# MANMADE: Complexity and Criticality
# of real Infrastructure Networks

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## 0   Content

# 1   Project and Collaboration

MANMADE is a project within the EU NEST pathfinder initiative.

The scope of the project concerns the mathematical methods required to understand the dynamics of the network of networks that comprise Europe's critical infrastructure:
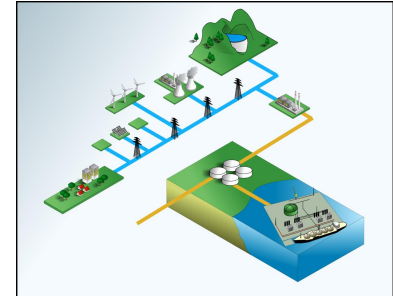
- energy supply (gas, electricity, wind)

- traffic, urban networks

- production chains and spot price markets

Critical events

- blackouts

- cascading breakdowns

- traffic jams

Interconnected networks

- gas

- electricity

- transport

Collaboration

- Queen Mary, University of London
  (D.K. Arrowsmith - mathematical modelling and coordination)

- EU joint research centre, Ispra (Italy)
  (E. Guiterrez - network collation/data processing)

- Universita Carlo Cattaneo, Castellanza (Italy)
  (F. Strozzi - supply chains and market volatility)

- Macedonian Academy of Sciences and Arts, Skopie
  (L. Kocarev - vulnerability of interconnected networks)

- Collegium Budapest
  (I. Kondor - electricity and wind power grids)

- Stakeholders
  (National Emergency Supply Agency, FINGRID, Finland)

- External
  (IRRIIS/ETH Zürich, Universita di Catania)

## 2   Infrastructure Networks and Datasets

Electricity (European high voltage electricity grid)

- Data sources: Platts GIS datasets (www.platts.com)
  substations, transmission lines, power plants

- Data structure:

  – Nodes (10494) power stations, power plants
    Node attributes position, power plant capacity
  – Links (15413) power lines
    Link attributes voltage level, length
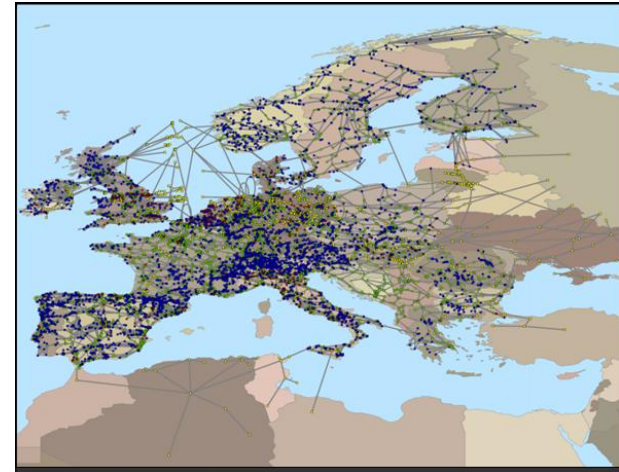


Wind power networks

- wind power histograms

- wind power maps
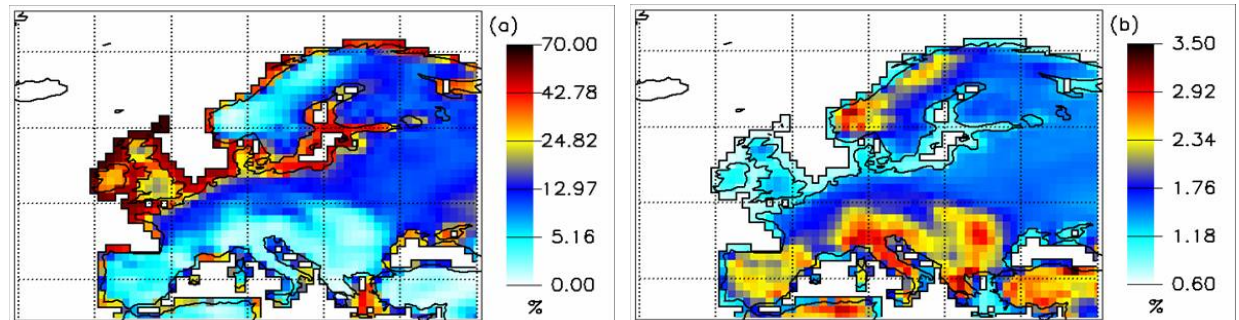
## Gas (major gas lines between and into Western Europe)

- Data sources: Platts GIS datasets
  (www.platts.com)
  compressor stations, pipelines,
  gas facilities, storage facilities,
  LNG terminals, extractable natural
  gas reserves

- Data structure (transmission network)

  – Nodes (2207) compressor stations,
    LNG terminals, city gates
    Node attributes position, storage
    and LNG terminal capacities

  – Links (2696) pipelines
    Link attributes length, diameter

- Complete network
  (transmission and distribution)

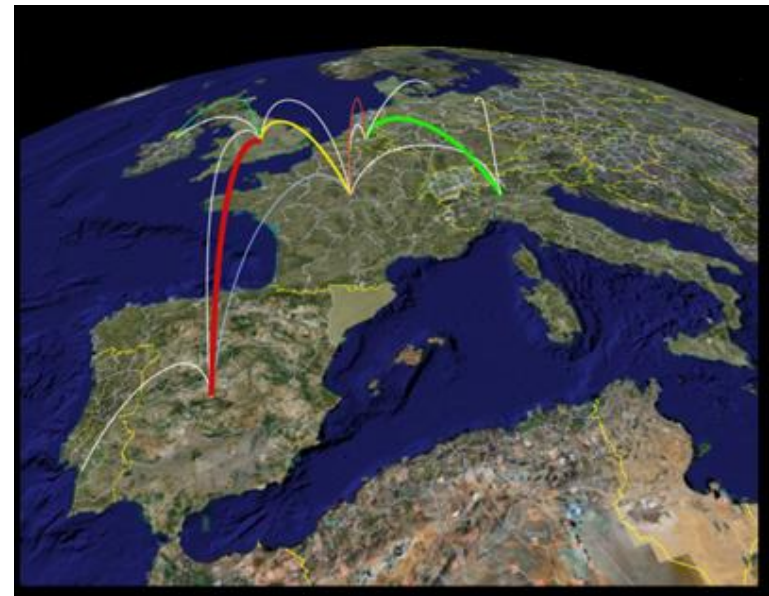  – 24010 nodes

  – 25554 links



European Gas Network
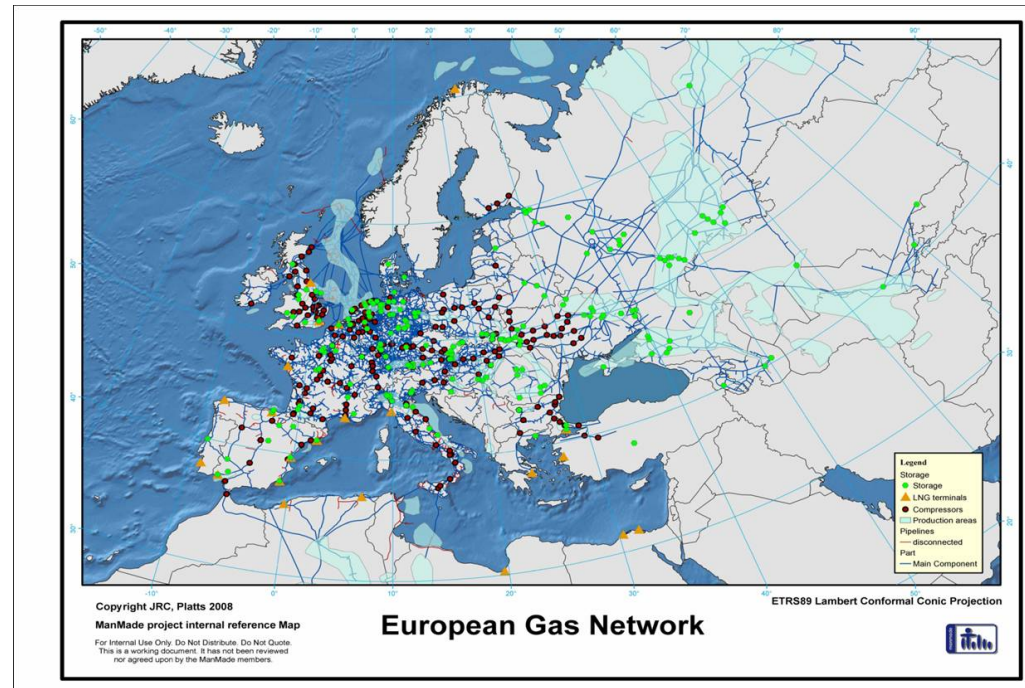
## Traffic (Urban street network)

- Data Sources: Tele Atlas, UK DfT
  traffic counts from 1999 to 2006

- Data structure (London)
  2232 counters
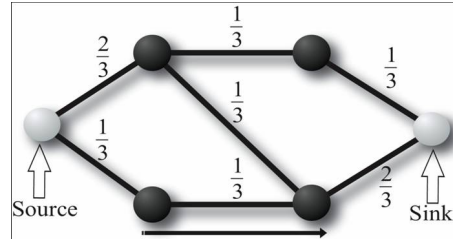  8566 nodes
  15573 arcs
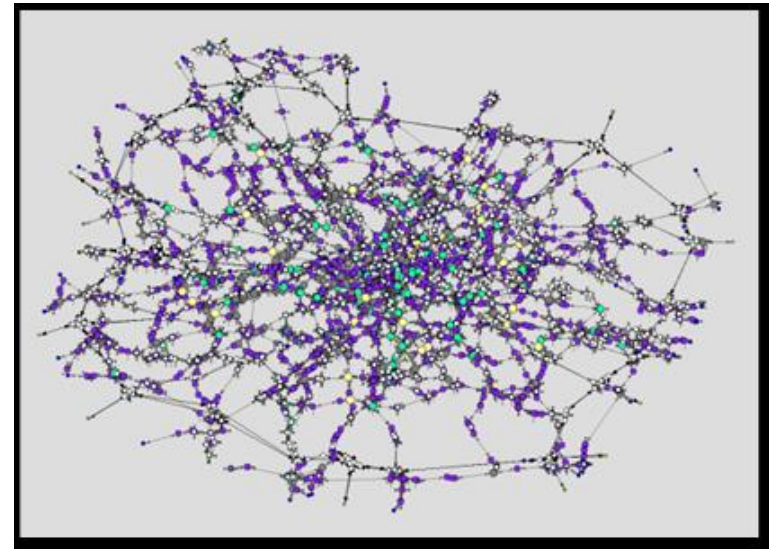


## Trade and markets

- Time series of European spot price
  electricity markets (NORDPOOL)

- Commodity flows
  27 countries
  6 major groups
  225 products
  years 2005-2007

# 3    Concepts

Topological quantification of the relevance of connections (links/nodes) in networks
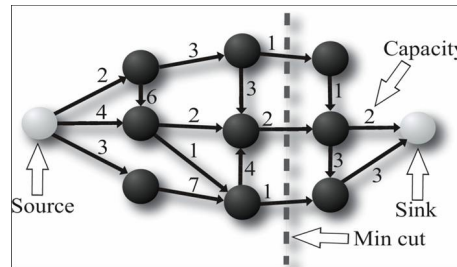
- betweenness centrality



$$\sigma_{st}(e_{ij})/\sigma_{st}$$

$\sigma_{st}$ : no. of shortest paths

$\sigma_{st}(e_{ij})$ : no. of paths through $e_{ij}$

- maximum flow



$$\Delta_{st}(e_{ij})/f_{st}$$

$f_{st}$ : maximum flow

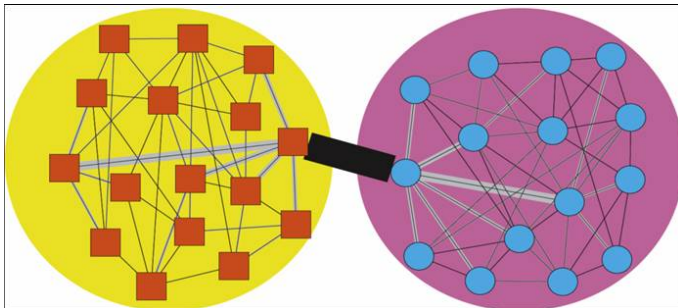$\Delta_{st}(e_{ij})$ : change in max. flow
when $e_{ij}$ blocked

- generalisation for substrate networks (flow data only available on aggregate level)



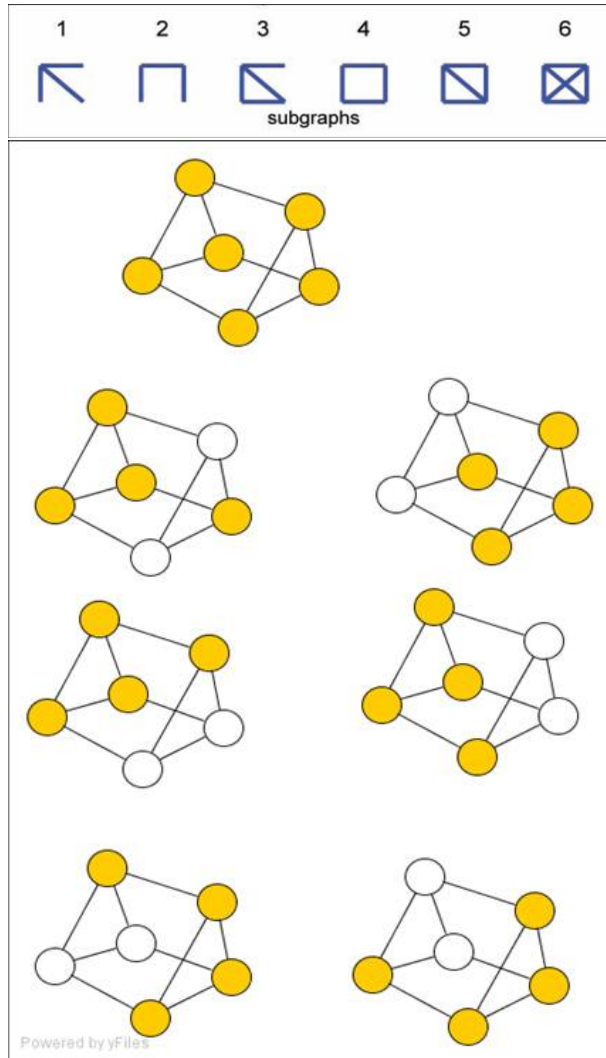Generalised betweenness centrality

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

Generalised maximum flow vitality

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

7

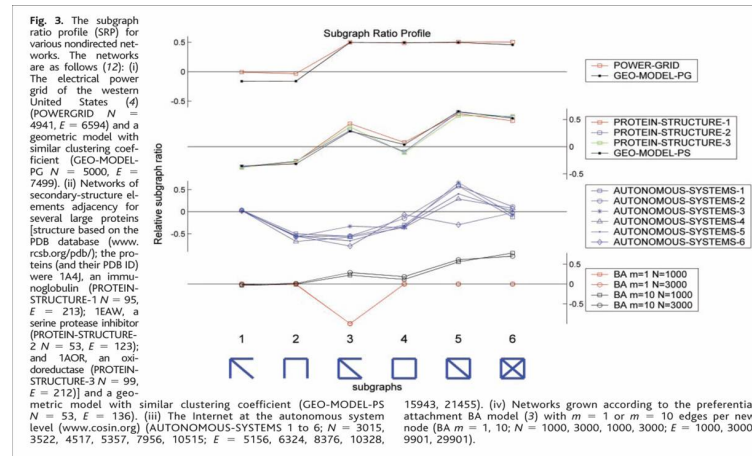# Classification of recurring subgraphs (motifs) of interactions from which networks are built



- abundance of each subgraph $\ell$ relative to its appearance in random networks

$$\Delta_\ell = \frac{N_\ell^{(G)} - \langle N_\ell^{(rand)} \rangle}{N_\ell^{(G)} + \langle N_\ell^{(rand)} \rangle}$$

- subgraph ratio profile

$$SRP_\ell = \frac{\Delta_\ell}{\sqrt{\Delta^2}}$$

- superfamilies of evolved and designed networks

(Milo et al., Science 204, 1538)



8

Quantify structural vulnerability against errors and/or attacks

- node and edge removal leads to network fragmentation

- behaviour of the largest connected component

- errors: random node removal

- attacks: higher degree nodes are removed first

Dynamical models to study cascading failures

- flow of a physical quantity $\Theta$: loads $J$ on edges

- maximal load is limited by the capacity of the edge

- edge removal leads to redistribution of the initial loads

- overloading and propagation through the whole network (cascading breakdown)

- power flow models: transport equation (linear or nonlinear) for $J(\Theta)$
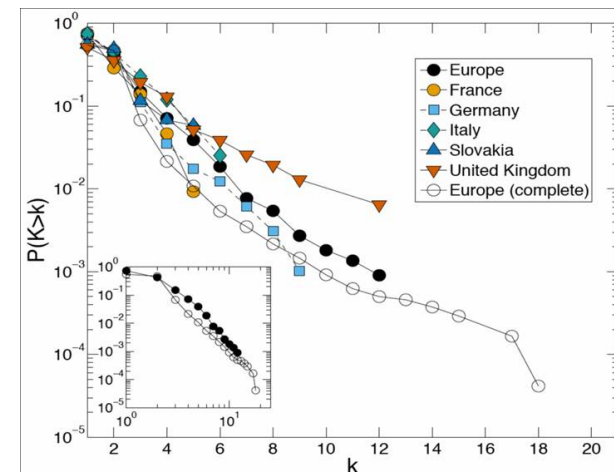
# 4    Results

Topology of gas network

layout (Germany)
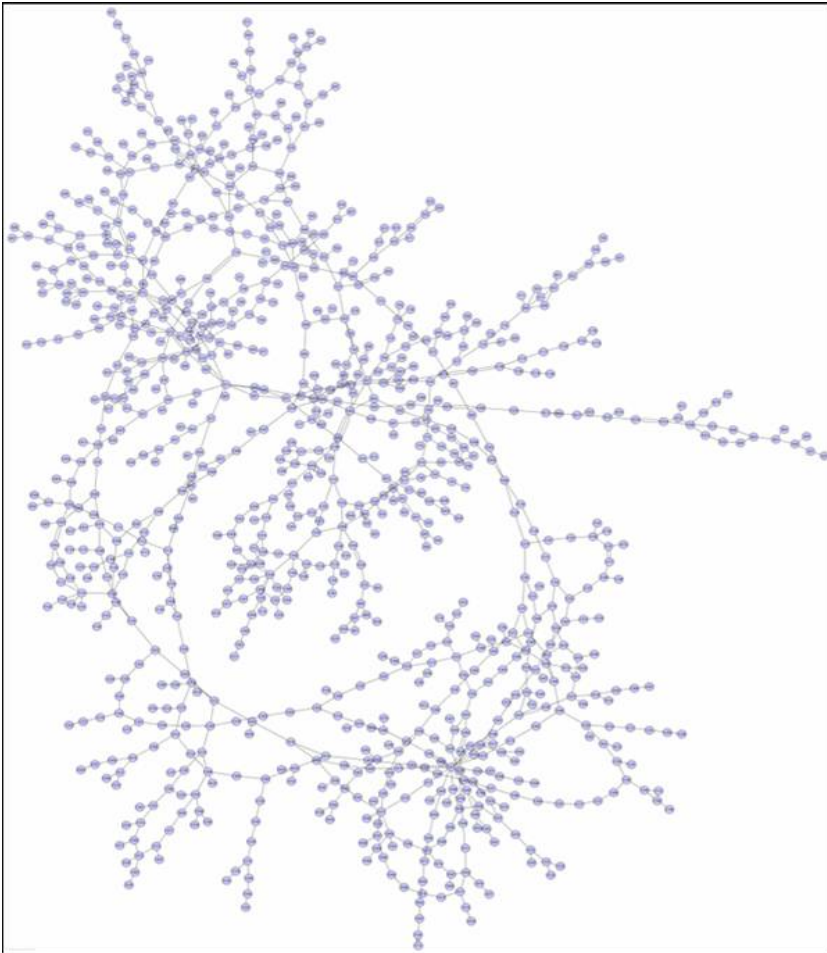


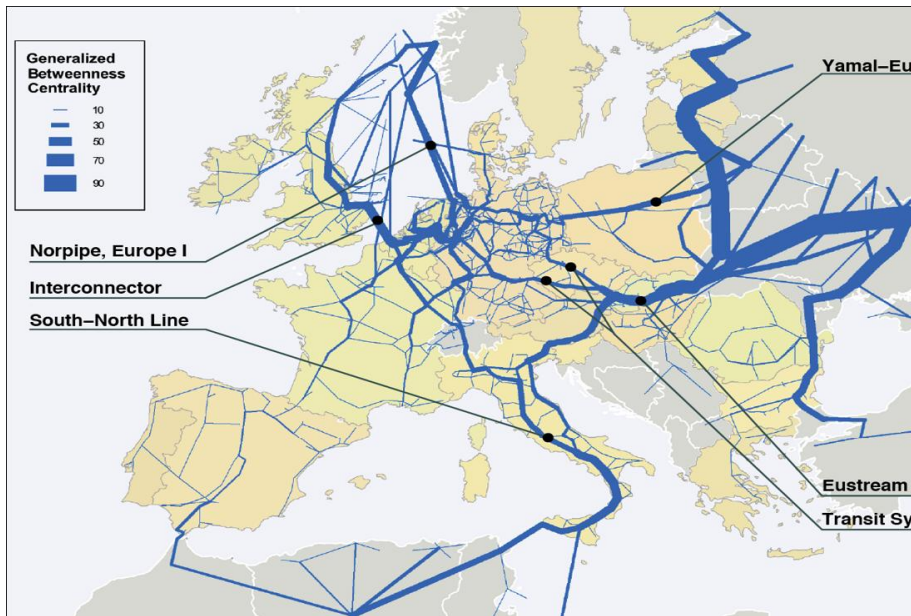extensive ($\langle k_{transm} \rangle = 2.4$, $\langle k_{tot} \rangle = 2.1$)
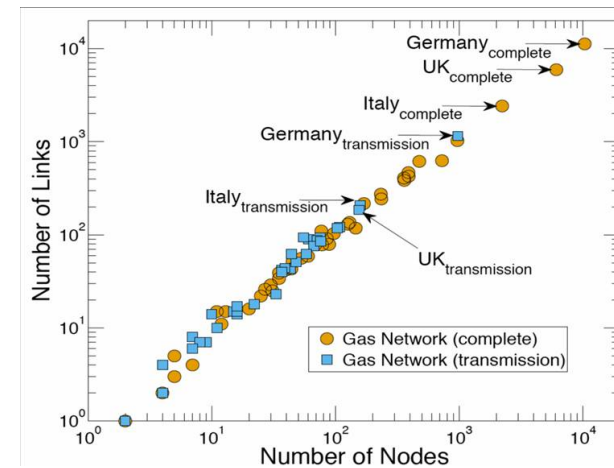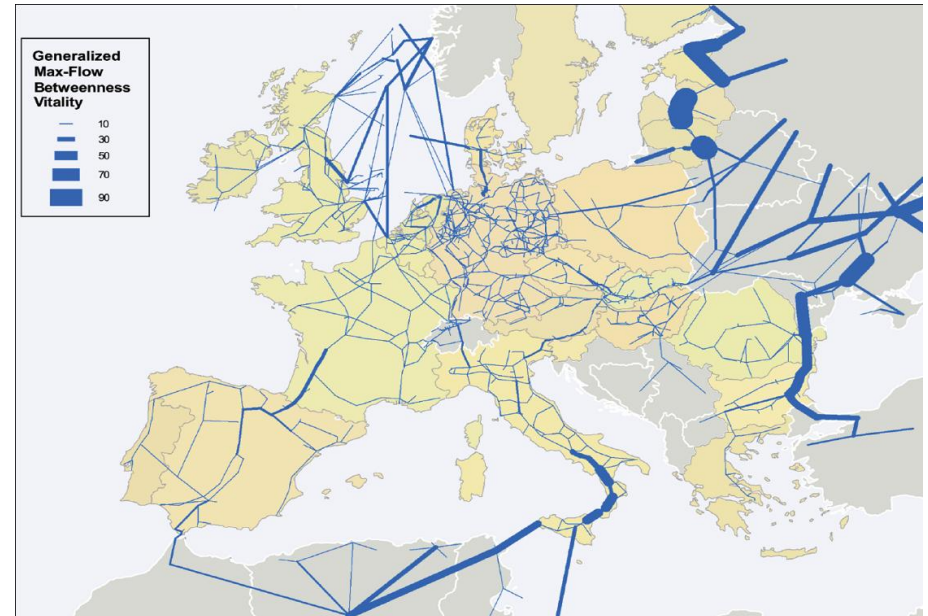


degree distribution

# The hot backbone of the gas network

## Generalised betweenness centrality



## Generalised maximum flow vitality



- generalised betweenness is higher than the corresponding values of generalised vitality

- the major pipelines are crossed by many shortest paths, but a non-operational pipeline causes only a minor capacity drop

- robustness of the trans-European gas pipeline network (error-tolerant to failures of high load links)

## Motifs (gas and electricity)
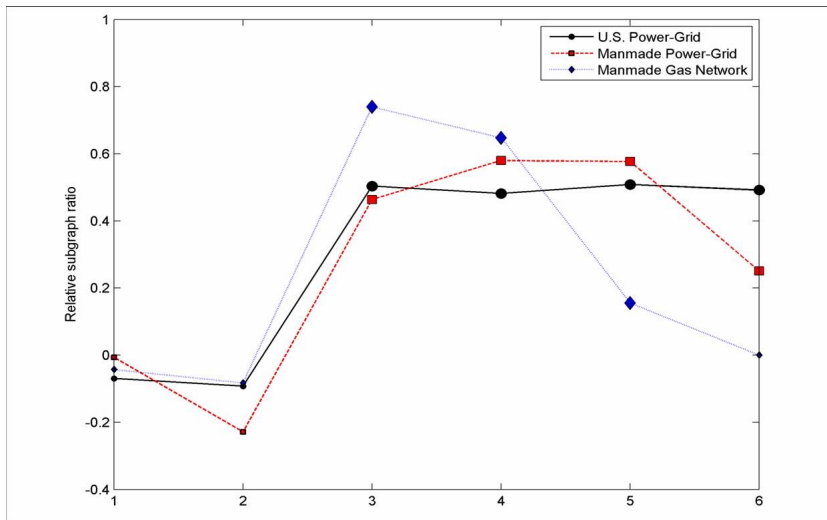


gas network and electricity networks show distinctively different topological characteristics (fewer highly connected motifs)
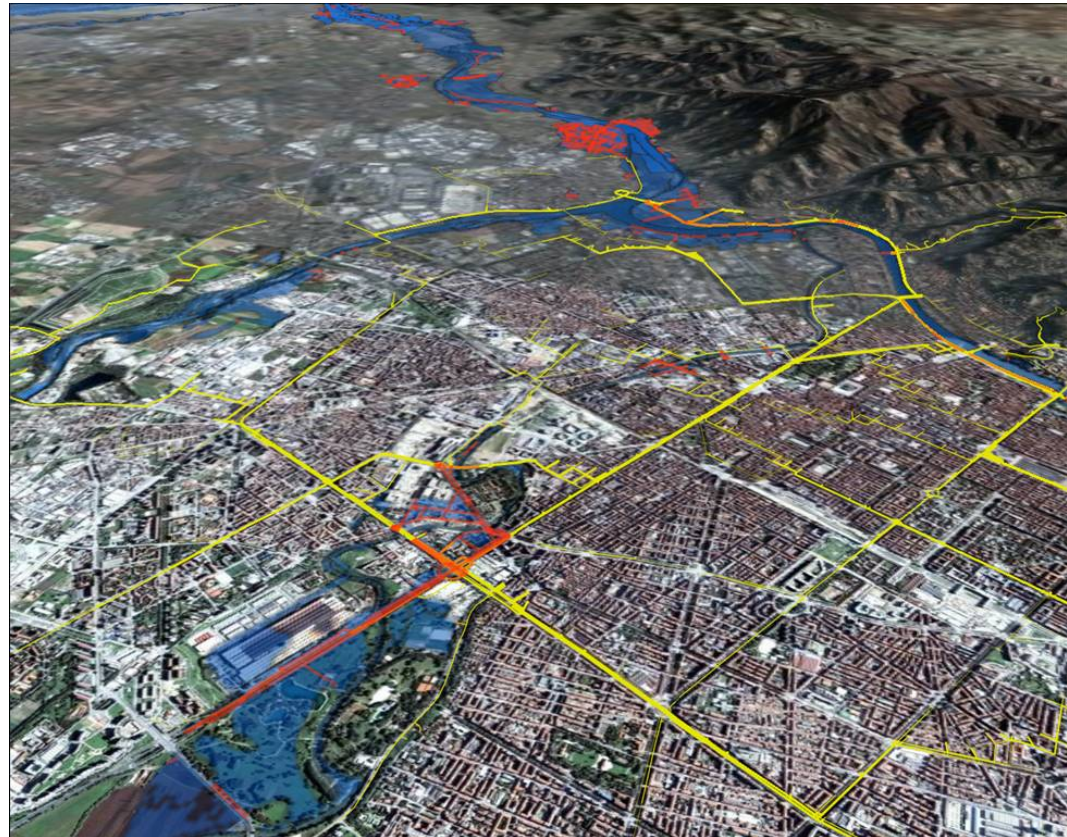
## Vulnerability against errors and attacks (gas and electricity)
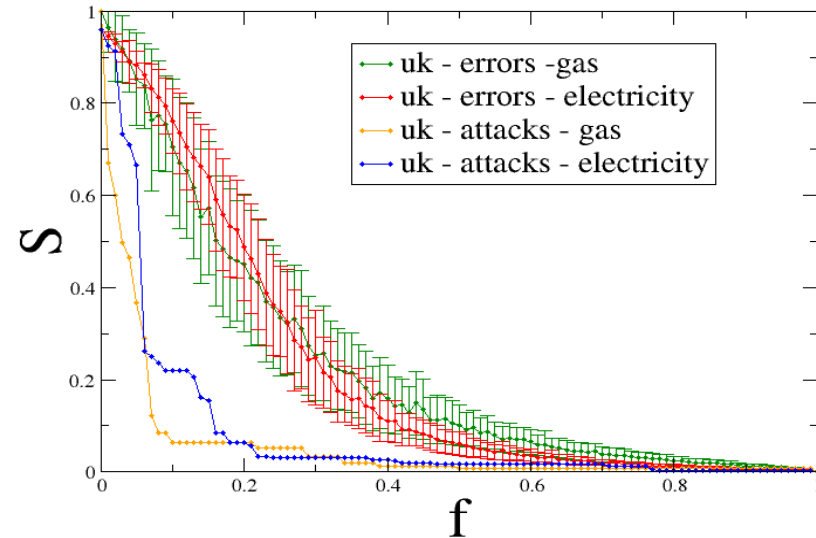


UK gas network compared to electricity network is more vulnerable against attacks
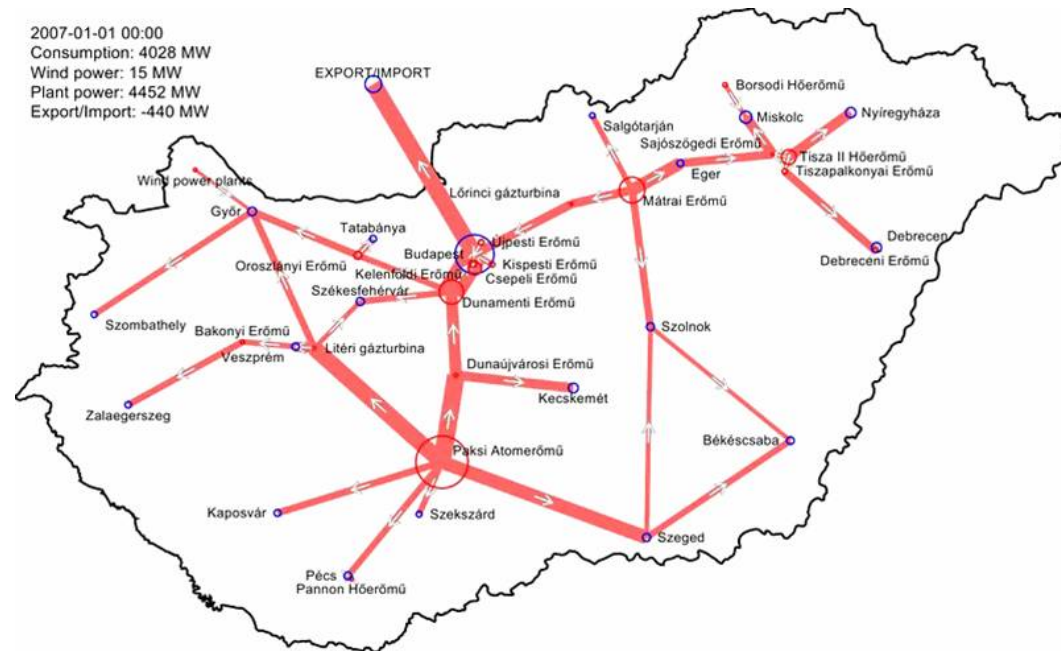
## Urban networks

- centrality as a topological measure of connectivity

- flooded area
  (Turin October 2000)

- intersection of flood and high centrality (orange)

# Cascading breakdown of electricity networks

Composite electricity
model for Hungary
including wind energy

# 5   Conclusion

- detecting topological key elements in infrastructure networks

- identification of the most vulnerable parts of the network

- suggesting new transmission lines which make a network more fault tolerant

- understanding the interconnection between different networks

- dynamical models for infrastructure networks

- crises in socio-economic systems