Realizing Future Energy Grid Potential With the Power of Intelligence

Ke Meng
Lecturer
School of Electrical and Information Engineering
Email: ke.meng@sydney.edu.au

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Contributors to this Talk

- **Students**
  - Mr Wang Zhang (USyd, HKU)
  - Mrs Yuan Zhang (USyd)
  - Mr Weicong Kong (USyd)
  - Mrs Xiaodan Gao (UoN)
  - Mr Dongxiao Wang (UoN)
- **Faculty members**
  - Prof Joe Dong (USyd)
  - Prof David Hill (HKU)
  - A/Prof Zhao Xu (PolyU)

A Reminder of History for Context

Year	Events
Circa 1920-	The electric power sector started as a collection of unconnected townships with their own generation and demand – effectively local grids and distributed generation
Circa 1930-	Townships interconnected to share reserve
Circa 1920-	Large scale remotely located generation emerged around fuel (coal and hydro) – increasing economies of scale
Circa 1920-60	Major transmission developed from remote sites to cities State electrification programs
Circa 1950-90	Township generation progressively retired – withered away – but connected by state-wide grids – electrification of the state seen as a major positive
1980-2000	Central generation dominates
2000-	Technology and policies for distributed generation returning distributed generation to economic prospect
2010-	Beginning of reversal to historical trend and move to off-grid township based on solar/wind/thermal and storage

Renewable Integration

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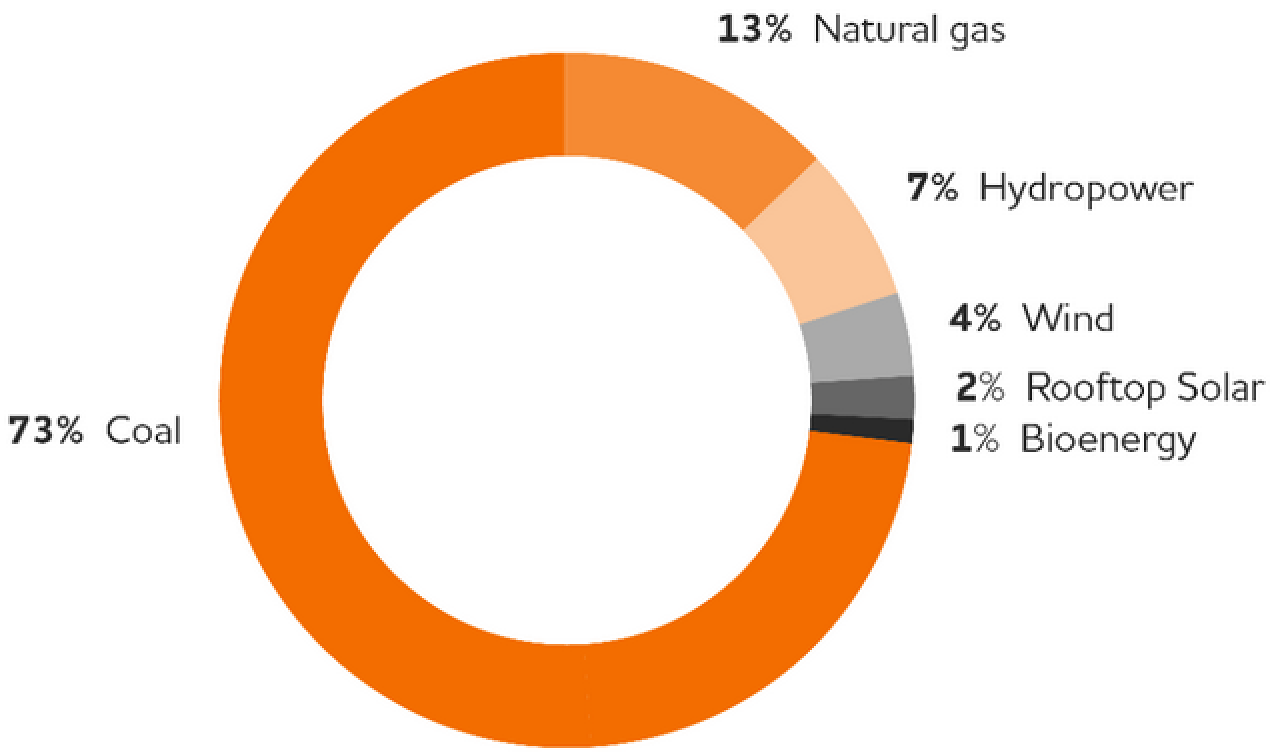
Energy in Australia



Renewables (Cont.)

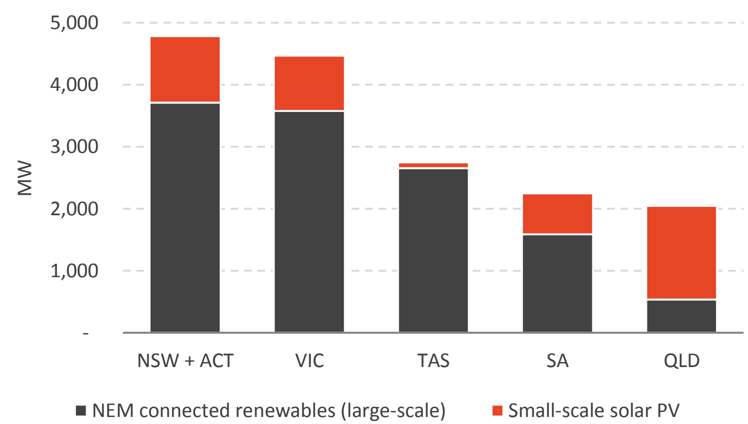
Drivers and Targets

- Increased interest and investment in renewable energy sources
- Drivers:
  1. Environmental concerns, carbon emission
  2. Energy security, geopolitical concerns
- Ambitious targets:
  1. AU: 20% renewable penetration by 2020
  2. US: 20% wind penetration by 2030
  3. DK: 50% wind penetration by 2025
- **How will we meet this aggressive target in Australia?**

Renewables (Cont.)

Where and how much?

- **Transmission-level**: large-scale onshore/offshore wind farms, large PV facilities, thermal-solar plants
  1. away from population centres
  2. need transmission investment
  3. centralized dispatch
- **Distribution-level**: small rooftop PV
  1. local generation/consumption
  2. transition to off-grid
  3. decentralized control
- **Large fraction of renewable investments will be on distribution-level.**



Renewables (Cont.)

Enabling Technologies

- Balancing supply and demand
- Grid-side:
  1. better planning
  2. improved forecasting
  3. stronger transmission system
- Demand-side:
  1. microgrid, energy storage, electric vehicles
  2. HVACs
- Market-side:
  1. new incentive strategies
  2. trading schemes

Transmission Level

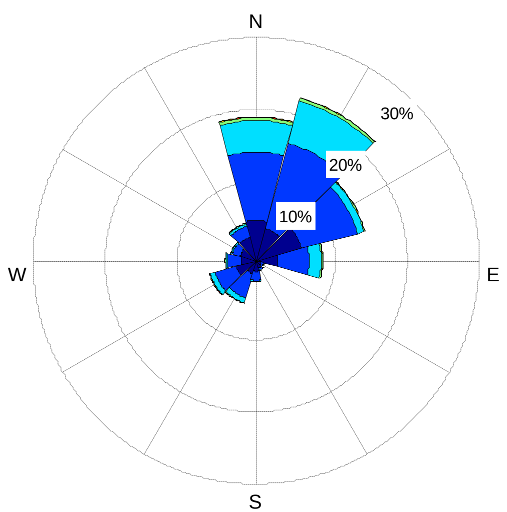
Wind Farm Planning

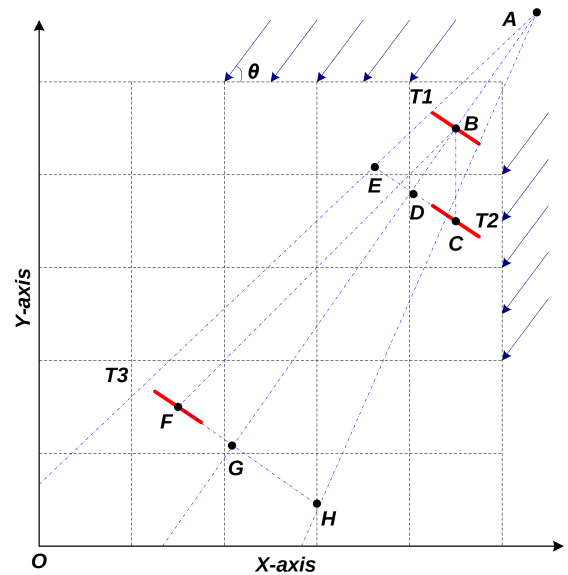
Background

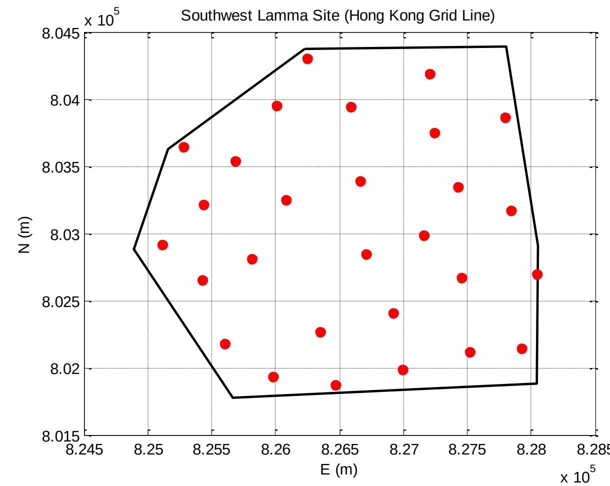
– Design process

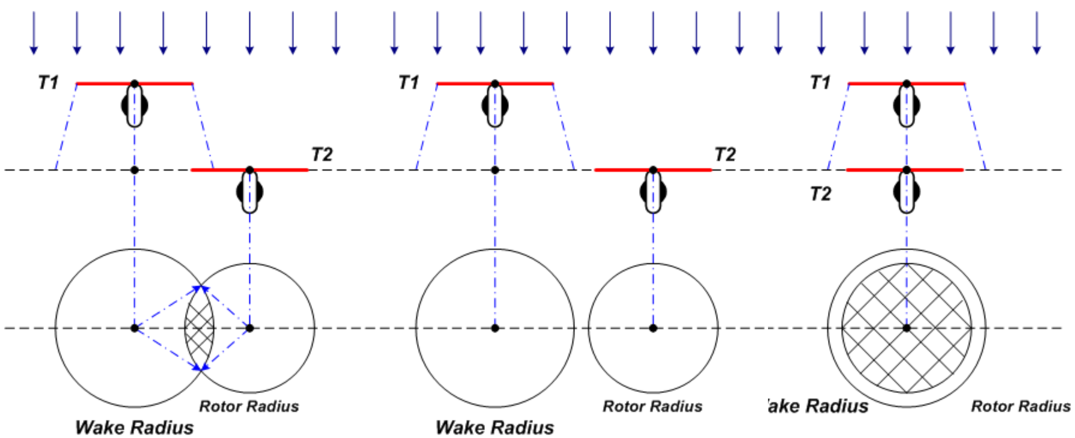
1. potential site selection (wind resource, land use, topography, hydrology, soil, etc.);
2. potential impacts assessment (fire, flora and fauna, vegetation, heritage, noise, landscape and visual, aviation, transportation, telecommunications, socioeconomic, etc.);
3. onsite turbine micrositing determination (turbine type, wake effect, terrain, etc.);
4. electrical layout design and electromagnetic interference evaluation (cables, transformers, reactive power compensation, energy storage, reliability evaluation, etc.).

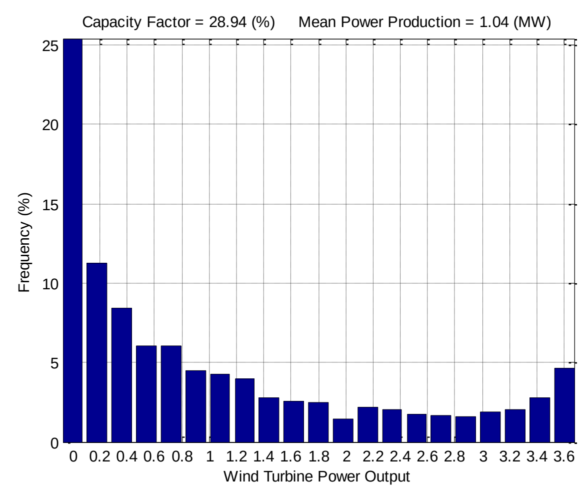
Micrositing Optimization





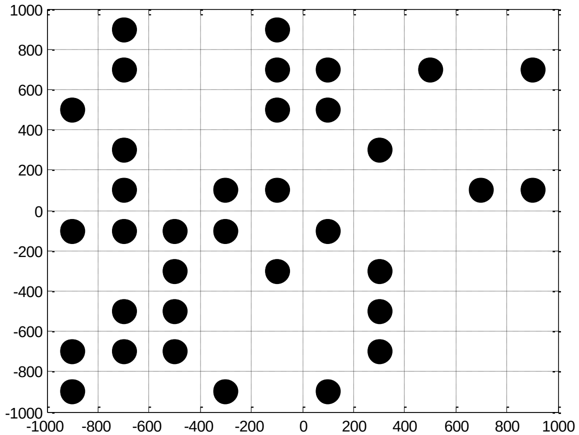




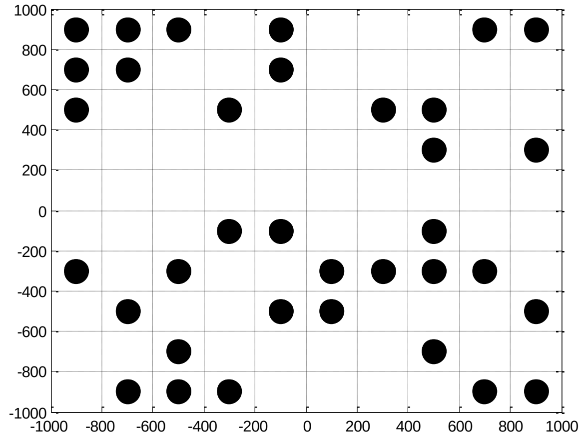


K. Meng, Z.Y. Dong, and K.P. Wong, HEC Wind Project Report, 2010.

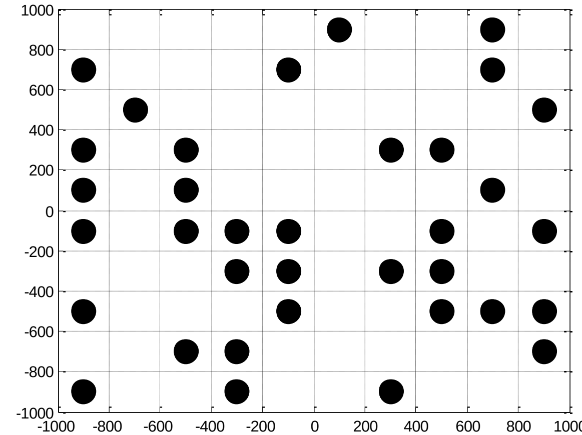
Micrositing Optimization (Cont.)



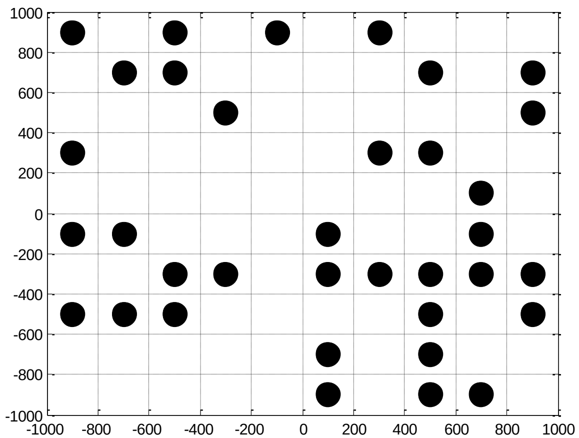
Mean Power Output = 7.8700 MW
Mean Power Losses = 0.7679 MW
9.76%



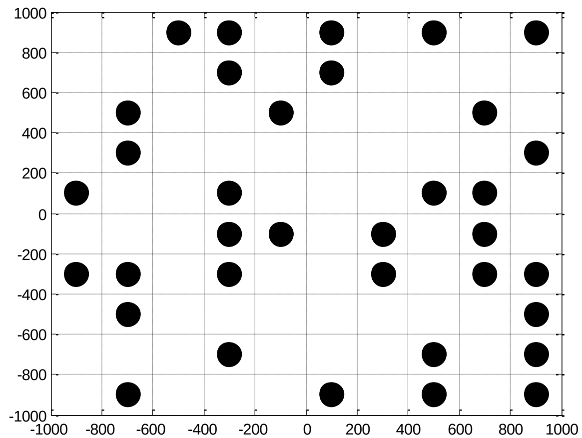
Mean Power Output = 7.9883 MW
Mean Power Losses = 0.6496 MW
8.13%



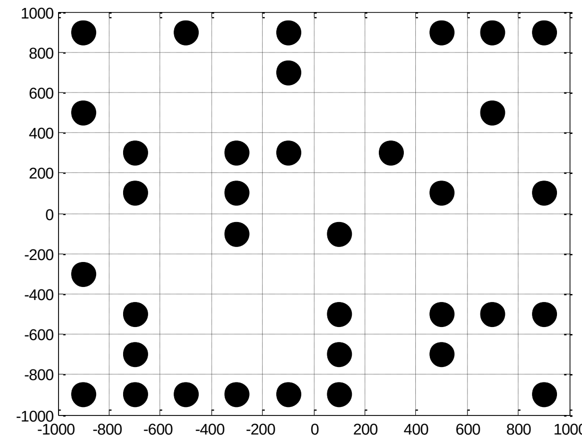
Mean Power Output = 8.0725 MW
Mean Power Losses = 0.5654 MW
7.00%



Mean Power Output = 8.1751 MW
Mean Power Losses = 0.4628 MW
5.66%



Mean Power Output = 8.2034 MW
Mean Power Losses = 0.4345 MW
5.29%



Mean Power Output = 8.2852 MW
Mean Power Losses = 0.3527 MW
4.26%

K. Meng, Z.Y. Dong, and K.P. Wong, HEC Wind Project Report, 2010.

Electrical Layout Design

Mitigation Approaches

- Electrical layout design is an engineering task that
  1. optimizes the equipment installation and maintenance costs
  2. subject to geographic, environmental, social, and legal constraints
- We developed an efficient optimal electrical layout design approach for large-scale offshore wind farms
  1. to minimize the capital cost, power loss cost, and network maintenance cost
  2. taking into account the constraints of wind turbines, electrical cables, substations

Y. Chen, Z.Y. Dong, K. Meng, and et al., IEEE Transactions on Sustainable Energy, 2016.

Electrical Layout Design (Cont.)

Constraints

– Active power flow constraints:

$$P_i^g = \sum_{j=1}^{N} V_i V_j \left[G_{ij} \cos\left(\delta_i - \delta_j\right) + B_{ij} \sin\left(\delta_i - \delta_j\right) \right]$$

– Reactive power flow constraints:

$$Q_i^g = \sum_{j=1}^{N} V_i V_j \left[G_{ij} \sin\left(\delta_i - \delta_j\right) - B_{ij} \cos\left(\delta_i - \delta_j\right) \right]$$

– Capability limits of cables:

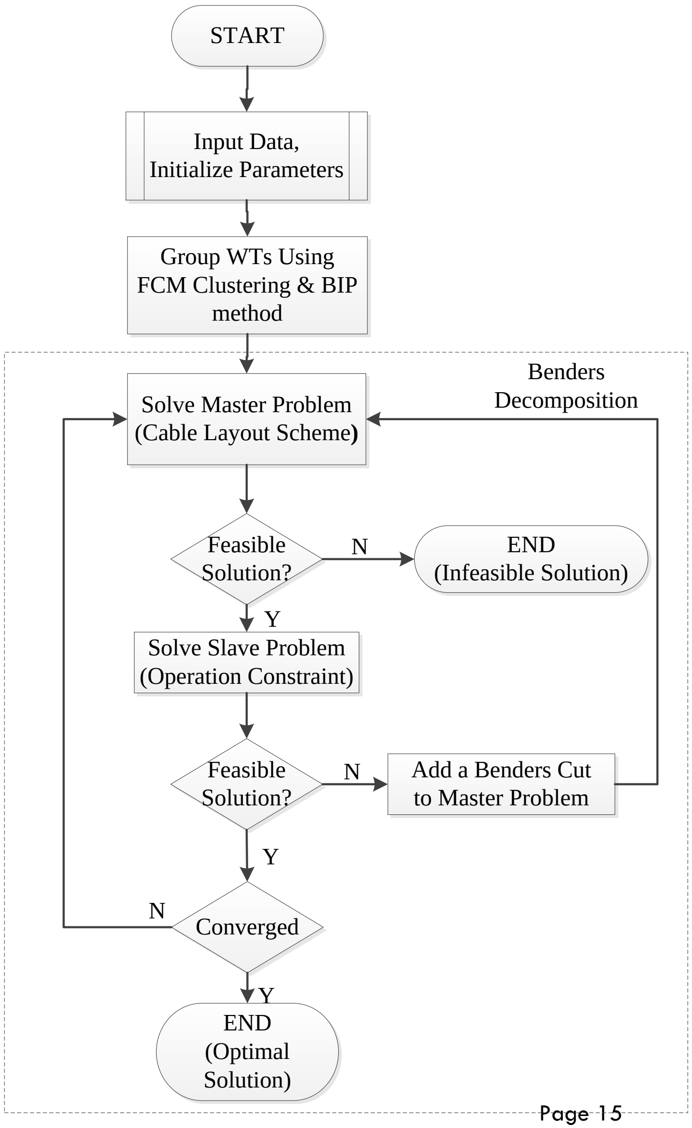
$$\left|S_{ij}\right| \le S_{\max}, \forall i \in N$$

– Bus voltage limits:

$$V_{\min} \le V_i \le V_{\max}, \forall i \in N$$

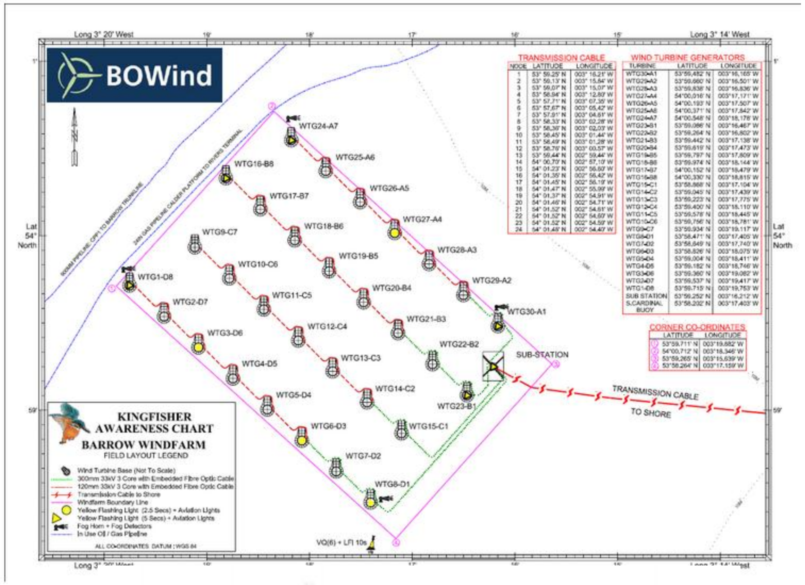
– Radial constraints:

$$\sum_{i=1, i \ne j}^{N} x_{ij} \le 1, \forall j \in N$$

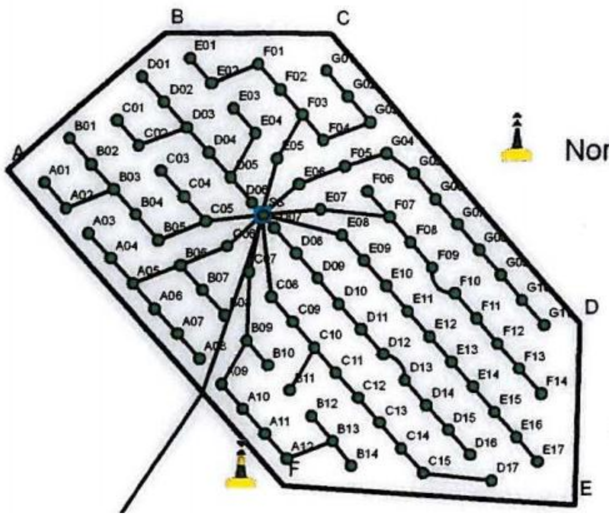


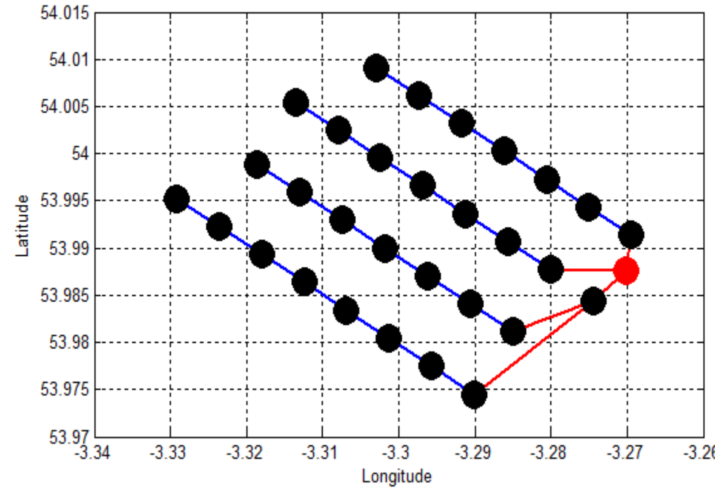
Y. Chen, Z.Y. Dong, K. Meng, and et al., IEEE Transactions on Sustainable Energy, 2016.

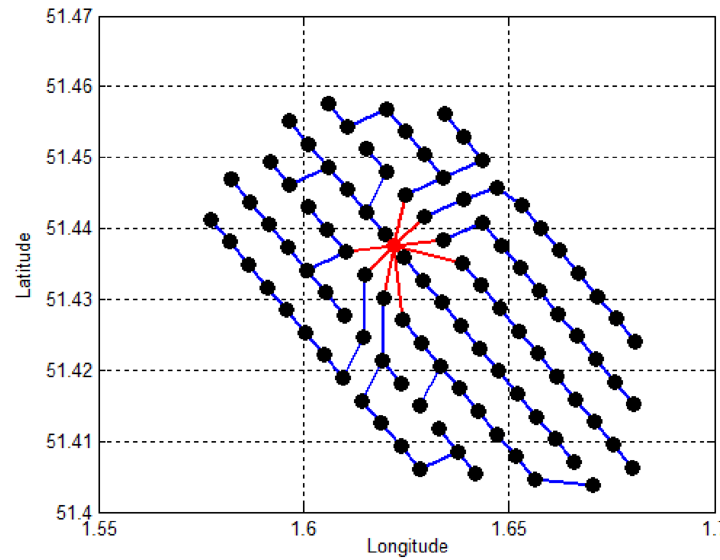
Electrical Layout Design (Cont.)



Barrow Offshore

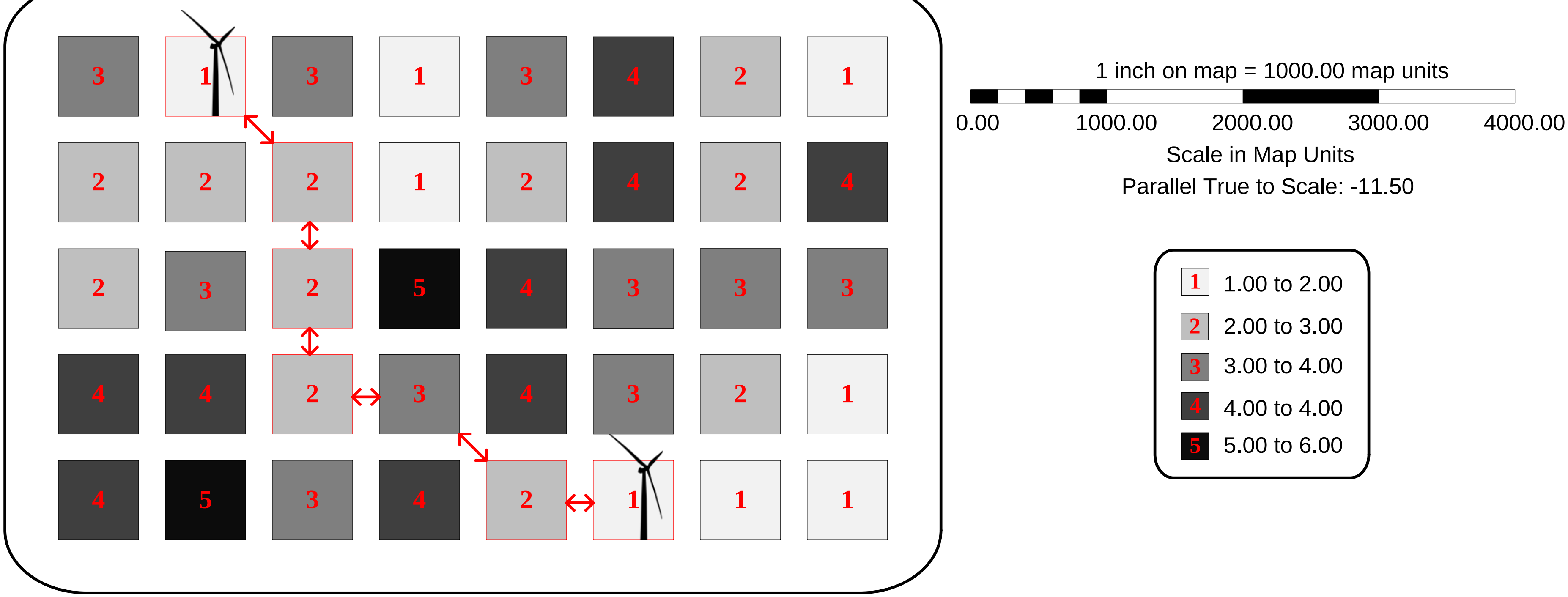






Y. Chen, Z.Y. Dong, K. Meng, and et al., IEEE Transactions on Sustainable Energy, 2016.

Electrical Layout Design (Cont.)

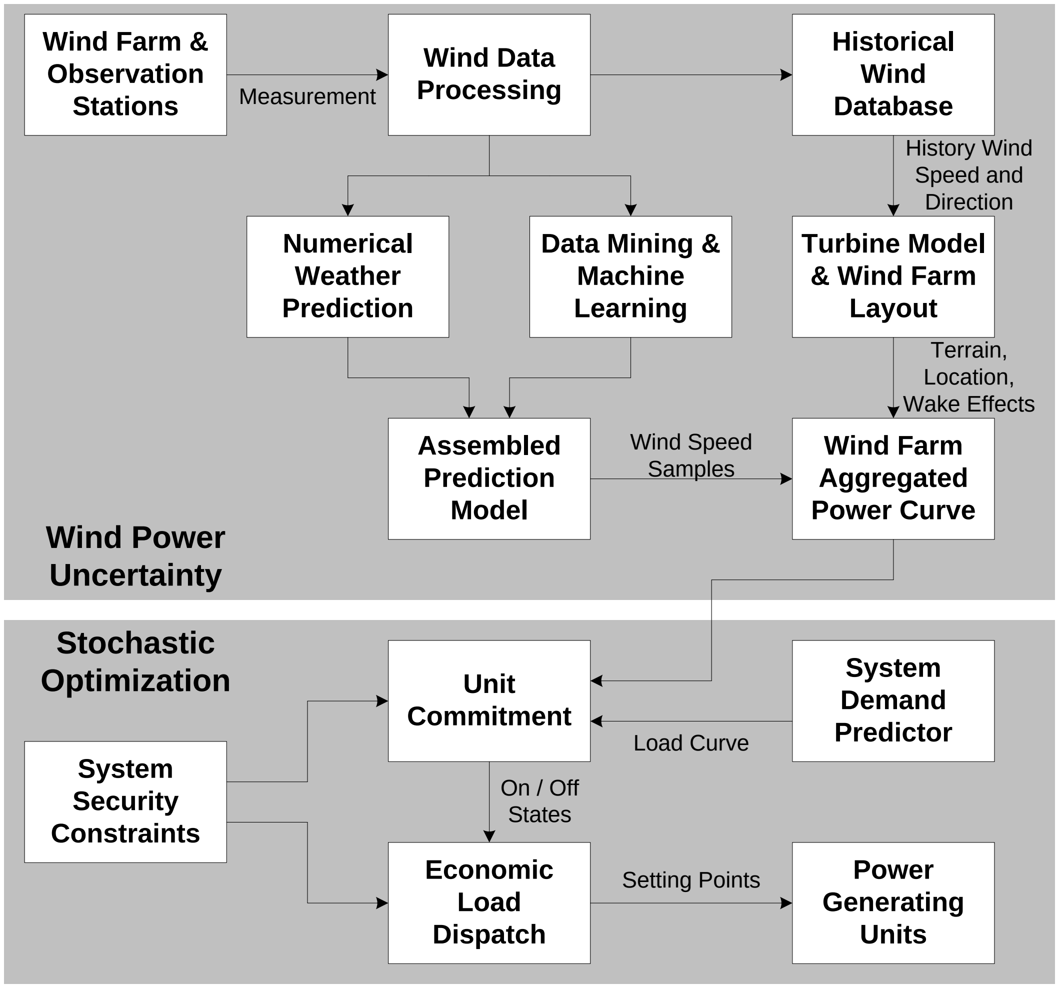


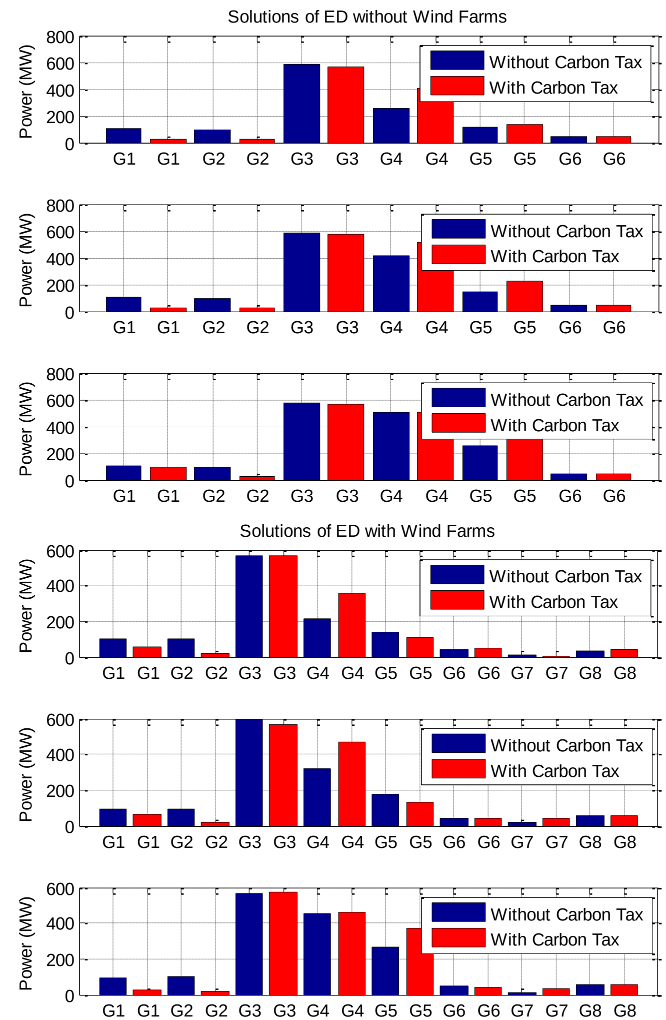
Wind Farm Dispatch

Core Problems

- Balancing supply and demand
  1. economically through markets;
  2. with transmission constraints, assuring reliability against contingencies, and maintaining power quality (voltage, frequency).
- Today
  1. all renewable power taken, treated as negative load
  2. subsidies: feed-in tariffs, etc
  3. tailor supply to meet random demand
- Tomorrow
  1. renewables are market participants
  2. tailor demand to meet random supply

Carbon Emission





F. Yao, Z.Y. Dong, K. Meng, and et al., IEEE Transactions on Industrial Informatics, 2010.

Flexible Operational Planning Framework

Step 1: Database and Model Update

Wind Forecasting Service Providers
(historical and real-time meteorology data, customized computer models, wind farm maintenance schedules, wake effect models)

Step 2: Wind Power Forecasting

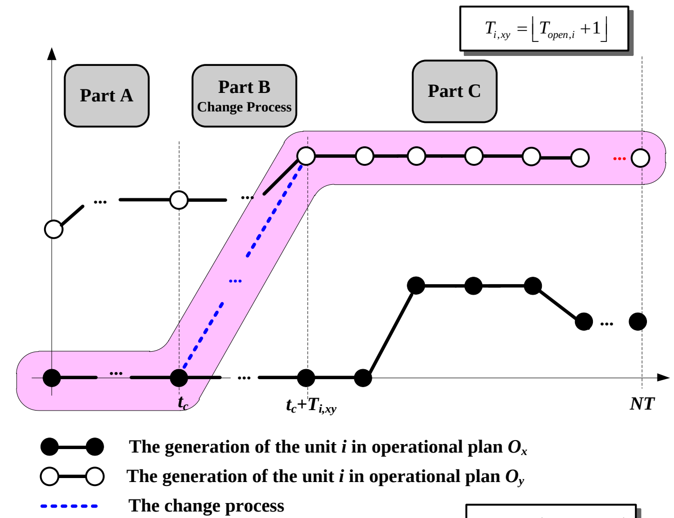
Wind Forecasting Service Providers
(probability density function, Monte Carlo sampling, scenario generation, evaluation, and reduction)

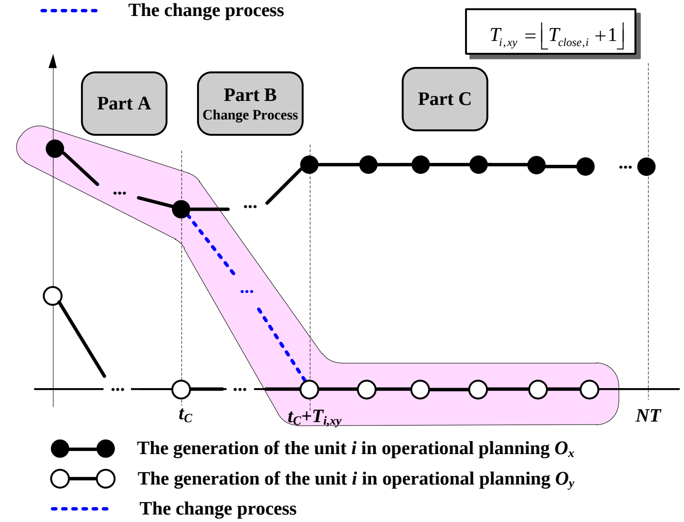
Step 3: System Operation Planning

System Operators
(system demand, network topology, unit parameters, system and unit constraints, stochastic security-constrained unit commitment)

Step 4: Flexible Operational Plan Selection

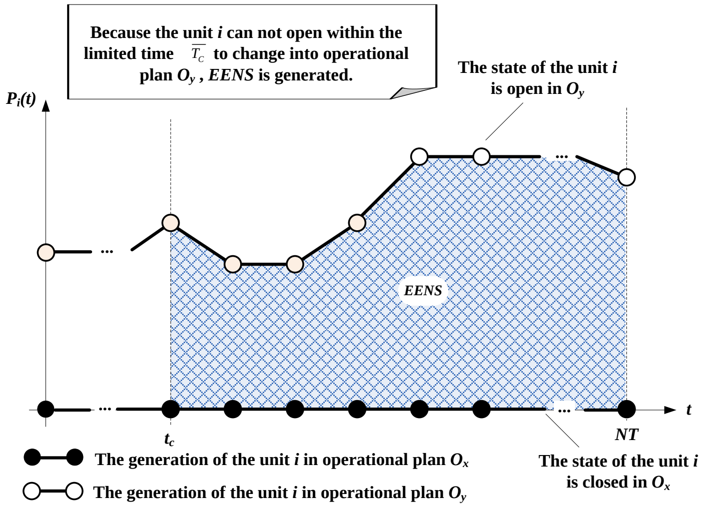
System Operators
(candidate operational plans, adaption cost calculation, final schedule)

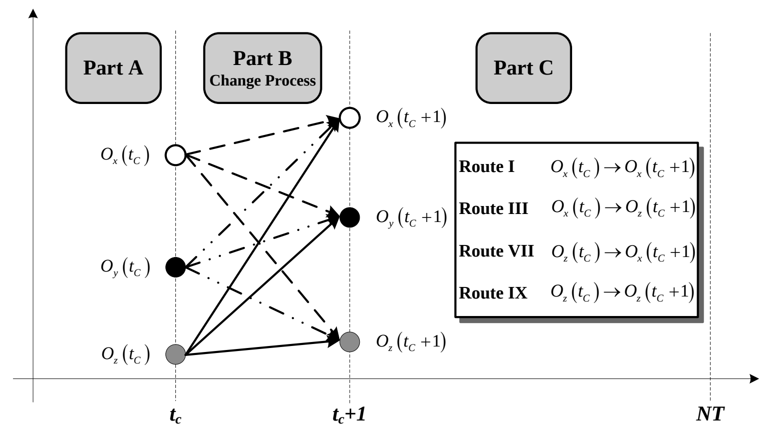




K. Meng, Z.Y. Dong, and et al., IEEE Transactions on Sustainable Energy, 2016.

Flexible Operational Planning Framework (Cont.)





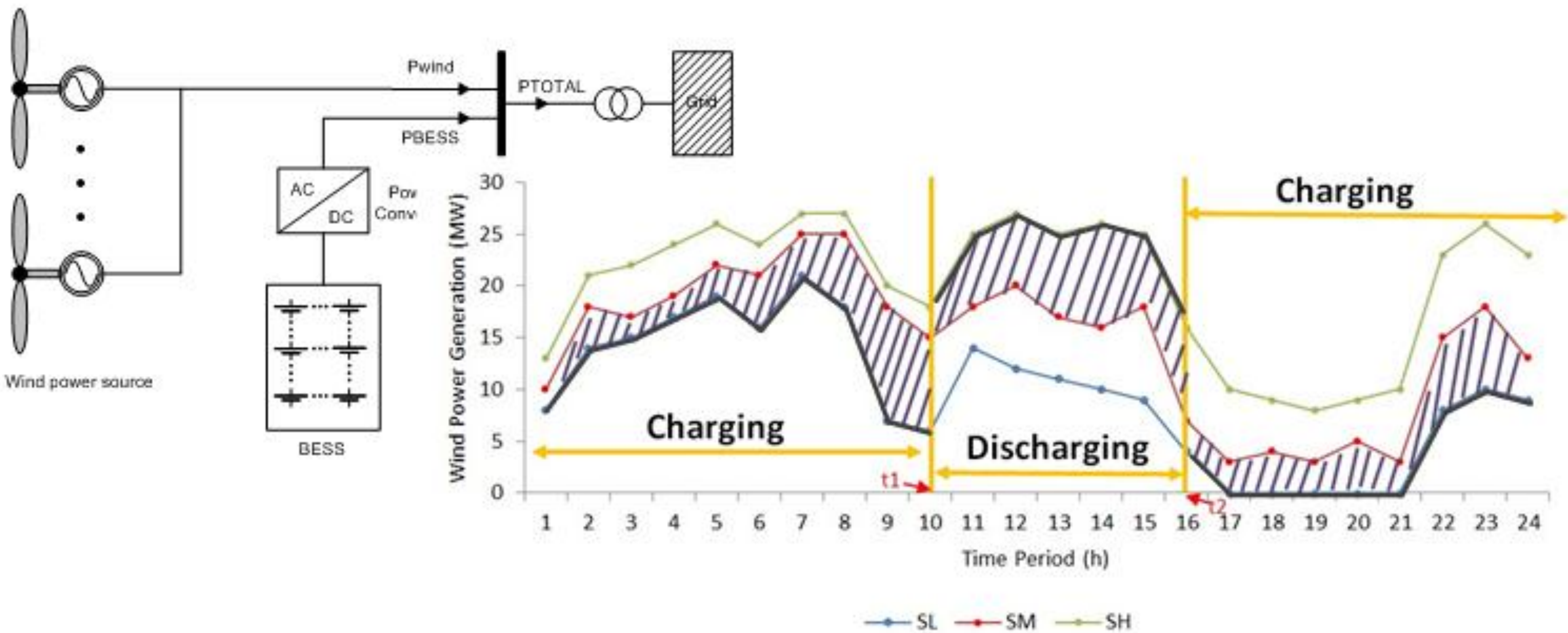
Operational Plan	Combined Operational Plan	Combined Expected Operational Cost ($) Schedule Changes at 04:00	Combined Expected Operational Cost ($) Schedule Changes at 21:00
X	X→X	601,219.20	601,219.20
	X→Y	597,029.83	598,740.36
	X→Z	598,254.12	599,254.91
Y	Y→X	600,041.33	598,944.29
	Y→Y	595,642.65	595,642.62
	Y→Z	597,332.86	597,110.33
Z	Z→X	601,685.01	597,836.57
	Z→Y	595,639.40	596,705.29
	Z→Z	596,751.54	596,751.54
Optimal Operation Plan		Y	Z

K. Meng, Z.Y. Dong, and et al., IEEE Transactions on Sustainable Energy, 2016.

Wind Farm Dispatch

Wind Farm-BESS Dispatch Scheme

– The benefits of this idea are, the wind power output can be controlled; the maximum capacity of battery storage system can be reduced, the optimal size can be estimated; the lifetime of energy storage device can be prolonged.



F. Luo, K. Meng, Z.Y. Dong, and et al., IEEE Transactions on Sustainable Energy, 2015.

Future Grid Cluster - $13 million research collaboration between CSIRO and four leading Australian universities

Aims – Project II

- Develop the nation’s capacity to plan and design the most efficient, low emission electricity for Australia;
- Deliver the first analytical framework of its kind for Australian electricity and natural gas networks;
- Allow systematic investigation of the most economically efficient energy network configurations, enabling the power sector to make operating and planning decisions to develop and evolve the nation’s future grid.

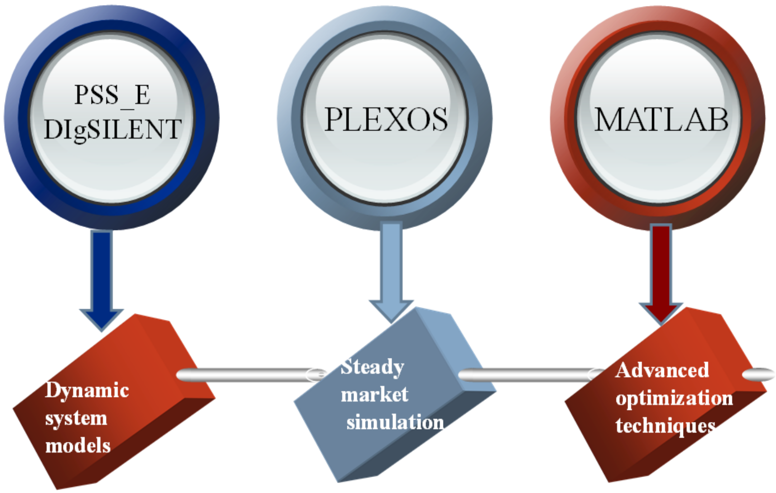
Co-planning

Gas-CCGT-Electricity

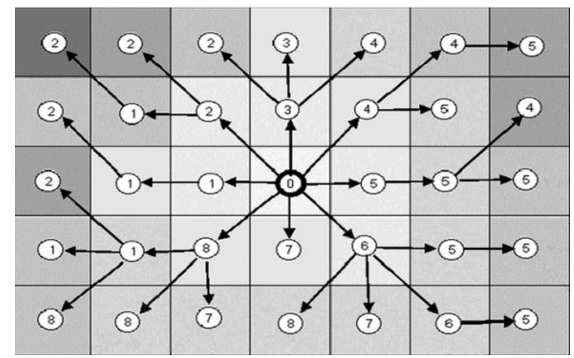
- Primary energy
- Gas wells/producers
- Transmission pipelines/gas interconnection, distribution pipelines, underground storages, compressors and valves
- Customers
- Branch, nodes, pressure, net gas supply
- Gas flow simulation

- Secondary energy
- Generators
- Transmission system, distribution system, energy storage, controls
- Customers
- Branch, nodes (buses), voltage, injection power
- Power flow computation

Co-planning



GIS-based implementation tool



PSS_E & DIgSILENT

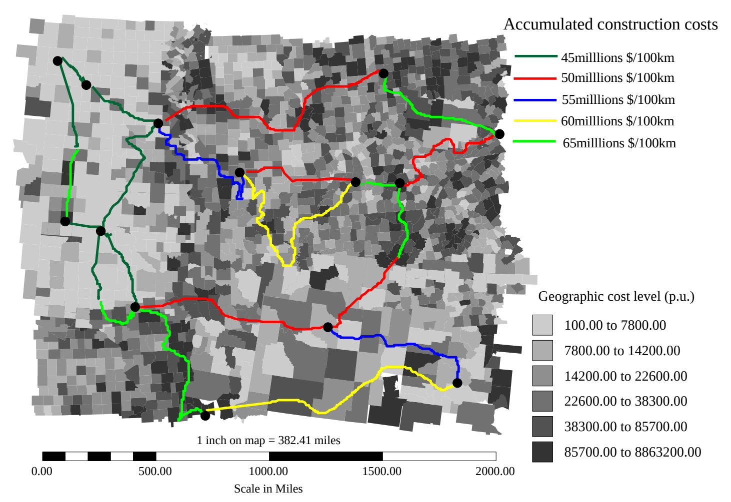
- Dynamic power system simulation
- Small signal and eigenvalue analysis
- Optimal power flow
- Short circuit calculations
- Balanced and unbalanced fault analysis
- Deterministic and probabilistic contingency analysis
- Transient stability studies
- Voltage stability analysis
- Assessing impacts of geomagnetic induced currents

PLEXOS

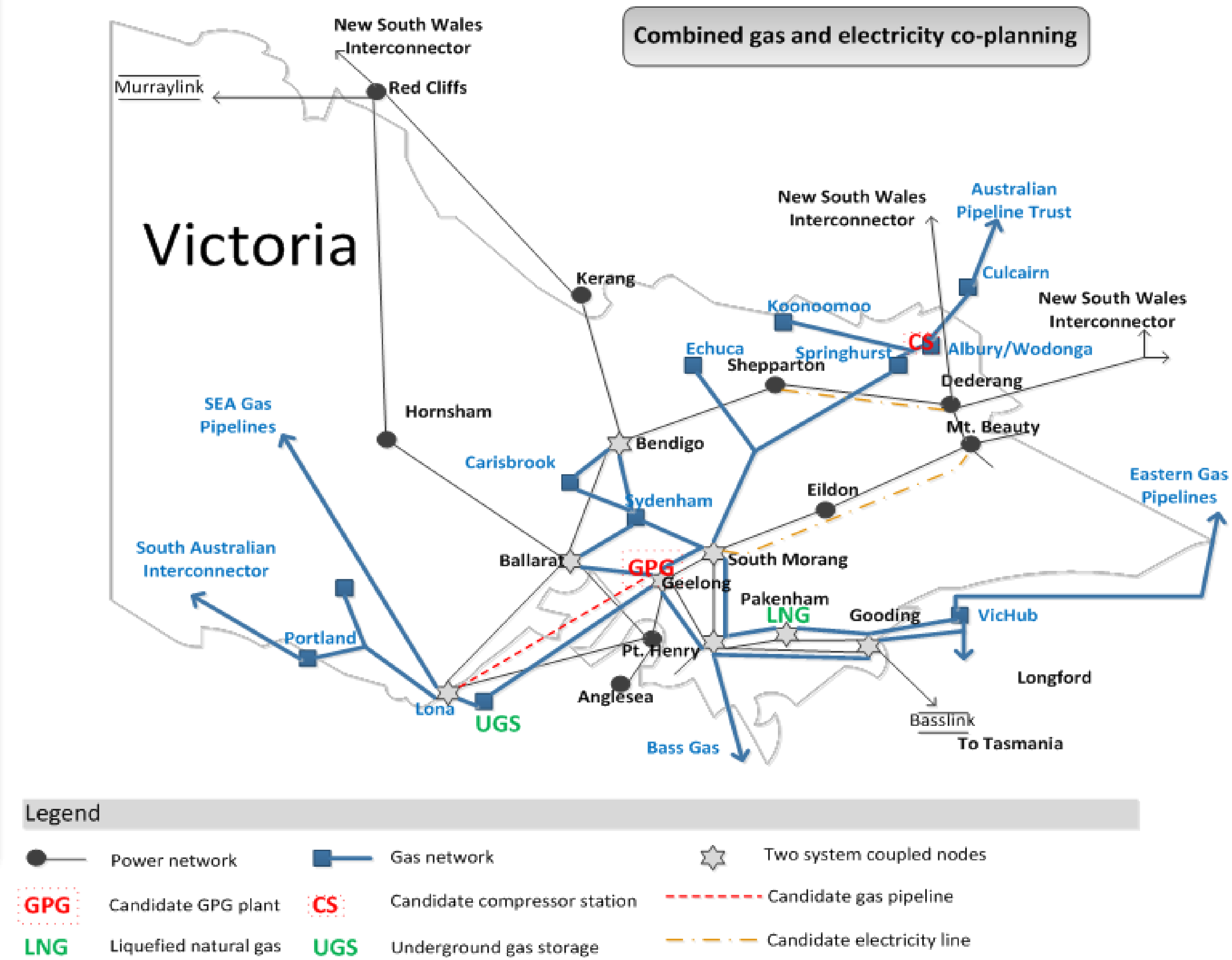
- Market analysis and design
- Electricity price and gas price forecasting
- Capacity expansion planning
- Generation and transmission asset evaluation
- Transmission analysis and congestion management
- Renewables integration analysis
- Portfolio optimization
- Gas modelling
- Risk management
- Fuel and emission constraint management
- Bid information and trading decision support

MATLAB

- Game-theoretic simulations
- Variance reduction technique
- Distributed computing technique
- Mathematical optimization (mixed-integer programming, iterative algorithm, network flow programming, analytic hierarchy approach, branch and bound, Benders decomposition, Lagrangian relaxation, etc.)
- Heuristic optimization (artificial immune system, genetic algorithm, fuzzy-sets, simulated annealing, expert systems, differential evolution, particle swarm optimization, etc)



Co-planning

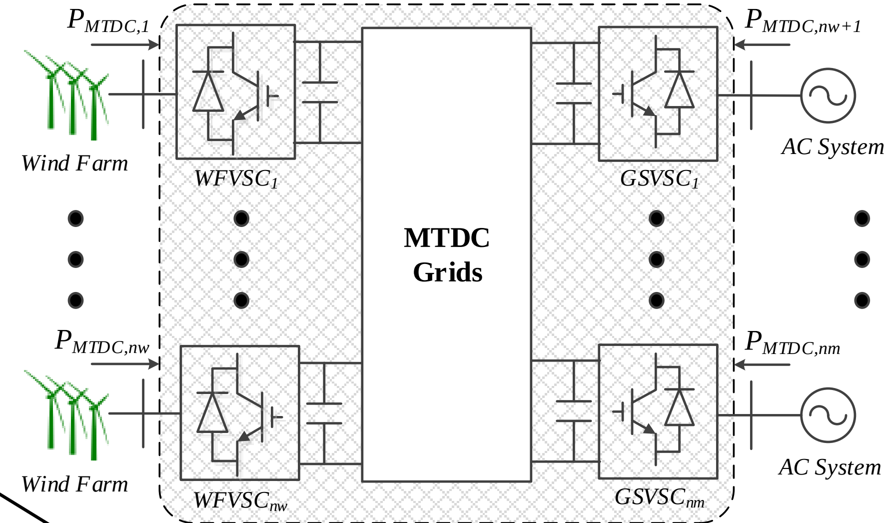


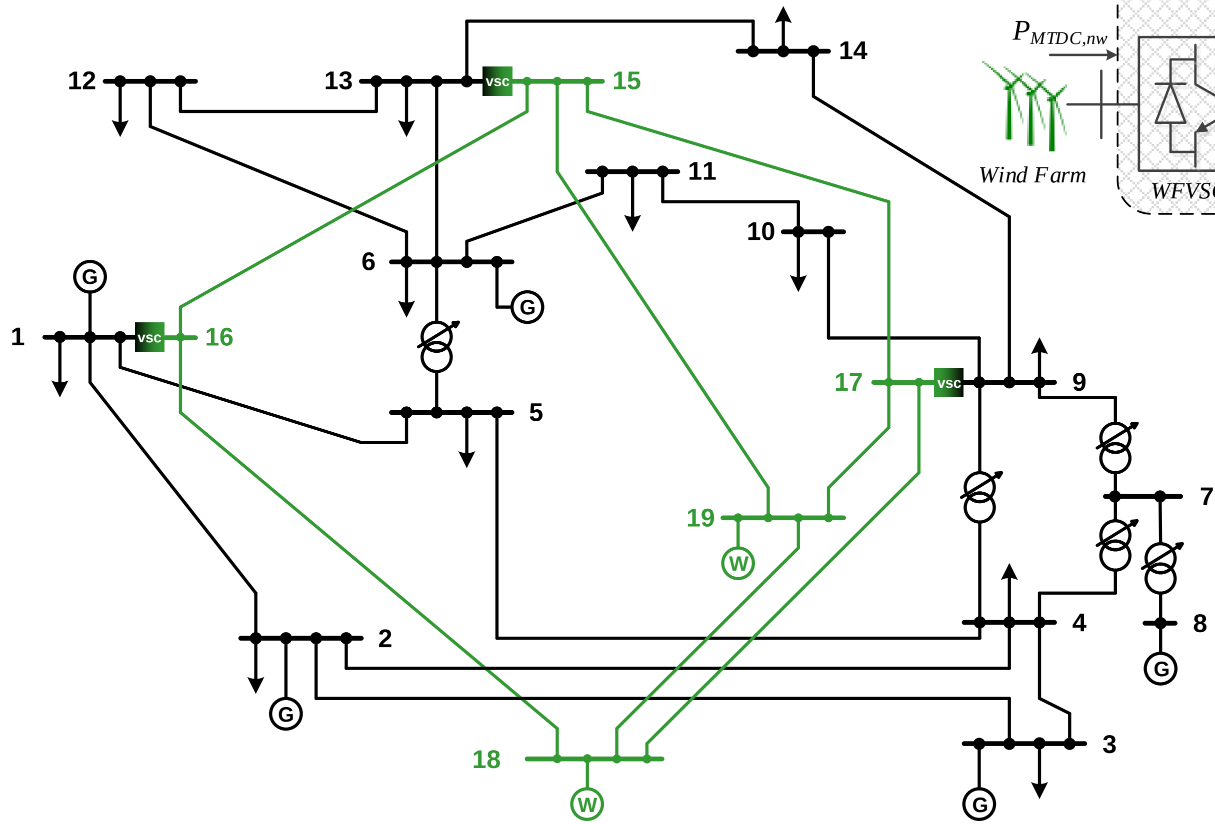
J. Qiu, Z.Y. Dong, D. Hill, and et al., IEEE Transactions on Power Systems, 2015 and 2016.

Clean Energy Highway (Grants)

- Wide-area Interconnected Clean Energy Highway; Z.Y. Dong, K. Muttaqi, K. Meng, S. Rahman, D. Hill; Australian Research Council (ARC) Discovery Grant (DP170103427), Australia, AUD $406.5K, 2017-2019.
- Modelling and Control of Multi-terminal HVDC Grids in Future Pan-Asia Energy Highway; K. Meng, Z.Y. Dong, and Yong-June Shin; The University of Sydney and Yonsei University Joint IPDF, The University of Sydney, Australia, AUD 20K, 2017-2018.
- Inter-islands Multi-terminal High-voltage Direct Current Transmission System for Renewable Integration; K. Meng, Z.Y. Dong, W. Zhang; Australia-Indonesia Centre Energy Cluster, Australia, AUD 20K, 08/2016-03/2018.
- Fault-tolerant Multi-terminal HVDC Grid Power Dispatch Framework; K. Meng, J. Berteen; Clean Energy and Intelligent Networks Cluster Funding, Faculty of Engineering & Information Technologies, The University of Sydney, Australia, AUD 7.5K, 2016.

Multi-terminal HVDC Power Dispatching





K. Meng, W. Zhang, Z.Y. Dong, and et al., submitted to IEEE Transactions on Power Systems, 2016.

MTDC

Research Opportunities

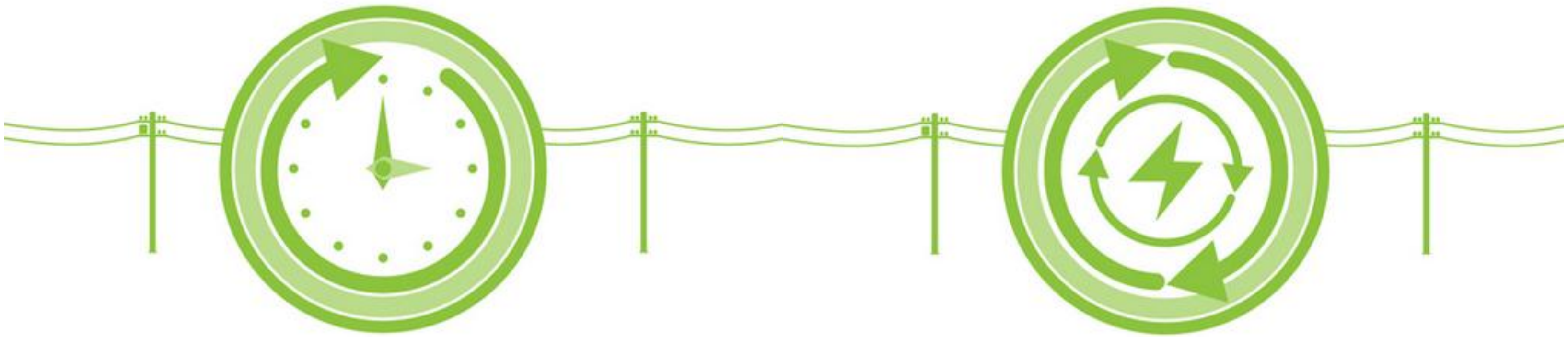
- Unique/sequential ac/dc power flow
- Optimal topology design
- Autonomous power sharing
- Control and protection
- MVDC/LVDC microgrid

Distribution Level

Why Microgrid Matters

A more RELIABILITY grid

A more RESILIENT grid



is one with fewer and shorter power interruptions

is one better prepared to recover from adverse events

What is a microgrid?

– electricity distribution systems
– loads and distributed energy resources (such as distributed generators, storage devices, or controllable loads)
– operated in a controlled, coordinated way
– connected to the main power network or islanded.

Microgrid Landscape

Five

most commonly used classes of Microgrids (vary in size: generation, storage, control)

Microgrid

Technical Challenge

- High complexity of feeder topology and network characteristics, no standard management framework for microgrid
- Controller as the brain of microgrid systems coordinating with upstream substation, peer microgrids and downstream device controllers
- Capability of both grid-connected and islanded operating modes and seamless transition between two operating modes
- Protection solutions for microgrid

Economical/Market challenges

- Responsibilities, costs and benefits allocation due to ownership
- Development of a market mechanism of microgrid services and business model

Microgrid (Grants)

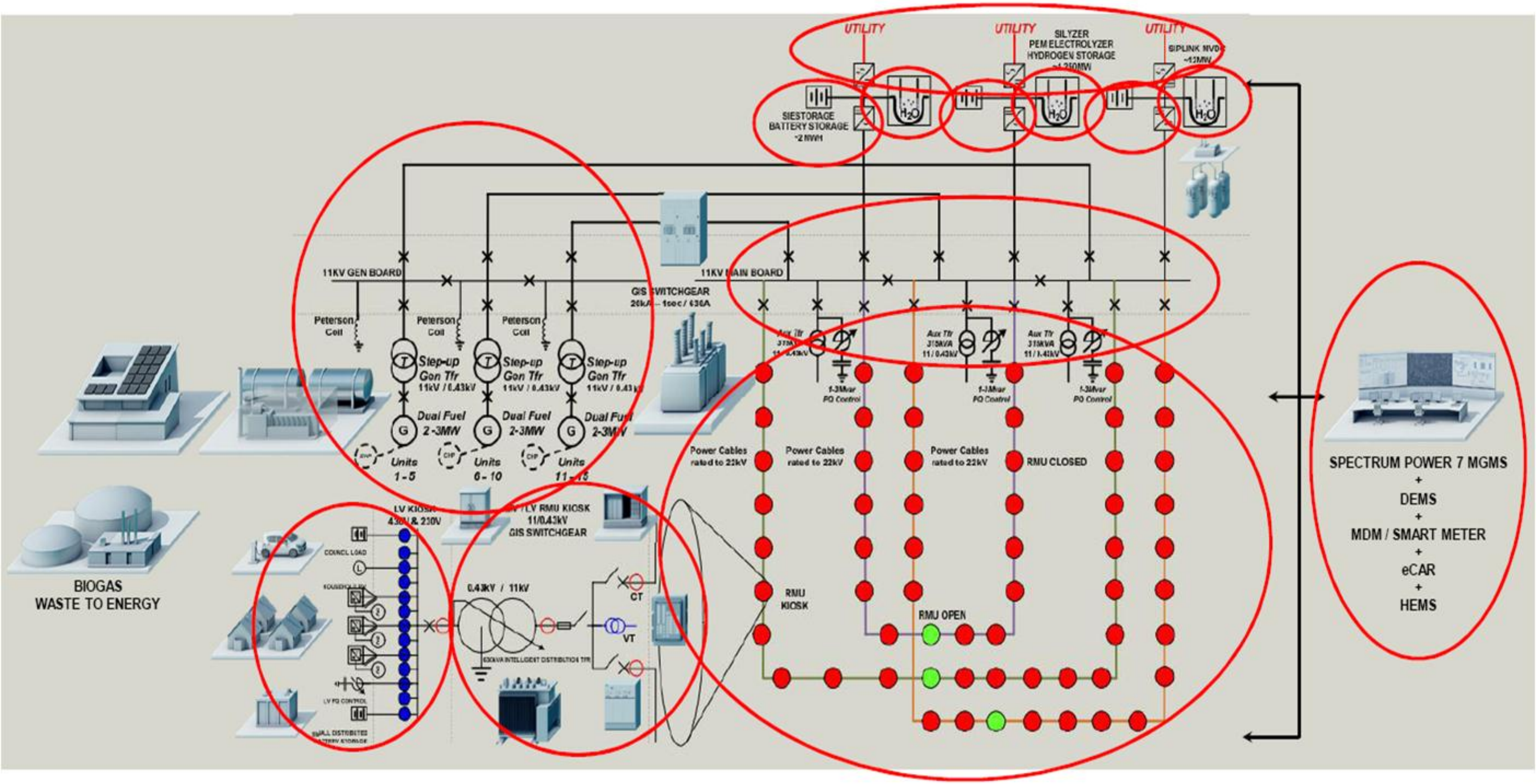
- Reliable Microgrid Technologies for Remote Communities with a Communication based Control Architecture; Z.Y. Dong, K. Meng, J. Ma, Y. Li, Tyree Foundation, Australia, AUD 3M, 2017-2019.
- Distributed Control Platform for Wireless Networked Microgrids; K. Meng and Z.Y. Dong; Major Equipment Scheme, Faculty of Engineering & Information Technologies, The University of Sydney, Australia, AUD 140K, 2017.
- Nested Microgrids for Remote Indigenous Communities in Australia; K. Meng; Mid-Career Researcher Development Scheme, Faculty of Engineering & Information Technologies, The University of Sydney, Australia, AUD 35K, 2017.
- Development of a Demonstration System of Hybrid Smart Power System to Emulate the Energy Efficiency and Reliability of Deployed Base Power Supply System; Z.Y. Dong, D. Lu, D. Hill, K. Meng; Department of Defence: Army Research Funding, Australia, AUD 77K, 09/2015-08/2016.

Laboratory-scale Microgrid

– Source: Ten PV panels (3 kWp), Diesel generator (4kW)
– Energy storage: Lithium-ion battery (6.5 kWh)
– Load: lighting system, programmable ac/dc load

Z.Y. Dong, D. Lu, D. Hill, K. Meng, Department of Defence, 2016.

50MW Commercial Microgrid (SIEMENS-Hunterlee)



Shared Facilities and Collaborations

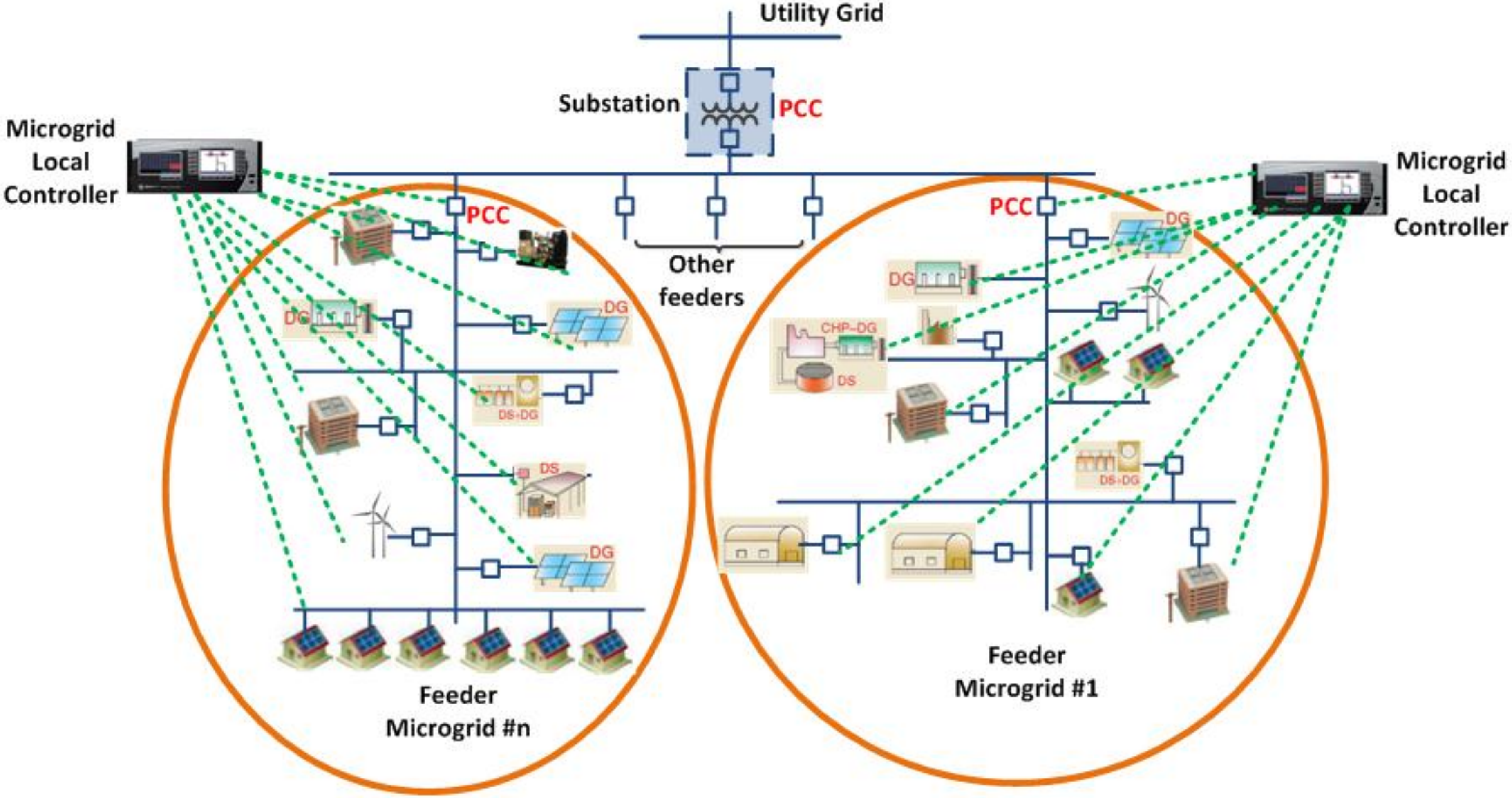
Share Complementary Skills

- Foster a group with critical mass in microgrid technology
- Power: Joe Dong, Ke Meng, John Fletcher, Jayashri Ravishankar
- Telecommunication: Yonghui Li, Jinhong Yuan
- Control: Jin Ma, Hendra Nurdin

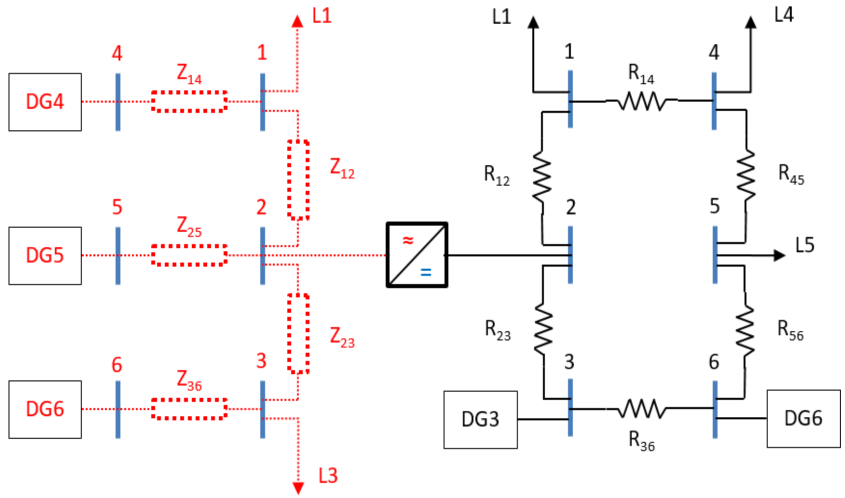
Share Laboratory Facilities

- Sir William Tyree Laboratory
- RTDS facility at Tyree Energy Technologies Building
- ABB Power Engineering Lab
- Microgeneration Test Bench
- Centre of Excellence in Telecommunications

Wireless Networked Microgrids (Tyree Foundation)



Sequential/Unified Power Flow for Mixed AC/DC Microgrids



$$J = \begin{bmatrix} \frac{\partial dP_{ac}}{\partial V_{ac}} & \frac{\partial dP_{ac}}{\partial \omega} & \frac{\partial dP_{ac}}{\partial \delta} & \frac{\partial dP_{ac}}{\partial V_{dc}} \\ \frac{\partial dQ_{ac}}{\partial V_{ac}} & \frac{\partial dQ_{ac}}{\partial \omega} & \frac{\partial dQ_{ac}}{\partial \delta} & \frac{\partial dQ_{ac}}{\partial V_{dc}} \\ \frac{\partial dP_{dc}}{\partial V_{ac}} & \frac{\partial dP_{dc}}{\partial \omega} & \frac{\partial dP_{dc}}{\partial \delta} & \frac{\partial dP_{dc}}{\partial V_{dc}} \end{bmatrix}$$

Bus	Proposed method						PSCAD/EMTDC					
	V_{ac} [pu]	δ [pu]	V_{dc} [pu]	P_{ac} [pu]	Q [pu]	P_{dc} [pu]	V_{ac} [pu]	δ [pu]	V_{dc} [pu]	P_{ac} [pu]	Q [pu]	P_{dc} [pu]
1	0.9908	0	0.9893	-1.6140	-1.0680	-1.0000	0.9907	0	0.9893	-1.6170	-1.0540	-1.0000
2	0.9934	-0.0002	0.9944	0.0456	0.8880	-0.0046	0.9934	-0.0002	0.9944	0.0513	0.9182	-0.0046
3	0.9884	-0.0061	0.9970	-2.1450	-1.5160	1.1834	0.9881	-0.0060	0.9970	-2.1470	-1.5190	1.1834
4	0.9987	0.0116	0.9946	1.2439	0.1780	-0.7300	0.9986	0.0116	0.9946	1.2430	0.1756	-0.7300
5	0.9980	0.0053	0.9946	1.2439	0.2746	-0.7300	0.9979	0.0054	0.9946	1.2430	0.2712	-0.7300
6	0.9907	-0.0053	0.9968	1.2439	1.2804	1.2922	0.9904	-0.0052	0.9968	1.2430	-1.3050	1.2922
P_{IC} [pu]	45.6273						45.6998					

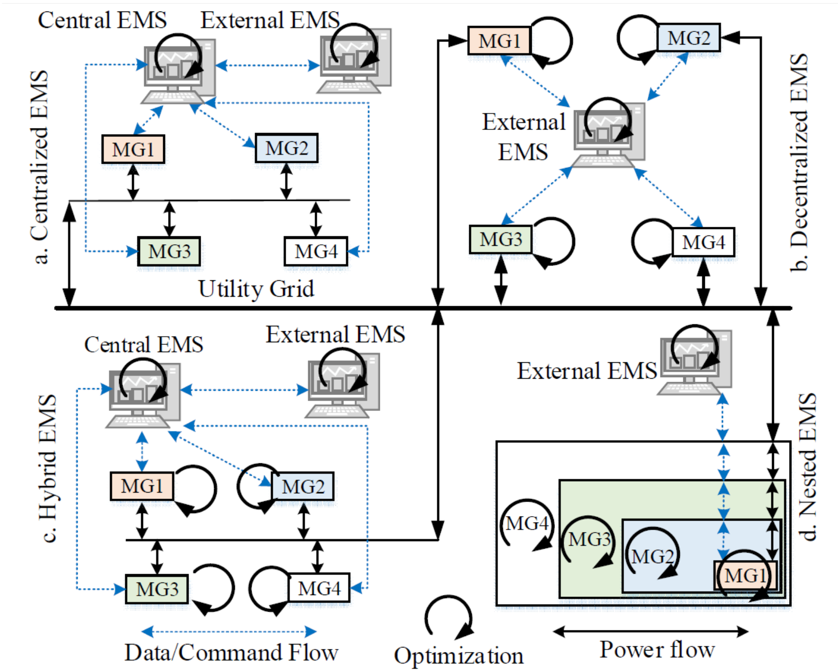
L. Marpaung, K. Meng, Z.Y. Dong, and et al., submitted to IEEE Transactions on Power Systems, 2016.

Microgrid

Research Opportunities

– Planning and design: addressing system architecture, monitoring and analysis, and system design; and

– Operations and control: addressing steady-state control and coordination, transient-state control and protection, stability evaluation, and operational optimization.

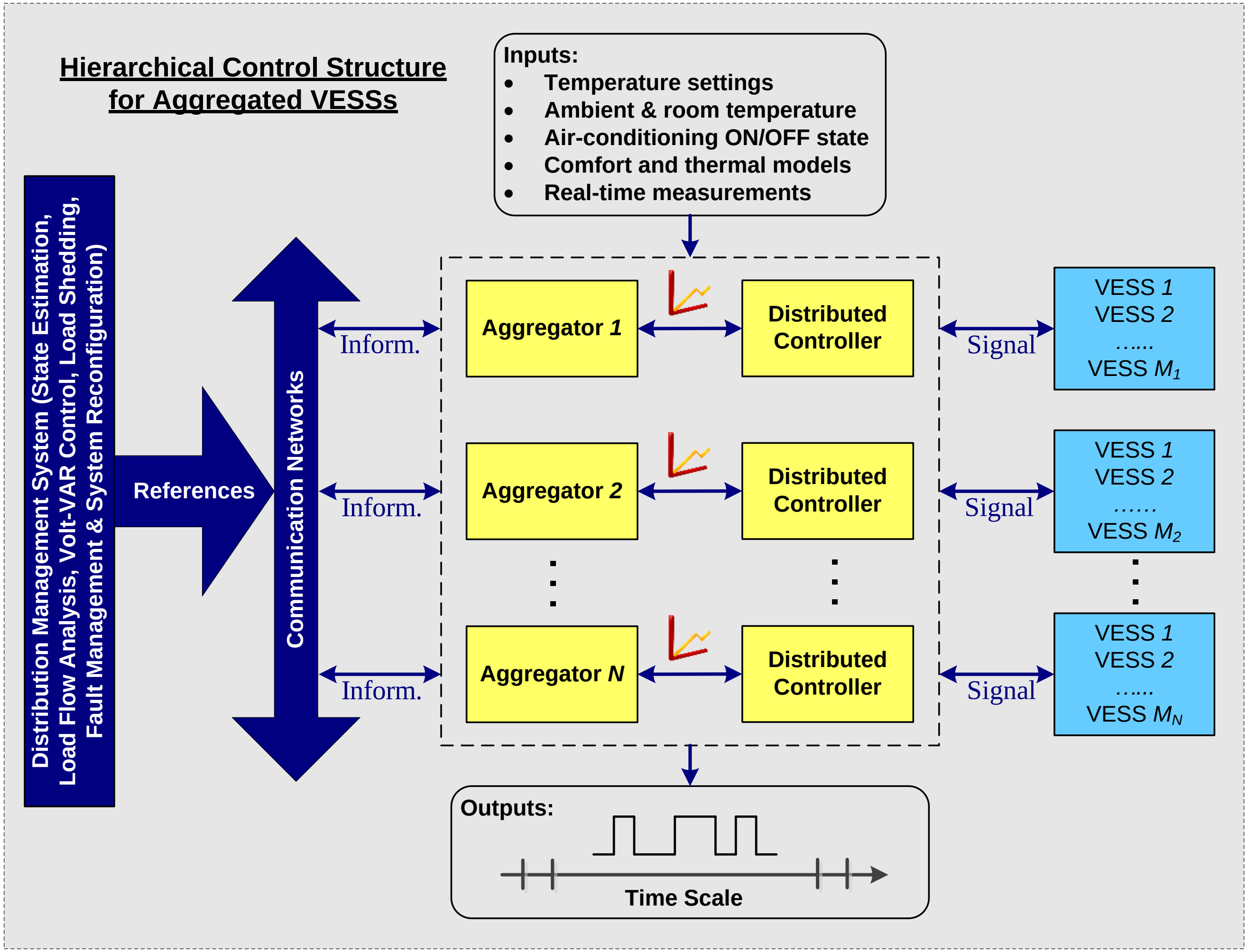


Demand Side Management (DSM)

A Paradigm Shift

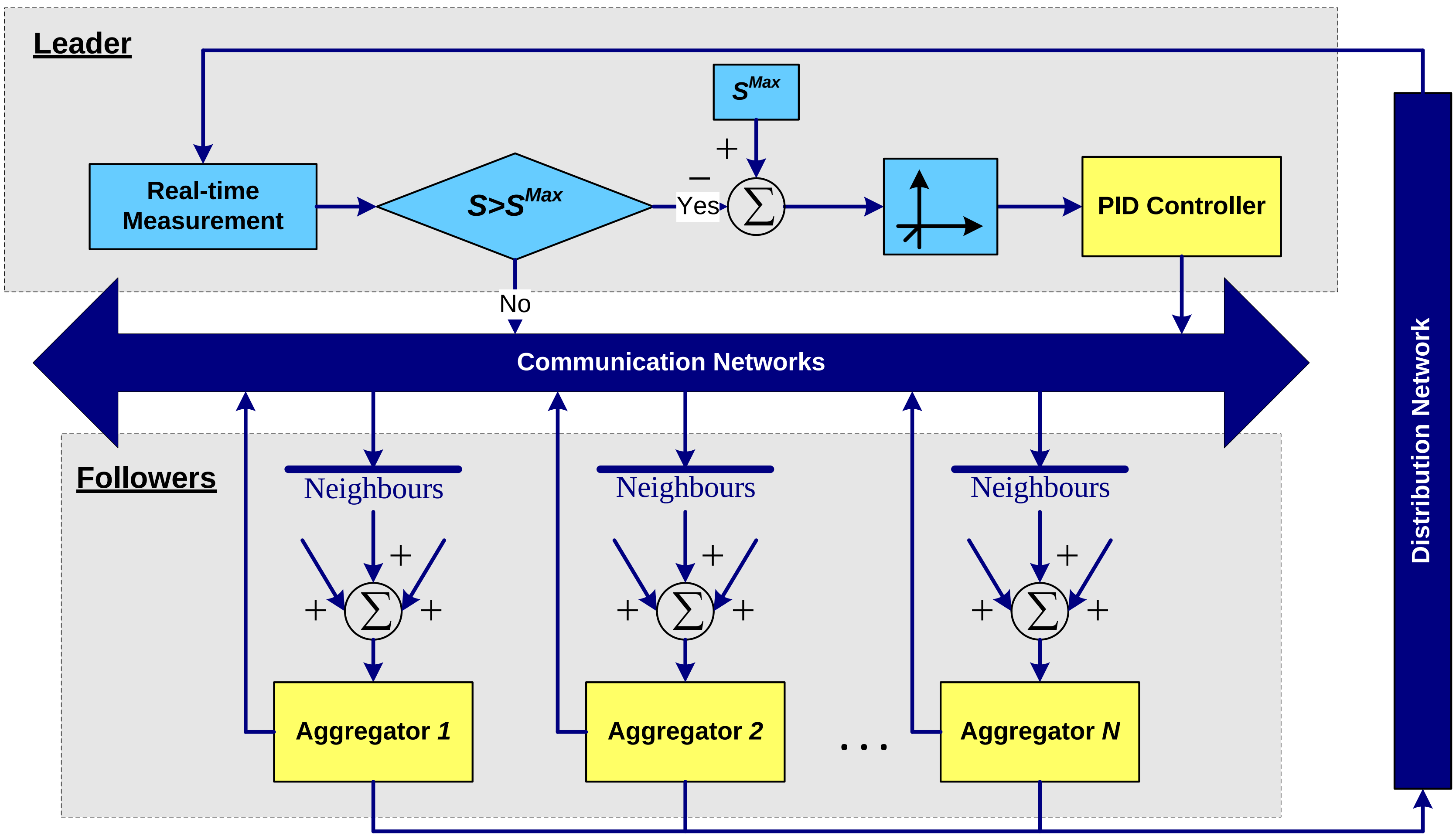
- Today: tailor generation to meet random load
- Tomorrow: tailor load to meet random generation
- Enabling ingredient: flexible loads
  1. residential HVAC
  2. commercial HVAC
  3. deferrable appliance loads
  4. electric vehicles
- Flexible loads will enable deep renewable penetration without large increases in reserves

Demand Side Management (Cont.)



K. Meng, Z.Y. Dong, D. Hill, and et al., submitted to IEEE Transactions on SMC.

Demand Side Management (Cont.)



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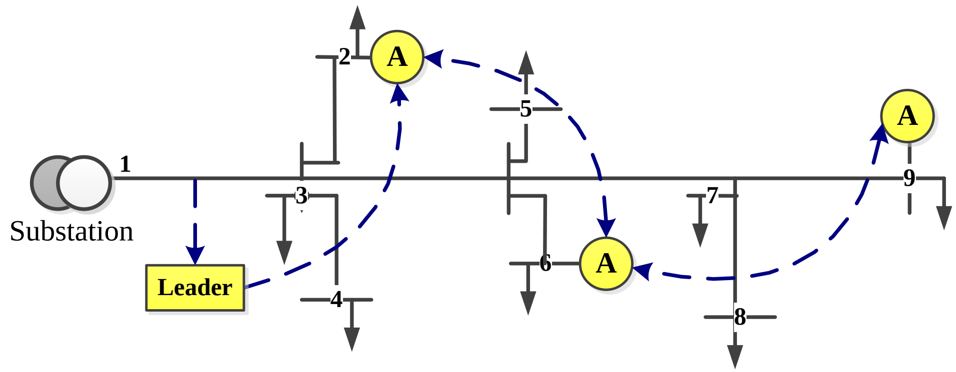
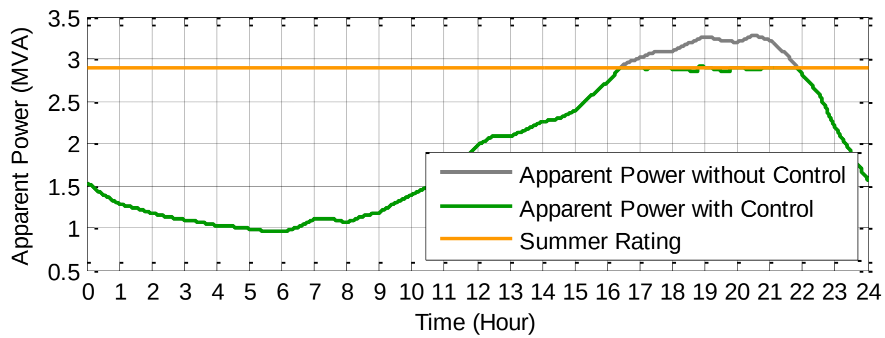
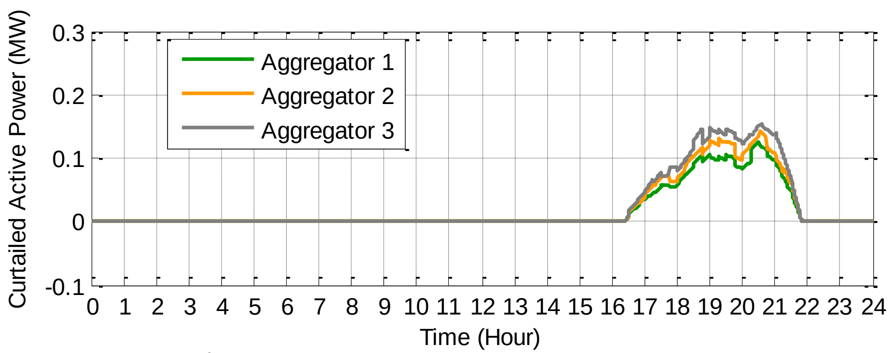
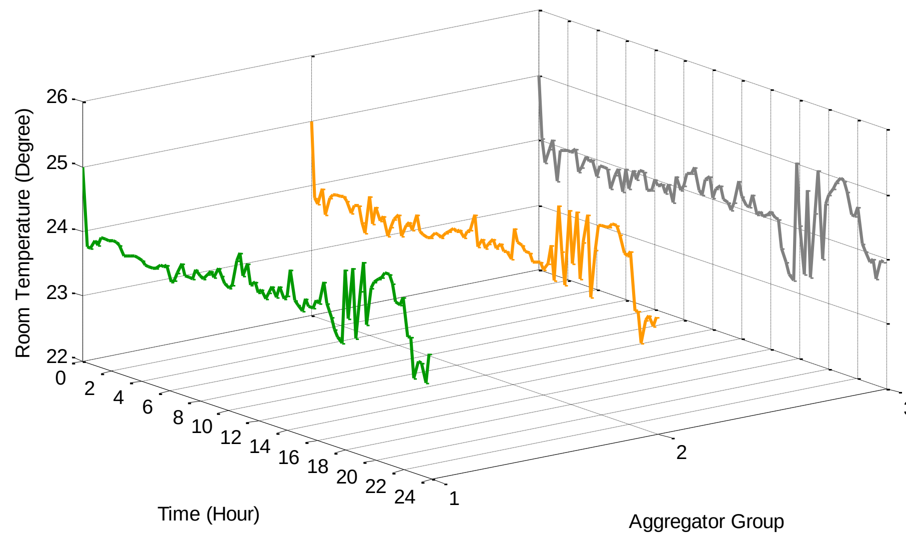
Demand Side Management (Cont.)









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Big Data Analytics

THE UNIVERSITY OF SYDNEY

The "Smart" Meter

It is smart because …

- It can report the energy consumption every 15 minutes or an hour remotely!
- It can refresh power consumption reading every 5 or 10 seconds[1]!

Therefore,

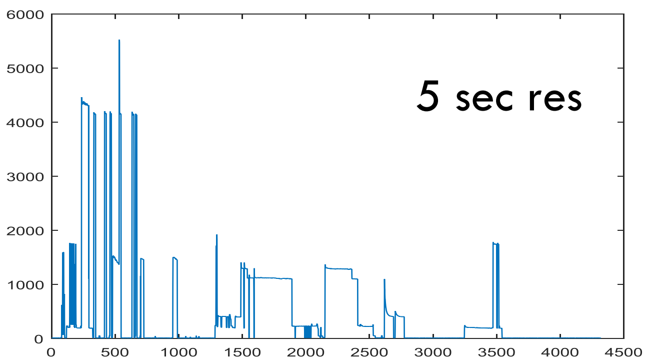
- It can improve energy saving awareness, facilitate smart grid technologies, …

Really? The Gap is huge…

[1]NSMP, "Smart Metering Infrastructure Minimum Functionality Specification," 2011.

Can smart meter be smarter?

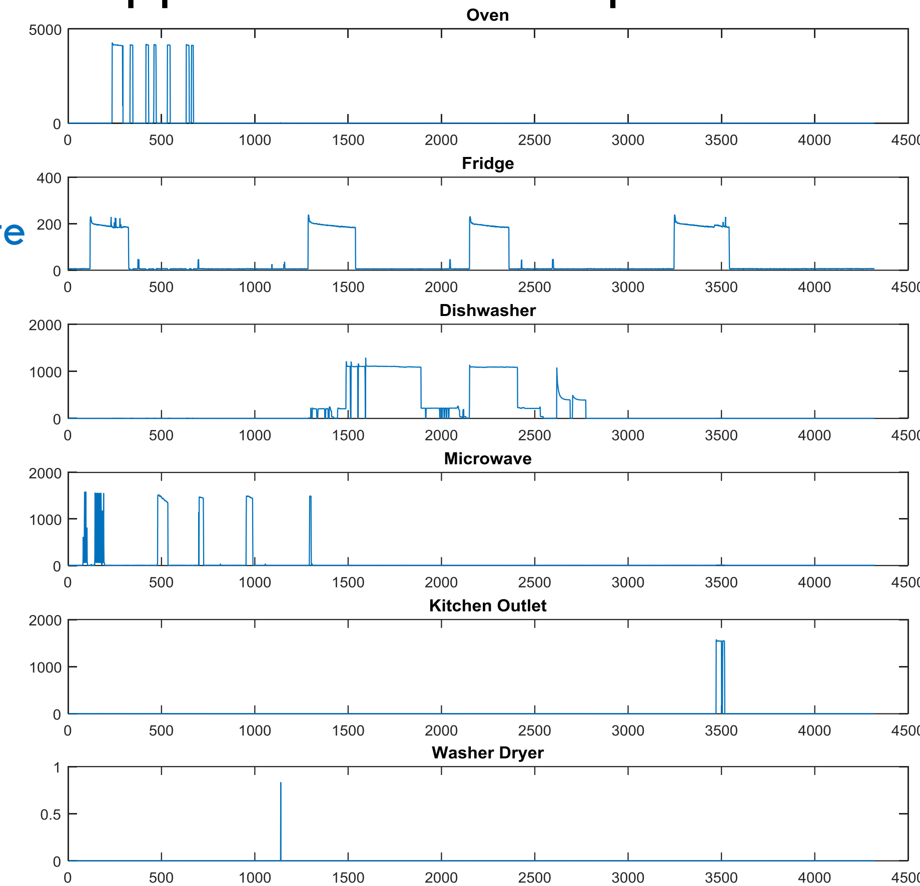
Aggregated Profile



disaggregate

Smart Meter

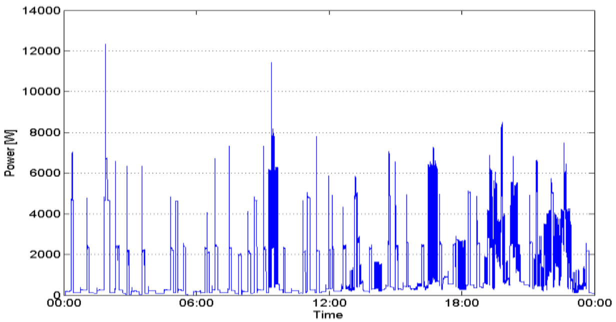
Appliance-wise load profile



Non-Intrusive Load Monitoring (NILM)

Facilitate Smart Grid Tech: Demand Response

Aggregated Profile



Smart Meter

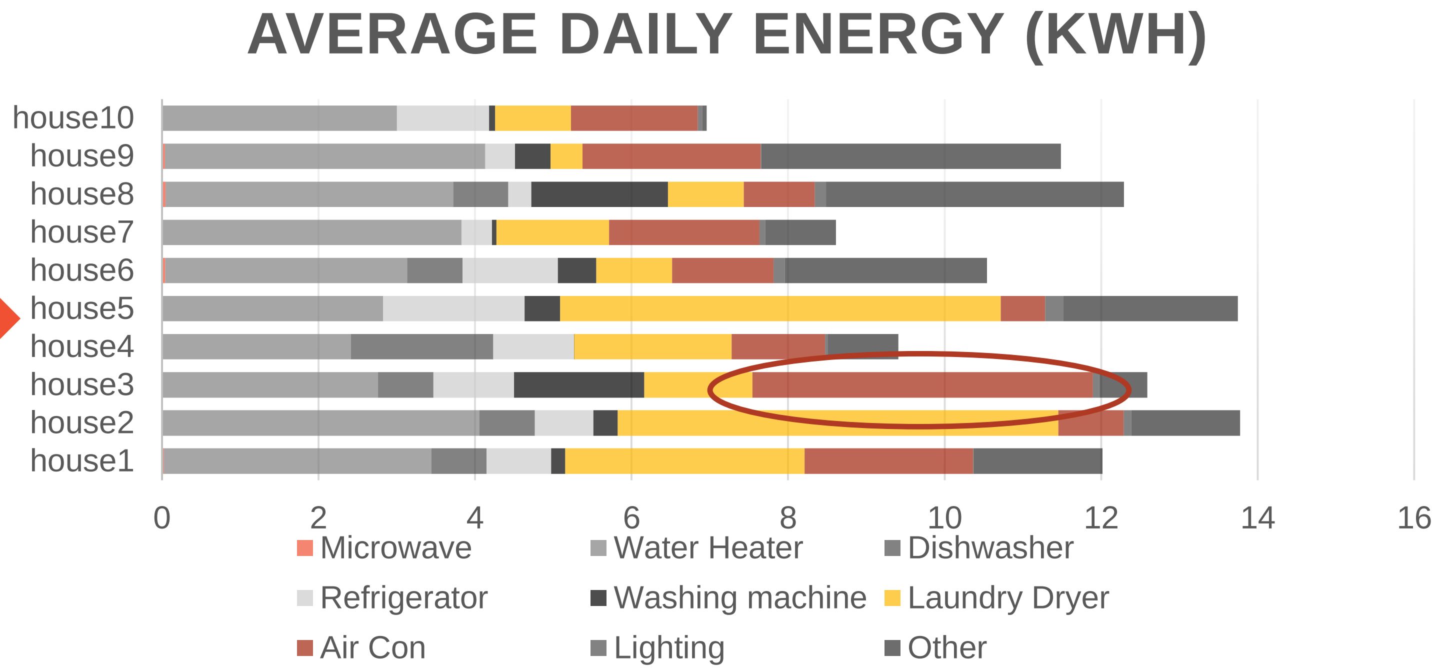
Non-Intrusive Load Monitoring (NILM)

- Break the aggregated load profile down to device-level profiles
- DR potential differs among appliances
- Allows dynamic assessment of DR performance/potential

High DR Potential

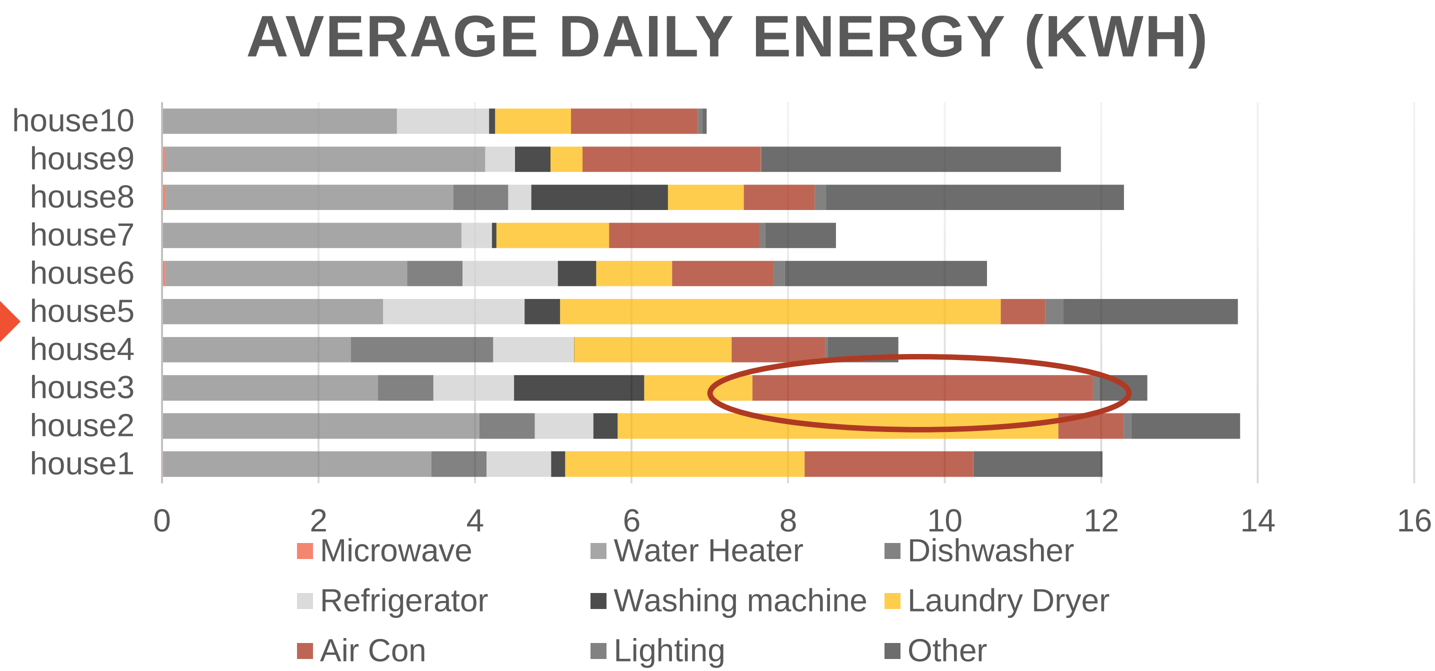
Low DR Potential

Facilitate Smart Grid Tech: Demand Response



- This is an example of what insights the NILM technology can provide
- After disaggregating, we found that house3 consumes the most for air-con. Therefore, house3 may be of the greatest interest for **monetary based demand reduction** program
- Also, we may look deeper into the minute-to-minute consumption profile of each appliance to learn the time when this user is most likely to participate in demand reduction.

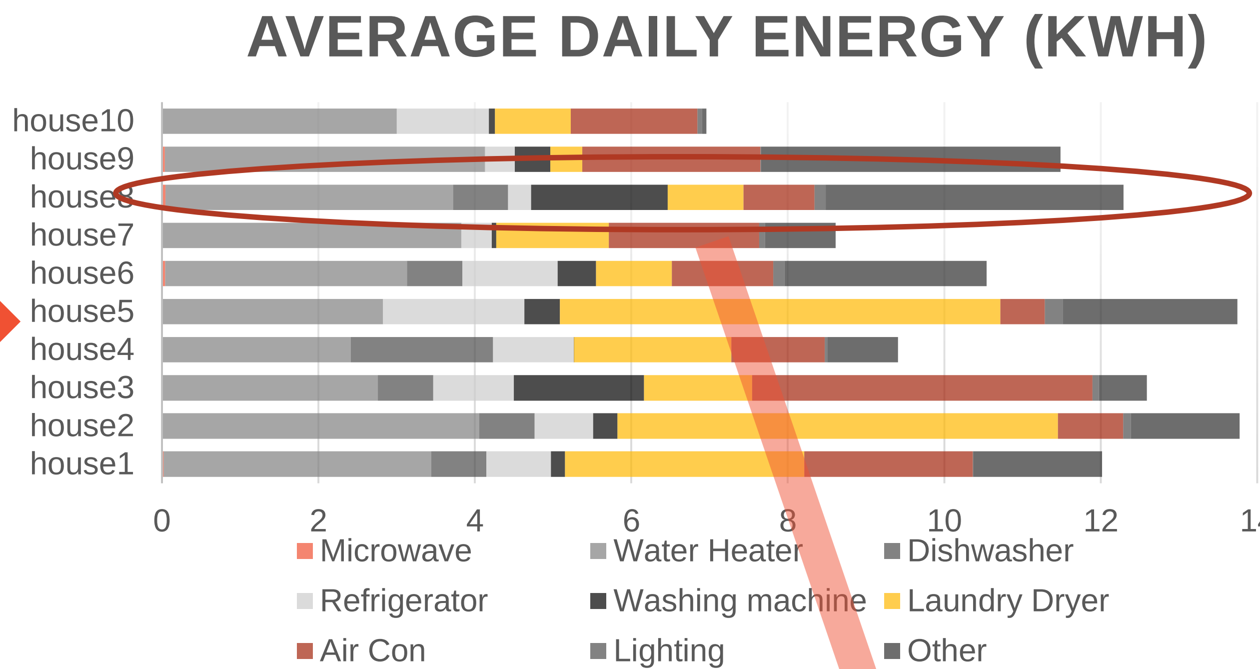
Facilitate Smart Grid Tech: Energy Awareness



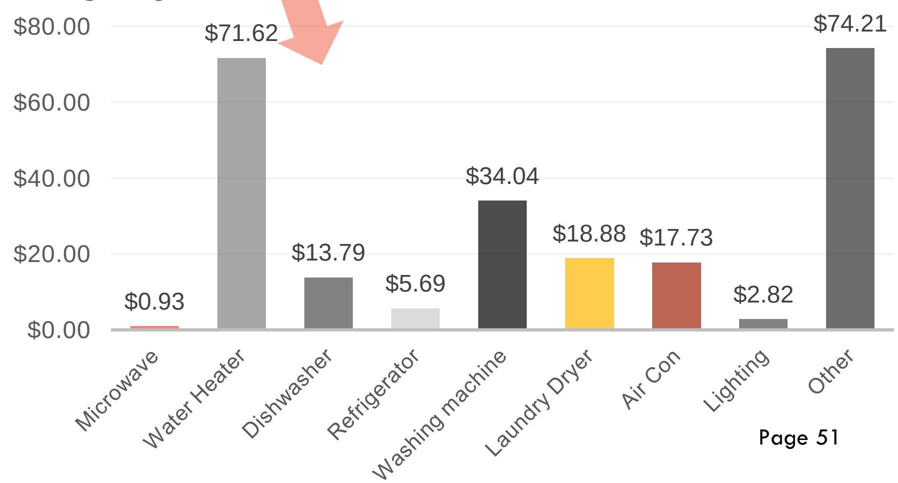
- by disclosing the comparison of the NILM results between the customers, it will trigger the behavioral reaction leading to save more energy and lower the electricity bills[2]
- In this example, house3 can realize that they are using much higher electricity in air-con than social average. This may make the householders to double check whether their high usage is necessary and remember to switch off the air-con when no one is in the room

[2] https://opower.com/

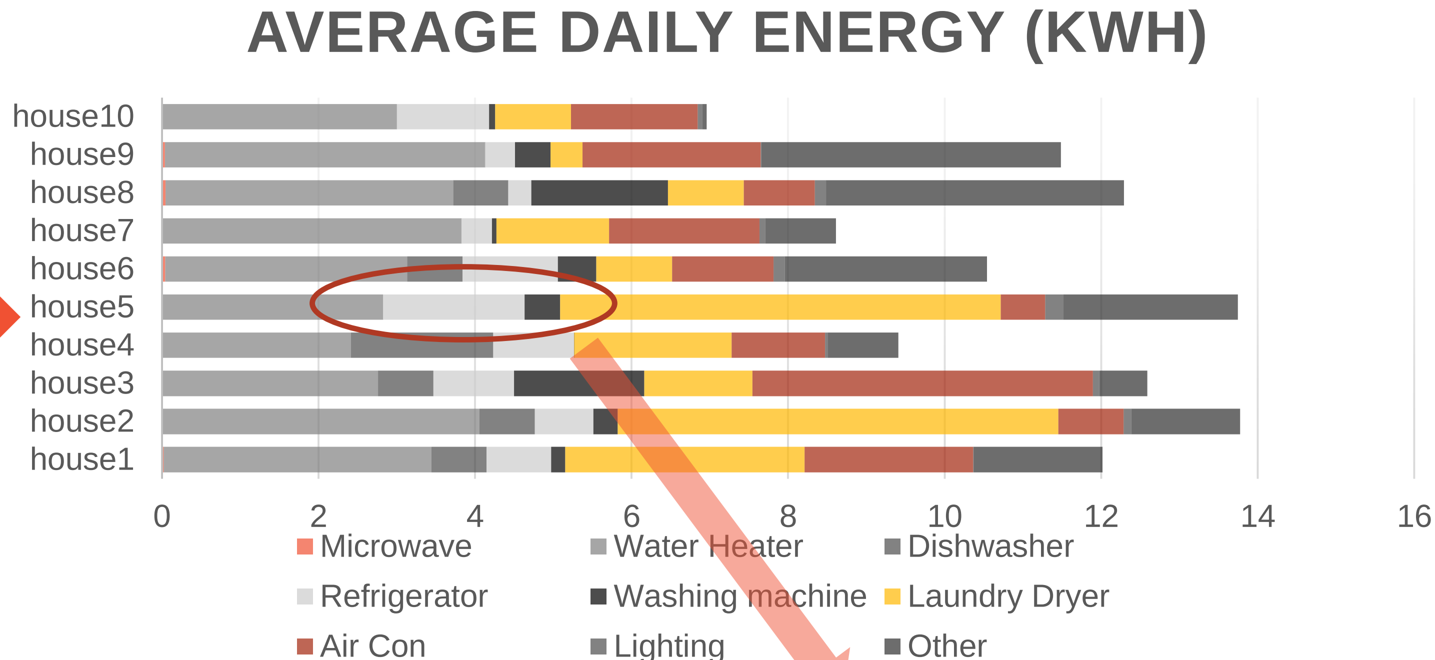
Facilitate Smart Grid Tech: Energy Awareness

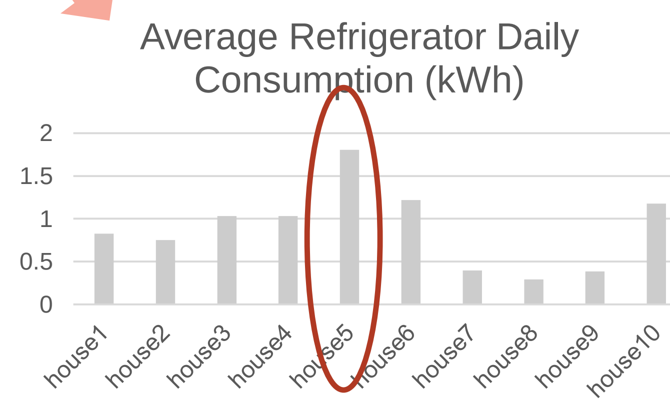


- With NILM technology, the electricity bill of an household can be itemized
- This information cultivates better energy awareness for customers



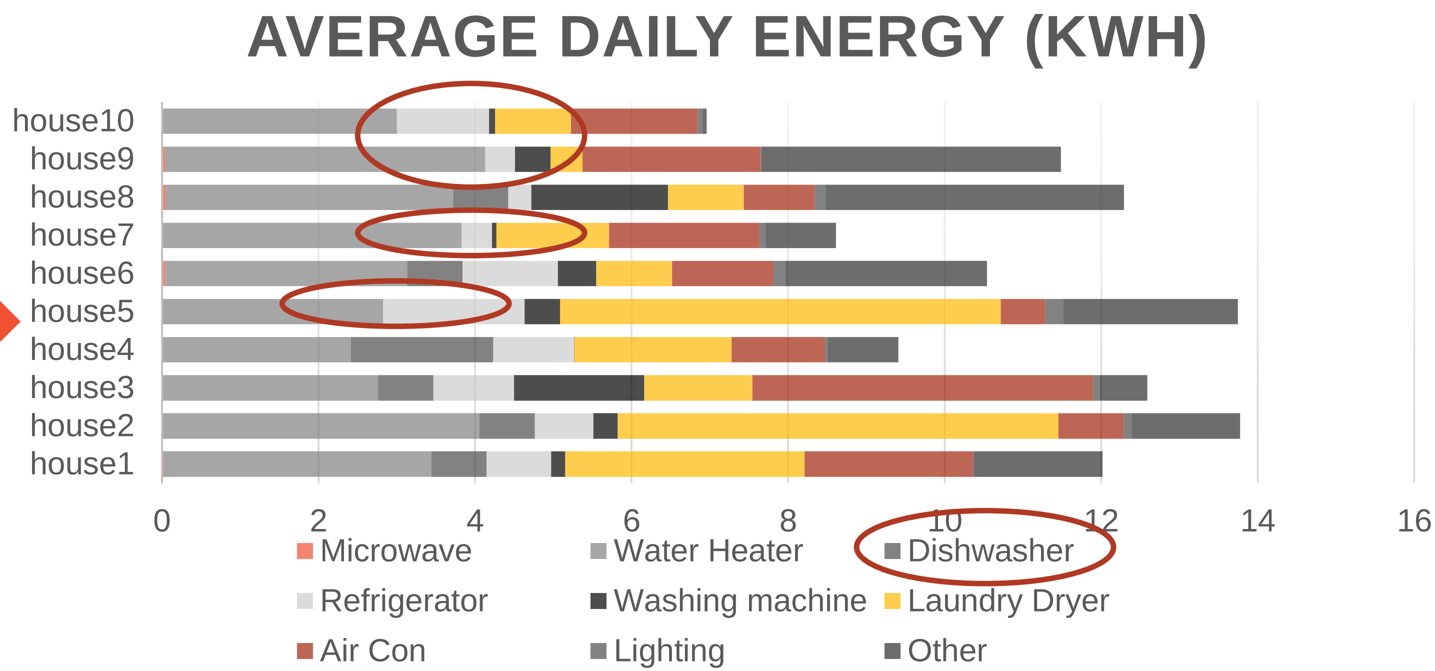
Facilitate Smart Grid Tech: Advertisement





- As this example, NILM may help us to spot that house 5 consume much higher energy than social average for refrigerator
- This could mean that either this household uses an **aged model or a low efficient model**
- So we can target this house to recommend more efficient models of fridge or alert the user to inspect the fridge

Facilitate Smart Grid Tech: Advertisement

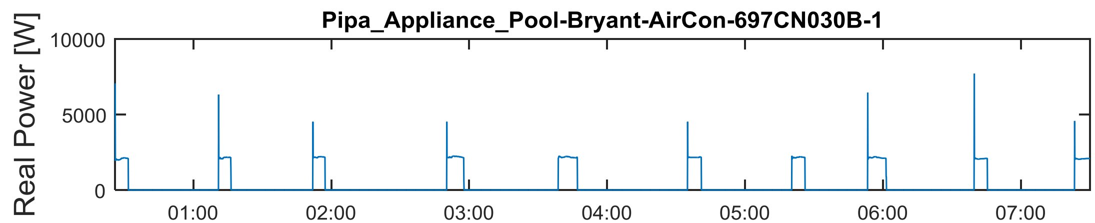


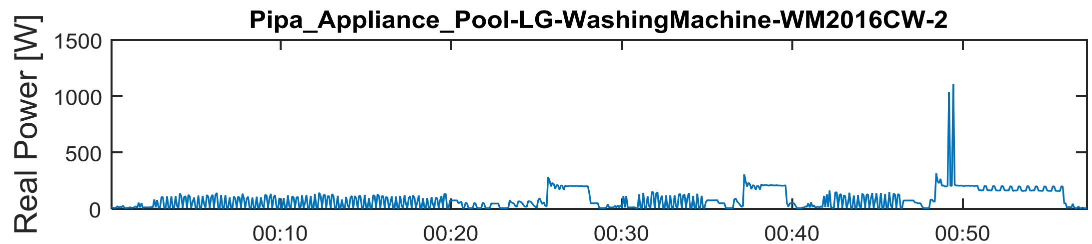
- On the other hand, house5, 7, 9 and 10 are found that they are equipped with dishwasher. Using dishwasher is a much more economical and efficient way to wash cooking utensils and plates

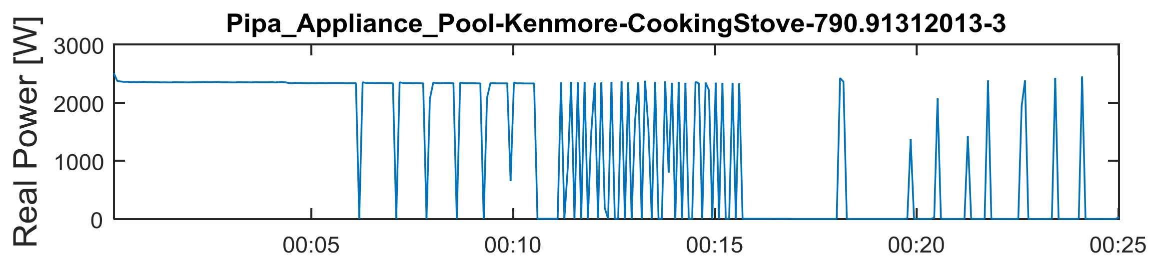
- So these customers can be targeted for dishwasher recommendations.

Challenge

Each type of electric appliances has a unique fingerprint, it is also called the *Power Signature*.

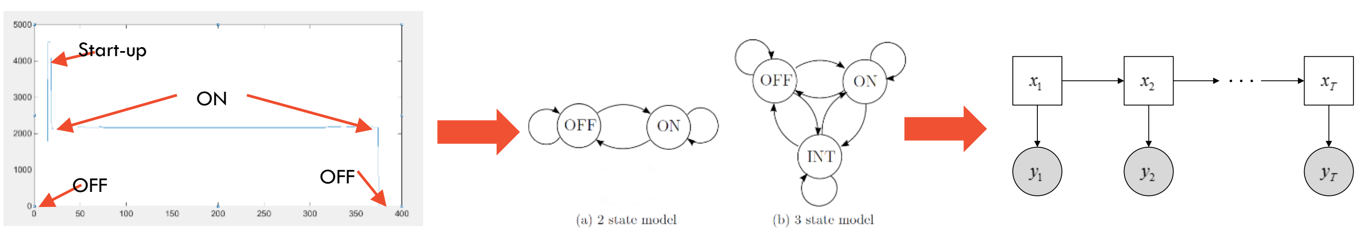






Our Approach

- Based on readily available smart meter data
  - smart meters are required to update the reading of power consumption **every 5 seconds** according to Australian National Smart Metering Program's minimum functionality specification[8]
- Dynamic probabilistic models are built by analysing different appliances to capture the distinct state transition relationships



Example of an Air-conditioning operation cycle

- Can effectively work with data sampled at 5-second interval to 1-minute interval to provide appliance-level insight

Electricity Plan Recommendation

If your electricity or gas bills are on the rise, Talk to me! We can compare residential electricity and gas plans and find the one that's right for you!

Research Directions

THE UNIVERSITY OF SYDNEY

Future Energy Grid

Research Directions

- Renewable energy: multi-terminal high voltage direct current, energy storage…
- Demand side management: big data, retail pricing, customized advertising….
- System operation and planning: co-planning (gas and electricity, traffic and electricity), risk-based dispatch and planning…
- System stability and control: stability assessment (rotor, voltage, and frequency), cyber security (false data injection, detection, and protection), centralized vs. distributed control (hierarchical, coordination, delay), distributed optimization…
- Energy internet: communication protocols, energy USB, energy router…

Thanks!

Ke Meng
Lecturer
School of Electrical and Information Engineering
Email: ke.meng@sydney.edu.au