EE6509 – "Renewable Energy Systems in Smart Grids"

Part I (Assoc Prof Xu Yan)

Week #1: From "Smart Grid" to "Energy Internet"

Week #2: Advanced metering in smart grids

Week #3: Energy storage technologies

Week #4: Energy storage applications in smart grids

Week #5: Distributed generation

Week #6: Microgrid

Assessment:

- Assignment (20%): a teamwork-based report
- Quiz (20%): a quiz
- Final exam (60%): close-book, 2 questions

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From "Smart Grid" to "Energy Internet": an introductory review of power system's evolution

Dr Yan Xu
Associate Professor | School of EEE
Nanyang Technological University
Email: xuyan@ntu.edu.sg

EE6509 – "Renewable Energy Systems in Smart Grids"

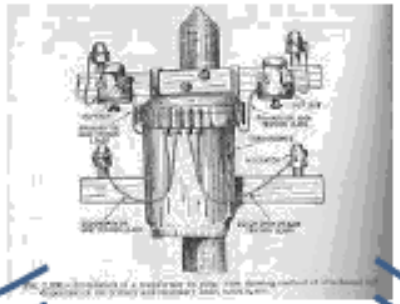
Outline

1. Brief history of power system
2. “Smart Grid”
3. Power System Security
4. “Energy internet”

First power system: Sep 4, 1882

Pearl Street Station

electric pole



electric light

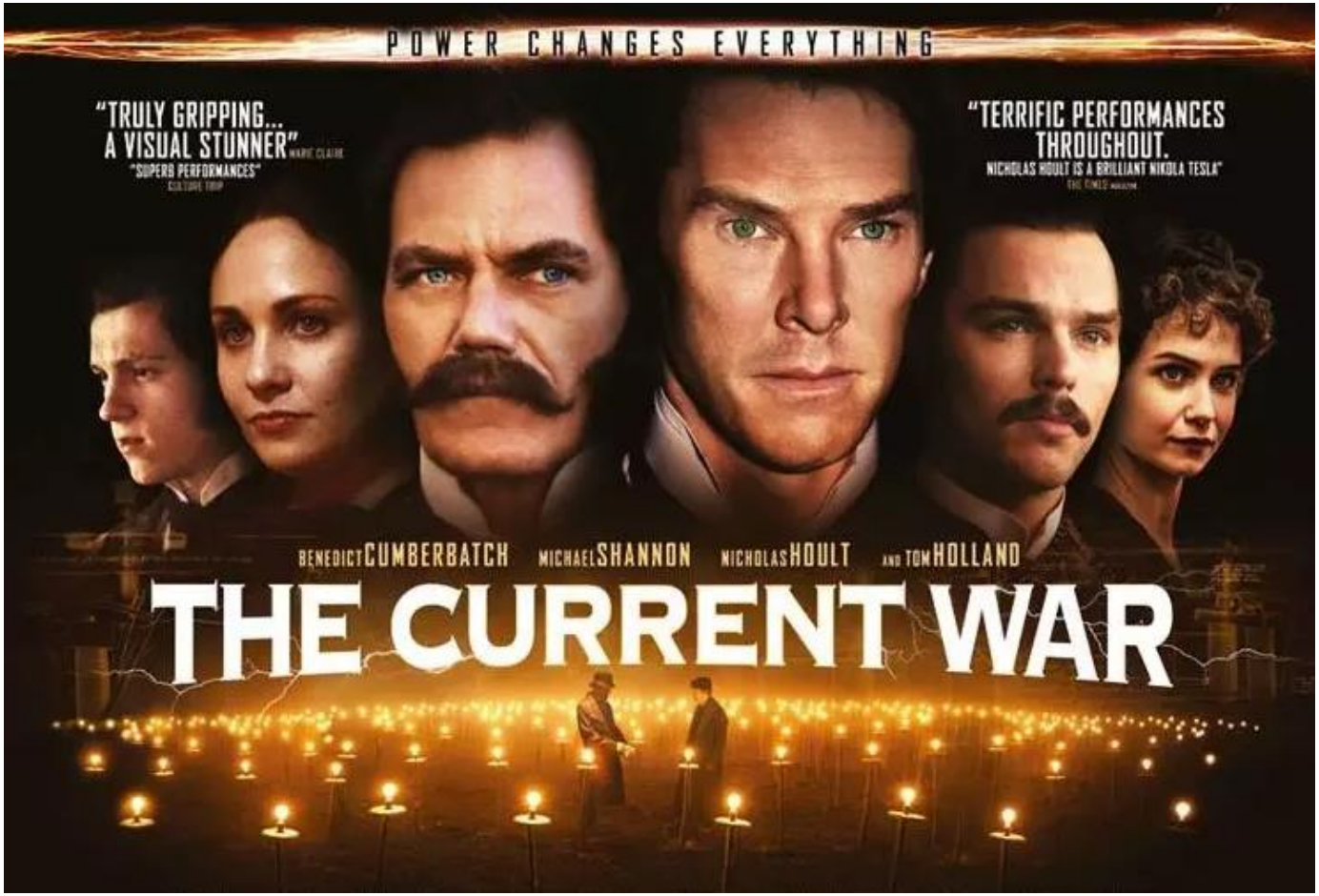
located at 255 – 257 Pearl Street in Manhattan, New York, a **DC generator** serving 85 customers, providing electricity to 400 lamps.

AC Power System: 1893~

- Transformer was invented in 1885 by William Stanley: be able to change voltage
- Induction motor was invented in 1888 by Nikola Tesla: replace dc motor and produce ac power
- first three-phase ac was generated at 2.3kV in 1893

ac system can produce more power at higher voltage than dc system because ac generator does not need commutators

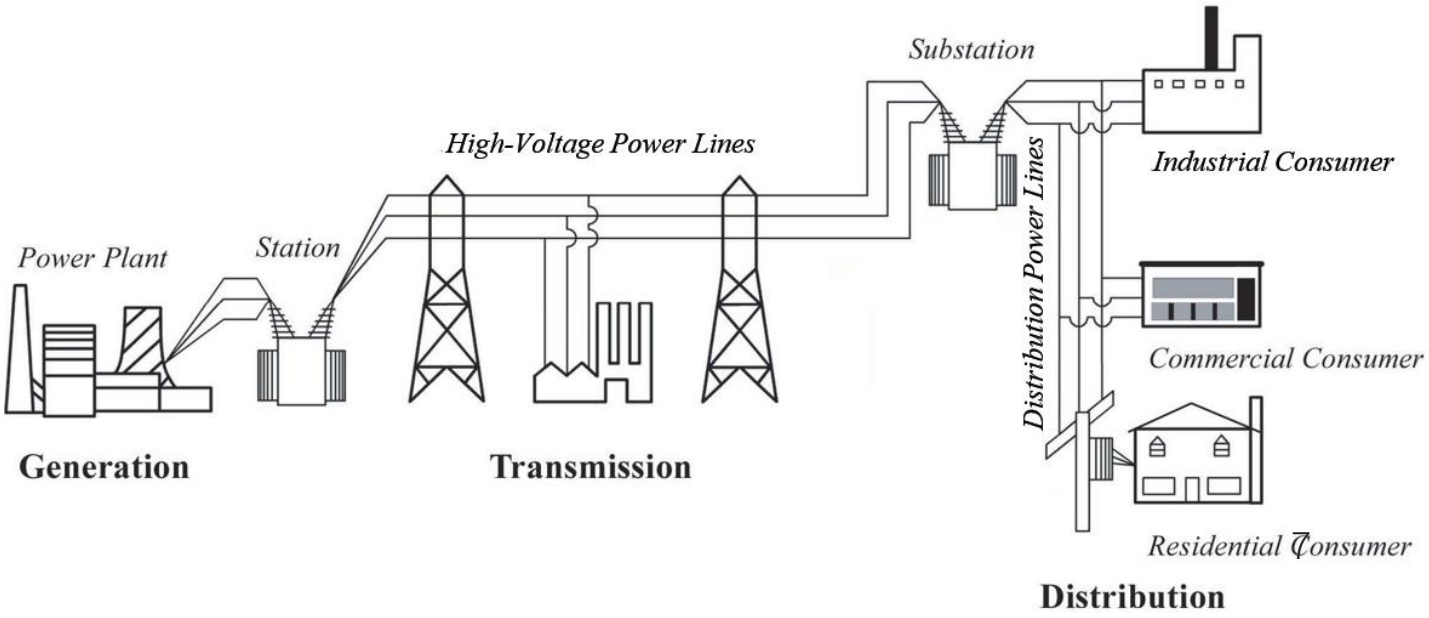
“The Current War” – A Movie



More detailed stories:
https://en.wikipedia.org/wiki/War_of_the_currents

Later Development

- High Voltage Transmission (1000kV AC, ±800kV DC): remote power transmission, lower power loss
- Interarea connection: more reliable and economical
- Electricity market (1990~): deregulation (de-monopoly), competition



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Outline

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“Smart Grid” era: 2009~

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The White House
Office of the Press Secretary

For Immediate Release October 27, 2009

President Obama Announces $3.4 Billion Investment to Spur Transition to Smart Energy Grid

Applicants say investments will create tens of thousands of jobs, save energy and empower consumers to cut their electric bills

ARCADIA, FLORIDA – Speaking at Florida Power and Light's (FPL) DeSoto Next Generation Solar Energy Center, President Barack Obama today announced the largest single energy grid modernization investment in U.S. history, funding a broad range of technologies that will spur the nation's transition to a smarter, stronger, more efficient and reliable electric system. The end result will promote energy-saving choices for consumers, increase efficiency, and foster the growth of renewable energy sources like wind and solar.

The $3.4 billion in Smart Grid Investment Grant awards are part of the American Reinvestment and Recovery Act, and will be matched by industry funding for a total public-private investment worth over $8 billion. Applicants state that the projects will create tens of thousands of jobs, and consumers in 49 states will benefit from these investments in a stronger, more reliable grid. Full listings of the grant awards by category and state are available **HERE** and **HERE**. A map of the awards is available **HERE**.

Obama Admin Announces A Myriad Of Smart Grid Projects

WRITTEN BY: GOV TECH JUNE 20, 2016

TN Note: Obama has no legacy as he prepares to exit the Whitehouse. However, he will leave his mark on Smart Grid, which he kick-started i 2009 with stimulus funds from the last financial meltdown. Smart Grid is a key element to implementing Technocracy on a global basis.

Smart grid: Obama includes US$3.5bn for grid modernization in 2016 budget

In the US, the Obama Administration last week released the first installation of a Quadrennial Energy Review, which includes initiatives to promote grid modernization.

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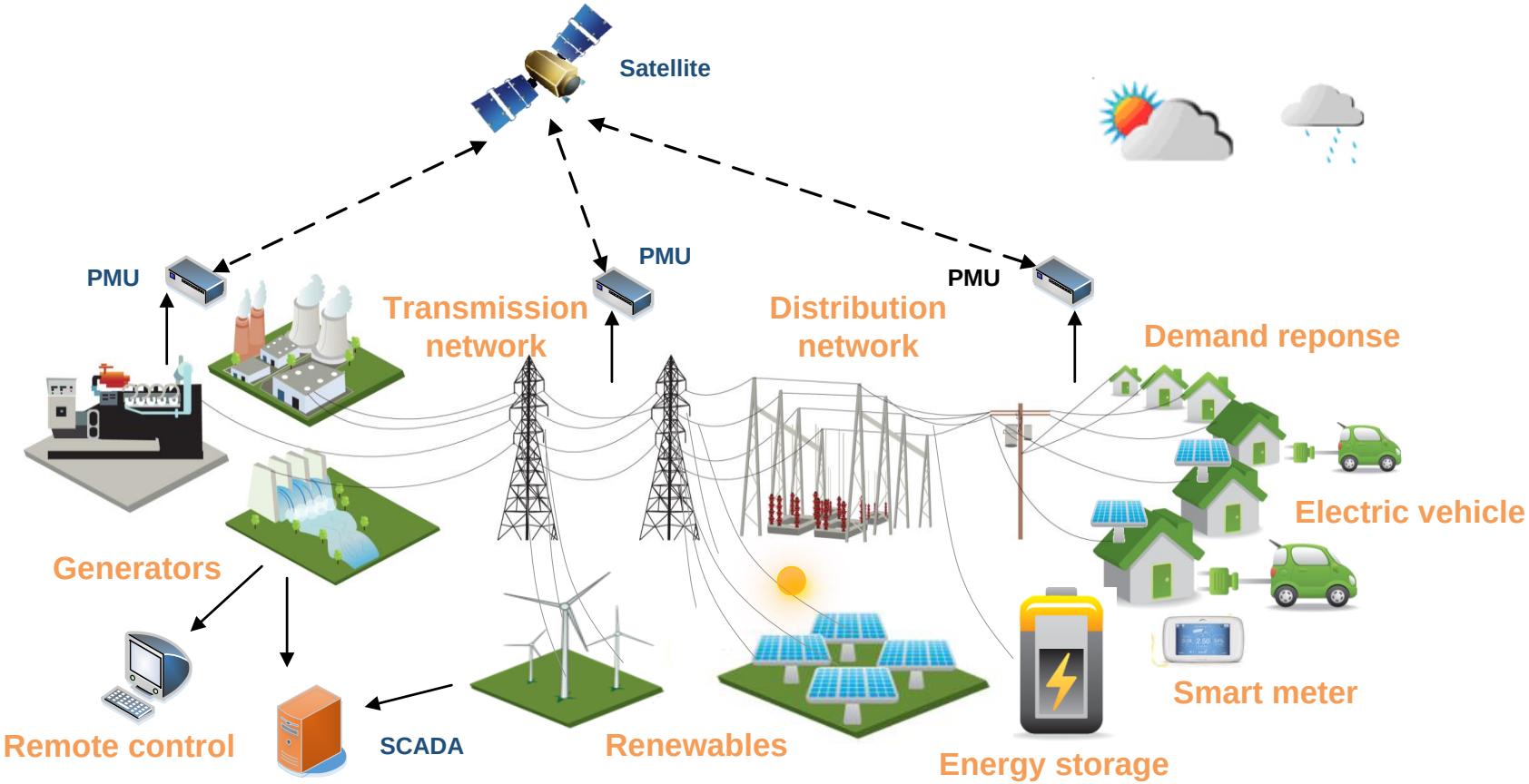
Motivation for “Smart Grid”

- Environmental pressure: global warming, carbon emission, fossil energy crisis
- Grid modernization: old electric facilities
- Network reinforcement: transmission & distribution (HVDC)
- New loads: electric vehicle, responsive customer
- …

What is a “smart grid”?



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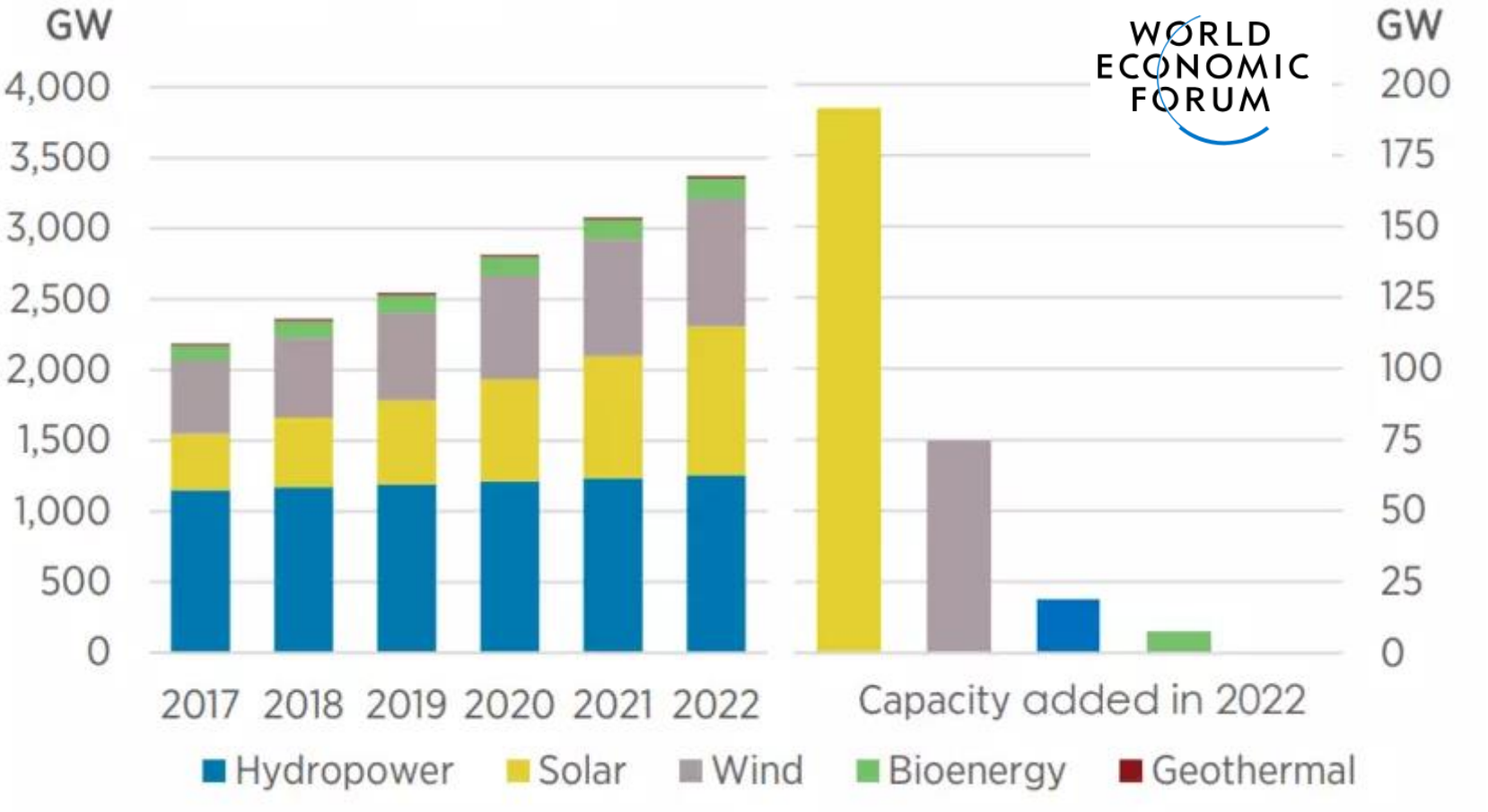
Renewable energy capacity growth



Source: https://www.weforum.org/agenda/2023/03/energy-transition-renewable-capacity-up-in-2022/

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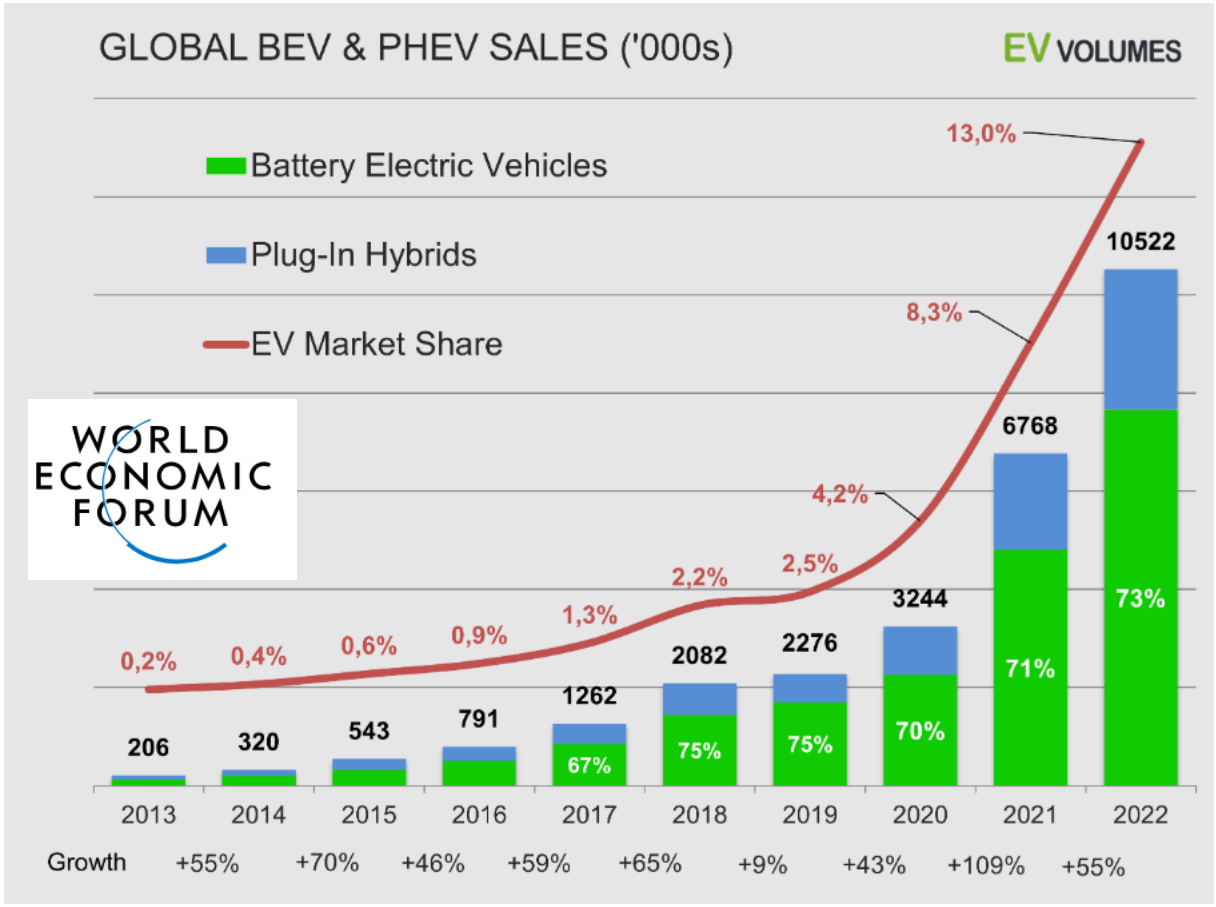
Electric Vehicle uptake



Source: https://www.weforum.org/agenda/2023/05/electric-vehicles-ev-sales-growth-2022/

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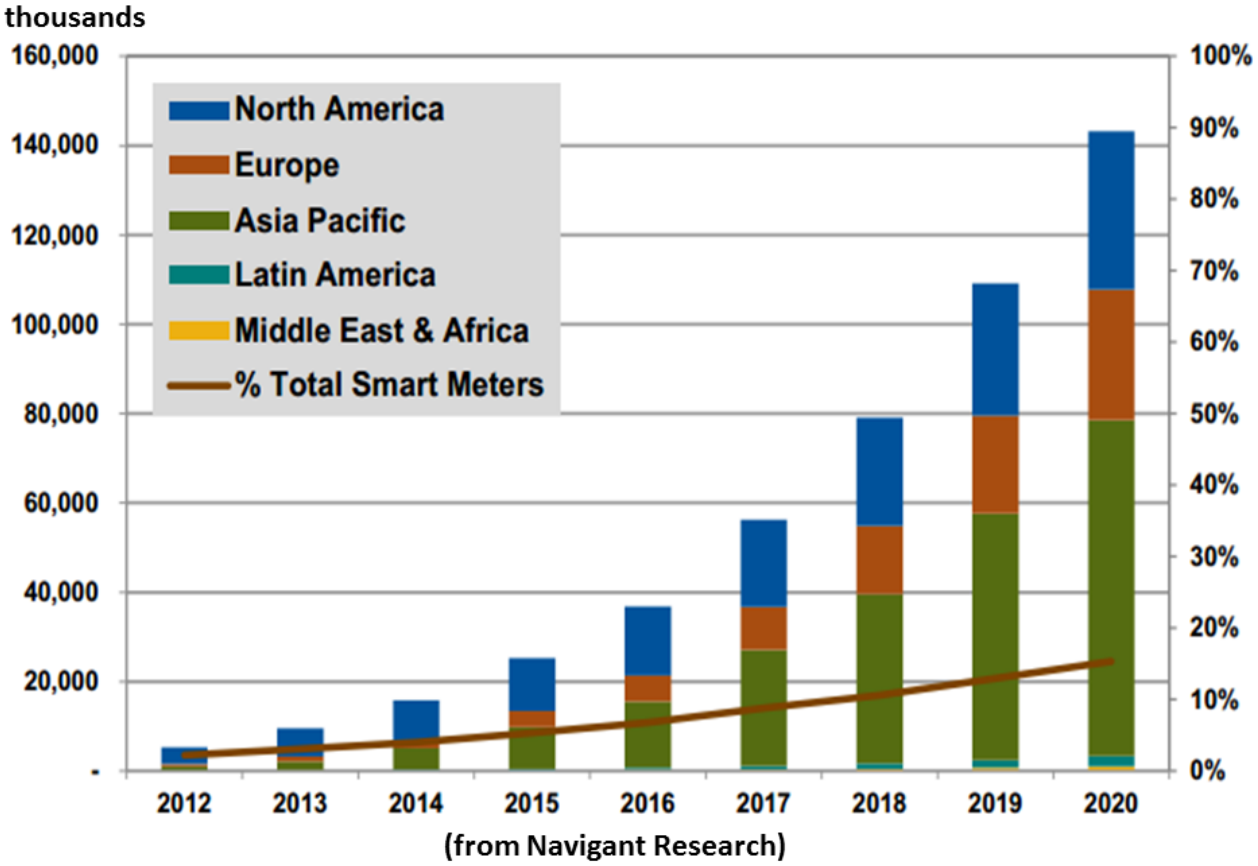
Smart meters installation

Smart Meters for DA Applications Installed Base by Region and Percentage of Total Smart Meters, World Markets: 2012-2020



(from Navigant Research)

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Summary for "Smart Grid"

Different countries have different emphasis, but in general a "smart grid" has the following three major features:

1. High-level integration and utilization of renewable energy resources.
2. More participation of demand side resources in power system operation, such as demand response, electric vehicles, smart appliance, distributed energy storage, etc.
3. Wide-spread deployment of advanced information and communication technologies (ICT), such as smart meter, phase measurement unit, advanced metering infrastructure (AMI), etc.

Benefits added by “Smart Grid”

wind

solar

energy storage

Renewable energies are environmental friendly

More controllable resources to support power system’s operation and control, e.g., customers can respond to renewable power variation, maximize the use of renewable energies, electric vehicle can support generation backup, etc.

ITC can provide more data and information about the power system

EV

PMU

Smart meter

Useful websites

- Singapore Energy Market Authority (EMA): https://www.ema.gov.sg/index.aspx
- SP Group: https://www.spgroup.com.sg/
- Australian Energy Market Operator (AEMO): https://www.aemo.com.au/
- US Department of Energy (DoE): https://www.energy.gov/
- US Electric Power Research Institute (EPRI): https://www.epri.com/
- European Union (EU) Energy: https://energy.ec.europa.eu/index_en
- IEEE Power and Energy Society (PES): https://ieee-pes.org/
- Energy Research Institute @ NTU (ERI@N): https://www.ntu.edu.sg/erian
- Smart Grid + Power Electronics Consortium Singapore (SPECS): https://www.specs.com.sg/
- Prof Xu Yan's SODA Group website: https://eexuyan.github.io/soda/index.html

GRID 2.0

https://www.specs.com.sg/publications

The grid has been a major consumer of fossil fuels, emitter of greenhouse gases, and often lacks compatibility with distributed or renewable energy sources.

Power grids are now challenged with the need for radical changes promoted by the demand to reduce the emissions from electricity supply, to replace and upgrade aging resources and to reap efficiencies.

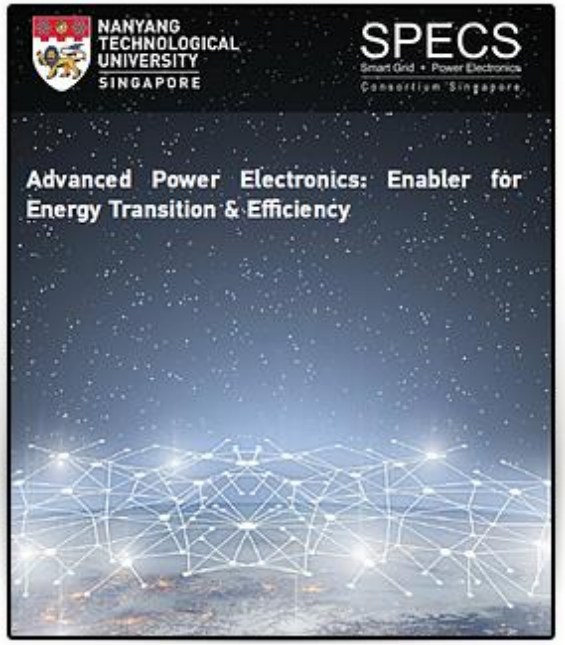
A Smart Grid incorporates the benefits of advanced communications and information technologies to deliver real-time information and enables the near-instantaneous balance of supply and demand on the electrical grid.

Advanced Power Electronics: Enabler for Energy Transition & Efficiency

Power electronics enable a very highly efficient conversion of electrical power and also provide optimal conditions for transmission and distribution. Because of their potential to enable digitalization and their highly efficient operations, it is estimated that the amount of electricity processed by power electronic components will double over the next decade, reaching up to 80% by 2030.

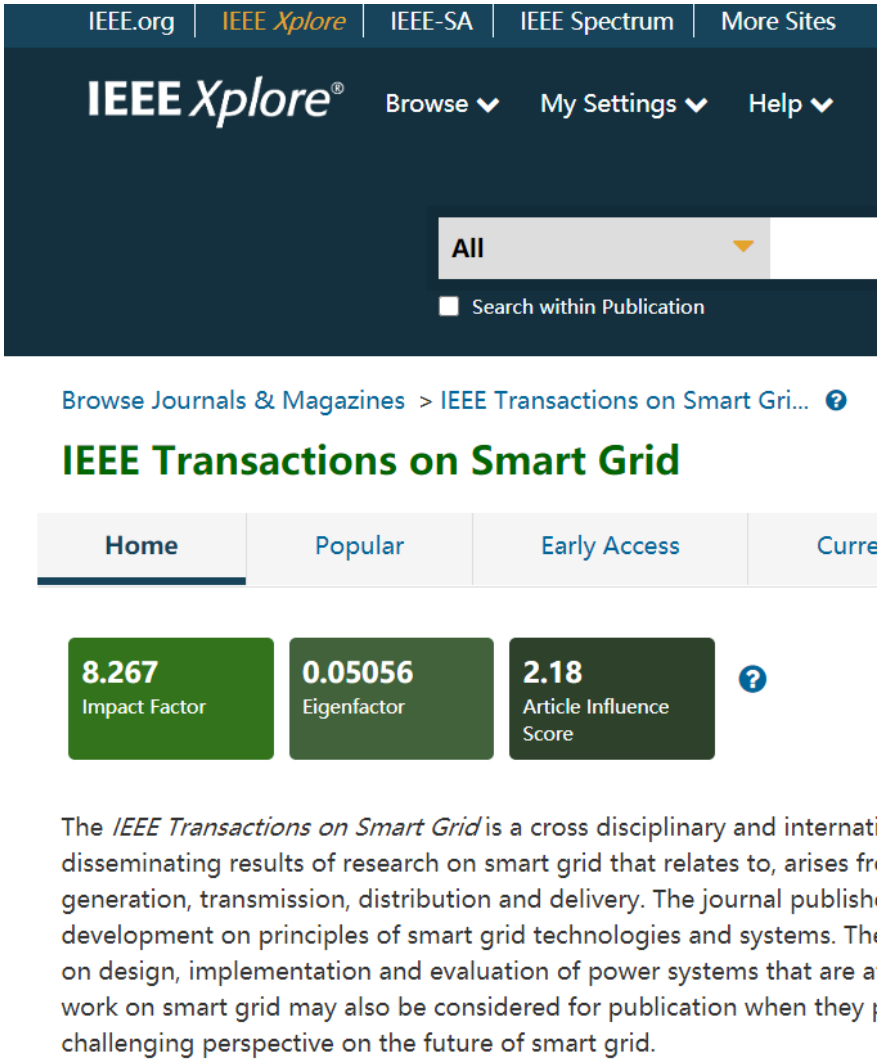
Applications of advanced power electronics can be broadly grouped under the four categories of:

Smart & Sustainable Buildings, Industrial Energy Efficiency, Transportation (Land, Air, Sea), and Smart Grids. Advanced power electronics is the



Advanced Power Electronics.pdf

Top international journals



Rank	Journal Title	IF2017	IF2018	IF2019	
1	Nature Energy	46.859	54.000	46.495	↓
2	IEEE Industrial Electronics Magazine	10.429	13.241	13.593	↑
3	Renewable & Sustainable Energy Reviews	9.184	10.556	12.110	↑
4	Proceedings of the IEEE	9.107	10.694	10.252	↓
5	IEEE Transactions on Industrial Informatics	5.430	7.377	9.112	↑
6	Applied Energy	7.900	8.426	8.848	↑
7	IEEE Transactions on Smart Grid	7.364	10.486	8.267	↓
8	Energy Conversion and Management	6.377	7.181	8.208	↑
9	IEEE Vehicular Technology Magazine	6.038	6.145	7.921	↑
10	IEEE Transactions on Industrial Electronics	7.050	7.503	7.515	↑
11	IEEE Transactions on Sustainable Energy	6.235	7.650	7.440	↓
12	IEEE Transactions on Power Electronics	6.812	7.224	6.373	↓
13	Renewable Energy	4.900	5.439	6.274	↑
14	Energy	4.968	5.537	6.082	↑
15	IEEE Transactions on Power Systems	5.255	6.807	6.074	↓
16	IEEE Transactions on Transportation Electrification	/	5.270	5.444	↑
17	IEEE Transactions on Vehicular Technology	4.432	5.339	5.379	↑
18	IEEE Journal of Emerging and Selected Topics in Power Electronics	5.177	5.972	4.728	↓
19	Solar Energy	4.374	4.674	4.608	↓
20	IEEE Transactions on Energy Conversion	3.767	4.614	4.501	↓
21	IEEE Power & Energy Magazine	2.689	4.800	4.093	↓
22	IET Renewable Power Generation	3.488	3.605	3.894	↑
23	IEEE Access	3.557	4.098	3.745	↓
24	International Journal of Energy Research	3.009	3.343	3.741	↑
25	IEEE Transactions on Power Delivery	3.350	4.415	3.681	↓
26	IEEE Transactions on Instrumentation and Measurement	2.794	3.067	3.658	↑
27	International Journal of Electrical Power & Energy Systems	3.610	4.418	3.588	↓
28	IEEE Transactions on Industry Applications	2.743	3.347	3.488	↑
29	Electric Power Systems Research	2.856	3.022	3.211	↑

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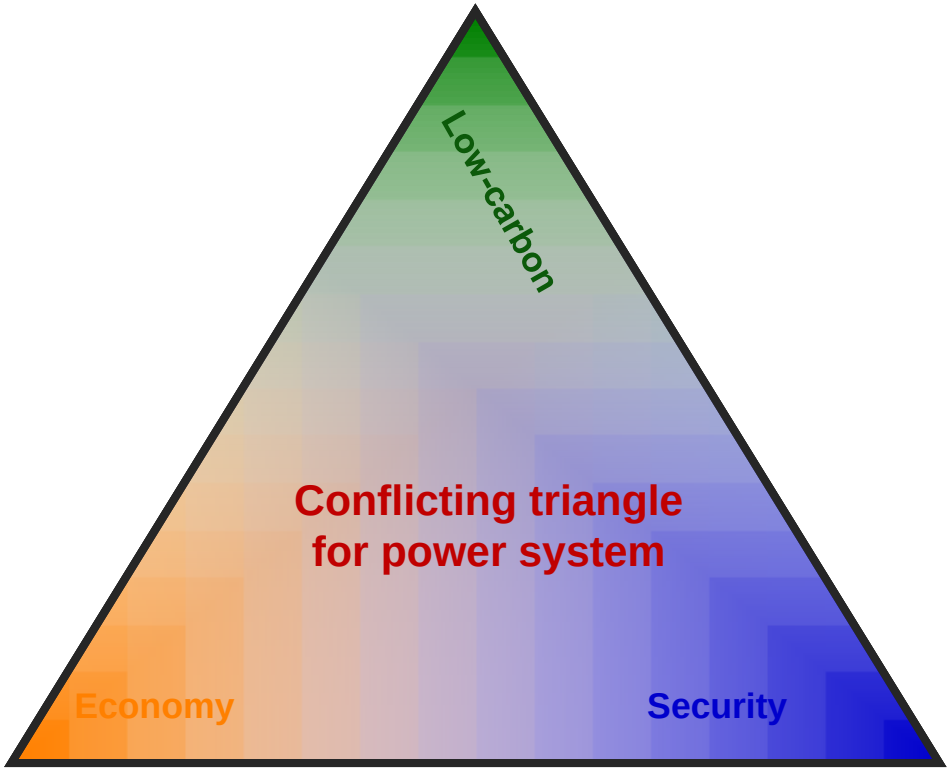
Utilize more renewable and clean energy resources



Minimize system operating & planning cost $

Withstand disturbances without power outage

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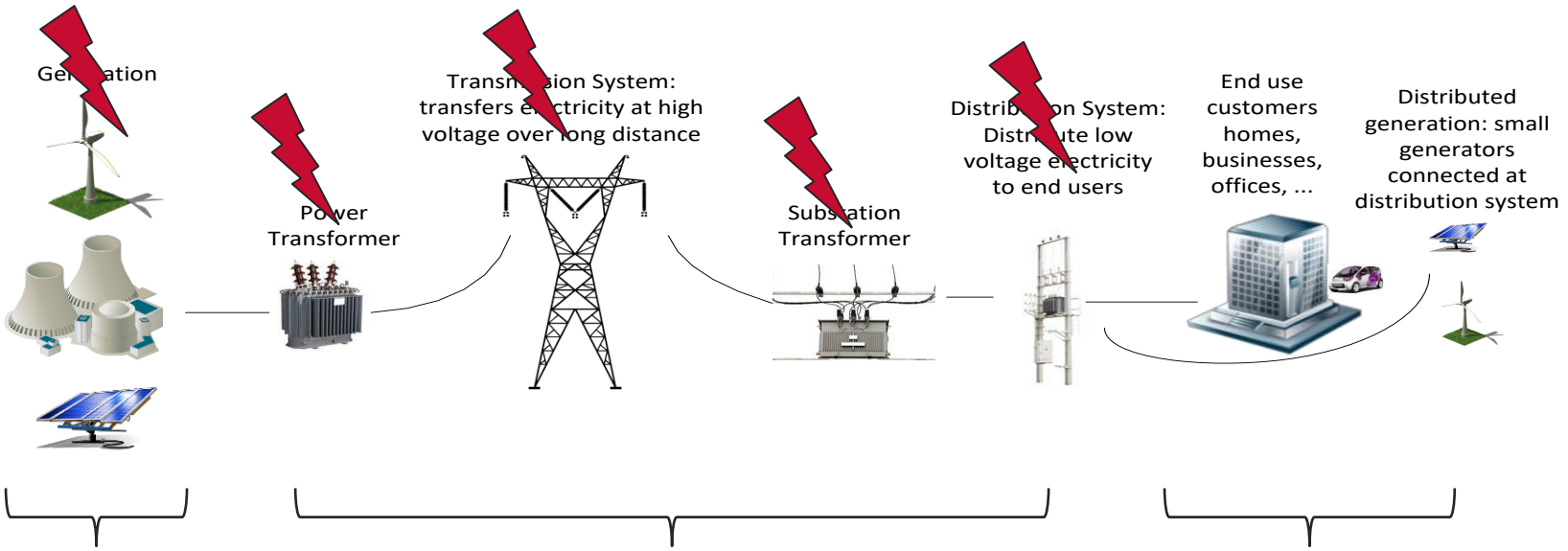
Typical power system structure



A power system should be able to maintain a secure electricity generation, transmission, distribution, and consumption process.

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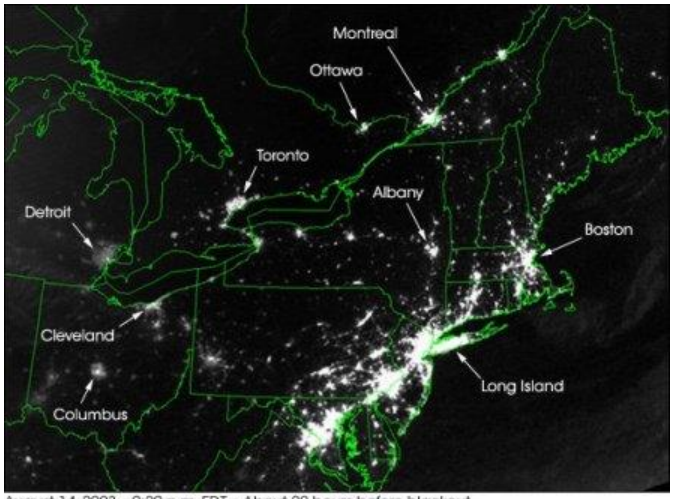
Power System Security



2003 North America "8.14" Blackout

The ability of the system to withstand a (or a set of) disturbance(s) without interrupting customer services

Major Electric Blackouts since 2000

- **2003** North America - **50m** people affected
- **2006** Western Europe - **10m** people affected
- **2009** Brazil - **50m** people affected
- **2012** India - **600m** people affected
- **2015** Ukraine - **cyber attack**
- **2016** South Australia – **wind power loss**
- **2018** Singapore – **147k** people affected
- **2019** New York – **73000** people affected
- **2019** UK – **1m** people affected
- **2020** Venezuela – **cyber/physical attack**
- **2021** Texas USA – extreme weather

SG Power Grid Reliability Performance

Performance

There are two key indicators that our industry measures when assessing performance on network reliability: 1) SAIDI, a system index of average duration of interruption in the power supply indicated in minutes per customers, and 2) System Average Interruption Frequency Index (SAIFI), a system index of average frequency of interruptions in the power supply.

In FY2020/2021, our SAIDI for the electricity network improved by over 73 per cent.

		FY18/19	FY19/20	FY20/21
Electricity	SAIDI (min)	0.87	0.56	0.15
	SAIFI	0.0307	0.0366	0.0073
Gas	SAIDI (min)	0.0932	0.2637	0.4223
	SAIFI	0.0014	0.0019	0.0024

Source: SP Power Group Sustainability Review FY2020/2021

Singapore 19-Sep-2018 outage

Singapore has one of the most reliable power grids in the world (according to the latest international benchmarking report by DNV GL in 2018, Singapore's electricity grid is ranked top among major cities). However, a very serious blackout still happened in 2018.

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On June 1 this year, thousands of offices and businesses in the Central Business District and surrounding areas were hit by a power outage which affected 3,156 customers in parts of Raffles Quay, Robinson Road and Shenton Way for over half an hour. SP later traced the problem to maintenance work by its crew at a substation.

While major power outages are rare here, experts said they cannot be completely eliminated.

NTU Associate Professor Gooi Hoay Beng, who is from the School of Electrical and Electronic Engineering, said Singapore's average interruption time is less than a minute per customer a year. This is better than Tokyo (four minutes), New York (20.53 minutes) and Hong Kong (23.40 minutes), according to the EMA website.

Said Prof Gooi: "Typically, we are able to cover the outage of one generator unit without incidents. However, when you have simultaneous loss of two or more generating units, the system may not be able to handle it."

Assistant Professor Xu Yan, who is also from NTU, said the restoration of power in 38 minutes was "definitely fast", given the extent of yesterday's disruption.

As Singapore's power system becomes even more complex with the use of more renewable energies, such as wind and solar power, it is important to keep reinforcing the network and optimising the system's operations, Prof Xu added.

Dr Xu's comments on Sep-2019 Singapore blackout on 《The Straits Times》

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SP Group-NTU Joint Lab

SP Group embarks on S$30 million in research and education initiatives with NTU

SPgroup
Empowering the Future of Energy

"SP Group is focused on upholding reliable and efficient supply of electricity to consumers in Singapore. Together with NTU, we look forwards to developing first-in-class, innovative ways to strengthen our network planning, renewal and maintenance practices. In creating a sustainable network for future generations, we are committed to building a strong pipeline of engineering leaders for the energy sector."

- Mr Stanley Huang, Group Chief Executive Officer at SP Group, 2020.

"While the research collaboration leverages advanced technologies such as AI and machine learning to enhance the resilience and efficiency of our power grid, the gift for the endowment fund invests in the future of young minds that will see ever-growing returns for years to come."

- NTU President Professor Subra Suresh, 2020.

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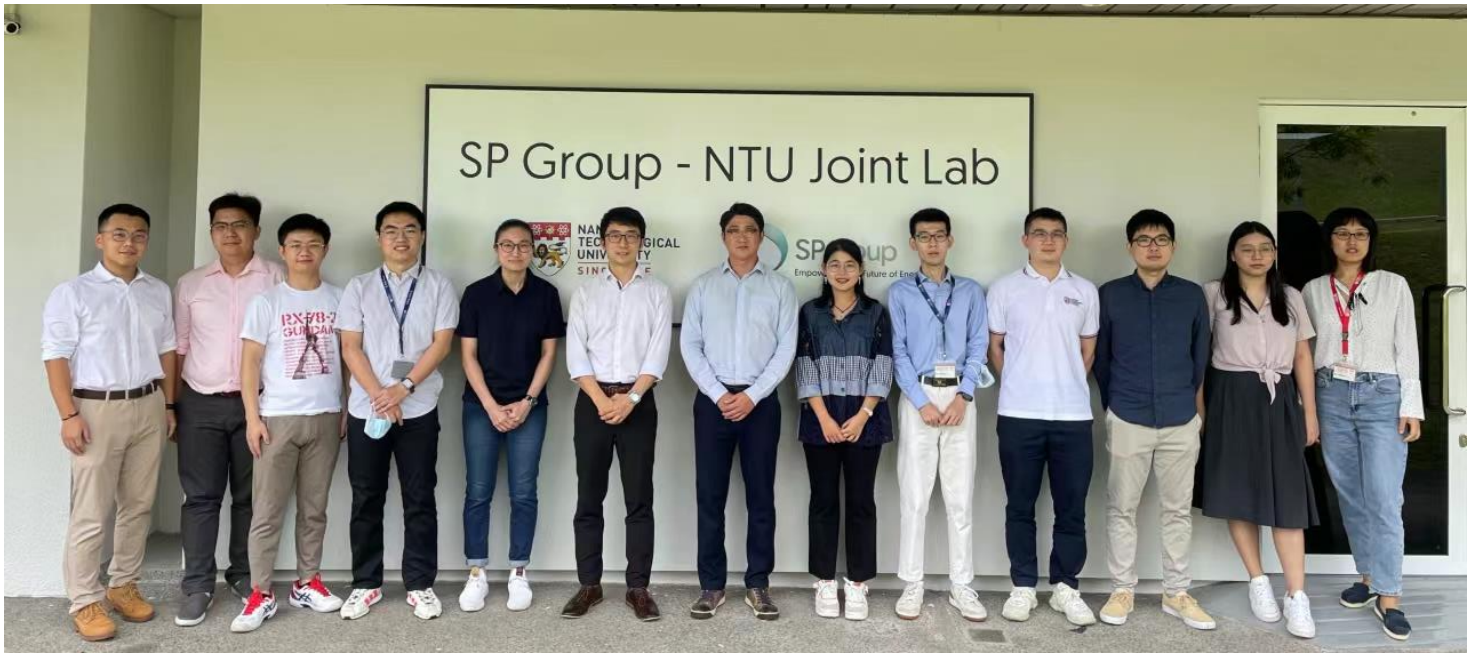
https://www.ntu.edu.sg/spgroup-ntu

SP Group-NTU Joint Lab



SP Group -NTU Joint Laboratory is currently focused on the following 4 Thrusts:

- Thrust A - Asset Health Modelling and Planning
- Thrust B - Component Degradation Studies
- Thrust C - Failure Mode Analysis
- Thrust D - Enhanced Condition Monitoring

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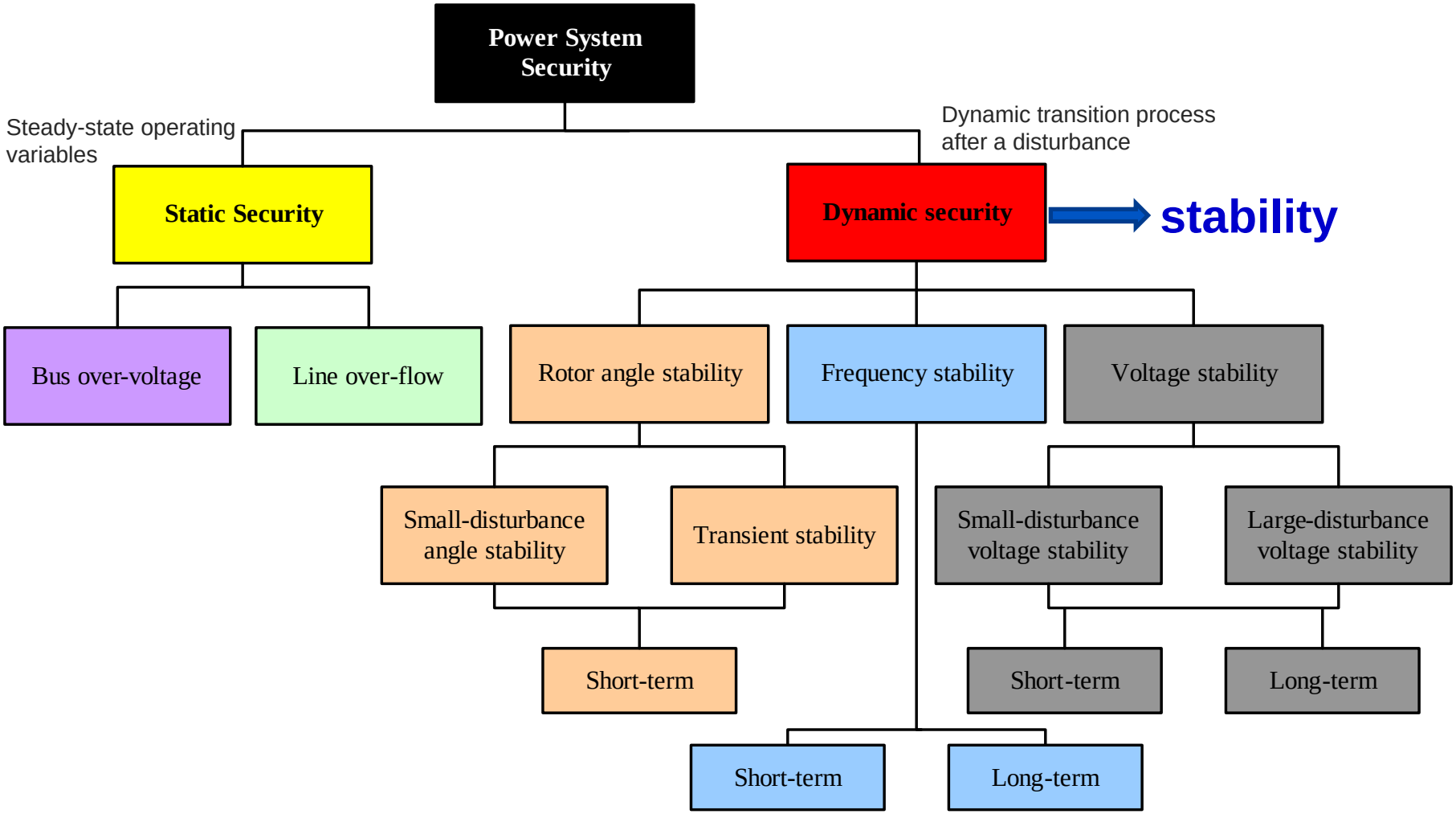
Classification of Power System Security



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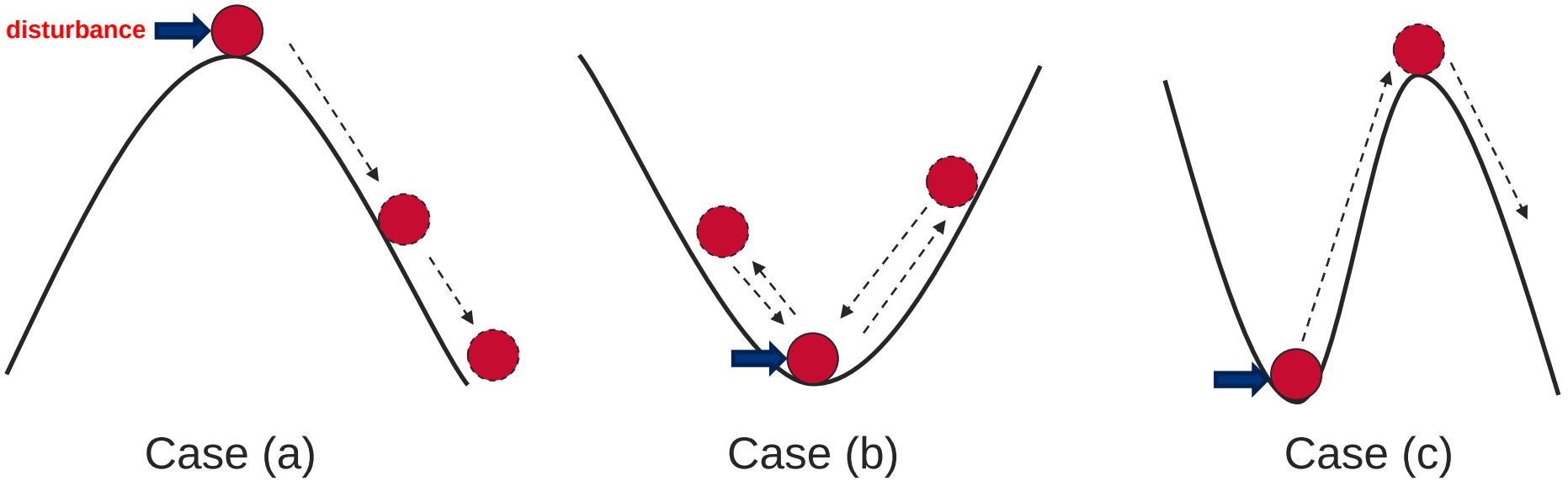
Power system stability (dynamic security)

Power system stability is the ability of an electric power system, for a given initial operating condition, ***to regain a state of operating equilibrium*** *after being subjected to a* ***physical disturbance****, with most system variables bounded so that practically the entire system remains intact.*

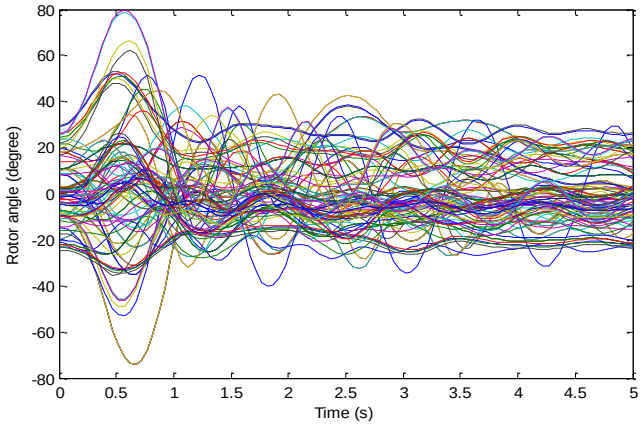
IEEE & CIGRE Joint Taskforce, "Definition and classification of power system stability," *IEEE Trans. Power Syst.*, vol. 19, no. 3, pp. 1387-1401, Aug. 2004.



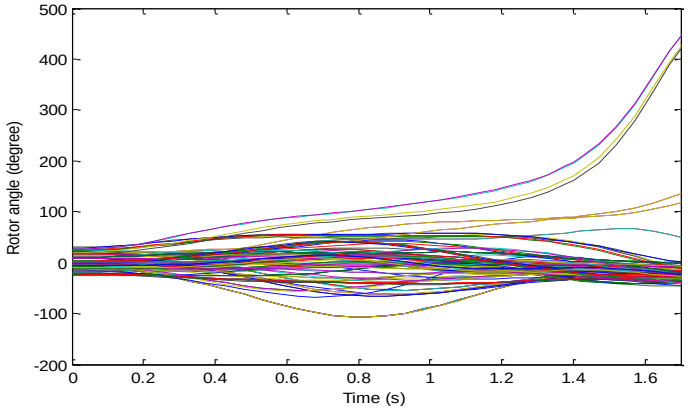
Case (a) Case (b) Case (c)

Which is stable?

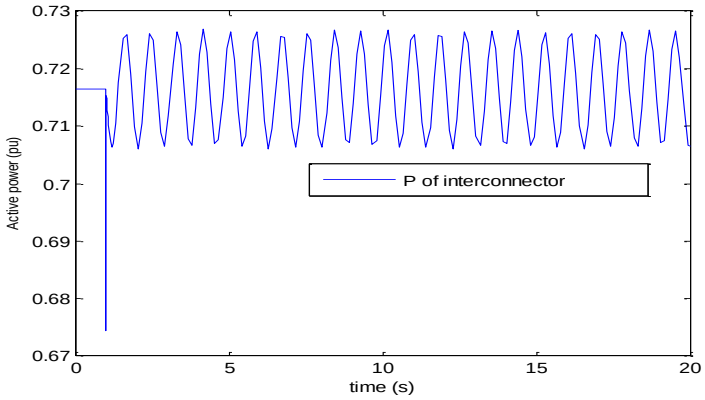
Phenomenon of instability: rotor angle



Rotor angles of a transient stable case



Rotor angles of a transient unstable case

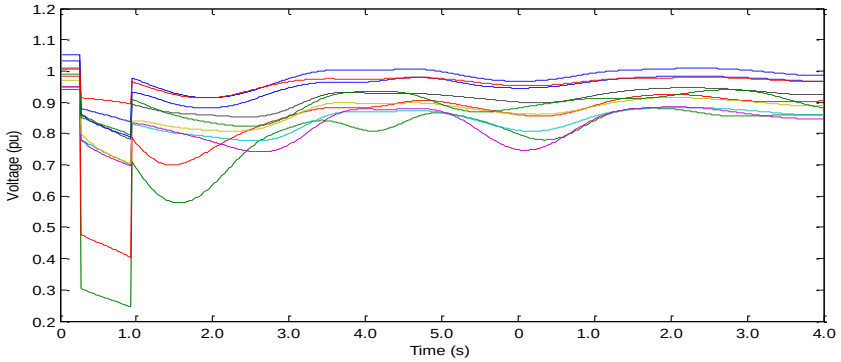


Active power oscillation due to the small-disturbance instability

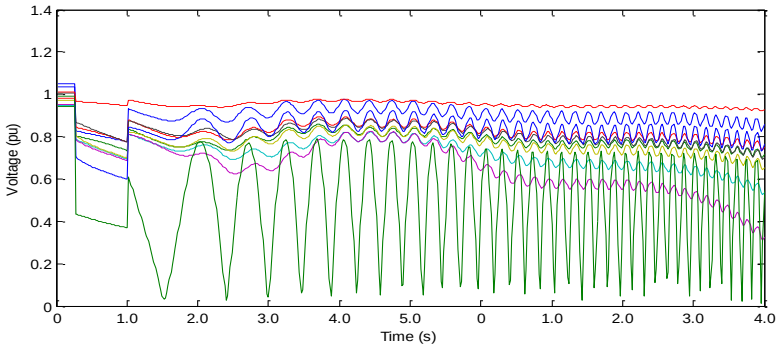
Solving 15000 differential-algebraic equations

Eigen value calculation

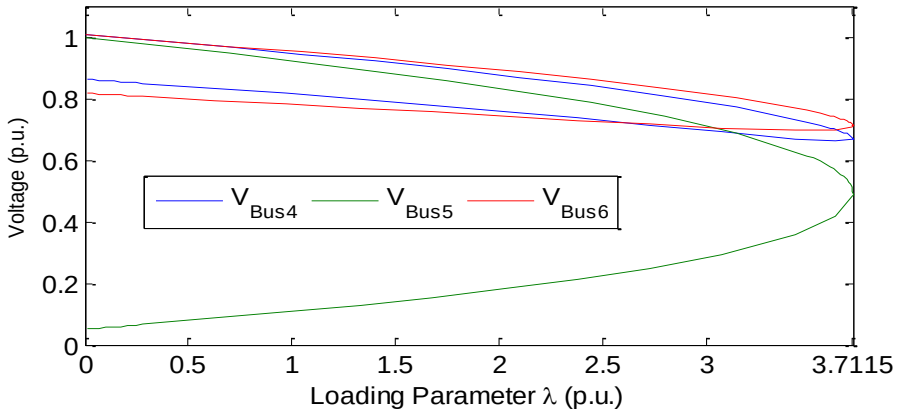
Phenomenon of instability: voltage



Voltage trajectories of the large-disturbance voltage stable case



Voltage trajectories of the large-disturbance voltage unstable case



Power-voltage (PV) curve

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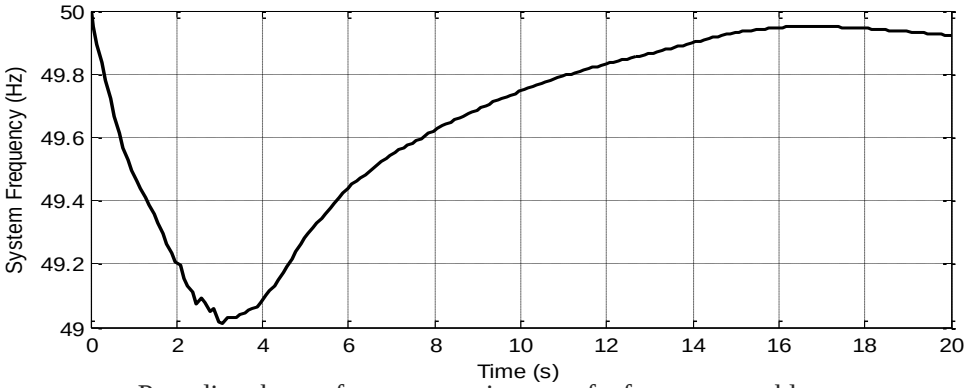
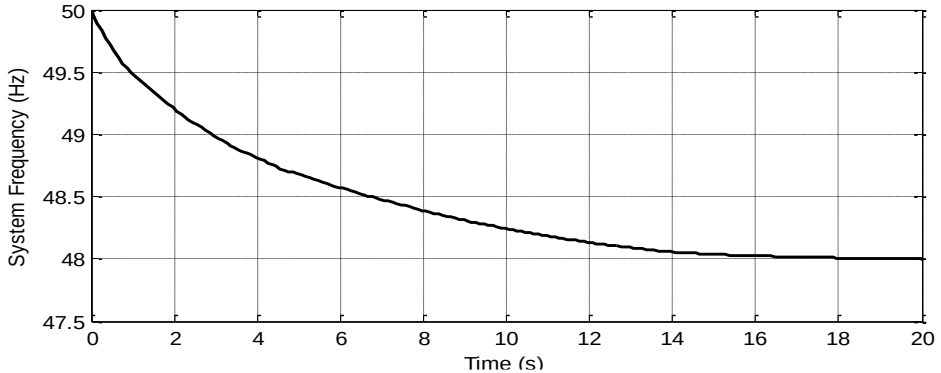
Phenomenon of instability: frequency



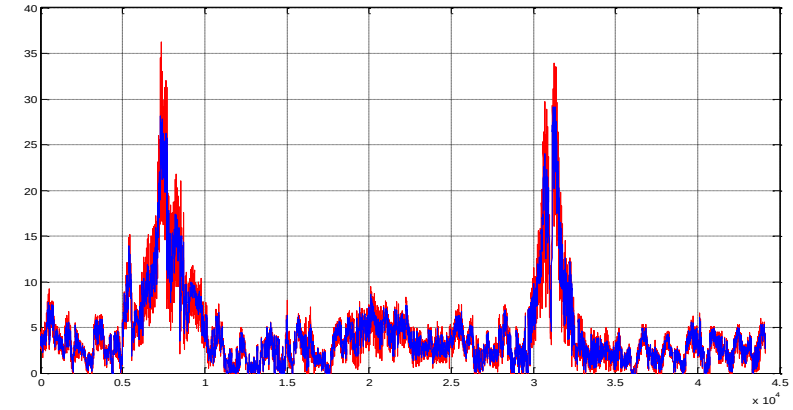
Post-disturbance frequency trajectory of a frequency stable case

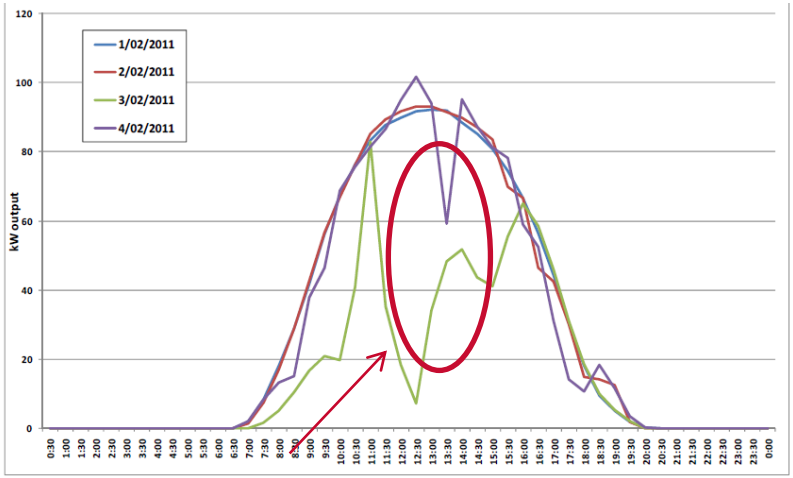


Post-disturbance frequency trajectory of a frequency unstable case

Impact of Renewable Energy Sources on Power System Stability

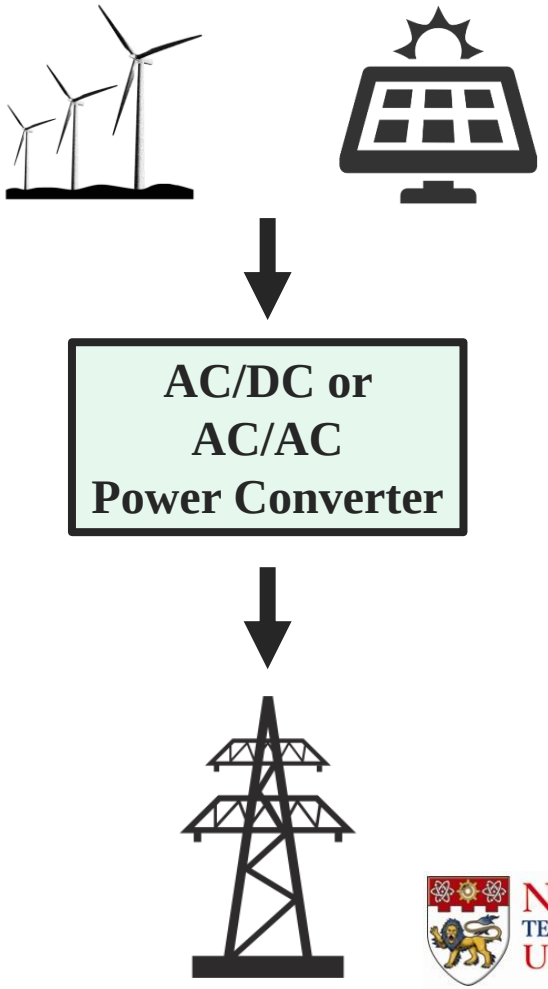
- Static characteristics





ramp down/up on the order of 15% of its capacity per minute with intermittent cloud coverage

- Dynamic characteristic



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Technical Challenges added by “Smart Grid”

wind

solar

energy storage

Renewable power generation and demand response behaviour are highly uncertain and difficult to predict. Therefore they will introduce considerable uncertainties to the power system’s operating state

Renewable power are usually interfaced through power converters, which can reduce the system’s inertia and lead to deteriorated system dynamic performance

Distributed generation can rise the bust voltage in a distribution network

ITC devices increase the exposure to cyber-attacks and raise customer privacy concerns

EV

PMU

Smart meter

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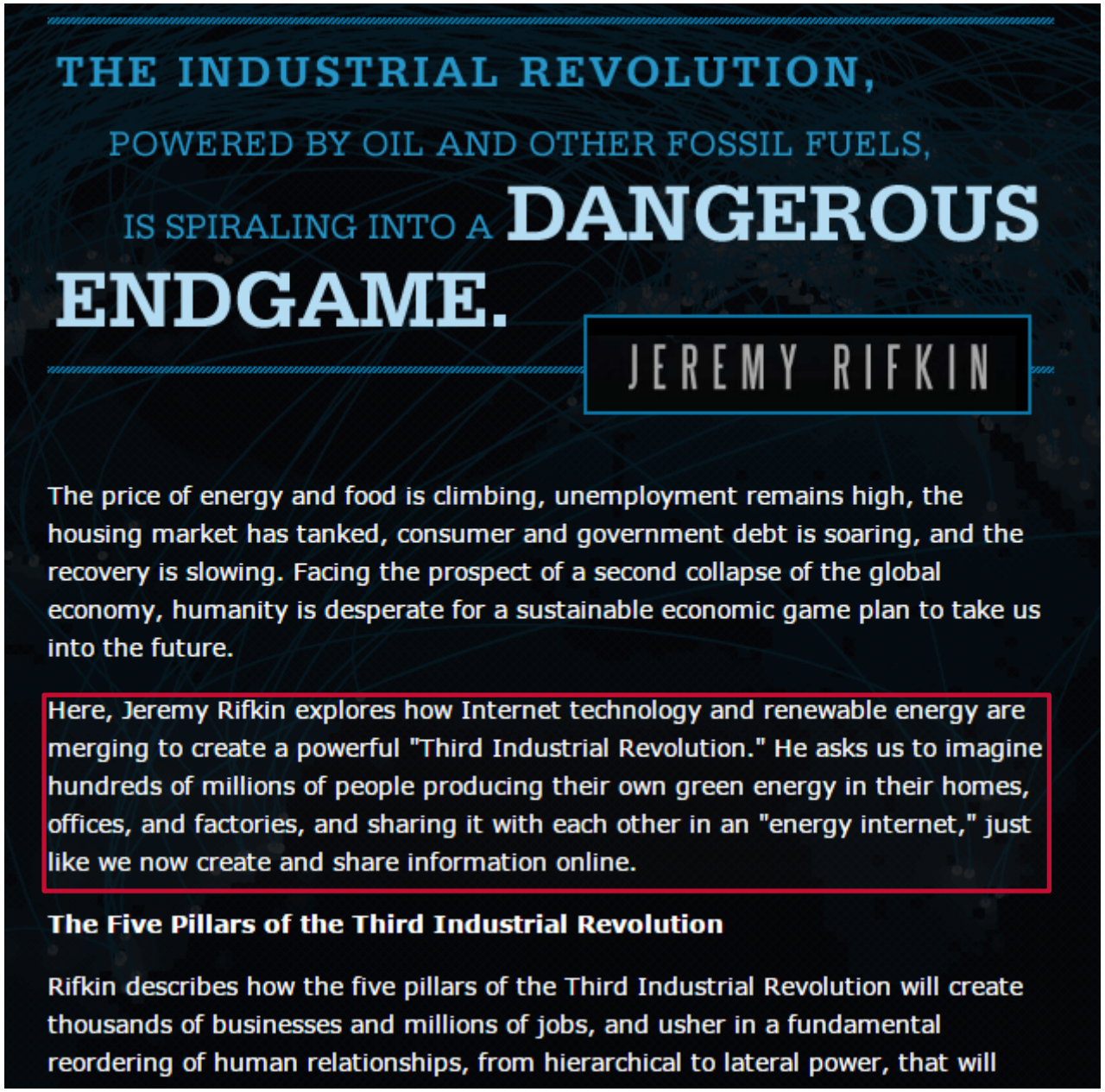
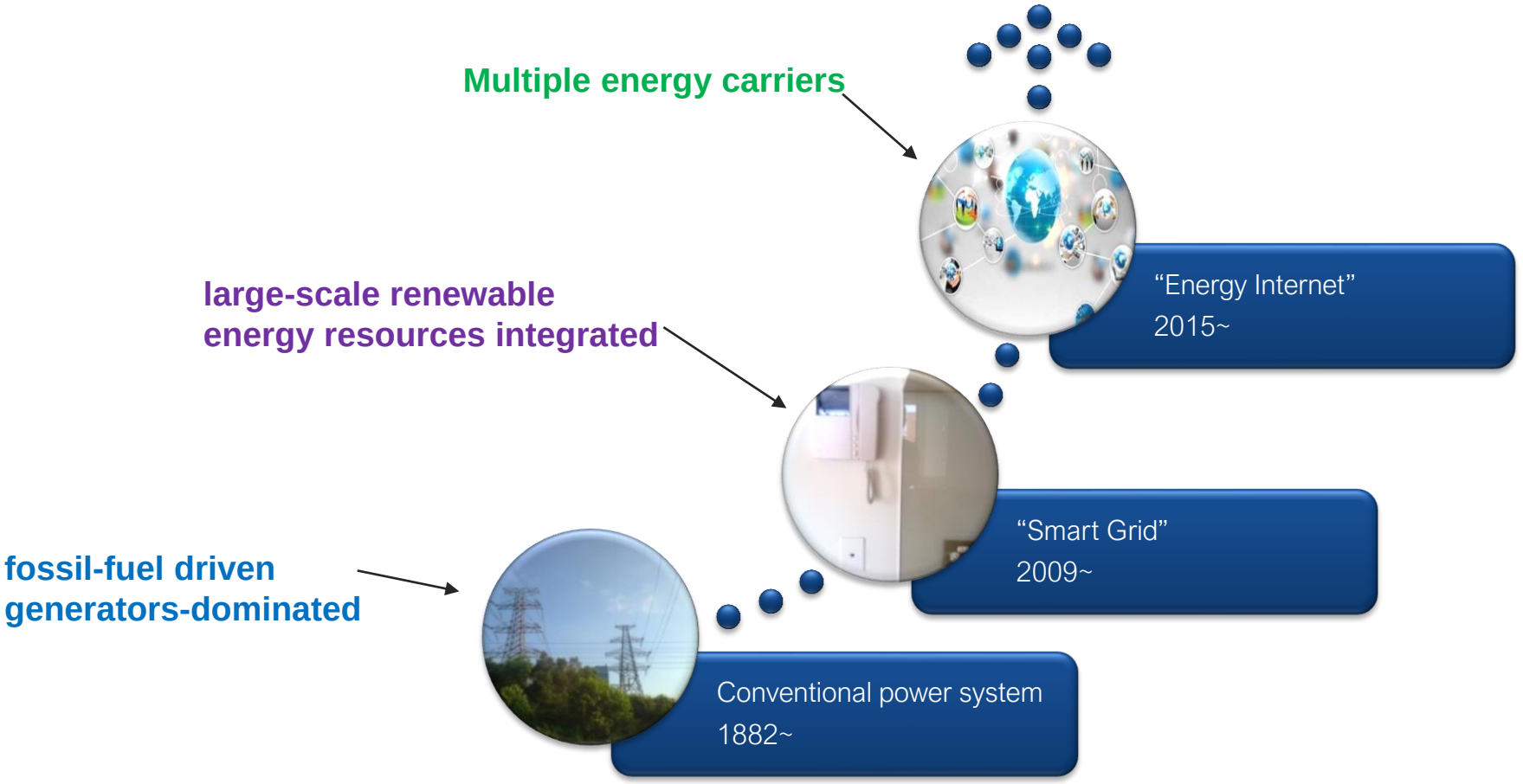
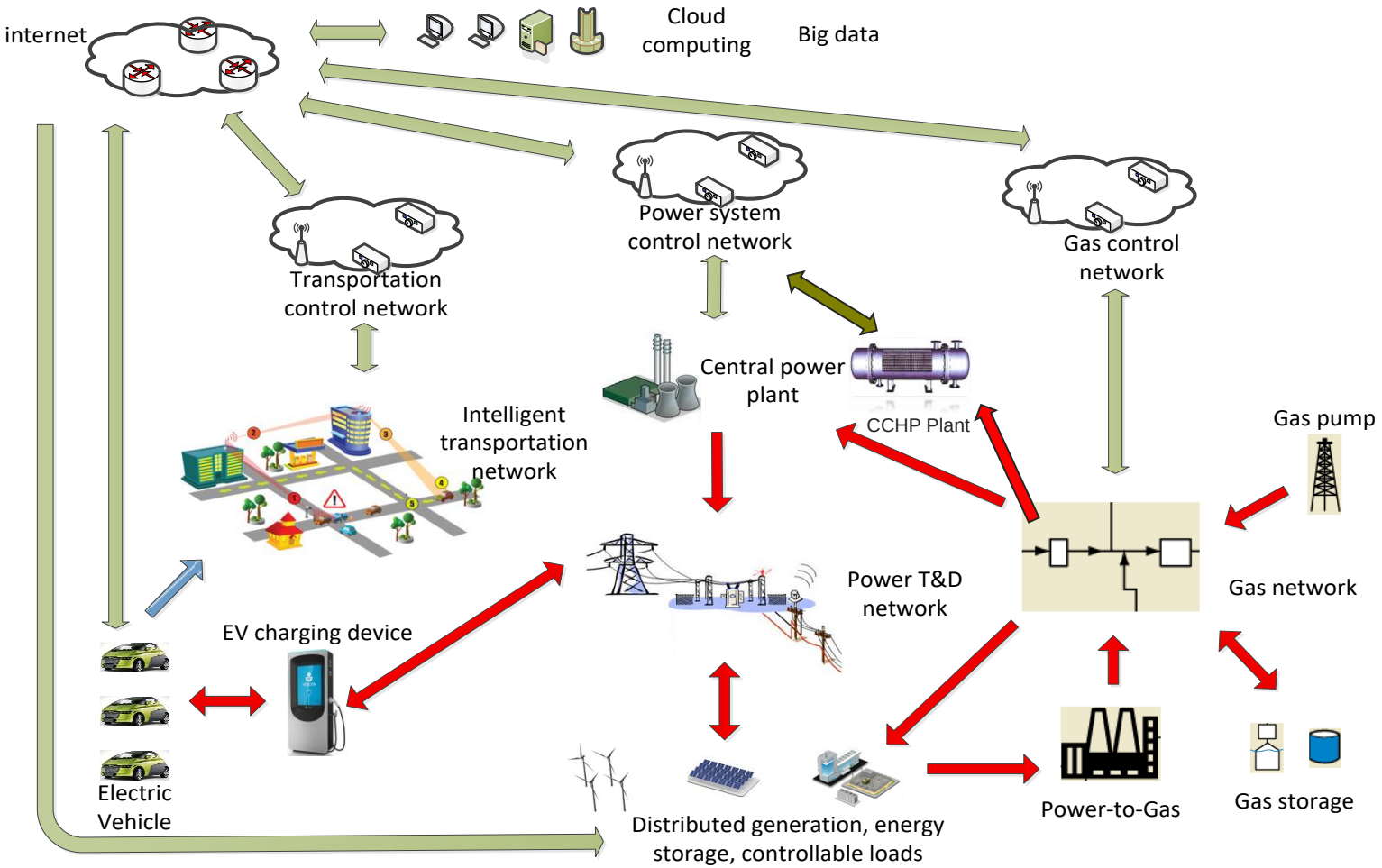
3. Power System Security
4. “Energy internet”


THE INDUSTRIAL REVOLUTION,
POWERED BY OIL AND OTHER FOSSIL FUELS,
IS SPIRALING INTO A DANGEROUS
ENDGAME.
JEREMY RIFKIN
The price of energy and food is climbing, unemployment remains high, the housing market has tanked, consumer and government debt is soaring, and the recovery is slowing. Facing the prospect of a second collapse of the global economy, humanity is desperate for a sustainable economic game plan to take us into the future.
Here, Jeremy Rifkin explores how Internet technology and renewable energy are merging to create a powerful "Third Industrial Revolution." He asks us to imagine hundreds of millions of people producing their own green energy in their homes, offices, and factories, and sharing it with each other in an "energy internet," just like we now create and share information online.
The Five Pillars of the Third Industrial Revolution
Rifkin describes how the five pillars of the Third Industrial Revolution will create thousands of businesses and millions of jobs, and usher in a fundamental reordering of human relationships, from hierarchical to lateral power, that will

Evolution path



One version of “Energy Internet”



“Smart Grid” v.s. “Energy Internet”

	Smart Grid	Energy Internet
Renewables penetration	Fossil fuel dominates, renewable energy supports	renewable energy dominates, fossil integrated
Energy generation	Centralised generation denominates, DG supports	Centralised & distributed generation integrated, generation & consumption integrated
Physical system	Power System	Power system + other energy systems
ICT network	Closed industrial network	Open service ICT network
Energy transportation	Electricity (only)	Integrated and interchangable : electricity, chemical energy, thermal energy etc.
System Control	Hierarchical control, local coordination	Big data, wide area control/coordination

Current Projects

USA - FREEDM (Future Renewable Electric Energy Delivery and Management)

http://www.freedm.ncsu.edu/

secured communication, distributed grid intelligence, high-frequency and high-voltage power conversion, and distributed energy storage devices

E-Energy – the Internet of Energy

ICT system concepts that **optimize entire** electricity supply system – generation, transport to distribution and consumption

http://www.efficiency-from-germany.info/ENEFF/Redaktion/EN/Standardartikel/e-energy.html

Australia's Future Grid

Renewables-dominated (100%) scenario, integrated power-gas network

Lead by CSRIO and 4 major universities (A$ 12 million)

http://www.futuregrid.org.au/

Central government series documents

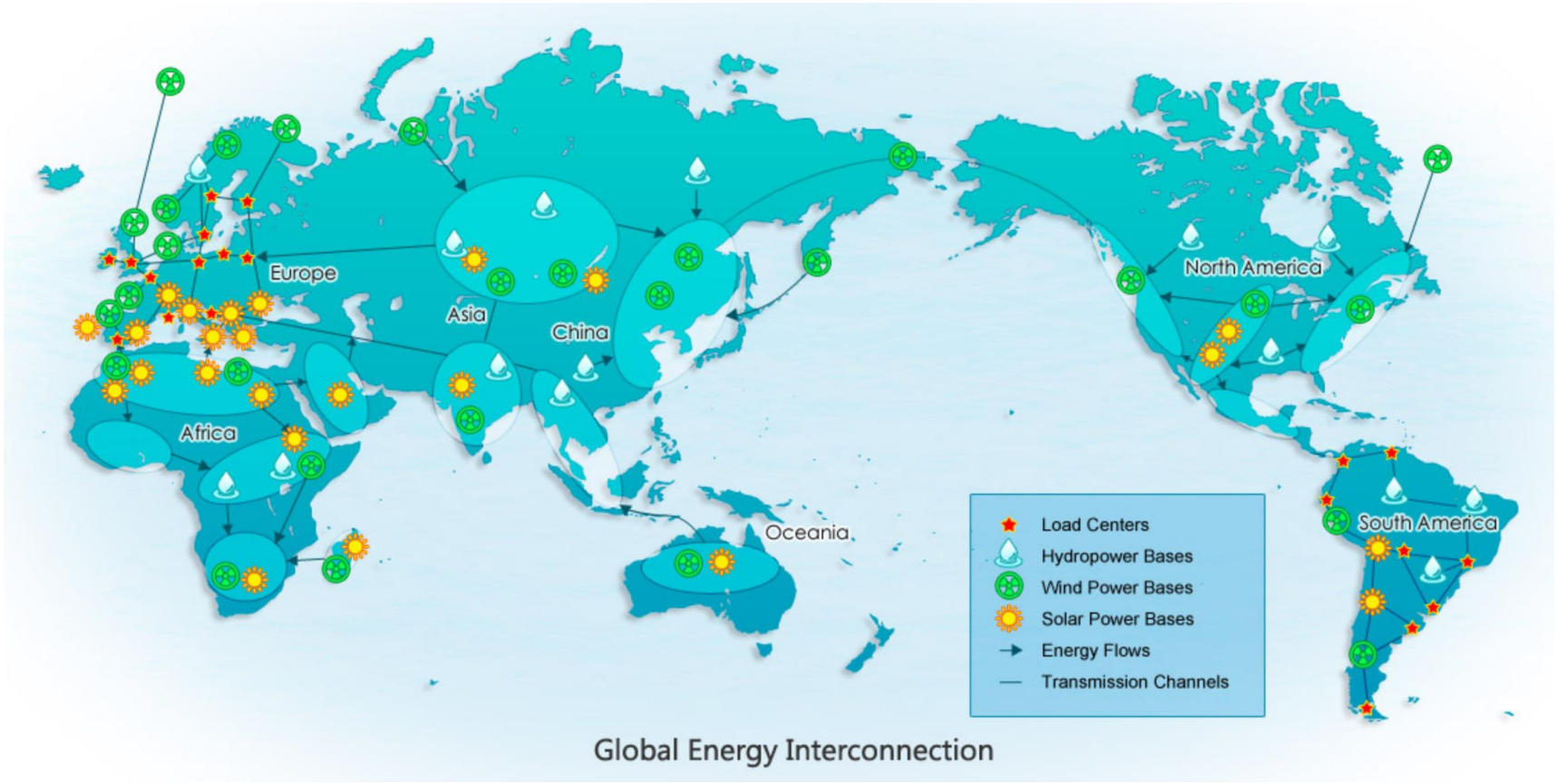
Natural Science Foundation of China

Ministry of Science and Technology

State Grid Co. & China Southern Power Grid Co.

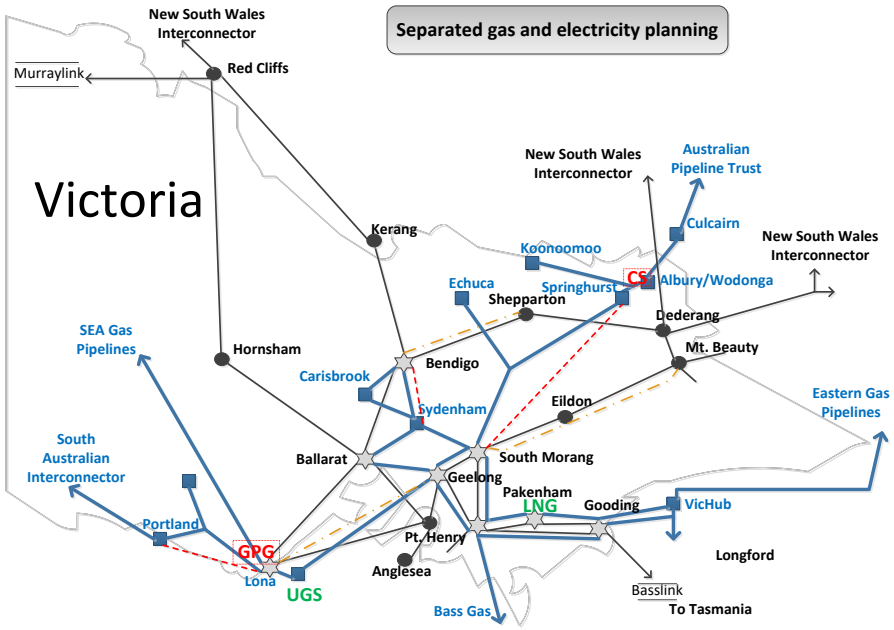
http://geidco.org/

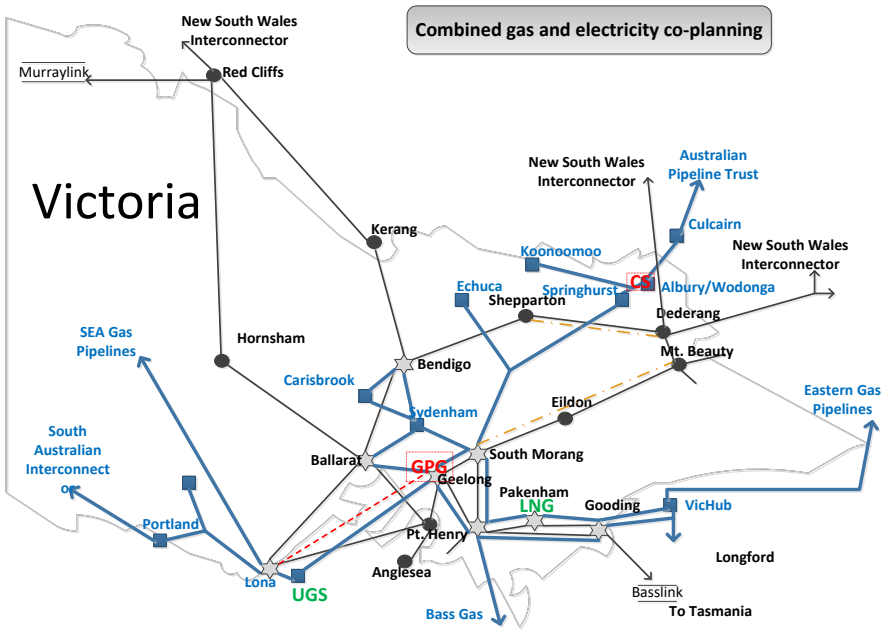
China's "Global Energy Interconnection"

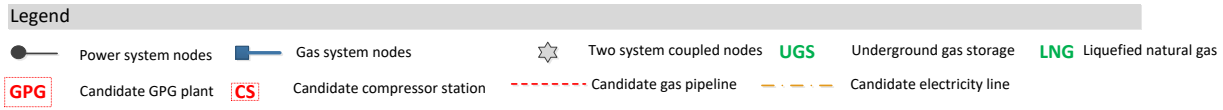


http://geidco.org/

Australia's "Future Grid"

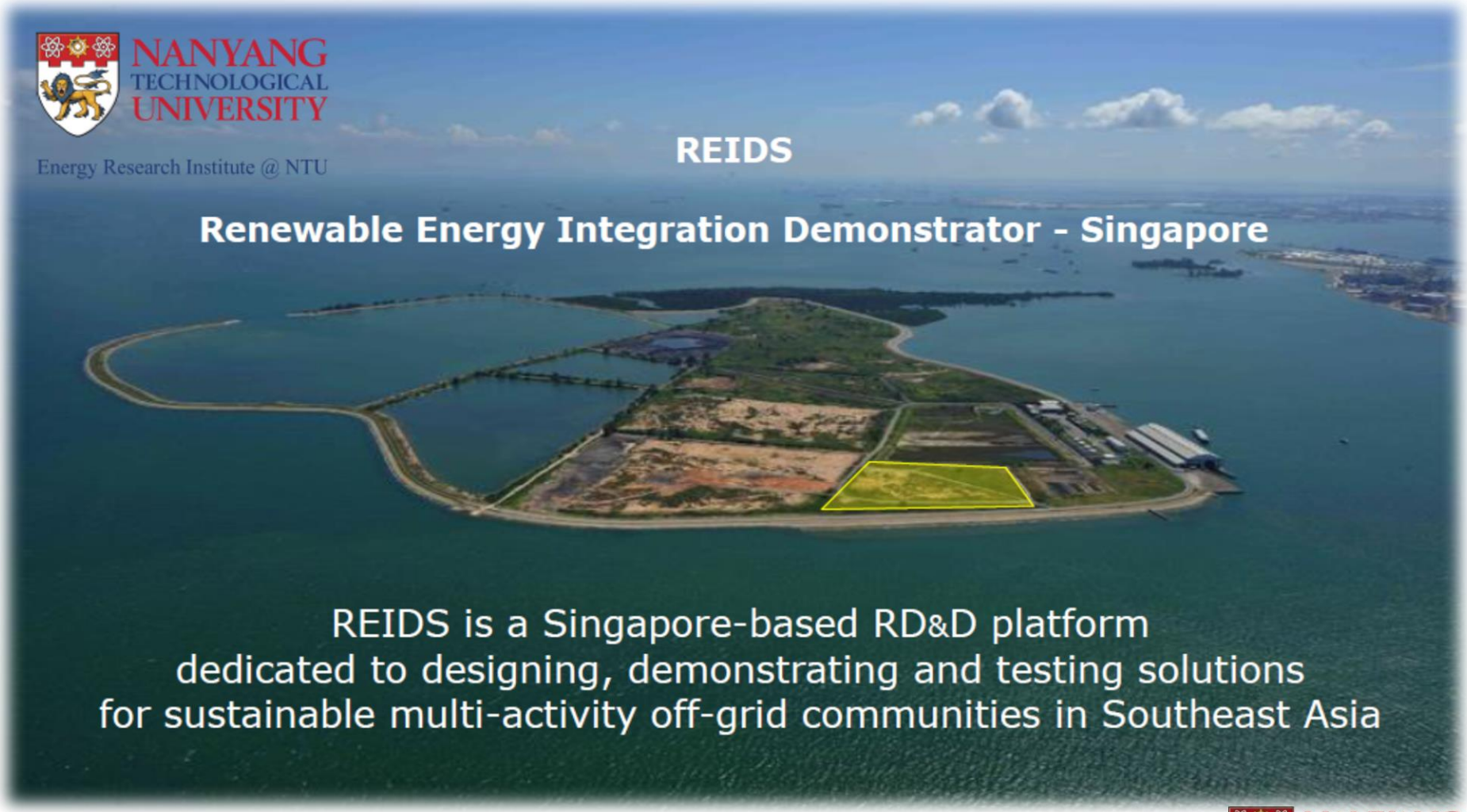






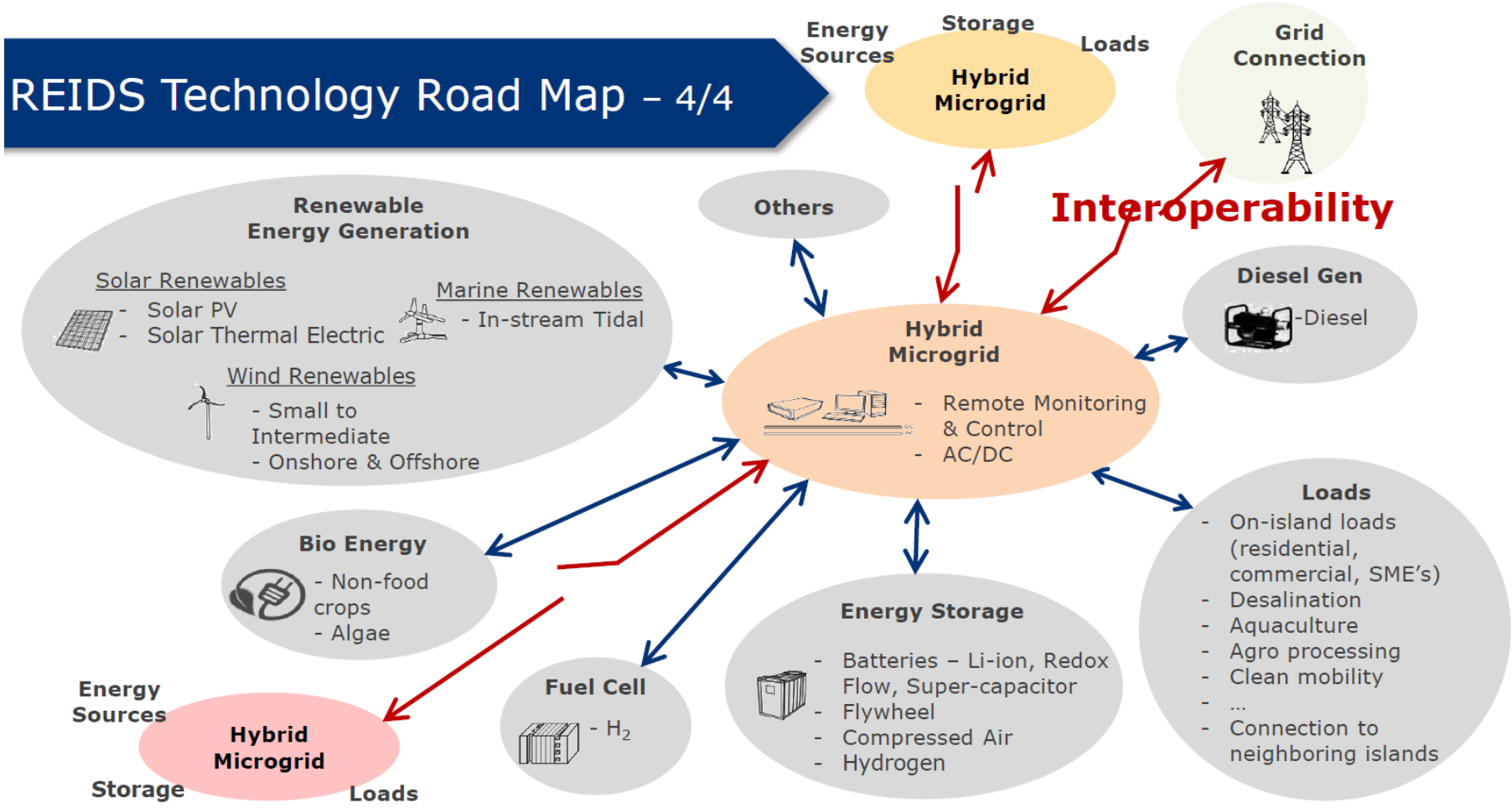
http://www.futuregrid.org.au/

NTU's REIDS Project



http://erian.ntu.edu.sg/REIDS/Pages/AboutREIDS.aspx

NTU's REIDS Project



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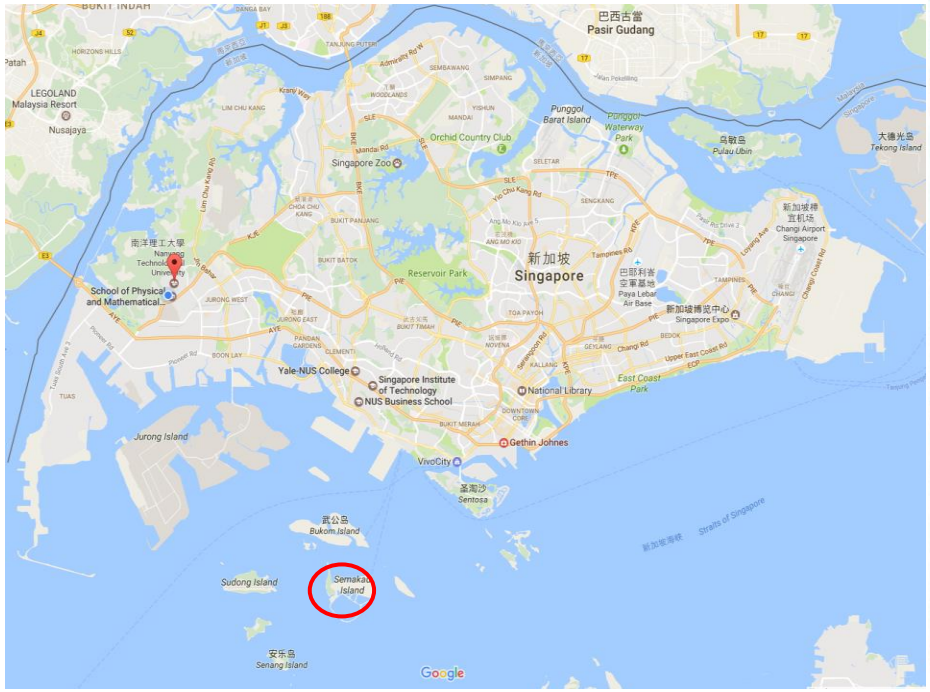
NANYANG TECHNOLOGICAL UNIVERSITY



REIDS Partners

accenture
adaro POWER
Bawah
ClassNK
DLRE
EDF
EMERSO
ENGIE
Evolution Energie
IDSUD ENERGIES
Keppel Offshore & Marine
MEDCOENERGI Power
MERALCO
muRata INNOVATOR IN ELECTRONICS
NORTIS ENERGY
REC
Rolls-Royce
Schneider Electric
SEAS Sustainable Energy Association of Singapore
sembcorp
SPgroup
Trinasolar
VDE RENEWABLES
Vestas

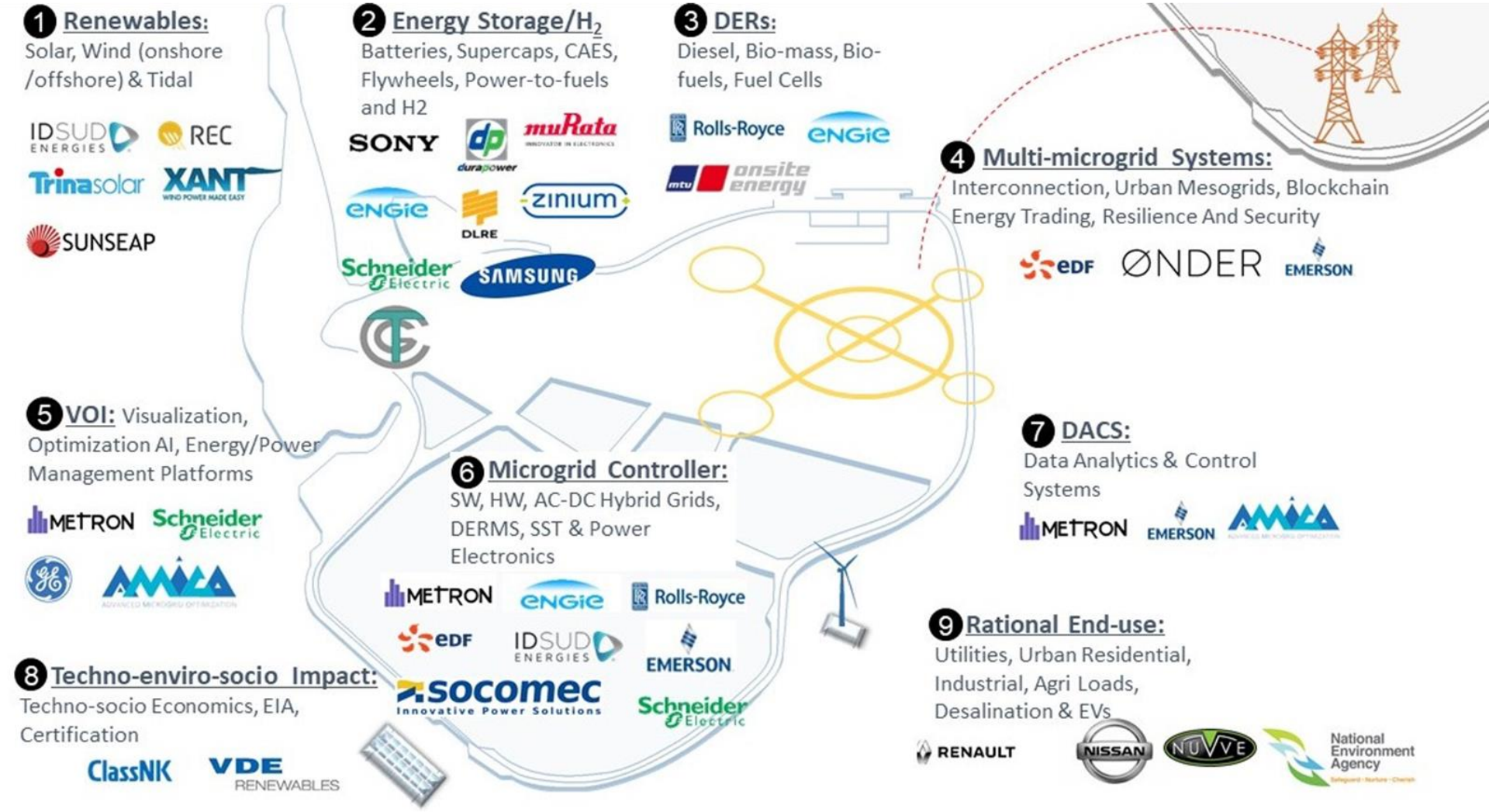
Research Leader

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

Supporting Agencies

EDB singapore
National Environment Agency Safeguard · Nurture · Cherish
ENERGY MARKET AUTHORITY Smart Energy, Sustainable Future
NATIONAL RESEARCH FOUNDATION

Onboard Industry Collaborators



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NANYANG TECHNOLOGICAL UNIVERSITY

MG0 Test & Commissioning - March 2017

NANYANG TECHNOLOGICAL UNIVERSITY

- Onsite pictures

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

Rolls-Royce@NTU Corporate Lab

https://www.ntu.edu.sg/rr-ntu-corp-lab

Phase 2 Projects

RRE1.1 Next Generation Aerospace Power Converters

RRE1.2 Novel Aerospace Electro-Mechanical System

RRE1.3 Aerospace Integrated Electrical System

RRE2.1 Power Converters

RRE2.2 Energy Storage System

RRE2.3 Electromechanical Systems

RRE2.4 Power and Propulsion System Design Tools

RRE2.5 Power and Propulsion System Design Architecture

RRE3.1 Smart Genset Systems

RRE3.2 Hybrid Microgrid Solution

RRE4.1 Electrical Equipment Health Management (eEHM) of Power Electronics Converters and Energy

RRE4.2 Electromechanical Systems Electrical EHM (eEHM)

RRE4.3 Power System Health Management (SHM)

Other popular terminologies – homework readings

- Net Zero & Carbon Neutrality

https://www.iea.org/reports/net-zero-by-2050

- Energy Transition to 2050

https://www.ema.gov.sg/energy-2050-committee-report.aspx

- New Power System

http://english.www.gov.cn/news/topnews/202301/10/content_WS63bd0a1ac6d0a757729e54ec.html