MANMADE

DIAGNOSING VULNERABILITY, EMERGENT PHENOMENA,
and VOLATILITY in MANMADE NETWORKS

www.manmadenet.eu

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Collaborators

- Collegium Budapest
- EU Joint Research Centre, ISPRA
- Macedonian Academy of Sciences and Arts
- Queen Mary University of London
- Università Carlo Cattaneo
- Stakeholders
  - National Emergency Supply Agency, FINGRID

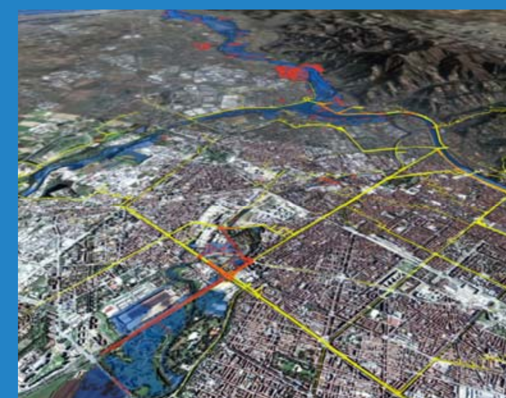
NETWORKS

- Social
- Energy
- Transport
- Communication
- ……networks of networks

What are the correct questions to ask and the most useful analytical tools to handle them?

MANMADE – its scope

- The project concerns the network of networks that comprise Europe’s critical infrastructure;
  - primarily on energy supply, emergency response systems and subsidiary key infrastructures
- Aim
  - is to assemble, develop and apply mathematical methods to analyse large, man-made multi-element infrastructure systems



More detailed activity

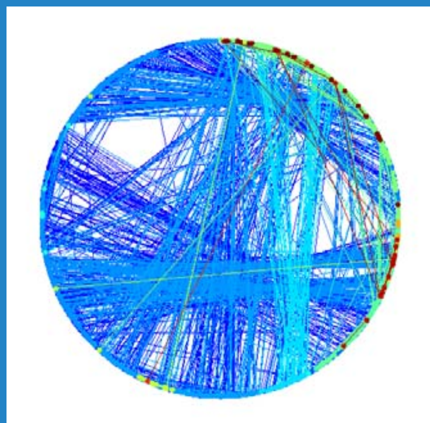
- Vulnerability
  - structural (catastrophic failure of network components)
  - functional (electricity grid blackouts, supply chain)
  - Strategy – green energy –wind farms
  - Overlaying of networks – interconnected gas and electricity
- Volatility and memory in markets
  - spot electricity pricing
- Motifs and profiling of graphs
  - sub-graphs which appear more than expected and their use in identification

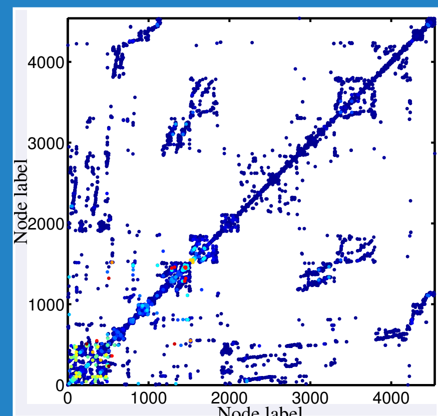
Electricity Blackout Analysis

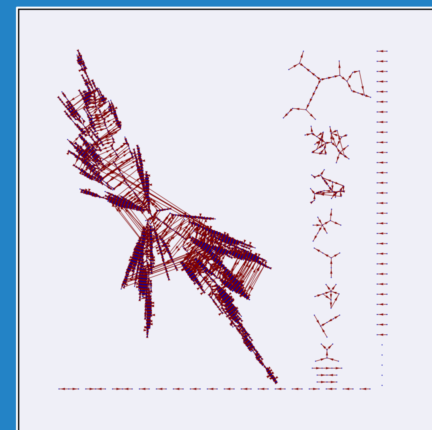
- To analyse the qualitative characteristics of power disruptions from a large synchronously-connected electricity grid. (Following from Carreras et al. *Evidence for self-organized criticality in a time-series of electric power system blackouts,* IEEE Trans. 2004)
  - Are European electricity grids critically organised systems?
  - What are the expectations of large blackouts?
  - Are events correlated or random?

Network classification

- Network classification (regular, random, small-world, scale-free)







- Various measures (average path length, clustering or transitivity, node betweeness/centrality, community structure)
- Resilience and robustness of networks
  - Robustness with respect to topology change
  - Reliability and efficiency
  - Black-outs

First steps - datasets

Data sets of major gas lines and exchange flows	Data sets of major gas lines between and into Western Europe
Datasets of spot price electricity	NORDPOOL time series spot price electricity in European markets NORDPOOL time series spot price NOK 2003-2007
Spatial and topological maps of the road network	Urban street network of Milan, Turin and London
High voltage electricity grid	European Electricity Lines by disconnected Regions European energy interconnected network

The Energy Interconnected Network

Data Sources:

Platts GIS datasets

Electricity: substations, transmission lines, power plants

Gas: compressor stations , pipelines, gas facilities, storage facilities, LNG terminals, extractable natural gas reserves

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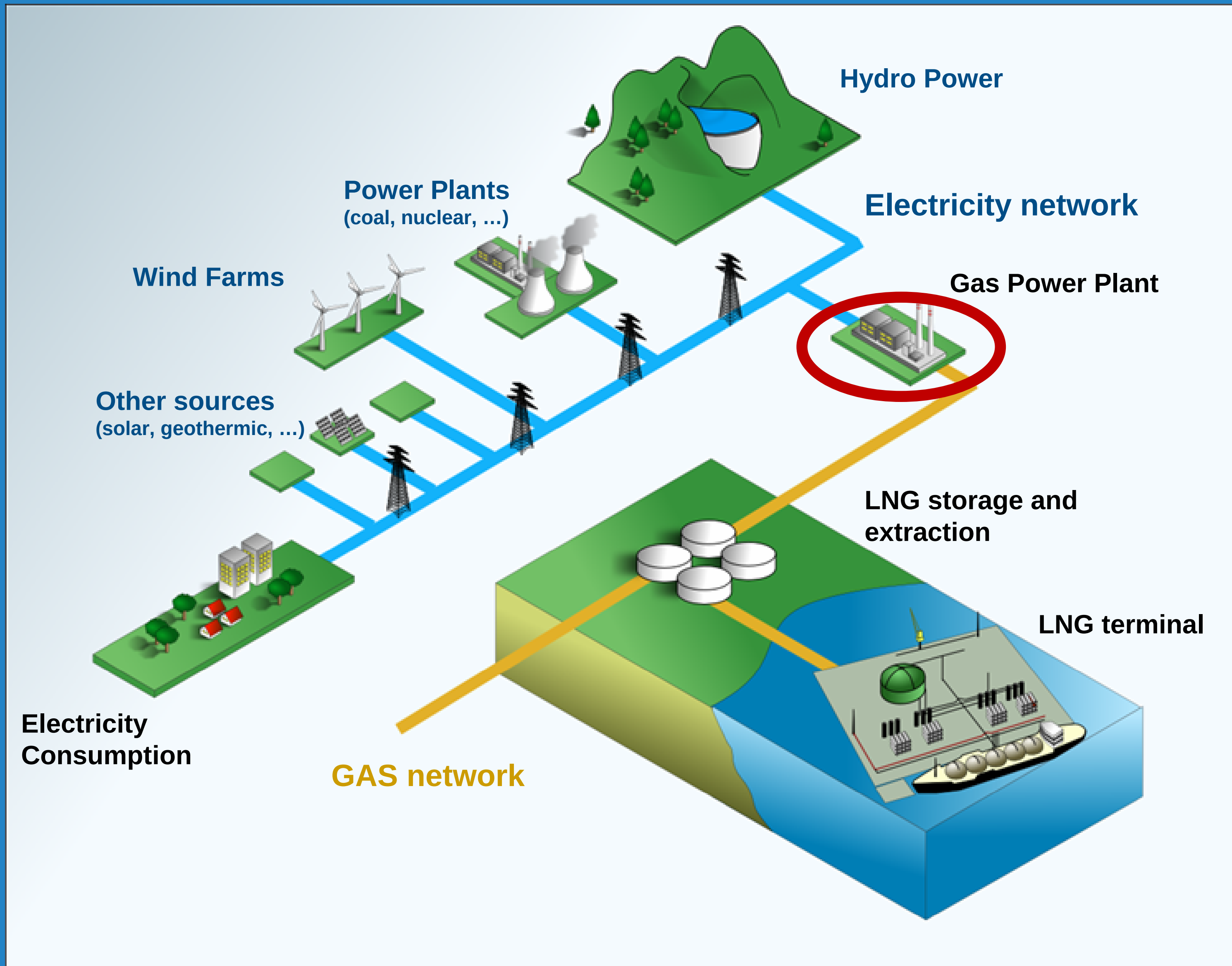
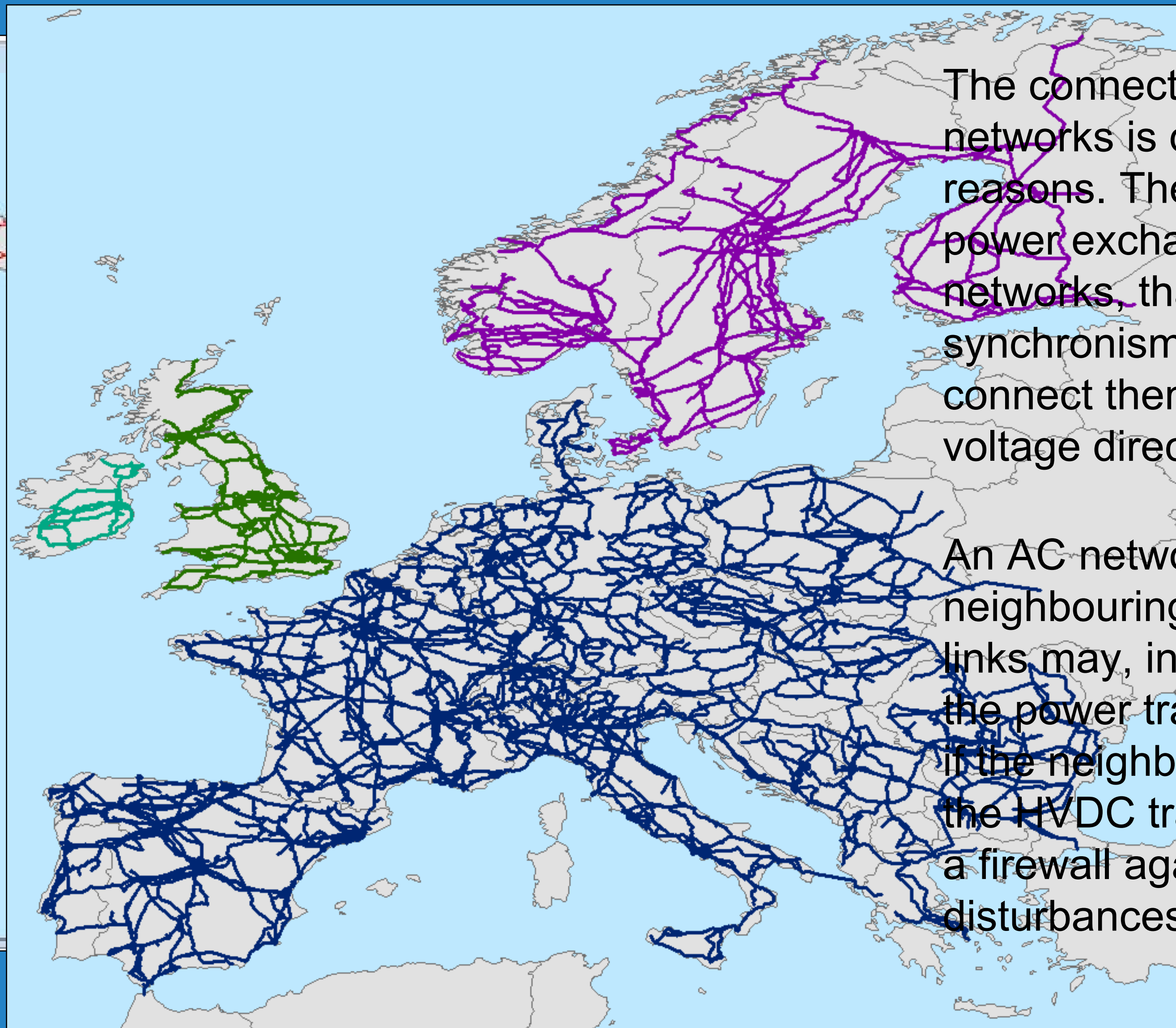
The Energy Network



The European Electricity Grid

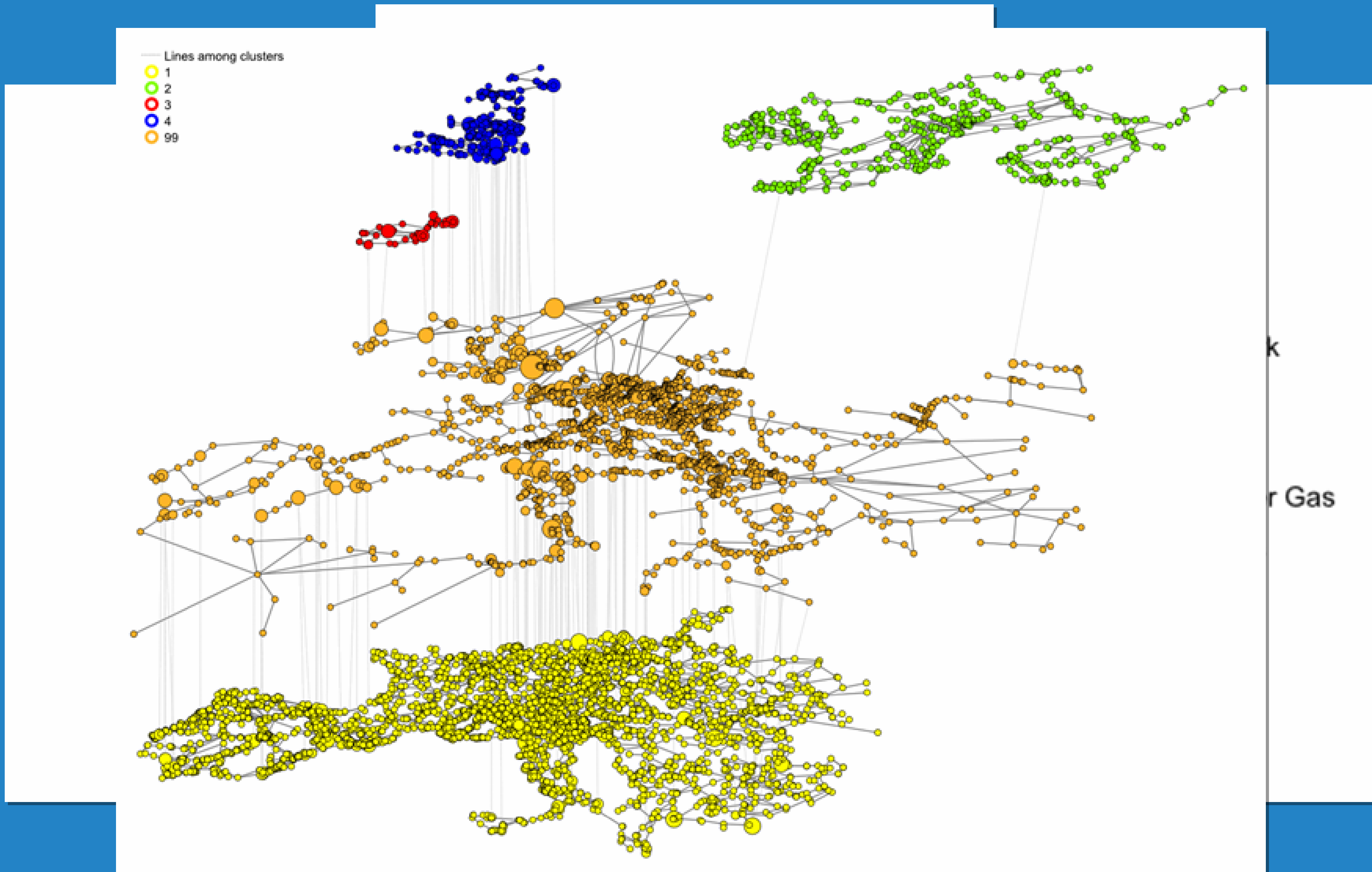


Four independent electricity grids

The connection between two AC networks is difficult due to stability reasons. The only way to make an power exchange between two AC networks, that are not running in synchronism with each other, is to connect them by means of high voltage direct current (HVDC) lines.

An AC network connected with neighbouring grids through HVDC links may, in the worst case, lose the power transmitted over the link; if the neighbouring grid goes down, the HVDC transmission will act as a firewall against cascading disturbances

The Interconnected Network



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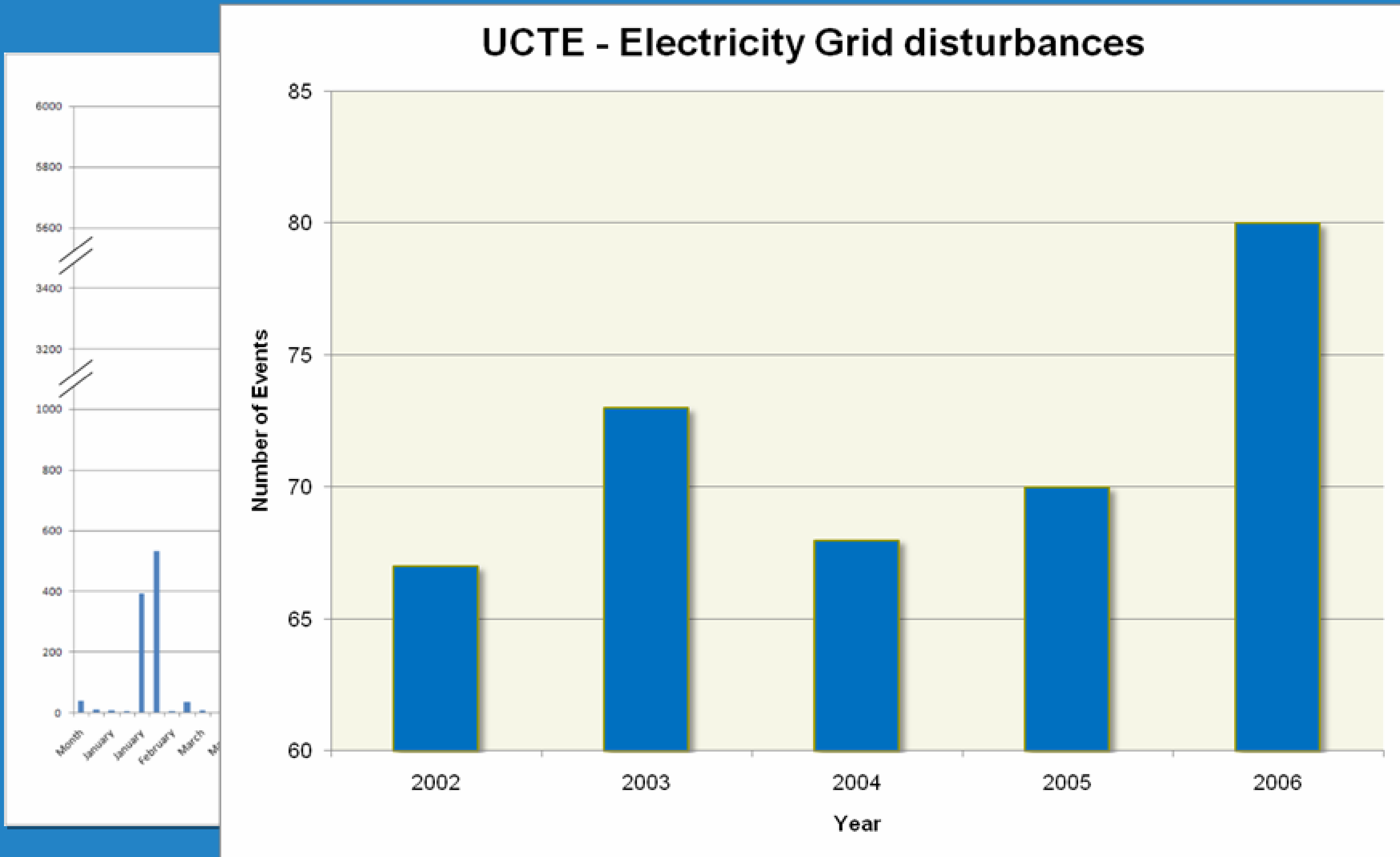
Electricity disruptions



UCTE

Year 2006

82 events

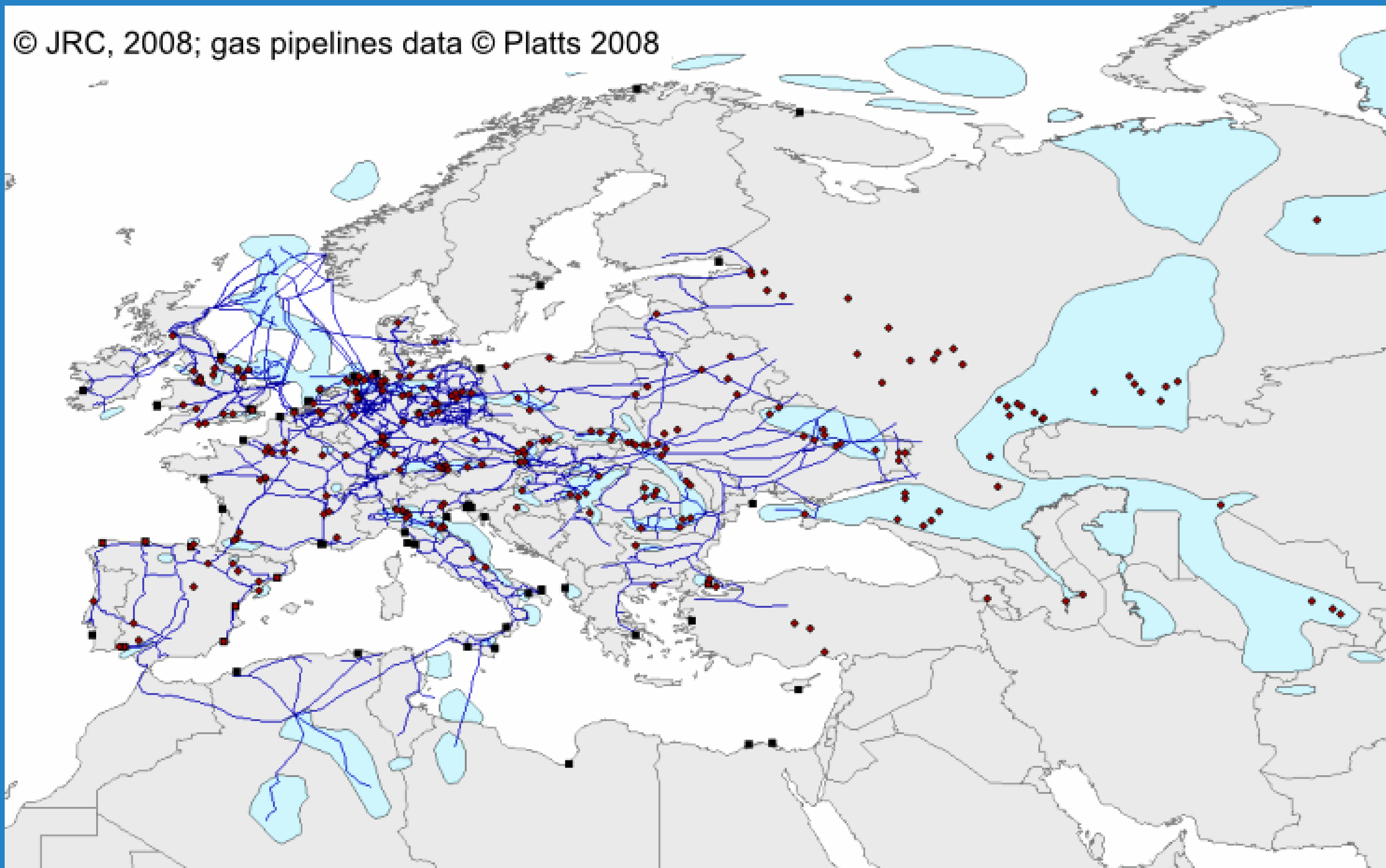
Gas disruptions

Failure to manage gas supply interruptions properly and efficiently can result in widespread disruptions in the supply of gas to industry and gas-fired power generation plants.

<u>Threats to gas supplies:</u>

- Terrorism-related hazards
- Natural disasters
- Materials failure
- Other hazards

Available information



Gas sources

LNG terminals

Pumping stations

Gas Deposits

Urban Networks

- Milan
- Turin
- London (in progress)

Data Sources:

- TeleAtlas
- UK DfT
  Department for Transports
- Civil protection surveys

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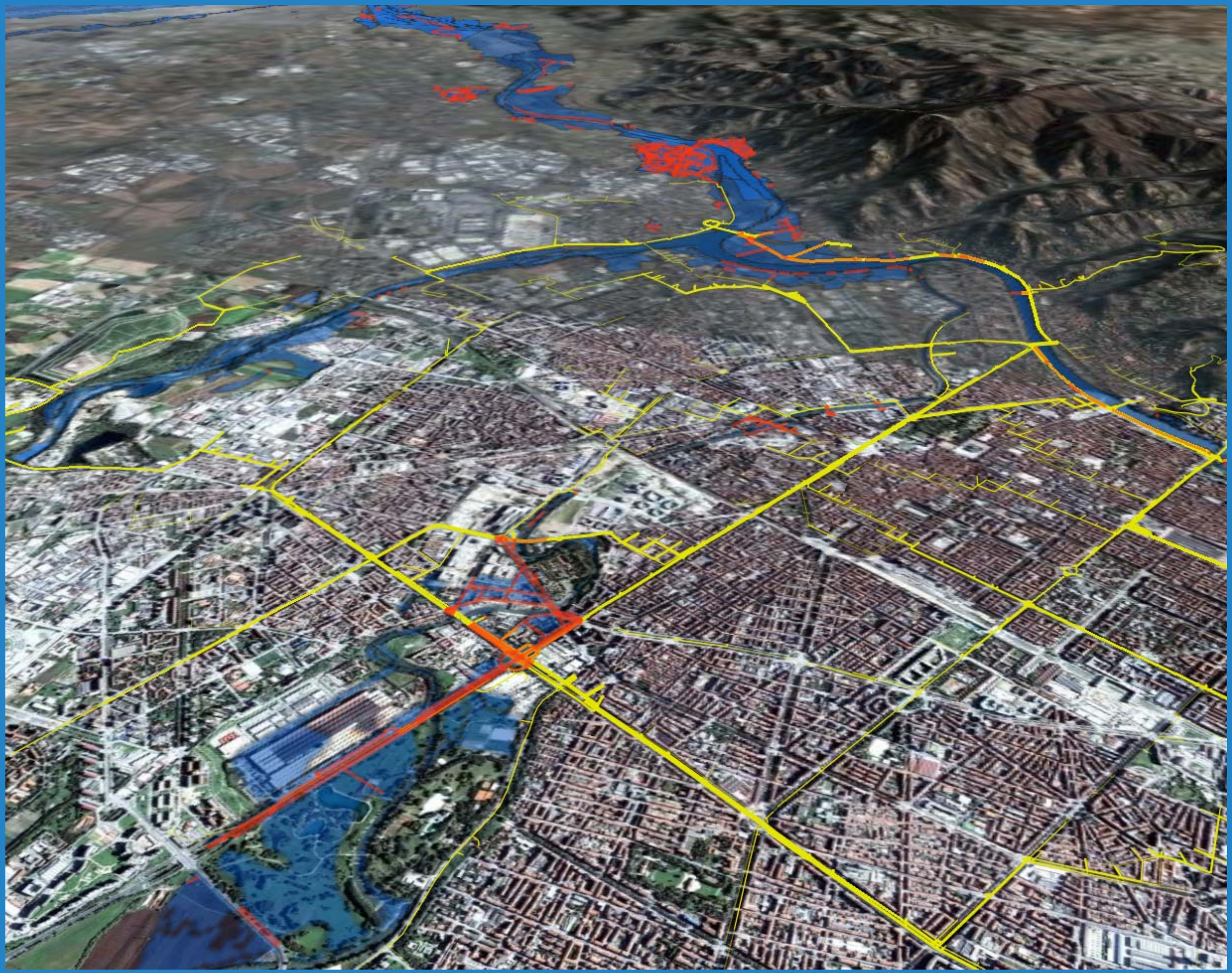
Identification of vulnerable transport infrastructures



Topological identifiers of damaged and undamaged network.

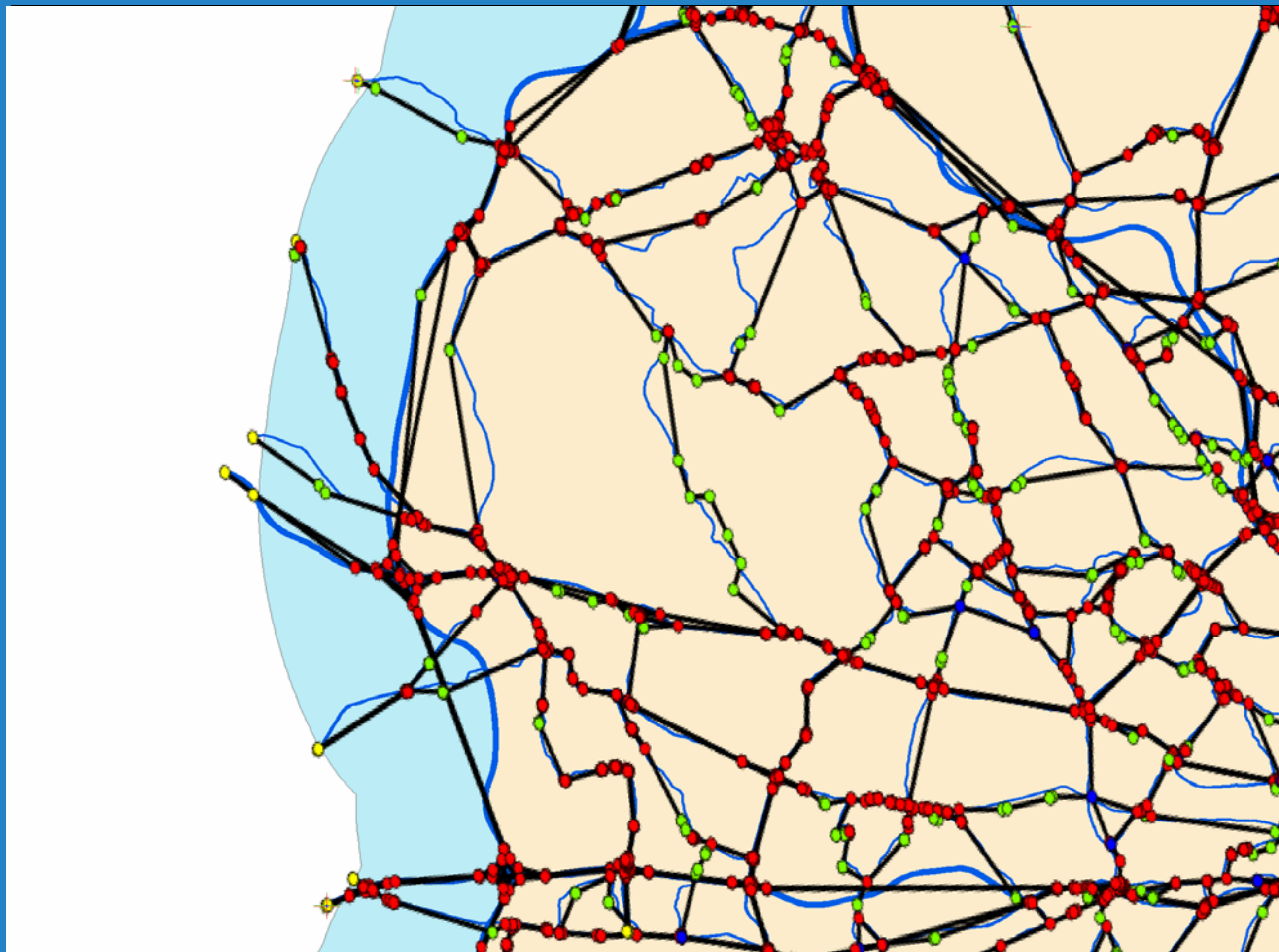
Structural vulnerability, key transport nodes, planning and **protection.**

Centrality is a topological measure of connectivity rank.

Flooded area
(Turin - October 2000).

Intersection of flood and high centrality (orange).

Urban Traffic



AADTF – annual average daily flow

Network simplification

Connectivity analysis

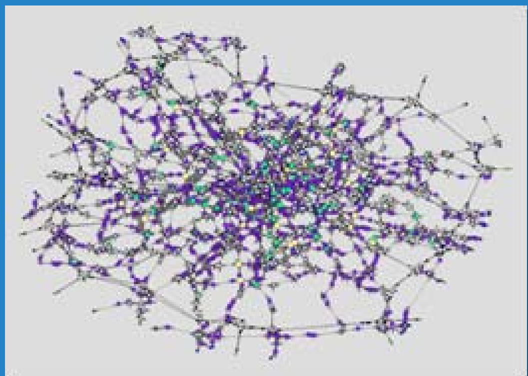
Urban Traffic

AADTF – annual average daily flow

Network simplification

Connectivity analysis

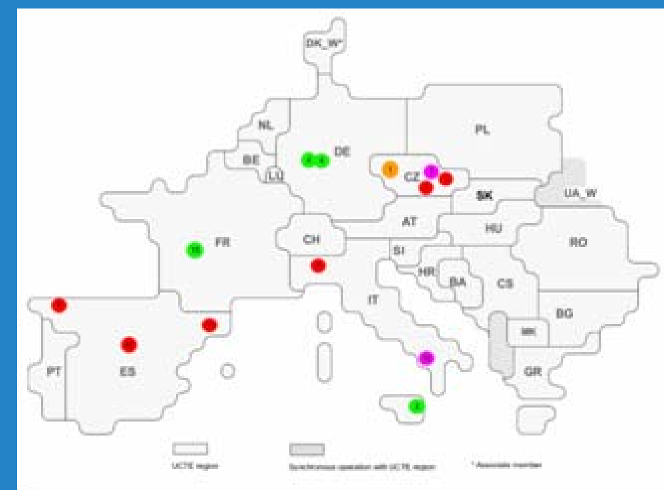
Future datasets

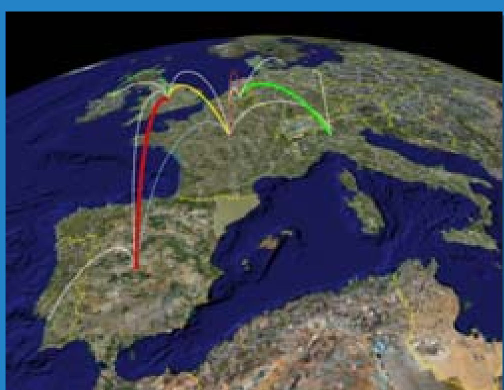


Urban street network of London and traffic counts

2232 counters, counts from 1999 to 2006, 8566 nodes, 15573 arcs

Electricity Network disruptions





Commodity Flows

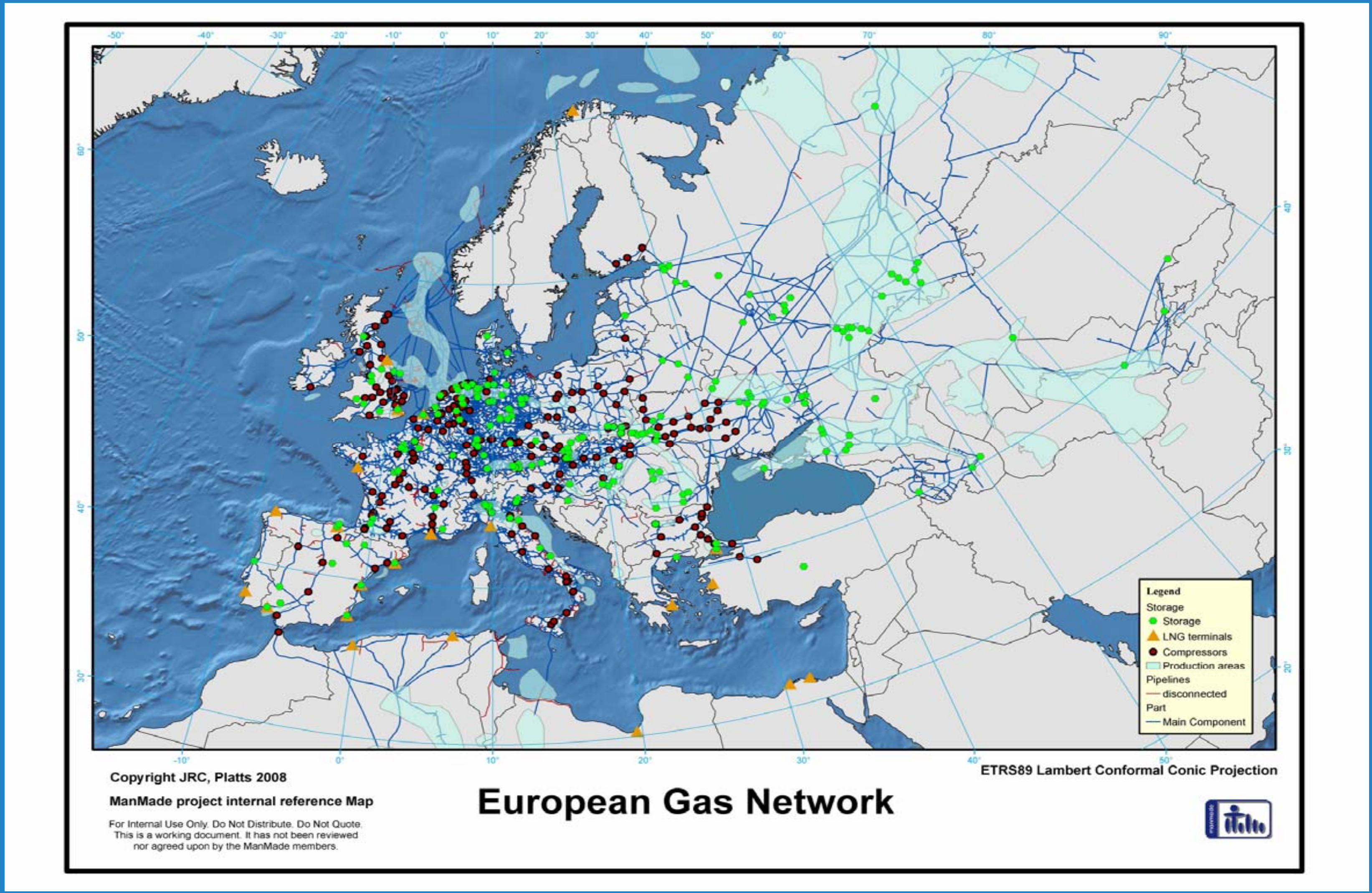
27 countries, 6 Major groups,
225 products, years 2005-2007

Case study: the European gas pipeline network

Consider

- modularity (network motifs)
- fragmentation of networks as a function of failure scenarios

European Gas Network (JRC, Platts)



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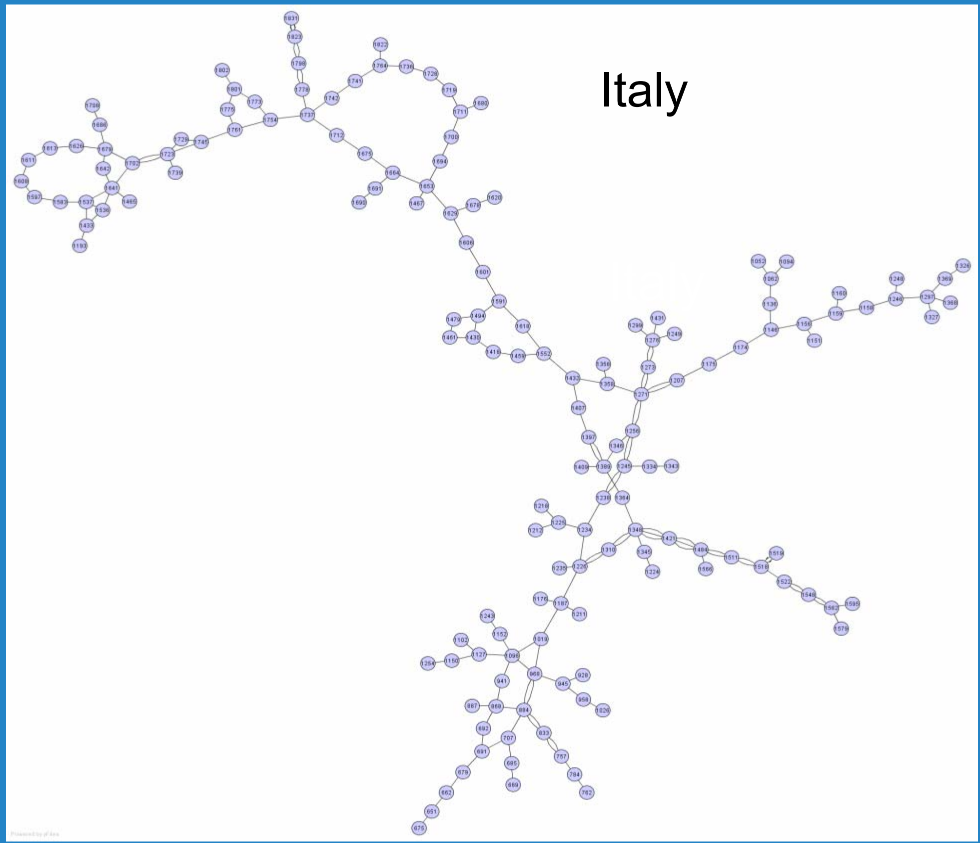
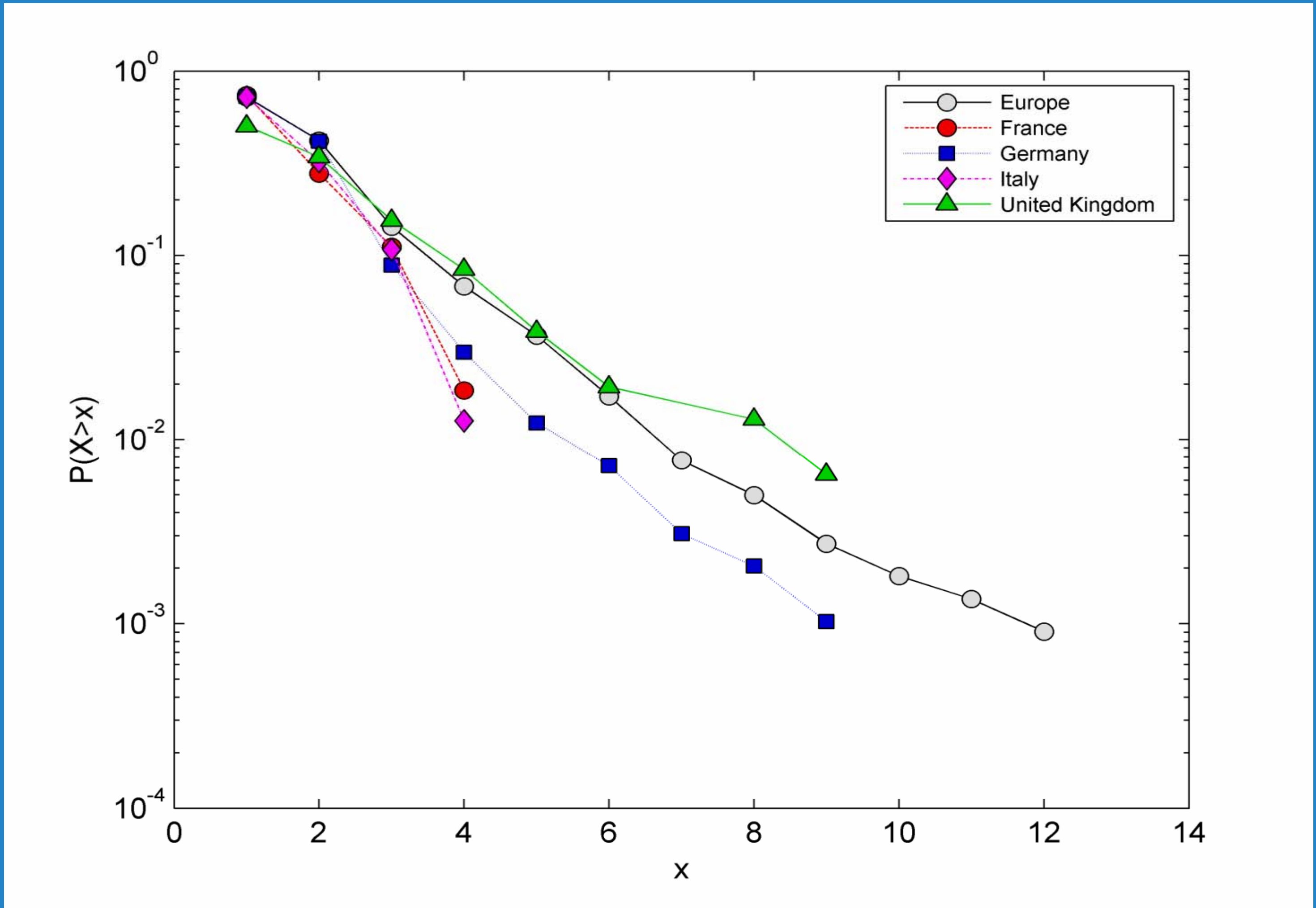
Gas Pipeline Network Layouts



Gas Pipeline Network: Cumulative Distribution of Node Degree



x: node degree
P(X>x): probability of node degree in excess of x
Exponential decay

Network Motifs: Motivation

- Basic idea: to consider the recurring circuits (subgraphs) of interactions from which networks are built.
- **Motif** (intuitive definition): Consider a “real world” network G.
- A subgraph H of G is a ***motif*** if the number of appearances of H in the real network exceeds the average number of appearances of H in a random network ensemble. Recall that H is a subgraph of a given graph G iff H is a graph whose vertices and edges form subsets of the vertices and edges of G.
- Claim: “real world” networks are organized in superfamilies according to their motifs.

Network Motifs: Formal Definition

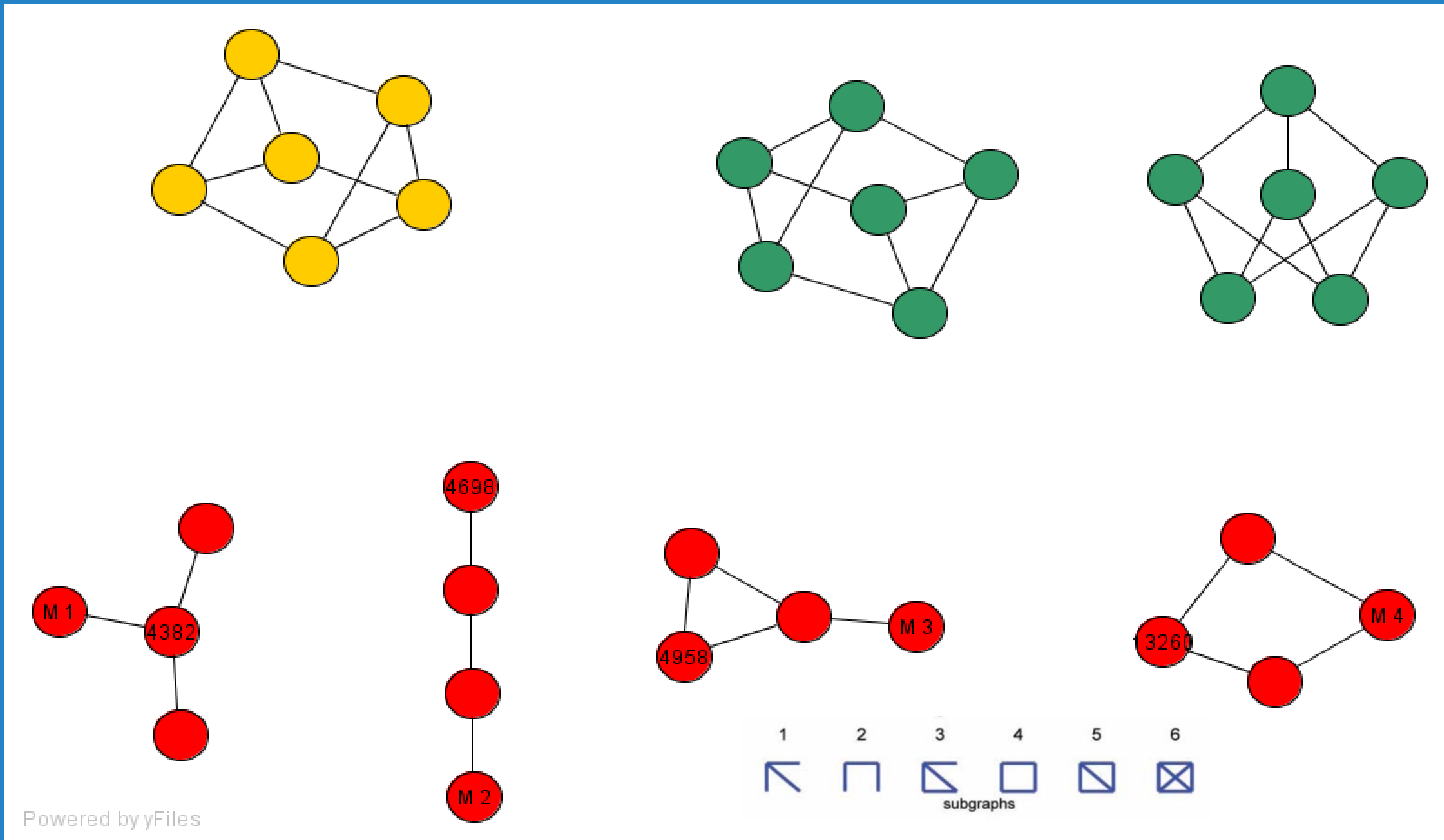
Milo et al. Network Motifs: Simple Building Blocks of Complex Networks, *Science* **298**(824), 2002

- Network motifs are subgraphs that meet the following criteria:
  - Take, say, 1000 randomized networks (built by the configuration model);
  - The subgraph appears at least 4 times in the real network;
  - The number of appearances in the real network is significantly larger than in the randomized networks:

$$\frac{N_{real} - N_{rand}}{10^{-1} N_{rand}} > 1$$

This is done to avoid detecting as motifs some common subgraphs that have only a slight difference between N_{rand} *and* N_{real} *but have a narrow distribution in the randomized networks*.

Network Motifs: Example



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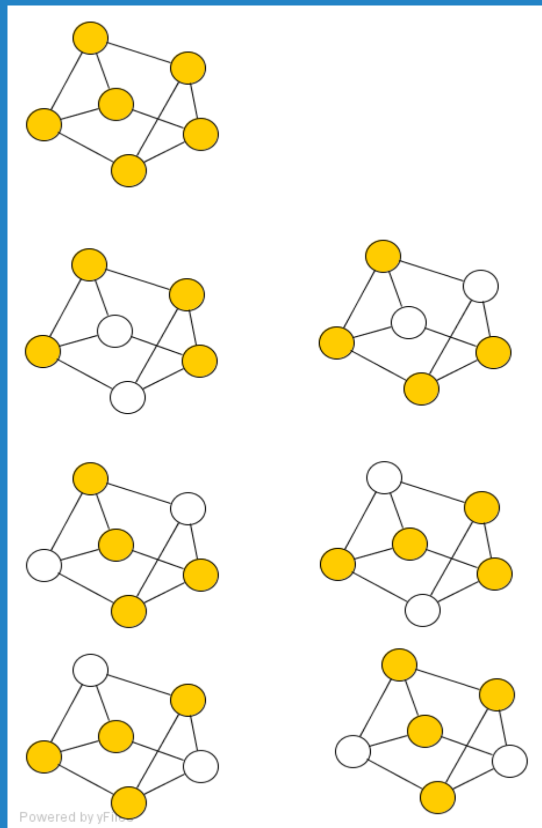
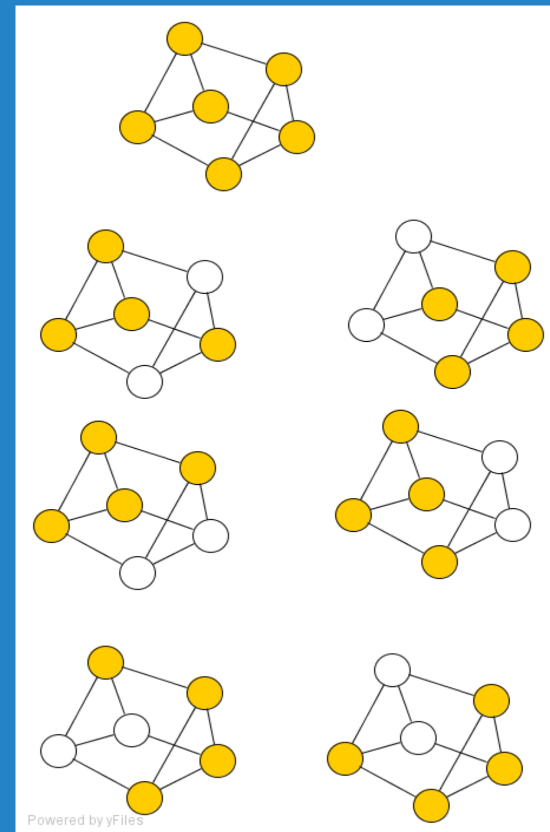
Network Motifs: Example

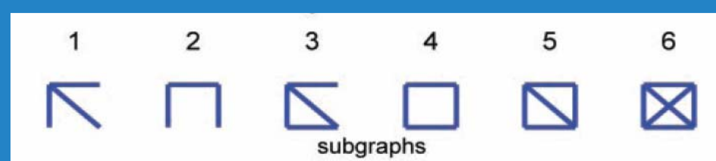
Presence of sub-graphs 2 and 3



Subgraph #2



Subgraph #3



Network Motifs: Superfamilies of Networks

Milo et al., Superfamilies of Evolved and Designed Networks, *Science* **204**, 1538

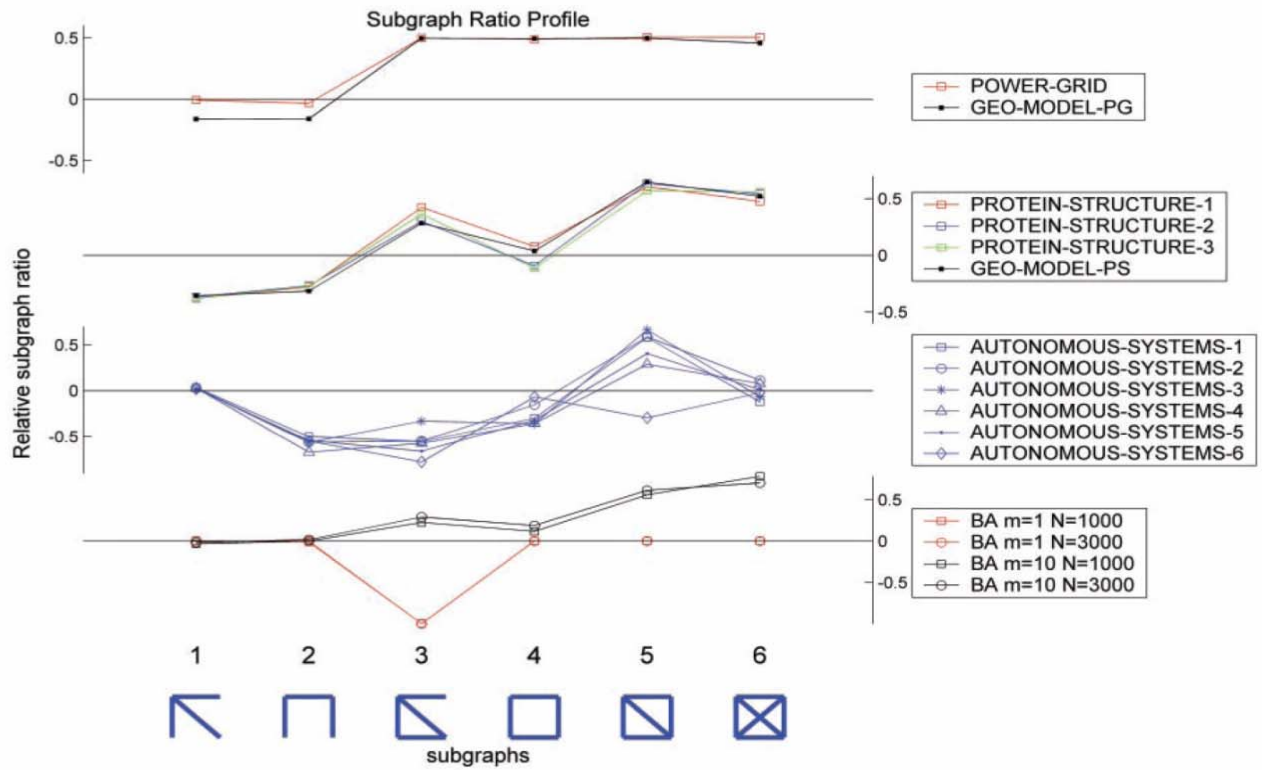


Fig. 3. The subgraph ratio profile (SRP) for various nondirected networks. The networks are as follows (*12*): (i) The electrical power grid of the western United States (*4*) (POWERGRID N = 4941, E = 6594) and a geometric model with similar clustering coefficient (GEO-MODEL-PG N = 5000, E = 7499). (ii) Networks of secondary-structure elements adjacency for several large proteins [structure based on the PDB database (www.rcsb.org/pdb/); the proteins (and their PDB ID) were 1A4J, an immunoglobulin (PROTEIN-STRUCTURE-1 N = 95, E = 213); 1EAW, a serine protease inhibitor (PROTEIN-STRUCTURE-2 N = 53, E = 123); and 1AOR, an oxidoreductase (PROTEIN-STRUCTURE-3 N = 99, E = 212)] and a geometric model with similar clustering coefficient (GEO-MODEL-PS N = 53, E = 136). (iii) The Internet at the autonomous system level (www.cosin.org) (AUTONOMOUS-SYSTEMS 1 to 6; N = 3015, 3522, 4517, 5357, 7956, 10515; E = 5156, 6324, 8376, 10328, 15943, 21455). (iv) Networks grown according to the preferential attachment BA model (*3*) with m = 1 or m = 10 edges per new node (BA m = 1, 10; N = 1000, 3000, 1000, 3000; E = 1000, 3000, 9901, 29901).

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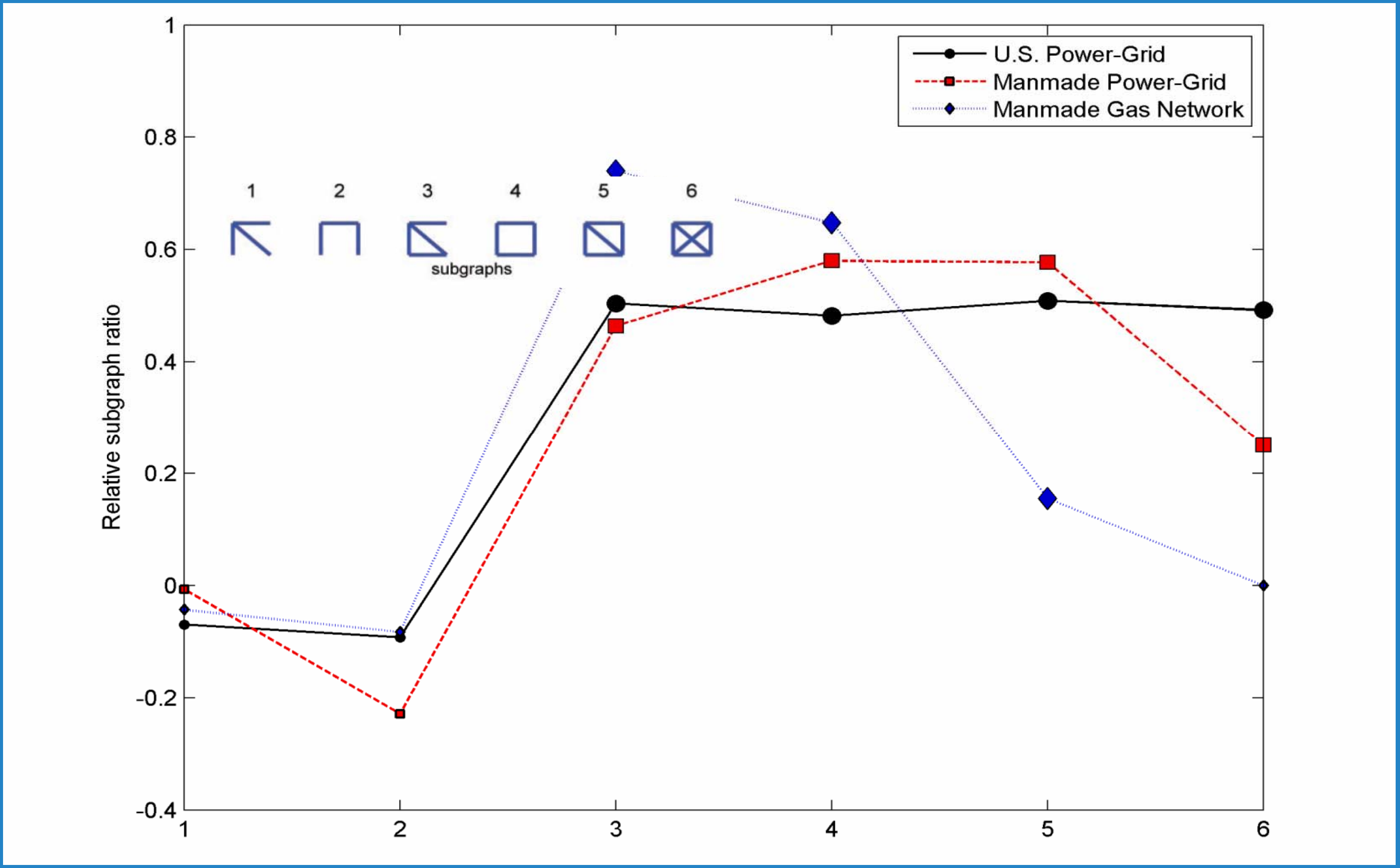
Motifs in manmade networks



Wind field construction

and maps of potential wind energy production over Europe

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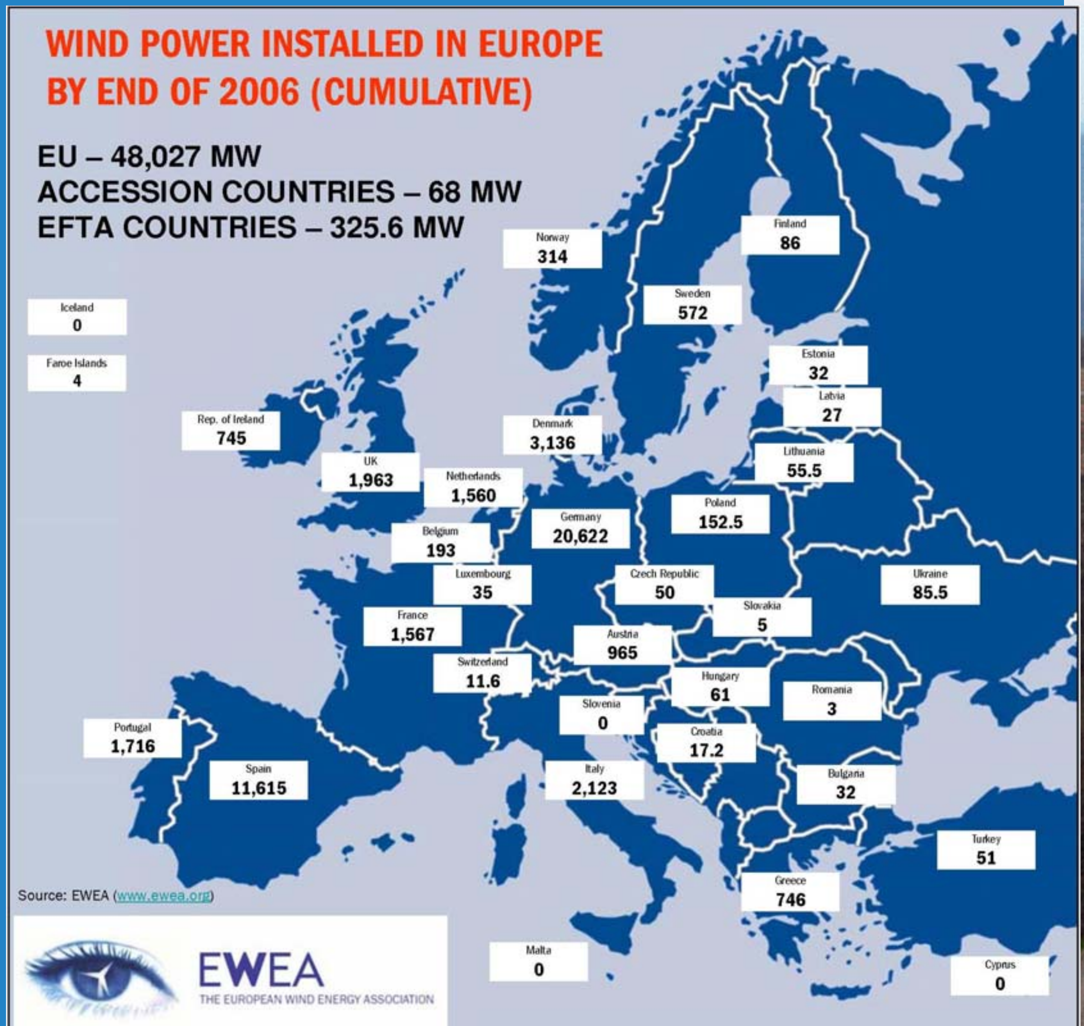
Data and methods

- Models for wind speed histograms
- Wind profiles – height dependence of wind speed
- Wind power estimations
- Wind power networks

Wind field construction

and maps of potential wind energy production over Europe



wind energy

as a %

of total energy

in EU

7-8%

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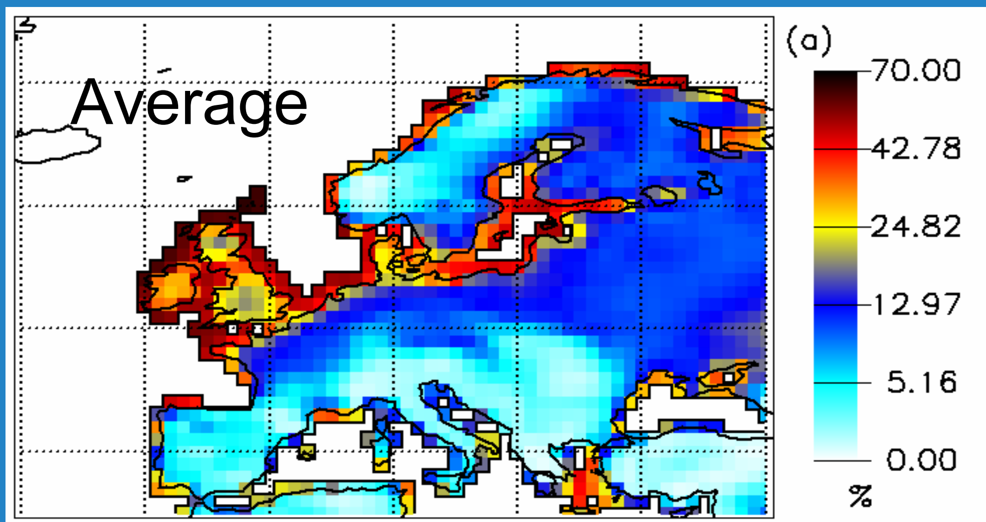
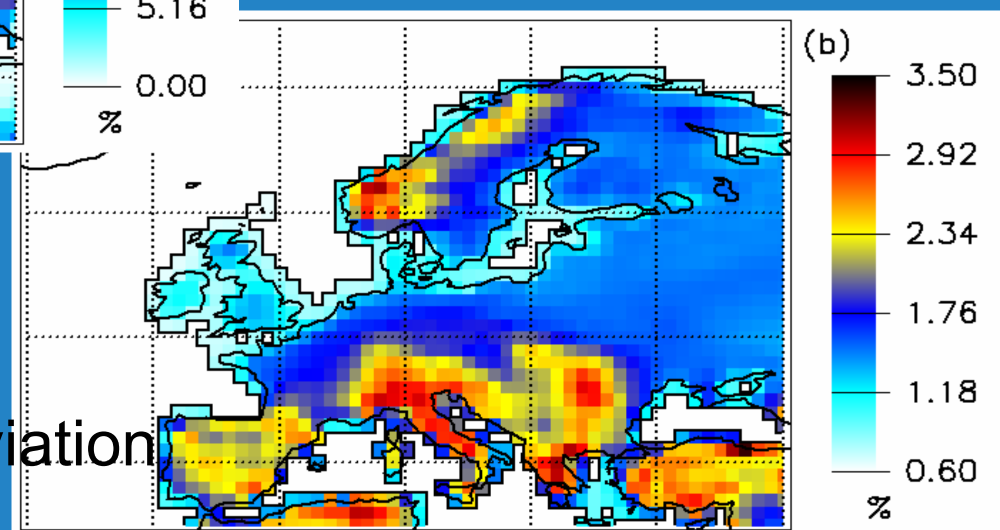
Wind field construction

and maps of potential wind energy production over Europe

Wind power networks

Average and standard deviation of wind power





Error tolerance of complex networks

Cascading failures

- flow of a physical quantity: loads on edges
- maximal load is limited by the capacity of the edge
- edge removal leads to redistribution of the initial loads – this may cause overloading
- this effect may extend to the whole network: *cascading breakdown*

DC Power Flow model I

- nodes are sinks or sources (or distributor)
- the power consumption and production of stations is characterized by vector **P**
- DC power flow equation: **P=BΘ**
- **Θ**: phase vector
- **B**: susceptance matrix
- X_{ij} is the reactance of the transmission line between node *i* and node *j*

$$B_{ij} = -\frac{1}{X_{ij}}, B_{ii} = \sum_{j} \frac{1}{X_{ij}}$$

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Power Flow model II

- the power flow on the *i—j* transmission line:

$$F_{ij} = U^2 \frac{\Theta_i - \Theta_j}{X_{ij}}$$

- model parameters are:
  - reactance, capacity of the transmission lines
  - power consumption/production of the substations
- approximations:
  - ignoring (ohmic) line losses
  - all voltage magnitudes are equal
  - the phase changes along each line are assumed to be small (linear approx.)

Cascading failures in the power flow model

- parameters (X_{ij}, U, P_i – for consumptions) are chosen to be unity
- power sources are randomly distributed among the nodes
- link capacities are proportional to the initial loads: (α≥1: tolerance parameter)

$$C_{ij} = \alpha \cdot F_{ij}^{0}$$

- network topologies: ER and BA type
- scenario: random edge removal – computation of flows – overloaded edge removal

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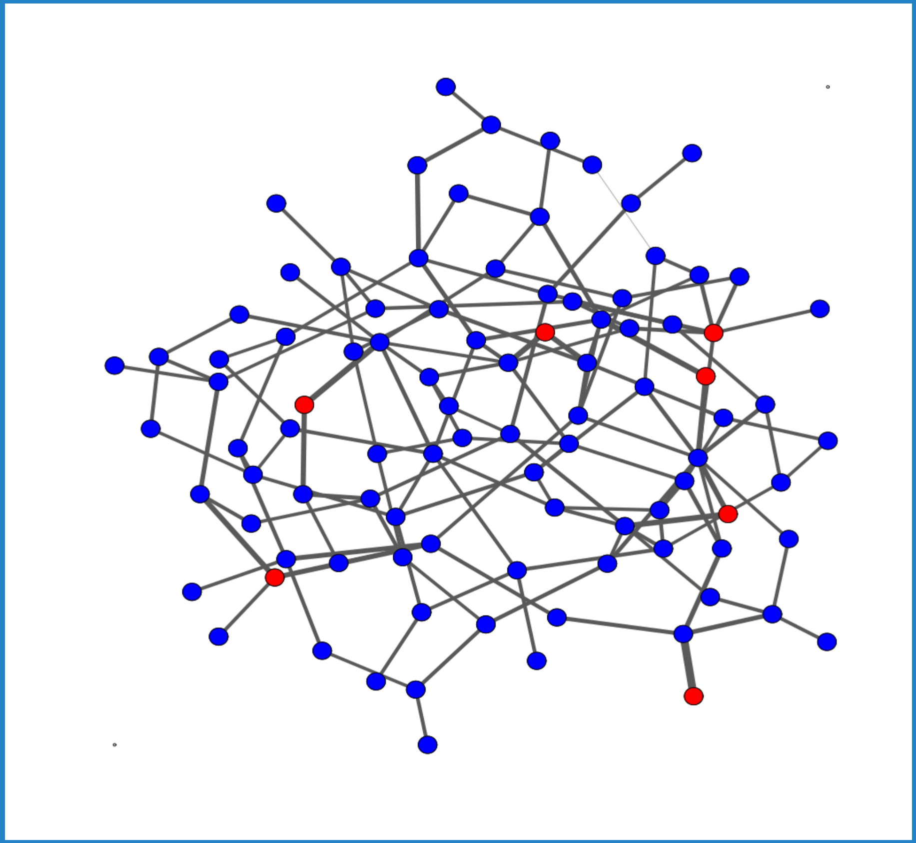
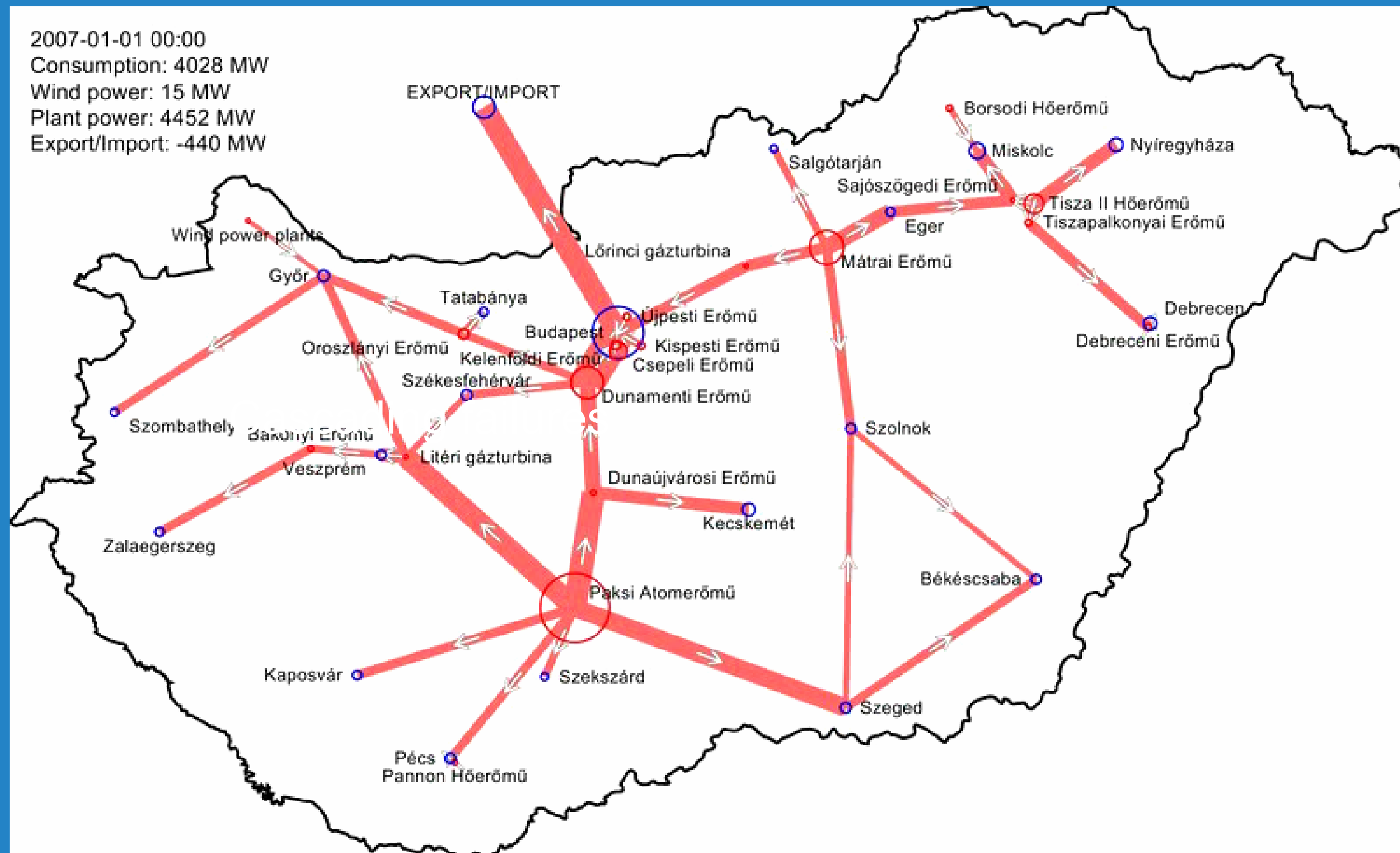
Realization of cascading breakdown



Cascading breakdown
flow of a physical quantity:
maximal load is limited by the capacity of the edge
edge removal leads to redistribution of the initial loads - overloading

Error tolerance of complex networks

Composite electricity model for Hungary including wind energy



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Error tolerance of complex networks

Dynamic network capacity modelling

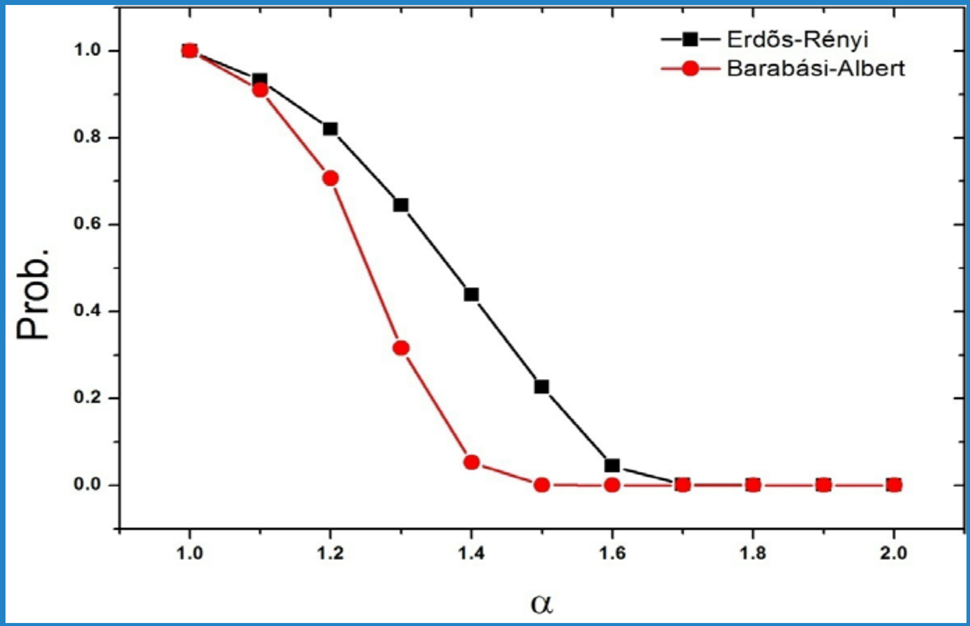
- extend the model to the whole European power grid network using available European grid topology and REWIRING on the basis of known offshore windspeed data
  - emergence of a new network topology incorporating windpower
- identifying the most vulnerable parts of the network –
- suggesting new edges (transmission lines) which make the network more tolerant

Error tolerance of complex networks

Network robustness

•What is the probability of a cascading breakdown after removing a single edge?
•How does this probability depend on the tolerance parameter α?

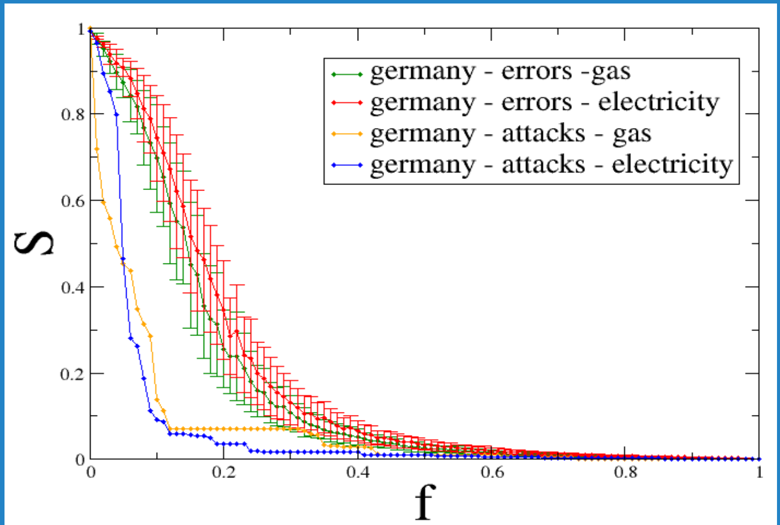
•networks tolerate single edge removal for α=link cap/init load ≥1.7
•scale-free type networks are more robust against random failures

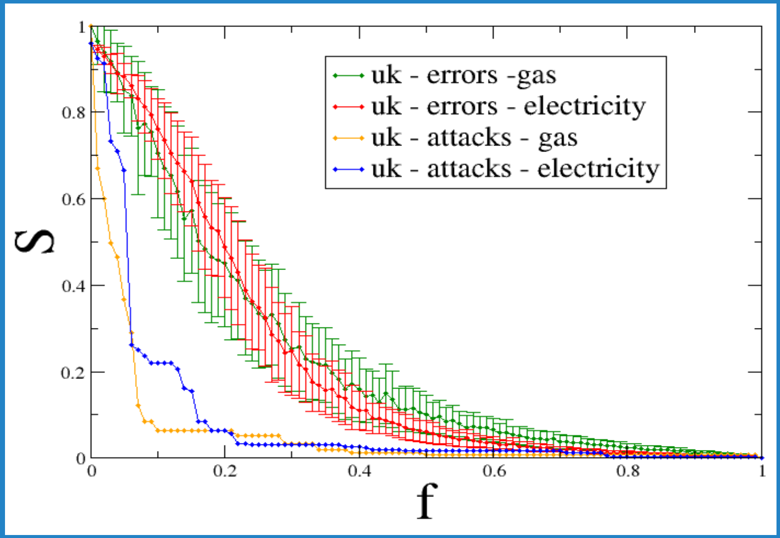


Network Tolerance Against Node Removals

The size of the largest connected component (S) as a function of the fraction of nodes removed (f) by:

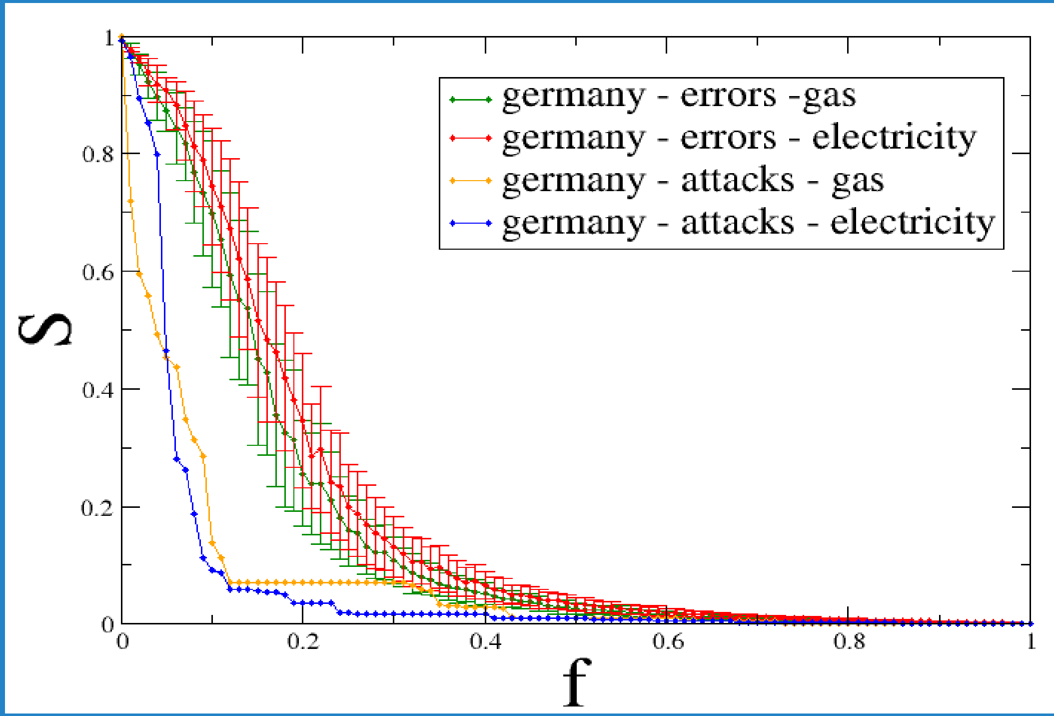
- Errors: random node removal
- Attacks: higher degree nodes are removed first

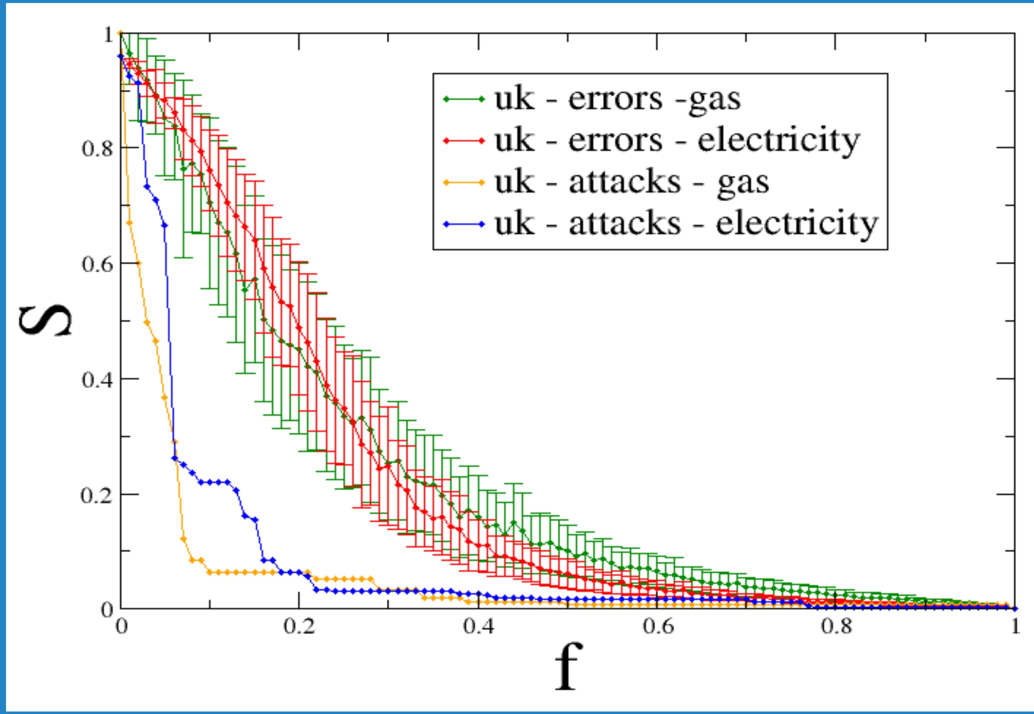




Network Tolerance Against Node Removals

selected countries





Network Tolerance Against Node Removals

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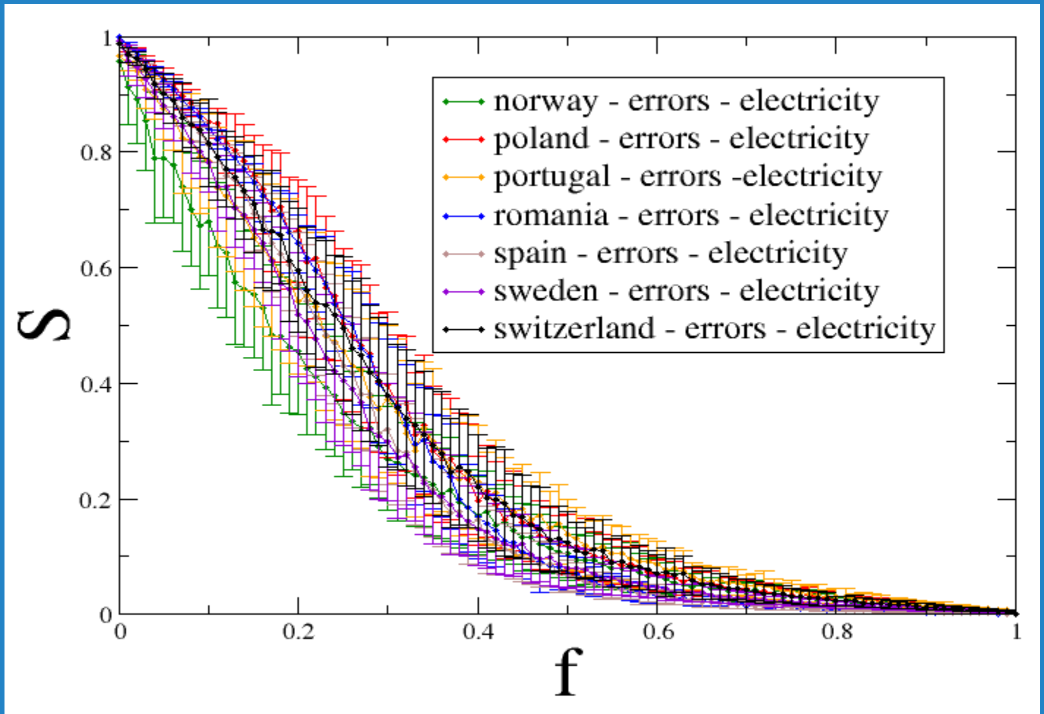

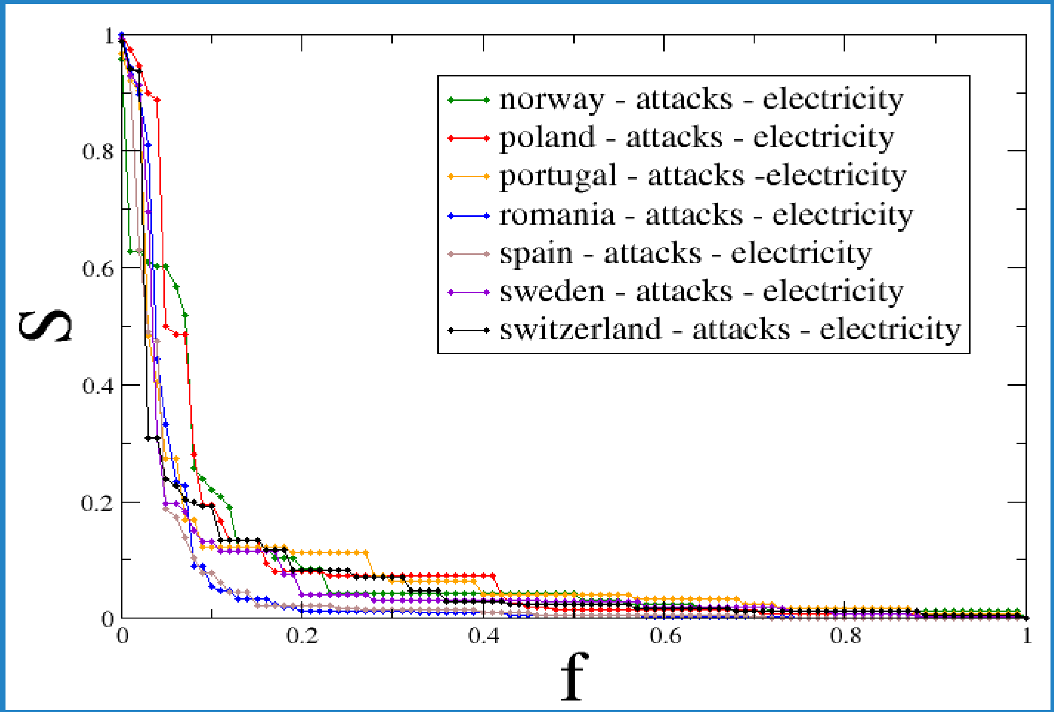

Network Tolerance Against Node Removals

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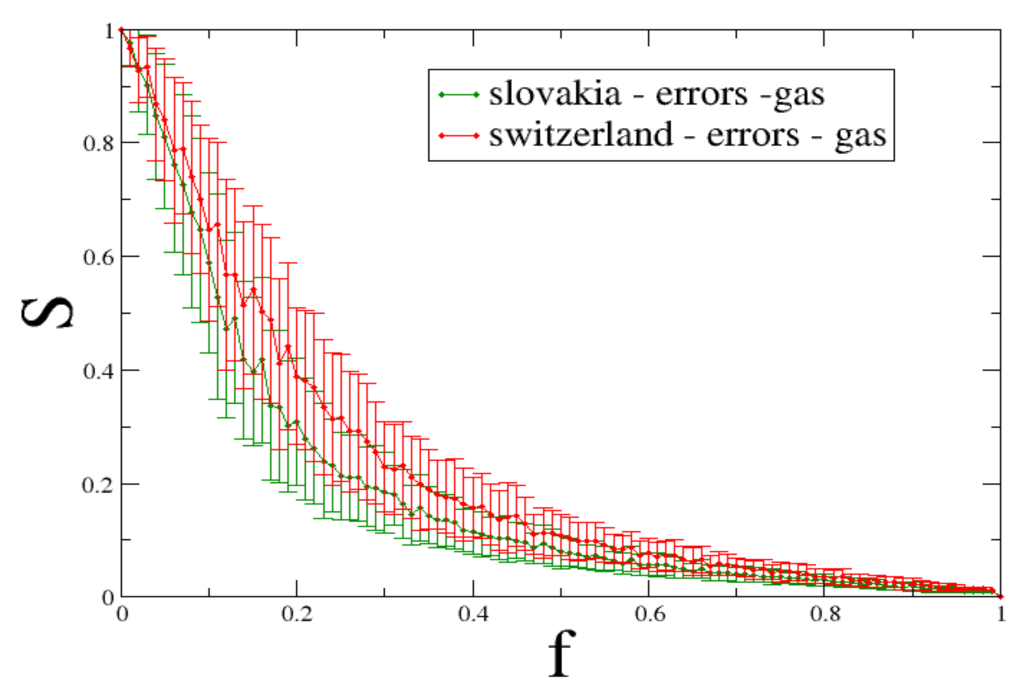
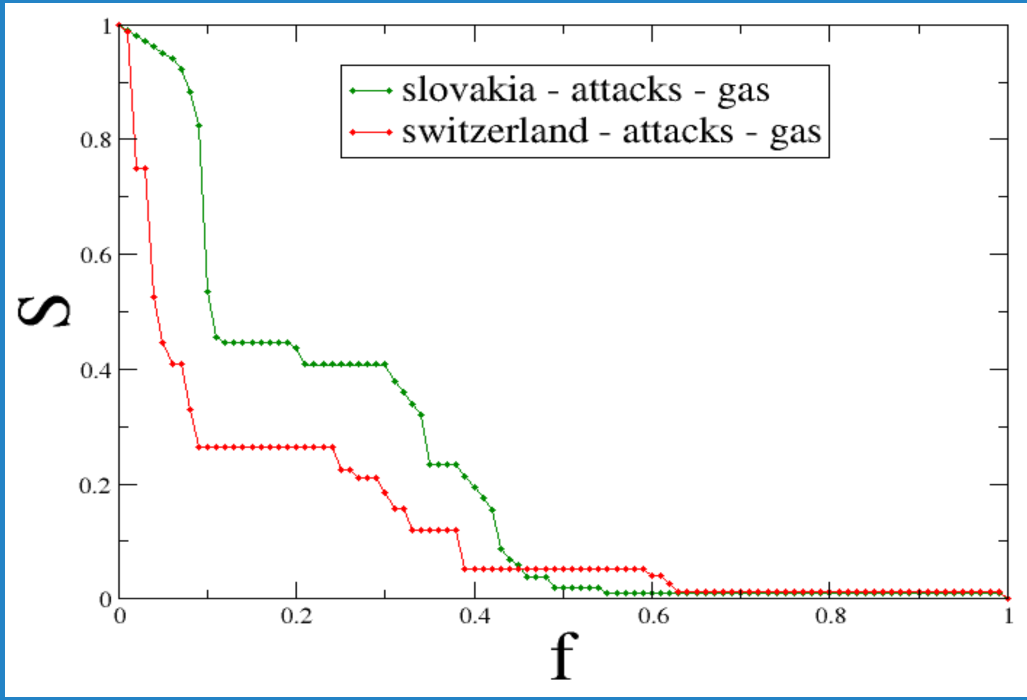
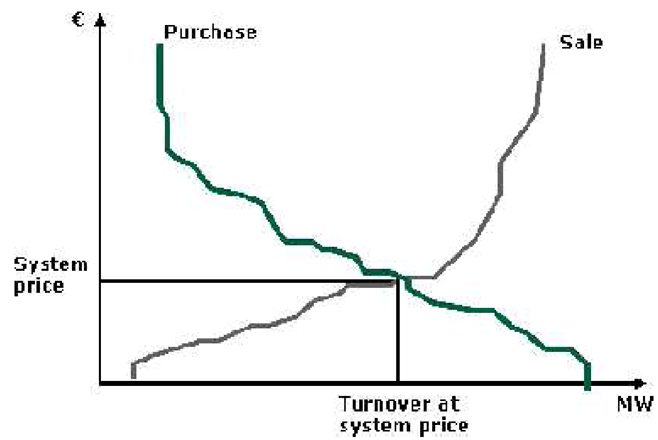


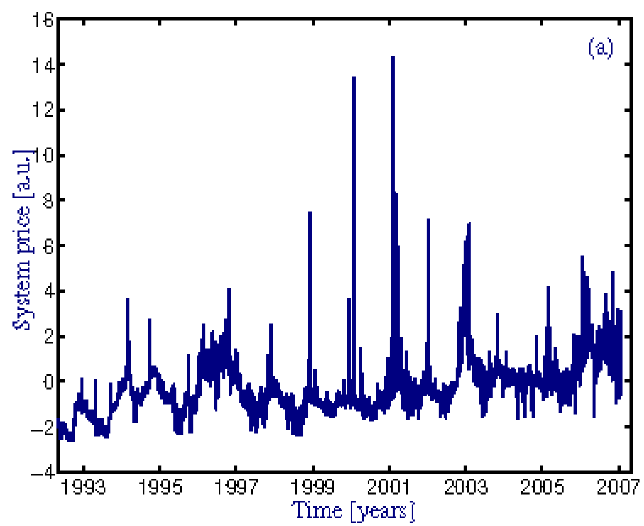


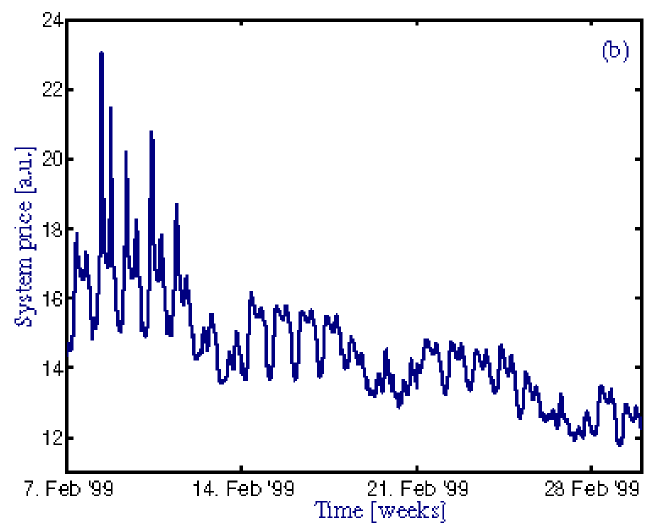
NORDPOOL ELECTRICITY SPOT PRICE DATA

Nord Pool

electricity spot price
market data (⟵ WP2)





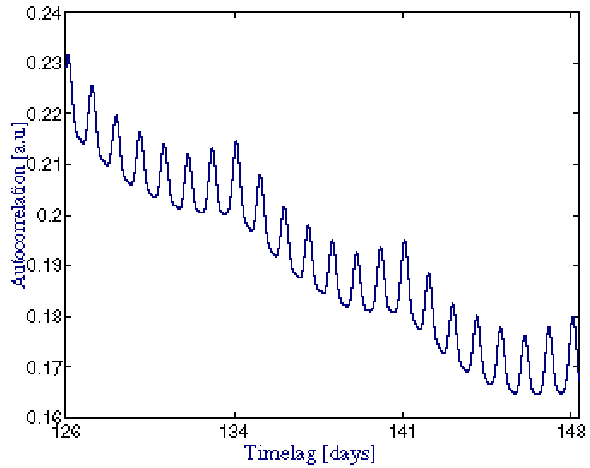


NORDPOOL ELECTRICITY SPOT PRICE DATA

Correlation analysis

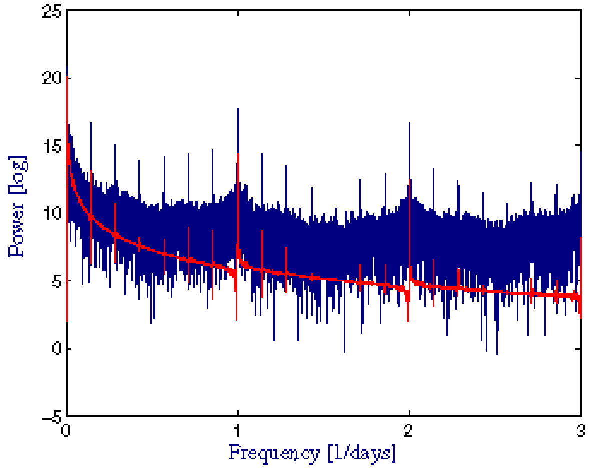
correlation function

$$C(n) = \frac{1}{N}\sum_{\ell} x_\ell x_{\ell+n}$$



power spectrum

$$S(k) = \left|\sum_{\ell} x_\ell \exp(2\pi i k \ell / N)\right|^2$$



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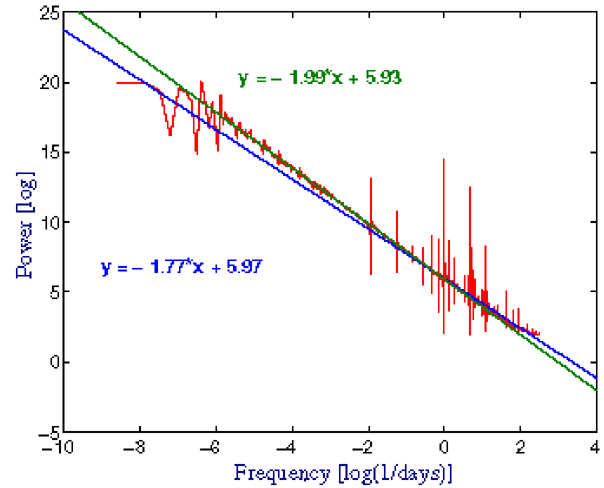
NORDPOOL ELECTRICITY SPOT PRICE DATA

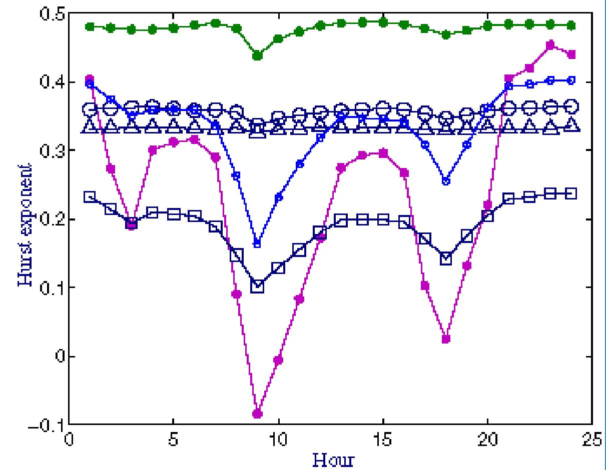
3 Multifractal properties

Hurst exponent ($\longrightarrow$ D3.1)

$$x(t) \sim \lambda^{-H} x(\lambda t)$$
$$\langle x^2(t) \rangle \sim t^{2H}$$
$$S(\omega) \sim \omega^{-1-2H}$$



- R/S
- DMA
- MF-DFA



DATA SOURCE

- **Monthly Disturbances**
- **Monthly Total Consumption**

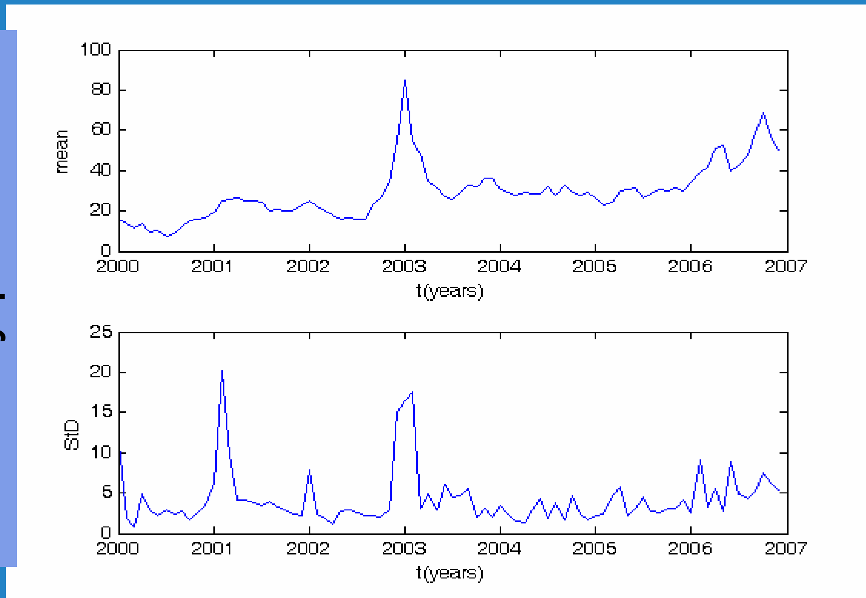
  http://www.nordel.org
- **Monthly Electricity prices**

  http://www.nordpool.com

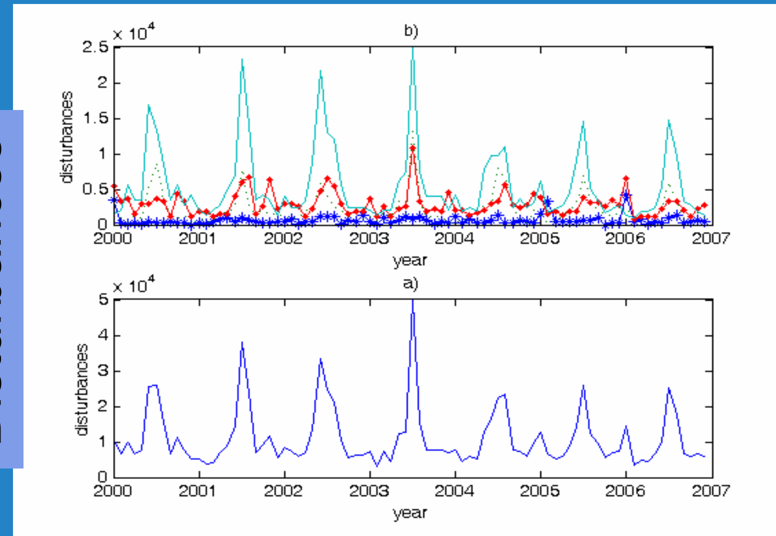
in Denmark, Finland, Norway and Sweden
from January 2000 until December 2006

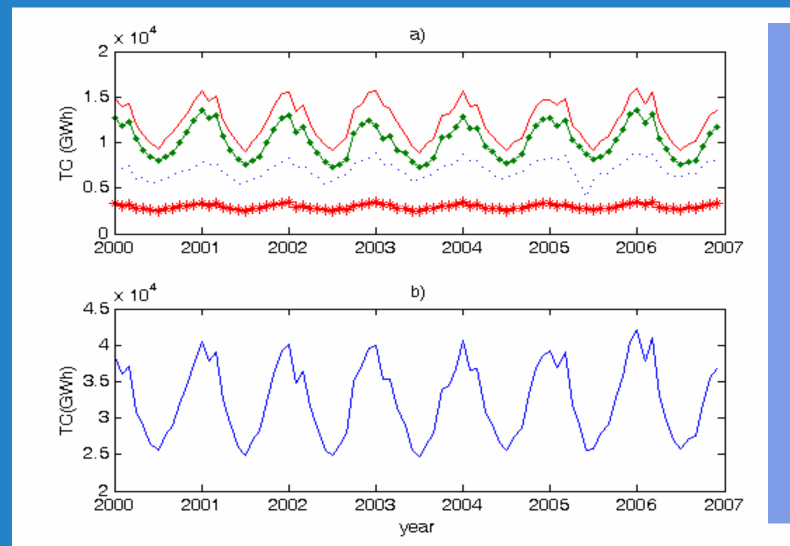
Data treatment

Electricity prices



Disturbances





Total Consumption

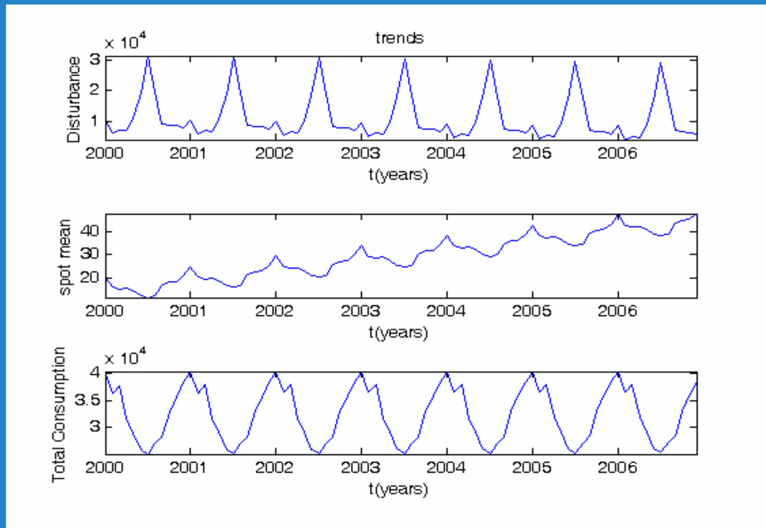
Denmark(*), Finland(:), Norway(.-) and Sweden(-).

Data treatment

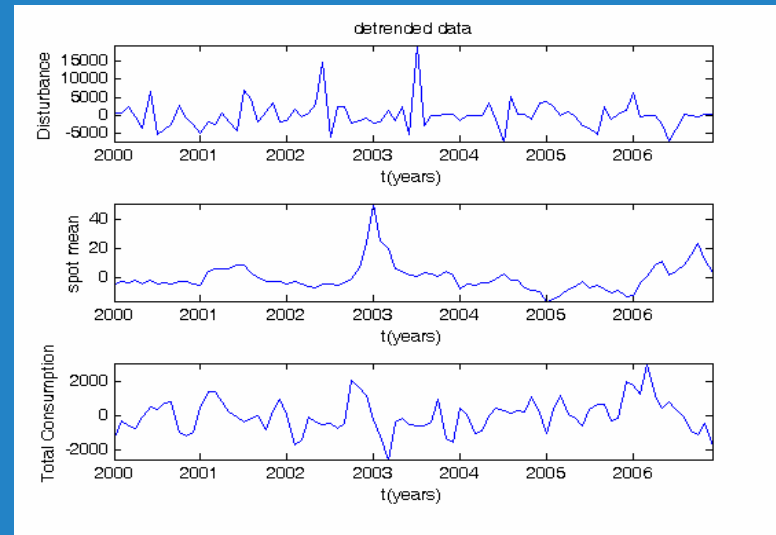
$$V_S(t) = std\left(\ln\left(\frac{P(t)}{P(t-\Delta t)}\right)\right)$$

$$\Delta t = 1\,\text{m},\ w = 2\,\text{m},\ s = 1$$

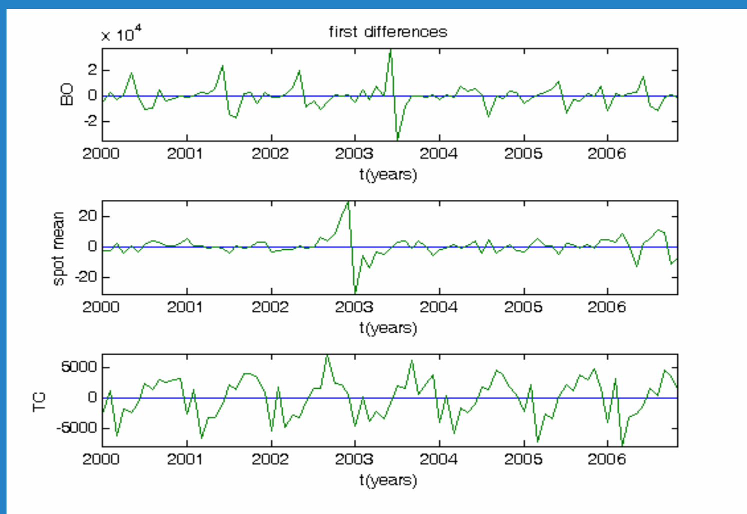
Trends



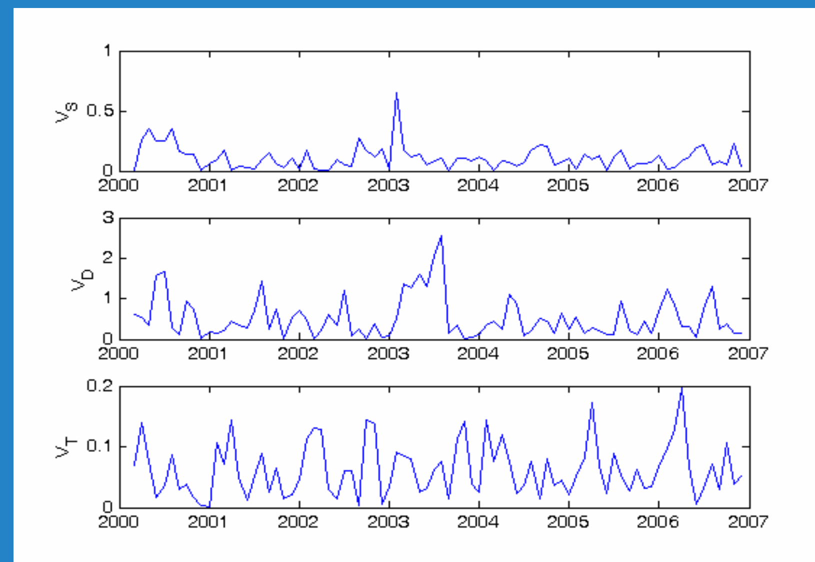
Detrended data



First differences



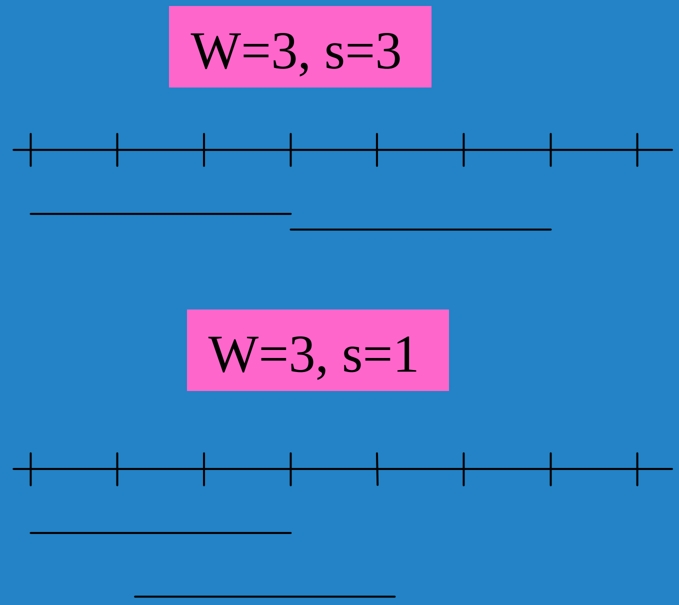
Volatilities



Data treatment

S	Mean monthly spot prices	*dt	Detrend of *
D	Monthly disturbances	*fd	First diff of *
T	Monthly Total Consumption	V_*	Volatilities of *

Window	shift	window	shift
1	1	2	1
3	3	3	1
6	6	6	1
12	12	12	1



Linear Correlation Coefficient

r values between Std (for V_S, V_D, V_T) and the mean (for the others time series), $|r|>0.7071$ ($r^2>0.5$), confidence level of 95%

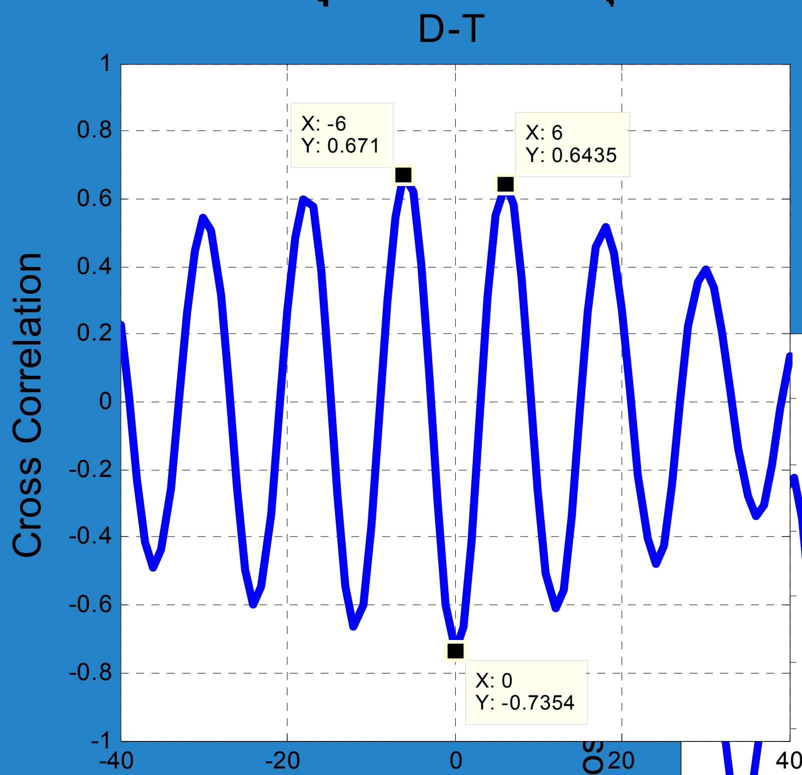
w=2; s=1	w=3; s=1	w=6; s=1	w=12; s=1
T,D (-0.7354) S, Sdt(0.7195)	T,D (-0.8057)	T,D(-0.9044) Tfd,Dfd(-0.8010)	T,D(-0.7807) D,Tdt(-0.7586) D,Ddt(0.8060) T,Tdt(0.9904)

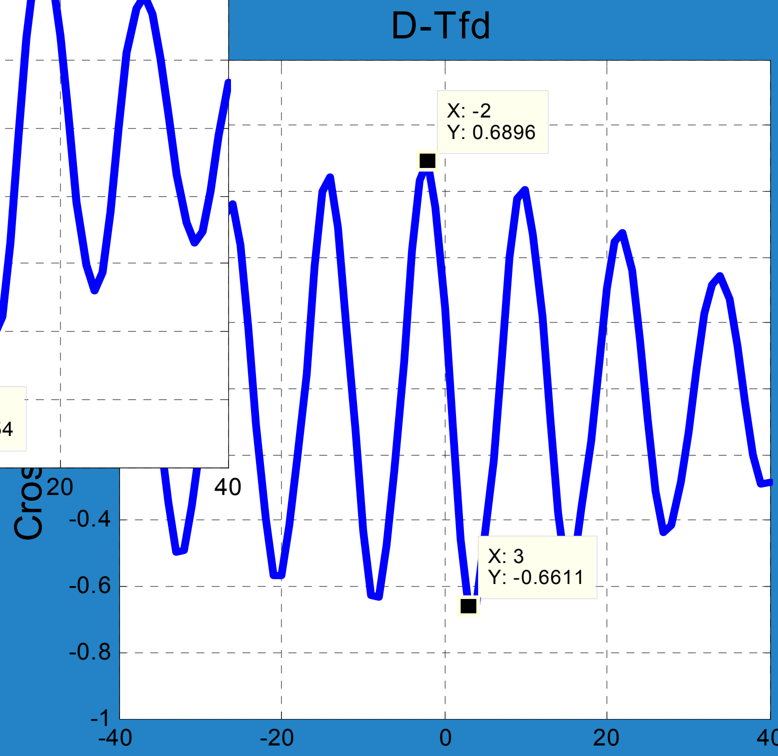
w=1, s=1	w=3; s=3	w=6; s=6	w=12; s=12
S,Sdt (0.7317) Sfd,Vs(0.8607) Dfd,V_D(0.8761) Tfd,V_T(0.9896)	D,T (-0.8154)	Dfd,D(-0.8503) Tfd,T(-0.8686) V_D,Dfd(0.7698) D,T(-0.8594) D, Tfd(0.776) T,Dfd(0.7752)	Tdt,T(0.9842) V_D,T(-0.9057) **V_D,Sdt(0.8138)** V_D,Tdt(-0.9014)

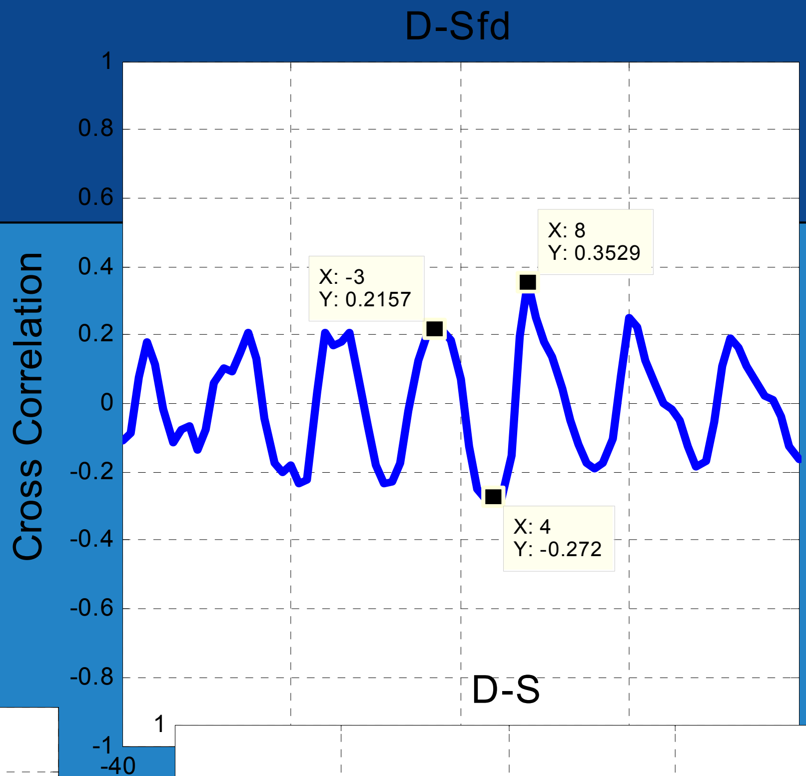
Cross Correlation Function

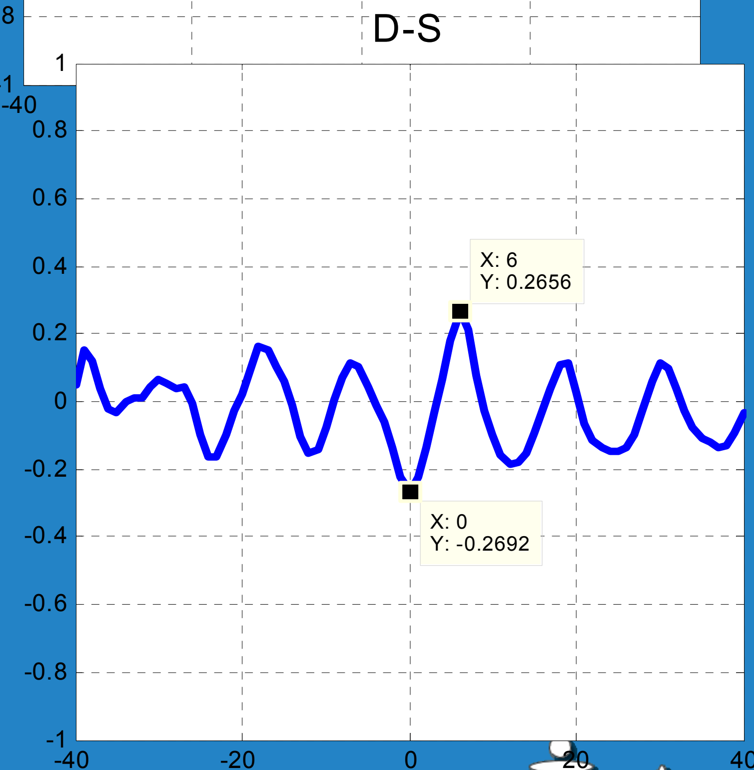
$$r(d) = \frac{\sum_i [(x(i) - mx) * (y(i-d) - my)]}{\sqrt{\sum_i (x(i) - mx)^2}\sqrt{\sum_i (y(i-d) - my)^2}}$$

w=2,s=1



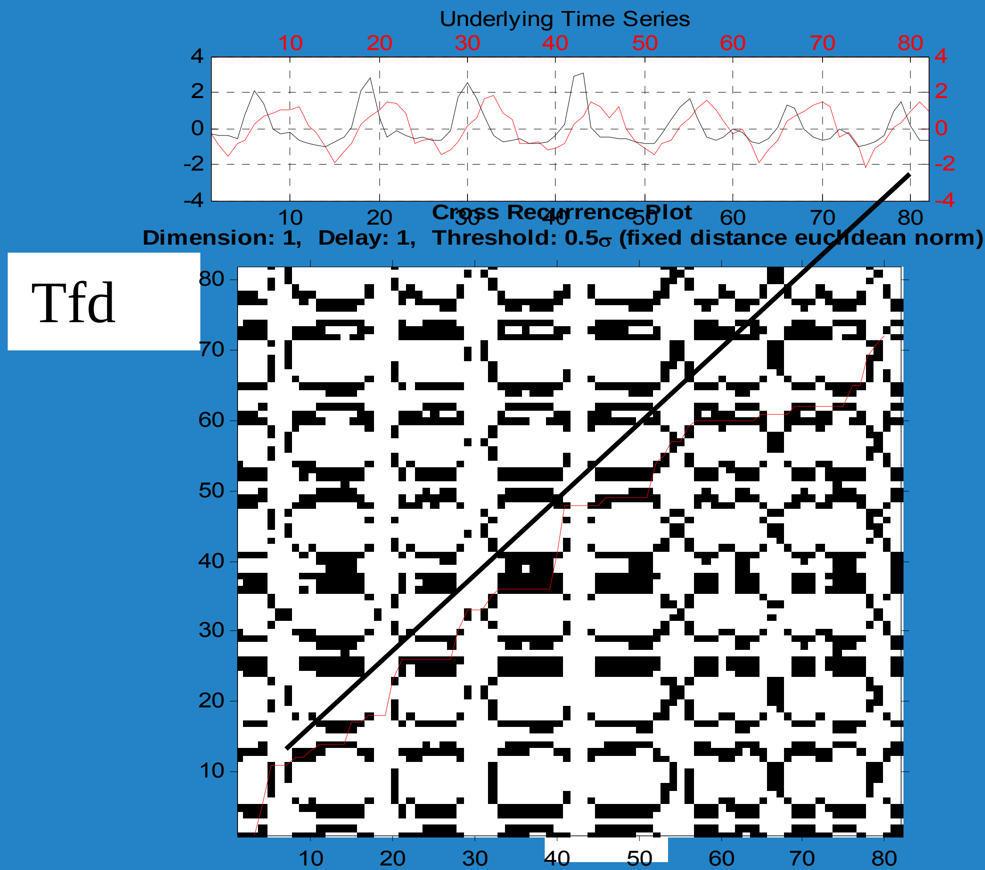


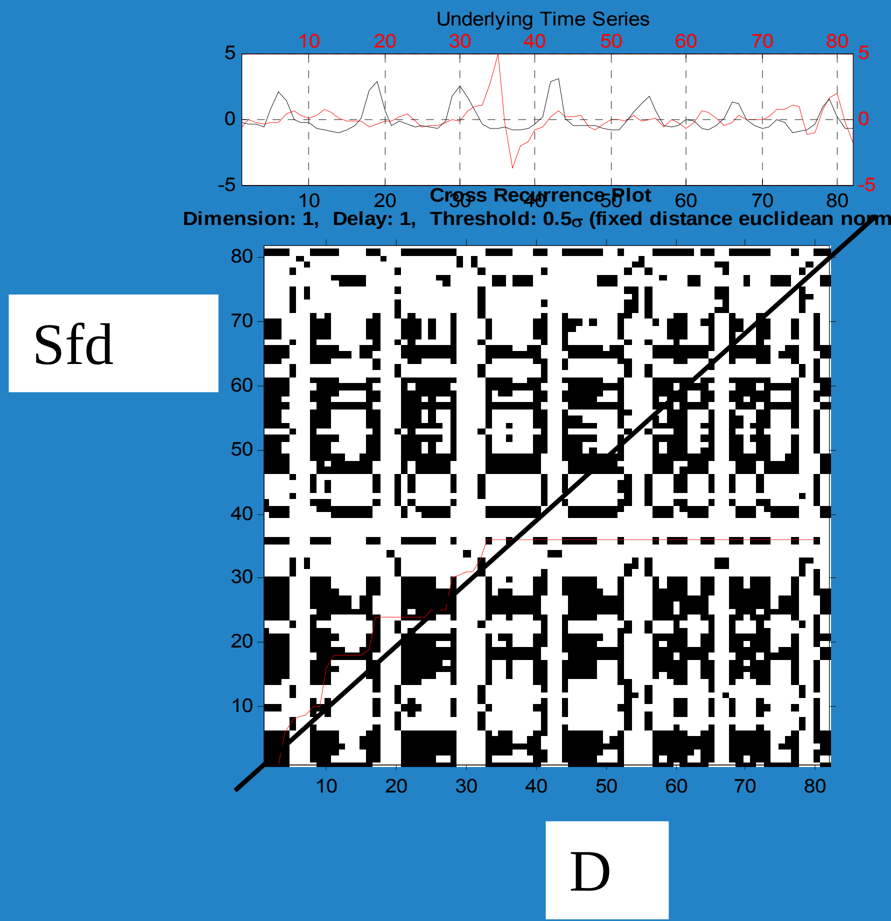




w=2,s=1,
ε=0.5

LOS calculation for electricity prices, disturbances and Total Consumption





LOS calculation in CRP between Disturbances and the other time series. Only the CRP with at least a part of the LOS parallel to the main diagonal is considered.

Figure	Temporal intervals considered	r using total time series	R using intervals suggested by CRP	Note
D-S	*D(10:20); S(1:11);*	*-0.2692*	*0.6304*	*Interval +shift*
D-T	*D(1:20); T(1:20)*	*-0.7354*	*-0.8087*	*interval*
D-Sfd	*D(1:30); Sfd(5:34)*	*0.0702*	*0.5466*	*interval+ shift*
D-Dfd	*D(1:19); Dfd(2:20)*	*-0.4119*	*-0.7021*	*Interval+ shift*
D-Tfd	*D(1:60); Tfd(3:62)*	*0.2429*	*0.7455*	*Interval +shift*

NORDPOOL DATA

S	Mean monthly spot prices
D	Monthly disturbances
T	Monthly Total Consumption

Linear Correlation Coefficient:

•For near all the windows *w* and time shifts *s* we found a high linear correlation between D and T or their modified versions. Exception w=1, s=1.

•For w=12 s=12 a correlation appears between V_D, Sdt(0.8138)

• It is not clear up to know how to use this result for modeling the electricity price.

OBSERVATIONS 1

- the integrity of the infrastructure data has been enhanced and extended
- dynamic models have been developed to simulate attacks and breakdown

  - disconnection and cascading failure

on ranked node sets – mainly topological

- dynamic breakdown models of consumption to be extended to Europe and introduce and compare nuclear power

OBSERVATIONS 2

- We are trying to get political and geographical rankings of nodes to weight with topological ones
- We have not integrated the various MANMADE activities to a satisfactory level
- Need to bring in more detailed weightings on networks
- Need to consider the network of networks…..

MANMADE

DIAGNOSING VULNERABILITY, EMERGENT PHENOMENA, and VOLATILITY in MANMADE NETWORKS