
$$V_{ij} = \sum_{e_{KL}\in E_F} \sum_{s\in V_K, t\in V_L} \frac{T_{K,L}}{|V_K||V_L|} \frac{\Delta^{G_F}_{st}(e_{ij})}{f_{st}(G_F)}$$

We assess the error tolerance of the network by calculating the weighted drop of existing network capacity between source and sink countries, when single pipelines are removed.

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



- Link thickness is proportional to the generalized betweenness centrality;
- We labeled several major EU pipeline connections;
- The large difference between the generalized betweenness of these pipelines and the rest of the network suggests that the network has grown, to some extent, to transport natural gas along the shortest available routes.



- Link thickness is proportional to the generalized max-flow vitality;
- Pipelines close to the major sources tend to have higher values, because this is where the capacity bottleneck is located;
- Pipelines along sparse interconnections between larger parts of the network (e.g. Spanish - French border) also tend to have high value of generalized vitality, when compared to neighboring pipelines.

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

Full paper: http://arxiv.org/abs/0903.0195

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