THE UNIVERSITY OF HONG KONG

Department of Electrical & Electronic Engineering

Centre for Electrical Energy Systems

Plenary 2: Multidisciplinarity Research – Power System and Computational Intelligence, PowerTech, Milan, 25th June 2019

The importance of new theory, computation and data-based methods research

– for all the new electrical grids ideas

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Outline

Introduction

Power network science

- Mathematics
- Computation
- Data-based

Engineering challenges

Some suggestions

A discipline not a sandpit

- Study fundamental questions in grids
- Engage the relevant science
- Develop a theory and algorithms core for grids
  - Math-based
  - Data-based (recent)
- Compute with more detail
- Impact the industry practice

➢ Power network science and engineering

Brief History (Power Network Science)

- Early: Russian schools (Gorev in 1930's, St Petersburg; Venikov in Moscow, ..); Magnusson, 1947 Energy functions, dynamics, voltage stability
- 1960-70's: Vasin, Pai, Willems, … Lyapunov, Popov methods
- California 1970's (Korsak, Smith..) Power flow theory
- USA DOE Systems Eng For Power (Fink) 1980's: (Wu, Varaiya in Berkeley; Baillieu, Zaborszky, etc) .. Differential geometry, stability, control theory
- 1990's, 2000's: Voltage stability (Andersson, Hill, Varaiya etc) Bifurcation methods
- 2010's: 'Smart grids'
  a. Modelling issues, stabilization (Ortega, Turitsyn, etc) New Lyapunov
  b. Cascading collapse, synchronism (Dörfler, Motter etc) Network science
  c. Power flow theory (Low, Lavaei etc) Convexity
  d. Network-based stability (Song, Hill etc) Graph theory
  e. Distributed control (Johannsson, Liu, etc) Control theory

Mathematics is changing

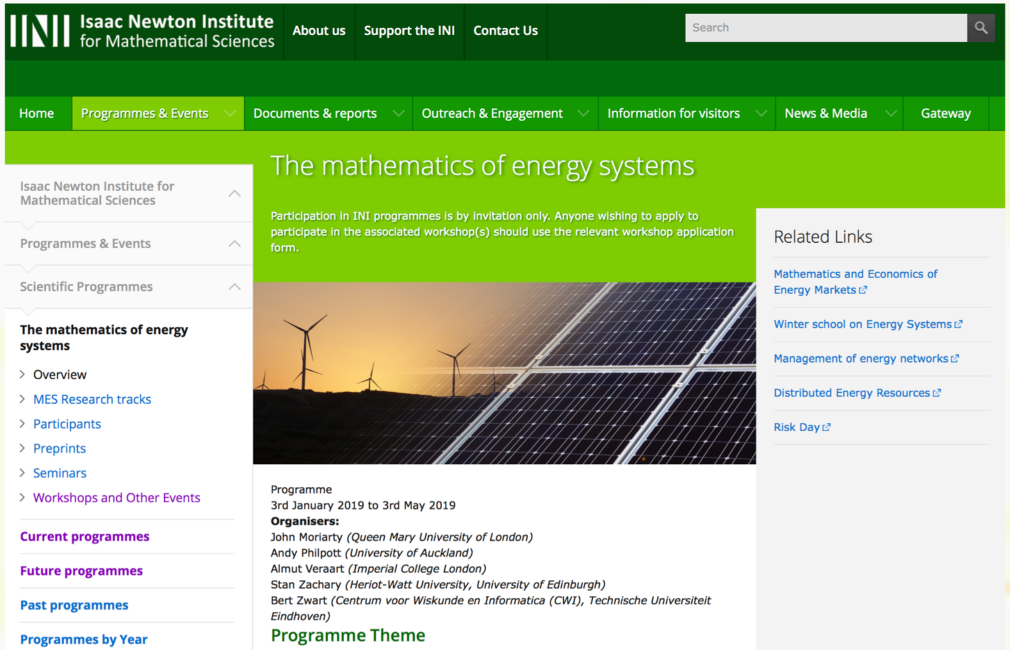
Conferences | May 01, 2019

Scientific Computing, Machine Learning, and Data Science: Recurring Themes at CSE19

By Paul Davis

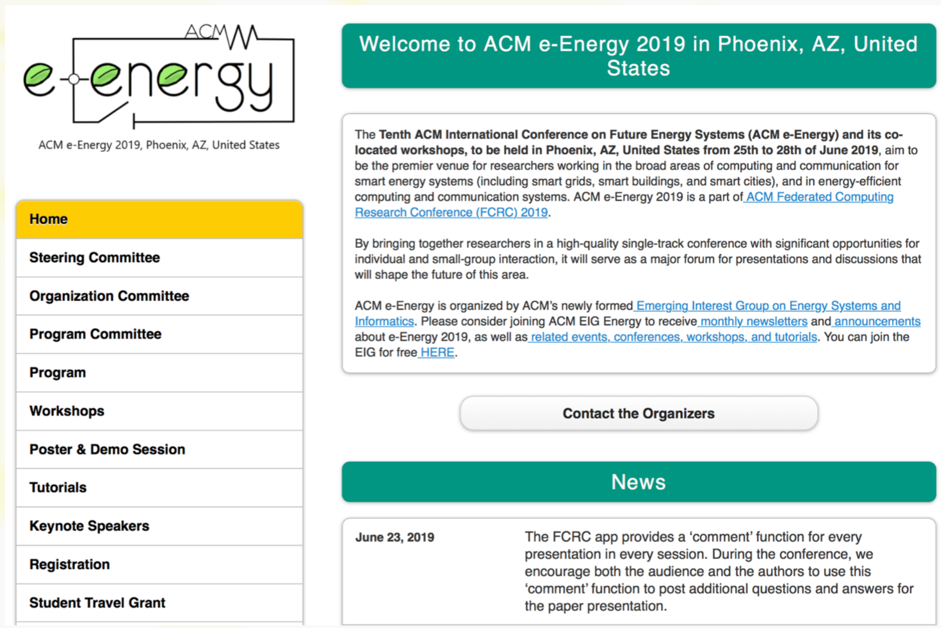
To its nearly 2,000 attendees, the 2019 SIAM Conference on Computational Science and Engineering (CSE19), which took place from February 25-March 1 in Spokane, Wash., may have seemed more like a lively music festival than a specialized scientific meeting. On the central stage, prize lecturers reprised beloved favorites while up-and-comers debuted newer hits. A host of minisymposia on the numerous smaller platforms drew their own devoted audiences. The overall effect was an engaging mix of robust scientific computing, innovative machine learning, and insightful data science. Old barriers fell while new ones were scaled.

Recent meetings



Cambridge Isaac Newton Institute MES Programme, Jan-May 2019

ACM e-Energy Conference, June 2019



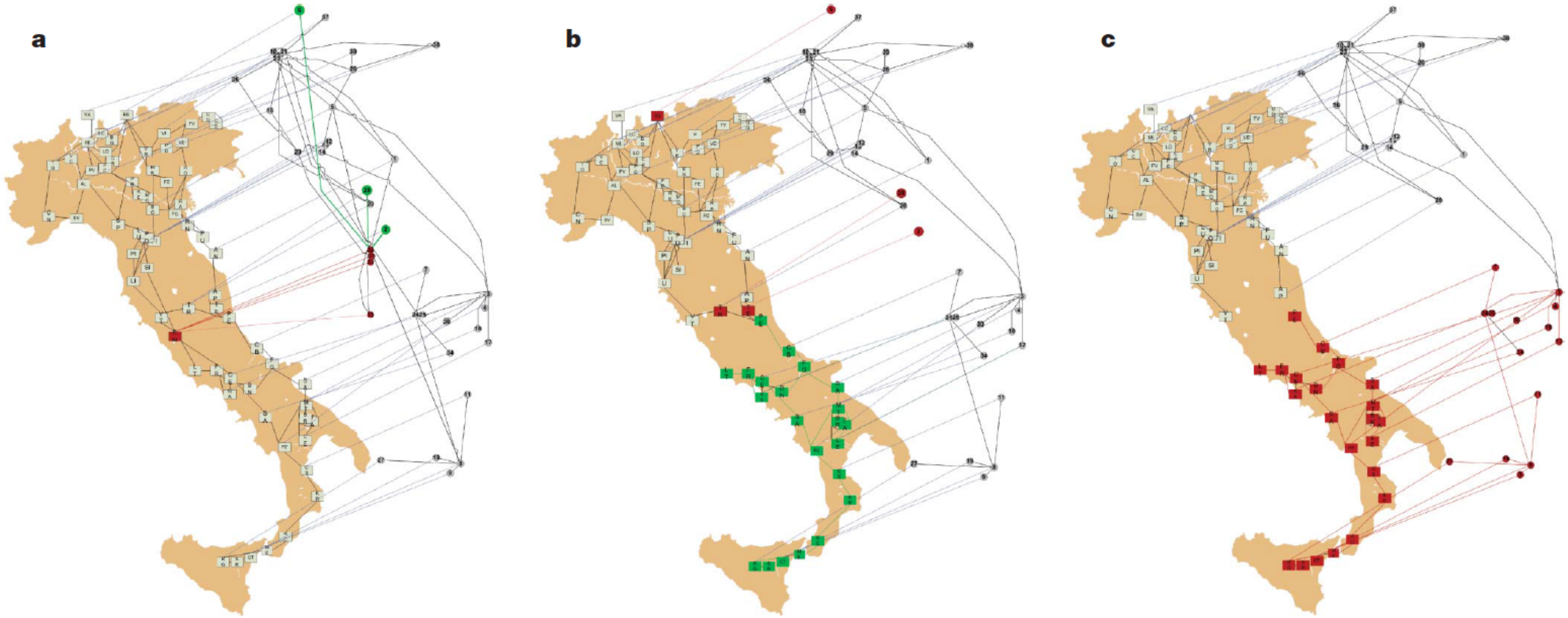


Figure 1 | Modelling a blackout in Italy. Illustration of an iterative process of a cascade of failures using real-world data from a power network (located on the map of Italy) and an Internet network (shifted above the map) that were implicated in an electrical blackout that occurred in Italy in September 2003[20]. The networks are drawn using the real geographical locations and every Internet server is connected to the geographically nearest power station. **a**, One power station is removed (red node on map) from the power network and as a result the Internet nodes depending on it are removed from the Internet network (red nodes above the map). The nodes that will be disconnected from the giant cluster (a cluster that spans the entire network) at the next step are marked in green. **b**, Additional nodes that were disconnected from the Internet communication network giant component are removed (red nodes above map). As a result the power stations depending on them are removed from the power network (red nodes on map). Again, the nodes that will be disconnected from the giant cluster at the next step are marked in green. **c**, Additional nodes that were disconnected from the giant component of the power network are removed (red nodes on map) as well as the nodes in the Internet network that depend on them (red nodes above map).

Ref: Buldyrev et al., "Catastrophic cascade of failures in interdependent networks," Nature, 2010.

On models

- ‘Science’ models often very poor, but ideas are good
- New questions everywhere across the various approaches, e.g. load modelling now must include PV, EV/storage etc
- Data-based approaches lead people to ask if we need models?

➢ Fragmented topic

Why do we have theory?

- Have guarantees: A implies B
- Transferring the burden of assumptions, e.g.
  - for SIMB system, EAC implies TS
  - assumptions about machines are easier to live with than about system behaviour
- If assumptions are known, we can use theory to obviate doing (some) tests
- Certificates in other areas, e.g. aircraft approvals

Ref: Bitmead, “Engine controller certification: the role of theory in practice,” CCDC 2019.

Other approaches

- Computation-based
  - More detailed models
  - Lots of simulation cases
  - Each simulation gives 'one point' in a relationship
  - Can be scientific, e.g. Monte Carlo sampling
  - But needs more CS involvement

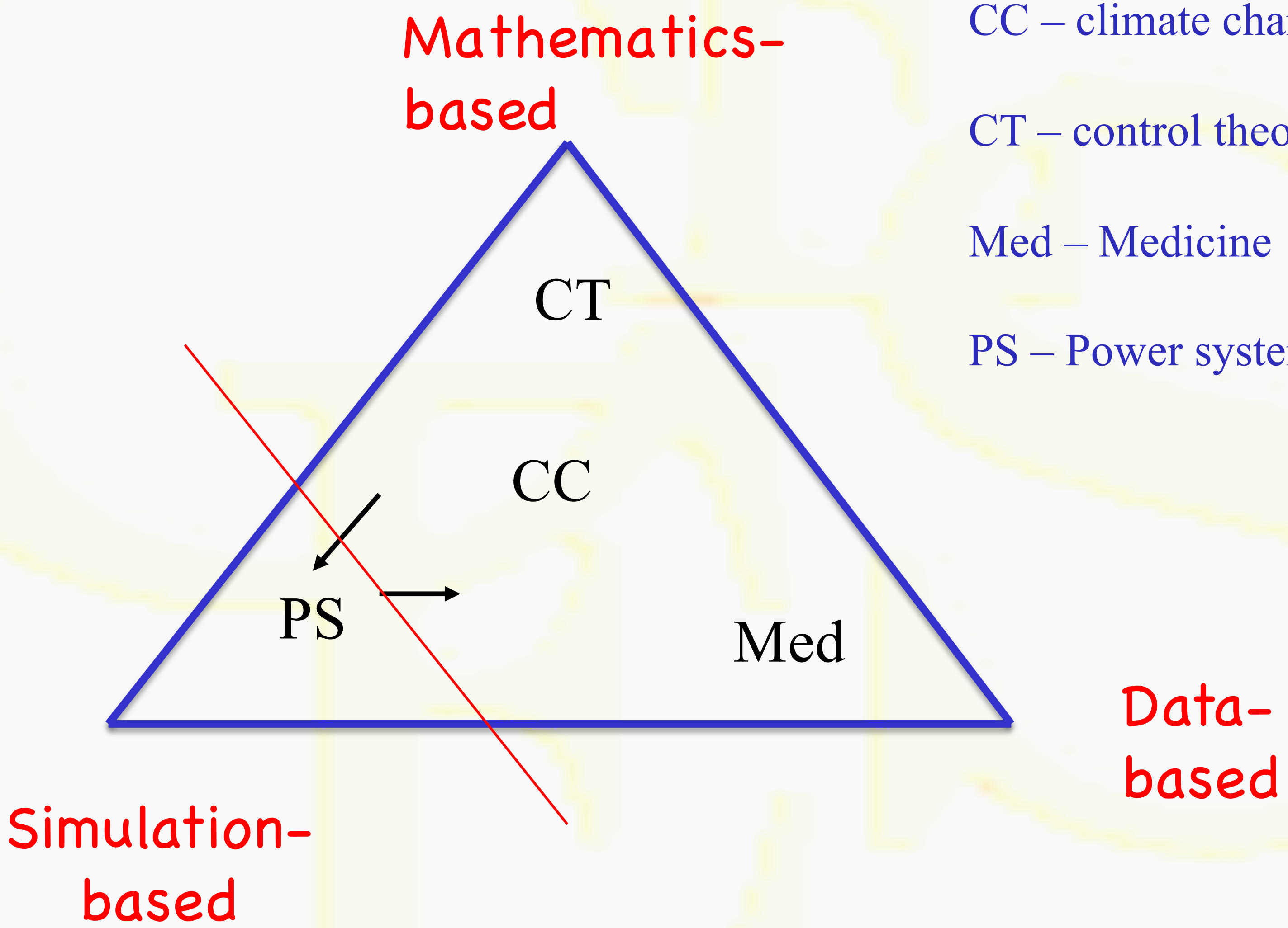
- Data-based
  - On-trend approach (money for research)
  - No explicit models
  - Use Machine Learning from Computer Science to infer relationships

➢ Ways to include system specific features, e.g. topology, give better research problems

In practice – hybrid approach

- Theory gives:
  - Mathematical indicators, 'certificates' to use in computations and data-based methods, e.g. a stability index
- Combine all three approaches:
  - Derive stability limit as exact in simpler situation
  - Carry out large number scenario-based simulations
  - Use these as data for deep learning techniques to derive a stability limit, e.g. China EPRI's EEAC technique

Math-comp-data triangle



CC – climate change

CT – control theory

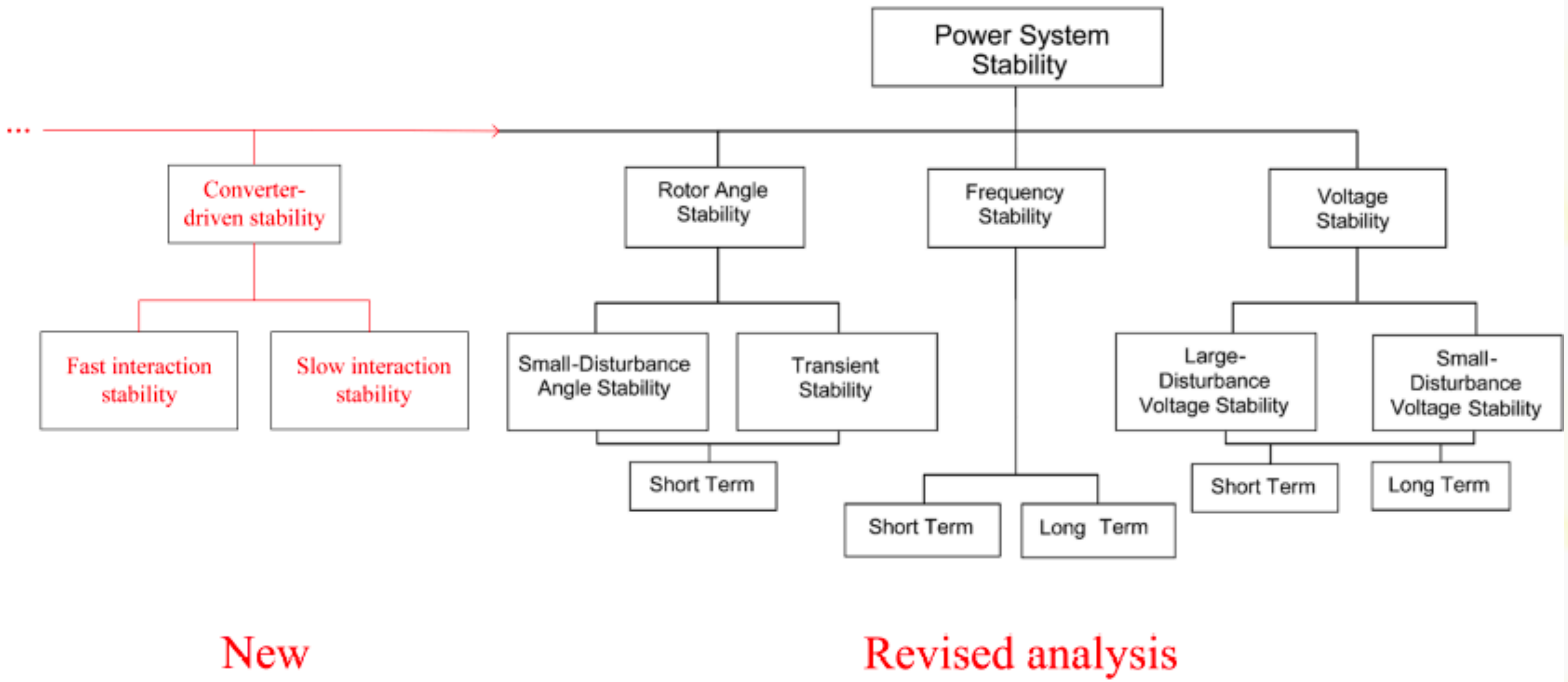
Med – Medicine

PS – Power systems

Eight Big Scientific Questions for FGs

1. New (faster) stability of high converter systems
2. Granular/distributed everything: markets, control etc, i.e. DER, aggregator, DO, DSO, RTO, ISO
3. Computation scaling (more computer science)
4. Data-based (adaptive) control
5. Better structures
6. Grid flexibility
7. Trilemma (long-term management)
8. Resilience integrated systems

1. New stability



Ref: IEEE TF in progress

Impact of DG connection topology on stability

- Theorems

  1) Algebraic connectivity

  Then $\lim_{n\to\infty} \lambda_2(L_{\mathcal{G}}) = 0$ if there exists a node i such that $\lim_{n\to\infty} d_i/n = 0$.

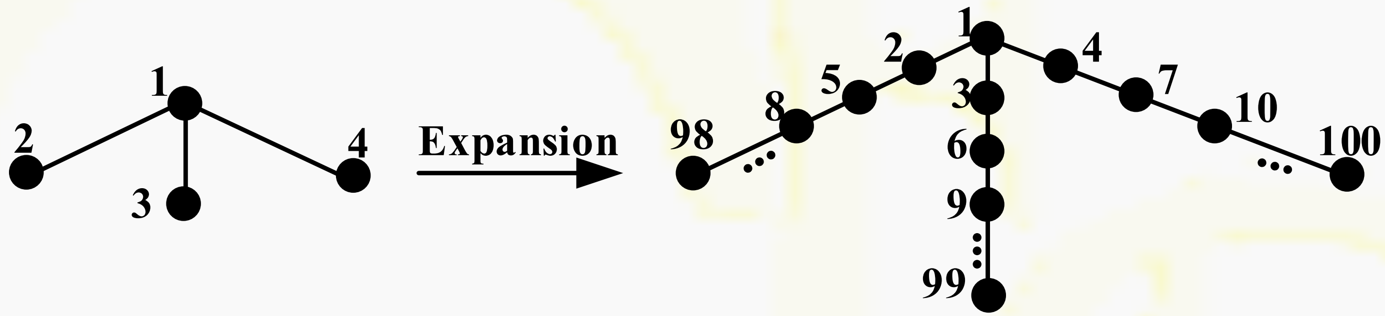
  where n is number nodes and d_i is degree of node *i.*

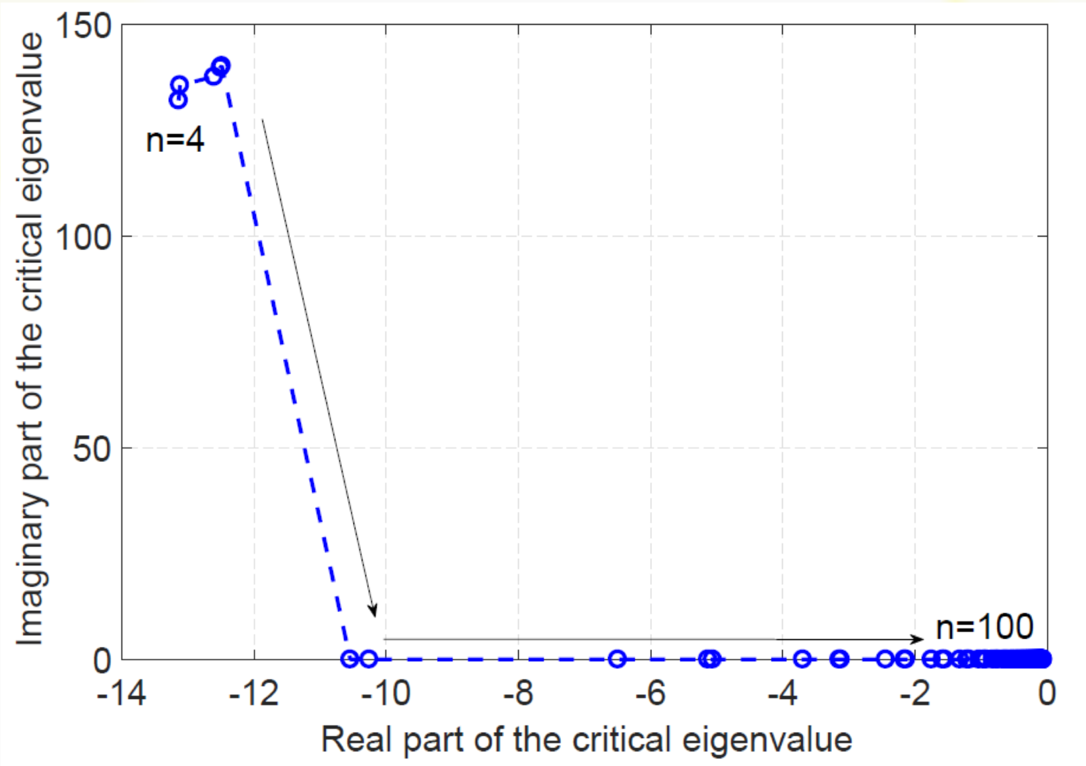
  2) An eigenvalue of the system dynamic Jacobian approaches zero if the algebraic connectivity of the microgrid approaches zero

  Note: the precondition $\lim_{n\to\infty} d_i/n = 0$ holds in the common tree-like connection where new DGs are connected to nearby nodes via single lines

Ref: Y. Song, D. J. Hill, and T. Liu, "Impact of DG connection topology on the stability of inverter-based microgrids," IEEE TPWRS, to appear.

Case Study



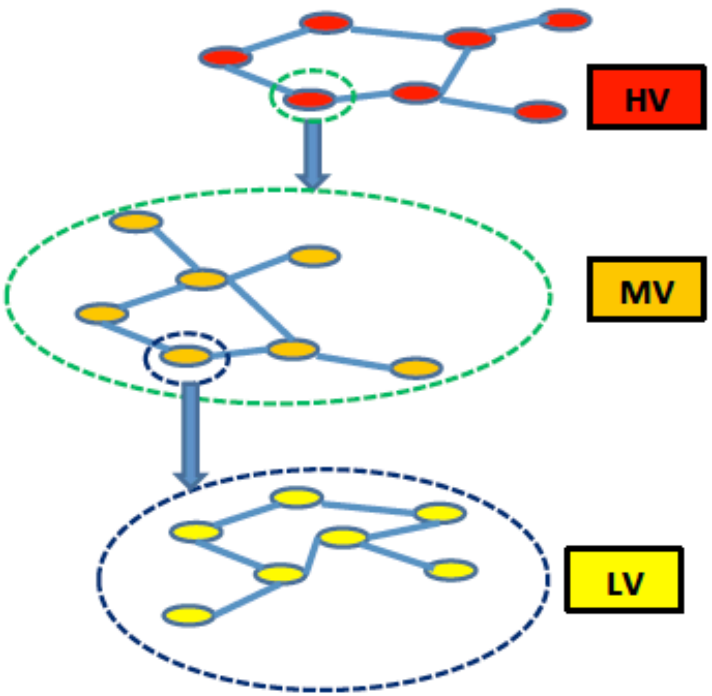


An eigenvalue of system dynamic Jacobian approaches zero with the expansion

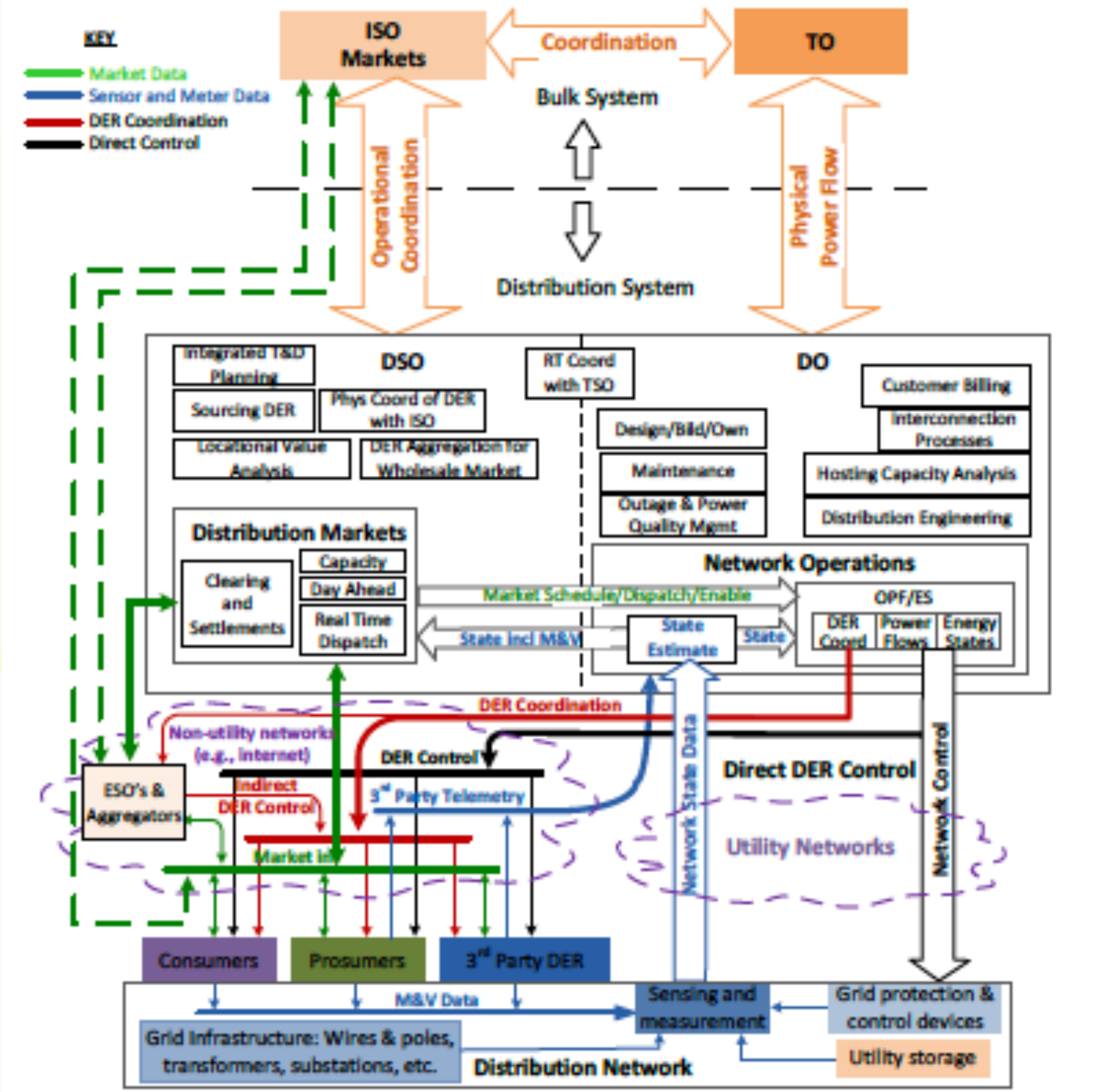
2. Granular/distributed methods

- DER now across houses to UHV grids (kW to GW)
- Coordination now flexibly across levels
- Planning, monitoring and control now needs distributed methods

Granular structure view



- d_i could be an aggregated electric spring system, storages, air-conditionings
- d_i can be served as a reference signal for an aggregator to control million of LV level devices
- How to control those LV devices such that they can work together to behave like d_i

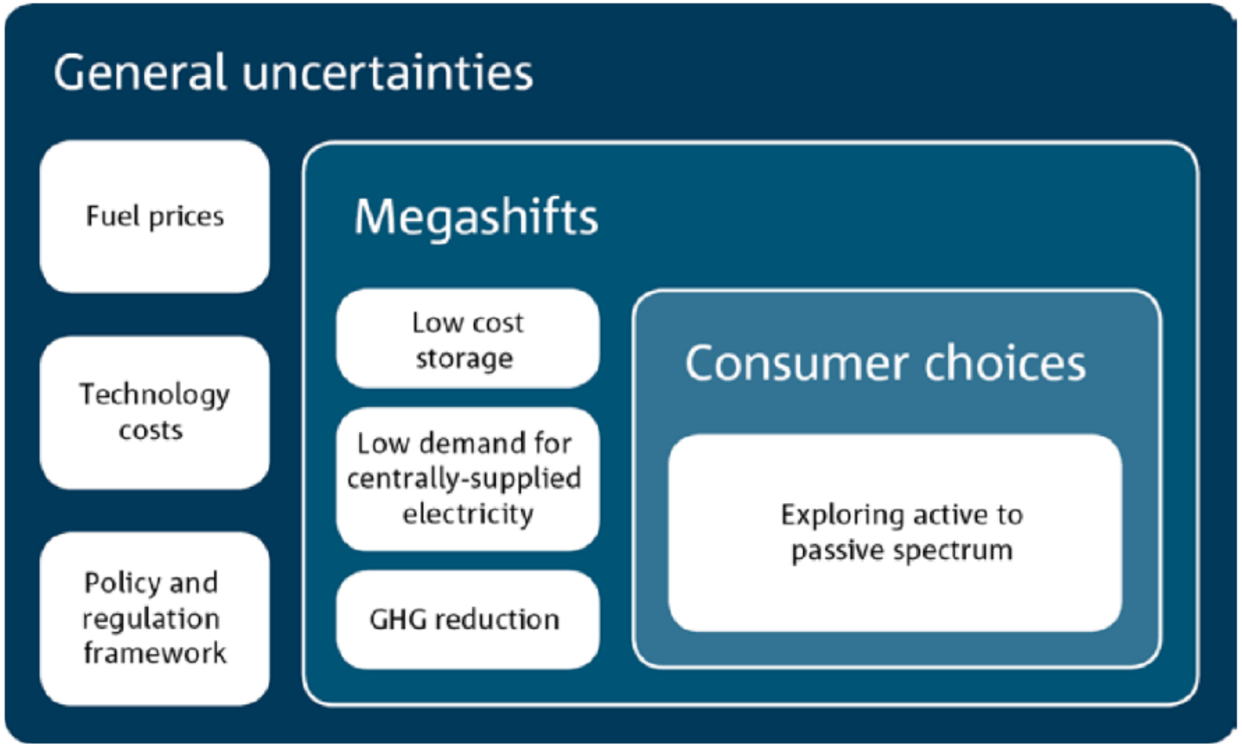


Ref: Price, "Distributiion market designs and business models," to USEA, 2017.

3. Computation

- Ad hoc simulation vs scientific computing
  - But large numbers of scenarios to reflect increased uncertainty
  - Huge computation times
  - More computer science based work needed

Scenario development framework



Ref: CSIRO, "Change and Choice-The Future Grid Forums analysis of Australias potential electrical pathways to 2050: Final Report," Tech. Rep. December, 2013.

Minimum RoCoF in an Australian study

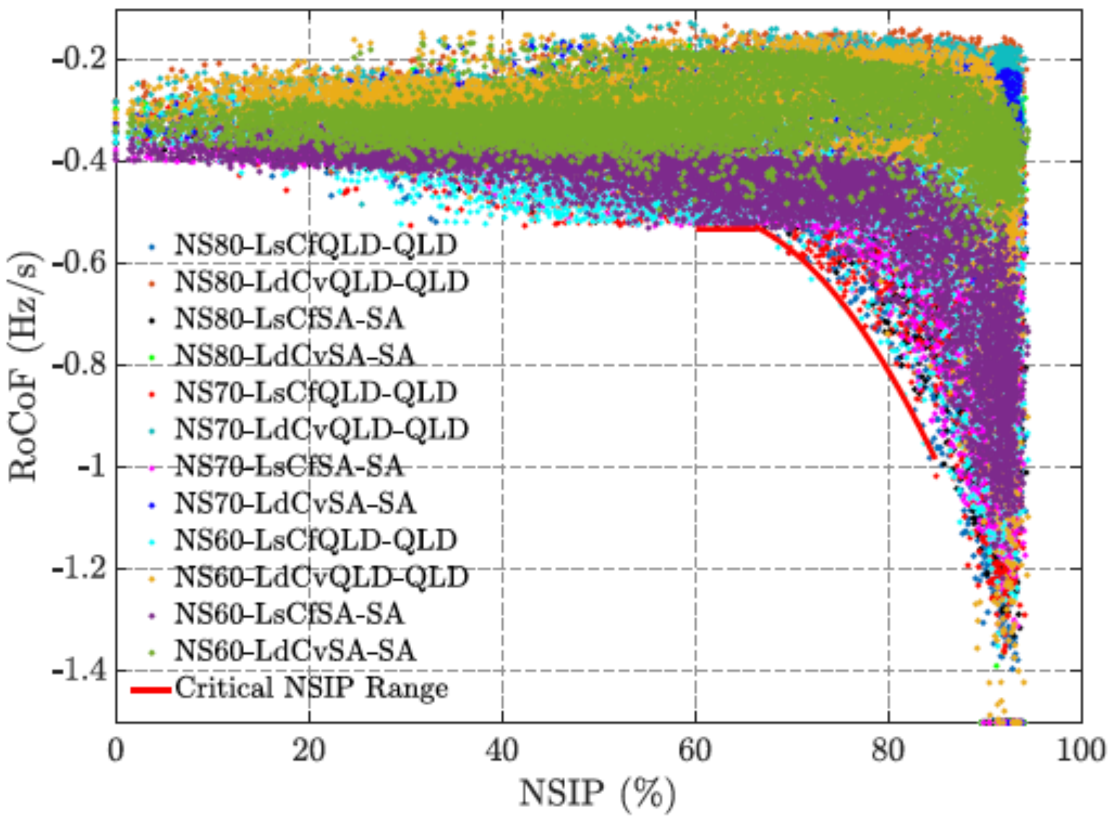


Fig. 11. Minimum RoCoF following a credible contingency based on NSIP.

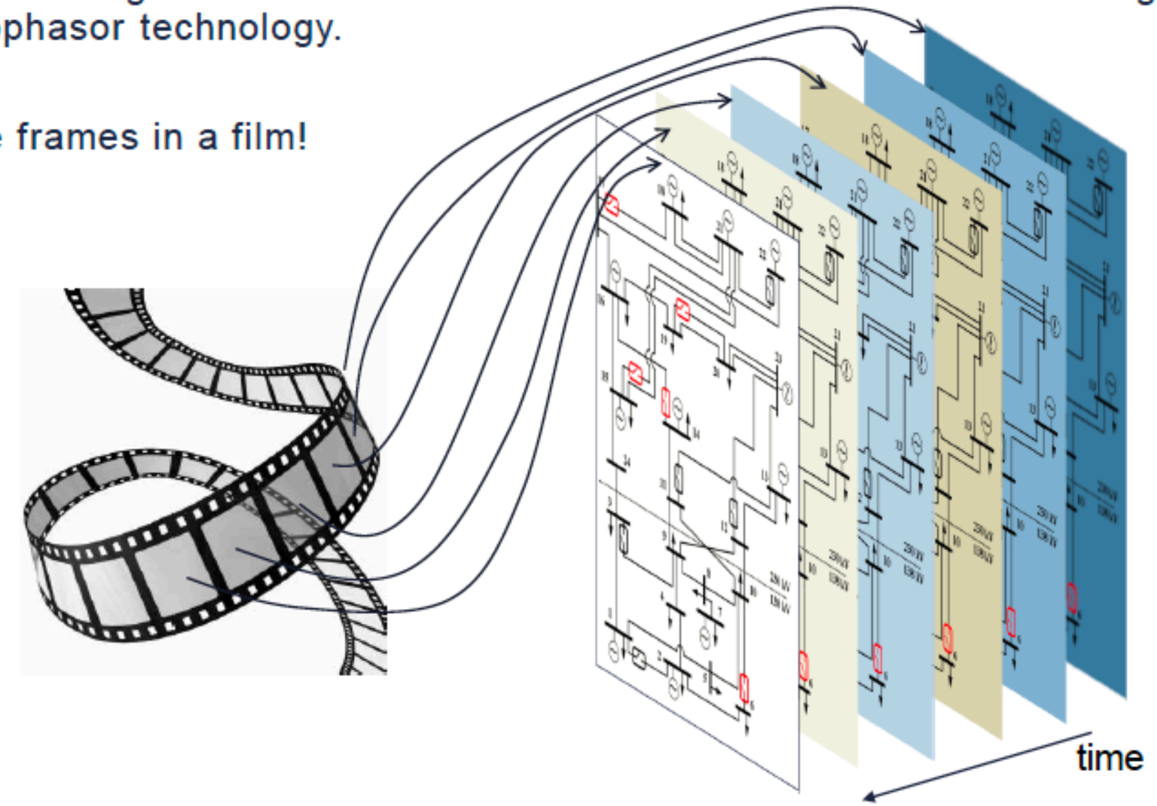
Ref: Ahmadyar et al., "A framework for assessing renewable integration limits with respect to frequency performance," IEEE TPWRS, July 2018.

4. Data-based

The continuous monitoring of a power system may now benefit from learning instead of relying on static models

All data arriving at the SCADA in a Control Center can become time-tagged with synchrophasor technology.

It is like frames in a film!



From Miranda, HK PolyU, Sept 2017.

Black-Box Deep Learning for DSA

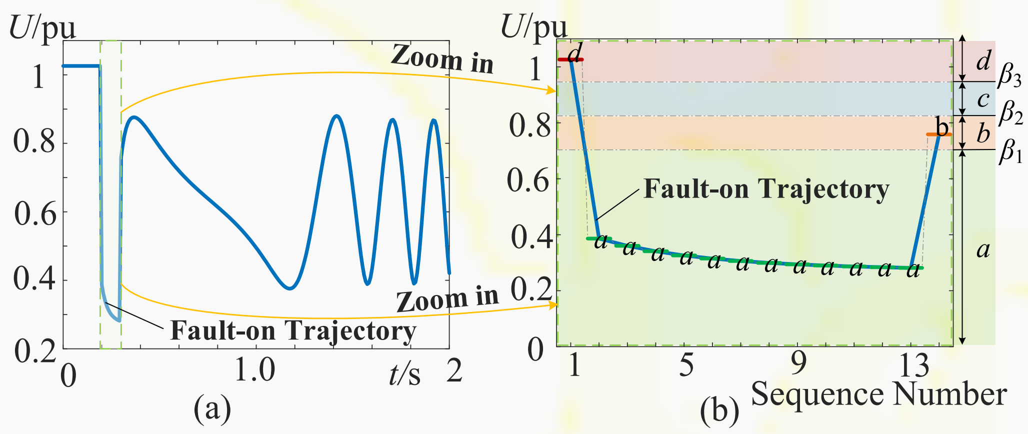
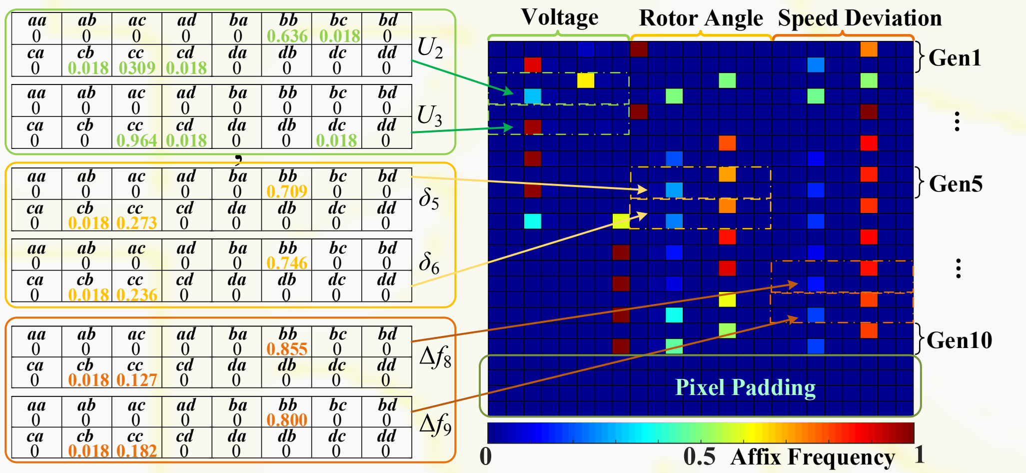


Illustration of SAX based trajectory quantization



(a) Statistics of affix frequencies (b) Bitmap depiction based on affix frequencies

Illustration of 2-D pictorial representation

Ref: Zhu, Hill and Lu, to appear IEEE PES GM 2019.

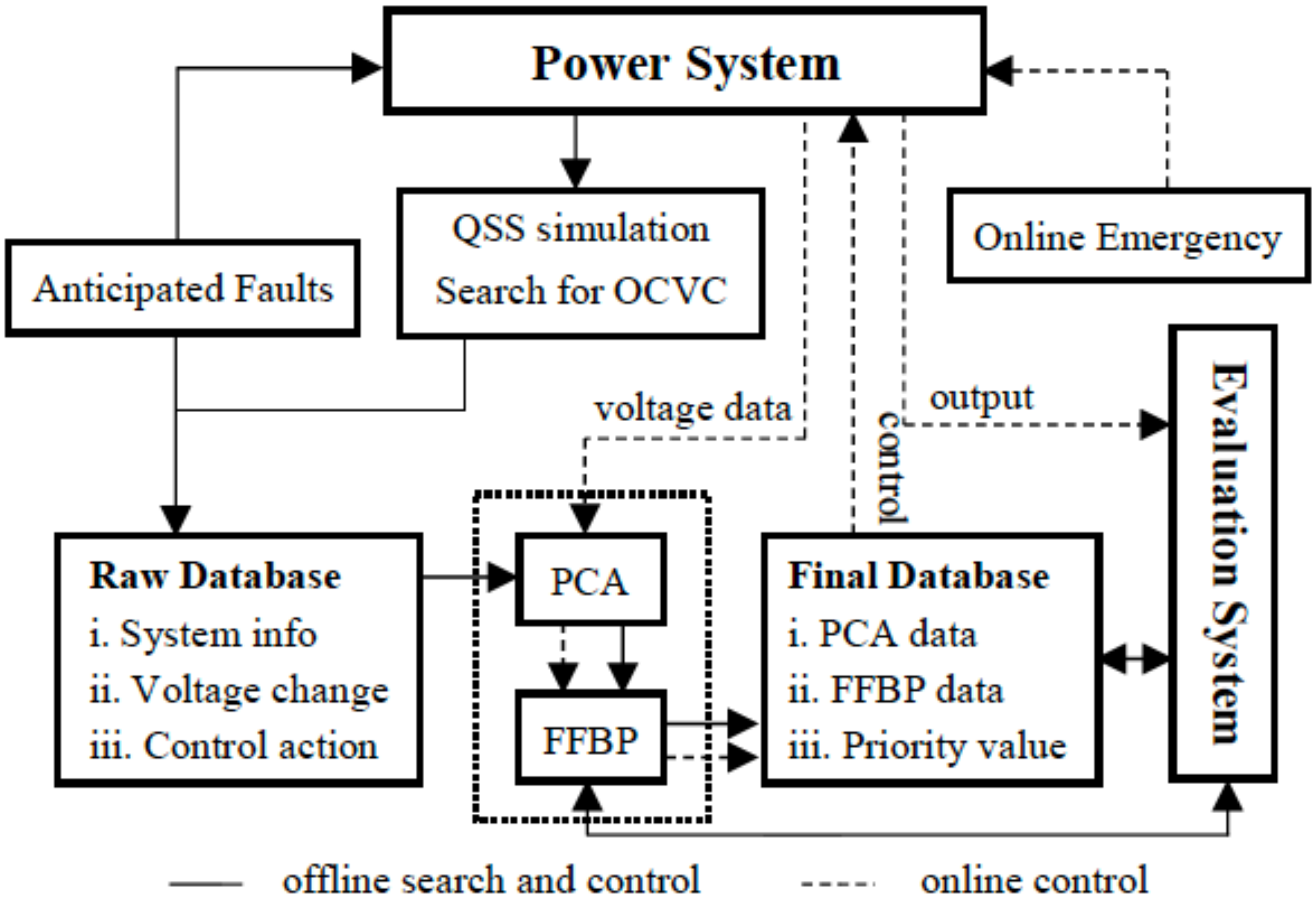


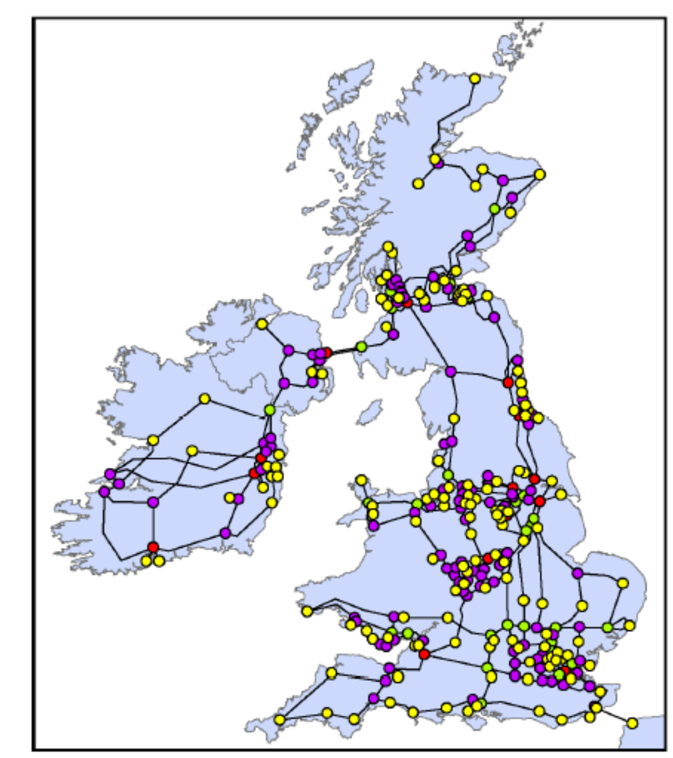
Fig. 1. Data-Based Learning and Control System for LTVS.

Ref: Cai, Ma and Hill, submitted IEEE TPWRS
Also Dorfler talk, INI MES, 2019

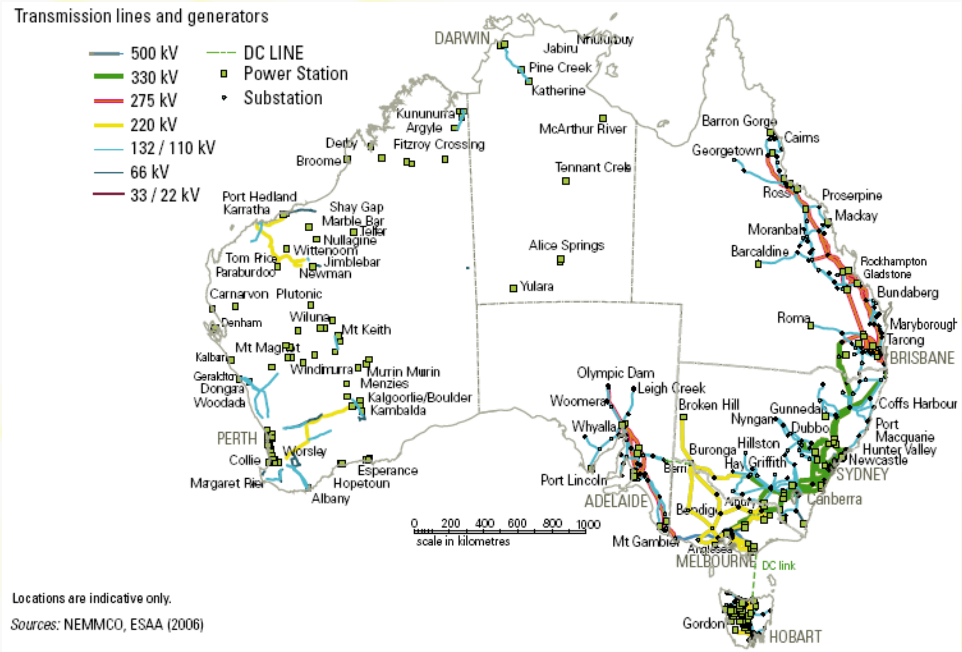
5. Better structures

- Practice focusses on one grid and might borrow from others
  - But what about future grids
  - Science gives general ideas for all grids
  - Influences everything, e.g. stability MGs seen above

Topologies of power grids



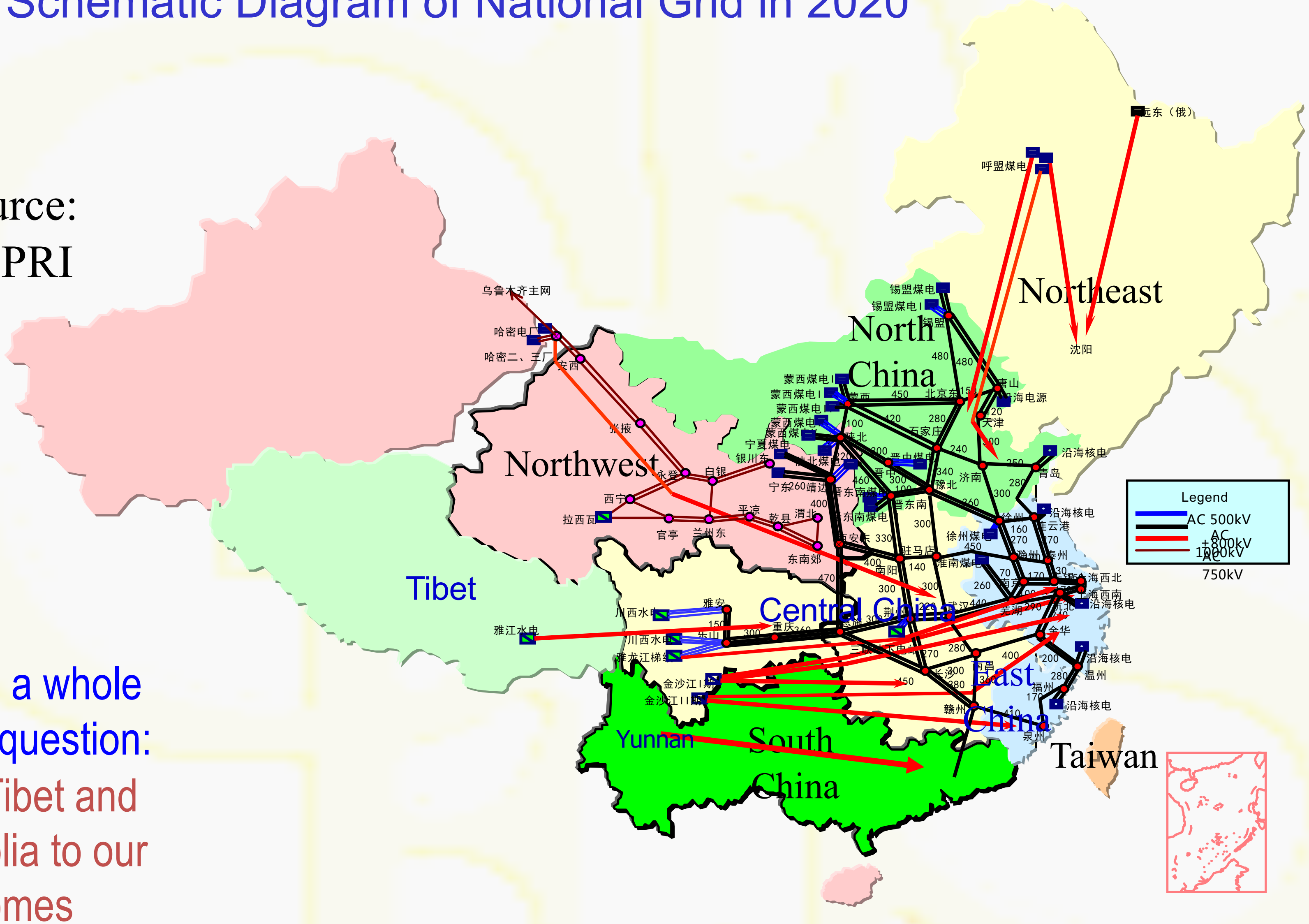
United Kingdom and
Ireland power grid



Australian power grid

Schematic Diagram of National Grid in 2020

Source:
CEPRI



This is a whole of grid question: from Tibet and Mongolia to our homes

6. Grid flexibility

- Stories of WFs cannot operate full output
- Controllable corridors of power needed
- Planning/reconfiguration
- "Used to have generation following demand; now need grid and demand following generation" - Yue Song

Grid inadequacy assessment

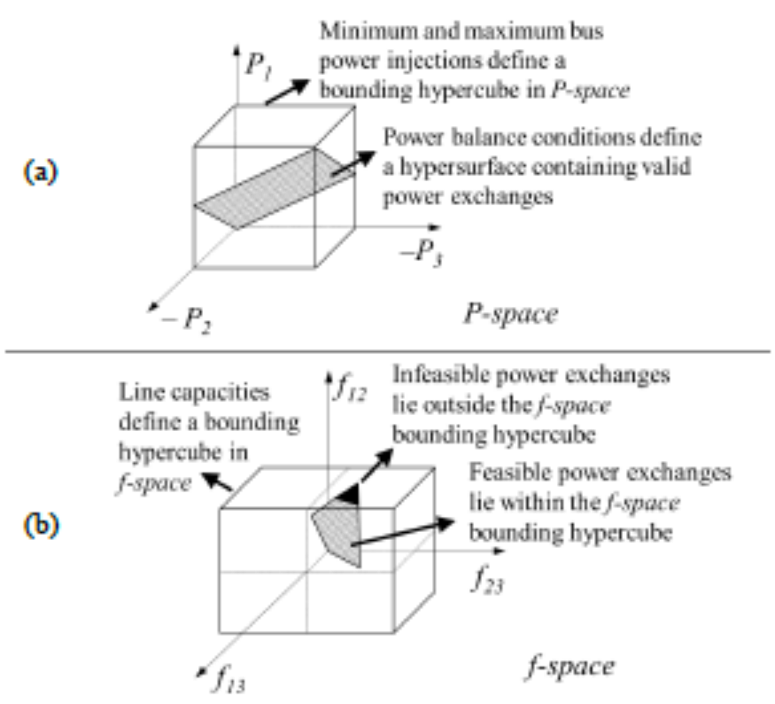


Fig. 2: Visualization of the constrained DC power flow model as a vector mapping: (a) a hypersurface represents the set of valid power injection scenarios in the power injection space, *P-space*, and (b) the vector projection of the hypersurface within the bounding hypercube in the line power flow space, *f-space*, determine feasibility.

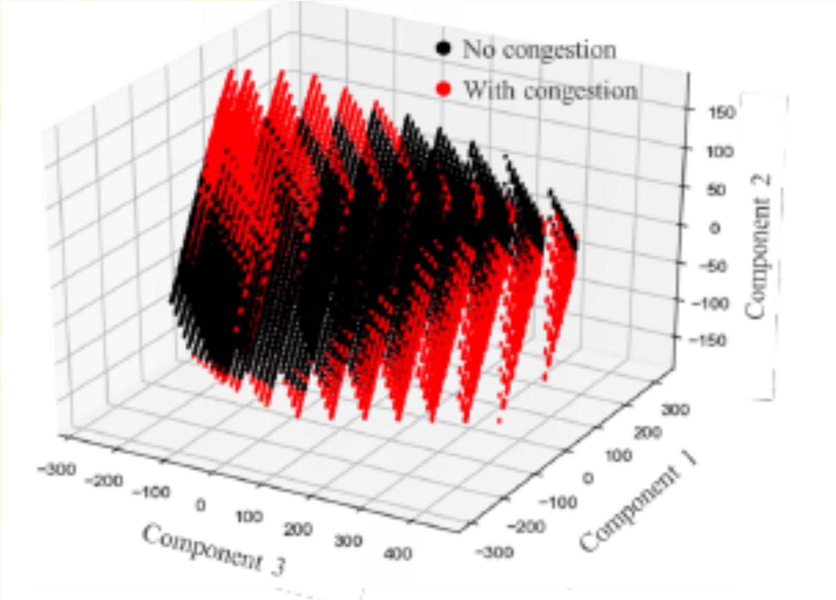
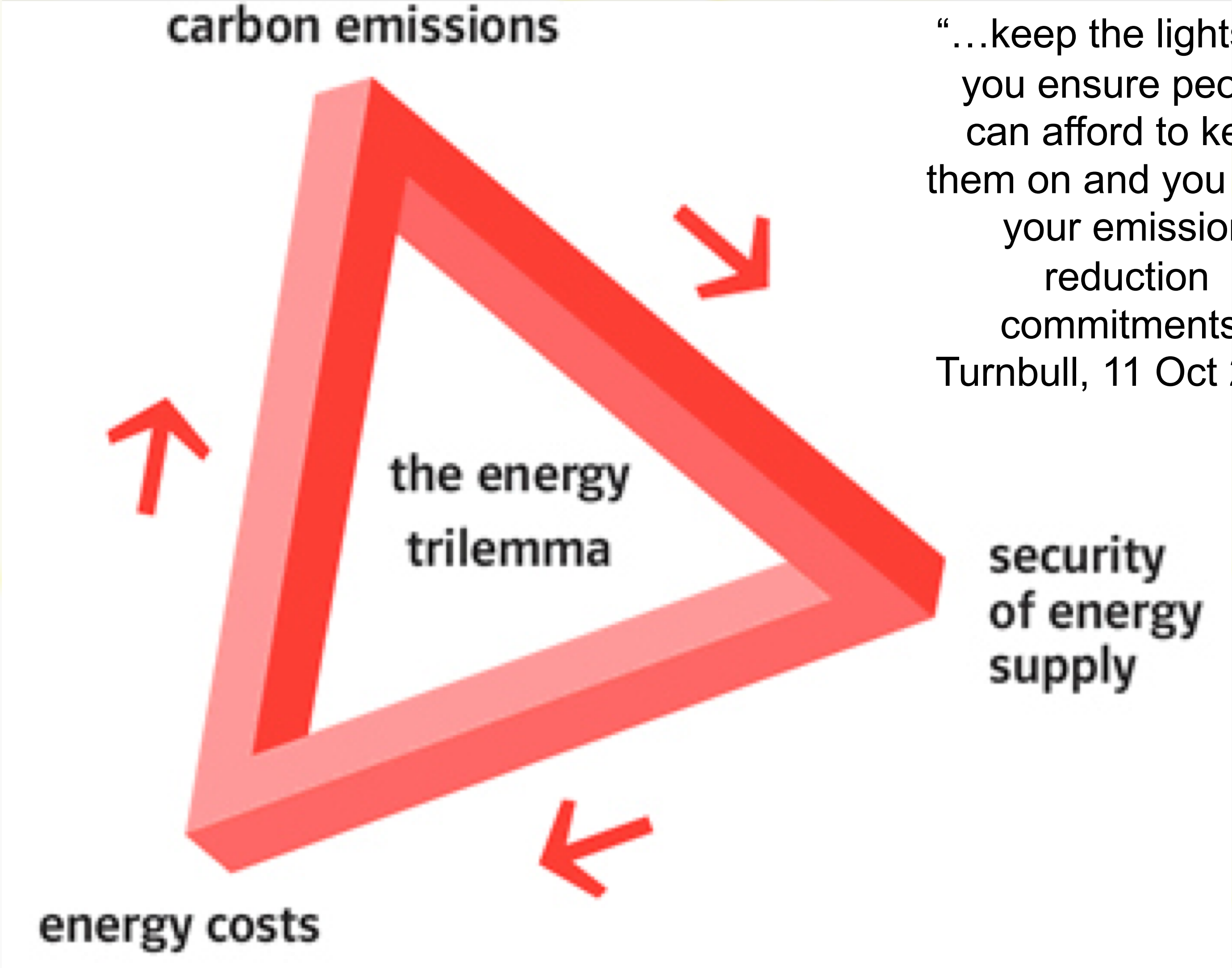


Fig. 5: Three-dimensional visualization of the 6-bus test system infeasible set using a scenario pool ($T = 3{,}139{,}831$) and PCA.

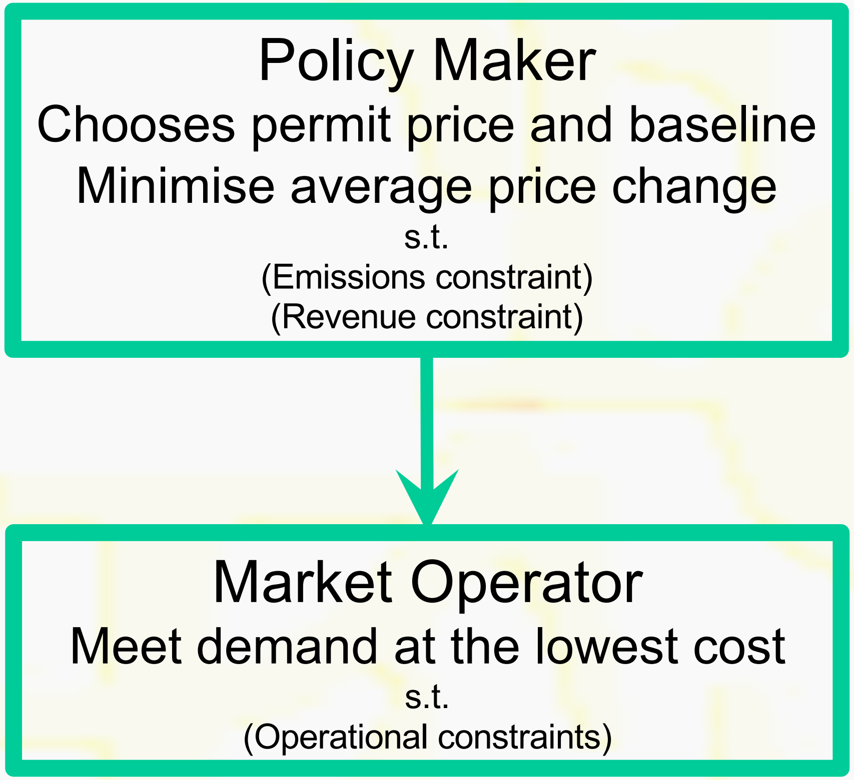
Ref: Tio, Hill and Ma, " Grid inadequacy assessment against power injection diversity from intermittent generation, dynamic loads, and energy storage," submitted to IJEPES

7. Energy trilemma



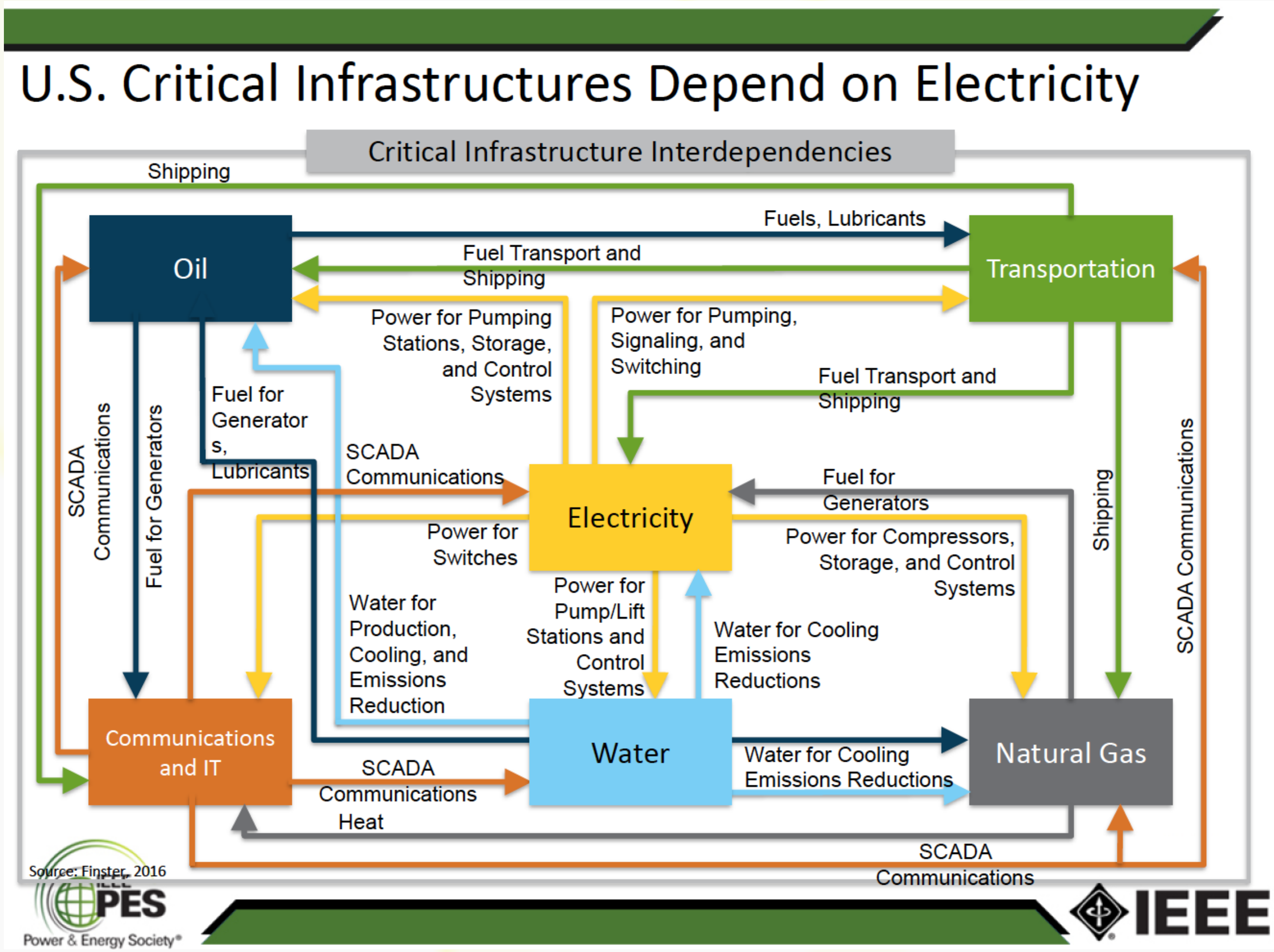
"…keep the lights on, you ensure people can afford to keep them on and you meet your emission reduction commitments"
Turnbull, 11 Oct 2017

Energy Trilemma Decision and Control



A.Xenophon and D.J.Hill, “Wholesale electricity price targeting via refunded emissions payments,” to appear Applied Energy.

8. Resilience integrated



Ref: PESISGTNA20180006 (Panel Session ISGT 2018)

How to approach integrated systems?

- Integrated systems give interdependent (network of) networks:
  - Future engineering systems provide a trilemma (cost, security, clean) solution for energy and information flows across integrated networks (IIoT, CP systems etc)
- Mathematics, computation or data-based for such complexity?
  - Researchers have plenty to do yet

Longer-term? 2050?

- Public energy discussions by consumers, industry, economists, engineers, scientists, politicians and journalists …
- Projects and workshops which have themes like 'energy for 2050' and some countries have clear long-term goals in terms of the energy trilemma
- Now have a large set of new ideas for new technologies, which we all, e.g. microgrids, smart grids, supergrids based on DER, storage, DR and much more, which can all address the long-term goals.
- Then a large multi-disciplinary community of power engineers as well as physicists, control and communication engineers, computer scientists and economists are pursuing research on aspects of the systems problems arising.
- What next?

One study on analytic foundations

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This PDF is available at http://nap.edu/21919

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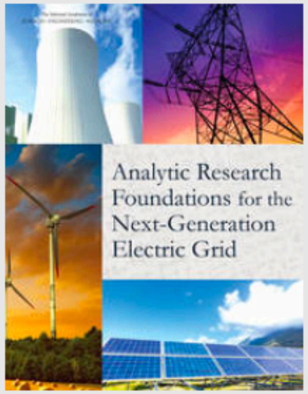

Analytic Research Foundations for the Next-Generation Electric Grid (2016)

DETAILS

161 pages | 8.5 x 11 | PAPERBACK

ISBN 978-0-309-39231-0 | DOI 10.17226/21919

Some final thoughts

- All this effort is too fragmented and there is the need to recognise a core *power* network *science and engineering* discipline where new theory, computational techniques, machine learning and data-based ideas can flourish
- Journals rather ad hoc in representing this idea
- Recall the Systems Engineering for Power Program in the USA started in the late 70's
- For instance, we need to show how high renewable grids can operate with acceptable stability limits
- It is also important that this community influence the public discussions to show there are scientific answers to many questions …