Resilience of natural gas networks during conflicts, crises and disruptions

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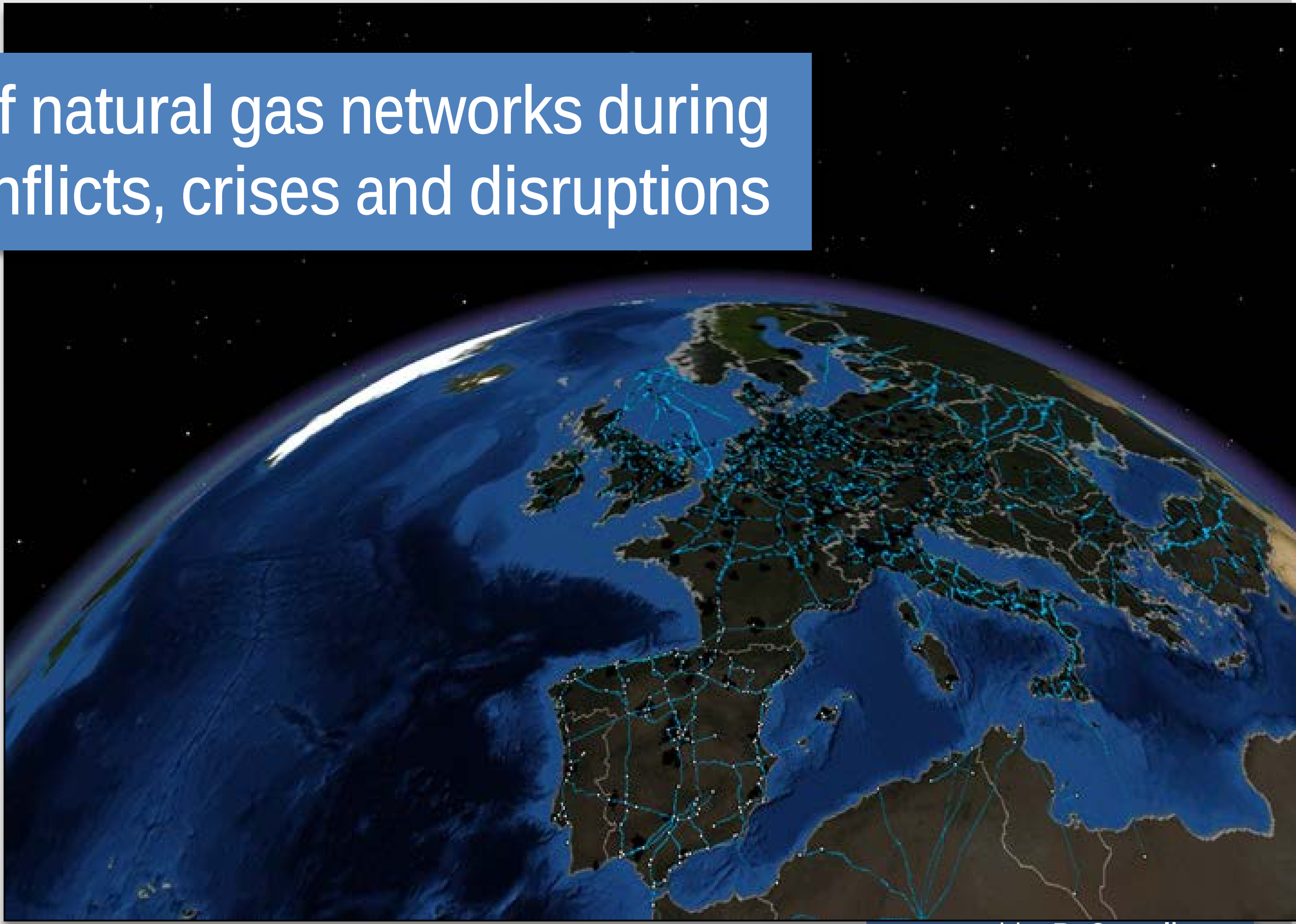

presented by R. Carvalho
at the Open University
April 4, 2014

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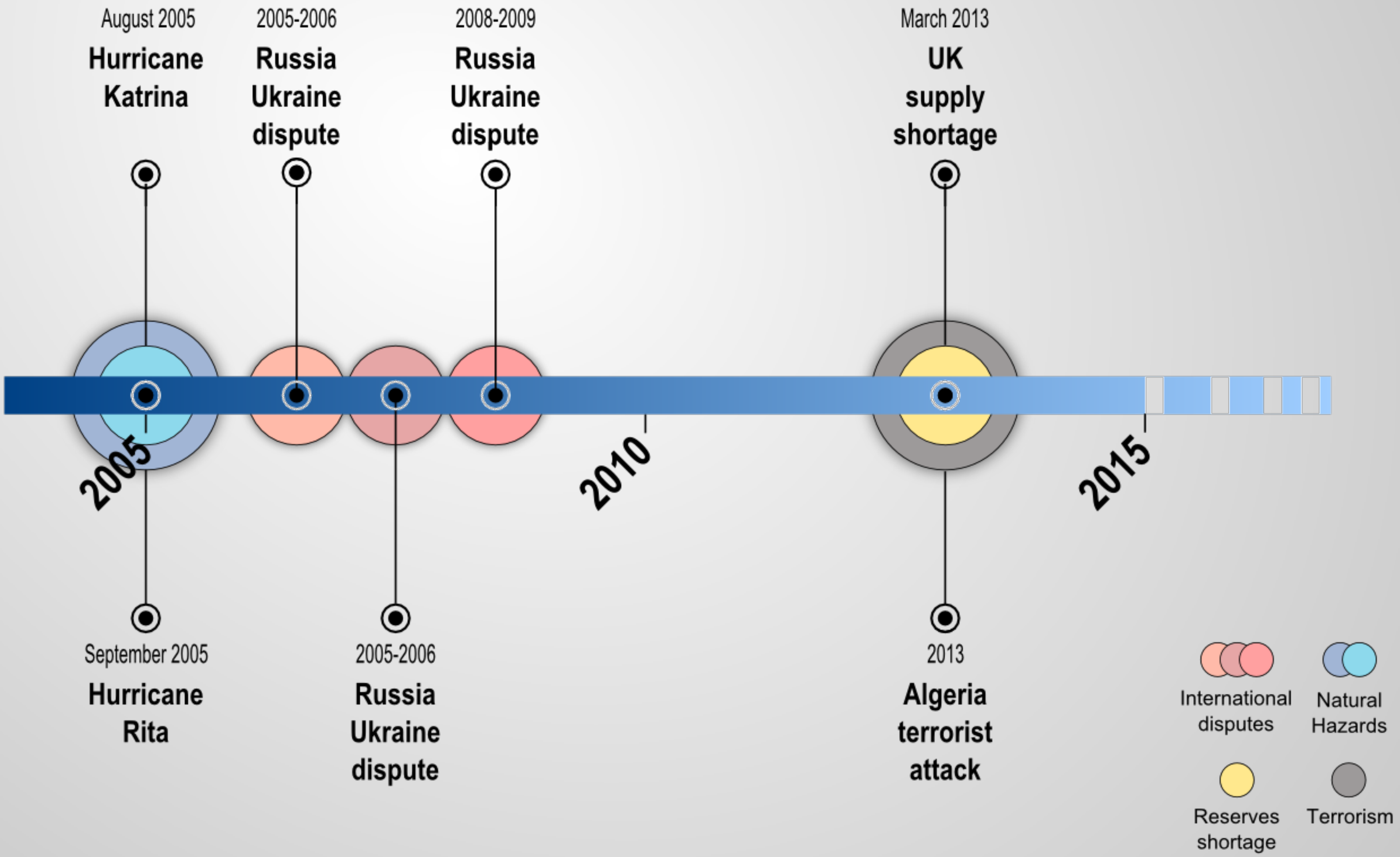
The looming energy security crises

History has taught us that the threats to the security of supply come in unexpected ways



Why do we need a method to handle congestion?

- In a crisis, less delivery may mean greater congestion.
- This is due to the breakdown of major transit routes or production losses in affected areas, which cause the supply network to be used in different ways from what it was designed for.
- Hence, the available resources cannot be distributed well with the remaining transport capacities. This is why we need a method to handle congestion.

A control panel for networks?

- So far, most research has focused on characterising complex networks,
- but researchers think they may be closer to getting networks to *“do something”*.
- 20 years ago mathematicians, physicists and control theorists locked horns over the study of chaos.
- Today, collaboration is becoming common place.

Scientific Link-Up Yields ‘Control Panel’ for Networks, Science **332**, 777 (2011)

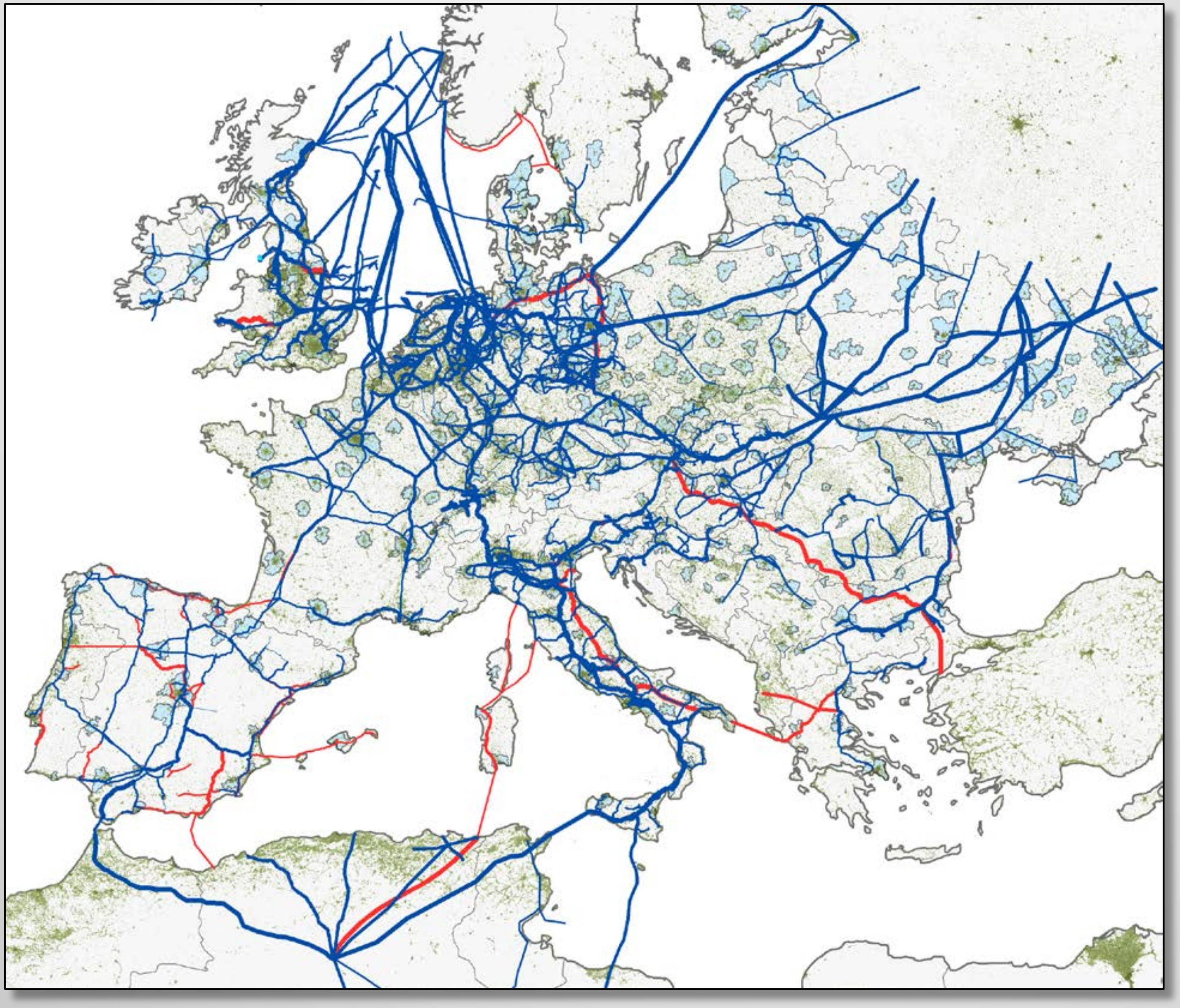
Degrees of control, Nature **473**, 158 (2011)

What to expect from this talk

- We analyse the **throughput** of the *present* and *planned* pipeline networks across a range of different crisis scenarios at European, country and urban levels.
- The **most challenging scenario** corresponds to a hypothetical crisis with Russia with a complete cut-off of supply to Europe.
- We analyse **how to alleviate the impact** of such scenarios, by the identification of country groups with similar interests, which should cooperate closely to manage congestion on the network.
- This acknowledges that many of the 21 century challenges, such as the management of energy grids and infrastructure networks, **cannot be solved by technology alone**, but do have a relevant behavioural or social component.

Methodology

Data: the European gas network



2,649 nodes

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

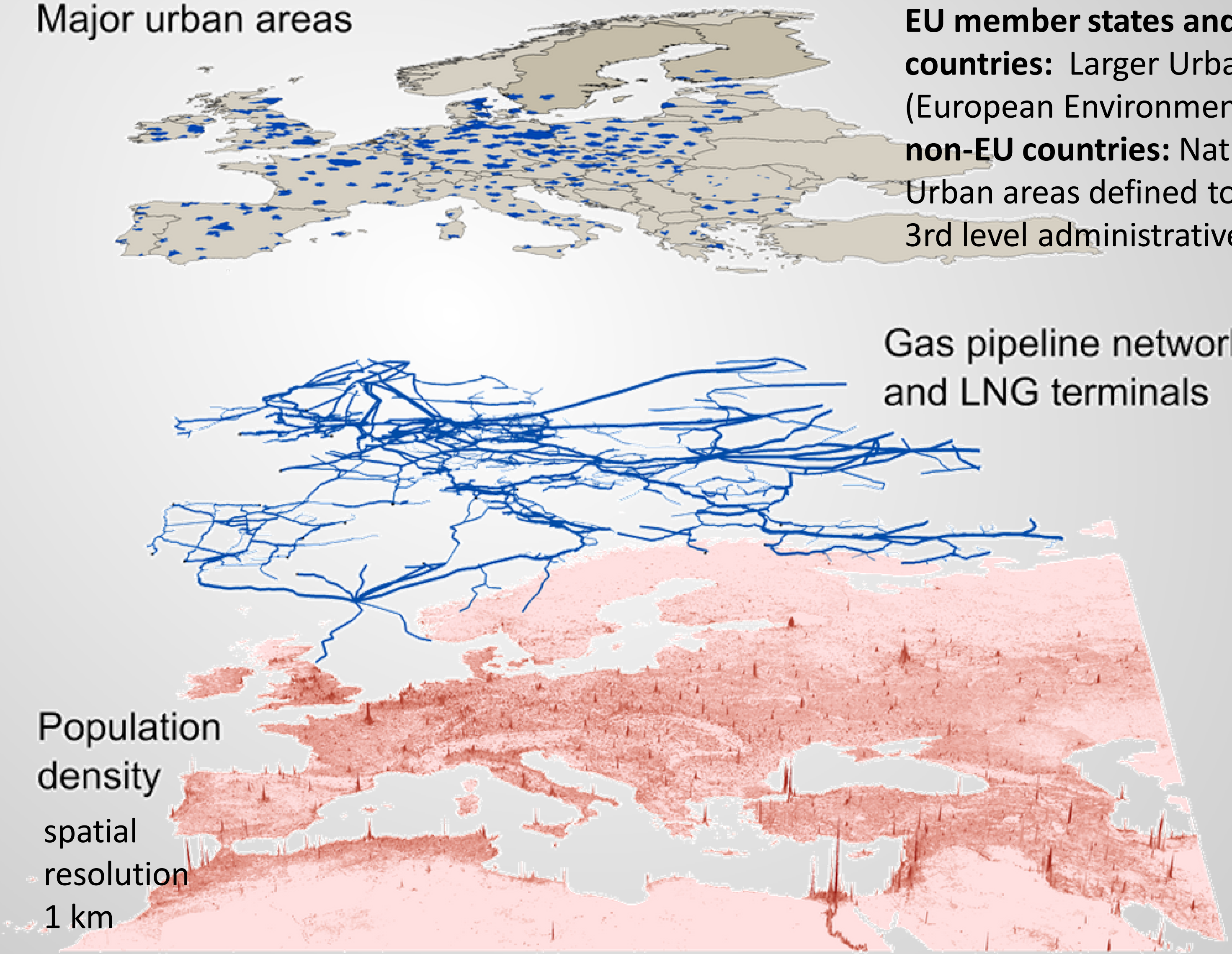
3,673 edges

Pipeline segments

186,132 Km

total length

Data: spatial data layers involved in the analysis

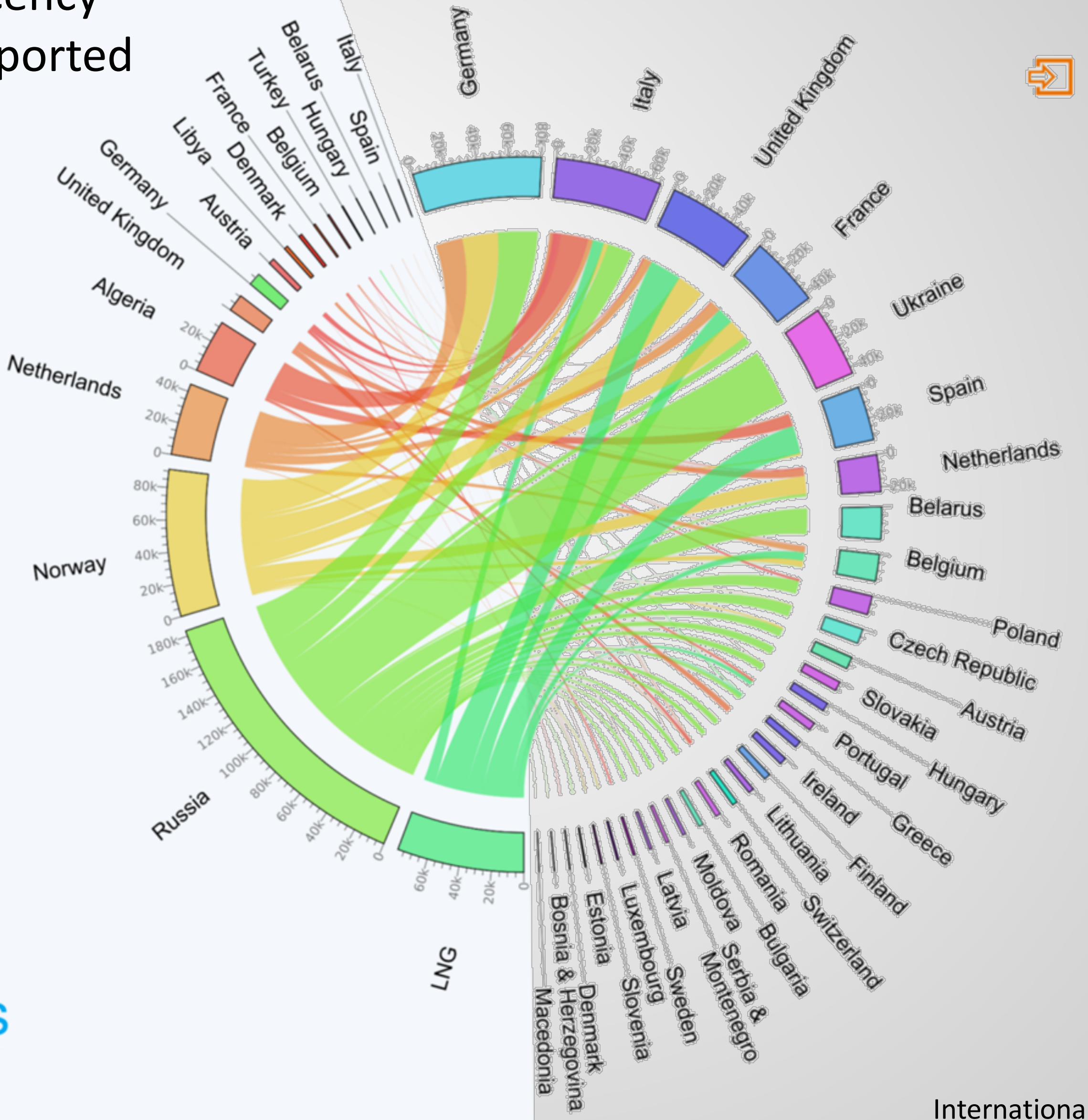


EU member states and candidate countries: Larger Urban Zones (European Environment Agency)
non-EU countries: NaturalEarth.
Urban areas defined to be union of 3rd level administrative divisions

spatial
resolution
1 km

Data: gas trade network

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



International Energy Agency, 2011

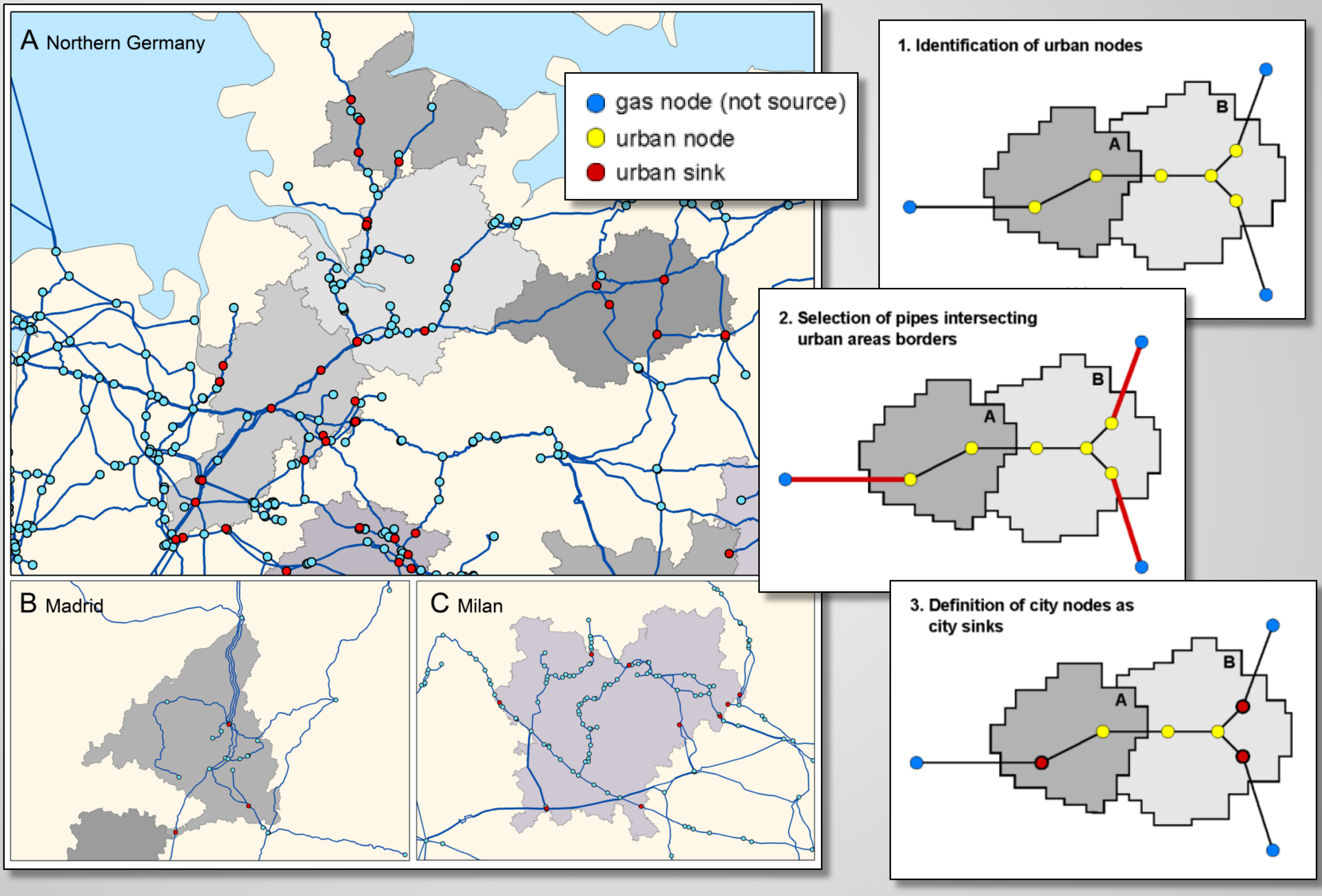
Routing: how we link the macro to the micro

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

- We rely on population density to distribute gas across the importing country (Bettencourt et al.)
- To find routes, we rely on:
  - geographical proximity (shortest paths);
  - pipeline diameter (paths with larger diameter may get higher flows).

Bettencourt et al, Growth, innovation, scaling, and the pace of life in cities. PNAS 104, 7301–7306.

Routing: location of sink nodes

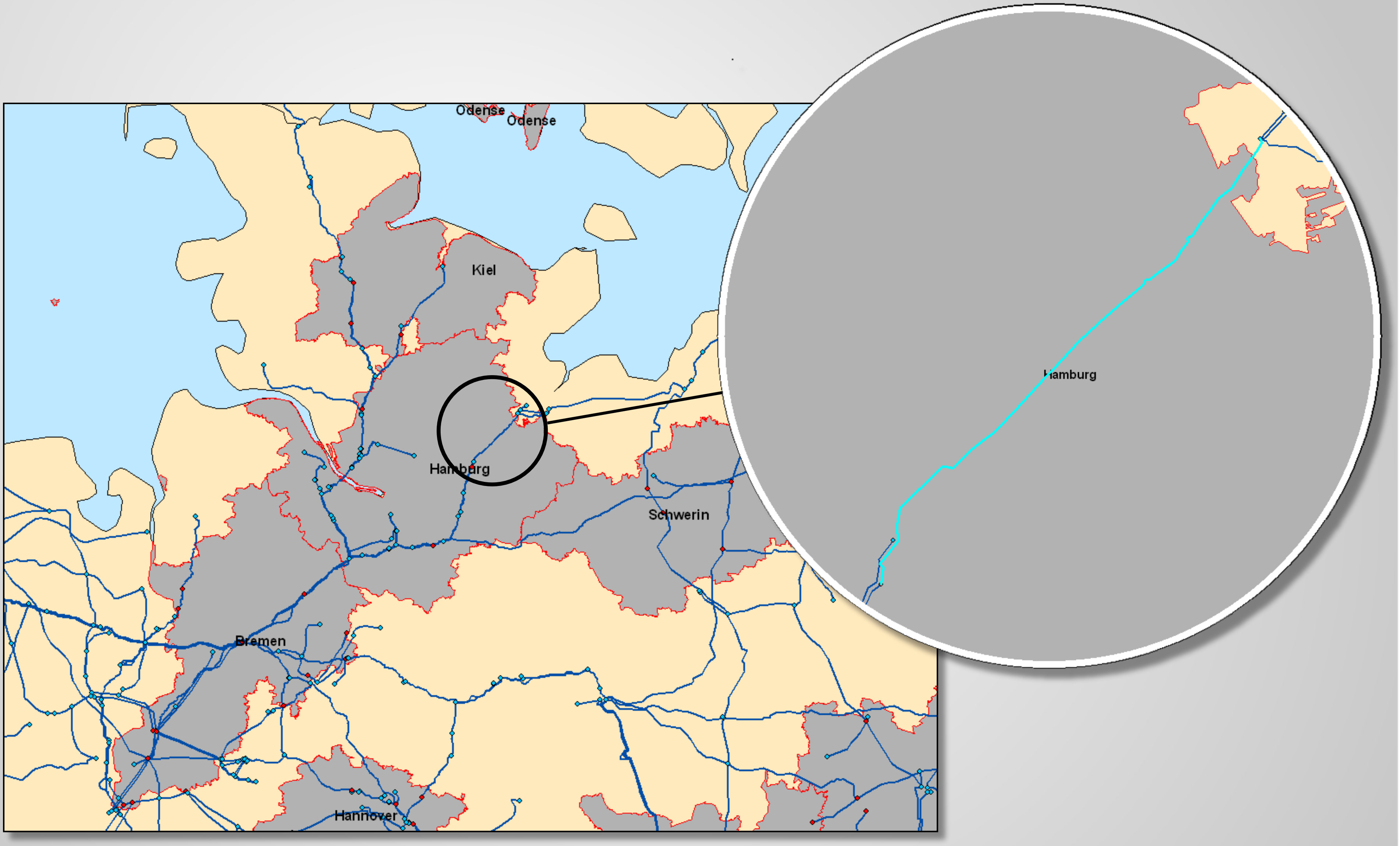


1. Identification of urban nodes

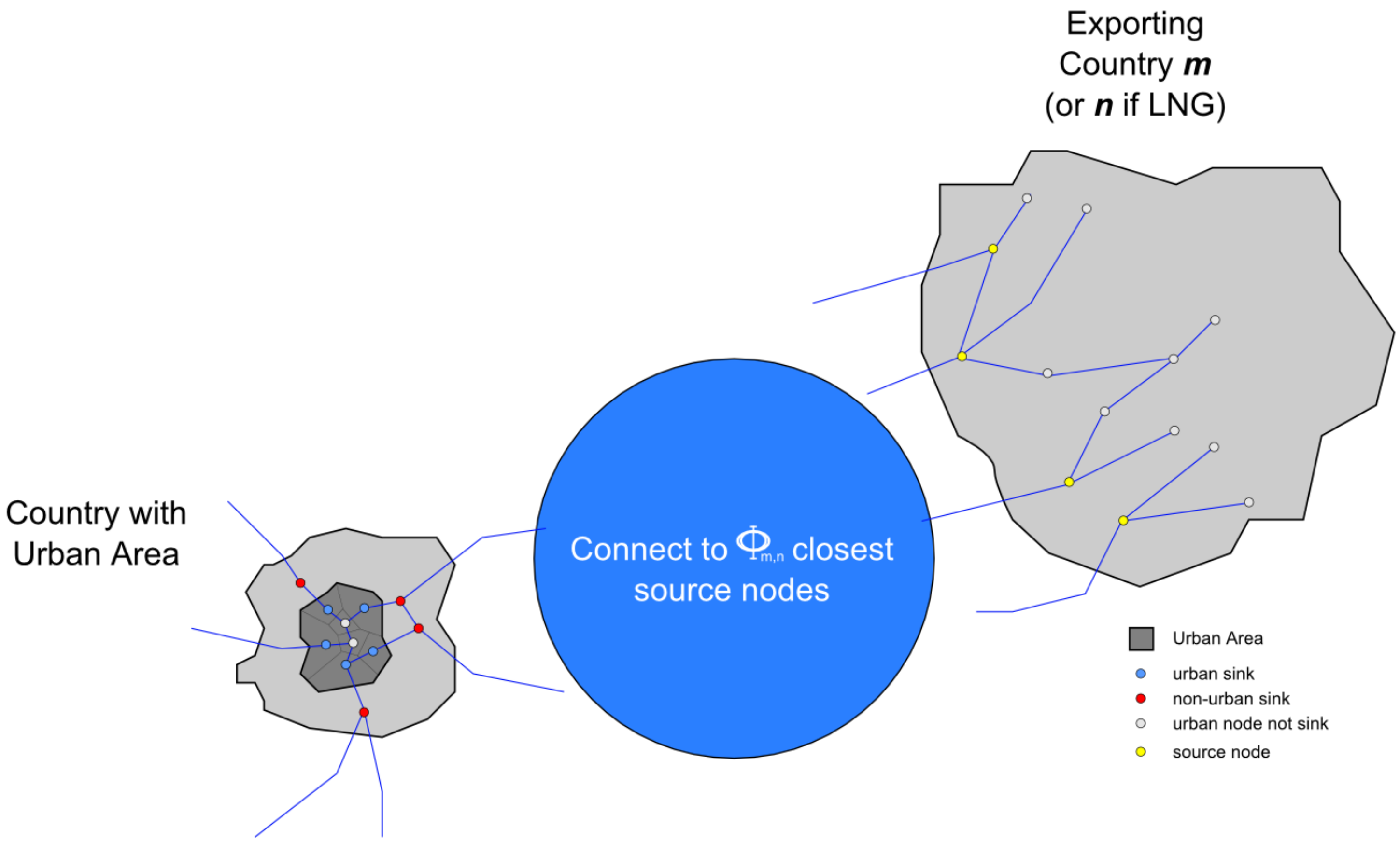
2. Selection of pipes intersecting urban areas borders

3. Definition of city nodes as city sinks

Routing: map detail of urban sink algorithm



Routing: how we pair source and sink nodes



Exporting
Country ***m***
(or ***n*** if LNG)

Country with
Urban Area

Connect to $\Phi_{m,n}$ closest source nodes

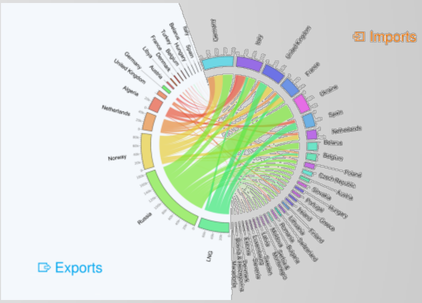
▨ Urban Area
● urban sink
● non-urban sink
○ urban node not sink
● source node

Routing: how we define demand

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

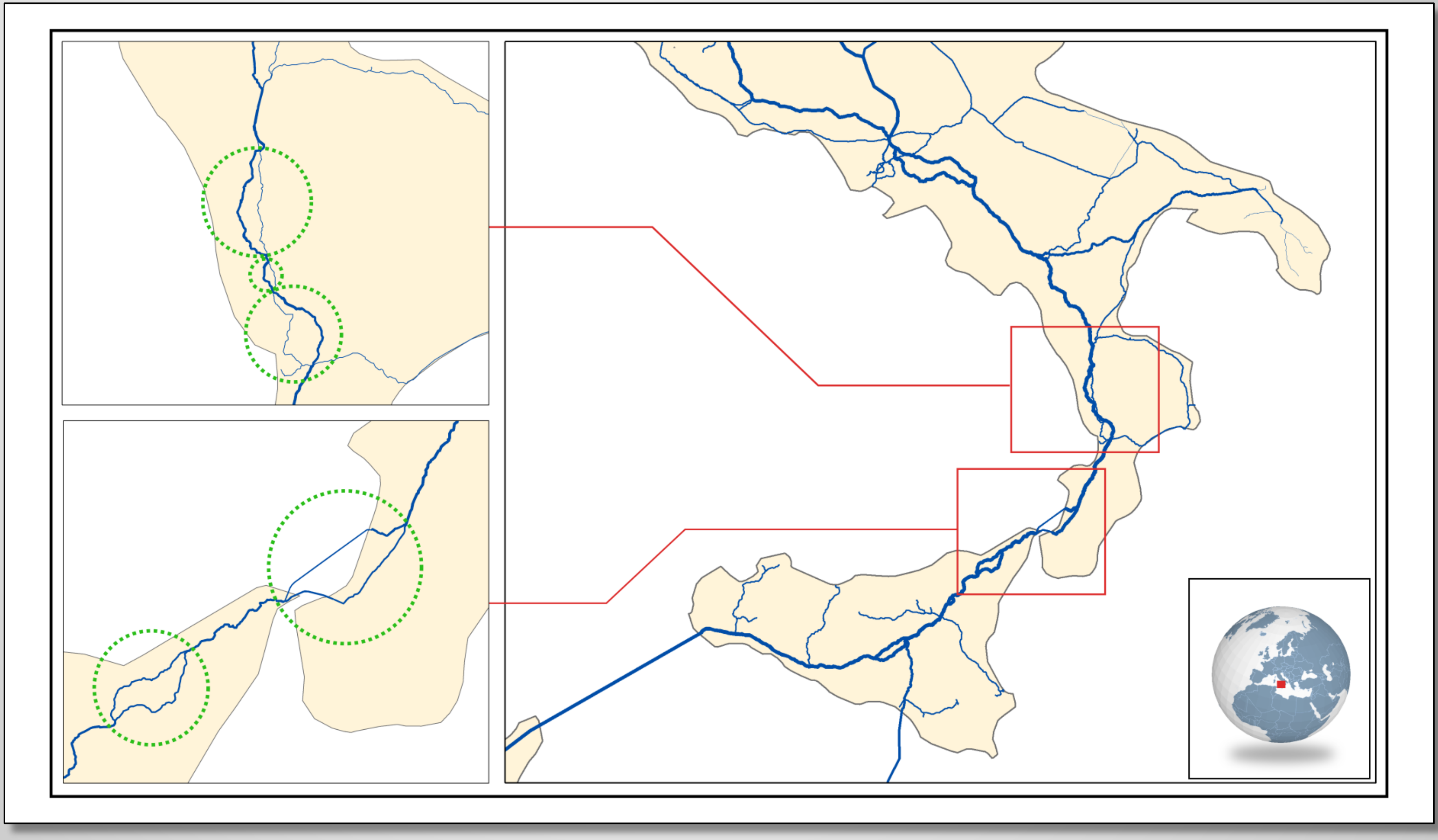
Because each sink node in an importing country n is connected by Φ_{mn} paths to source nodes in an exporting country m, each of these paths has a share of the demand T_{mn} given by

$$D_{mnl} = \frac{1}{\Phi_{mn}} \frac{Z_{nl} T_{mn}}{z_n}$$



where Z_{nl} is the population associated with sink node l of importing country n, z_n is the population of importing country n, T_{mn} is the volume of gas imported by an importing country n from an exporting country m.

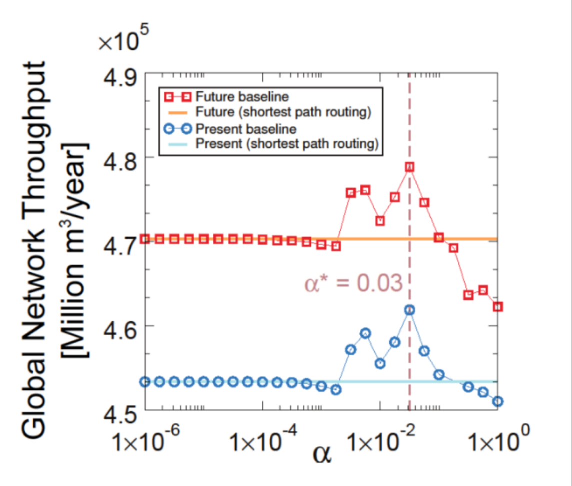
Routing: the problem with shortest path



Routing: how to determine the 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

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

Heuristic rerouting

- Go through each source to sink route and find a new path j connecting the two nodes. Compute the path length $\overleftrightarrow{l_j} = \sum_{i \in \text{path j}} \tilde{l}_i$;
- If $\overleftrightarrow{l_j}$ is lower than the previously found path, then it repalces the existing source to sink path;
- Recompute the weights $\tilde{l}_i$ 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.

Congestion Control: Decentralized Primal 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:

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

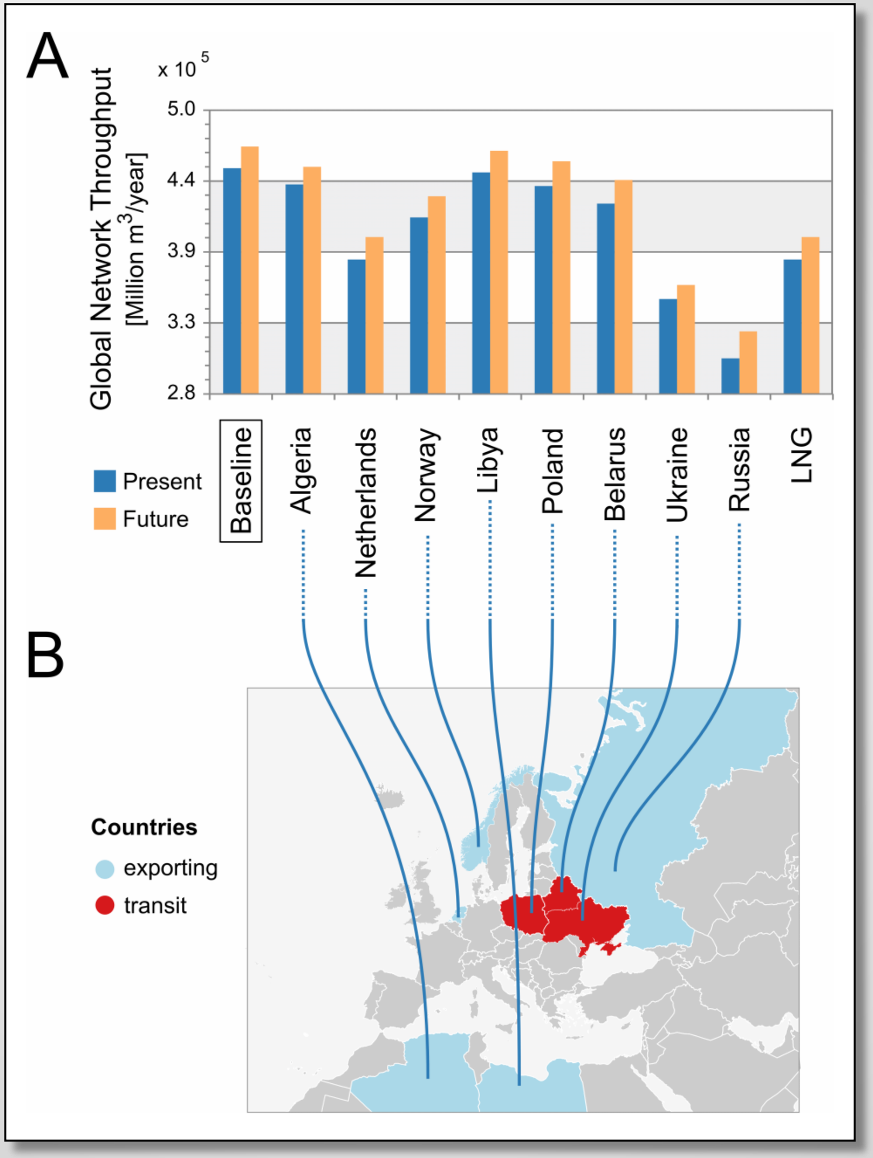
where

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

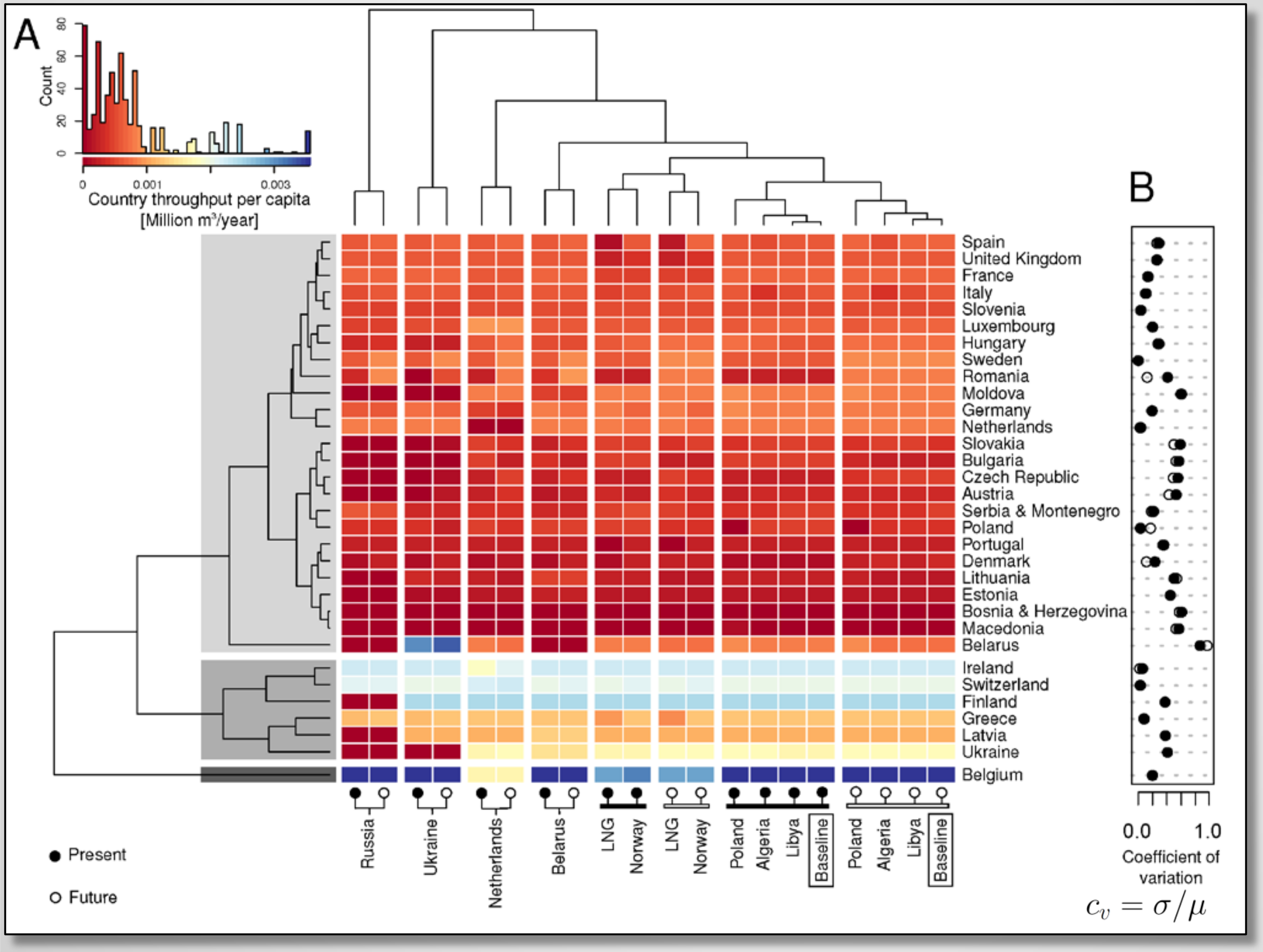
and $q(\cdot)$ is the inverse of $p(\cdot)$. As $\epsilon \to 0$, the dual and primal algorithms become equivalent.

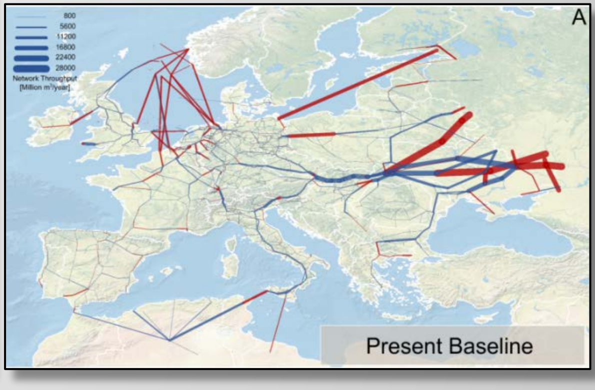
F. P. Kelly, A. K. Maulloo, and D. K. H. Tan, "Rate control for communication networks: shadow prices, proportional fairness and stability," *J. Oper. Res. Soc.*, vol. 49, no. 3, pp. 237–252, 1998.

Global network throughput by scenario



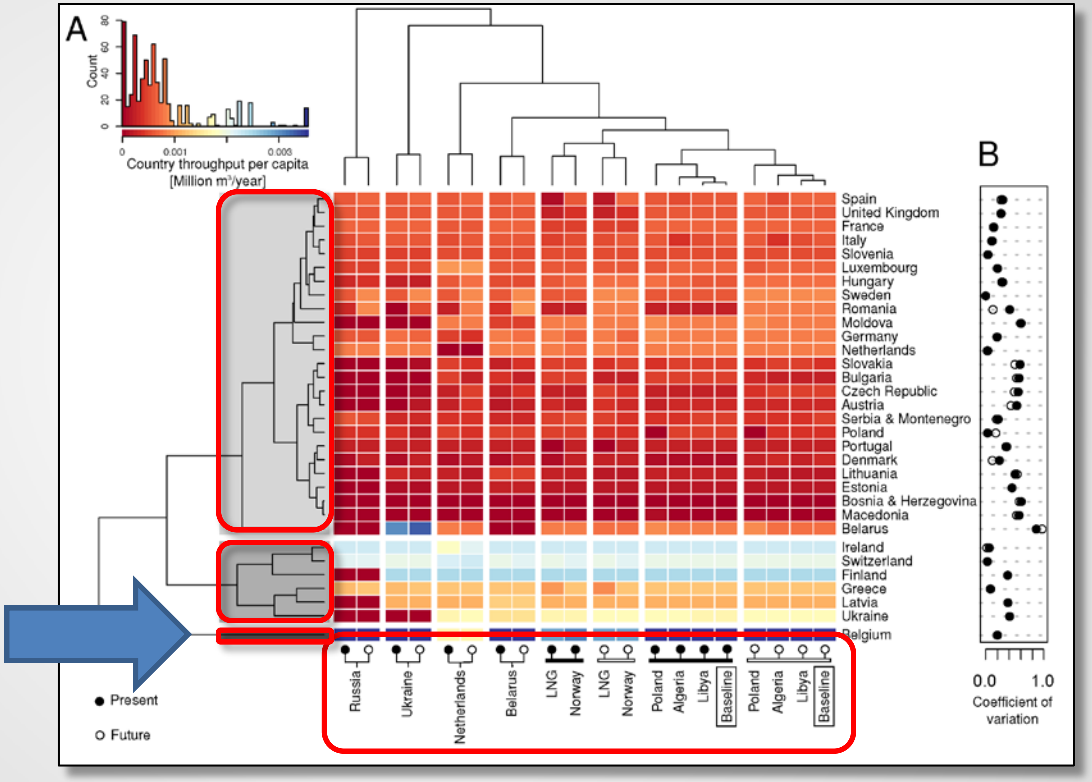
Resilience at country and network levels





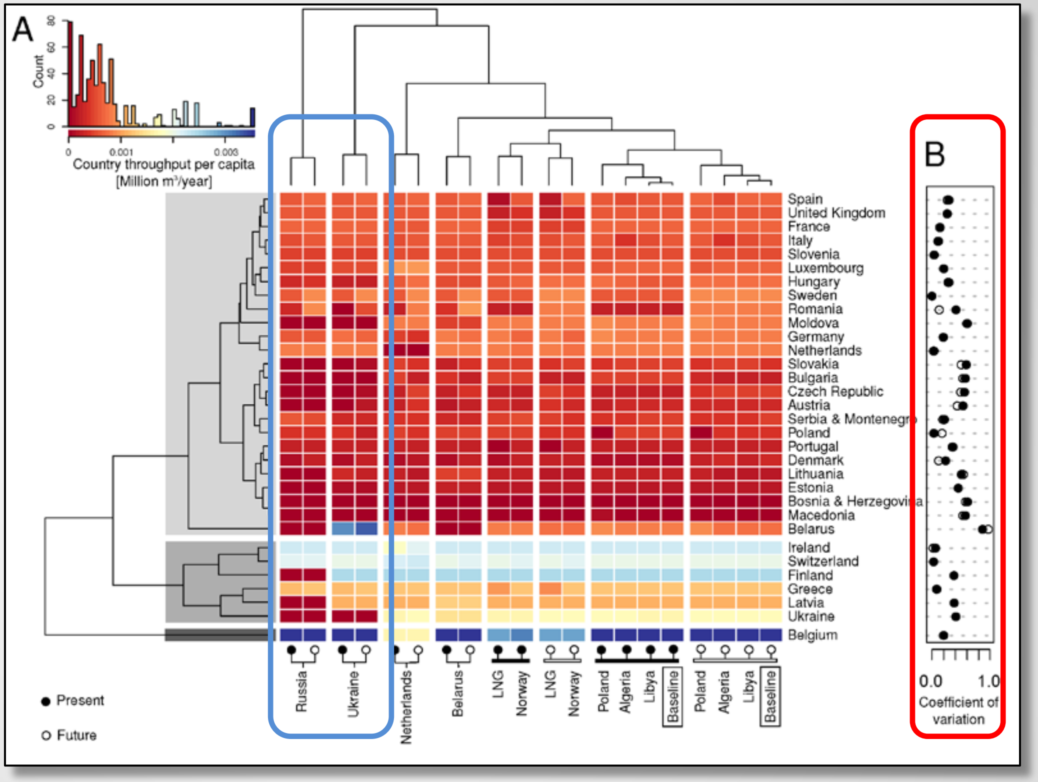
- A **country is resilient** to crises if it combines high throughput per capita across scenarios with a low coefficient of variation of throughput.
- The **network is resilient** to a scenario if the vectors of country throughput per capita for the scenario and the baseline scenario are similar.

Interpreting the heat map



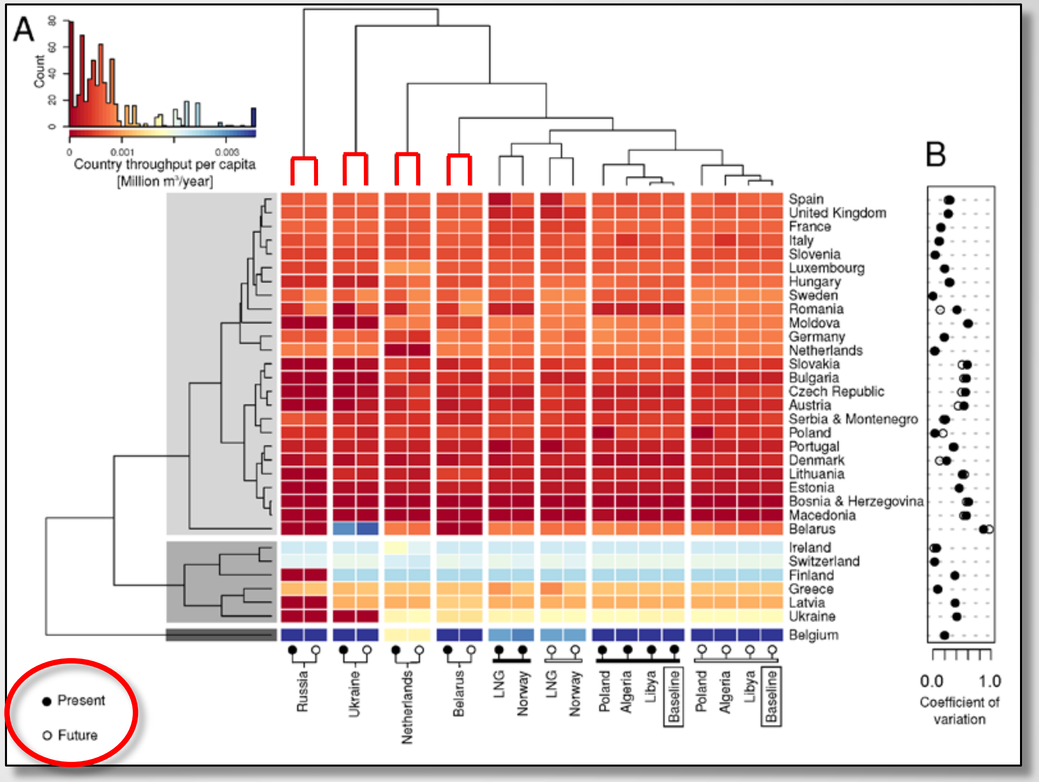
- We analyse the country throughput per capita in the scenario space (20 scenarios)…
- and in the country space (32 countries). The country groups highlighted in grey reflect a similar level of throughput per capita across scenarios;
- Countries belong to the high throughput per capita groups (dark grey) due to a combination of factors:
  - diversity of supply;
  - good access to network capacity (strategic geographical location);
  - relatively small population.

Interpreting the heat map



- Larger values of the *coefficient of variation* indicate that country throughput varies across scenarios;
- Eastern European countries are sensitive to the scenarios where we hypothetically remove Russia or Ukraine –they are dependent on these countries;
- 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.

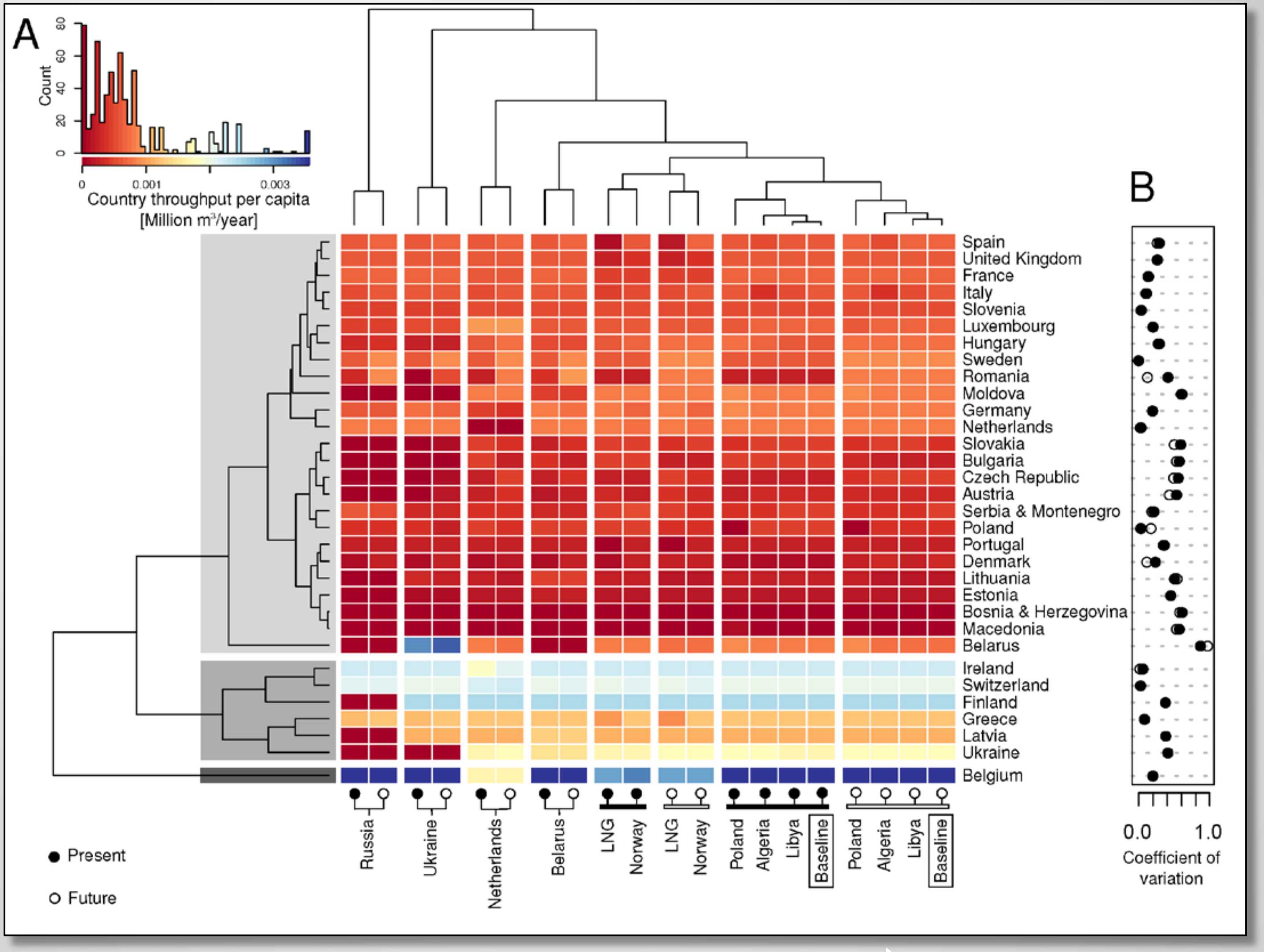
Interpreting the heat map



- The *present* and *future* scenarios are clustered together when either Russia, Ukraine, the Netherlands, or Belarus are removed from the network;

- Hence, it's very hard to change the consequences of such scenarios by building a few new pipelines.

Interpreting the heat map

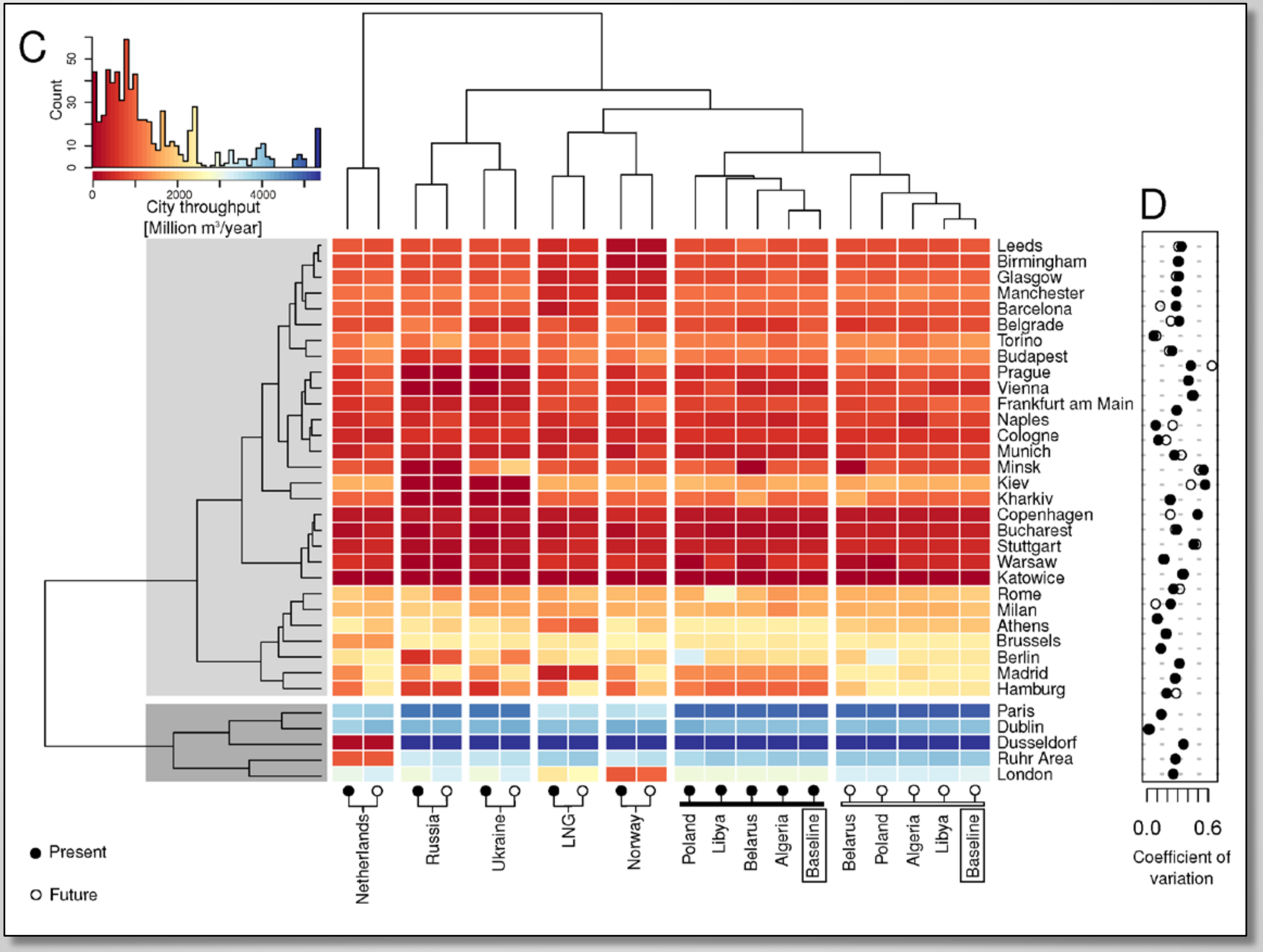


Largest disruption

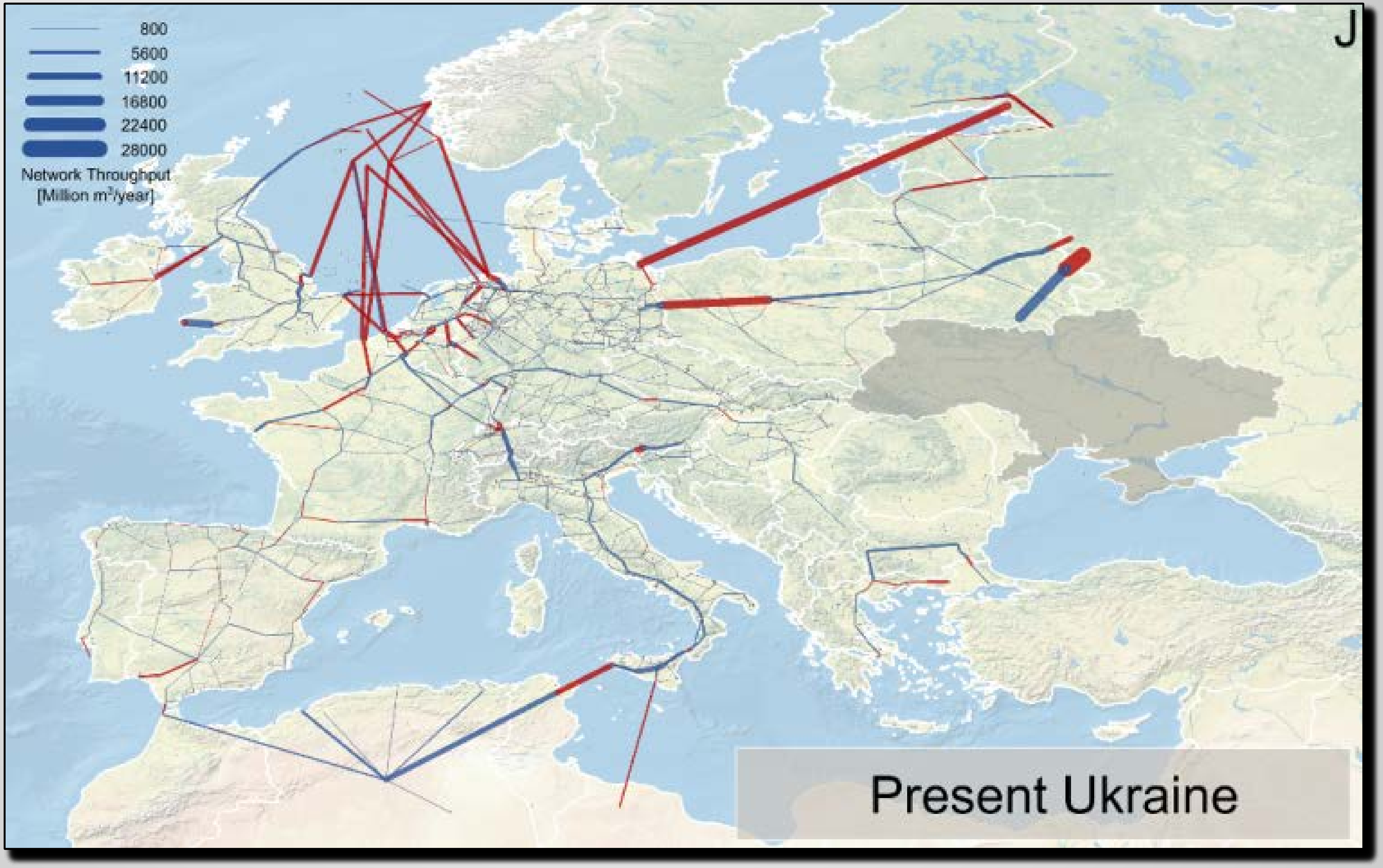
Most benign scenario

Variation of throughput and effect on the network

Urban Level



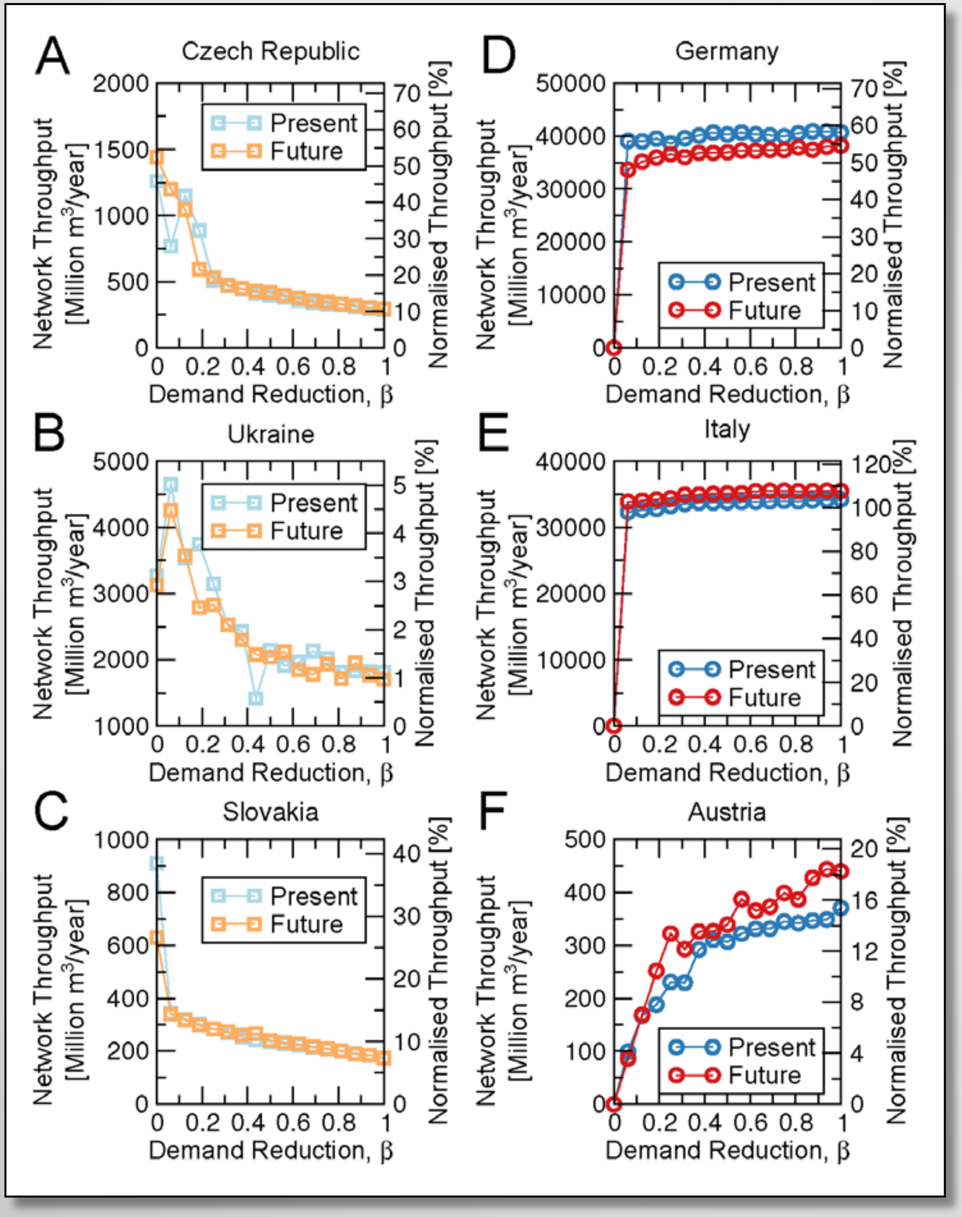
Present Scenarios



Mitigating the effect of a 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.

Mitigating the effect of a hypothetical crisis with Russia



We can hope to recover:

- between 40 and 50% of the baseline throughput for the Czech Republic and Slovakia;
- up to 5% for Ukraine;
- up to 20% for Austria.

- 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.

Discussion

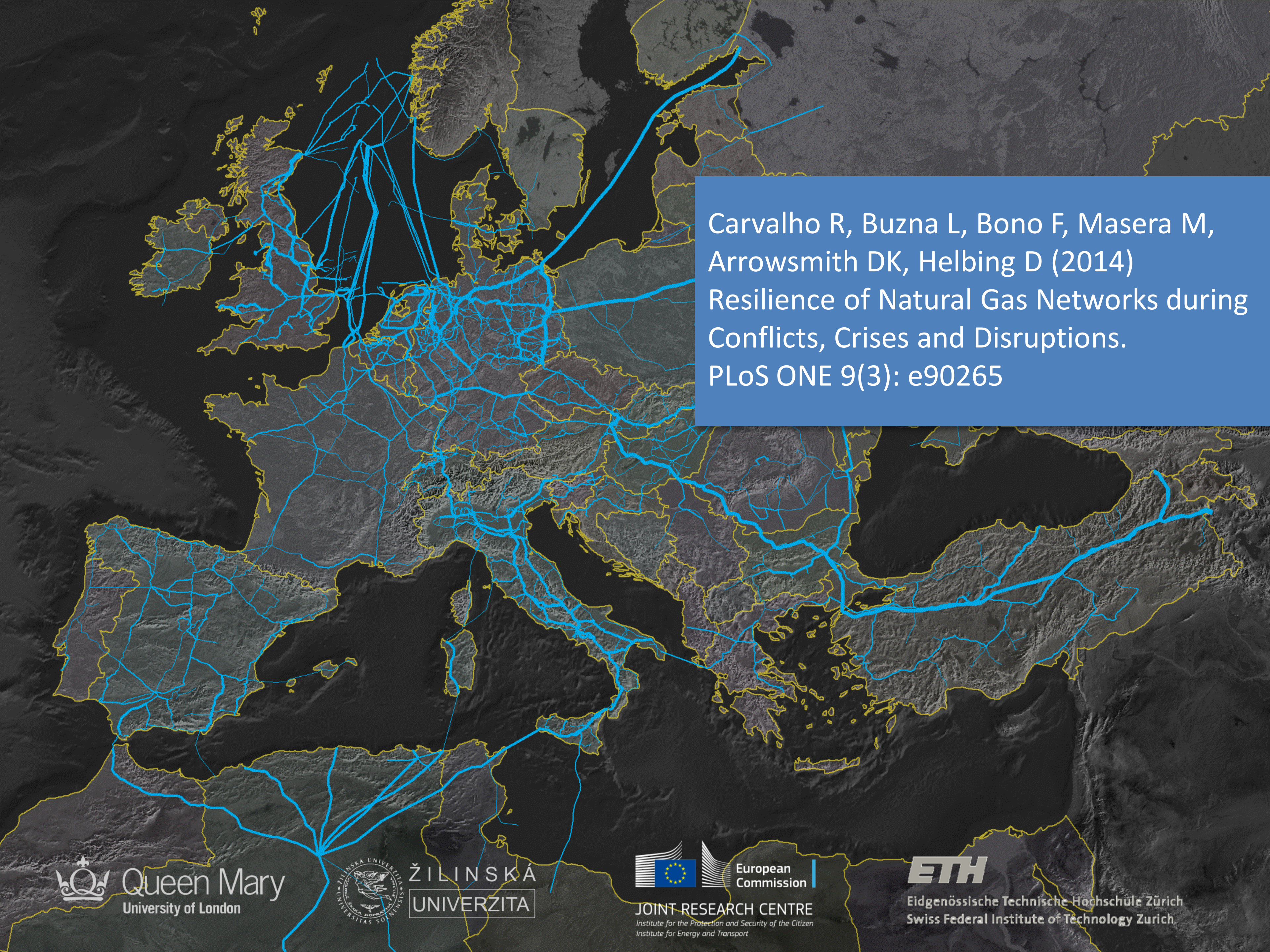
- Agreed political management processes are needed for crises scenarios, to guarantee supply to the most affected countries and urban areas and minimize the loss of gas by populations.

- We demonstrate how a wide range of scenarios impacts network throughput at global, country and urban levels, and how countries and urban areas react to scenarios of hypothetical crises.

- We show and quantify how countries that are heavily dependent on Russian supply can lower the impact of a crisis, if other countries accept to reduce their demand.

- Because the number of governments and companies ultimately involved in taking the decisions in Europe is relatively high, governments could implement decentralized solutions similar to the one we propose here, perhaps with a centralized control solution as backup.

- At its heart, energy security, like preparedness for future pandemics, is about cooperation among nations. To avoid European-wide crises, nations must cooperate to share access to their critical infrastructure networks.



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