IEEE IES Distinguished Lecture

Smart Grids: A Complex Network View

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Outline

1. The Need for Smart Energy
2. What are Smart Grids?
3. Smart Grids and Complex Networks
4. Discussions and Conclusions

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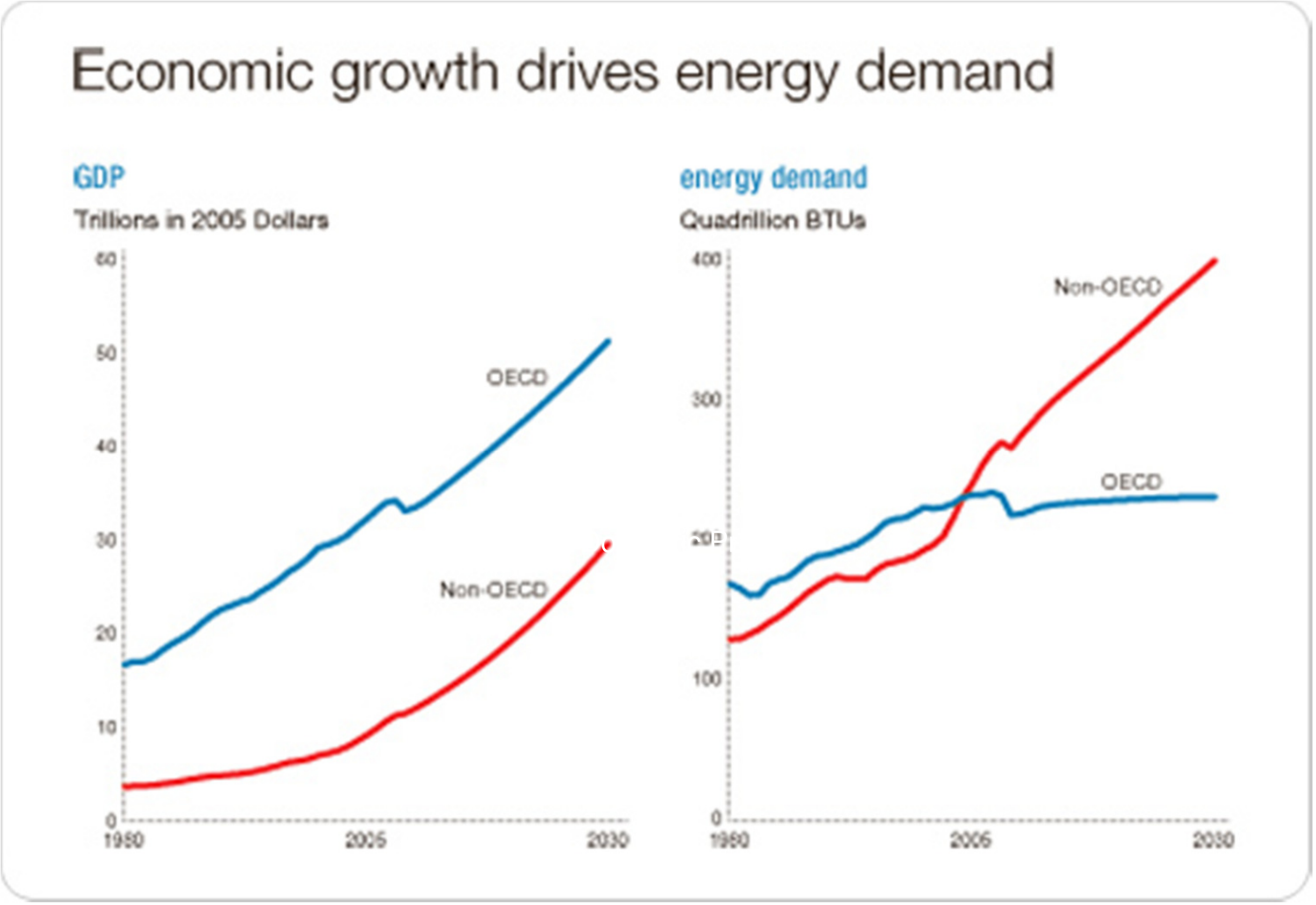
The world's need for energy …



http:://exxonmobil.com.

OECD (Organization of Economic Cooperation and Development) countries: Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States

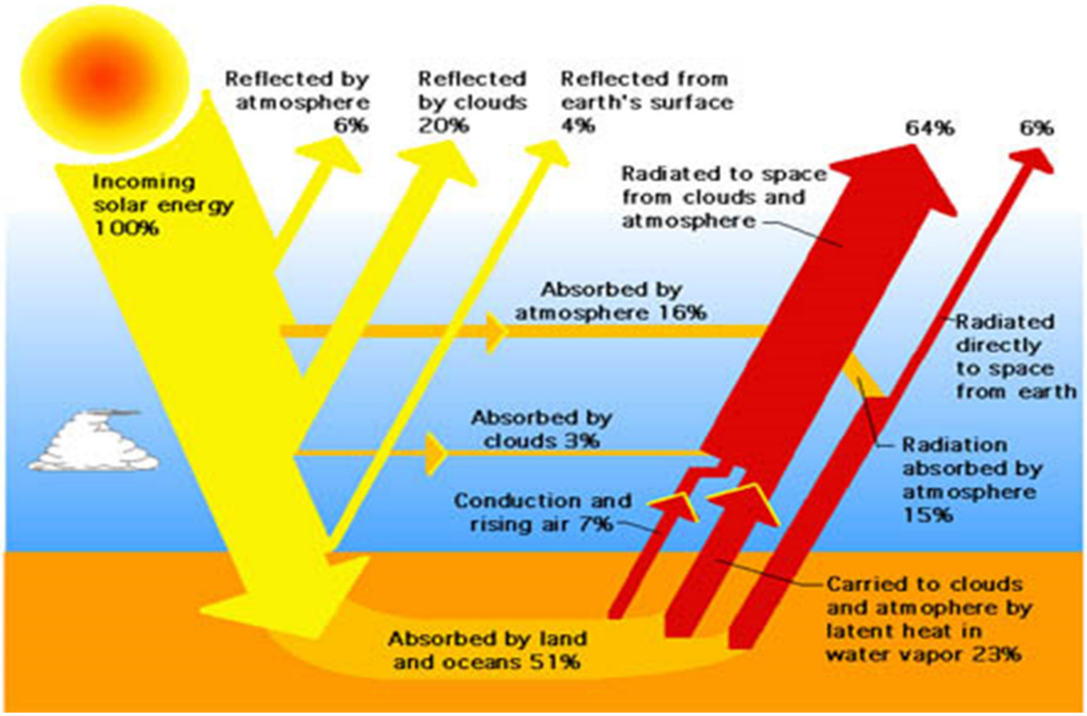
Energy pollution

Almost all energy production and use involves some form of pollution of our environment!

For example,

- Coal and Oil Plants generate Carbon Dioxide causing global warming, Nitrous Oxide causing smog and Particulate or Dust Air causing lung cancer.
- Nuclear Power Plants generate Radioactive Waste which is difficult to dispose of, Radiation Leaks causing radiation poisoning and increased risk of cancer.

Earth's Energy Budget



Wind, waves, convection currents: 0.23%

Photosynthesis: 0.022%

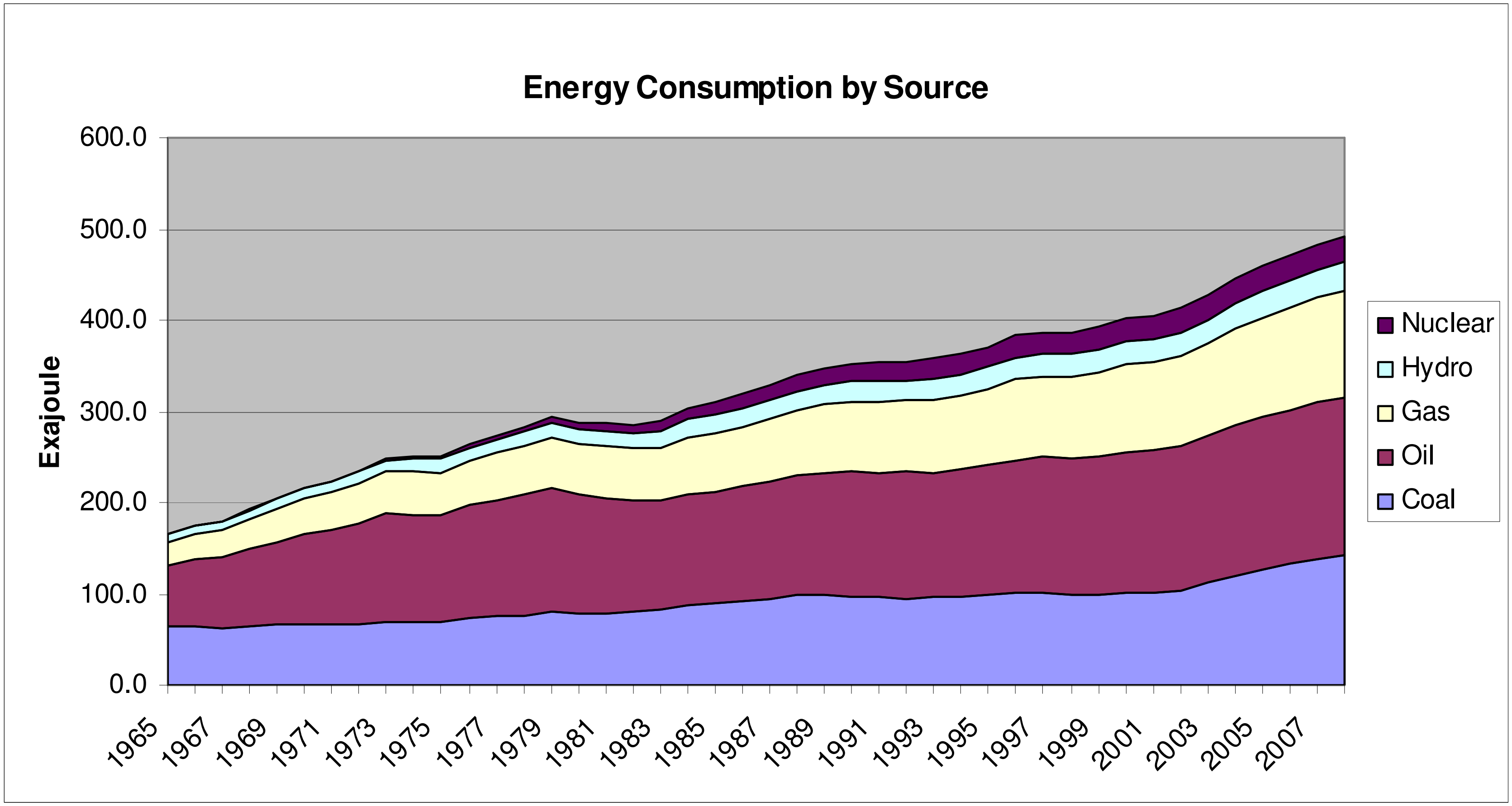
Source: Nasa

Total energy entering the Earth's atmosphere is 174 petawatts (~5.5 million EJ/year), consisting of:

- **solar radiation (99.978%, or nearly 174 000 000 GW; or about 340 W/m^2)**
- **geothermal energy (0.013%, or about 23 000 GW; or about 0.045/W m^2)**
- **tidal energy (0.002%, or about 3 000 GW; or about 0.0059 W/m^2)**
- **waste heat from fossil fuel consumption (about 0.007%, or about 13 000 GW)**

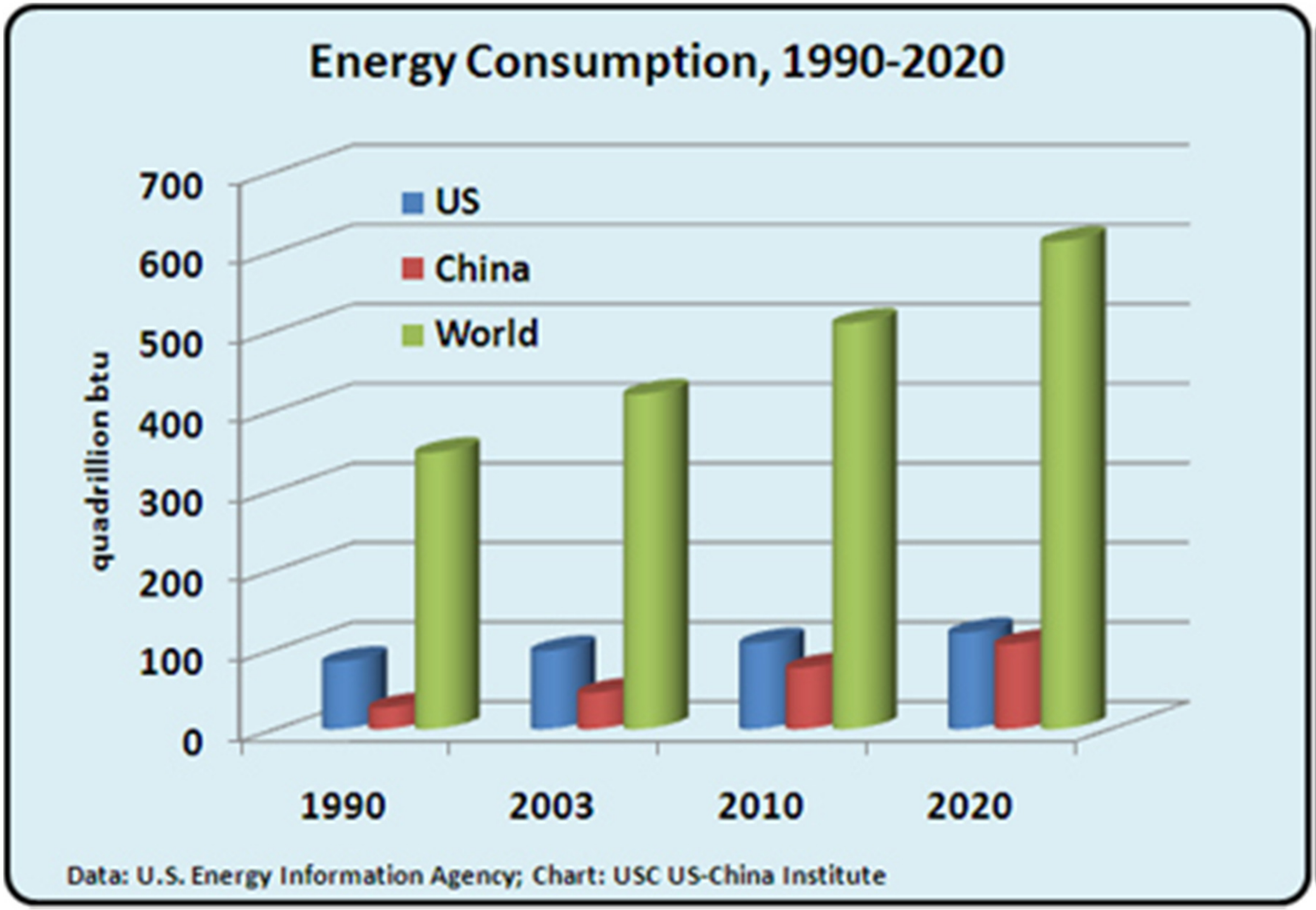
Source: Wikipedia

World Energy Consumption

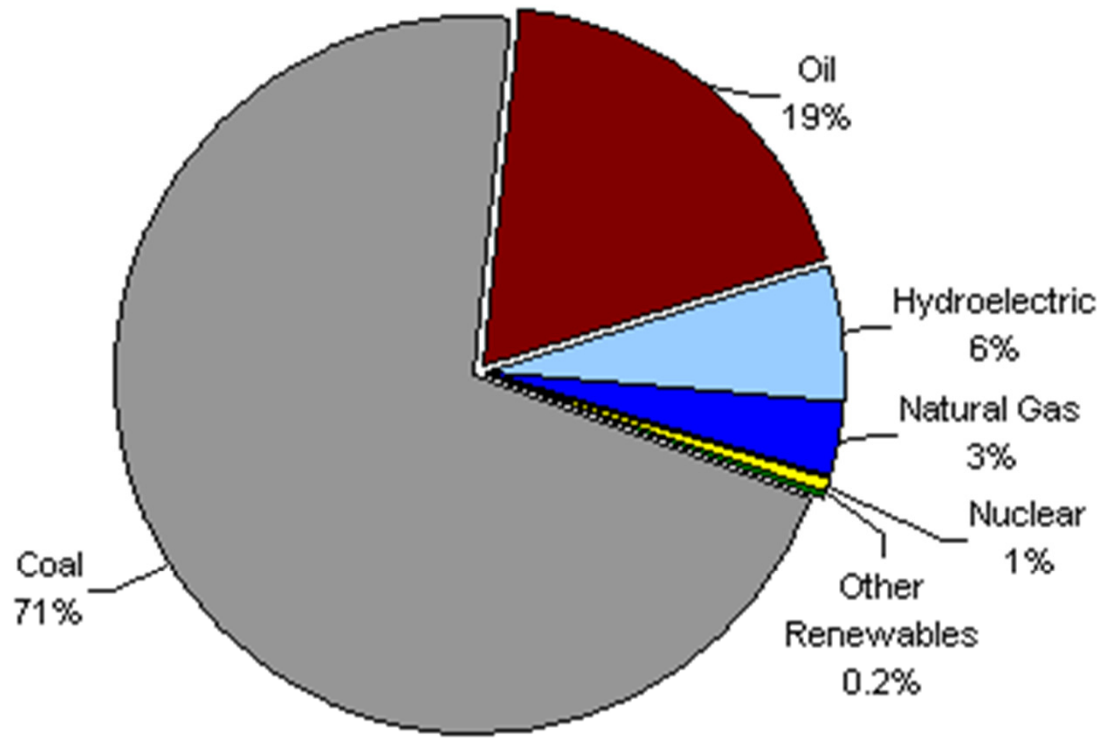


Proven Reserves: Coal – 23600 EJ (164 years)
Oil – 7400 EJ (43 years)
Gas – 7116 EJ (60 years)

Source: BP Statistical Review of World Energy June 2009

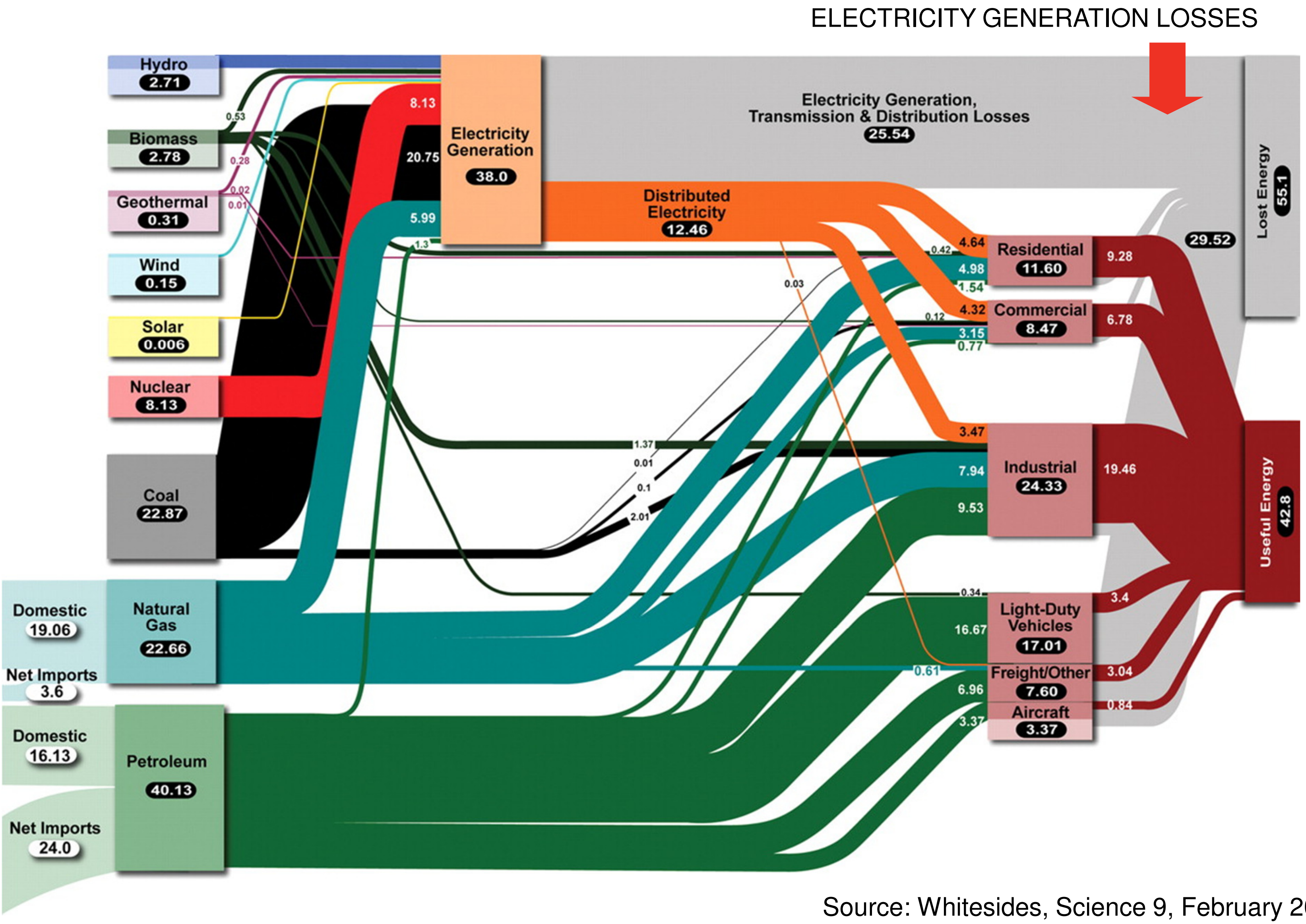

Energy Consumption, 1990-2020
700
600
500
400
300
200
100
0
quadrillion btu
US
China
World
1990
2003
2010
2020
Data: U.S. Energy Information Agency; Chart: USC US-China Institute

Total Energy Consumption in China, by Type (2008)



Source: EIA International Energy Statistics 2008

Patterns of US Energy Usage - 2005



Source: Whitesides, Science 9, February 2007

Summary of Energy Usage

Present Status

- There is more than enough incident Renewable Energy received by the earth each day to meet our needs.
- **However**, Renewable Energy is diffuse, and hence difficult and expensive to use.
- **So**, present energy use is based essentially on higher energy density fossil (non renewable) fuels, which are much cheaper to access and use.

Summary of Energy Usage

Future Status

- Non-renewable fuels are very limited (only several 10's years remaining supplies).
- Mostly, their use creates substantial CO_2, which is a major contribution to Global Warming.
- Clearly, the present usage rates and energy sources are unsustainable in the long run.
- The question of how long we can continue with current practices is a subject of considerable debate (i.e. how long have we really got to change our behaviour??)

“Smart Energy” Paradigm Changes

<u>Alternative “Smart Energy” Generation Sources</u>

- New technologies to effectively extract and use renewable energy – wind, solar, waves, geothermal – for electrical generation.

<u>Improved “Smart Grid” Energy Distribution</u>

- Improved distribution of existing (electrical) energy, to better use existing assets, reduce capital expenditure and reduce losses.

<u>Better “Smart Load” Energy Utilisation</u>

- Better management of energy use to reduce losses
- New technologies to achieve the same outcome with less energy usage.

Alternative "Smart Energy" Sources

<u>Wind Generation</u>

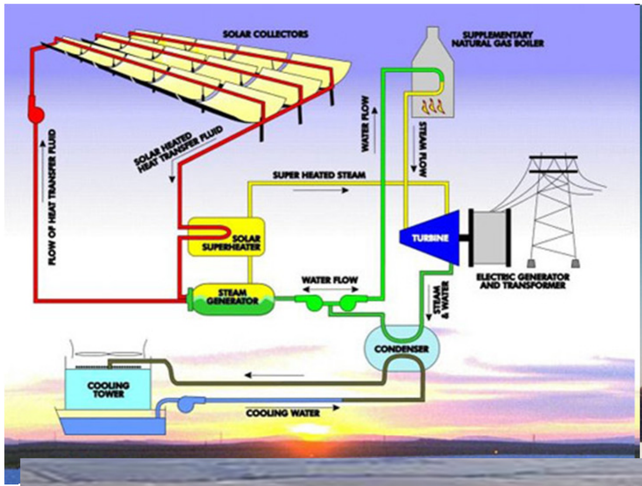
Ararat, Victoria, Australia

Offshore, Denmark

Typically many 10's of 2-3MW turbines = 200-300 MW/farm

Alternative “Smart Energy” Sources

Solar Thermal Generation



Kingman, Arizona

100-300MW systems are under construction. But very limited experience to date.

Alternative "Smart Energy" Sources

PV (Photovoltaic) Generation

Kyushu Japanese Microgrid System

Waldpolenz Solar Park, Germany: 40 MW

(generation cost approx $0.30 - $0.40/kWh)

(~ 5 times more than fossil fuel generation)

Alternative "Smart Energy" Sources

Technical Issues

- Intermittent availability.
  - Larger scale generation penetration change main grid operating paradigms (wind generation "failure" in Texas in 2008).
  - Storage required for significant generation penetration.
- Variable Electricity "Quality".
  - Requires power electronic conversion systems to convert DC to AC for PV, variable frequency to 50/60Hz for wind.
- Large numbers of small distributed generation systems.
  - Rewrite the fundamental operating principles of electrical grid networks! (compare train to automobile transport systems).

Outline

1. The Need for Smart Energy
2. What are Smart Grids?
3. Smart Grids and Complex Networks
4. Discussions and Conclusions

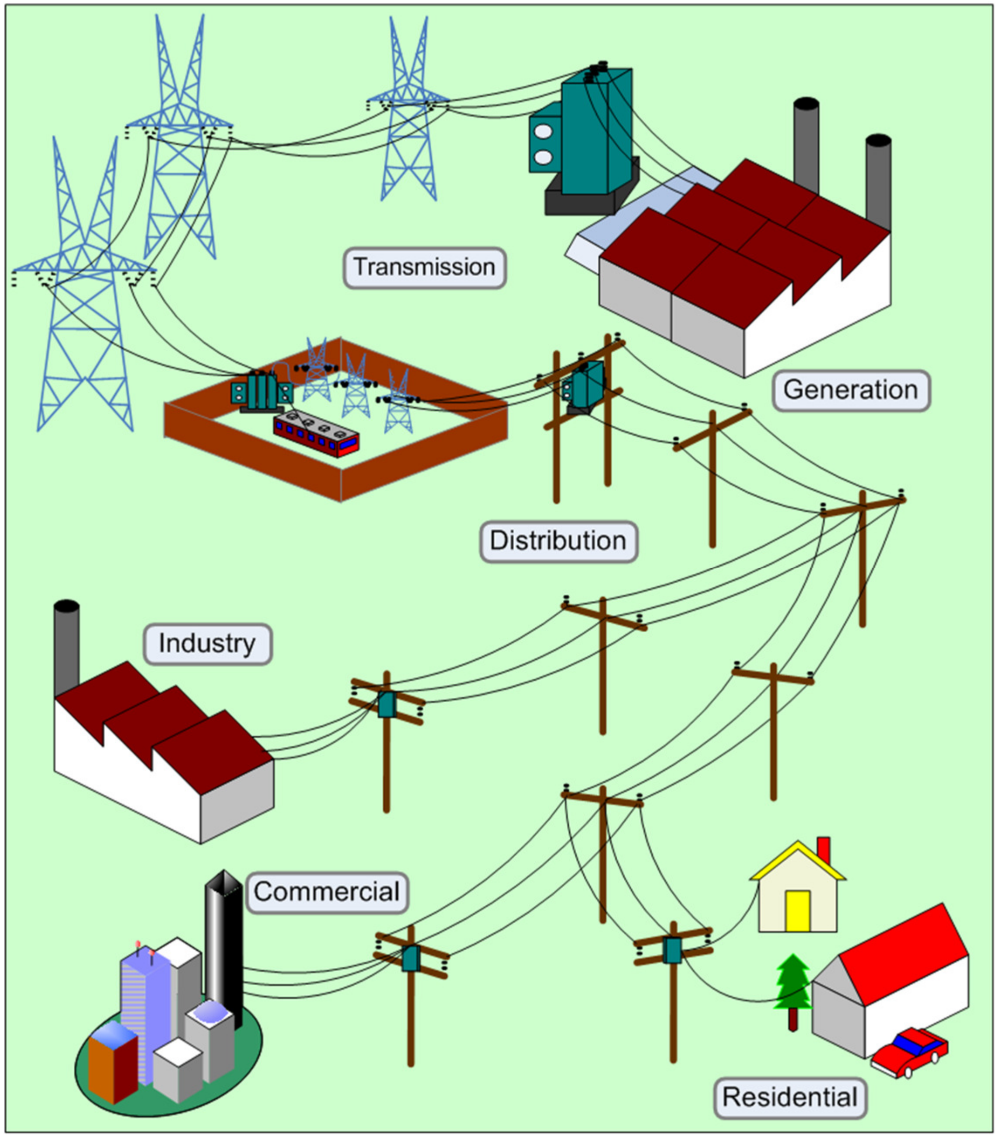
What are Smart Grids?

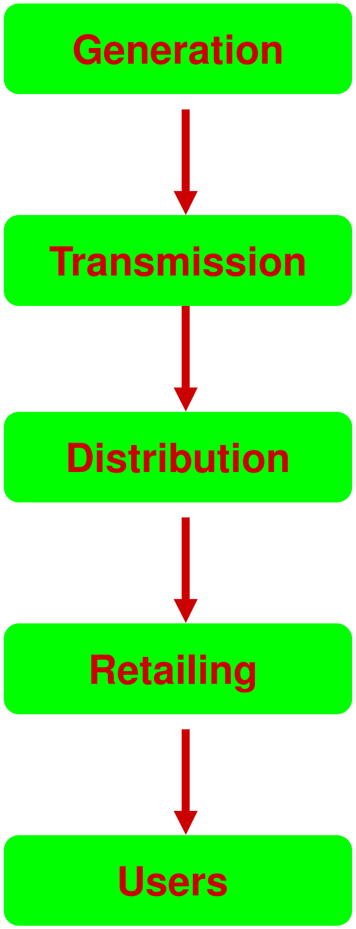
The term Smart Grids refers to electricity networks that can intelligently integrate the behaviour and actions of all users connected to it - generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies.

(European Technology Platform SmartGrids www.smartgrids.eu)

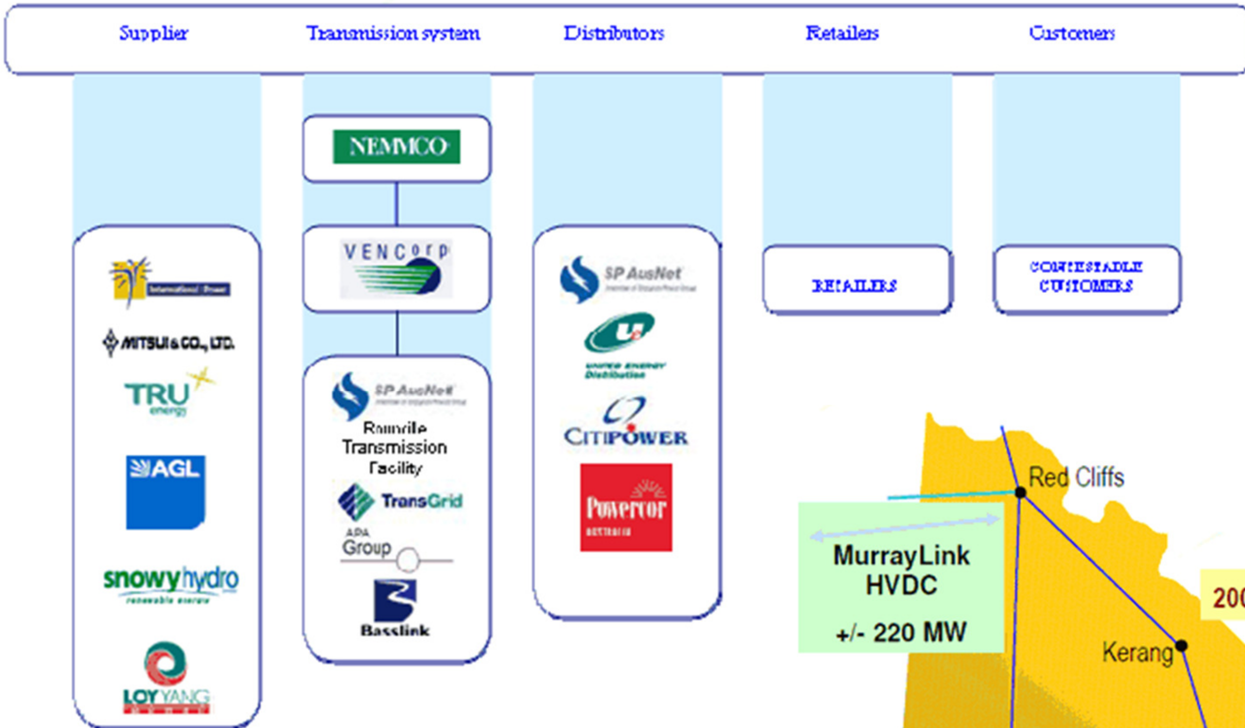
It can be considered as bringing the power of the Internet to the transmission, distribution and use of electricity.

Electricity Supply

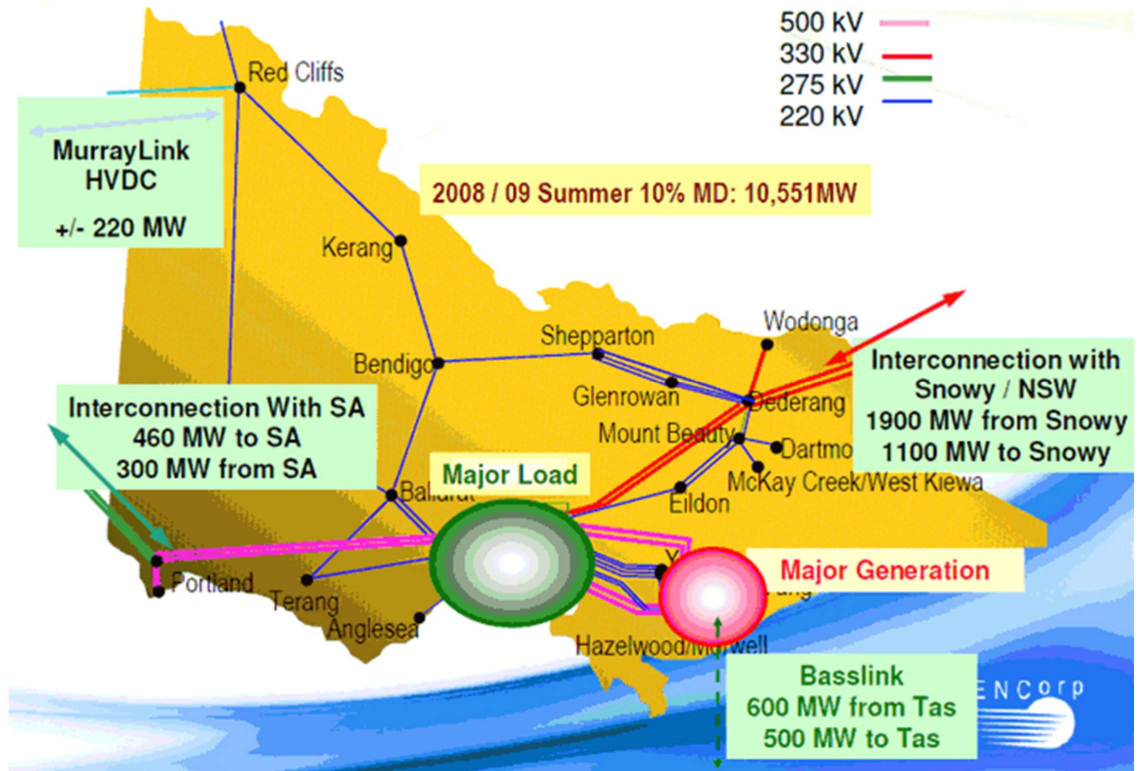




Electricity Supply: An example

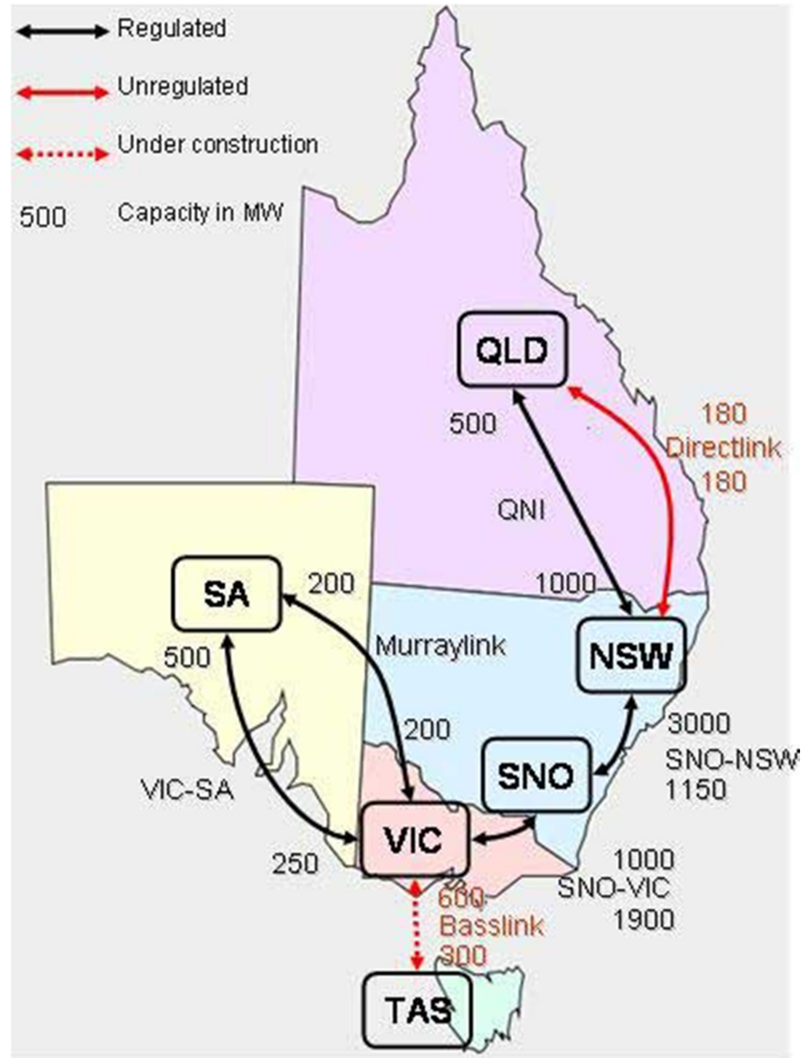


Victorian Energy System



Example: Australian National Electricity Market

- The largest interconnected power system runs for more than 5000 kms with 8m users and $10bns electricity supply (AEMO)
- In 2003, there were
  - 41 generator companies
  - 20 network service providers
  - 39 market customers/traders

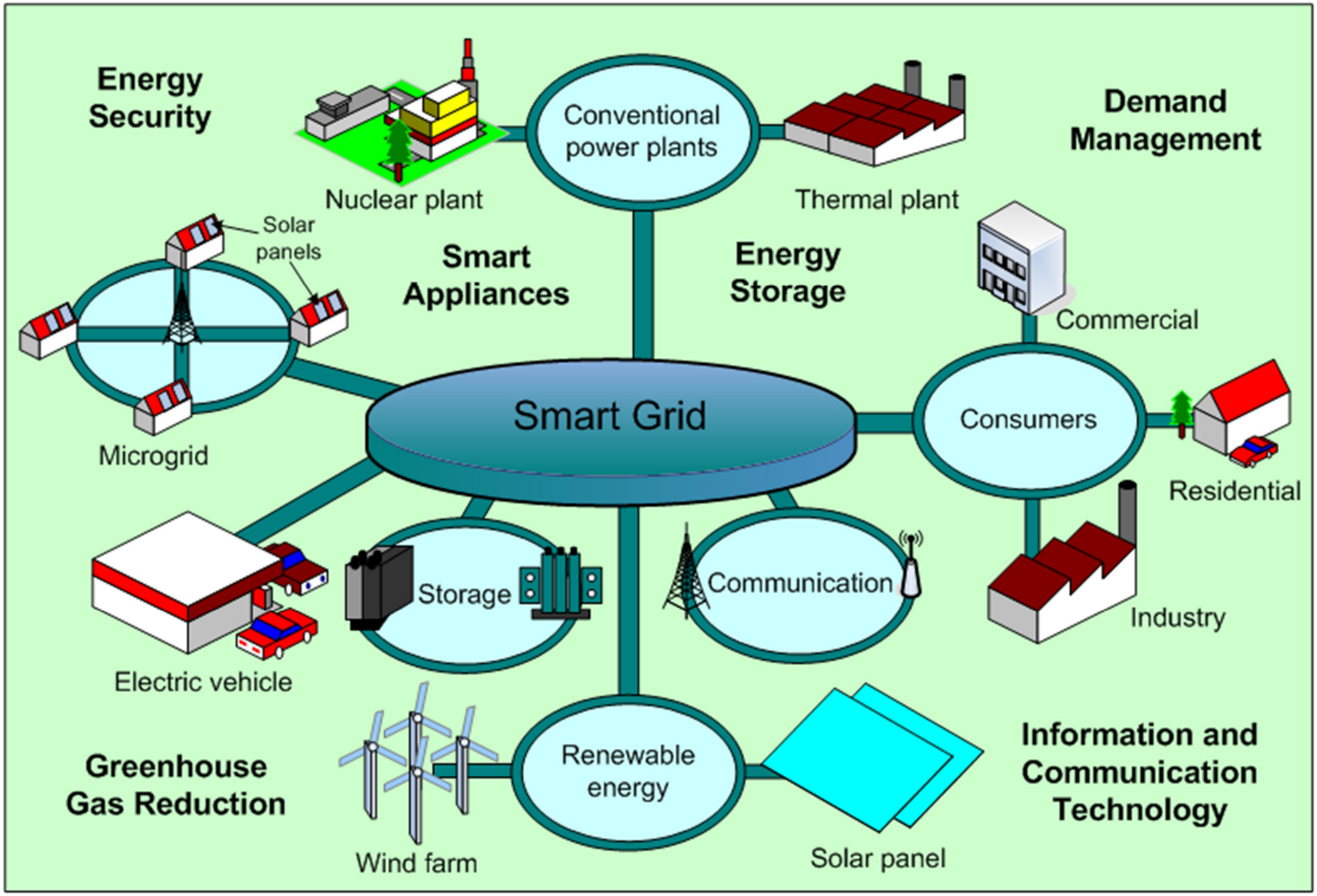


Australian Electricity Network

Current Structure of Electrical Grid

- Large Scale Generation Plant located near primary energy source.
- High Voltage High Power transmission network to transport energy to load centres.
- Terminal and substations to reduce voltage levels.
- Lower Voltage Distribution Network to distribute electrical energy.
- Consumers are the end of the distribution chain.
- Marketing operating principles have been overturned by privatisation in recent decades.
- Technical principles of operation are essentially unchanged for some decades.

Future Electricity Grid



The Complexity of Future Electricity Supply

- Needs for deeper control
- Increased cross connectivity
- Embedded generation
- Smart metering
- Wires as carriers for telecoms, data, enhanced services
- Electricity trading in a free market

SMART Grid Concept (Europe)

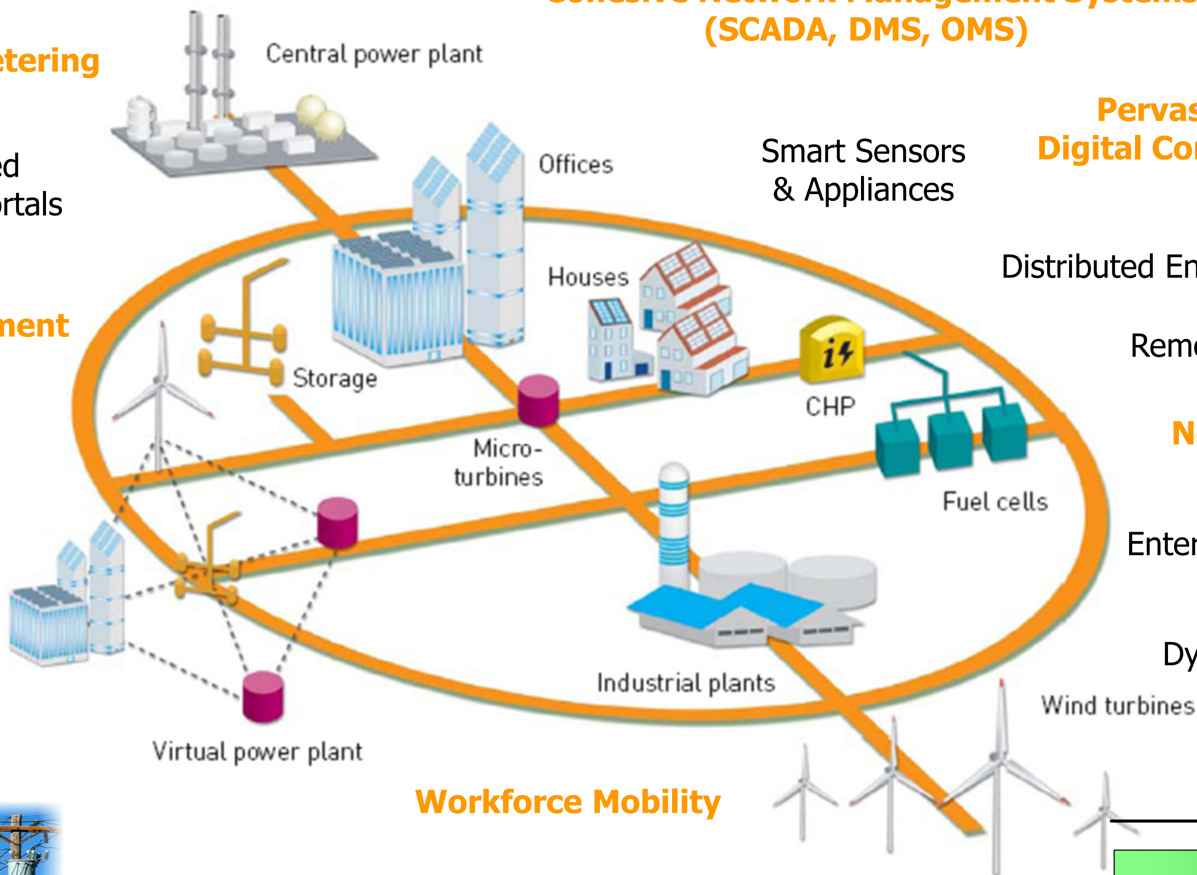
Advanced Metering

User Oriented Presentation Portals

Enterprise Asset Management Systems

Sustainable Network Cells

Cohesive Network Management Systems (SCADA, DMS, OMS)



Smart Sensors & Appliances

Pervasive Wide-Bandwidth Digital Communications Capability

Distributed Energy Resources

Remote Control & Monitoring

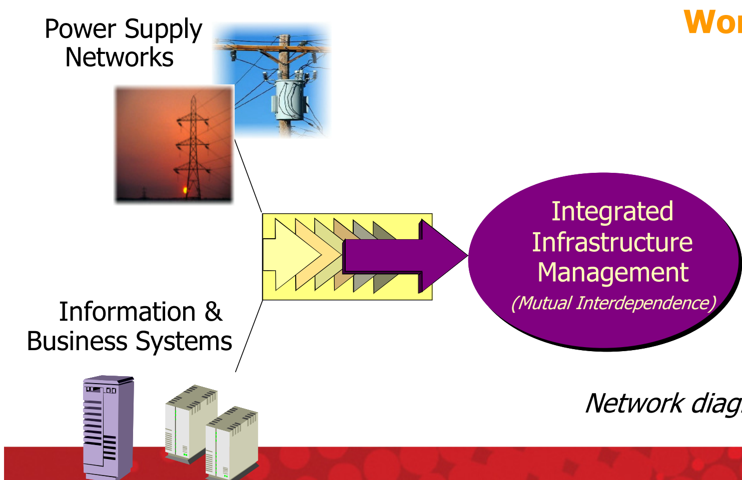
Network Automation & Self-Healing

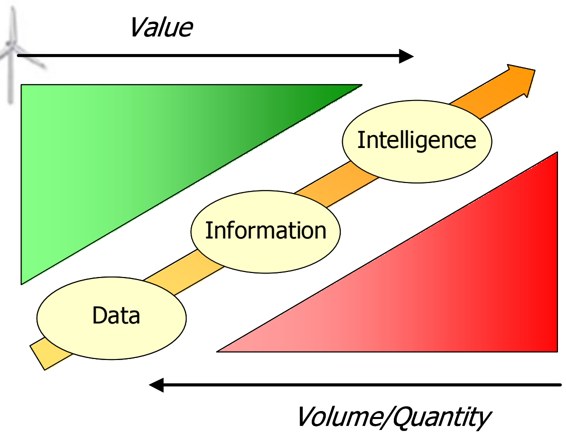
Enterprise Data Management Systems

Dynamic Load Management

Workforce Mobility

Analytics that Transform Data into Intelligence

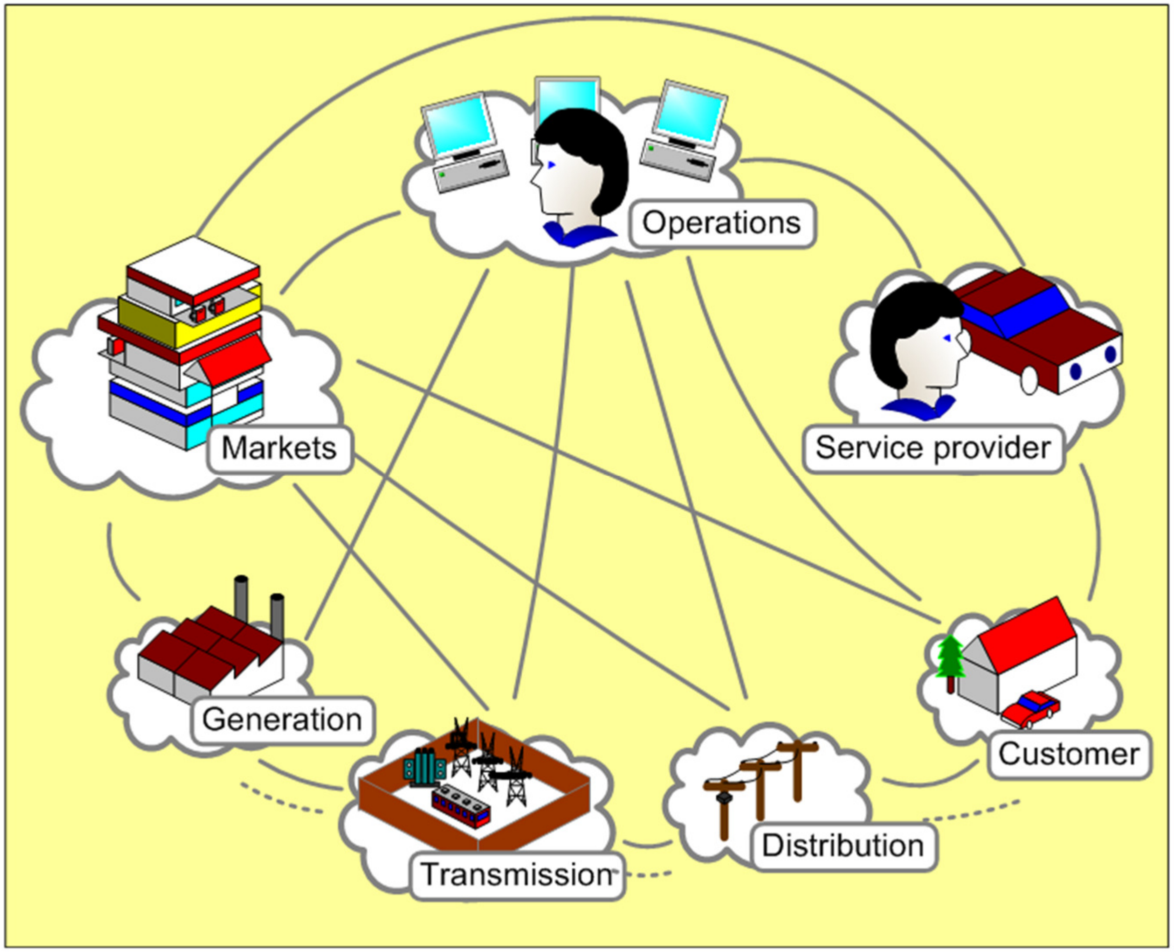




Network diagram courtesy of European Commission EUR 22040

SMART Grid Concept (USA)

USA's SG refers to a means to transform the electric industry from a centralized, producer-controlled network to one that is less centralized and more consumer-interactive.



Australia's Key R&D Issues in Smart Grids (1)

- **Governance & Policy (industry frameworks)**
  - Policy & regulatory setting
  - Pre-standardisation R&D
  - Large systems simulation
  - Demonstration projects
- **'Operational' Technologies & Systems**
  - Control systems
  - Grid security & stability
  - Fault detection and prediction
  - Data & communication
  - Demand management
  - Self-healing grids
  - Long distance energy supply

Ref: SmartGrid Australia, 2010

Australia's Key R&D Issues in Smart Grids (2)

- **Informational Technologies & Systems**
  - Carbon mitigation
  - Grid to consumer
  - Modeling & optimization
- **End-use**
  - Customer behaviors
  - Model validation (3BL)
  - End-use technologies
- **Cross-sectoral Integration**
  - Sectors and utilities; communication, entertainment and other services
  - Cross-system modeling

Ref: SmartGrid Australia, 2010

Smart Energy

Energy Efficiency

Solar thermal
Waste heat recovery
Heating, cooling and electricity

"Trigeneration"

"Cogeneration"

Embedded Generation

Reciprocating engines
Small gas turbines
Fuel cells
Local solar PV & Wind

"Mini grids"

"Virtual utilities"

Demand Management

Peak shifting & levelling
Energy storage
Load management
Aggregation of DRR

(Terry Jones, CSIRO)

Use less; Use it more efficiently; Waste less!

Use Less : Elements of a Smart solution

Building & site
Appliances
Household lifestyle and behaviour
} **Demand/load**

Energy source → **‘Supply’**

Systems approach

Use It More Efficiently

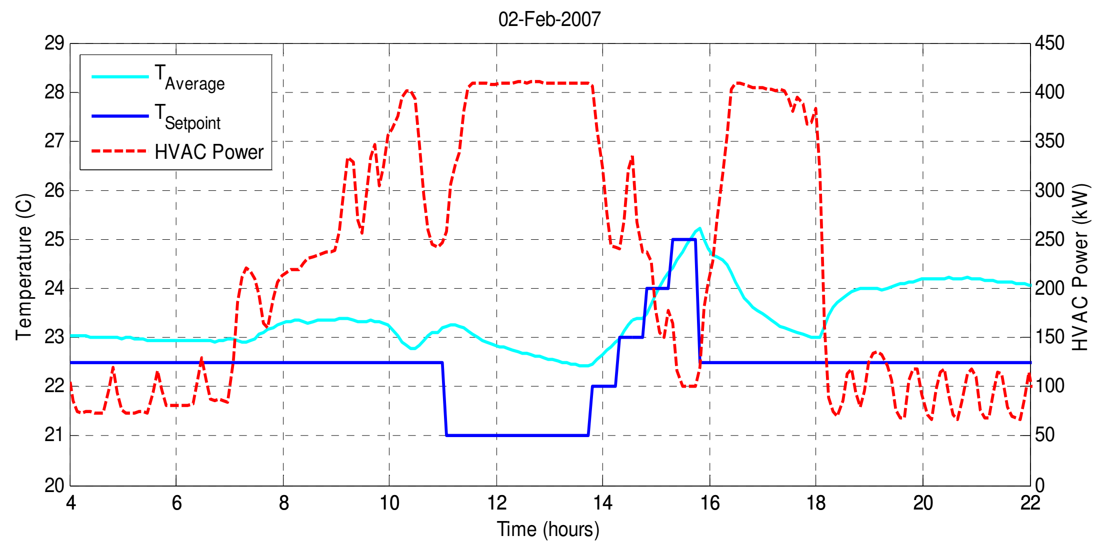
- Generate locally to reduce losses
- Kill the peaks

Thermostats in Commercial Buildings

- **Benefit of 1˚C**
  - Identical conditions method – 15-20% power saving
  - Conditions inside ASHRAE comfort guidelines
  - Variable steady state conditions method – 10-20% power saving
  - Transient conditions method – 5-10% power saving

- **Believable ??**
  - Chiller Carnot efficiency ~ 3% improvement per deg C
  - Heat load ~10% reduction in outside heat per deg C
  - Fans, chilled water pumps etc unchanged, ~ 50% of load

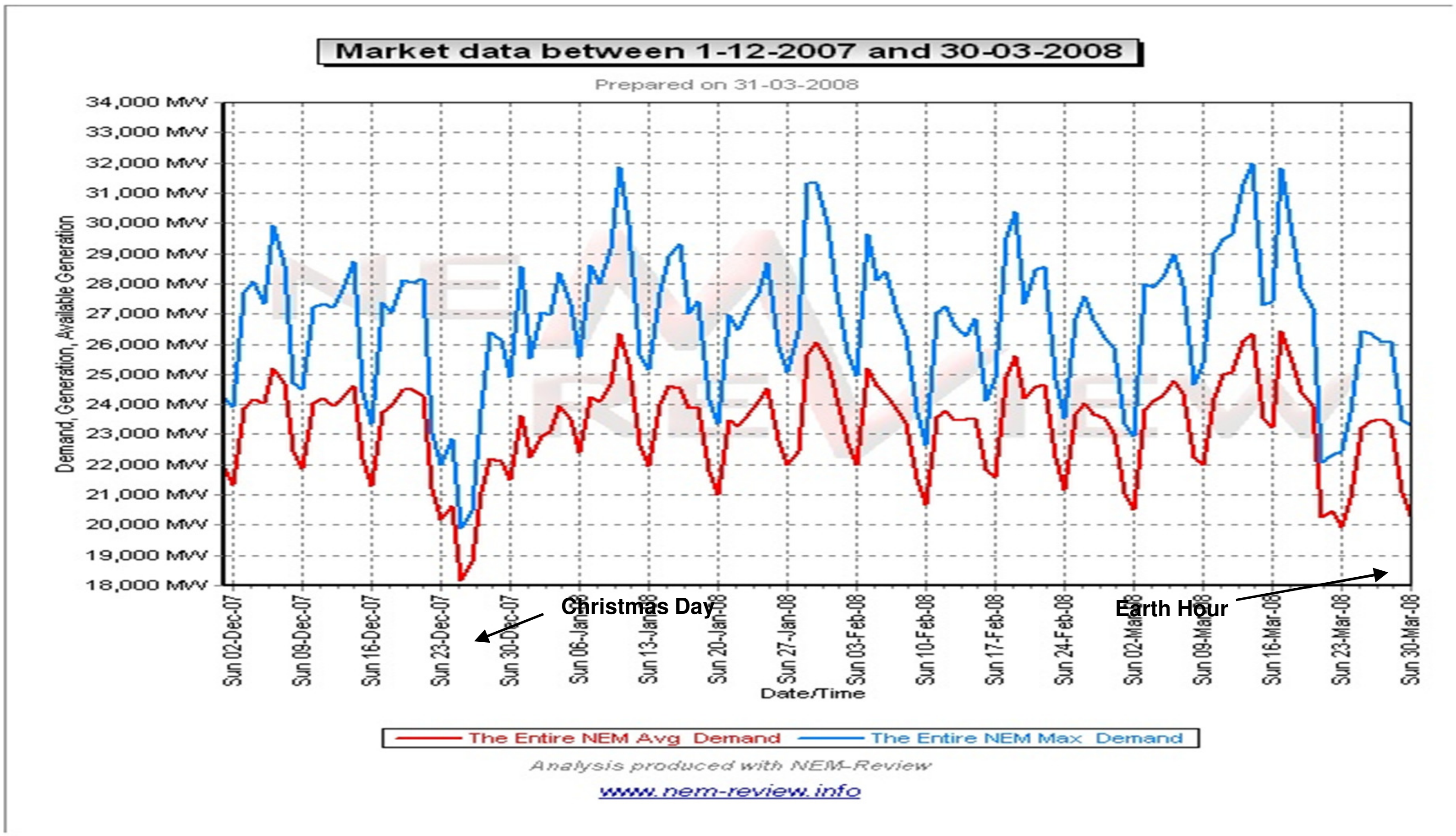
- **No comfort complaints**



SMART SOLUTION use less

CenDEP report: White, Ward CSIRO; Peters SV; Doherty Investra

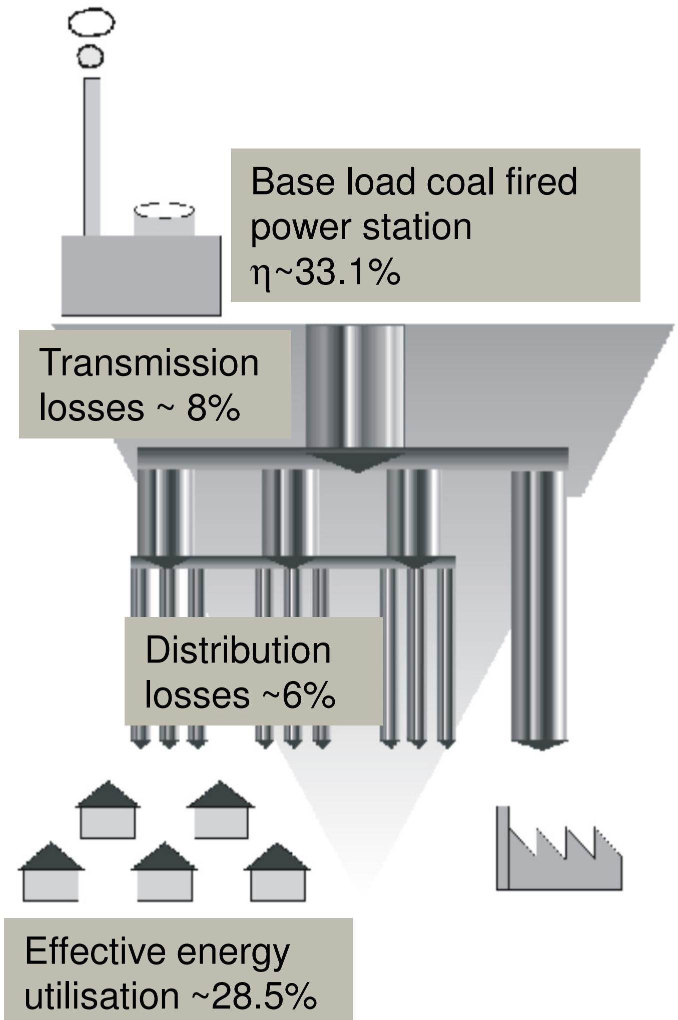
Use It Efficiently: Peak demand driving capacity



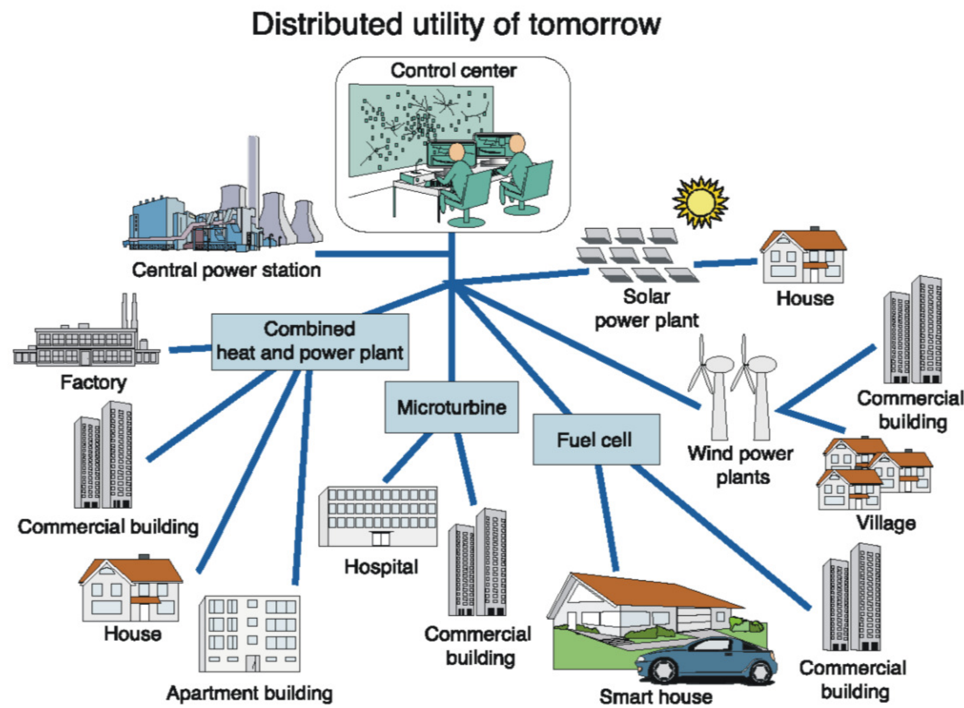
Peak Demand driving capacity : NEM Average & Peak Demand 4 months

Waste Less - NEM Efficiencies

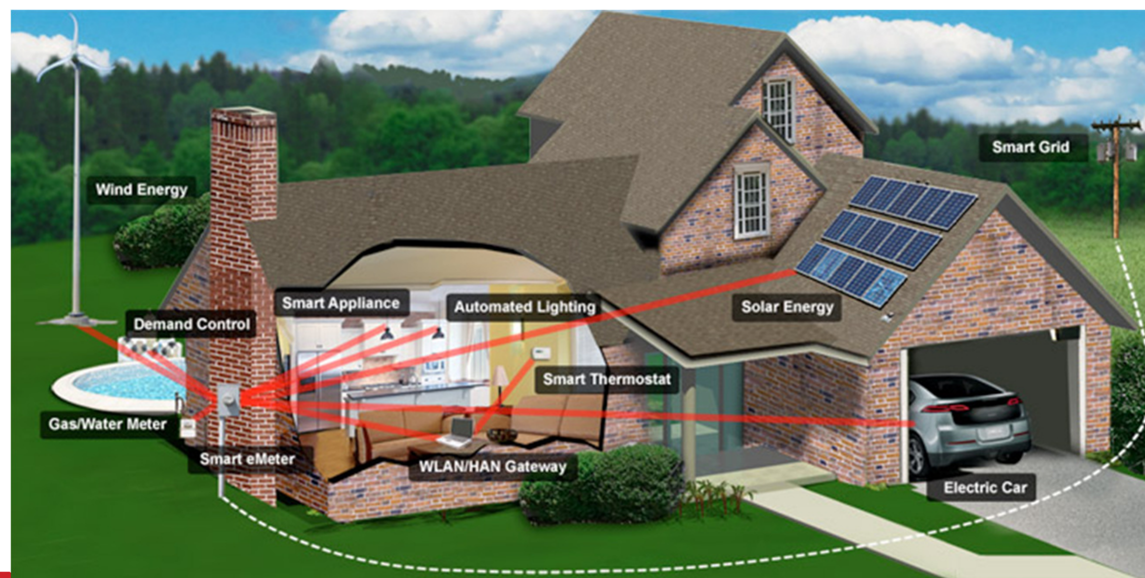
Existing
Centralised Supply Industry



New
Distributed supply Industry



Smart metering = smart meter + communication infrastructure + data processing



Usage of Smart Metering

Outline

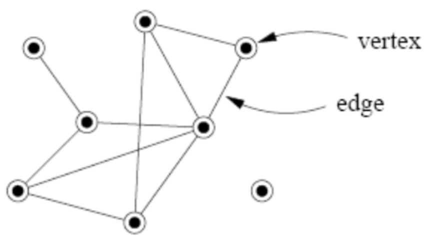
The Complexity Underlining Smart Grids

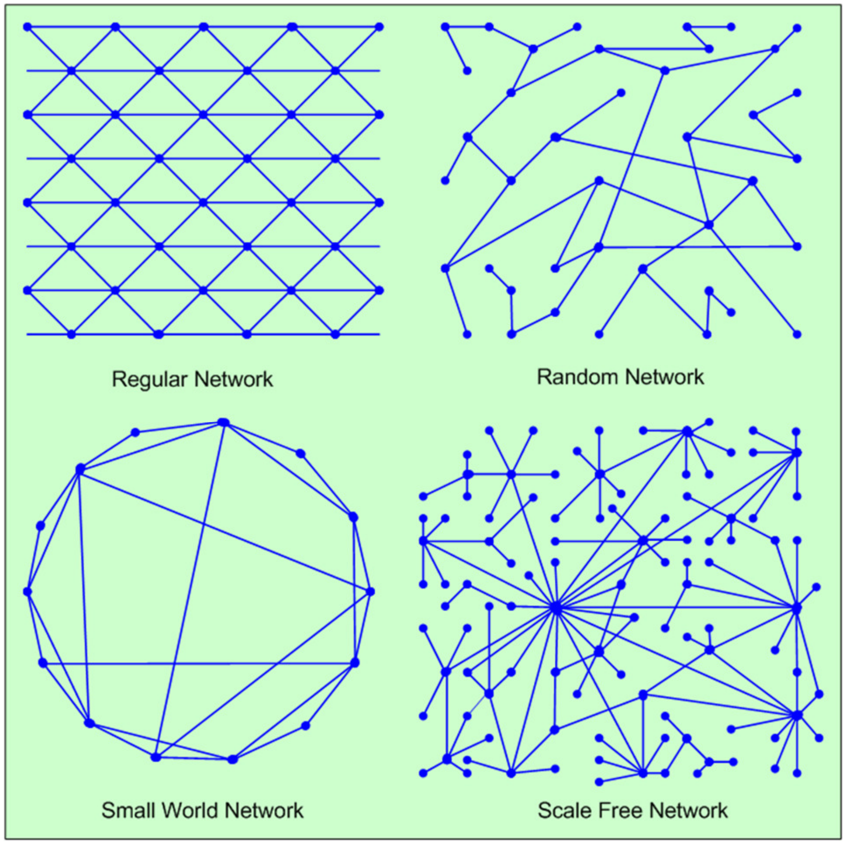
- High complexity: large-scale, nonlinear, switched, uncertain, networked, multi-agent, multi-objective
- Bidirectional electricity flow
- Randomness (e.g. switching on/off, electric vehicle charging behaviours)
- Massive nodes (e.g. renewable energy sources, smart meters)
- Power quality monitoring and control
- Data stream mining applications
- Social behaviours (flocking, swarming, human psychology)

Research Issues

- Miltilevel monitoring and diagnosis (e.g. fault detection and early warning) – self awareness
- Distributed adaptive control responding to uncertainties – self-organising
- Reconfigurability. Attach problems when they arise – self-healing
- Data stream mining
  - Real-time electricity consumption estimation
  - Modelling of real-time electricity demand and supply
- Smart Grids modelling and optimisation
- Network security and safety
- Communication technologies
- Almost everything to do with Smart Grids requires knowledge of Networks …

Complex Network Theory





Examples:

- World Wide Web
- Internet
- Communication
- Citation Network
- Community Networks
- Biological Networks
- Power System Network

Terminology:

- Vertex or Nodes
- Edges or Links
- Degree
- Degree Distribution
- Directed/Undirected
- Geodesic Path
- Weight
- Betweenness
- Giant Component

Reference: M.E.J. Newman, “The structure and function of complex networks,” SIAM Review, vol. 45, pp. 167-256, 2003.

Some of Our Recent Research Projects …

- Power Network Vulnerability Analysis
- Data Stream Mining for Smart Metering
- Network-based Fault Detection and Early Warning
- Impact of Plug-in Hybrid Electric Vehicles on Smart Grids
- Control Systems in Smart Grids …

Understanding a Power Network and its Vulnerabilities

- How is the topology of a power network related to its function and behaviour?
- Is it possible to capture the characteristics using its topological and mathematical model?
- It is possible to predict its future behaviour under different circumstances?
- Tolerance of a power network to failure of certain nodes and links.
- Intentional attacks (network hackers).
- Cascading Failures and black outs.
- Analysis of vulnerability of a power grid using complex network theory using topological factors such as characteristic path lengths, degree distribution, clustering coefficient, betweenness centrality etc. to identify critical nodes and links in a power network.

Famous Blackouts:

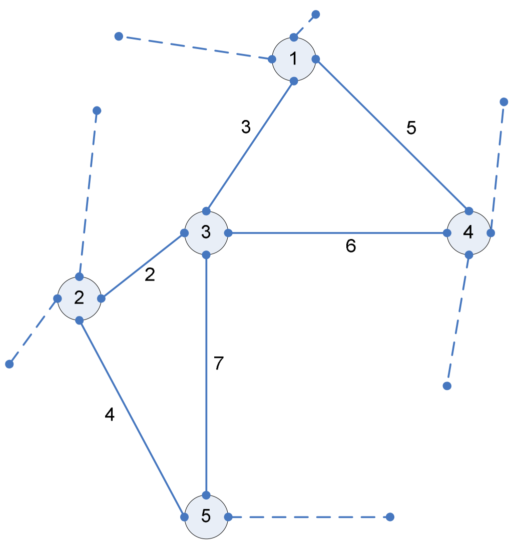
Blackouts	Millions Affected	Location	Day
Java-Bali Blackout	100	Indonesia	2005-08-18
Southern Brazil Blackout	60	Brazil, South and Southeastern	1999-03-11
Italy Blackout	55	Italy	2003-09-28
Northeast Blackout 1	50	North America, Northeastern	2003-08-14/2003-08-15
Northeast Blackout 2	30	North America, Northeastern	1965-11-09

Reference:

http://en.wikipedia.org/wiki/List_of_power_outages (Visited: April 2009)

Modelling a Power System as a Network

- A power grid can be modeled using the complex network theory by the use of a connection matrix $E = \{e_{ij}\}$, also know as adjacency matrix.
- Suppose, $G = (V, E)$ is a network with n nodes and k edges, then the elements e_{ij} of the adjacency matrix E define the connectivity of the network.
- If there is a connection between two nodes i and j then the value of e_{ij} will be 1 and if there is no connection then the value of e_{ij} will be 0.
- We can also assign weights to the connecting links.
- The weights in case of a power system could be parameters like impedance, Admittance of a transmission line, power transmitted via a link etc depending on the application.



$$A_w = \begin{bmatrix} 0 & 0 & 3 & 5 & 0 \\ 0 & 0 & 2 & 0 & 4 \\ 3 & 2 & 0 & 6 & 7 \\ 5 & 0 & 6 & 0 & 0 \\ 0 & 4 & 7 & 0 & 0 \end{bmatrix}$$

Electrical Model of a Power Network

- Power flows in a power network according to the Kirchhoff's laws.
- Current or power usually follows the path of least resistance in a circuit.
- Alternatively, Admittance is a measure which is directly proportional to power flow or decides the ease with which the current will flow through the circuit

$$\bar{I}_B = \bar{Y}_B \bar{V}_B \quad \Rightarrow \quad \begin{bmatrix} I_1 \\ I_2 \\ . \\ I_n \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & . & Y_{1n} \\ Y_{21} & Y_{22} & . & Y_{2n} \\ . & . & . & . \\ Y_{n1} & Y_{n2} & . & Y_{nn} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ . \\ V_n \end{bmatrix}$$

$Y_{ij} = -(G_{ij} + jB_{ij})$ for $i \neq j$ and $\sum_{i \neq j} (G_{ij} + jB_{ij})$ for $i = j$

$Y = Z^{-1} = \frac{1}{Z}$ and $Z = R + jX$ $\Rightarrow$ $Y = Z^{-1} = \frac{1}{R + jX} = \left(\frac{R}{R^2 + X^2}\right) + j\left(\frac{-X}{R^2 + X^2}\right)$

$Y = G + jB$ where $G = \mathrm{Re}(Y)$, $B = \mathrm{Im}(Y)$ $\Rightarrow$ $|Y| = \sqrt{G^2 + B^2} = \frac{1}{\sqrt{R^2 + X^2}}$

If $R << X$ then $|Y| \approx \frac{1}{X}$

Important Definitions

- Shortest path – Smallest sum of distance among all possible paths from any node *i* to node *j.*
- Weight or betweenness index – The weight put of the connecting links.
- Betweenness centrality – Total number of shortest paths that pass through a particular node or link.
- Efficiency of a power network – It can be defined as the inverse of the shortest electrical path.

$$J = \frac{1}{N(N-1)} \sum_{i \neq j \in G} \left(\frac{1}{x_{ij}}\right)$$

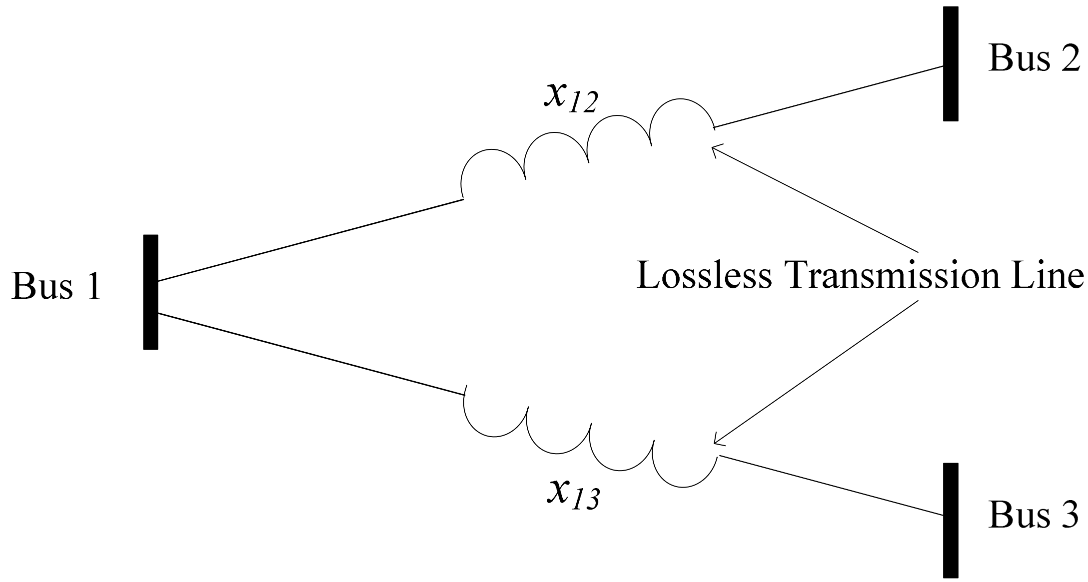
- New betweenness index – Based on the simplified power flow equations for lossless lines, the reactance of the line is chosen as the new betweenness index.

Random and Targeted Attacks

Random Attack - means connecting links are picked and removed randomly. A total of ten random links are removed one after the other and the efficiency of the network is calculated after every attack. It is expected that the system will be robust to such attacks.

Targeted Attack - means the links with highest betweenness based on the new betweenness index are removed. A total of ten such links are removed one by one and the efficiency of the network is calculated after every attack. It has been demonstrated that the system is very vulnerable to such attacks.

Power Network and Power Flow



Simplified power system network

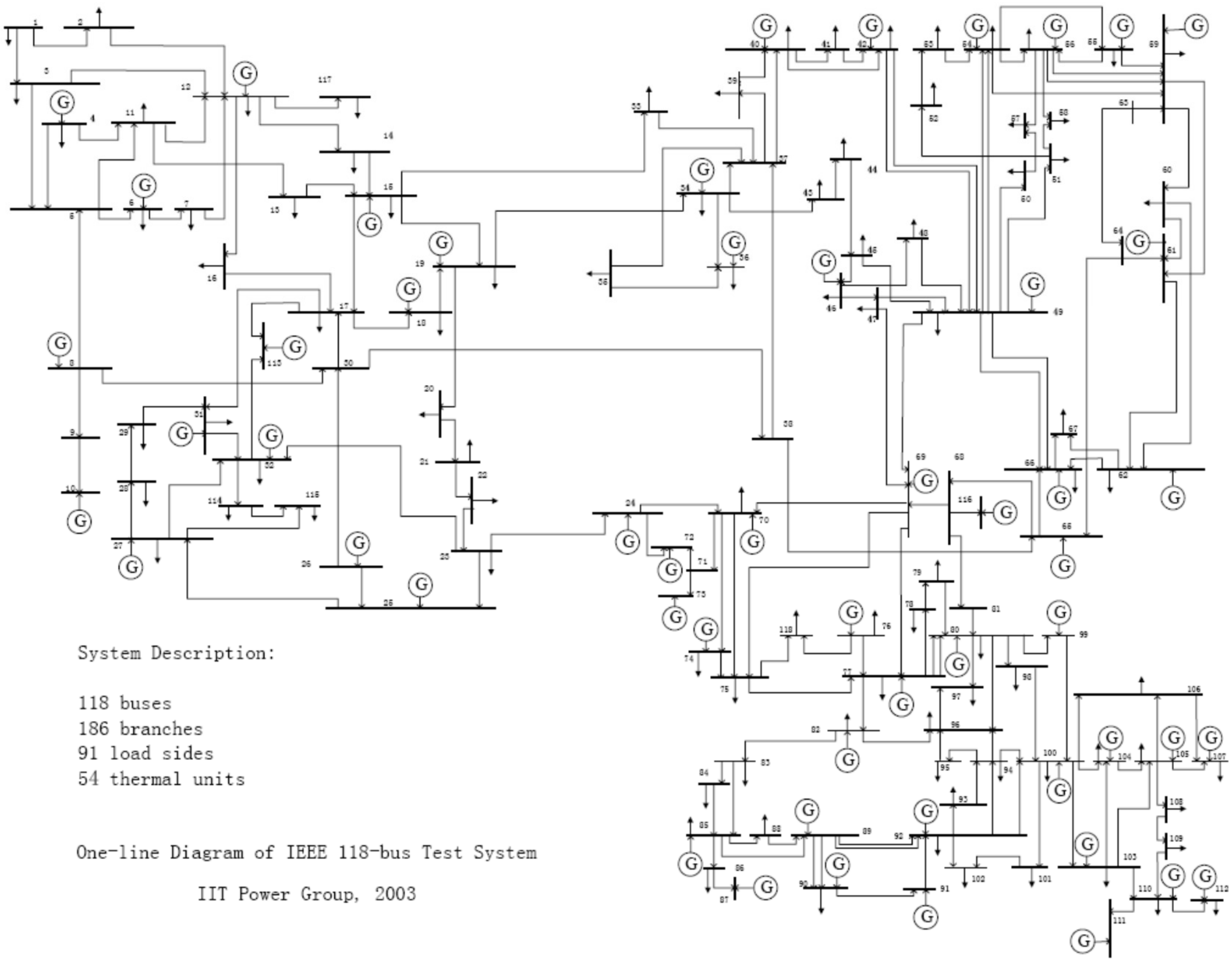
Power Flow Equation for a lossless transmission line:

$$P = \frac{v_i v_j}{x_{ij}} \sin \alpha_{ij}$$

Power flowing through any transmission line from node *i* to node *j* is inversely proportional to the reactance of that line i.e.

$$P \propto \frac{1}{x_{ij}}$$

Case Study – IEEE 118 Bus System



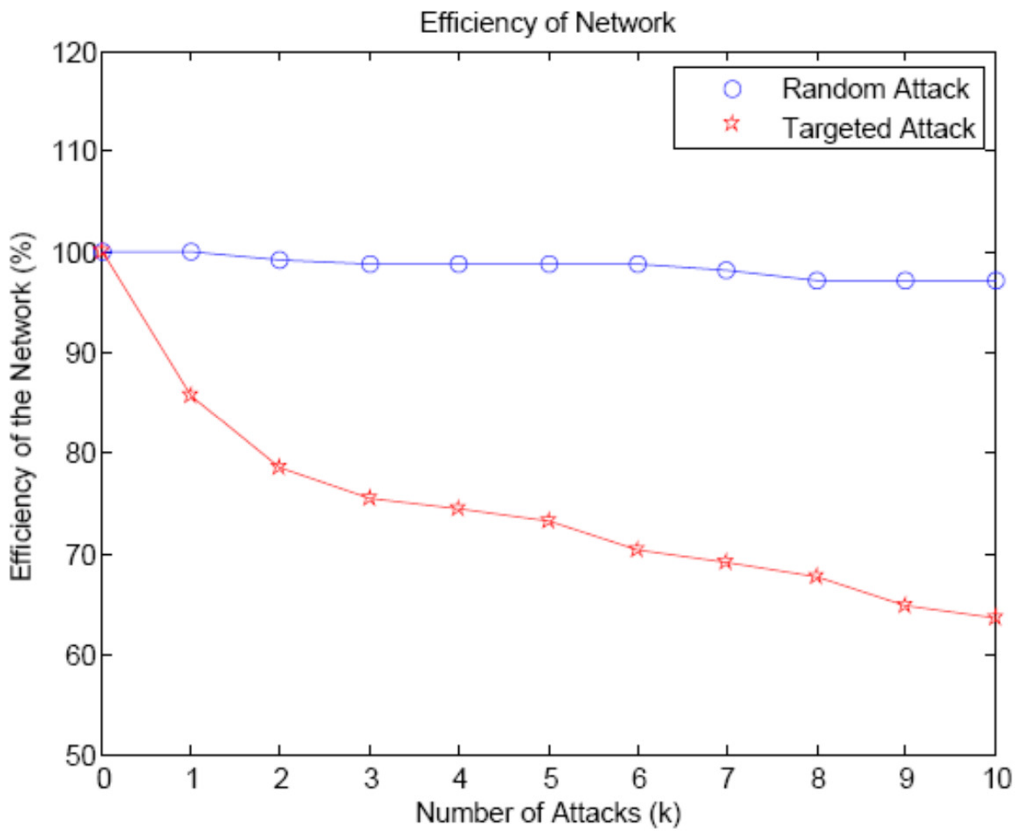
System Description:

118 buses
186 branches
91 load sides
54 thermal units

One-line Diagram of IEEE 118-bus Test System

IIT Power Group, 2003

Efficiency and Sensitivity to Random and Targeted Attacks

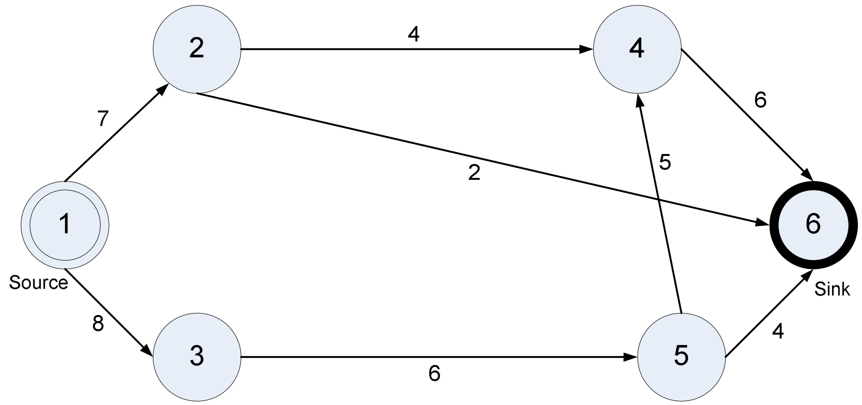


- System efficiency drops by less than 3% after 10 random attacks
- System efficiency drops to almost 60% after 10 targeted attacks

Problems with the Betweenness Approach

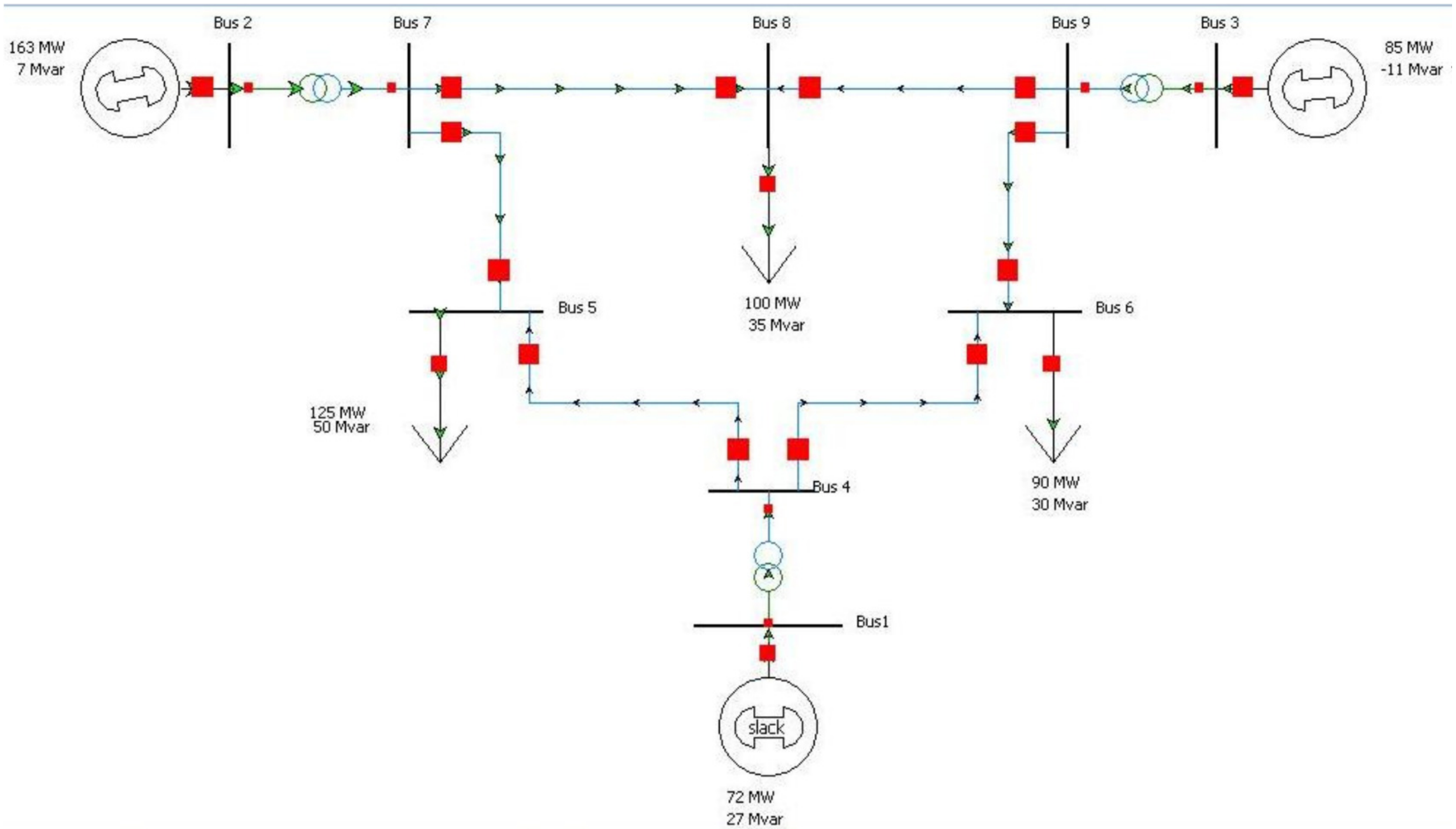
- In a power system, the power does not necessarily flow along the shortest path but along all available lines from node *i* to node *j*.
- The power does not flow between all node combinations but only from generators to loads using the buses or links in between to connect them.
- Thus, there is a need for newer techniques to eliminate above assumptions and still identify the important lines in a power network.
- So, defined a betweenness measure based on network flow model.

Directed and Capacitated Network



- The node which transmits the information is termed as the *source*, for which the *in-degree* is zero and the node which absorbs the information is termed as *sink* for which the *out-degree* is zero.
- The intermediate nodes and connecting edges form the *augmenting path* and the *inflow* is always equal to the *outflow* from them.
- The network is considered to be directed.
- The transmitting edges have a *capacity* or *weight* associated with them so they are called *capacitated networks*.
- A feasible flow in a *capacitated* network such that the value of flow is largest possible is called *maximum flow.*
- In our analysis, we use a directed graph so cannot have reciprocal elements. Hence, if there is a direct flow from node *i* to node *j* then $e_{ij}=Y_{ij}$ and $e_{ji}=0.$

Power System as a Directed Network



Simulated in PowerWorld Simulator

Centrality Index

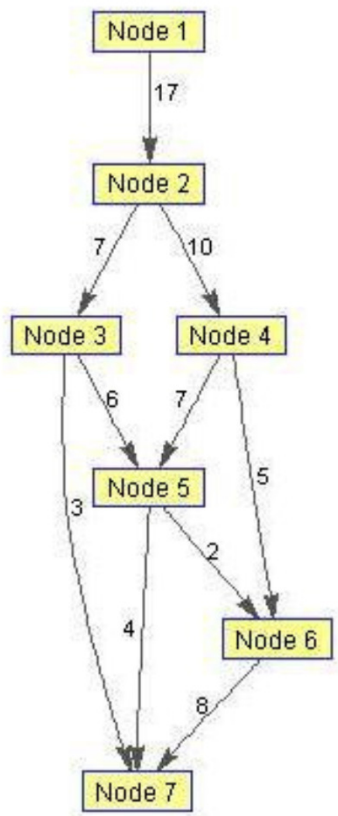
- For any network G with m sources and n sinks, let f_{max} be the maximum flow from the node u to the node v and let f_{ij} be the portion of maximum flow passing through the edge E_{ij} (where $i \neq j$) of the network.
- Then the centrality index can be defined as:

$$C_{ij} = \sum_{u=1}^{m} \sum_{v=1}^{n} f_{ij}^{uv}$$

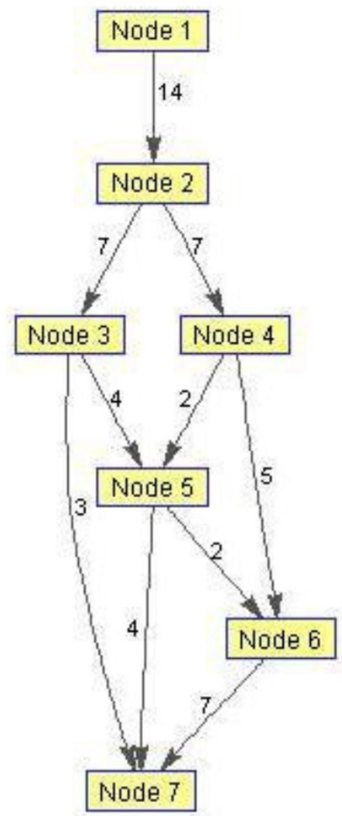
- Further, if we do not have a direct representation of flow, we can normalize the above equation for relative values by dividing it by the total maximum flow.

$$\overline{C_{ij}} = \frac{\sum_{u=1}^{m} \sum_{v=1}^{n} f_{ij}^{uv}}{\sum_{u=1}^{m} \sum_{v=1}^{n} f_{\max}^{uv}}$$

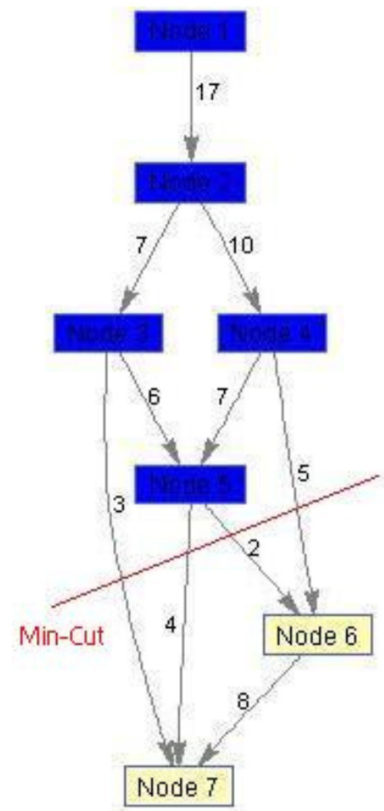
One Source-One Sink Example



Original Network

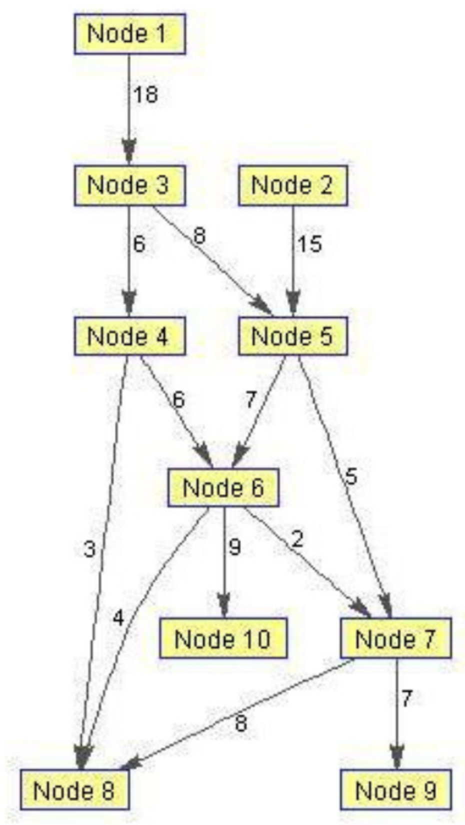


Max Flow

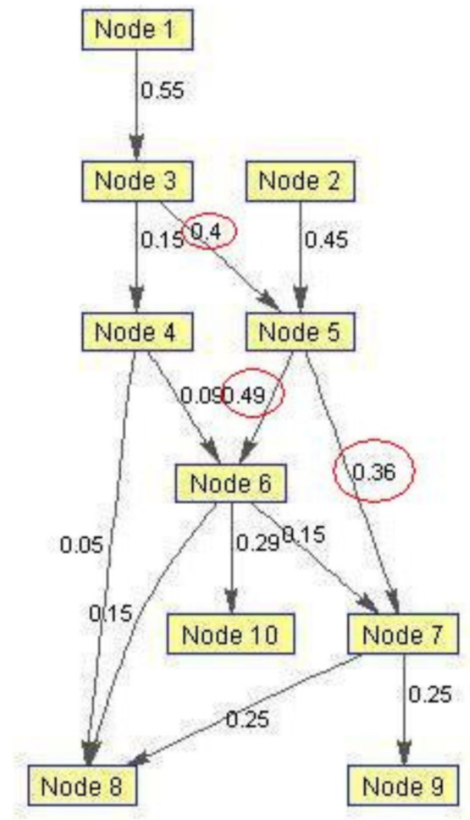


Min-Cut

Multiple Source-Multiple Sink Example

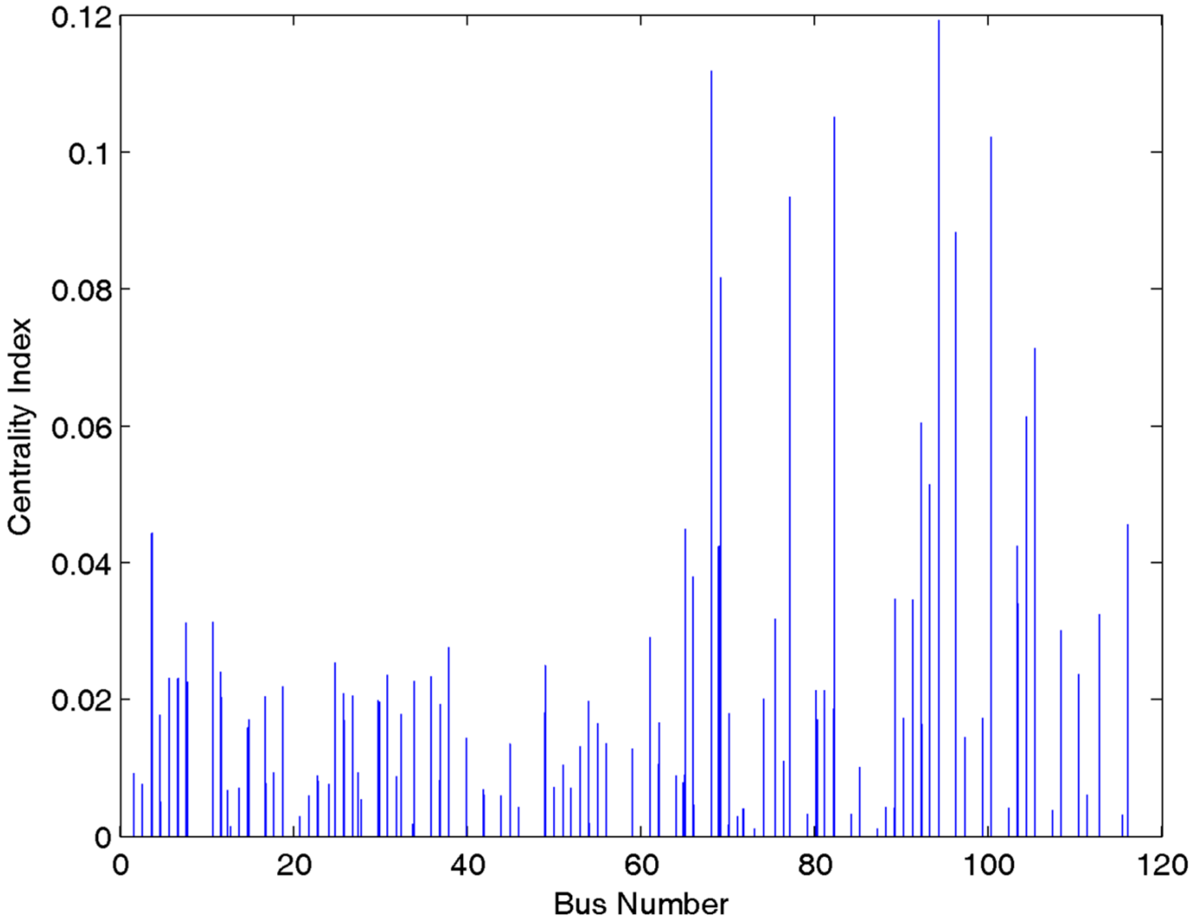


Original Network



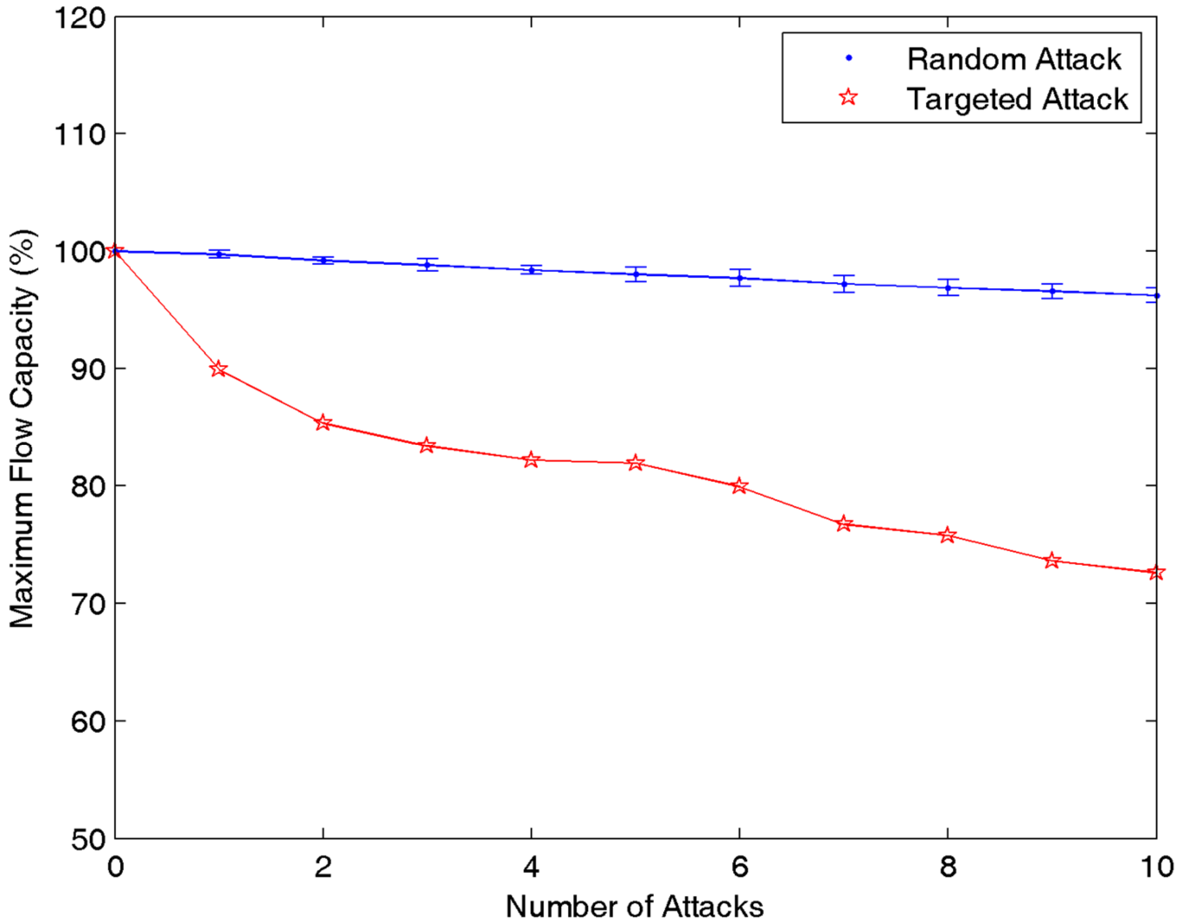
Normalized Max Flow

Normalized Max-Flow Values in the IEEE 118 Bus System



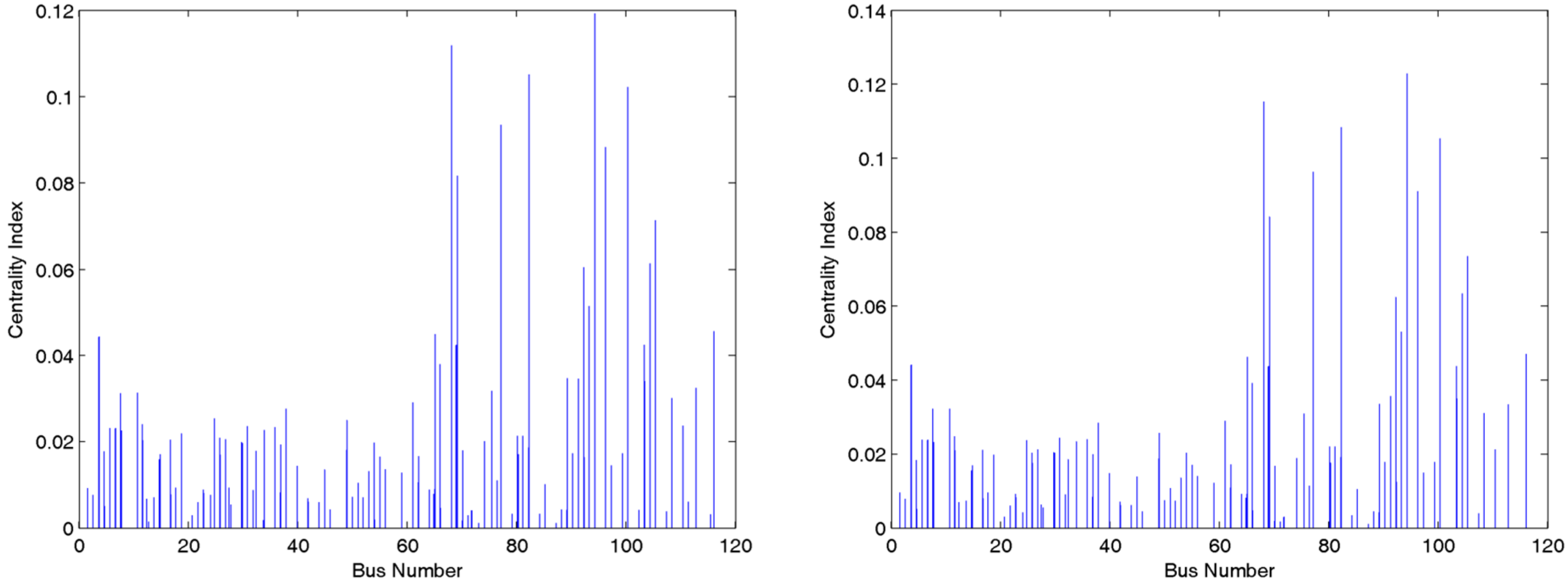
Centrality Index for IEEE 118 Bus System

Network Performance after Random and Targeted Attacks



Decrease in Max Flow Capacity of Network after Attacks

Load Shifting After 10 Random Attacks

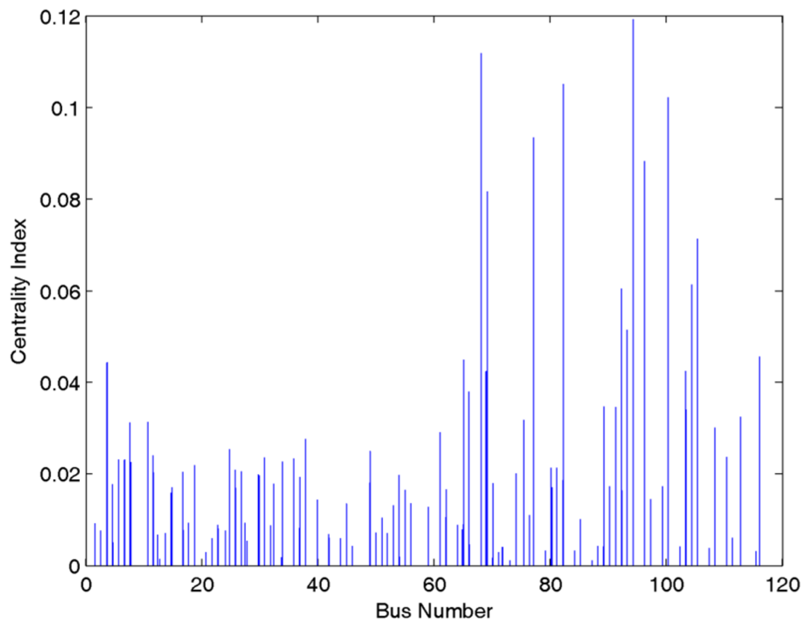


(a) (b)

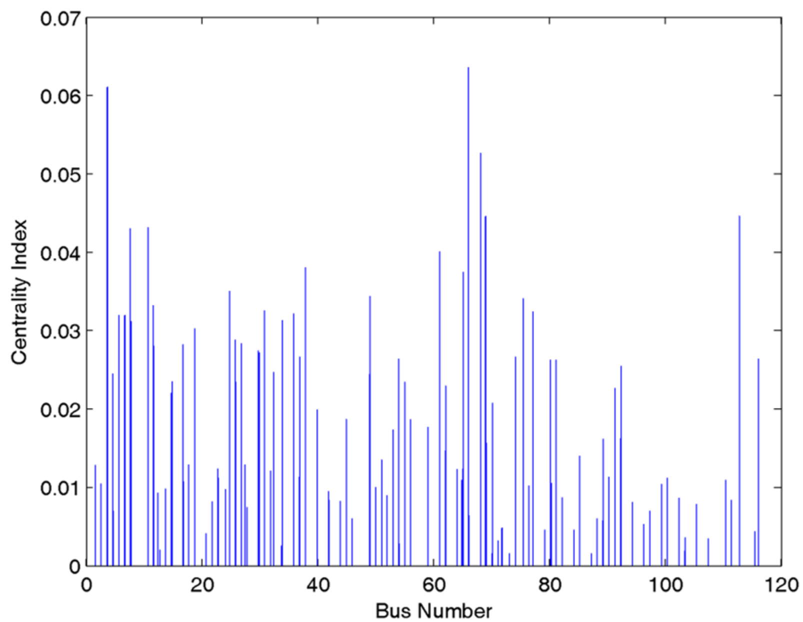
Effect of Random Attack on Load Distribution

(a) Original Load Distribution (b) Load Re-distribution after 10 Random Attacks

Load Shifting After 10 Targeted Attacks



(a)



(b)

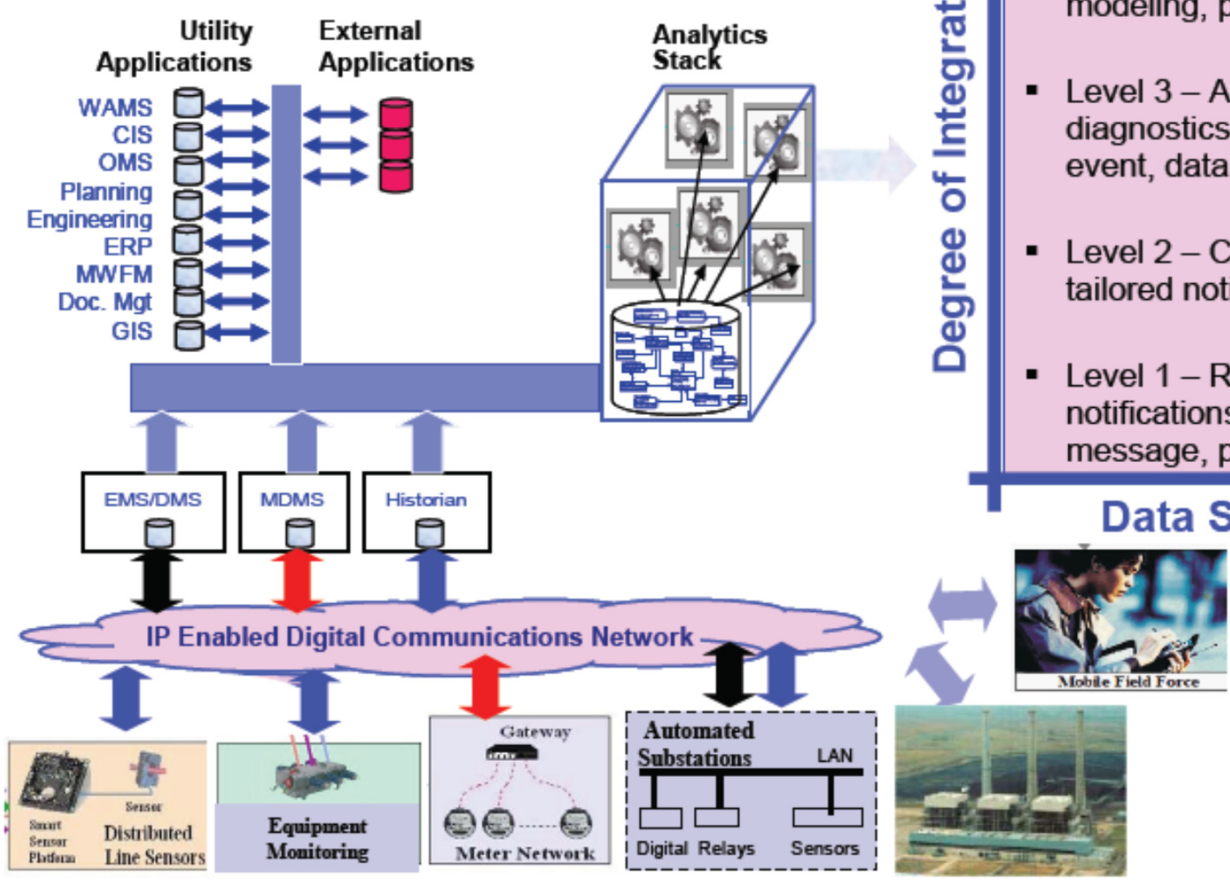
Effect of Targeted Attack on Load Distribution

(a) Original Load Distribution (b) Load Re-distribution after 10 Targeted Attacks

Data Stream Mining for Smart Metering

- Traditional database – data stored in finite, persistent data sets
- New data management issue associated with Smart Grid – data input as frequent (continuous/discrete), ordered data streams similar to telecommunication, network traffic, web logs, manufacturing processes
- Huge temporal data sets and numbers of sources
- History, timing and arrival orders are critical
- Hugh volumes, high speed and time-stamped
- Fast data mining for assessing power quality, energy consumptions, user behaviors using complex network characteristics

- *Transforms data into information*



Analytics Levels of Functionalities

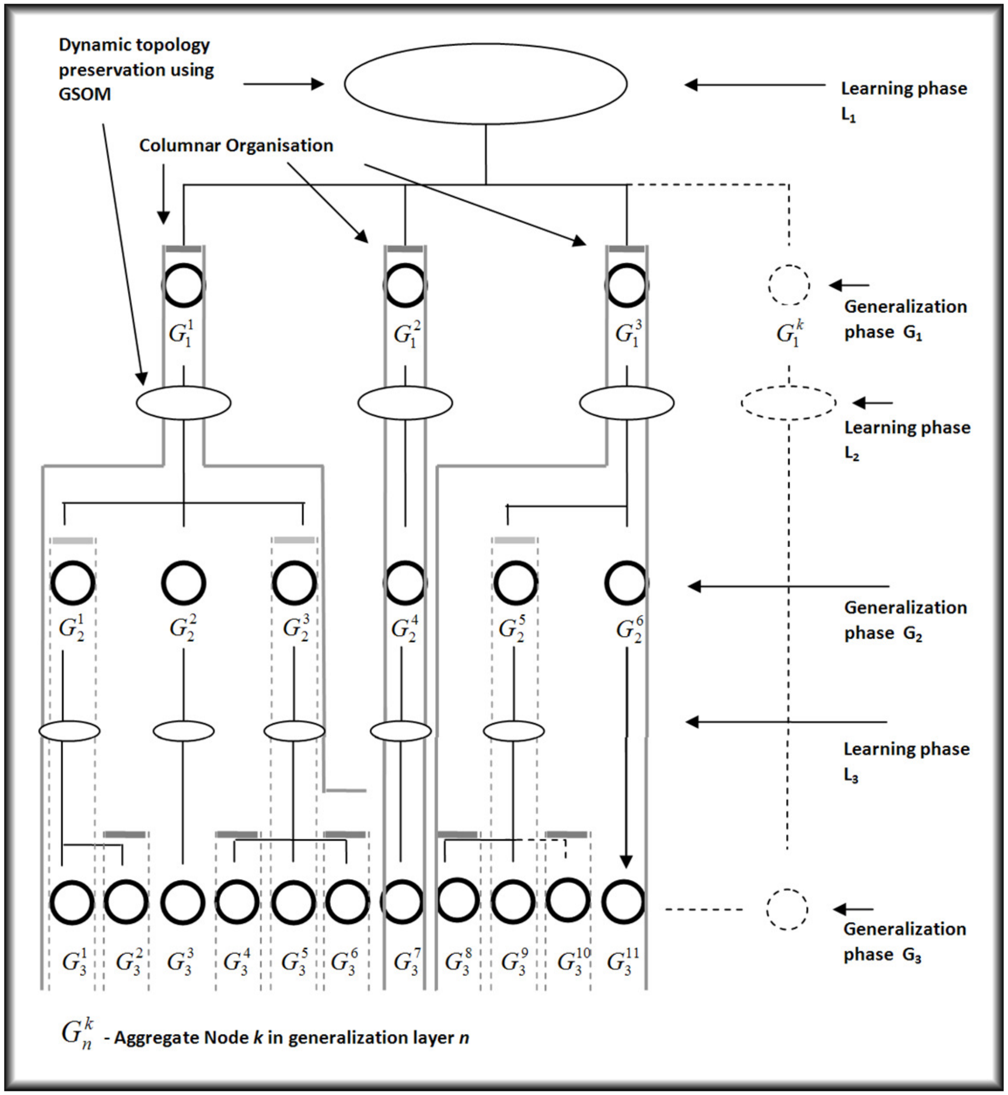
- Level 4 - Advanced optimizations, modeling, planning, decision support
- Level 3 – Analysis of data, events diagnostics, both real time and post event, data mining
- Level 2 – Calculated metrics, trends, tailored notifications, etc.
- Level 1 – Real time events, thresholds, notifications; screen display, email message, pager

Beneficiaries of Smart Metering

- Easier process flow from "Meter to Bill"
- Saves manual labour cost associated with meter reading and data processing
- Fewer complaints on meter reading errors
  - results in cost savings at call centersMeasuring power quality
- Energy balance ($E_{in} = E_{out}$)
  - easier detection of energy losses (possible fraud) in the network
- Fast detection of disturbances in the energy supply
- Demand-response leads to energy savings and more efficient use of electricity generating capacity and the electricity grid
- Limit energy use in the event of regional power shortages
- Easier disconnection of defaulters
- Early warning of blackouts

A New Approach: Incremental learning

- Natural learning is a lifelong process.
- Initiated with encodings about the basic structure of the surrounding environment.
- These initial impressions are continuously augmented, updated and corrected to develop new understanding.
- Stability and plasticity are key properties of the human brain that facilitate incremental learning.



Key Features

- A perpetual, self learning algorithm.
- A dynamic structure for acquisition and preservation of learned knowledge.
- Generation and sustenance of computationally efficient, generalised representations of knowledge accumulated in the learning process.
- Regulation of generalised representations as the basis for subsequent learning.
- Utilisation of accumulated knowledge to determine relevance and correlations to new inputs and thus facilitate the development of self-awareness of the problem space.

Smart Meter Stream Mining

- The dynamics of data stream environments have proven impenetrable to conventional data mining and knowledge discovery techniques due to three primary constraints,

  (a) data is transient and thus can be read only once

  (b) order of arrival of data cannot be predetermined

  (c) the restriction of computing resources available for real-time processing.

The new algorithm IKASL-Stream has been developed to address these constraints.

Smart Meter Stream Mining

Type of data :

VAAA000501-01 RMIT UNIVERSITY - BUILDING 8 & 10 330 SWANSTC					
Date Time	PF	Kwh	Kva	Kw	Kvar
9/1/2008 0:30	0.7593	49.06	129.23	98.13	84.09
9/1/2008 1:00	0.7592	48.49	127.75	96.98	83.15
9/1/2008 1:30	0.7657	48.66	127.12	97.33	81.77

PF, Kwh, Kva, Kw and Kvar recorded at half hour intervals, continuously from 2008-2009.

Data stream mining can be take advantage of the time intervals with mining outputs generated at a range of frequencies such as,

- hourly
- daily
- weekly
- monthly
- weekday –weekend

On going work ..and anticipated benefits

- Extend the technique to automate cyclic pattern identification
- Develop a pattern monitoring system (fed by this algorithm) which can monitor fluctuations, unusual behaviour etc
- Build up an evolving knowledge base of patterns - which can be used to identify normal, unusual behaviours
- Analyse and compare electricity usage across geographic areas, different types of oraganizations etc.
- Power quality assessment
- ……

Fault Detection and Early Warning

- How to detect fault from the network topological structure?
- How to do it fast?

The fire at Liz Horne's Beaumaris property on January 29.

Firefighters attend the blaze.

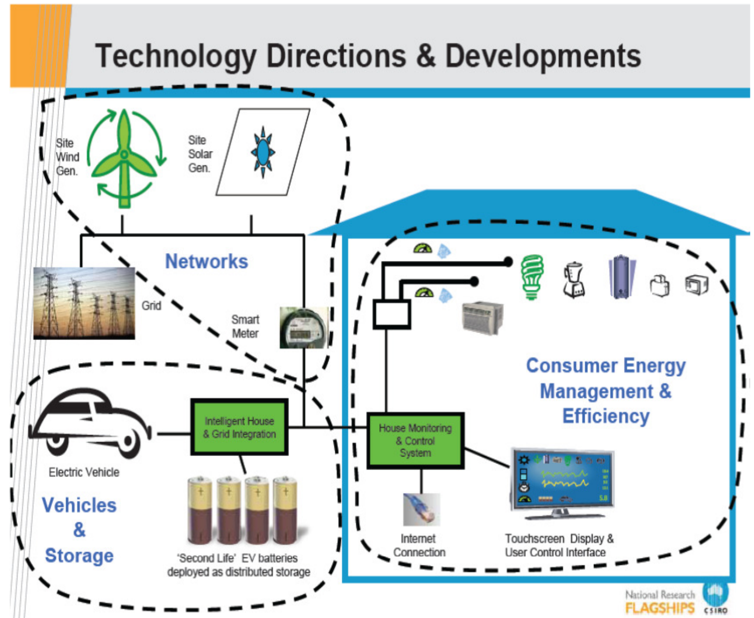
Ms Warne said the blaze was under control by 8.30pm and it was believed to have been started by an electrical transformer on a nearby power pole.

Reference:

Bayside Leader (Australian Local Newspaper), Tuesday, February 24, 2009

Impact of Plug-in Hybrid Electric Vehicles on Smart Grids

- Obtaining operation conditions for charging a PHEV on local household distribution grid. This includes investigate power losses, power quality (voltage and current profiles, unbalance and harmonics) for PHEV at home.
- Modelling large scale (spatial-temporal) deployment of PHEVs and quantifying the impacts on distribution operation conditions and infrastructures.
- Investigating optimal PHEV charging profiles that result in maximal economic, environmental benefits and minimal operation disturbance (transformer, feeder overload, power losses, power quality problems)



Outline

1. The Need for Smart Energy
2. What are Smart Grids?
3. Smart Grids and Complex Networks
4. Discussions and Conclusions

Discussions and Conclusions

- Smart Grids as a new frontier pose many research questions that may not be solved using existing technologies given the complexity and sheer size of Smart Grids
- New paradigm changes are needed
- New theories and methodologies are needed for modelling, optimisation, control of Smart Grids
- Complex Network theory will play an important role in addressing new problems encountered in Smart Grids

Thank you!