The 2nd International Symposium on Smart Grid — Methods, Tools, and Technologies

Weihai, Shandong, CHINA

July 4-7, 2017

CARDIFF UNIVERSITY

PRIFYSGOL CAERDYDD

Robust Analysis of Smart Distribution Networks

Prof. Jianzhong Wu

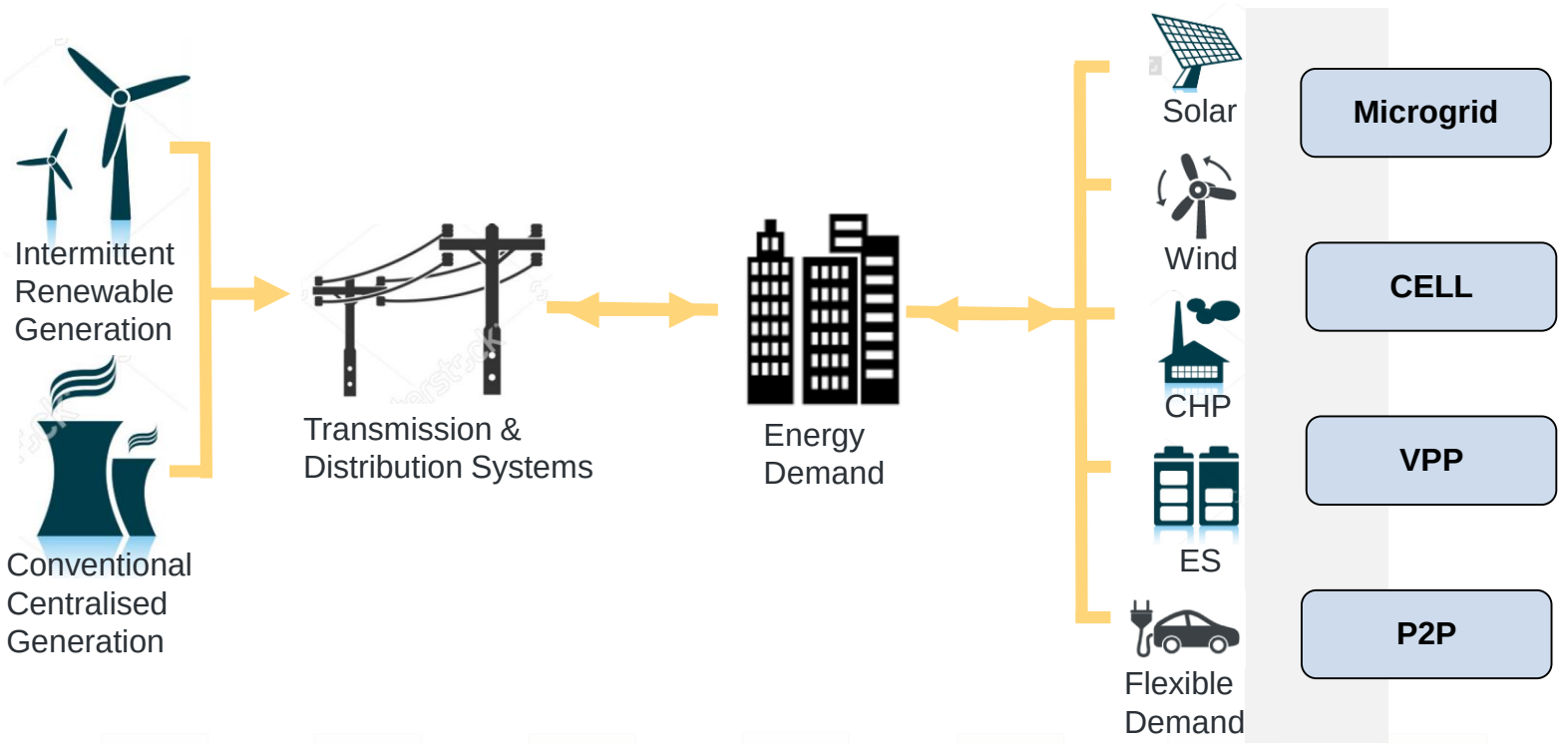
Professor of Multi-Vector Energy Systems

Subject Editor of Applied Energy (IF 7.182)

Cardiff University, UK

6th July 2017

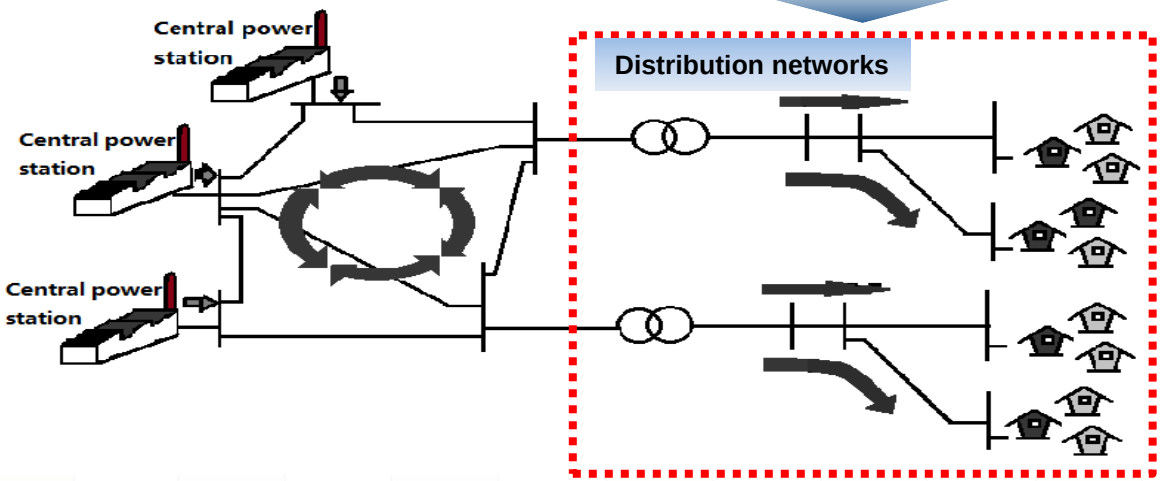
Background



- **A large penetration of intermittent renewable generation**
- **Distributed Energy Resources are dispersed in the system**
- **Various methods are being investigated for better management of DERs and the distribution networks**

Background

Lack of sensors, communication systems and control equipment, therefore limited real-time monitoring and control below the primary substations



80%-90% power outages, with high power losses

"Worst case scenario" and deterministic methods are widely used for analysis of distribution networks.

Robust Analysis of Smart Distribution Networks

Passive features

Intolerance of information gaps and uncertainties

Analysis tools for distribution networks

Slow calculation speed

Difficulties in generalising the results

Robust Analysis of Smart Distribution Networks

Robust State Estimation	STM	Statistically Similar Networks
Incomplete and inaccurate information	Uncertain customer behaviour	To obtain generalised conclusions

Robust Analysis of Smart Distribution Networks

Passive features

Intolerance of information gaps and uncertainties

Analysis tools for distribution networks

Slow calculation speed

Difficulties in generalising the results

Robust Analysis of Smart Distribution Networks

Robust State Estimation

STM

Statistically Similar Networks

Incomplete and inaccurate information

Uncertain customer behaviour

To obtain generalised conclusions

Robust State Estimation

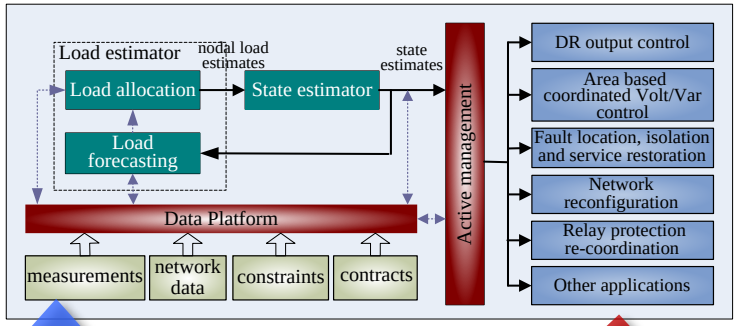
- State estimation is used to clean up errors in measurements and estimate the system state, and the data set is processed using statistical estimation techniques
- State estimation techniques are widely used in transmission systems where redundant measurements are available (i.e. the system is over-determined)
- For under-determined distribution systems, a large number of pseudo measurements have to be used as input to the distribution state estimator

Robust State Estimation

Difficulties in distribution state estimation

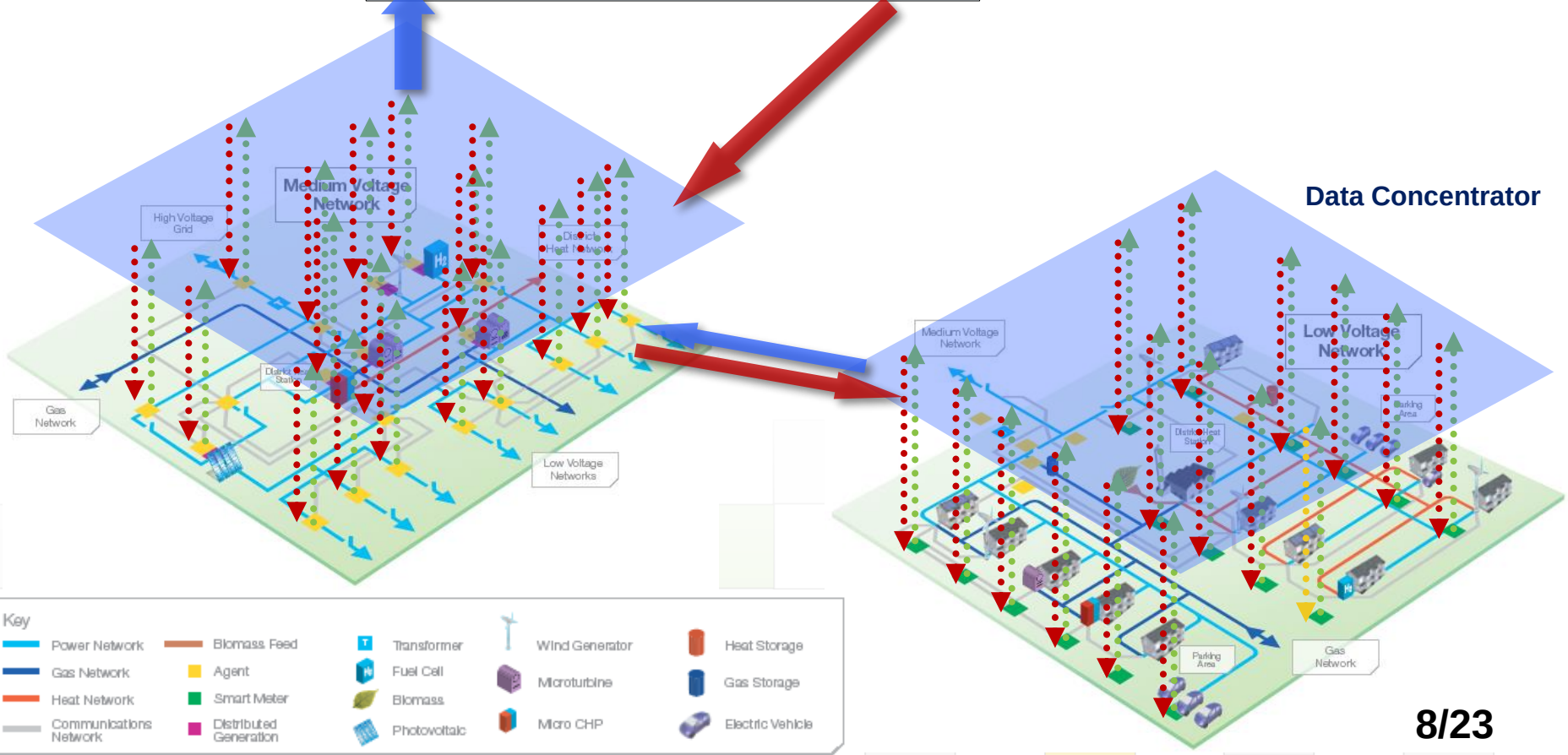
- The pattern of distribution load consumption is more dynamic
- The trend of the load variation is less apparent
- There are usually larger errors and more bad data in pseudo and real-time measurements

Robust State Estimation

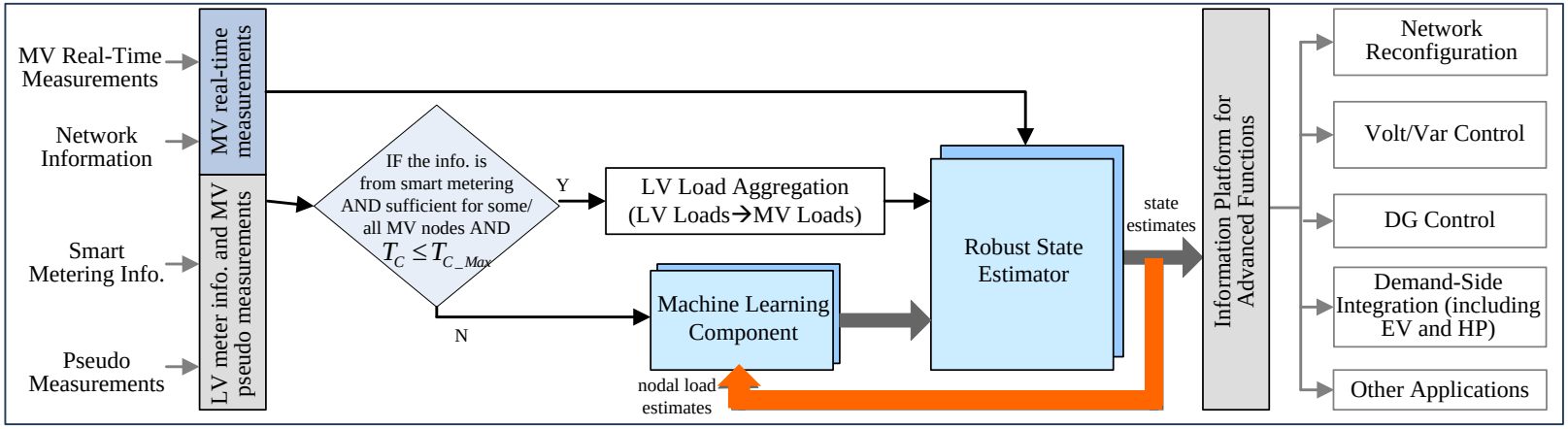


Increasing the Observability of Electrical Distribution Systems using Smart Meters

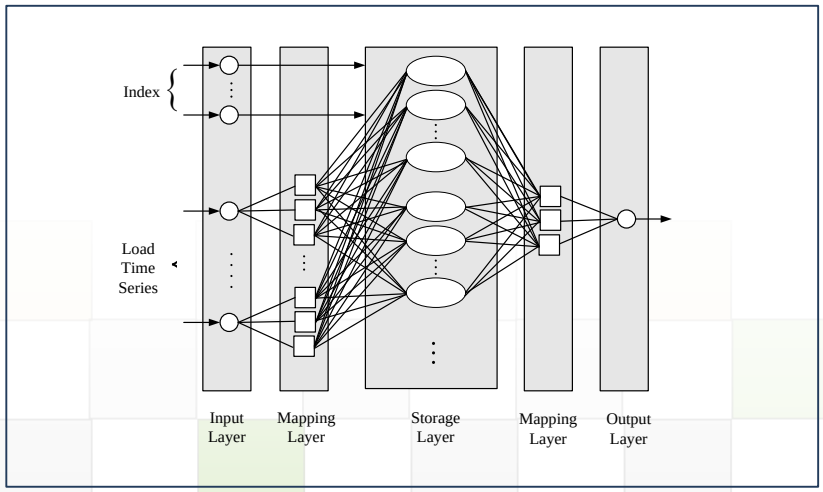
Data Concentrator



Robust State Estimation



Machine Learning Component



Robust Stator Estimator

$$IF(x,F,T)=\lim_{s\to 0}\frac{T((1-s)F+s\delta_x)-T(F)}{s}$$

$$\min \quad (\mathbf{z}-\mathbf{h}(\hat{\mathbf{x}}))^T\bar{\mathbf{W}}(\mathbf{z}-\mathbf{h}(\hat{\mathbf{x}}))$$
subject to
$$\mathbf{z}=\mathbf{h}(\mathbf{x})-\mathbf{e}=\mathbf{h}(\hat{\mathbf{x}})-\mathbf{r}$$

$$\bar{w}_i=\begin{cases} w_i, & D_i^{'}\le k_0 \\ w_i\dfrac{k_0}{D_i^{'}}\left(\dfrac{k_1-D_i^{'}}{k_1-k_0}\right)^2, & k_0<D_i^{'}\le k_1 \\ 0, & D_i^{'}>k_1 \end{cases}$$

$$D_i^{'}=\frac{|r_i|}{(1-J_{ii}+\varepsilon)\sigma}$$

$$\sigma=\alpha \underset{j}{med}\left|r_j-\underset{i}{med}\,r_i\right|$$

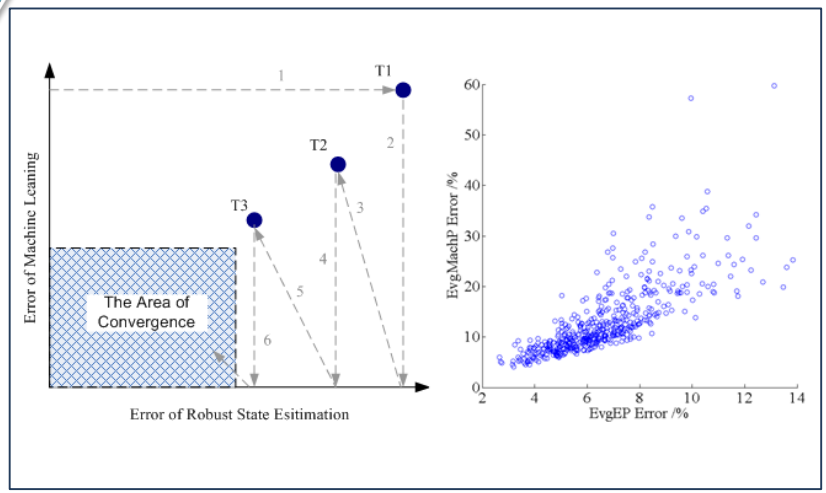
$$\Delta\mathbf{z}_n=\mathbf{z}-\mathbf{h}(\mathbf{x}_n)$$

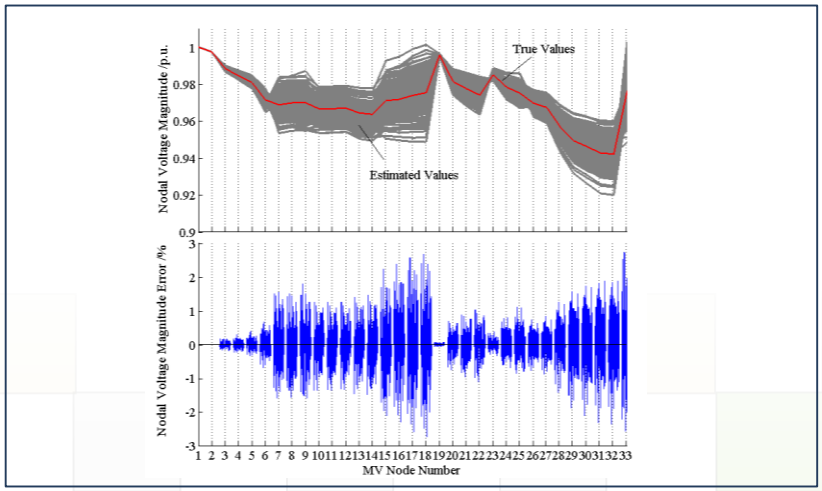
$$\Delta\hat{\mathbf{x}}_n=(\mathbf{H}^T\bar{\mathbf{W}}\mathbf{H})^{-1}\mathbf{H}^T\bar{\mathbf{W}}\Delta\mathbf{z}_n$$

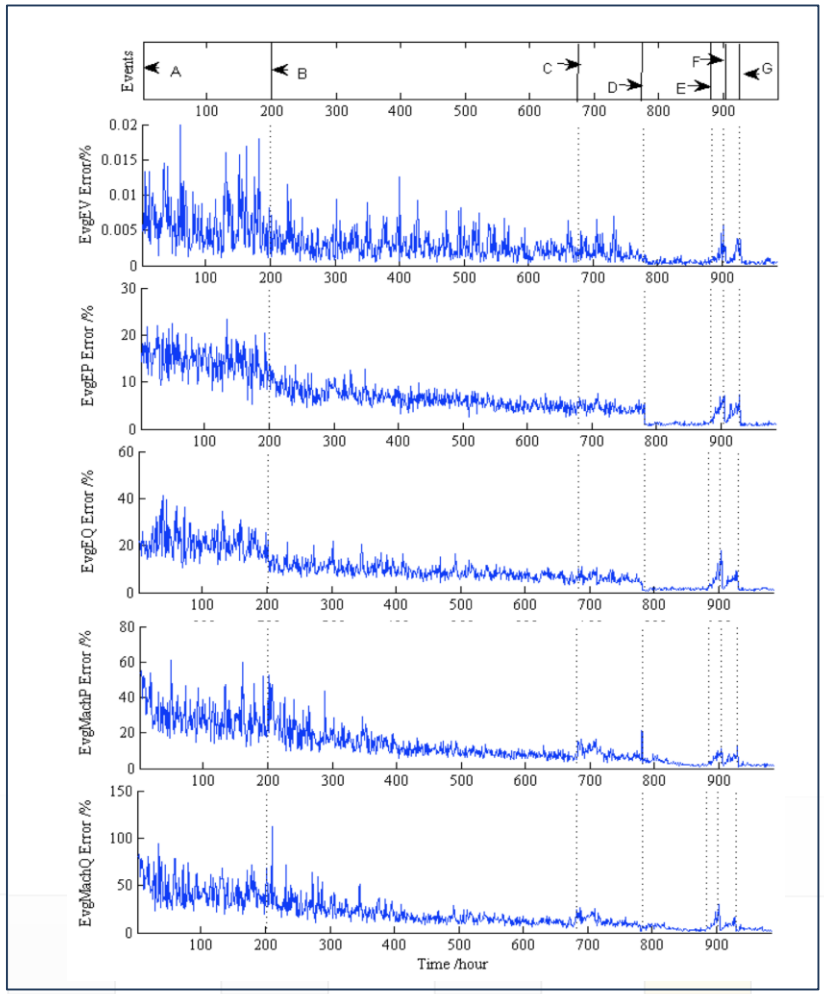
$$\mathbf{x}_{n+1}=\mathbf{x}_n+\Delta\mathbf{x}_n$$

Wu J, He Y, Jenkins N, A robust state estimator for medium voltage distribution networks, *IEEE Trans on Power Systems*, 28(2), (2013), 1008-1016

Robust State Estimation





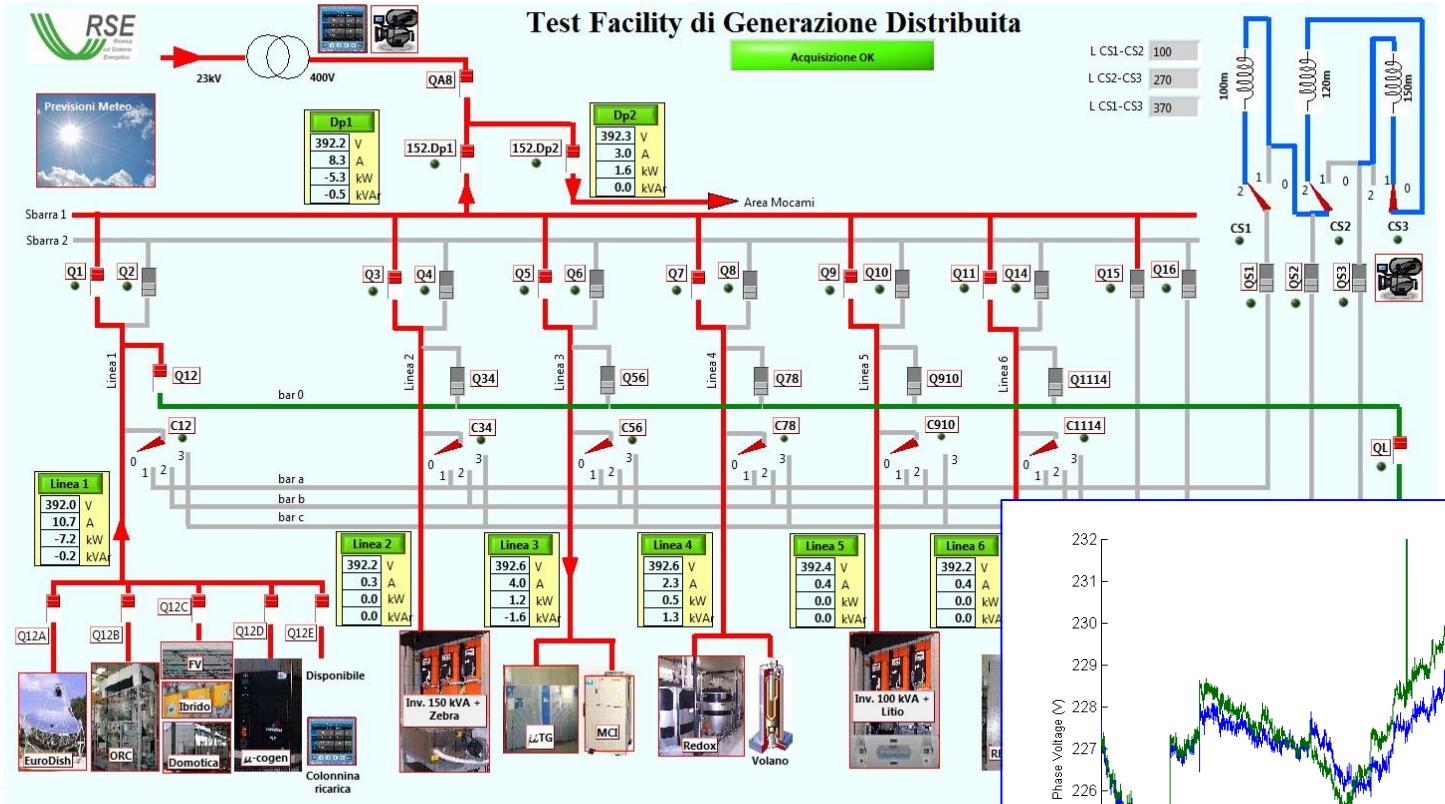


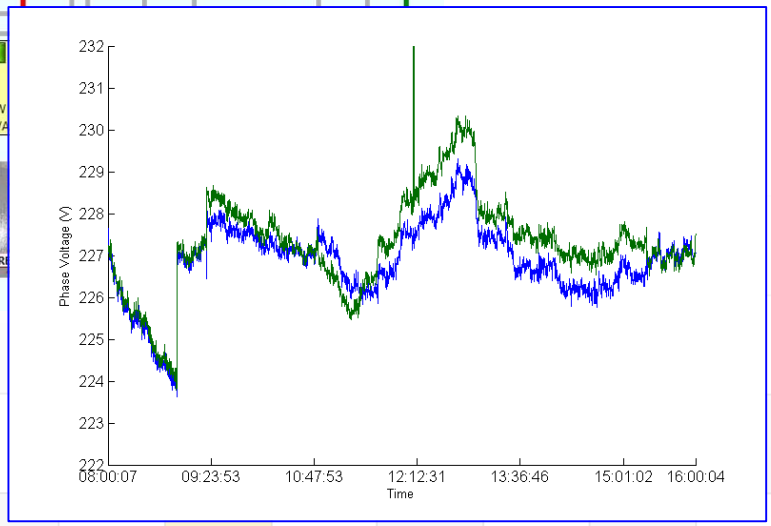
Wu J, He Y, Jenkins N, A robust state estimator for medium voltage distribution networks, *IEEE Trans on Power Systems*, 28(2), (2013), 1008-1016

Al-Wakeel, A., Wu, J. and Jenkins, N. State estimation of medium voltage distribution networks using smart meter measurements. *Applied Energy*, 184, 207-218, 2016

Al-Wakeel, Wu J, Jenkins N, *K*-means based load estimation of domestic smart meter measurements, *Applied Energy*, 194, 333-342, 2017

Robust State Estimation





Robust Analysis of Smart Distribution Networks

Passive features

Intolerance of information gaps and uncertainties

Analysis tools for distribution networks

Slow calculation speed

Difficulties in generalising the results

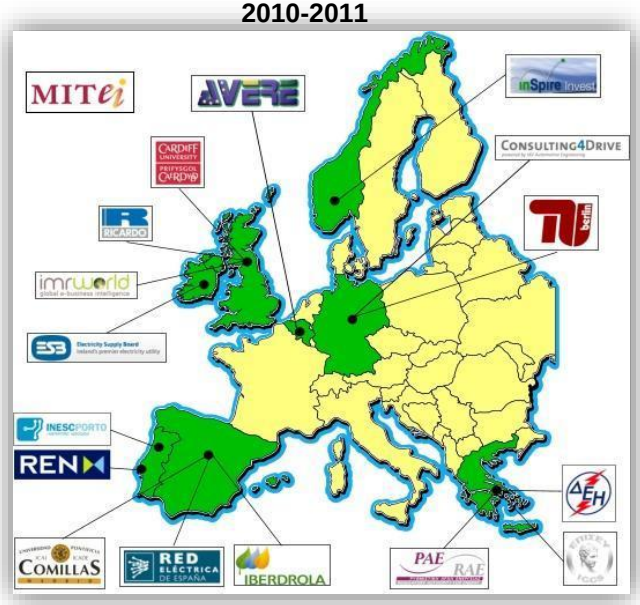
Robust Analysis of Smart Distribution Networks

Robust State Estimation	STM	Statistically Similar Networks
Incomplete and inaccurate information	Uncertain customer behaviour	To obtain generalised conclusions

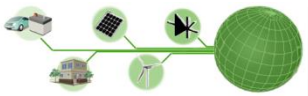
Spatial-Temporal Model

- **Expect a large EV penetration**
  - Decarbonisation of the transport sector
  - Reduce the reliance on imported fossil fuel
- **Impact on electric power networks**
  - New electricity demand
  - Voltage profile and branch current
  - System frequency
  - System reliability, stability and security
- **Characteristics**
  - Mobility
  - Spatial temporal distribution
  - Various charging strategies
- **Exiting methods**
  - Worst-case-scenario based
  - Probabilistic and fuzzy based

EU FP7 MERGE project: Mobile Energy Resources in Grids of Electricity 2010-2011



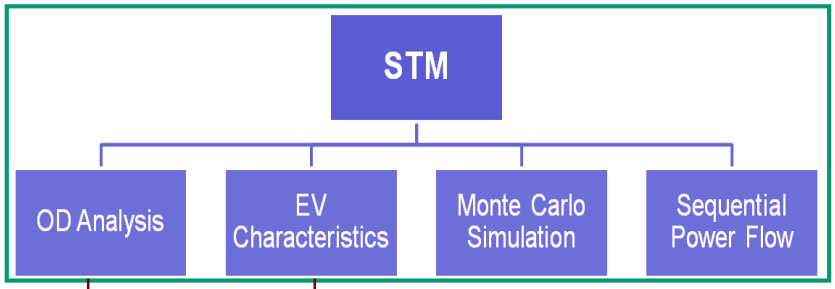
Top and Tail Transformation

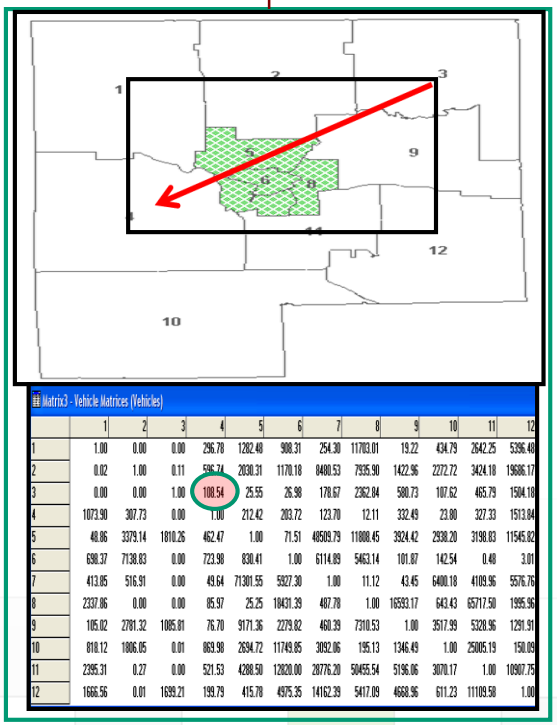


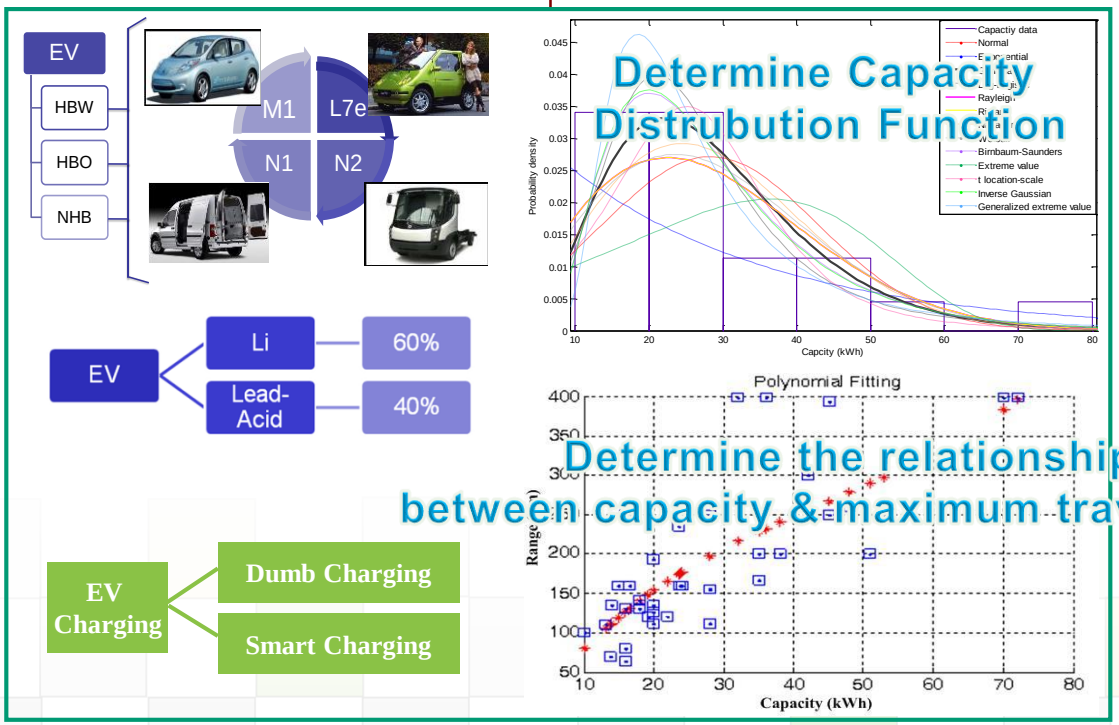
2011-2015

Grid Economics, Planning and Business Models for Smart Electric Mobility 2014-2016

Spatial-Temporal Model



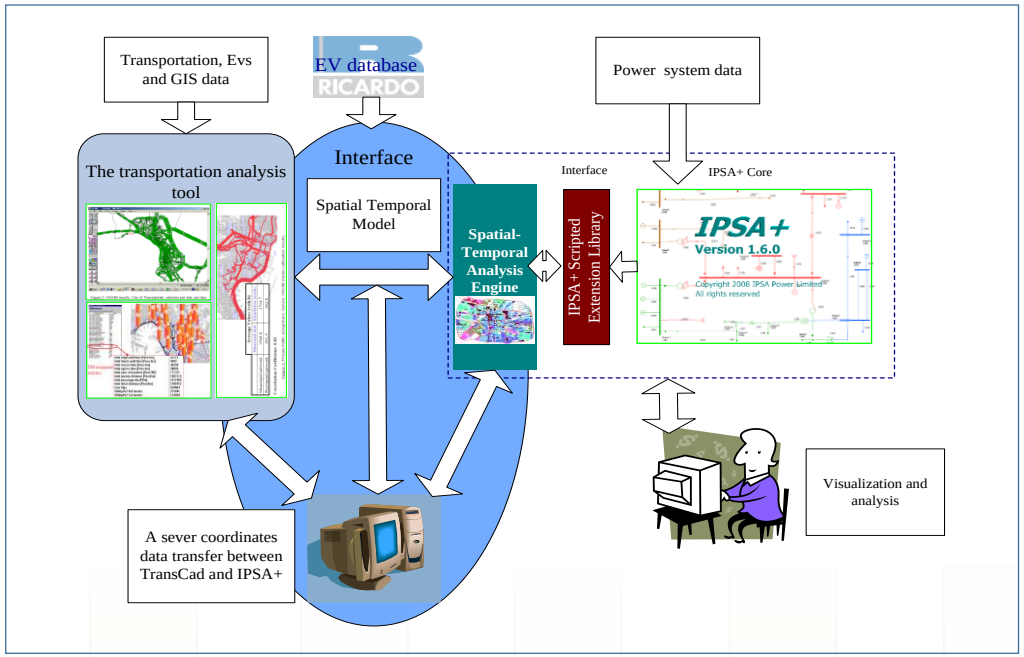


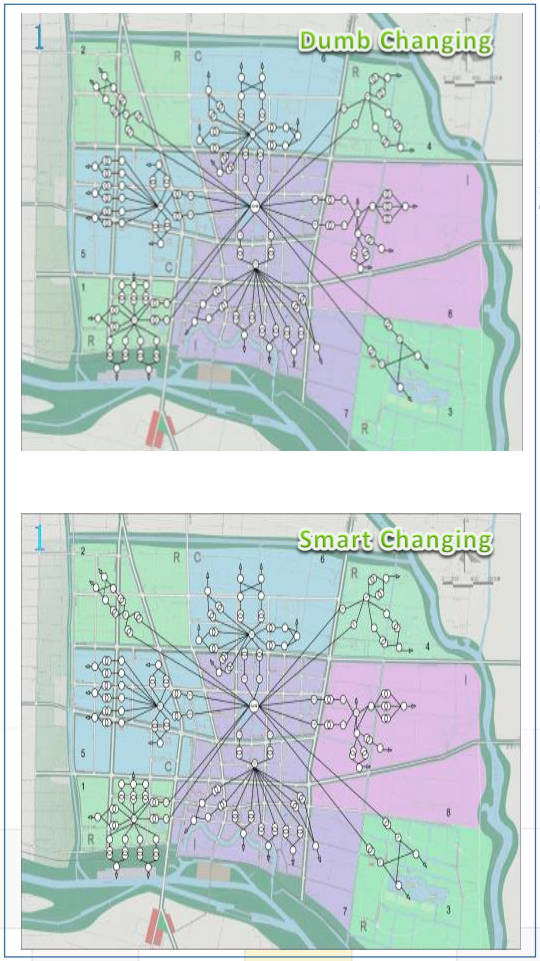


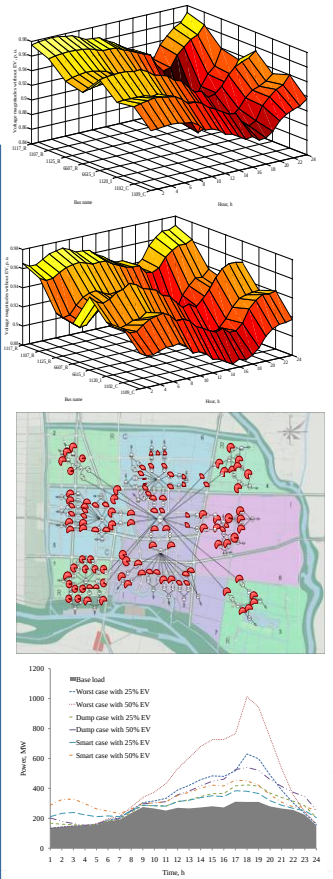
Mu Y. Wu J., Jenkins N., H. Jia, C. Wang, A Spatial-Temporal Model for Grid Impact Analysis of Plug-in Electric Vehicles, *Applied Energy*, 114, (2014), 456-465

Spatial-Temporal Model

Grid Impact Analysis of a Large Penetration of EVs



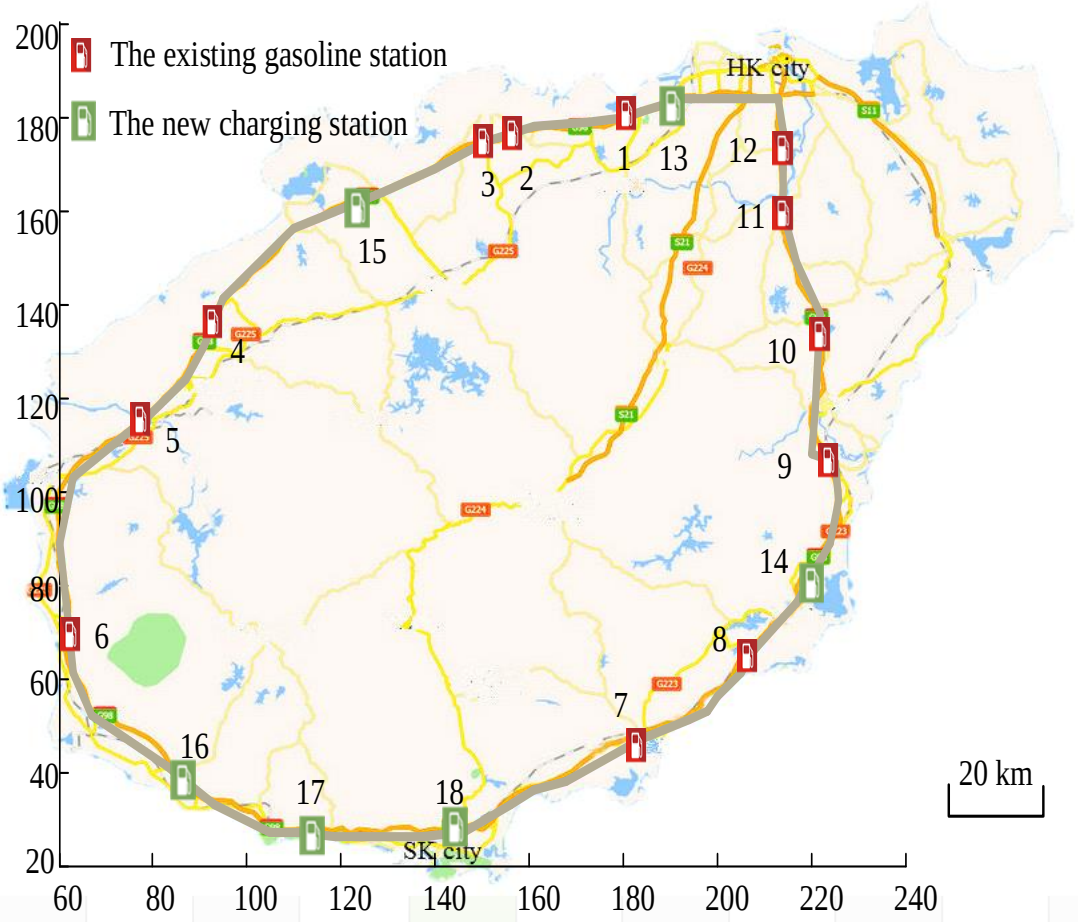




Mu Y. Wu J., Jenkins N., H. Jia, C. Wang, A Spatial-Temporal Model for Grid Impact Analysis of Plug-in Electric Vehicles, *Applied Energy*, 114, (2014), 456-465

Mu Y, Wu J, Ekanayake J, Jenkins N, Primary frequency response from electric vehicles in the Great Britain power system, *IEEE Trans on Smart Grid*, 4(2), (2013), 1142-1150

Spatial-Temporal Model



Dong X, Mu Y, Jia H, Wu J, Yu X, Planning of fast EV charging stations on a round freeway, *IEEE Trans on Sustainable Energy*, 7(4): 1452-1461, (2016)

Robust Analysis of Smart Distribution Networks

Passive features

Intolerance of information gaps and uncertainties

Analysis tools for distribution networks

Slow calculation speed

Difficulties in generalising the results

Robust Analysis of Smart Distribution Networks

Robust State Estimation

STM

Statistically Similar Networks

Incomplete and inaccurate information

Uncertain customer behaviour

To obtain generalised conclusions

Statically Similar Networks

- **Objective: To develop a statistical assessment tool for energy distribution networks, in order to achieve robust and generalised conclusions.**

Key features

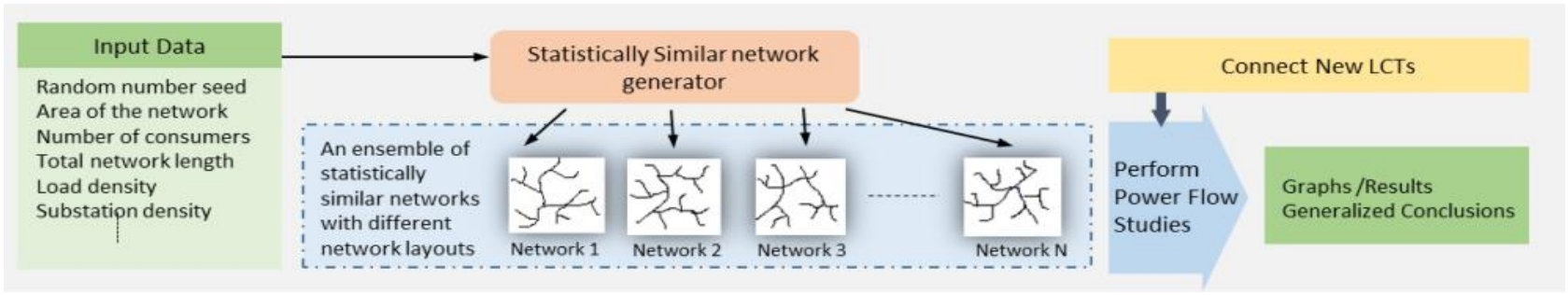
- Capturing essence of real networks using a few statistical parameters.
- Ability to generate many realistic, random test-networks which are statistically similar in terms of the selected topological and technical features and decisive for a given network study.
- The ability of performing studies on many such statistically similar networks to come up with statistically robust conclusions.

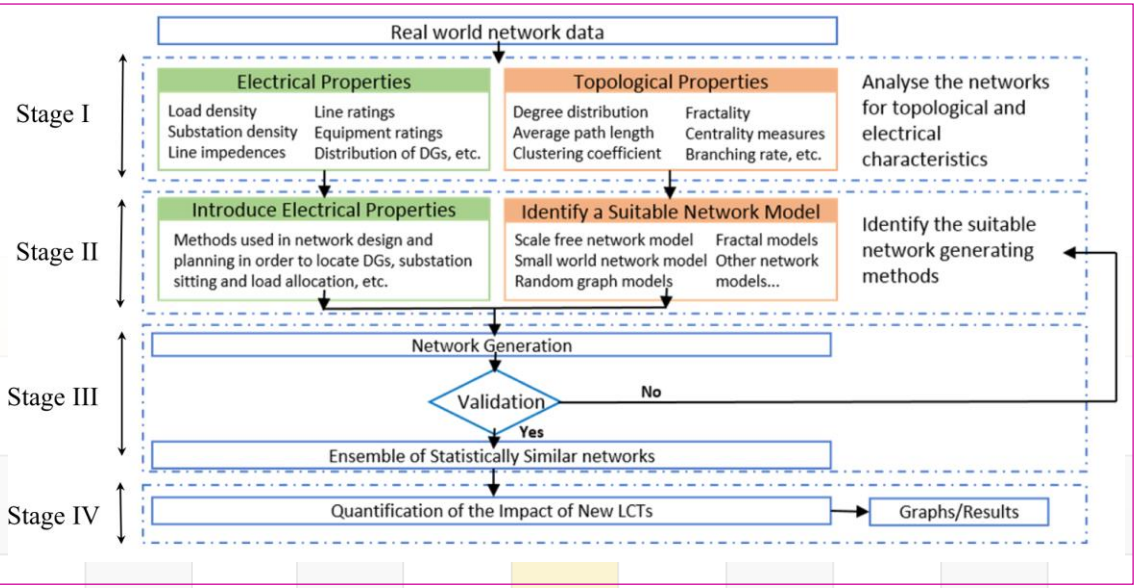
Applications

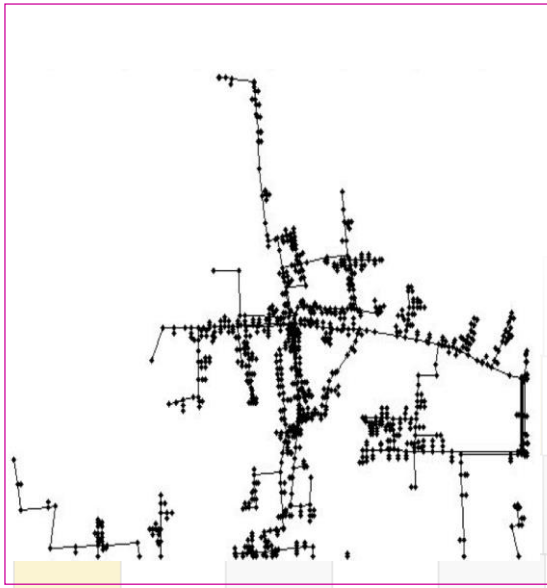
- To conduct network studies on specific real-world/future networks with limited availability of topological and technical information.
- To provide generalised conclusions on the behaviour of different types of networks (rural/semi-rural/sub-urban/urban) under different scenarios.
- To enable robust network planning and design.

Statically Similar Networks

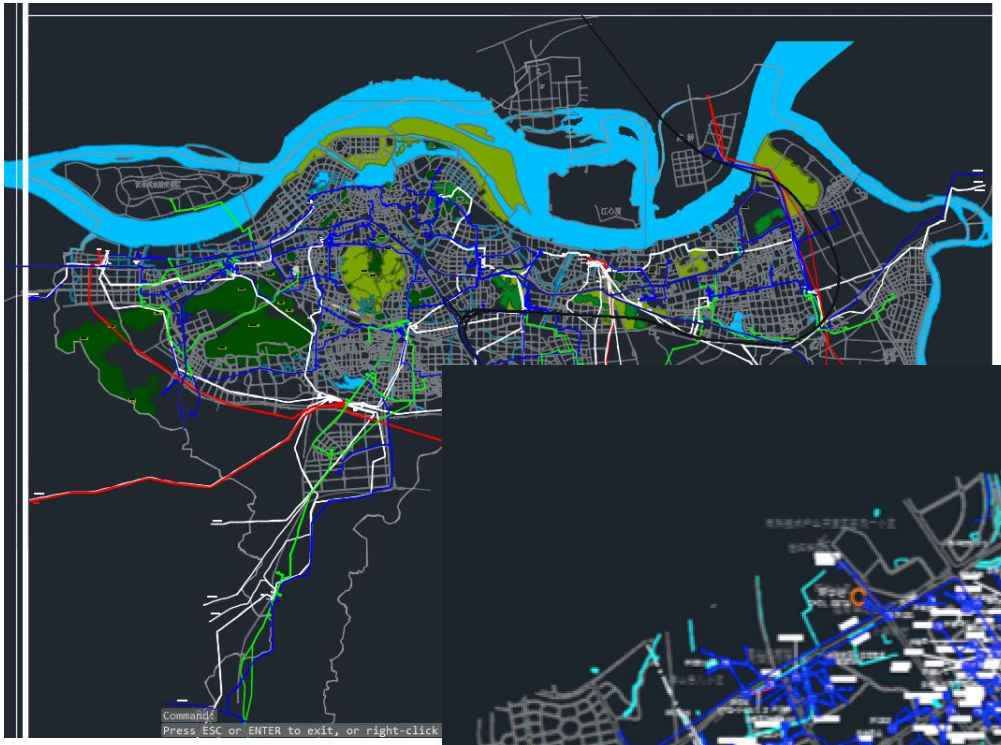
Statistical assessment tool for distribution networks



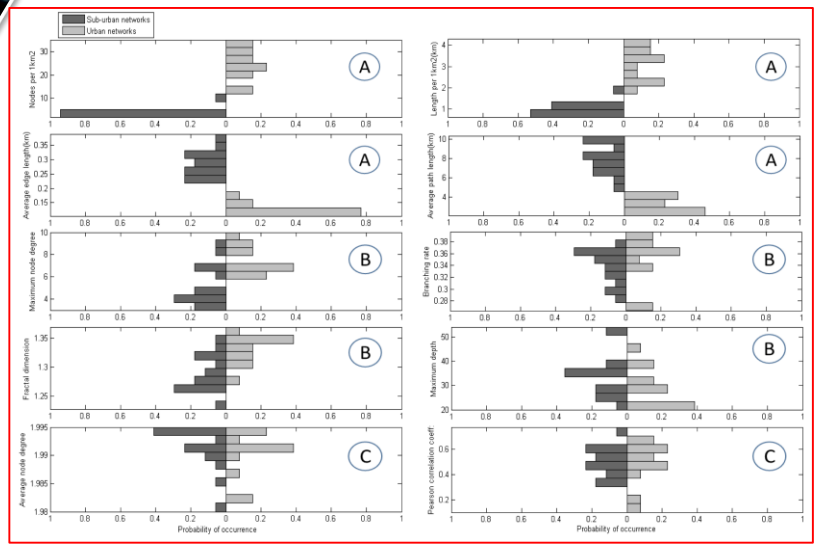


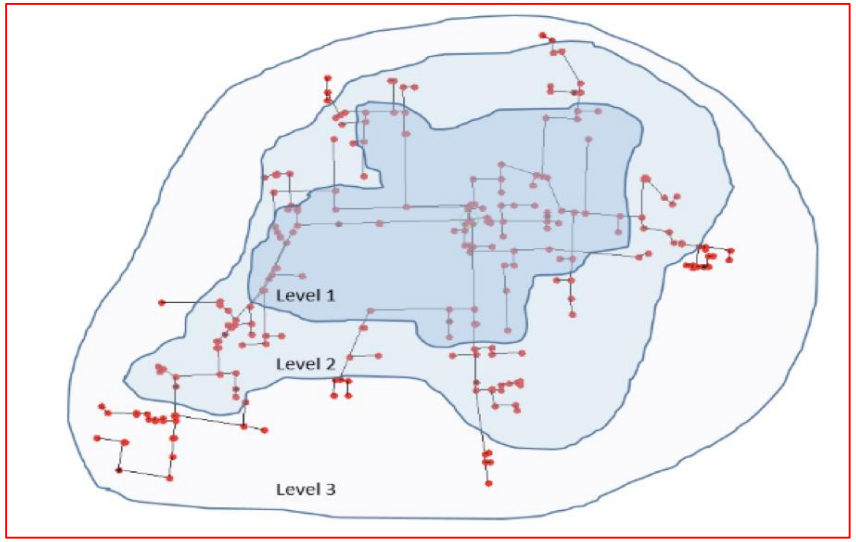


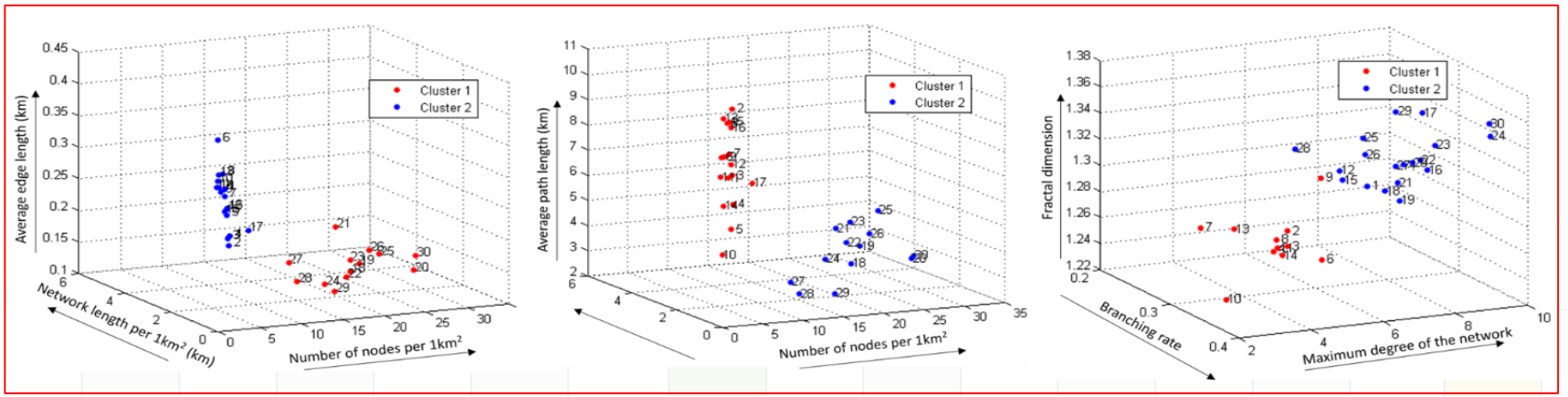
Statically Similar Networks



Statically Similar Networks







Some topological properties are able to clearly characterise the topological differences of urban and sub-urban networks

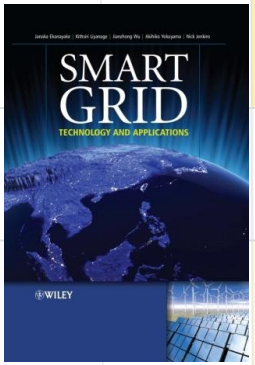
Abeysinghe S, Wu J, Soorihabandara M, Abeysekera M, Xu T, Wang C, Topological properties of medium voltage electricity distribution networks, *Applied Energy*, Accepted, 2017.

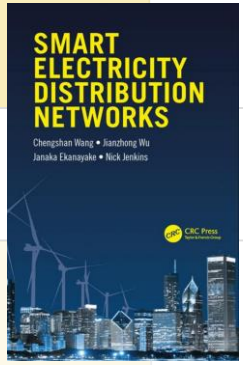
Summary

- **Due to the widespread use of distributed energy resources, the behaviour of distribution networks will become increasingly uncertain, which will lead to operational and planning difficulties.**

- **Robust analysis methods of smart distribution networks will play a critical role in the development of smart distribution networks.**

- **Close-loop robust state estimation with machine learning capability, spatial-temporal model, and statistically similar network generator are able to to better tackle information uncertainties, gaps and errors, from different angles, thus support distribution network operation.**





Thank You!

Prof. Jianzhong Wu

Professor of Multi-Vector Energy Systems
Subject Editor of Applied Energy (IF 7.182)
Email: WuJ5@cardiff.ac.uk