Resilience
of
INFRASTRUCTURE NETWORKS

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RAVEN

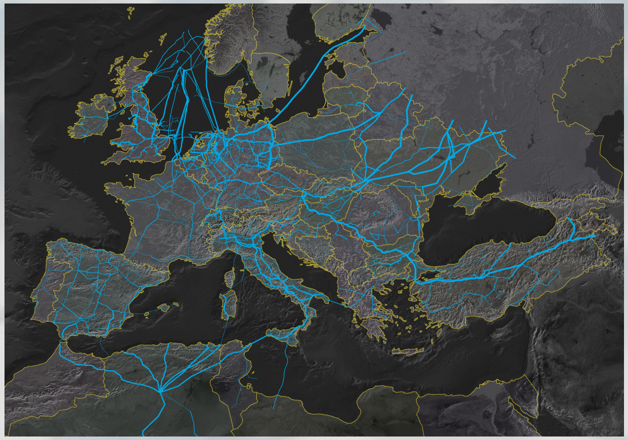
Resilience, adaptability and vulnerability in complex Energy Networks EPSRC

Queen Mary
University of London

MANMADE

DIAGNOSING VULNERABILITY, EMERGENT PHENOMENA, and VOLATILITY in MANMADE NETWORKS EU

Outline of talk

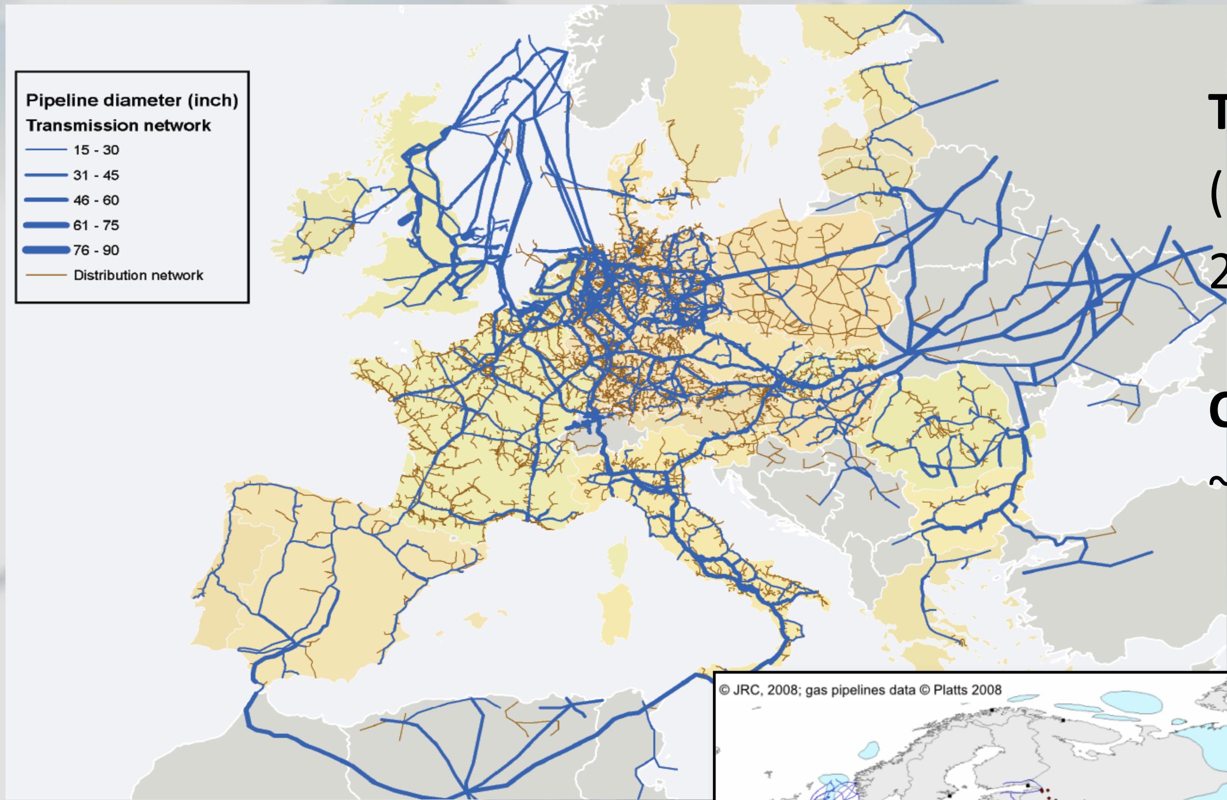


European infrastructure networks.

An approach to modelling of gas network supply crises in Europe

Future modelling challenges with renewable energy sources

Euro gas network (QMUL and JRC)



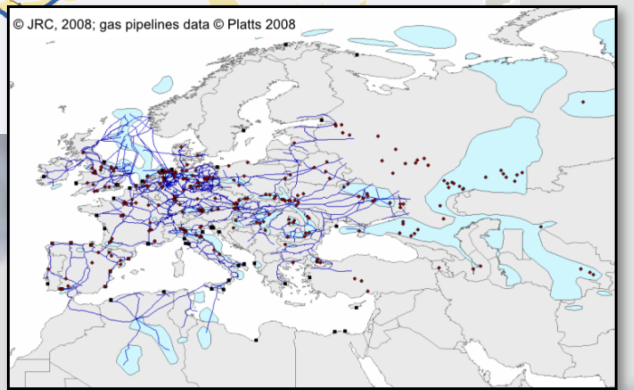
Transmission network

(D >= 15, + interconnections)

2000+ nodes, 3000+ links

Complete network

~25000 nodes, 26000 links

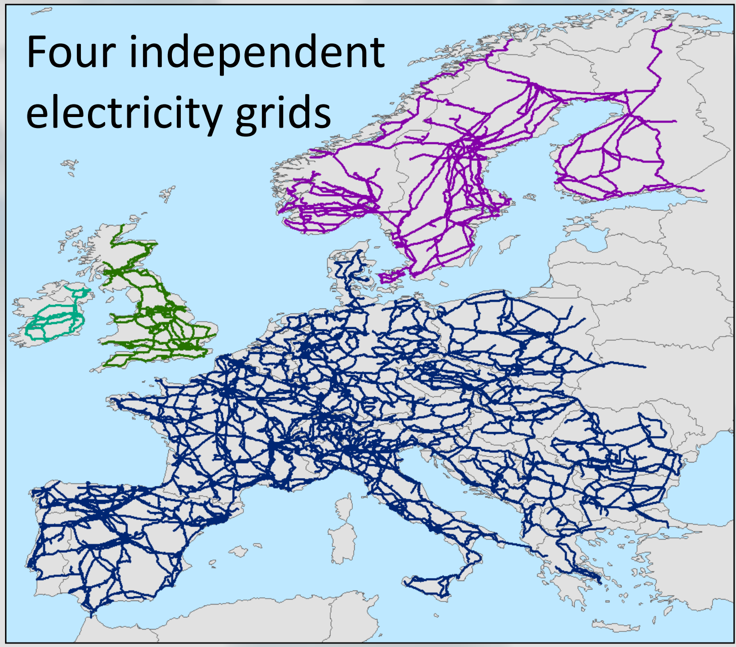


-- Gas sources
-- LNG terminals
-- Pumping stations
-- Gas Deposits

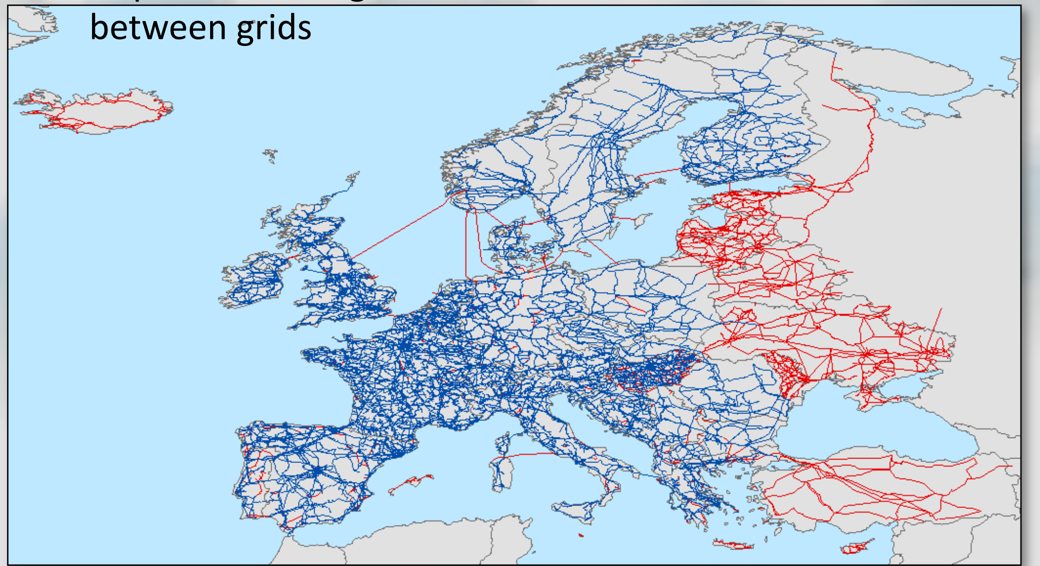
www.platts.com

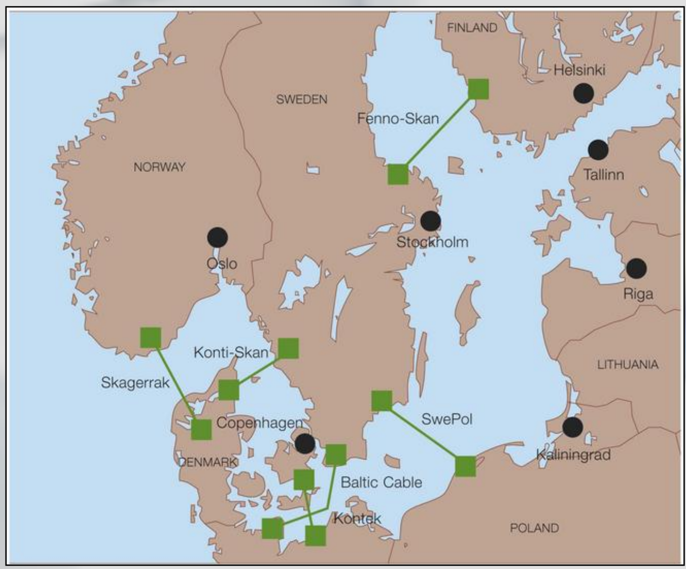
The European Electricity Grid

Four independent electricity grids



The synchronisation of phase of the HV current is required within grids but not between grids





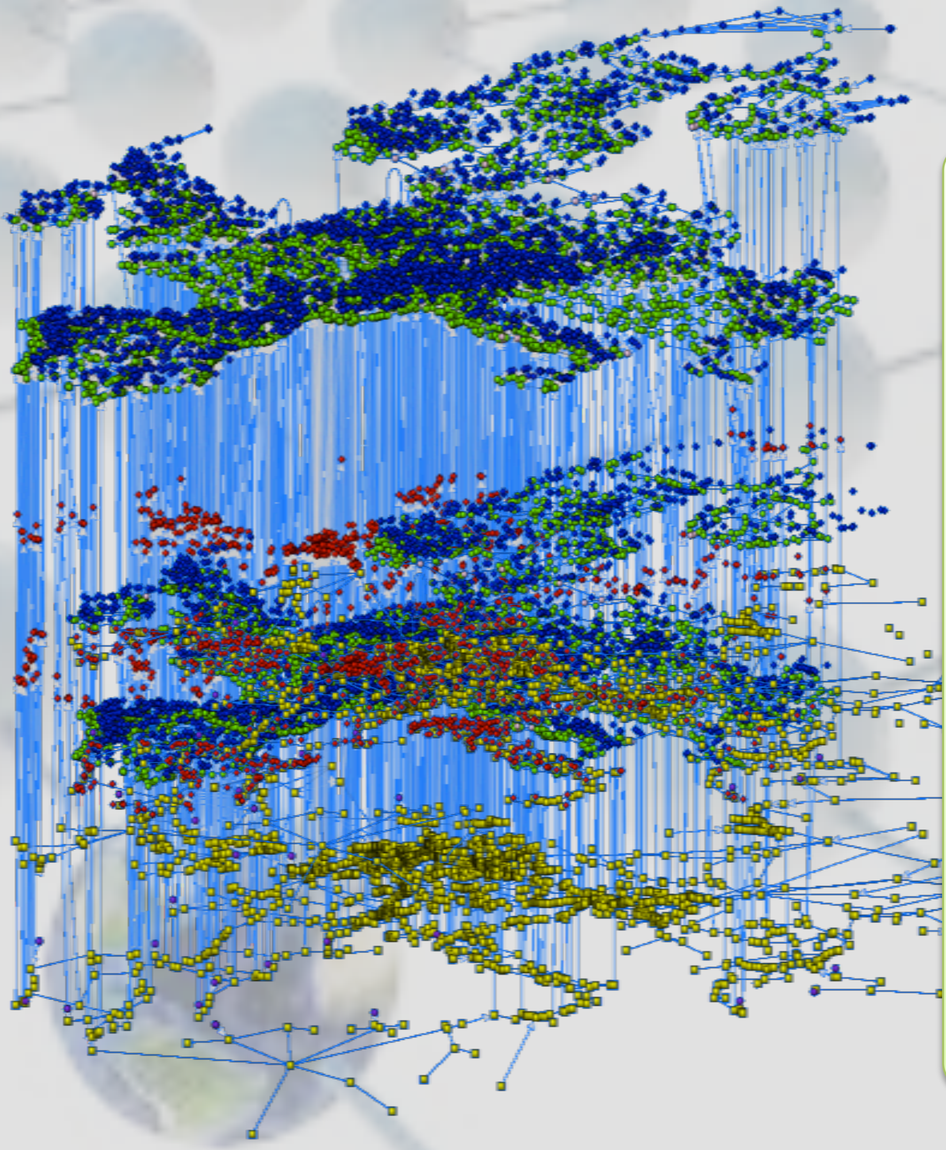
Power exchange between two AC networks that are not synchronized is by means of high voltage direct current (HVDC) lines
e.g. Scandinavia-Poland

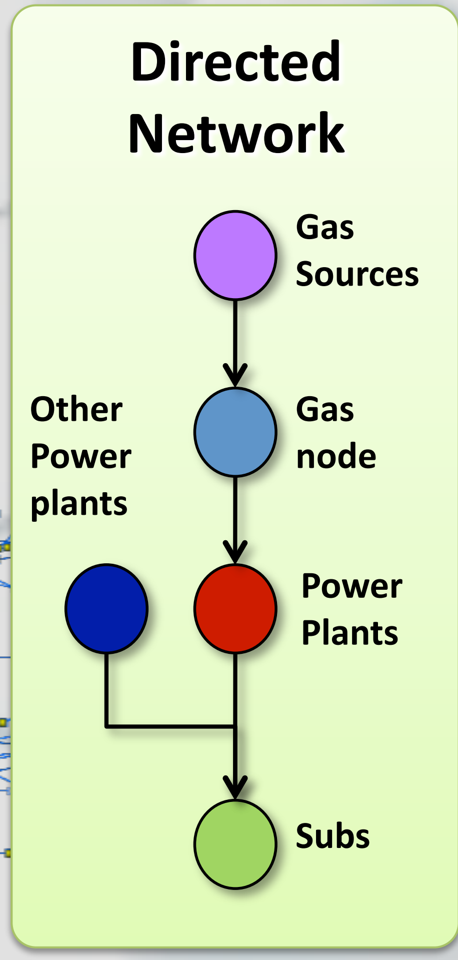
Interconnected infrastructure networks

Gas pipelines
2000+ nodes
2500+ edges
21 LNG terminals

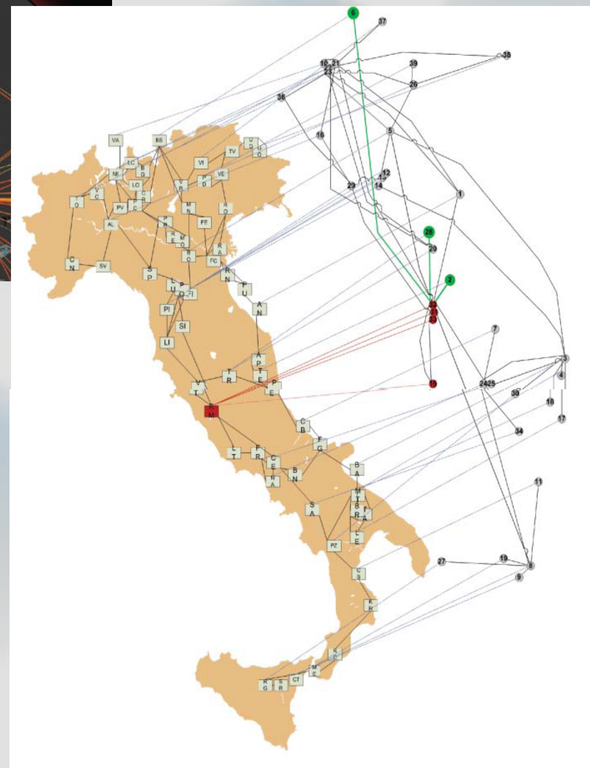
Electricity grid
5000+ subs
~7000 edges

Power plants
998 Natural Gas
4383 Others





Interdependent network modelling



The fragility of interdependency
A. Vespignani, *Nature* Vol 464 15 April 2010.
A study of failures in interconnected networks highlights the vulnerability of tightly coupled infrastructures….

Catastrophic cascade of failures in interdependent networks Buldryev *et al Nature* Vol 464| 15 April 2010| doi:10.1038/nature08932

Building on the 'percolation analysis' of two mutually dependent networks, highlights the subtleties of this problem.

Multilayer networks. Journal of Complex Networks 2 (3): 203–271. doi:10.1093/comnet/cnu016.
Kivelä et al. (2014).

Natural infrastructure crises and events

August 2005
Hurricane
Katrina

September 2005
Hurricane
Rita

2005-2006
Russia-Ukraine
dispute

2008-2009
Russia-Ukraine
dispute

2011
Arab spring

March 2011
Tsunami
Fukushima
nuclear plant

2013
Algeria terrorist
attack

March 2014
Russian invasion
of Crimea

Fracking!

- International disputes
- Natural disasters
- War - terrorism
- Reserves shortage

Why can be congestion a problem with such events?

- In a crisis, less delivery may mean greater congestion

  - breakdown of major transit routes
  - production losses in affected areas.

- The supply network has to adapted and used in different ways.

- Available resources may not be distributed well within the remaining network

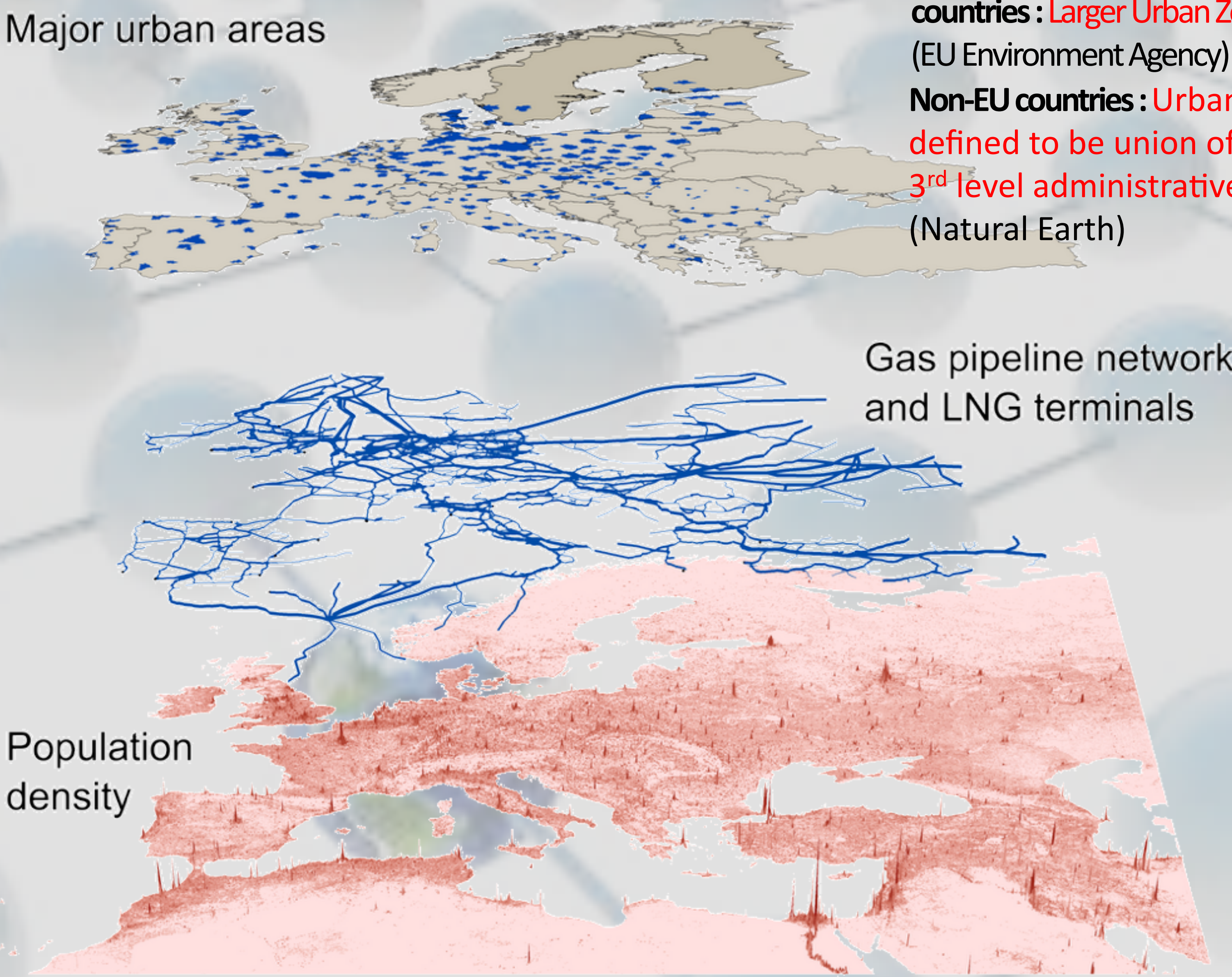
- How do we handle it?

Methodology

Data: spatial data layers involved in the analysis

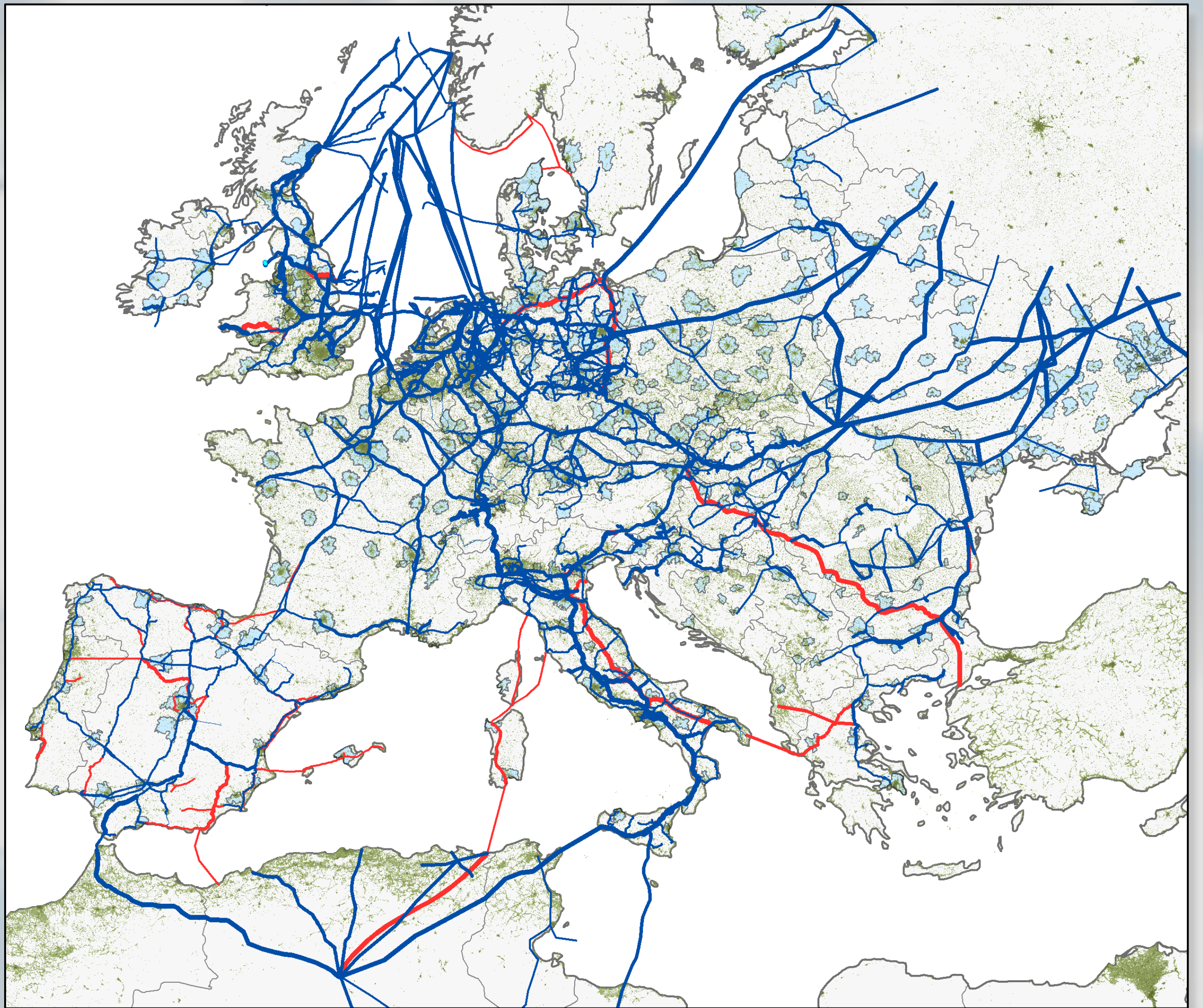
EU member states and candidate countries : Larger Urban Zones
(EU Environment Agency)

Non-EU countries : Urban areas defined to be union of 3rd level administrative divisions
(Natural Earth)



spacial
resolution
1 km

Data: the European gas network



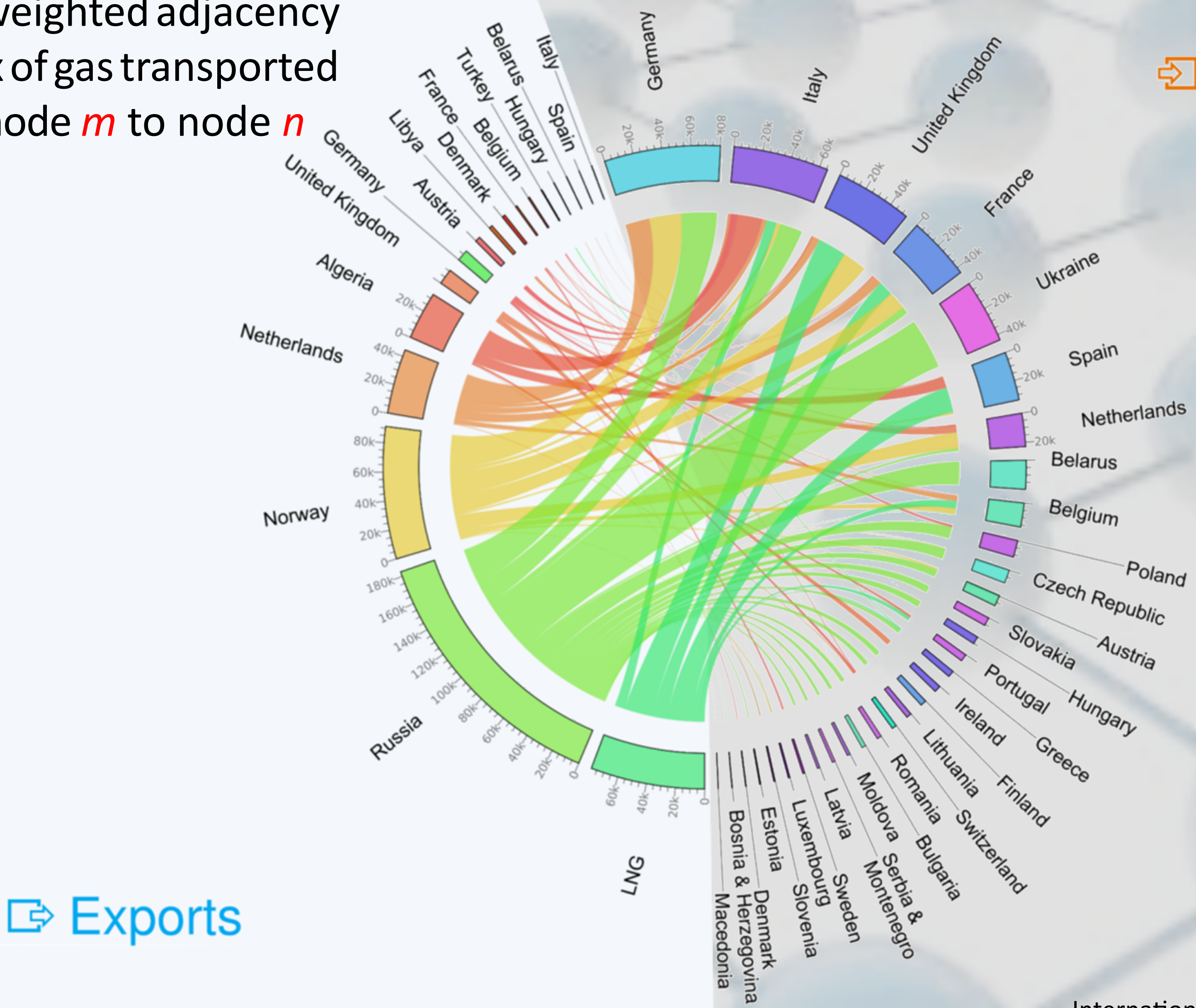
2,649 nodes
(compressor and city gate stations , LNG terminals, etc.)

3,673 edges
Pipeline segments

186,132 km
Total length

Gas trading data

T_{mn} weighted adjacency matrix of gas transported from node m to node n



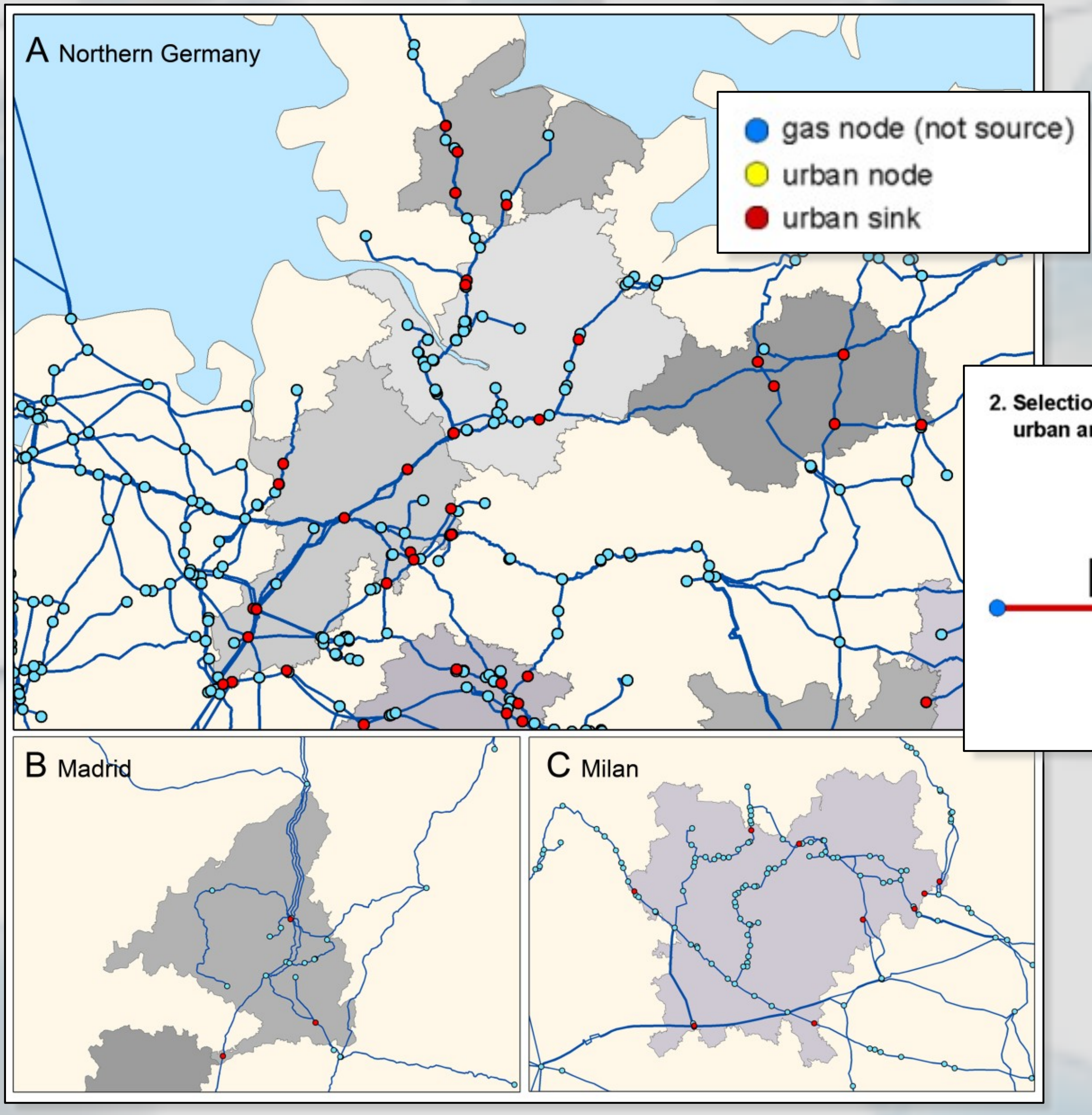
International Energy Agency, 2011

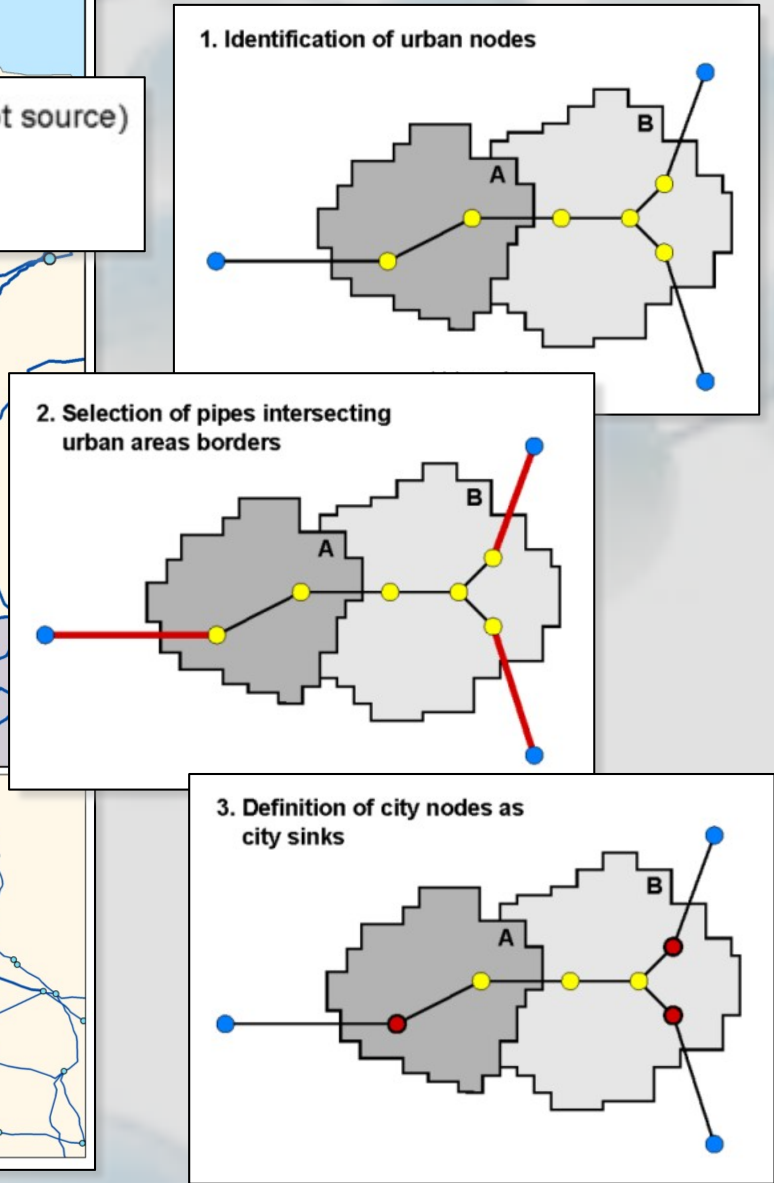
Macro routing to micro links

Problem: how to disaggregate the country level gas trade matrix to the level of network nodes?

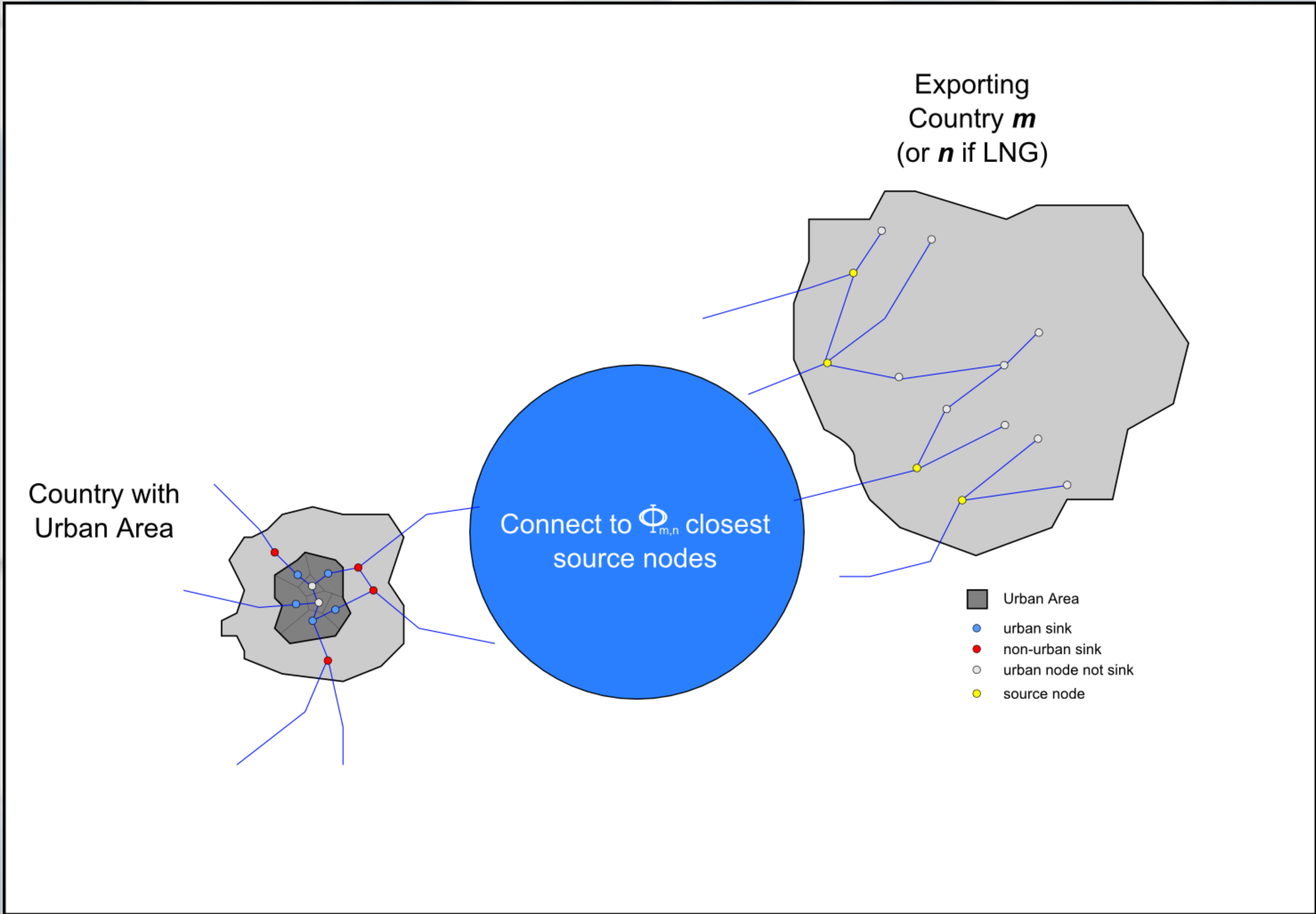
- Solution: *we need an algorithm to generate source to sink paths with an associated flow or demand*
- Observations:
  – *Assume demand proportional to population;*
  – *Shortest path routing - sometimes a poor routing choice because it can avoid routes with large capacity;*
- Structure of the algorithm:
  - *Locate sources and sinks;*
  - *Pair individual sources and sinks;*
  - *Define the demand of each source and sink pair;*
  - *Determine the source to sink paths.*

Routing (1) - Location of sink nodes





Routing (2) - How we pair source and sink nodes

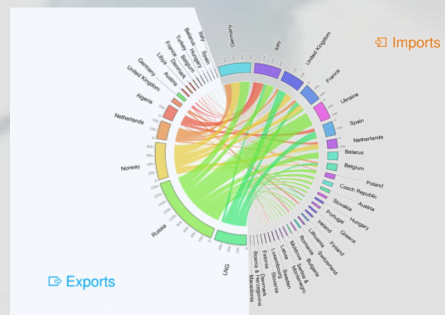


Routing (3) - how we define local demand

Demand of a geographical area: the country's demand weighted by the ratio between the population of the area and the country

Each sink node of an importing country *n is connected to* Φ_{mn} *paths from source nodes* in exporting country *m*

Each of these paths has a share of the demand T_{mn} at node *l* in country *m* given by



$$D_{mn}(l) = (Z_{nl} / z_n)\, T_{mn} / \Phi_{mn}$$

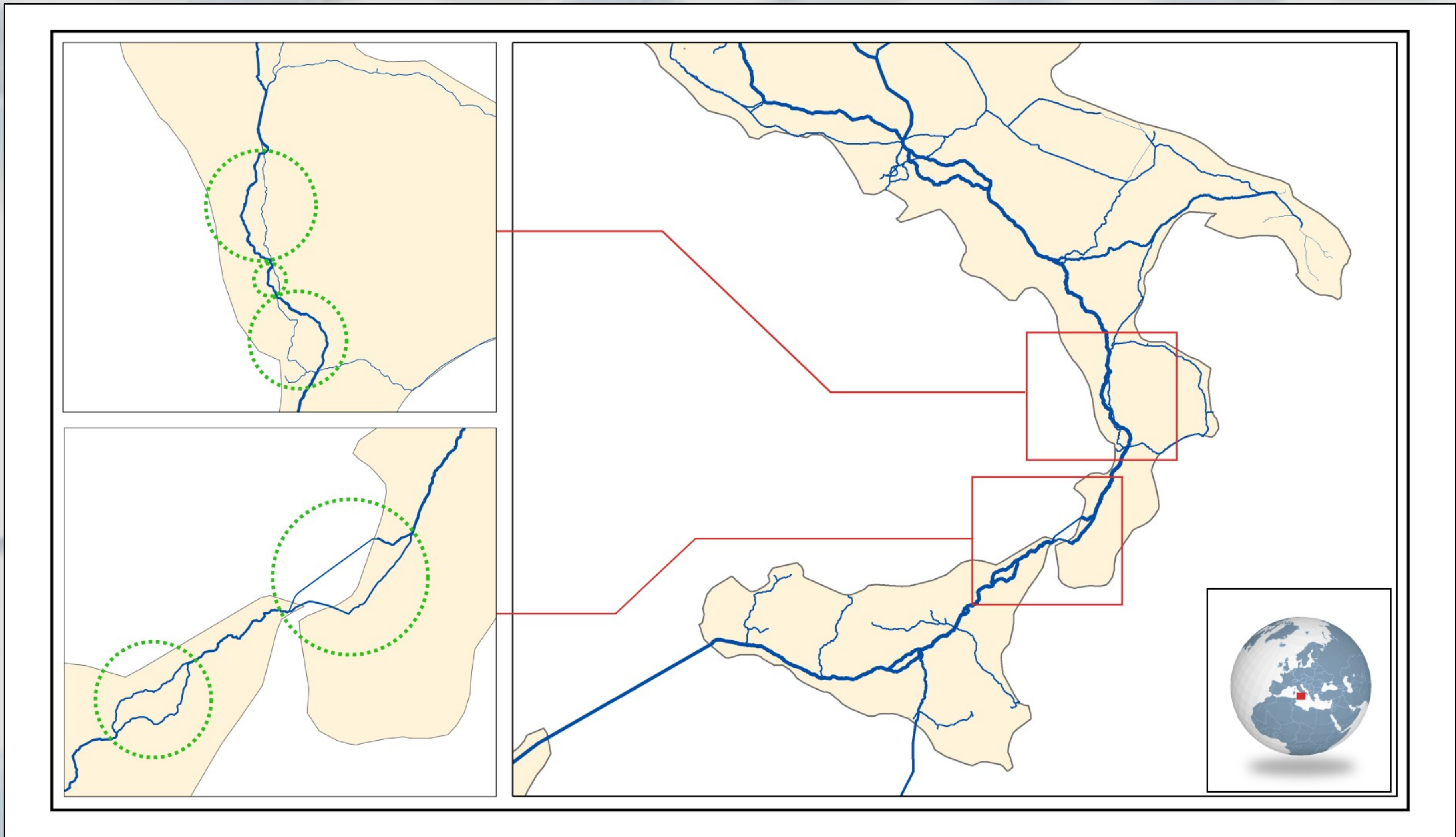
where

Z_{nl} is the population associated with sink node of importing country *n*

z_n is the population of importing country *n*

T_{mn} is the volume of gas transferred from country *m to country n*

Routing(4) – the problem with shortest path



How to determine source and sink paths

slice of capacity cake if we would reroute one path to edge i:

$$h_i = c_i / (1 + b_i)$$

Effective link length

$$\widetilde{l_i} = \left(\frac{\langle h_i \rangle}{h_i} \right)^{\alpha} l_i .$$

Heuristic rerouting

- Go through each source to sink route and find a new path j connecting the two nodes. Compute the path length $\overleftrightarrow{l_j} = \sum_{i \in \text{path j}} \widetilde{l_i}$;
- If $\overleftrightarrow{l_j}$ is lower than the previously found path, then it repalces the existing source to sink path;
- Recompute the weights $\widetilde{l_i}$ for all paths, and repeat the procedure for all paths until it has been executed 20 times.

Congestion control proportional fairness

Definition 1. A vector of path flows $f^* = (f_1^*, \ldots, f_\rho^*)$ is *proportionally fair* if it is feasible and if for any other feasible vector of path flows f, the sum of proportional changes in the path flows is non-positive:

$$\sum_{j=1}^{\rho} \frac{f_j - f_j^*}{f_j^*} \leqslant 0.$$

- A flow is proportionally fair if, to increase a path flow by a percentage ε, we have to decrease a set of other path flows, such that the sum of the percentage decreases is larger or equal to ε.
- Idea behind proportional fairness: **use pricing on the links to control congestion**.
- We view the network as an optimizer and the proportional fairness policy as a distributed solution to a global optimization problem.

Congestion control: The Primal problem

Proposition 1. *The unique set of feasible paths flows that maximizes the function* $U(f) = \sum_{j=1}^{\rho} \log(f_j)$ *is proportionally fair.*

To find the proportional fair allocation, we need to maximize $U(f)$, constrained to the vector of path flows being feasible:

$$\begin{aligned} \underset{f}{\text{maximize}} \quad & U(f) = \sum_{j=1}^{\rho} \log(f_j) \\ \text{subject to} \quad & Bf \leq c \\ & f_j \geq 0, \end{aligned}$$

The aggregate utility $U(f)$ is concave and the inequality constraints are convex. Hence the optimization problem is convex. Thus, any locally optimal point is also a global optimum.

Control algorithm

A primal algorithm

$$\frac{d}{dt} f_j(t) = 1 - f_j(t) \sum_{i=1}^{\eta} B_{ij} \mu_i(t),$$

where

$$\mu_i(t) = p_i \left(\sum_{j=1}^{\rho} B_{ij} f_j(t) \right)$$

$$p_i(y) = \frac{\max(0, y - c_i + \epsilon)}{\epsilon^2}$$

Congestion Control: Decentralized Dual Algorithm

A **dual algorithm**: consider a system where the shadow prices vary gradually as a function of the path flows:

$$\frac{d}{dt}\mu_i(t) = \sum_{j=1}^{\rho} B_{ij} f_j(t) - q_i(\mu_i(t)),$$

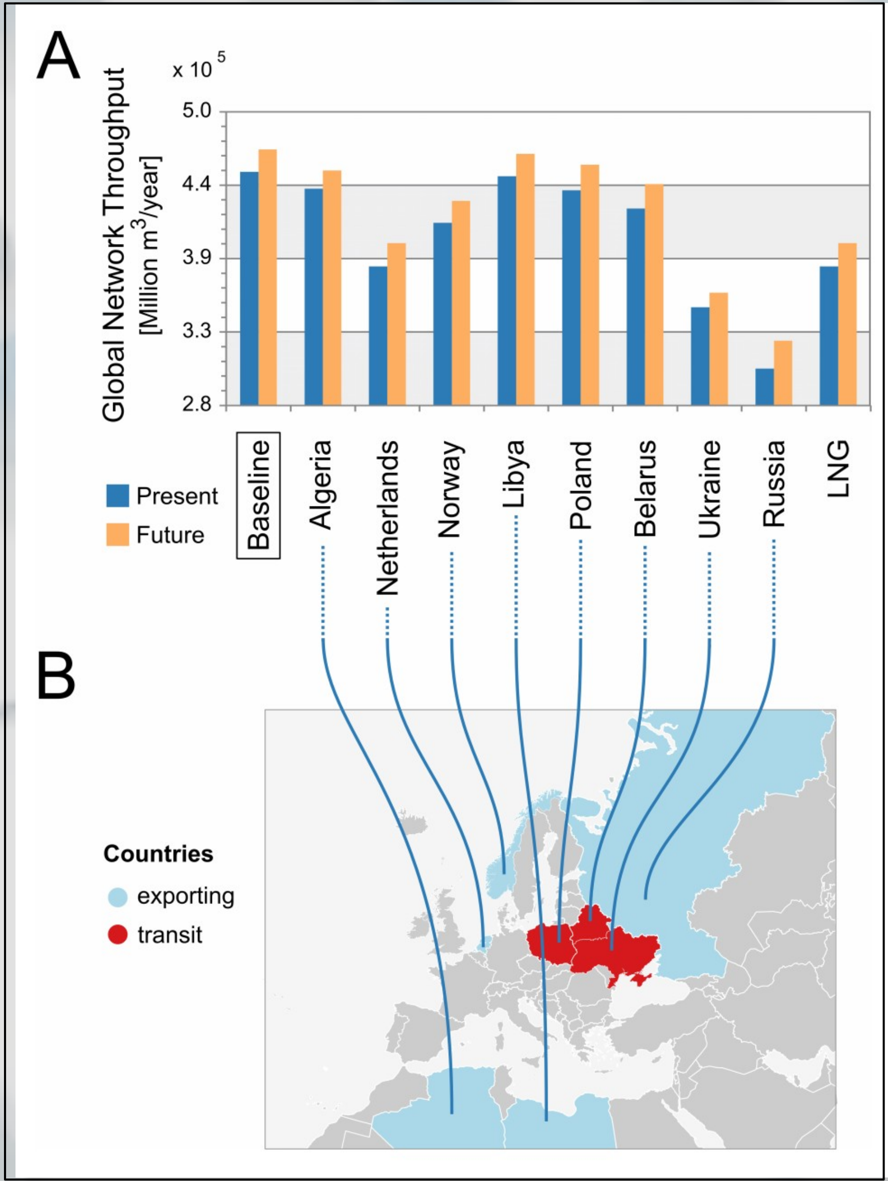
where

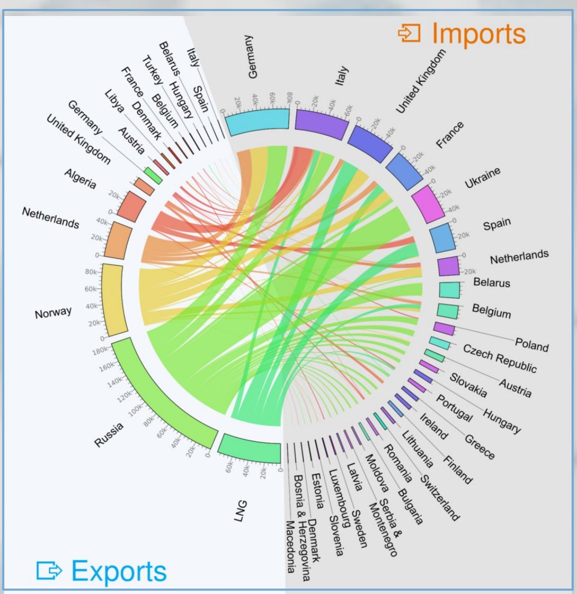
$$f_j(t) = \frac{1}{\sum_{i=1}^{\eta} B_{ij}\mu_i(t)},$$

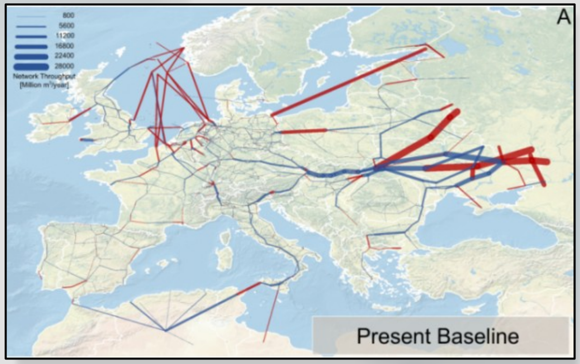
and $q(\cdot)$ is the inverse of $p(\cdot)$. As $\epsilon \to 0$, the dual and primal algorithms become equivalent.

F. P. Kelly, A. K. Maulloo, and D. K. H. Tan, "Rate control for communication networks: shadow prices, proportional fairness and stability," *J. Oper. Res. Soc.*, vol. 49, no. 3, pp. 237–252, 1998.

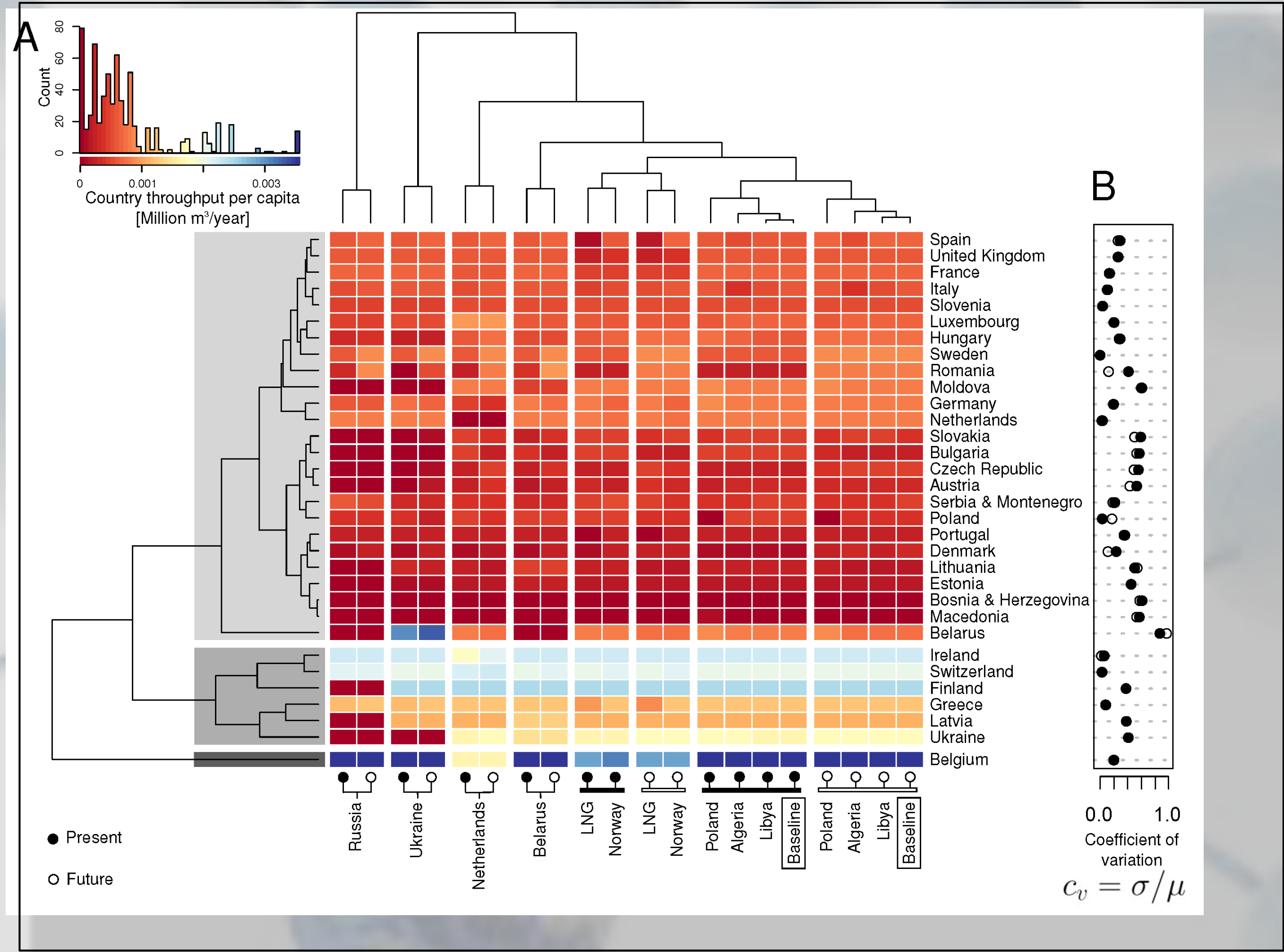
Global network throughput by scenario





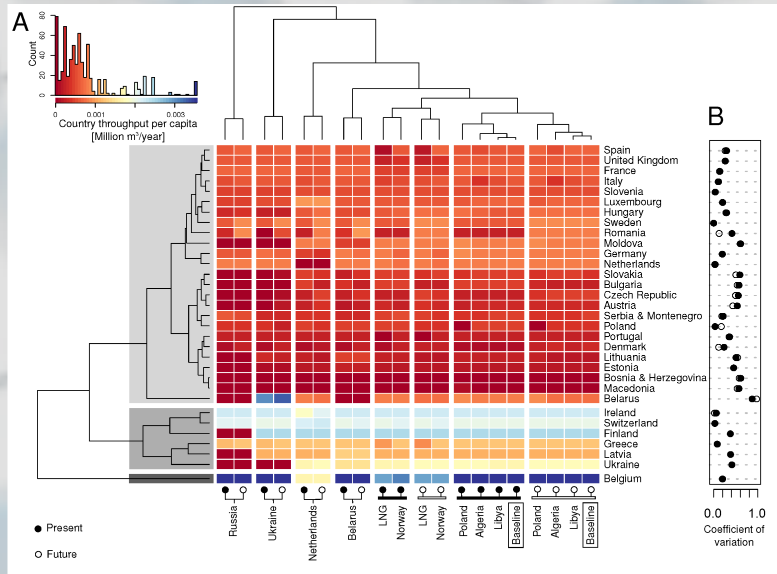


Resilience at country and network levels



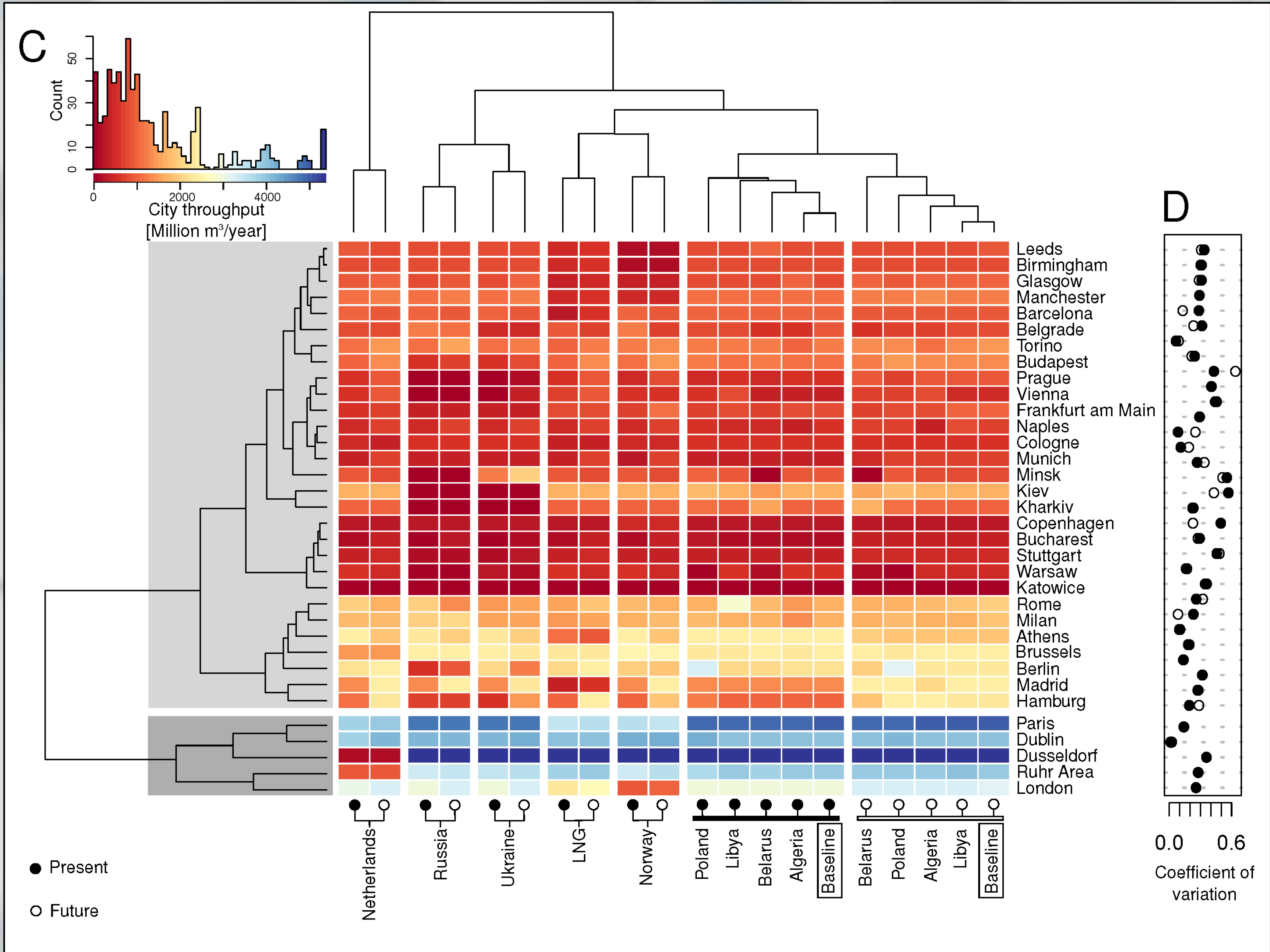
- **A country is resilient to crises** if it combines **high throughput** per capita across scenarios with a **low coefficient of variation of throughput**.
- **The network is resilient to a scenario** if the **vectors of country throughput per capita for the scenario and the baseline scenario are similar**.

Interpreting the heat map



- Coefficient of variation is large for countries in Eastern Europe;
- Countries belong to the high throughput per capita groups (dark grey) due to diversity of supply and good access to network capacity (strategic geographical location);
- Unexpected spill over effect from countries like Germany that make large investments in infrastructure:
  - these countries provide routes for neighbouring countries to access the network;
  - they benefit less from the investments than their smaller neighbours.

Resilience at the level of urban areas



Hypothetical crisis with Russia

- Two groups of countries:

– Group I (heavily dependent on Russia): eastern Europe, Estonia, Finland, Greece, Latvia and Lithuania;

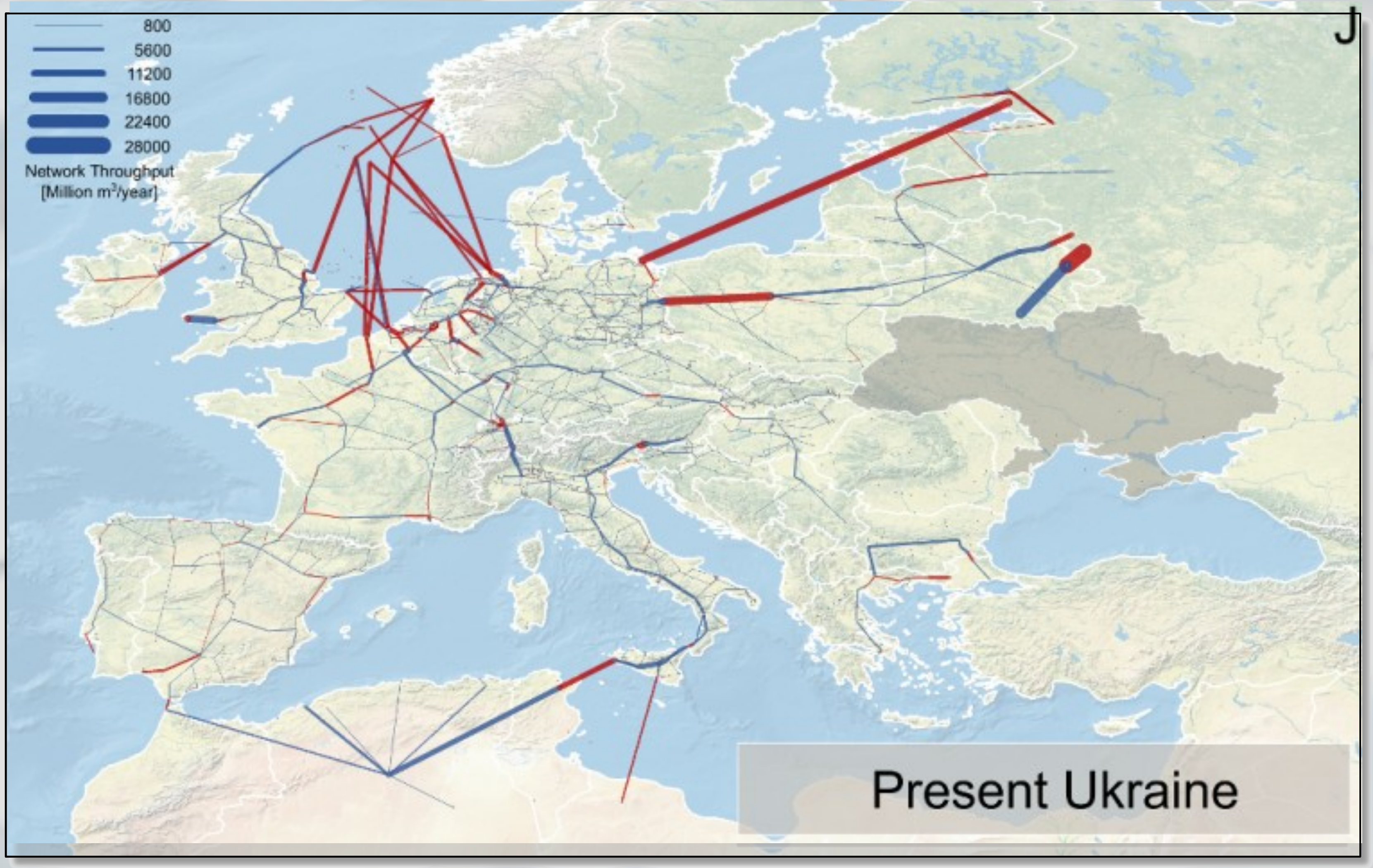
– Group II: all other countries

- New scenario: Russia removed from the network and demand of group I is rerouted to Norway and the Netherlands;

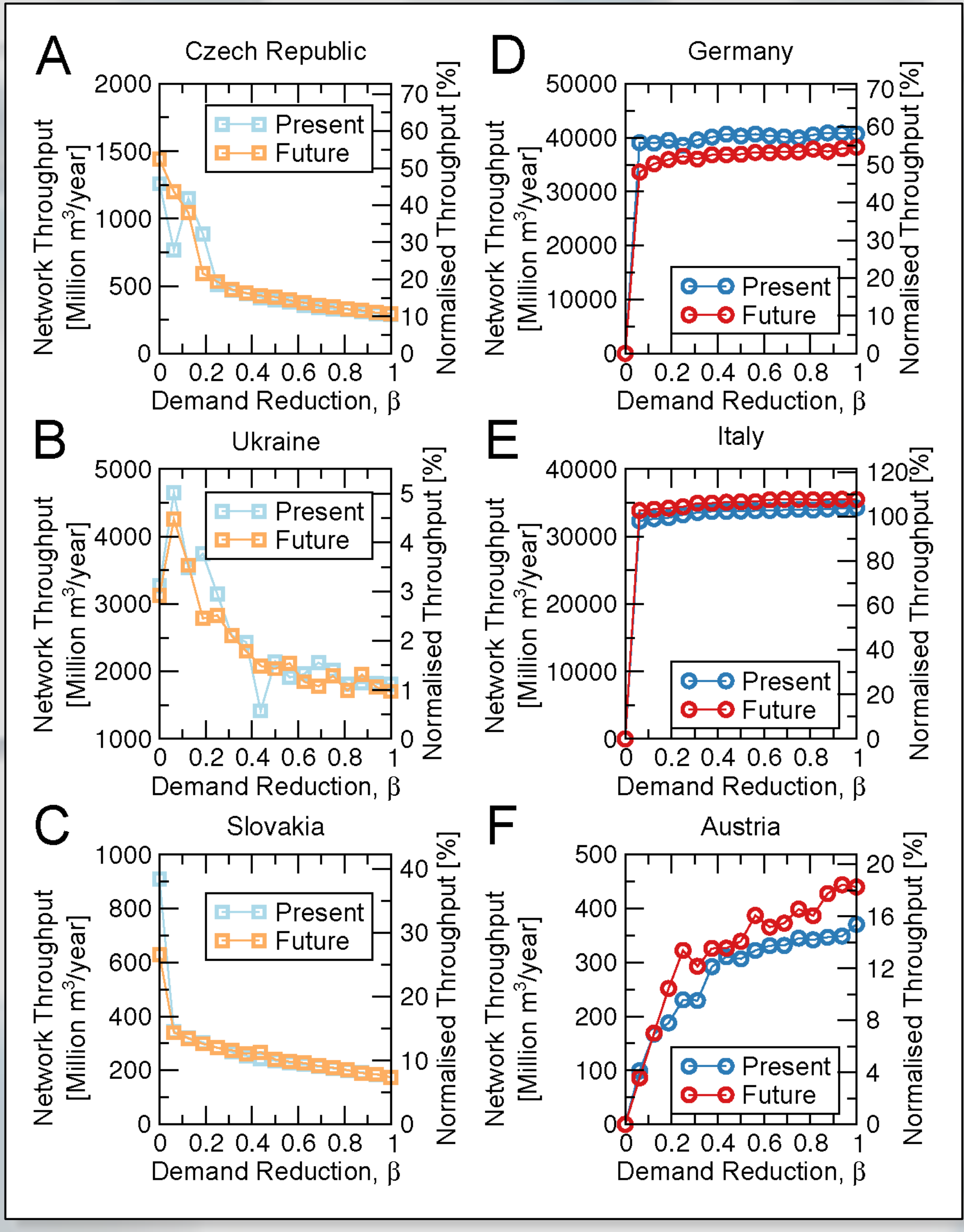
- New flow matrix found by relocating flow from Russia for group I countries to the Netherlands and Norway, proportionally to the production of these exporting countries;

- We apply a prefactor $0 \leq \beta \leq 1$ to the values of demand of countries in group II.

Present scenarios



Mitigating effects of the crisis



We can hope to recover:

- between 40-50% of the baseline throughput for the Czech Republic and 15-40% forSlovakia;
- up to 5% for Ukraine (at very reduced overall demand)
- Access to capacity of large group II (e.g. Germany, Italy) is broadly unaffected (group I countries use little of this capacity);
- Austria now becomes a transit country, its throughput decreases as it shares its capacity with group I.

Current and future challenges

The energy networks are pan-European, even intercontinental,

Efficient energy exchange between countries is vital .

Need more investigation of energy networks with real world and useful conclusions

Variety of mathematical approaches needed to validate robustness of results before they have practical use at the economic-political level

Vulnerability

- Structural (catastrophic failure of network components)
- Functional (electricity/gas supplies)

Interconnected data sets and multi-layer networks

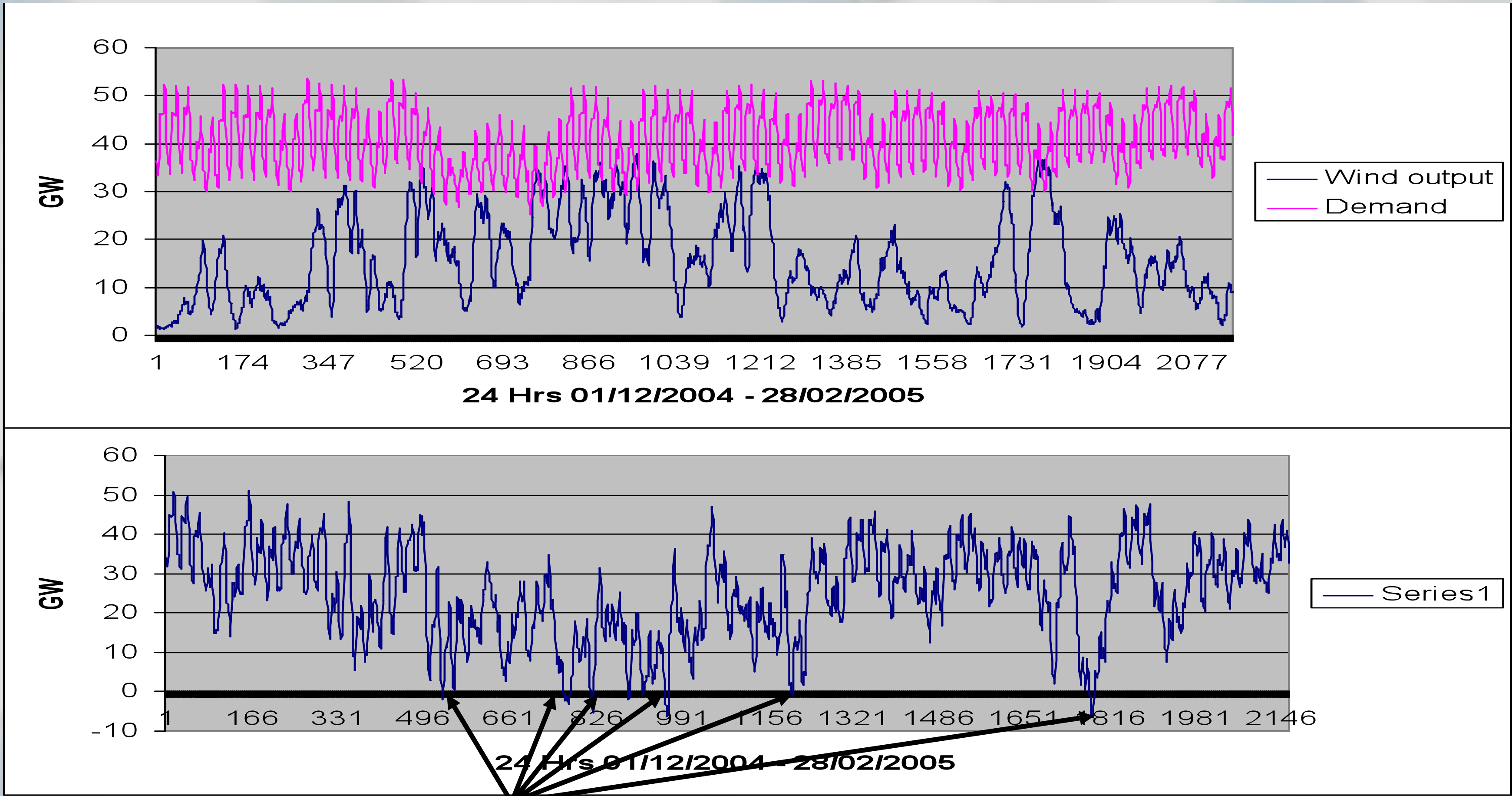
- strategy for resilience of gas, electricity and communications networks as an interconnected structure

Renewables

Moving to renewable sources of energy in a robust way

Intermittency of supply – the problem

3 month period modelled using 2005 demand data and projected 2030 levels of wind

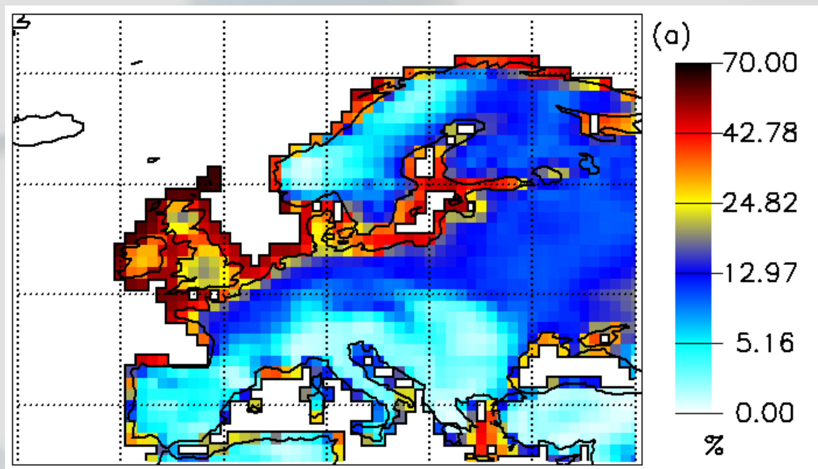


Generation greater than demand!

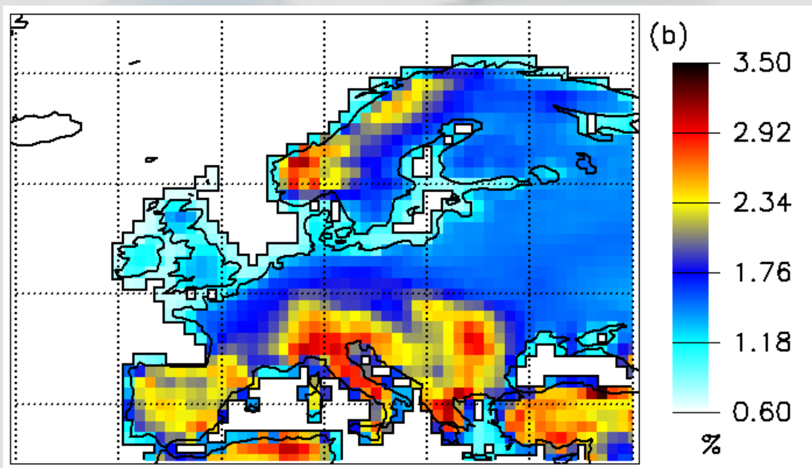
Wind power – geographical distribution

Wind data – clear implications at the political level

(pan European investment)



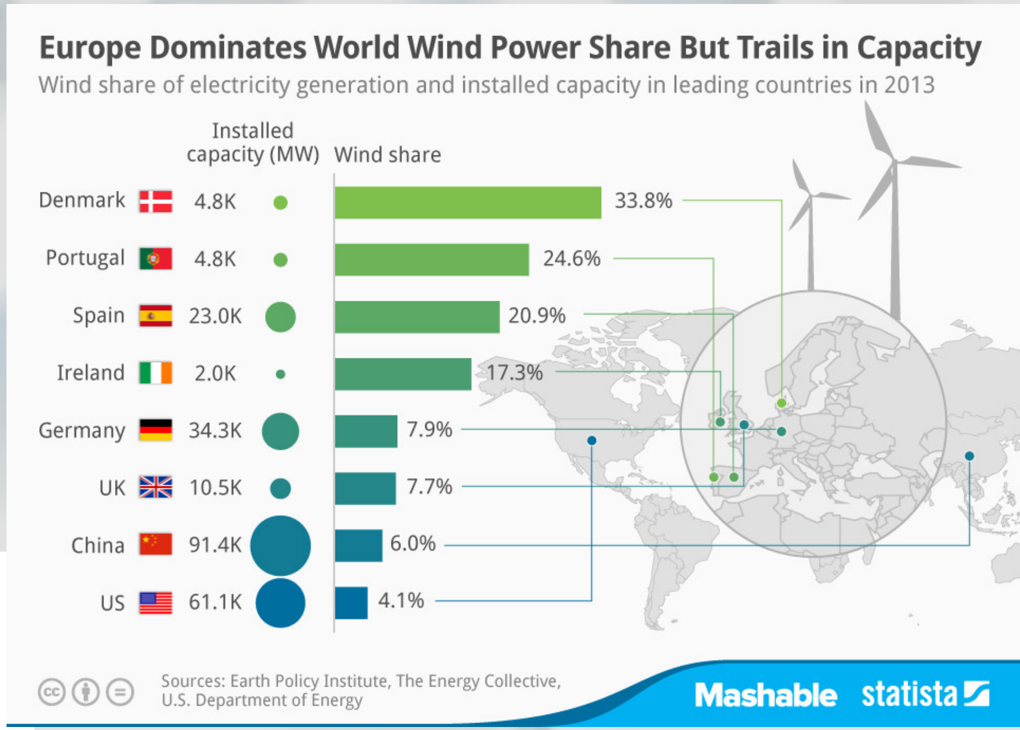
Average wind speed

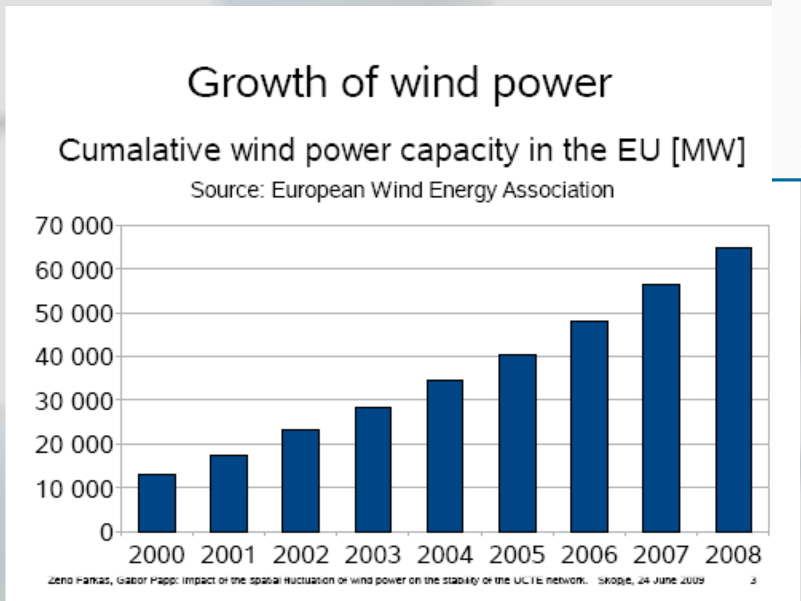


Variance of wind speed

Wind energy data 2008 and 2013

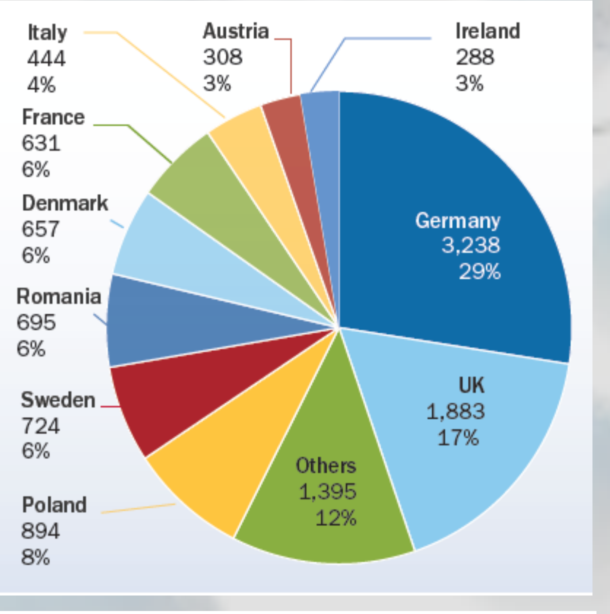
Increasing wind power capacity in the EU [MW]

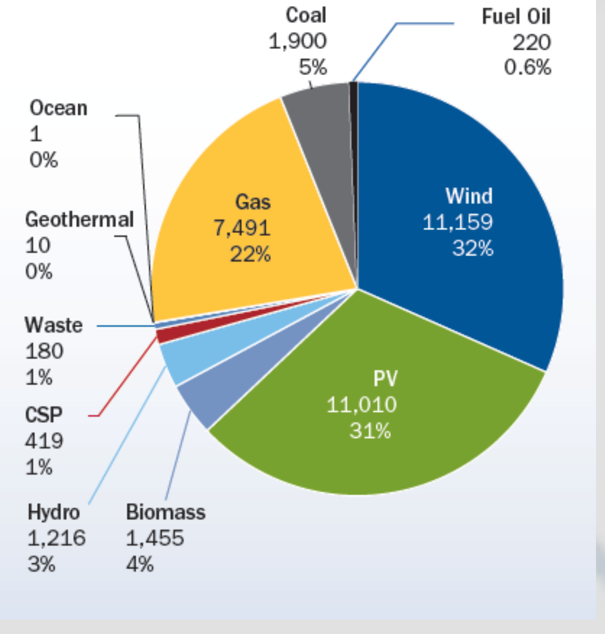


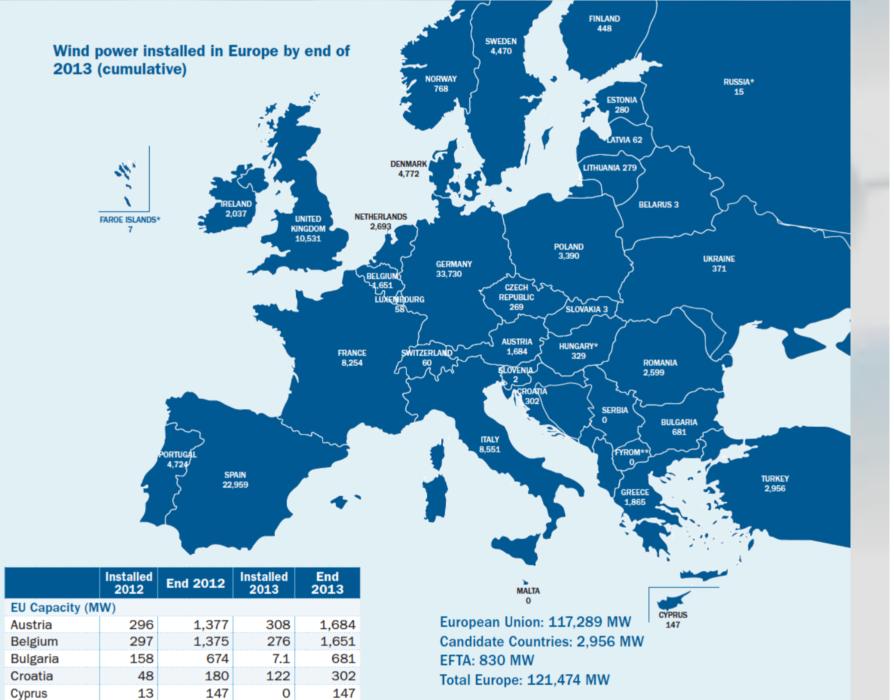


Renewable data (EWEA Feb 2014)

New capacity by (i) country (ii) type (2013)





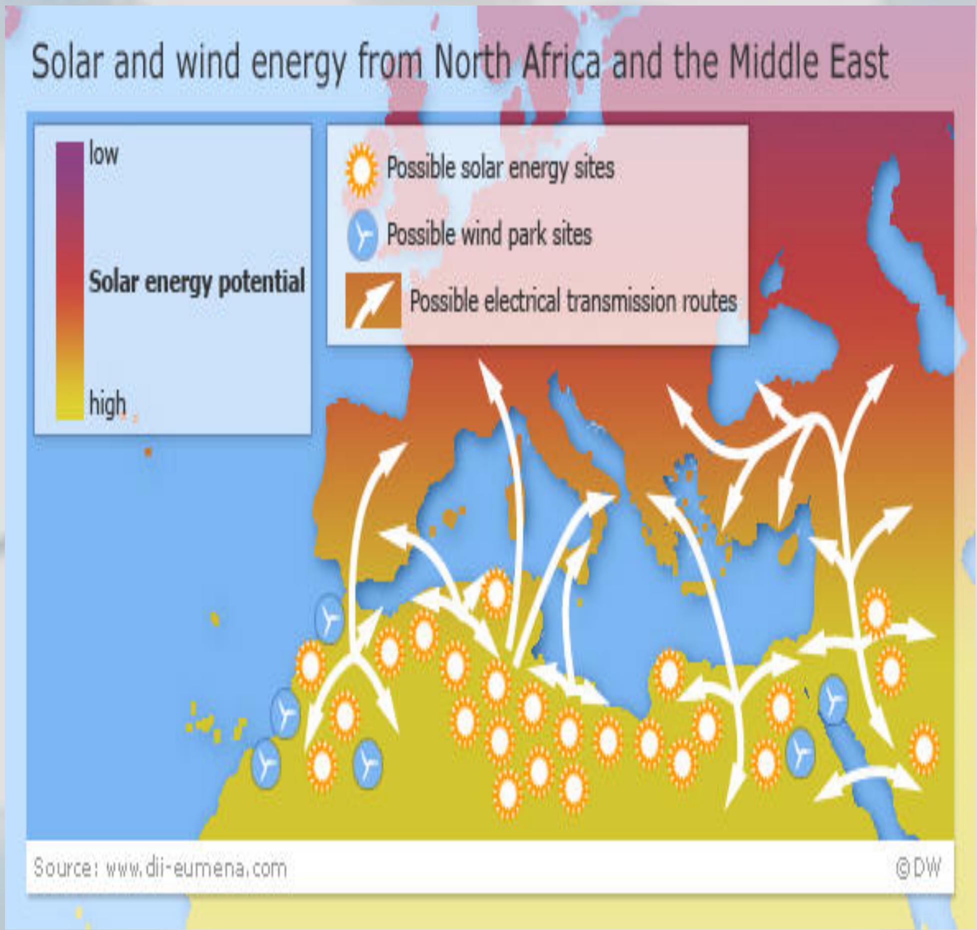


	Installed 2012	End 2012	Installed 2013	End 2013
EU Capacity (MW)				
Austria	296	1,377	308	1,684
Belgium	297	1,375	276	1,651
Bulgaria	158	674	7.1	681
Croatia	48	180	122	302
Cyprus	13	147	0	147
Czech Republic	44	260	9	269
Denmark	220	4,162	657	4,772
Estonia	86	269	11	280
Finland	89	288	162	448
France	814	7,623	631	8,254
Germany	2,297	30,989	3,238	33,730
Greece	117	1,749	116	1,865
Hungary*	0	329	0	329
Ireland	121	1,749	288	2,037
Italy	1,239	8,118	444	8,551
Latvia	12	60	2	62
Lithuania	60	263	16	279
Luxembourg	14	58	0	58
Malta	0	0	0	0
Netherlands	119	2,391	303	2,693
Poland	880	2,496	894	3,390
Portugal	155	4,529	196	4,724
Romania	923	1,905	695	2,599
Slovakia	0	3	0	3
Slovenia	0	0	2	2
Spain	1,110	22,784	175	22,959
Sweden	846	3,582	724	4,470
United Kingdom	2,064	8,649	1,883	10,531
Total EU-28	**12,102**	**106,454**	**11,159**	**117,289**
Total EU-15	**9,879**	**99,868**	**9,402**	**108,946**
Total EU-13	**2,224**	**6,586**	**1,757**	**8,343**

	Installed 2012	End 2012	Installed 2013	End 2013
Candidate Countries (MW)				
FYROM**	0	0	0	0
Serbia	0	0	0	0
Turkey	506	2,312	646	2,956
Total	**506**	**2,312**	**646**	**2,956**
EFTA (MW)				
Iceland	0	0	1,8	1,8
Liechtenstein	0	0	0	0
Norway	166	703	110	768
Switzerland	4	50	13	60
Total	**170**	**753**	**125**	**830**
Other (MW)				
Belarus	0	3	0	3
Faroe Islands	2	2	5	7
Ukraine	125	276	95	371
Russia*	0	15	0	15
Total	**127**	**297**	**100**	**397**
Total Europe	**12,906**	**109,816**	**12,030**	**121,474**

* Provisional data or estimate.
** Former Yugoslav Republic of Macedonia
Note: due to previous year adjustments, 372 MW of project de-commissioning, re-powering and rounding of figures, the total 2013 end-of-year cumulative capacity is not exactly equivalent to the sum of the 2012 end-of-year total plus the 2013 additions.

Future Add-in - Solar energy
PV(photo-voltaic) and CSP(Concentrated solar power)

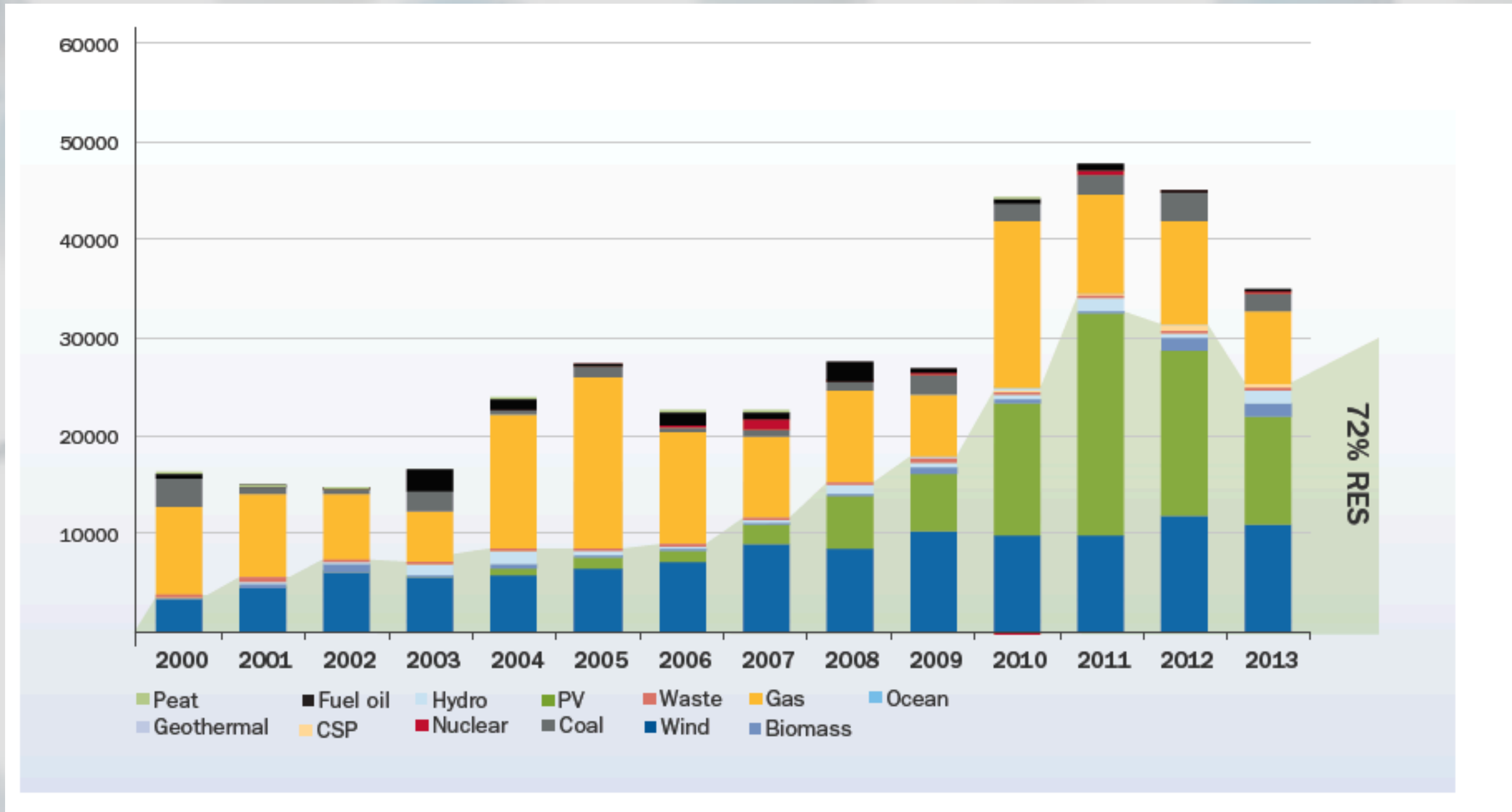


Initiatives(?)

MEDGRID is promoting new high capacity electricity links around the Mediterranean.

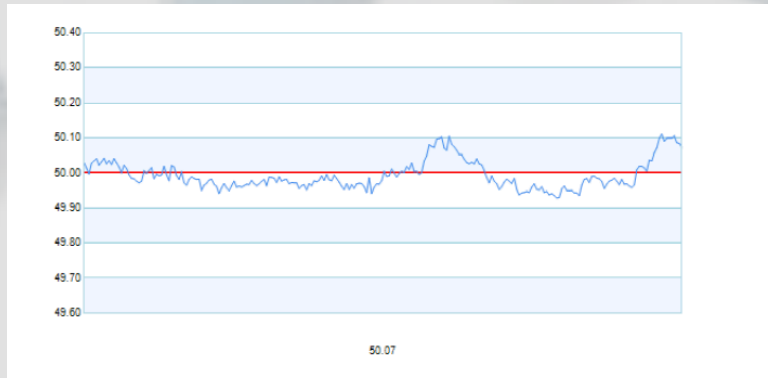
DESERTEC and **EUMEDGRID** are complementary and mutually reinforcing, the first focusing on energy generation and the second on energy transmission.

Installed power generating capacity per year in MW and renewable energy share (EWEA Feb 2014)



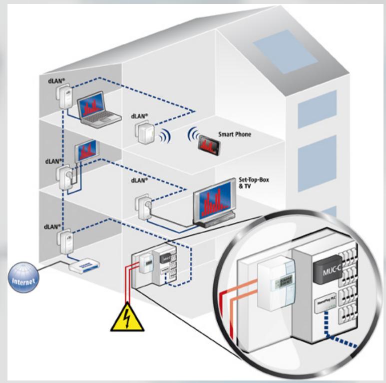
Balancing the grid

- Electrical network has AC distributed from power stations via a NATIONAL GRID to homes, offices and industry
- Frequency has to be maintained close to 50 cps
- One hour of frequency data for the UK national grid 12/08/2015



- Requires fine balance between production of electricity and its consumption otherwise **BLACKOUTS**
- Some countries live with daily programmed blackouts, but seen as crisis in the UK
- Conventional power stations able to deliver the balance around 50cps most of the time (+/- = 1 %)

SMARTGRID network control



Ability of the grid to run an increasingly complex and diverse network with balanced supply – demand of electricity which embraces renewables and local generation

Keeping the balance between supply and demand
-at a time of unprecedented change in supply

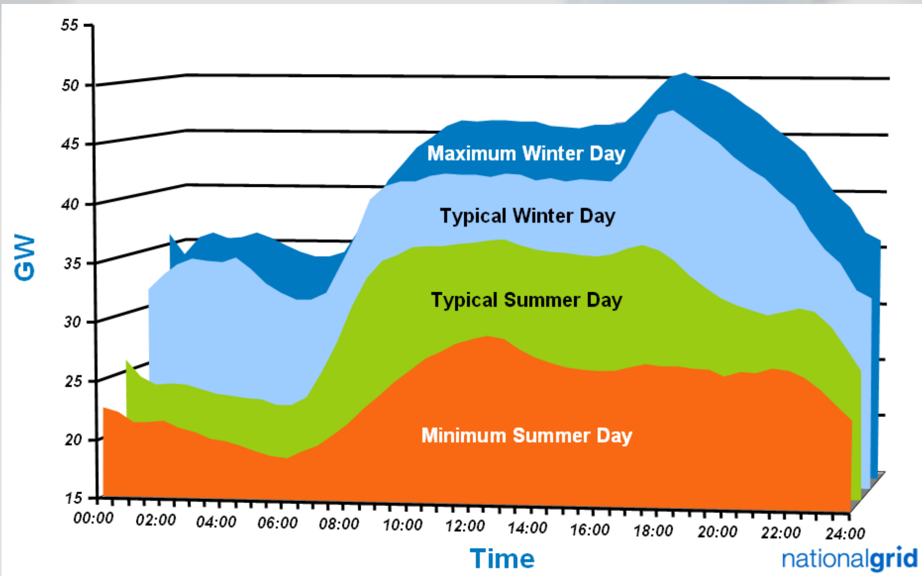
Power networks and the customer - *techno-social issues*

- Influence in social networks for change of customer behaviour
- Curtailing consumption at peak periods using SMART METERING
- Fixed demand side pricing vs. variable market pricing on supply side

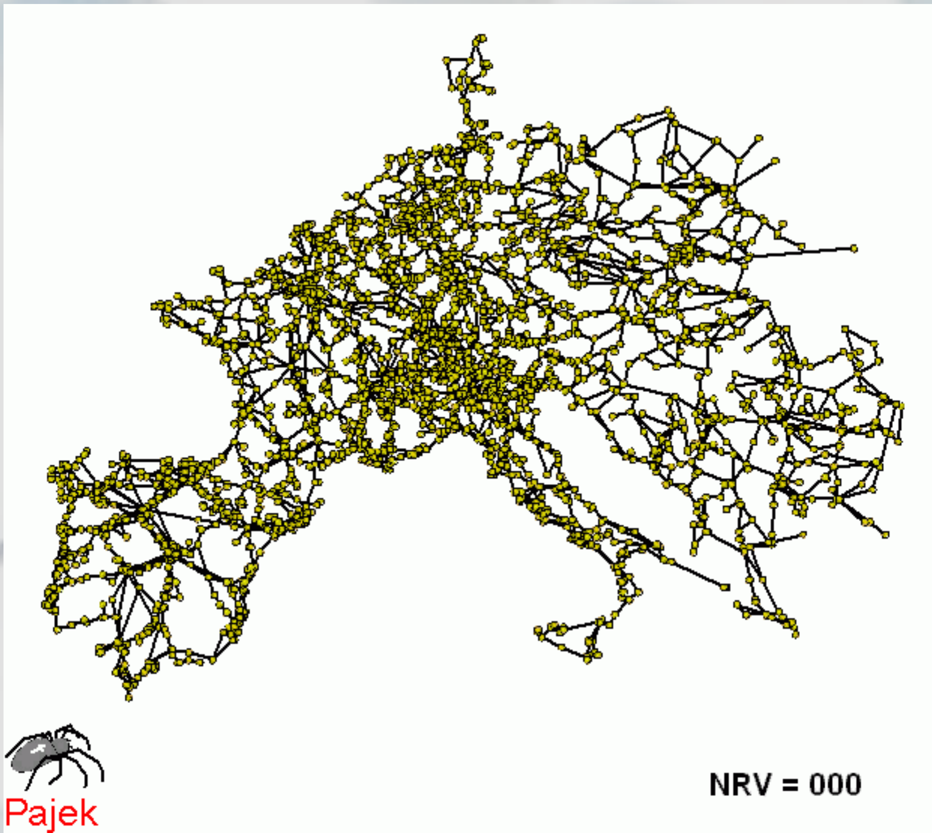
Control mechanisms

- Use smart metering to curtail customer usage at peak periods particularly in winter months
- the use of smart appliances agreements to remotely shape the power consumption profile (switching off fridges, washing machines)
- Demand side singular pricing
  – paying more for uninterrupted domestic supply

Problem that first generation smart meters in the UK will be passive – they will not be externally controllable - we need to look beyond this stage to smart metering which is fully interactive



Decay of network by betweenness centrality

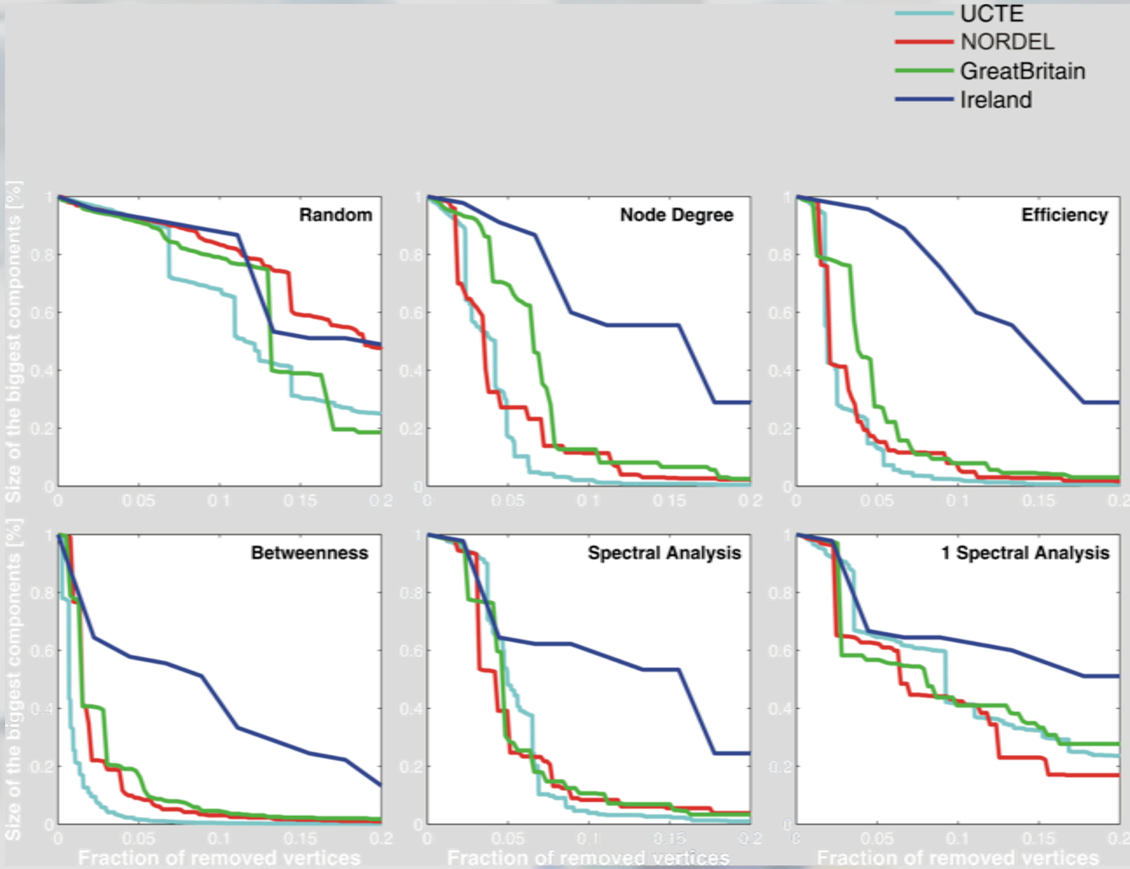


Rate of decay is dependent on the selection criteria

BETWEENNESS CENTRALITY

NRV – number of removed vertices

Measuring the consequences



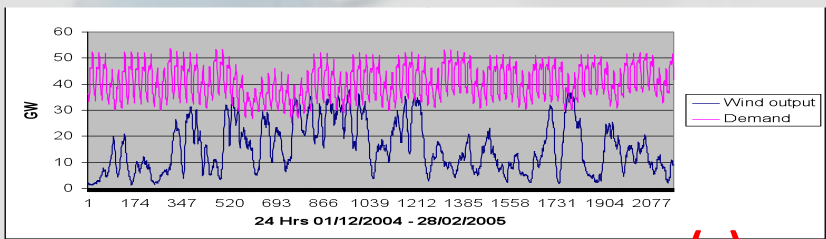
Size of largest connected component decreases most rapidly for betweenness centrality

By this measure of connected component size, the most effective targeted attack is BETWEENNESS

Mathematical challenge of the smart grid

- Modelling of the distribution grid
  - stochastic nature of renewable inputs
  - aggregate customer energy demand and use of singular demand side pricing
  - risk analysis

Resolving (a) while having to retain (b)!



(a)

Political-social aspects for the modelling

Absence of likely well-balanced supply and demand of electricity ,

- government shutdown of large industrial plant as a first move if

- will be reluctance to introduce any counter-demand pricing which might be viewed as harming certain sections of the population

STORAGE of ENERGY is the solution to all our problems!

Storage !

Is a major engineering problem – but also a network issue

Networks

- The likelihood of MEDGRID solar power in North Africa has reduced
- POOR capacity of network connections at international level vs. the resilience of more developed national infrastructures is a storage issue
- Islanding techniques for the future – controlled blackouts

Remarks

- Real world analysis of infrastructure is
  - detailed, data driven, incomplete network information
  - fundamentals assumptions can change (e.g. future security of solar PV supply from the Sahara)
- Congestion control methods might mitigate the effect of crises in gas pipeline networks.
- Other mathematical approaches need to be considered to model these problems to find robust methods of analysis and decision making.
- Fair sharing is a potential procedure for supply to countries during crisis in the European gas grid
- Other countries need to accept a reduction in demand.
- Good mathematical problems around the switch to future renewables supply and the stochastic risk element that needs to be addressed.