



THE VELUX FOUNDATIONS
VILLUM FONDEN × VELUX FONDEN

Renewables based power microgrids: architecture and components

Josep M. Guerrero

Center for Research on Microgrids CROM

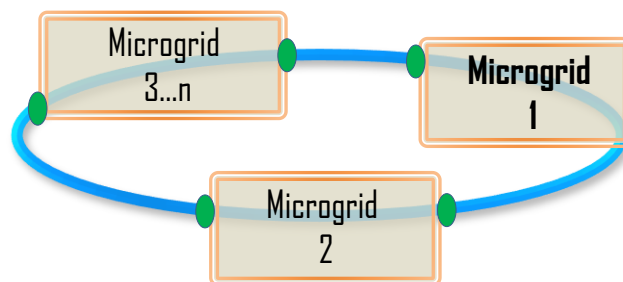
Department of Energy Technology, Aalborg University, Denmark

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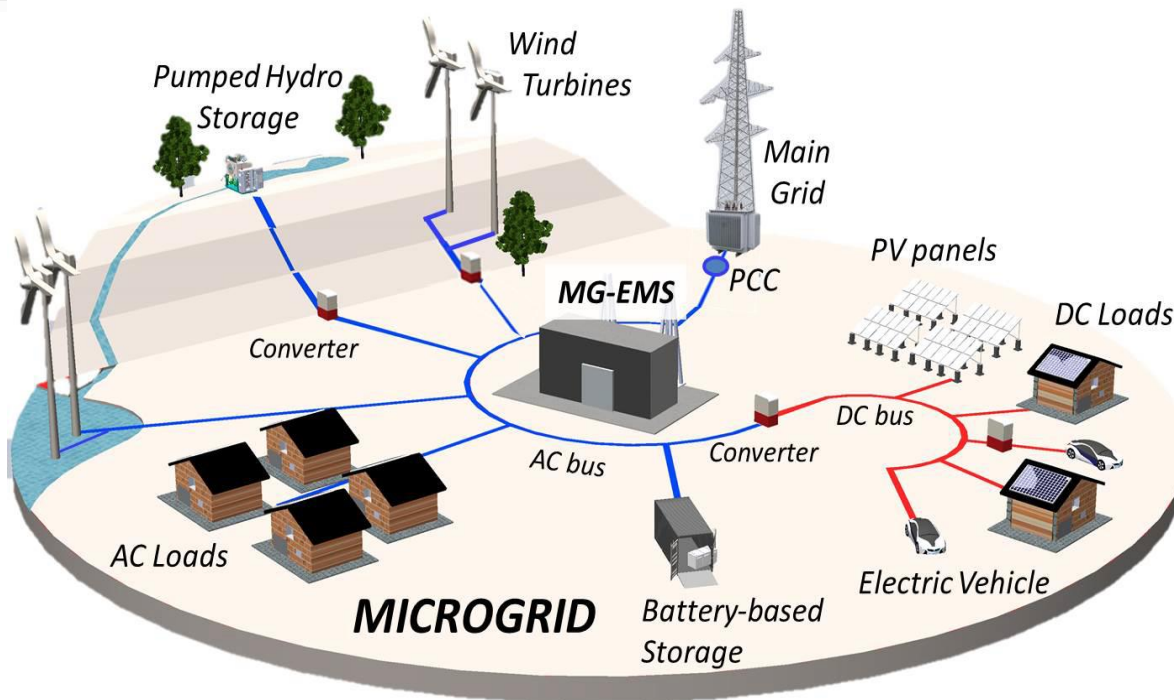
www.crom.et.aau.dk

The MICROGRID concept

Multiple microgrid clusters



System of Systems



Microgrids does not means "small" but "onsite" grids
MGs are "building blocks" of the Smart Grid

Available Infrastructure

- DC/AC & AC/DC Conversion

Setups already available in the AC and DC Microgrid Labs
Starting idea



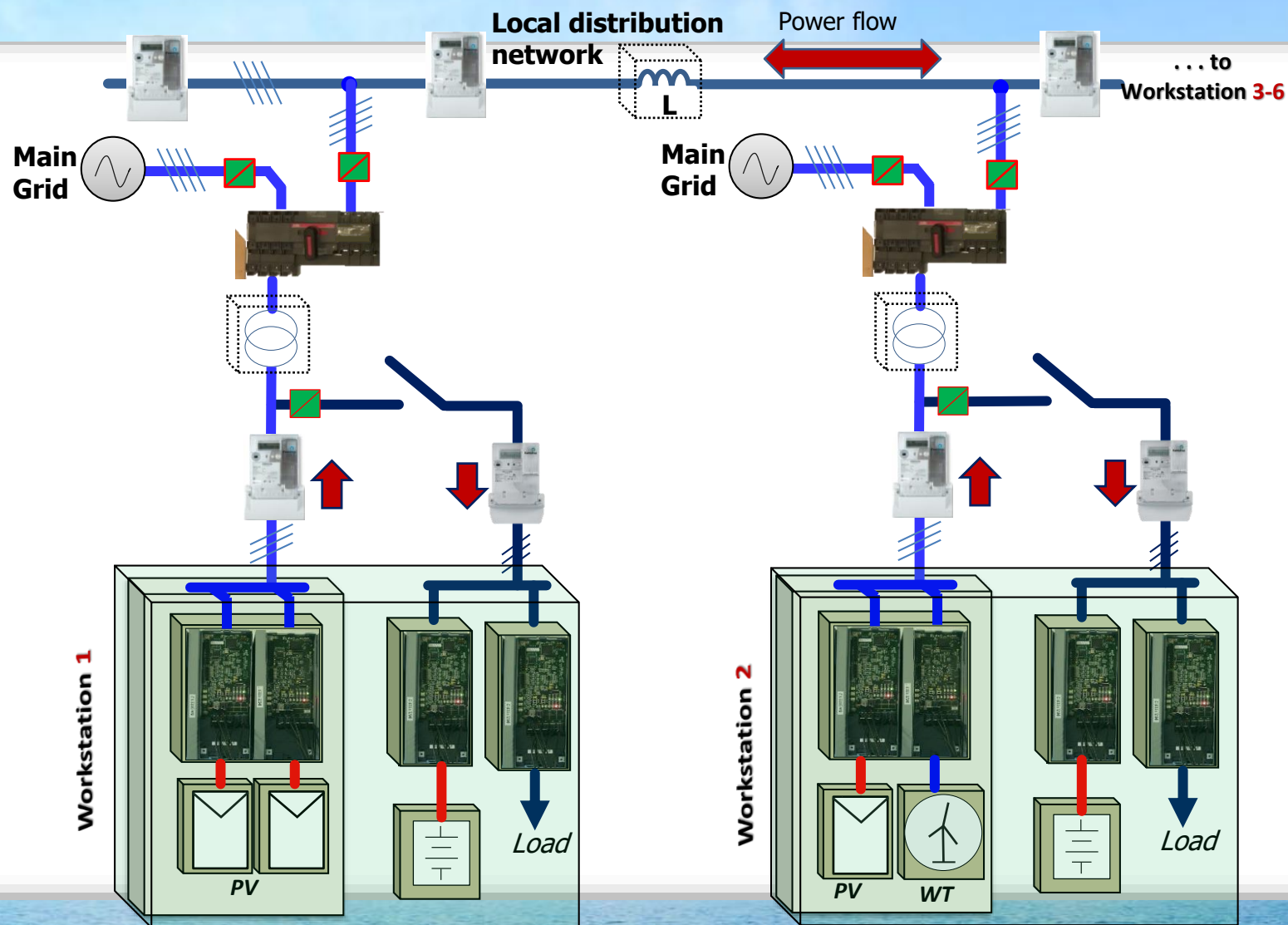




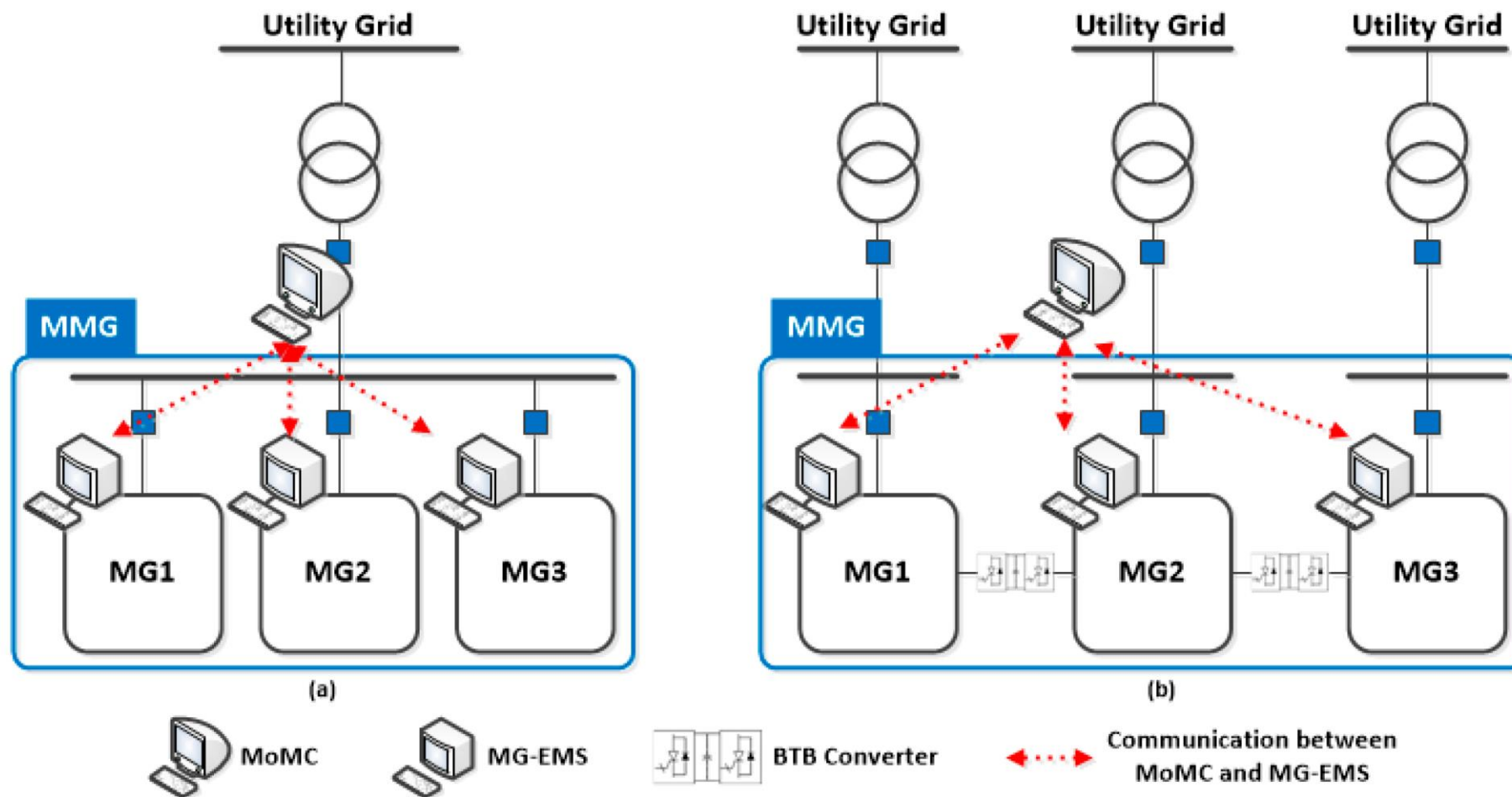
Microgrid Labs



Microgrid Labs



Multi-Microgrid System



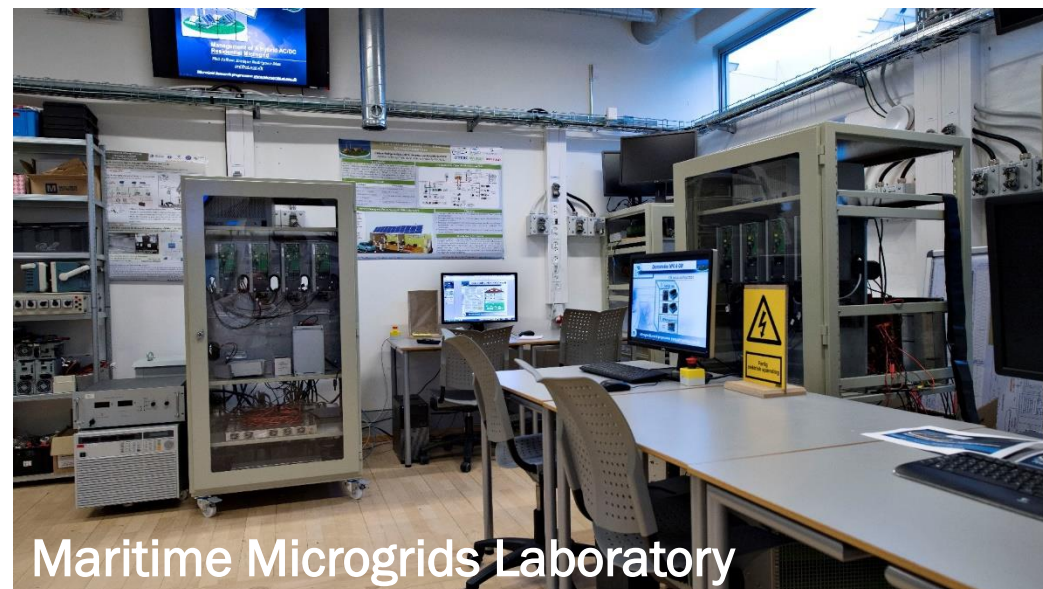


LABORATORY FACILITIES

IoT Microgrid Laboratory



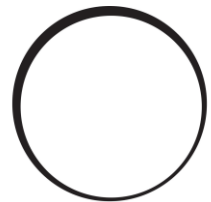
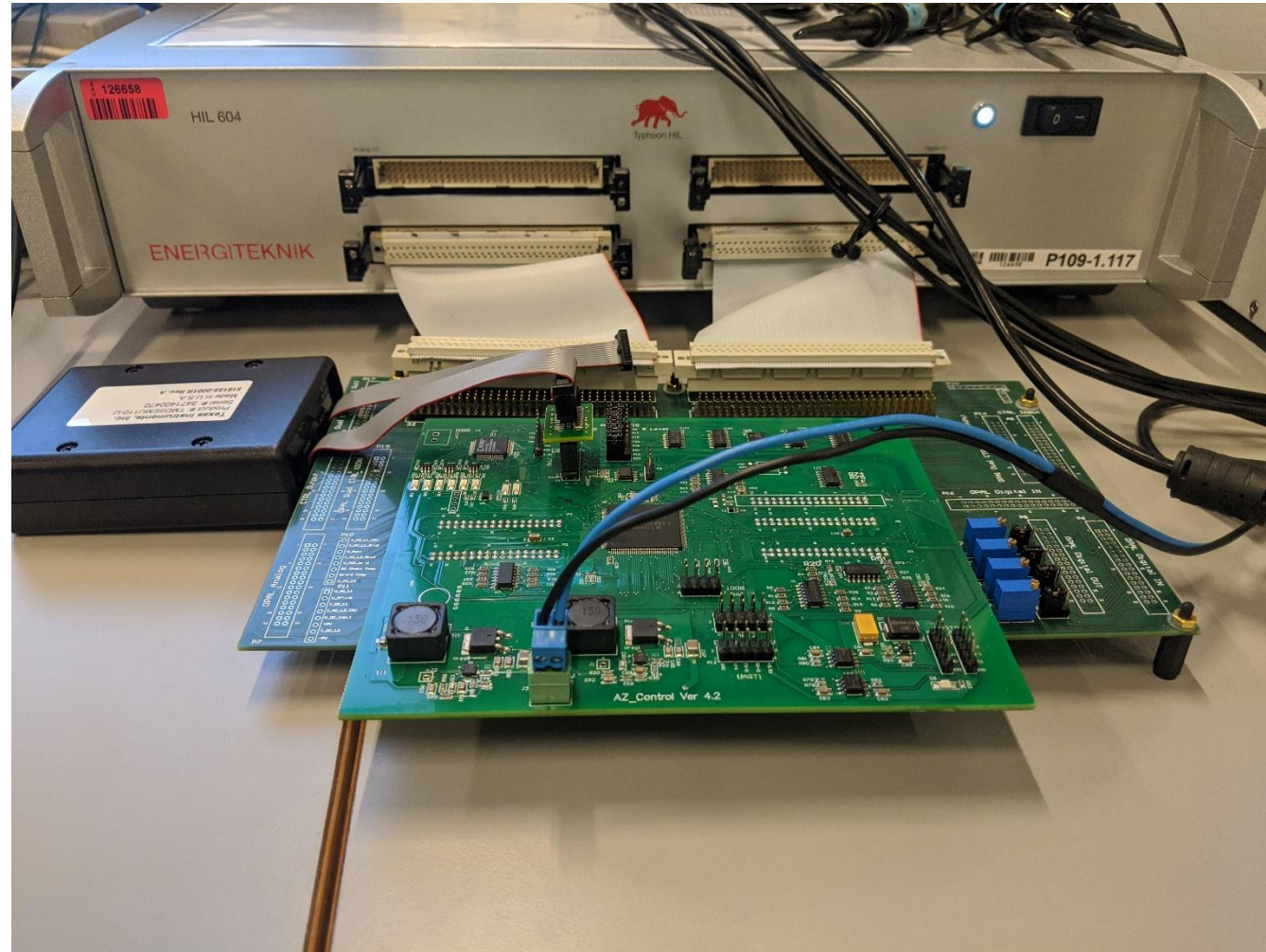
Microgrids and Energy Internet Laboratory



Maritime Microgrids Laboratory



LABORATORY FACILITIES



sonnen

CROM RESEARCH FRAMEWORKS



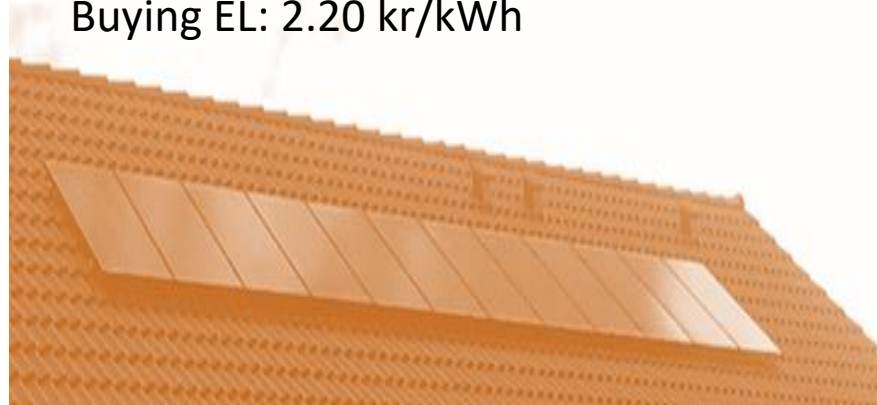


After years of researching microgrids... I decided to become a **prosumer**

PV 2.4 kW

Selling EL: 1.02 kr/kWh

Buying EL: 2.20 kr/kWh



EV
30 kWh
250 km



EV Charger
3.7 kW

Like a doctor taking your own pills...

Dr House?

(again) it's Lupus!



(again) it's a PI control!



If you really want to do something, you will find the way.
Otherwise, you will find the excuse...



We talk about AI – but do we know how our brain works?

Our three brains



MIND
Logic and
Intellect

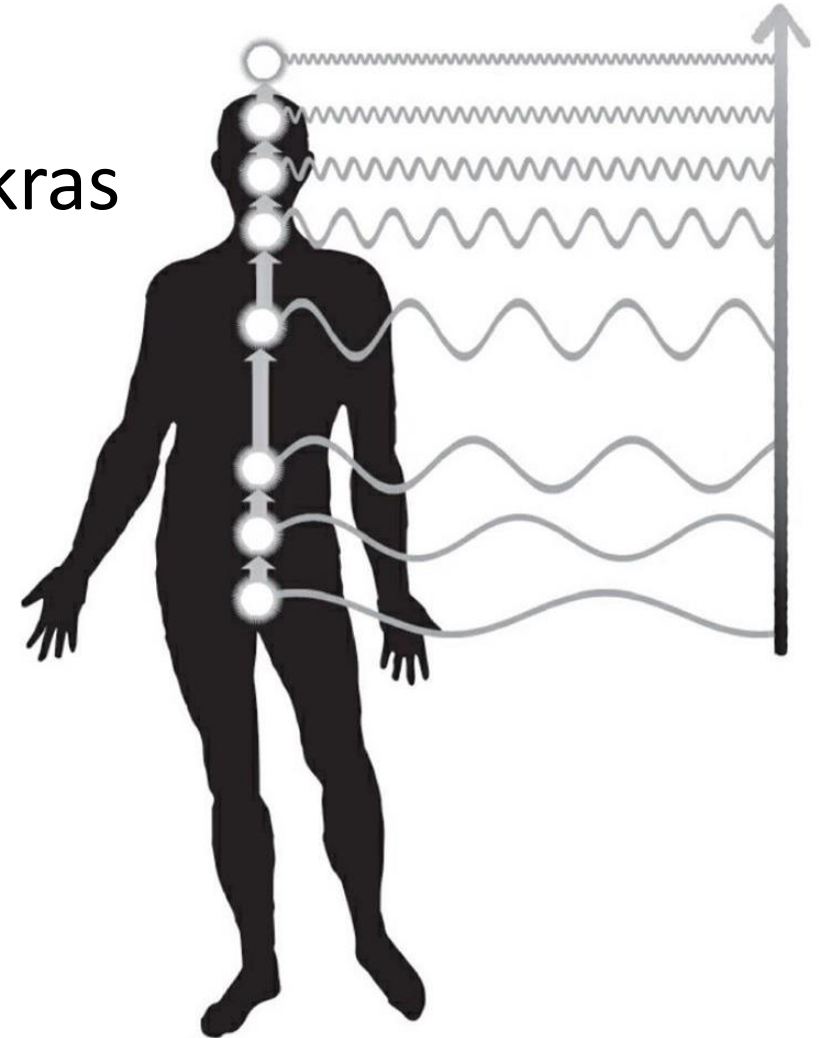


HEART
Intuition

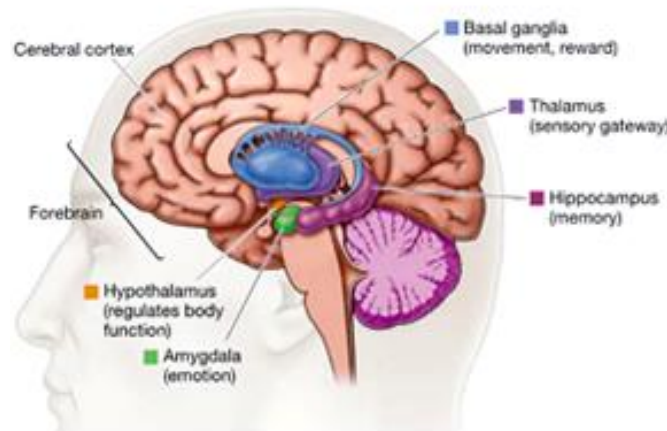


GUT
Gut
Feeling

Chakras



**Microgrids seriously
affect your brain**
www.aau.dk



EEG tests



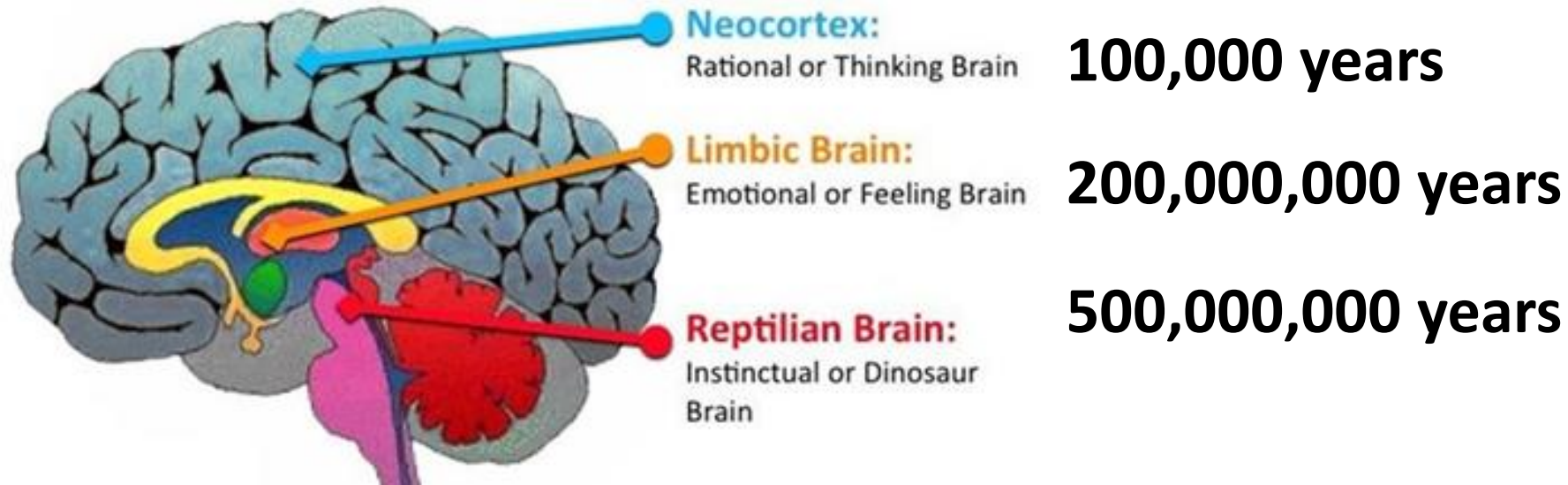
How much of our brain we use?



Use: 100% - Simultaneously: 2%
Due to glucose and O₂ limitation
Normally we use similar NN paths

Triune brain – MacLean model 1960

86,000 million neurons – interconnection (synapsis)

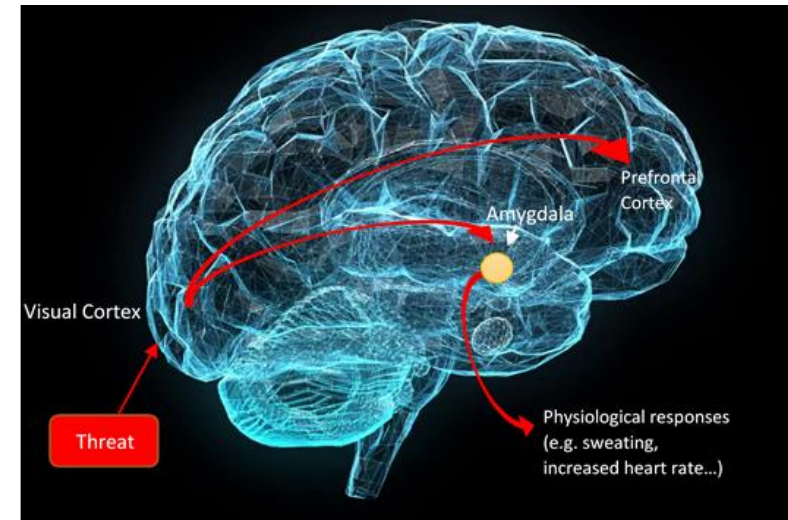
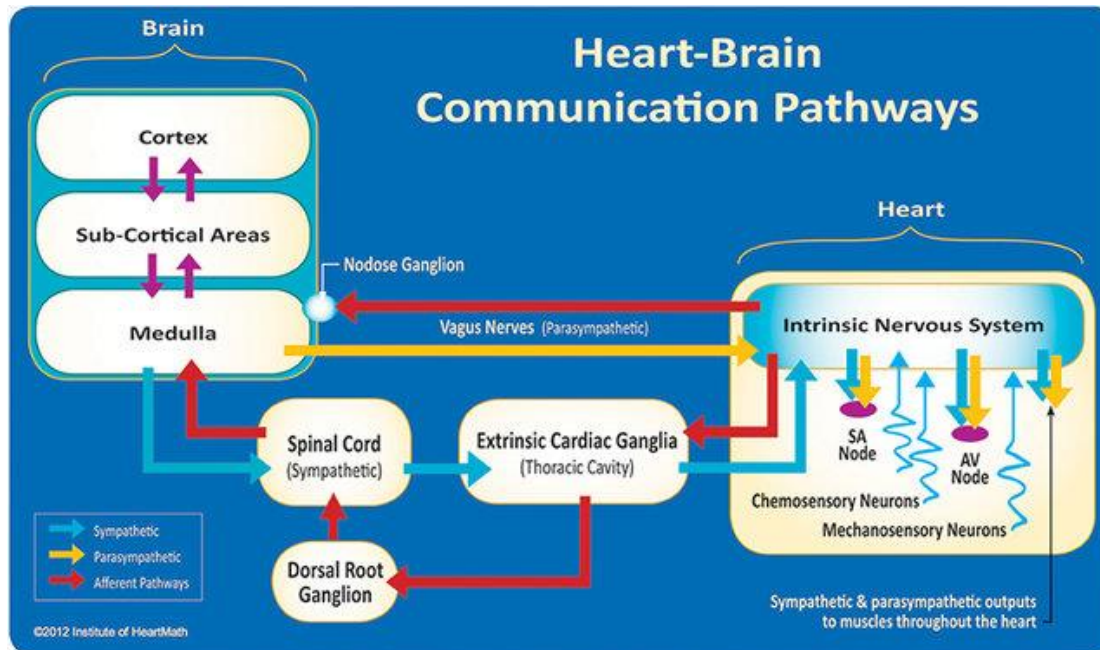


Emotions – Decision
Rational – Justification

Our heart

Generates hormones:

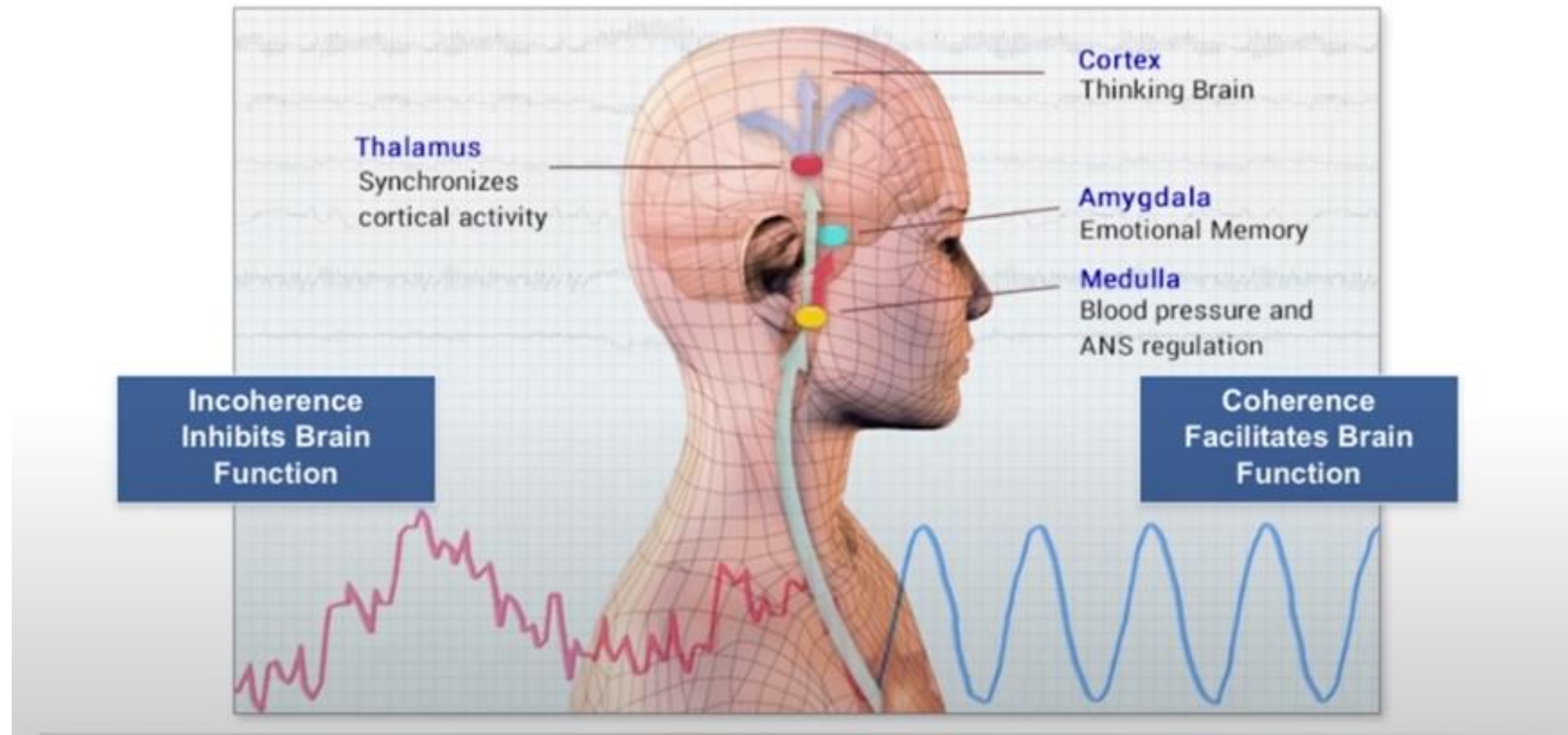
- 1 Amitriptyline: control stress neurons**
- 2. Oxytocin: love, trust, fidelity**



Shaffer, Fred, Rollin McCraty, and Christopher L. Zerr. "A healthy heart is not a metronome: an integrative review of the heart's anatomy and heart rate variability." *Frontiers in psychology* 5 (2014): 1040.

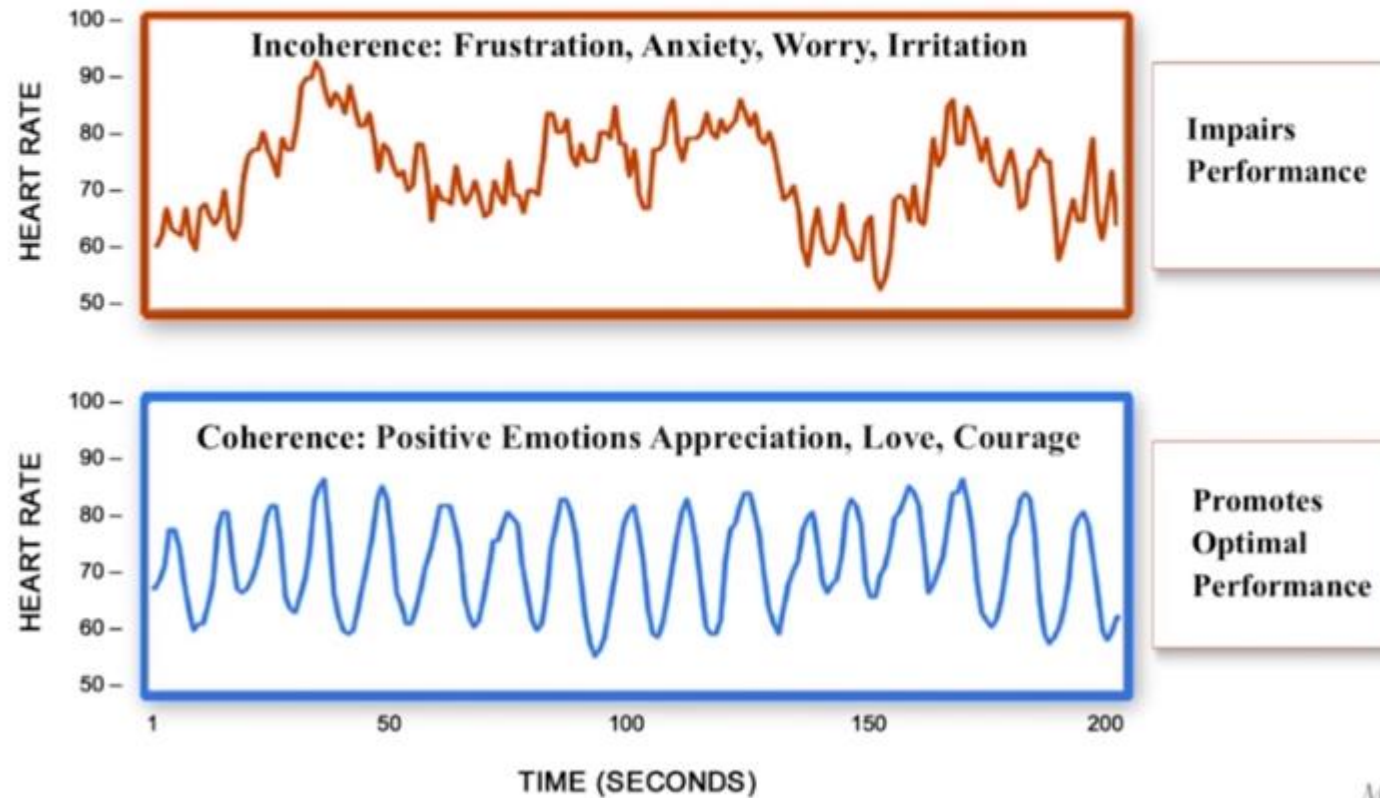
Heart Rhythms Directly Affect Physical and Mental Performance

Heart signals affect the brain centers involved in emotional perception, decision making, reaction times, social awareness and the ability to self-regulate.



Source: HeartMath Institute

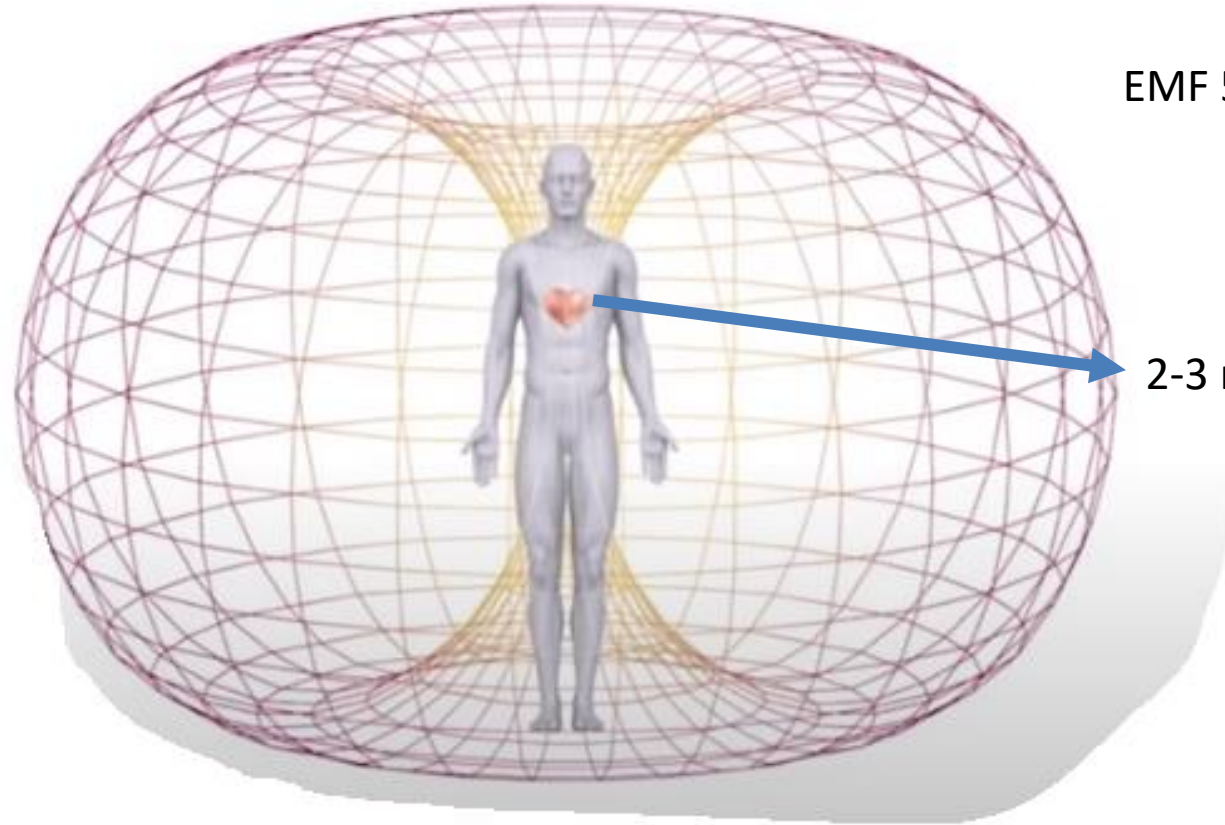
Heart Rhythm Patterns



McCraty, 1995

Source: HeartMath Institute

Electromagnetic field

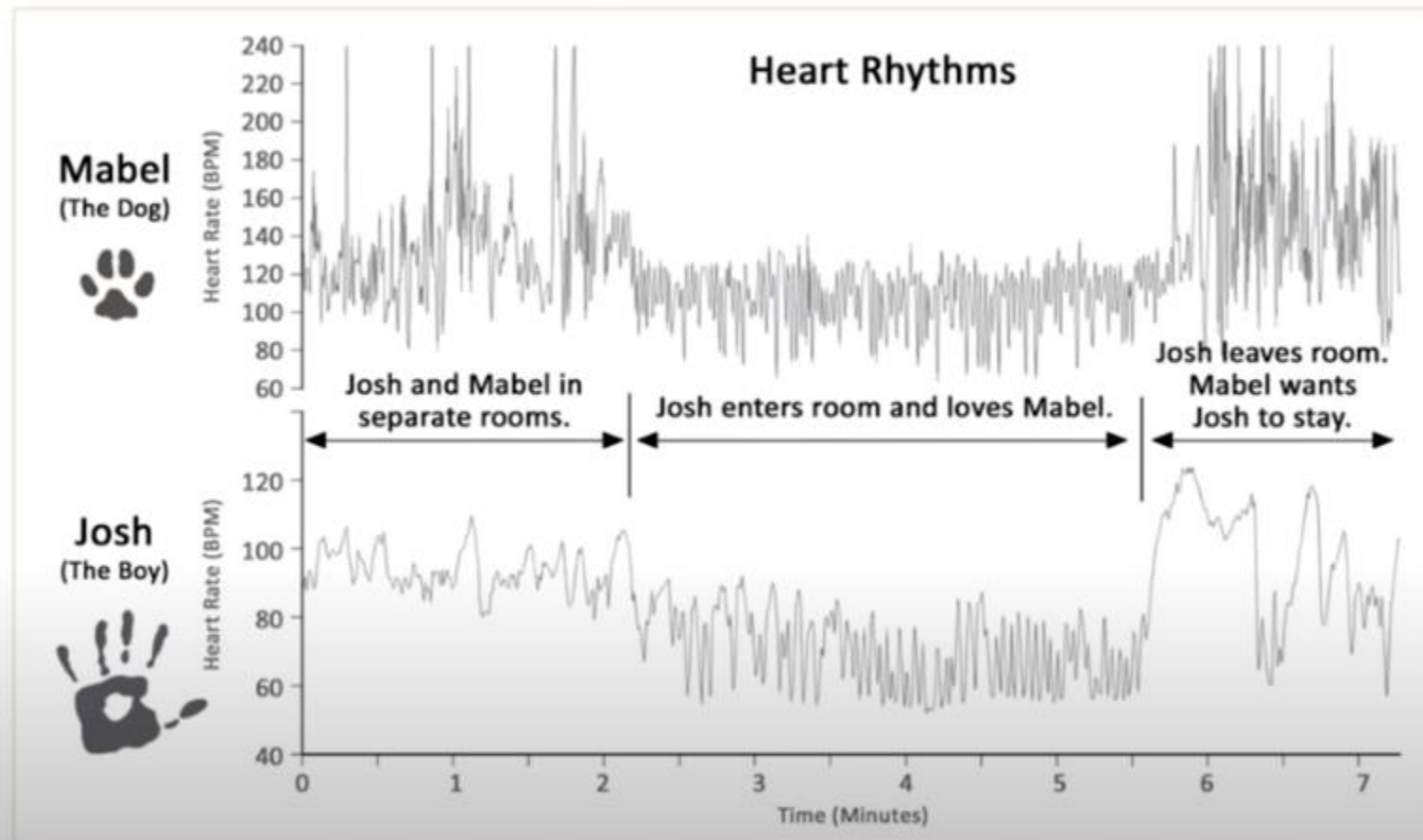


EMF 5,000 bigger than the brain

2-3 meters

Source: HeartMath Institute

A Boy and His Dog

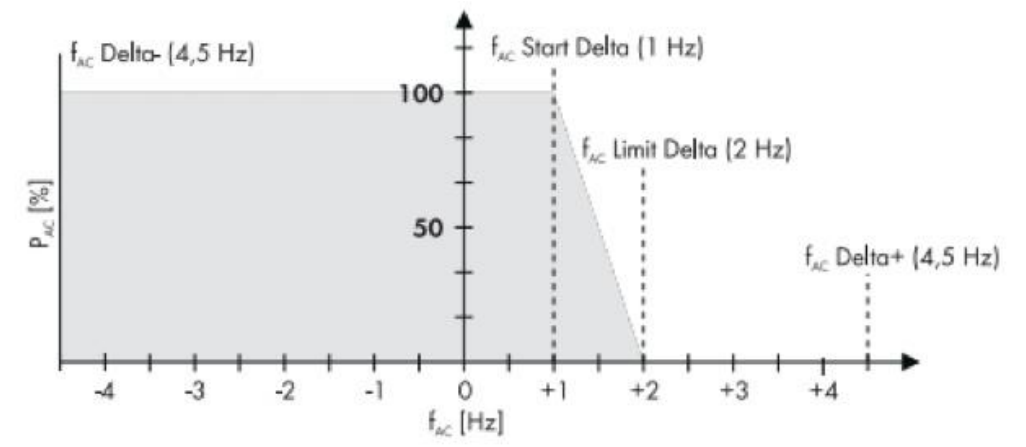
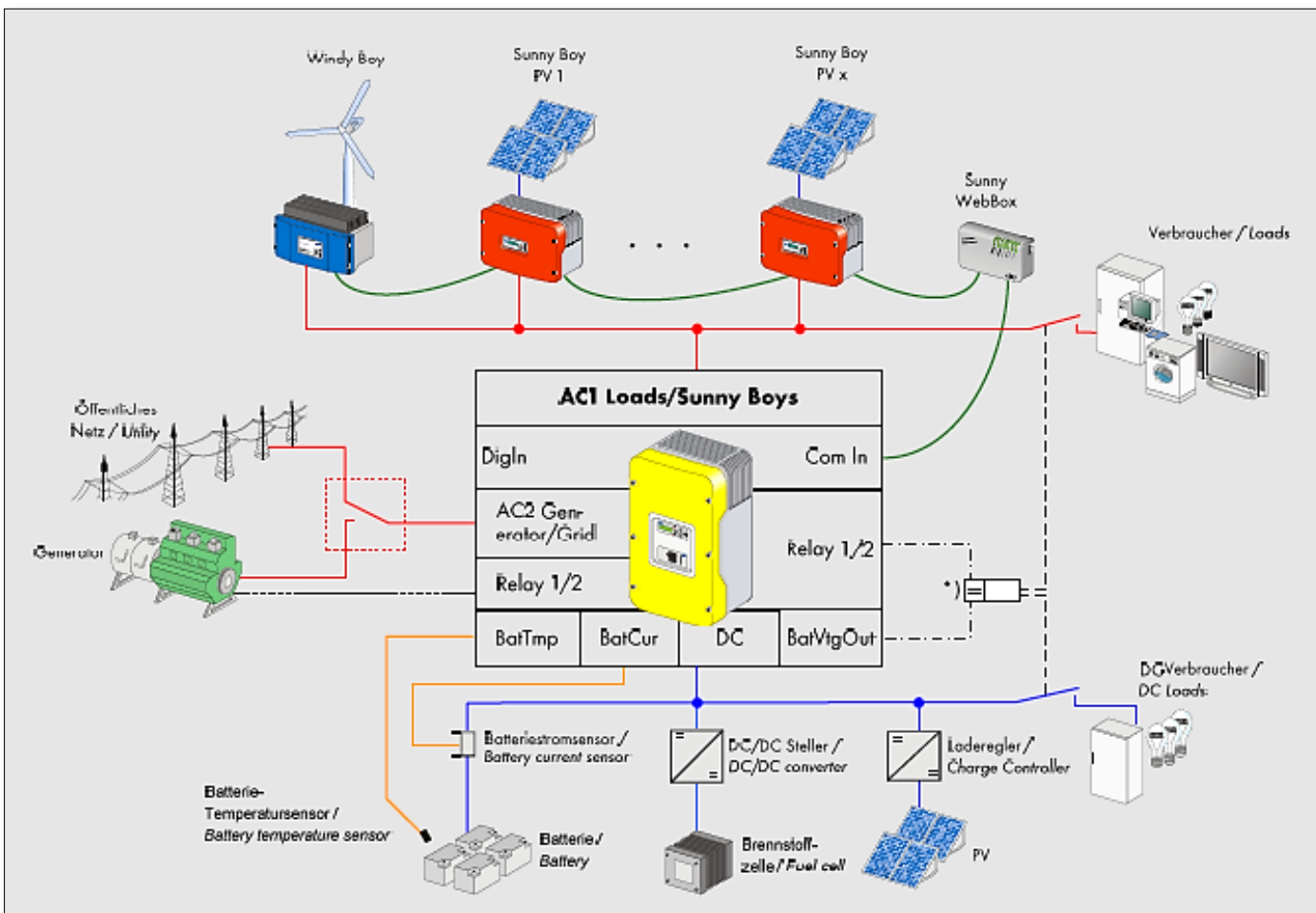


McCraty, 2015

Source: HeartMath Institute



Microgrid Configuration





Microgrid Configuration

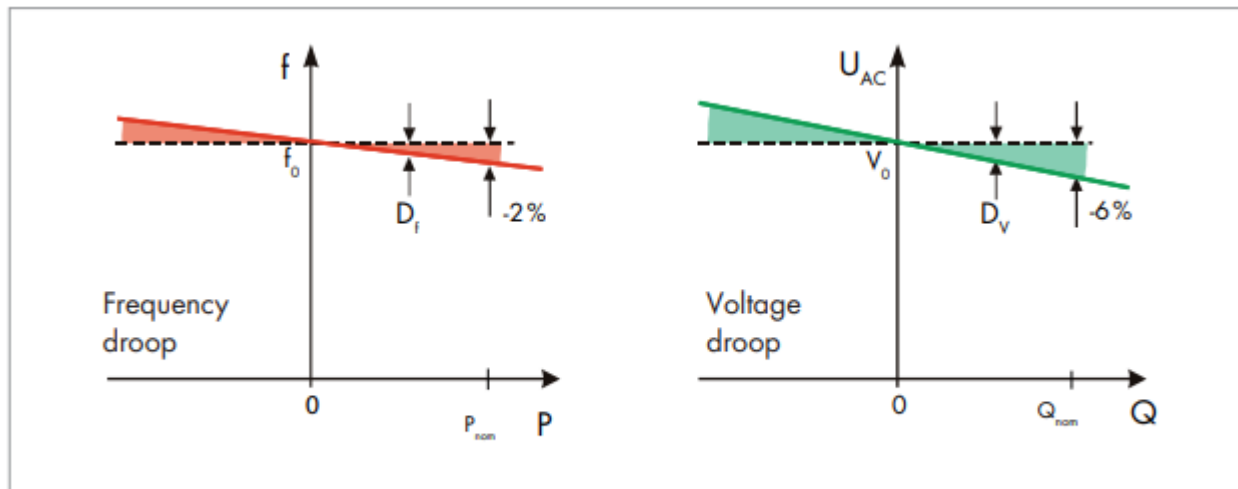
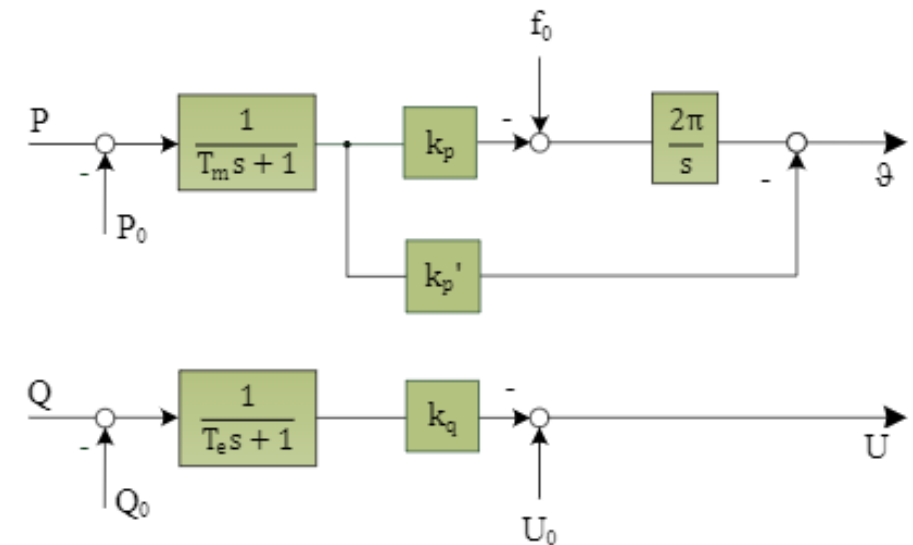


Fig. 2.1: Control algorithm in the SMA stand-alone power inverter (SelfSync®)

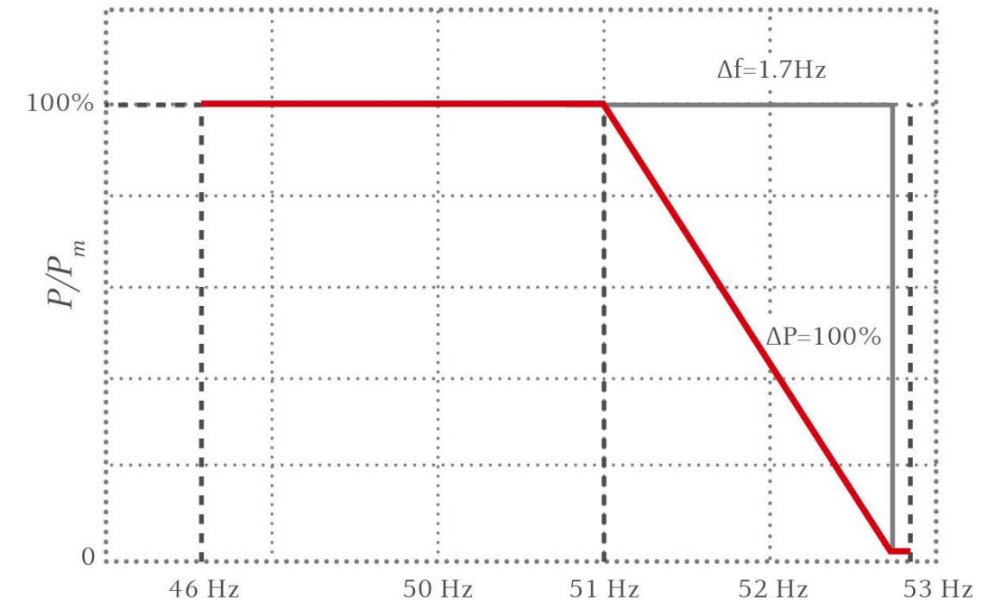
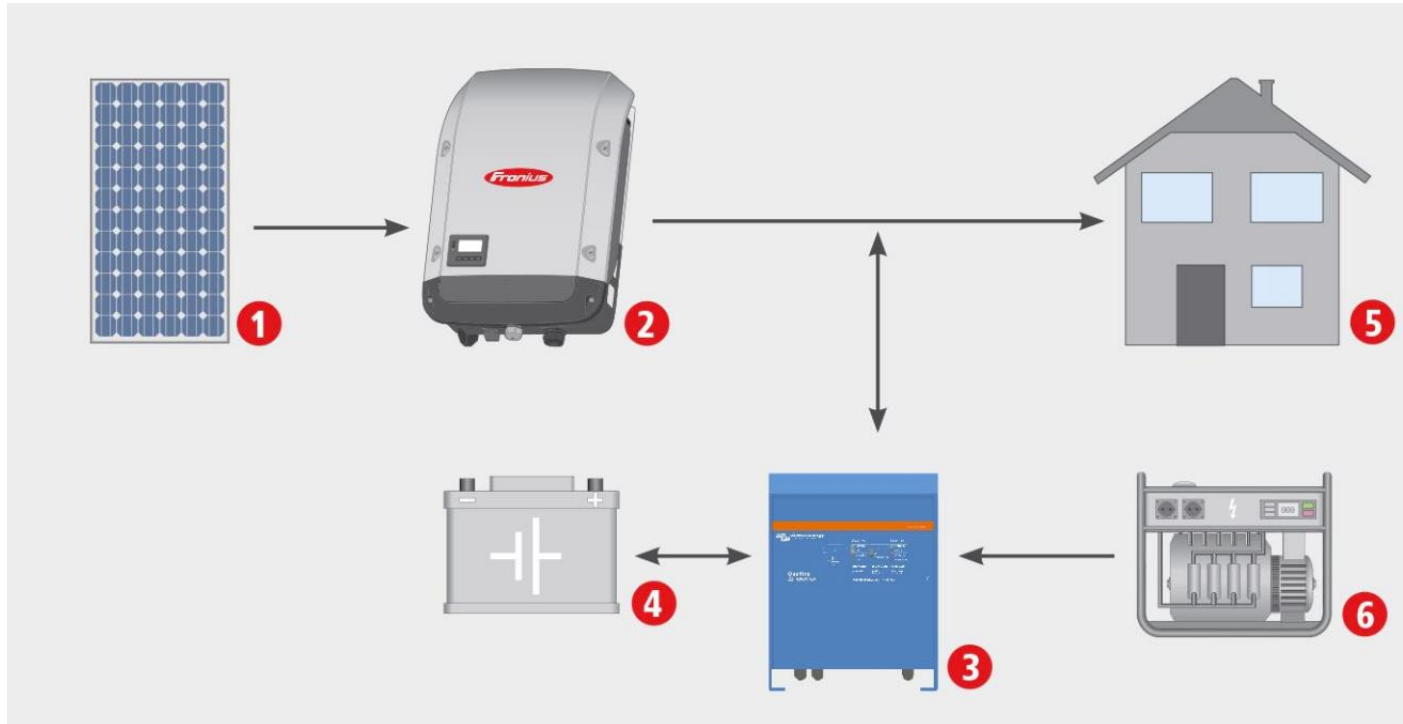
SelfSync(C)



Source: SMA

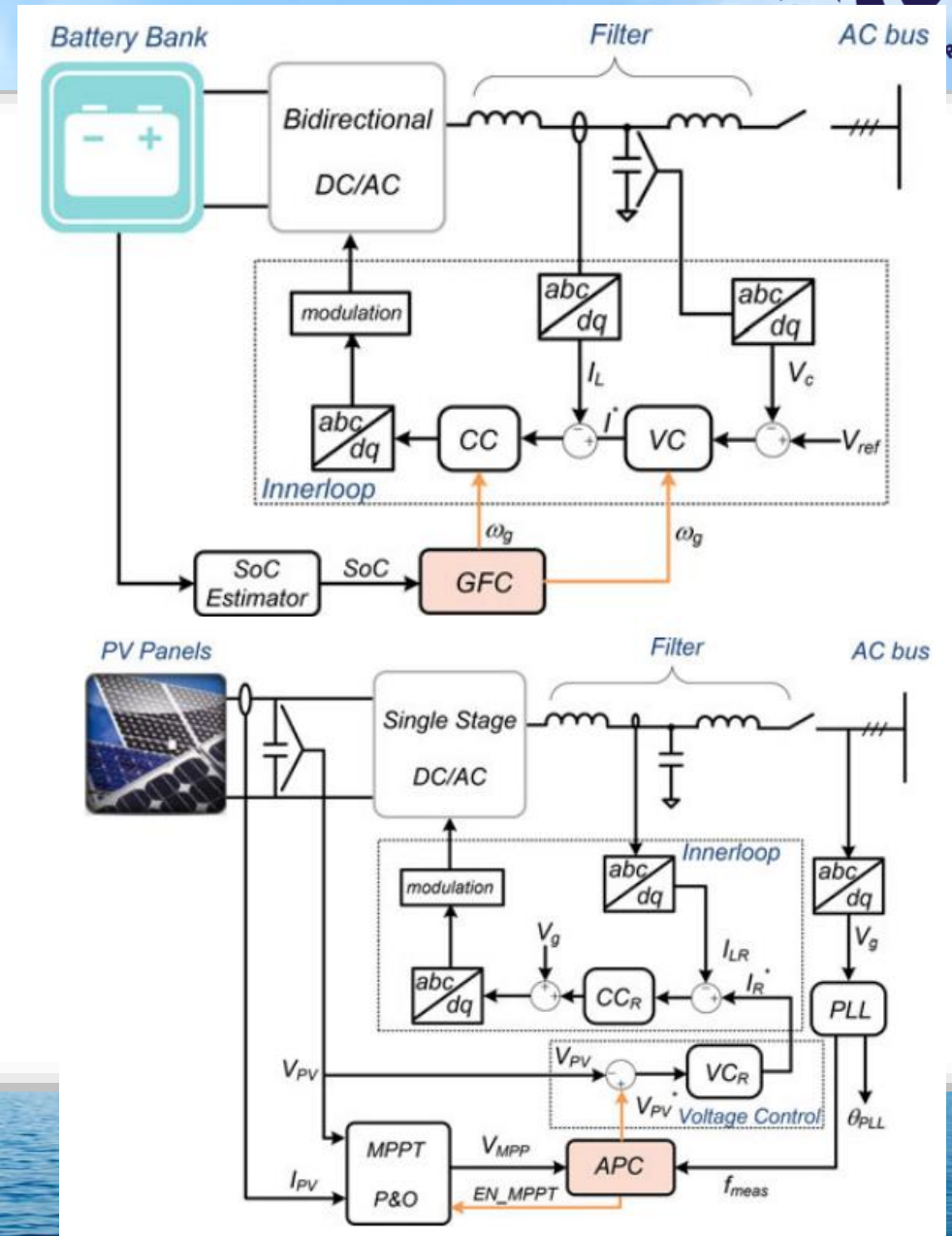
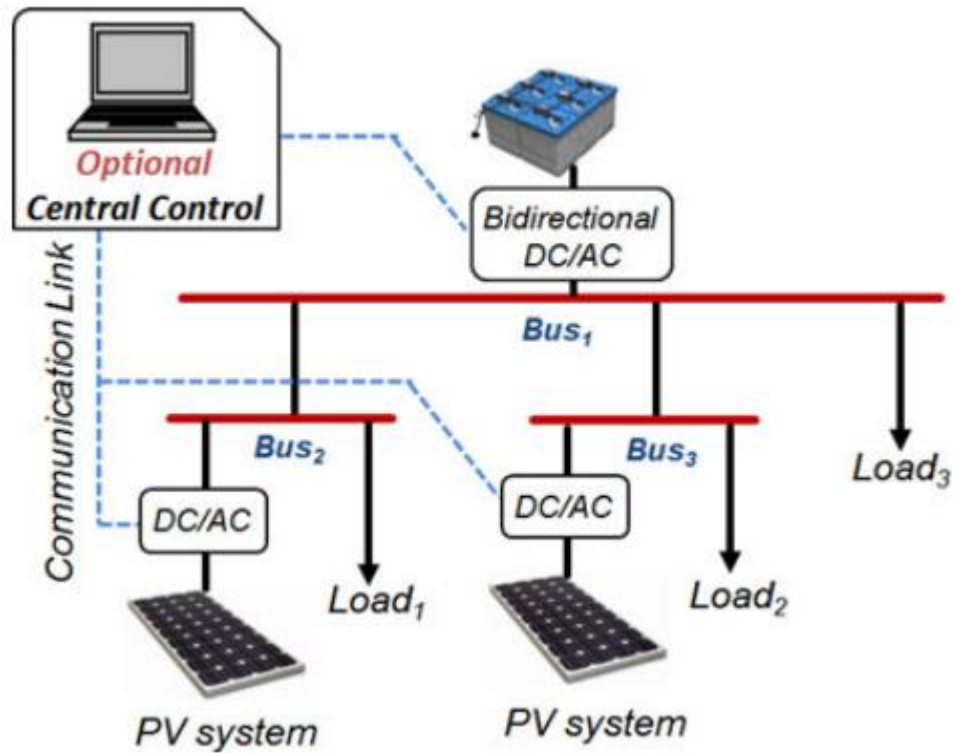


Microgrid Configuration



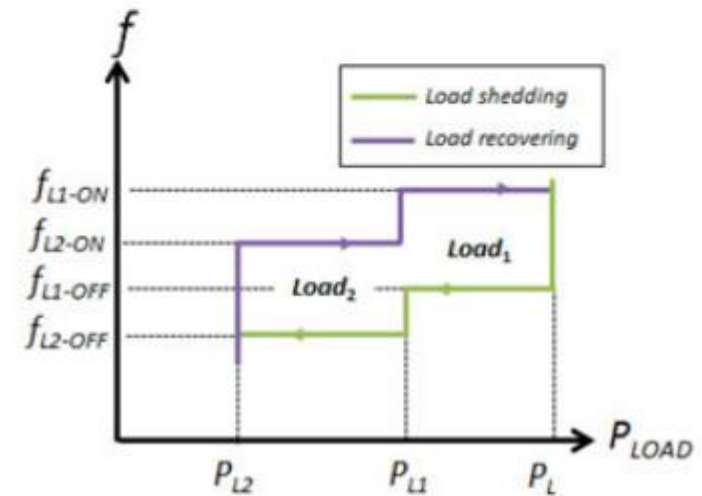
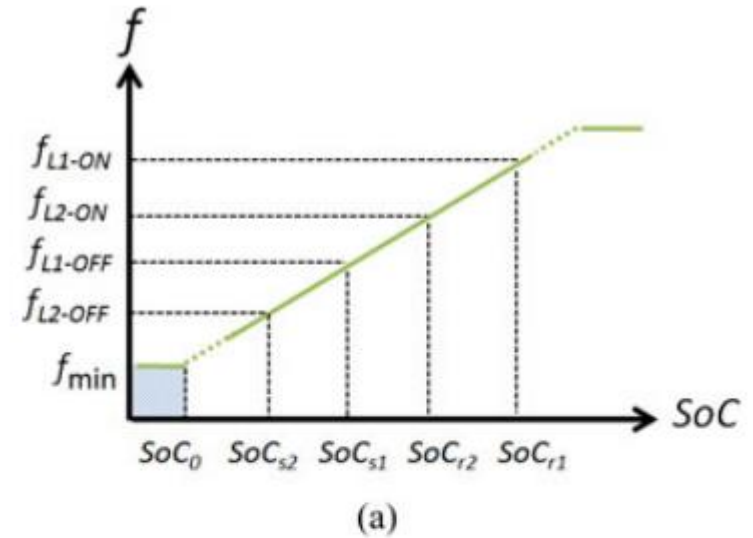
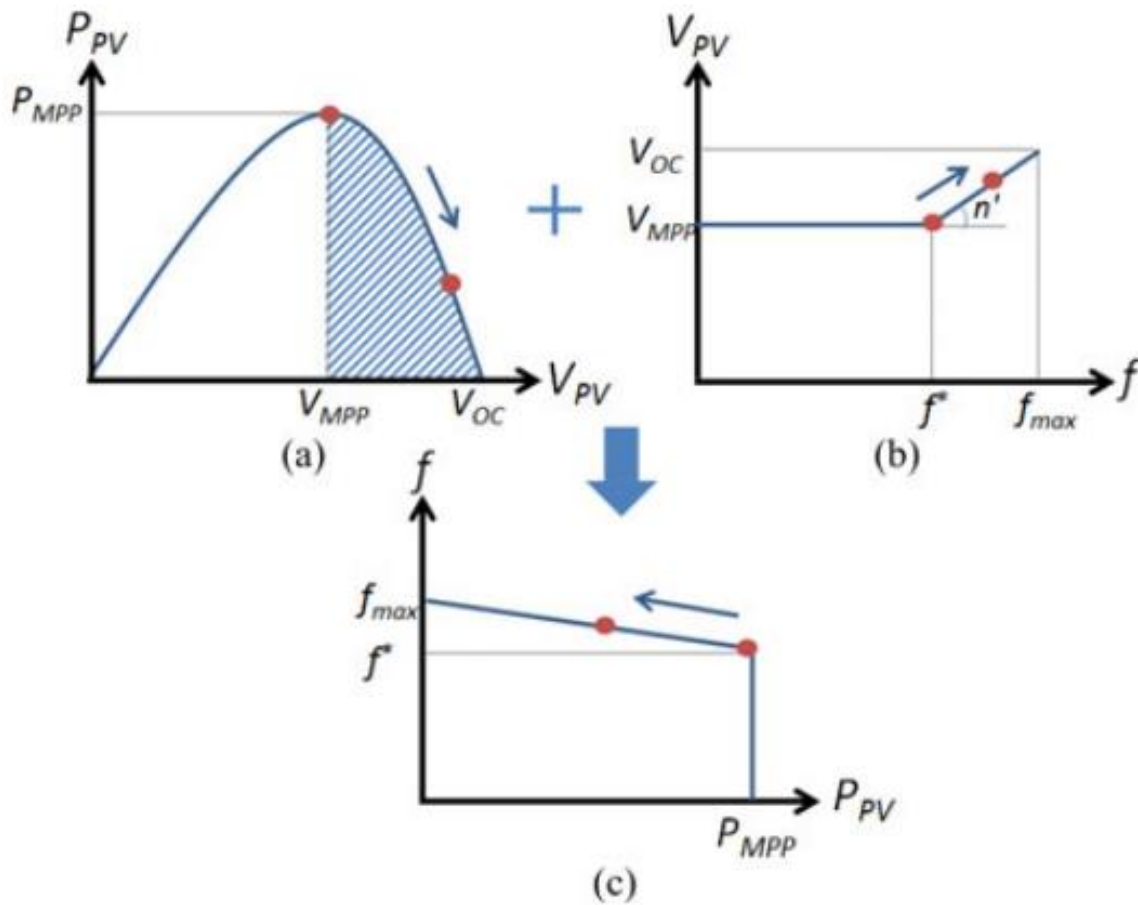
Source: Fronius

Microgrid Configuration





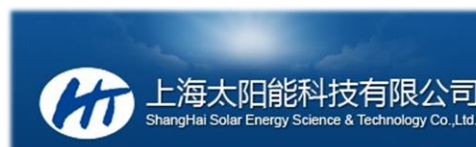
Microgrid Configuration



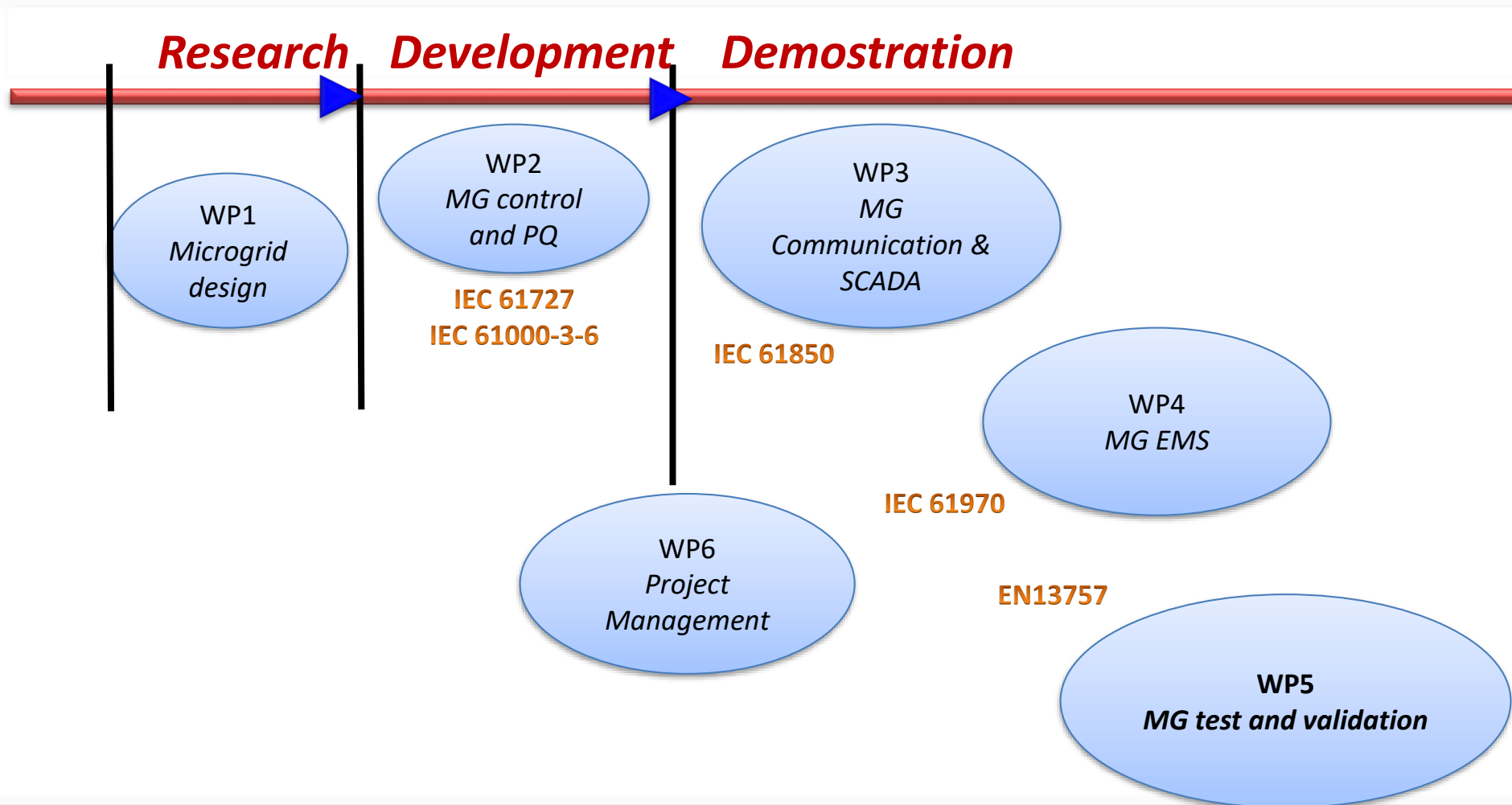


EUDP Chinese-Danish Cooperation Project

Microgrid Technology Research and Demonstration 2014 - 2017

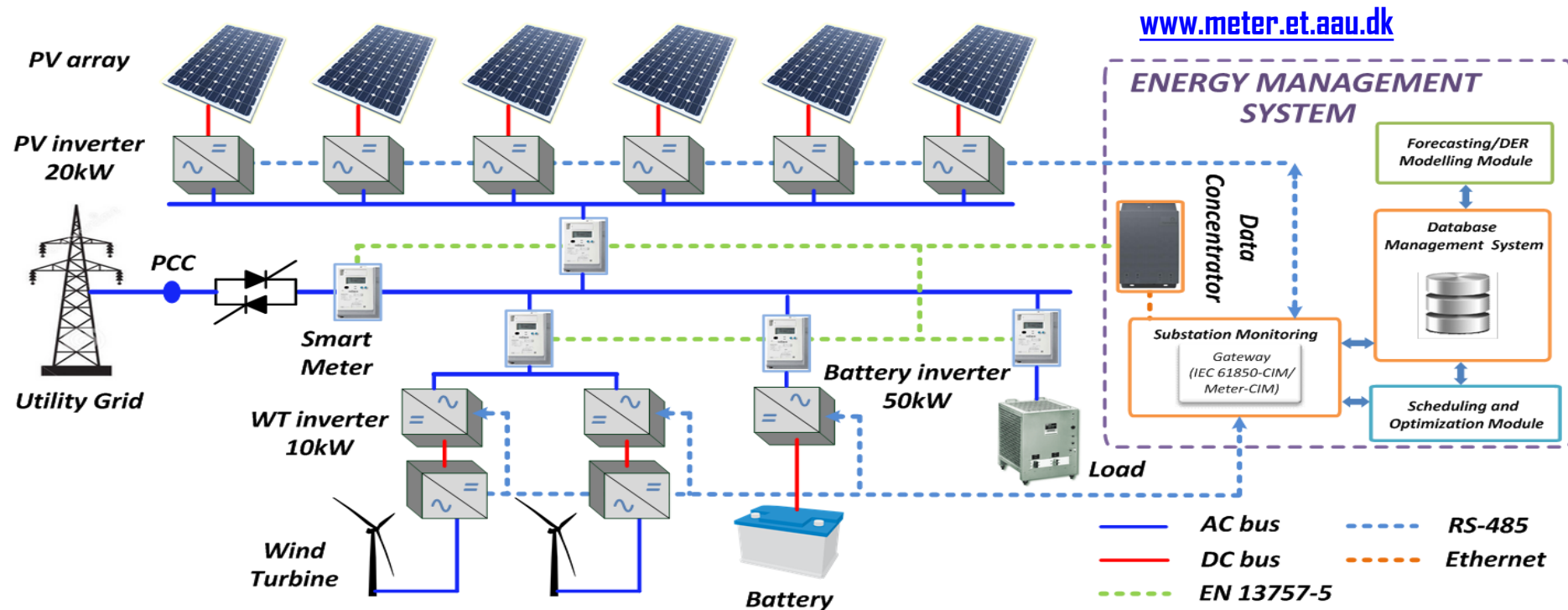


Microgrid Technology Research and Demonstration



Microgrid technology research based on wind/PV/storage hybrid system – HyMG

A 200 kW hybrid PV-wind-battery microgrid site built and tested in **Shanghai**.



A. Luna, et al, "Optimal Power Scheduling for a Grid-Connected Hybrid PV-Wind-Battery Microgrid System", APEC 2016

Microgrid technology research based on wind/PV/storage hybrid system – HyMG



PV power generation subsystem

PV array installed on the roof of **Shanghai ShenZhou** New Energy B plant, installed capacity of **130 kVA**, east-west array configuration, adopt the fixed angle best installation.



Microgrid technology research based on wind/PV/storage hybrid system – HyMG



Wind power generation subsystem

Total wind power installed capacity: 20kVA. (2 x 10 kW Wind Turbines)

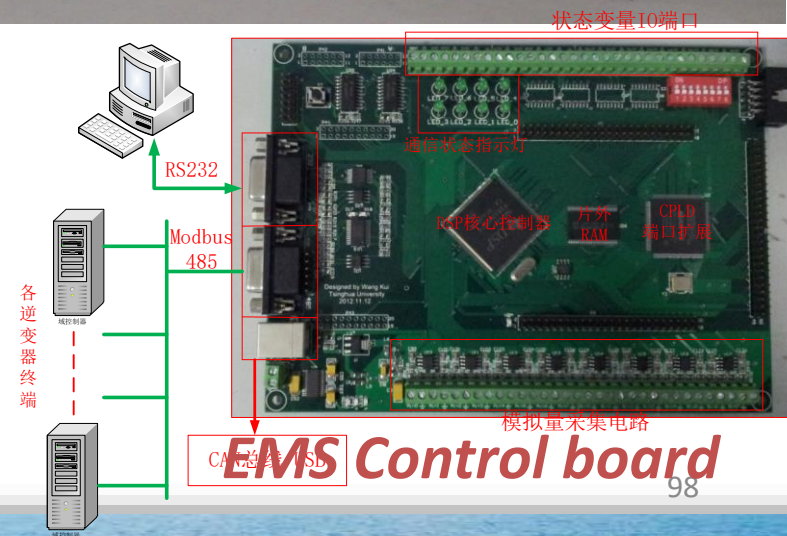
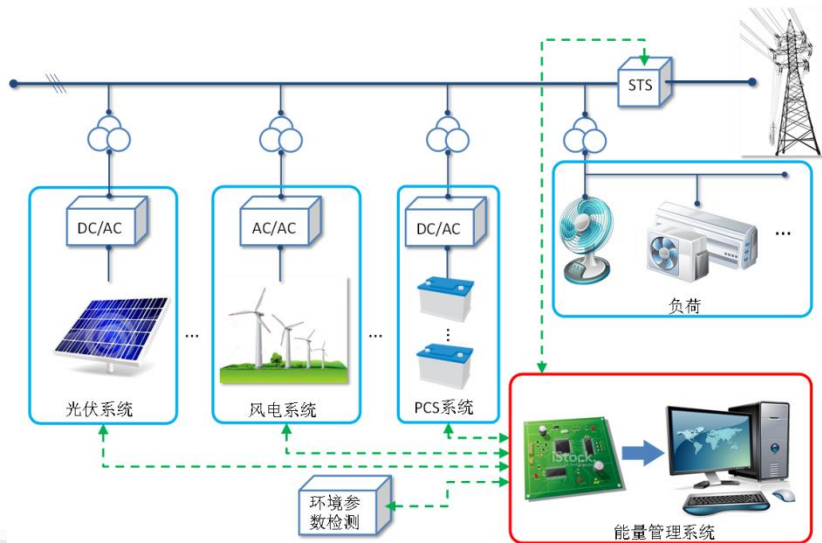
Microgrid technology research based on wind/PV/storage hybrid system – HyMG

Energy Storage System

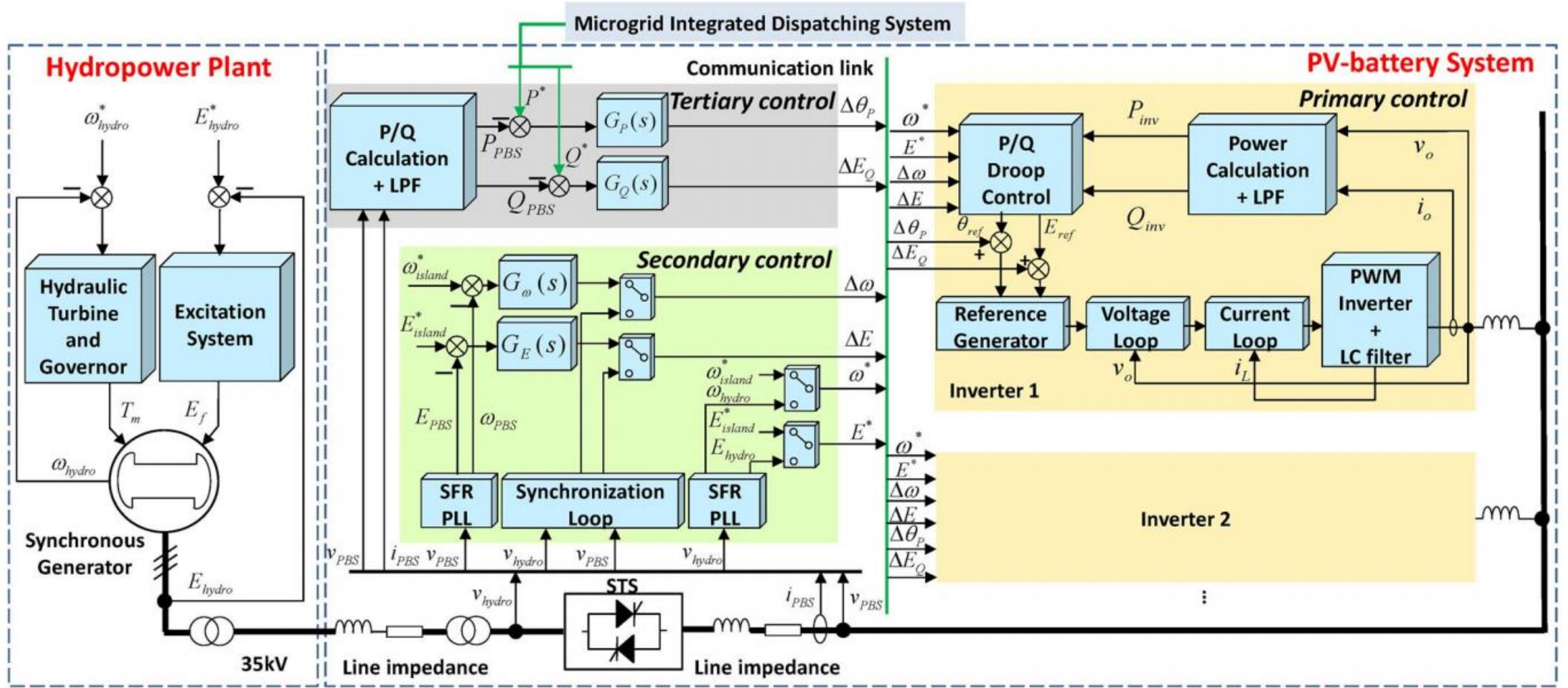
**50kVA Bi-Directional
Converter +
Lead-Acid battery**



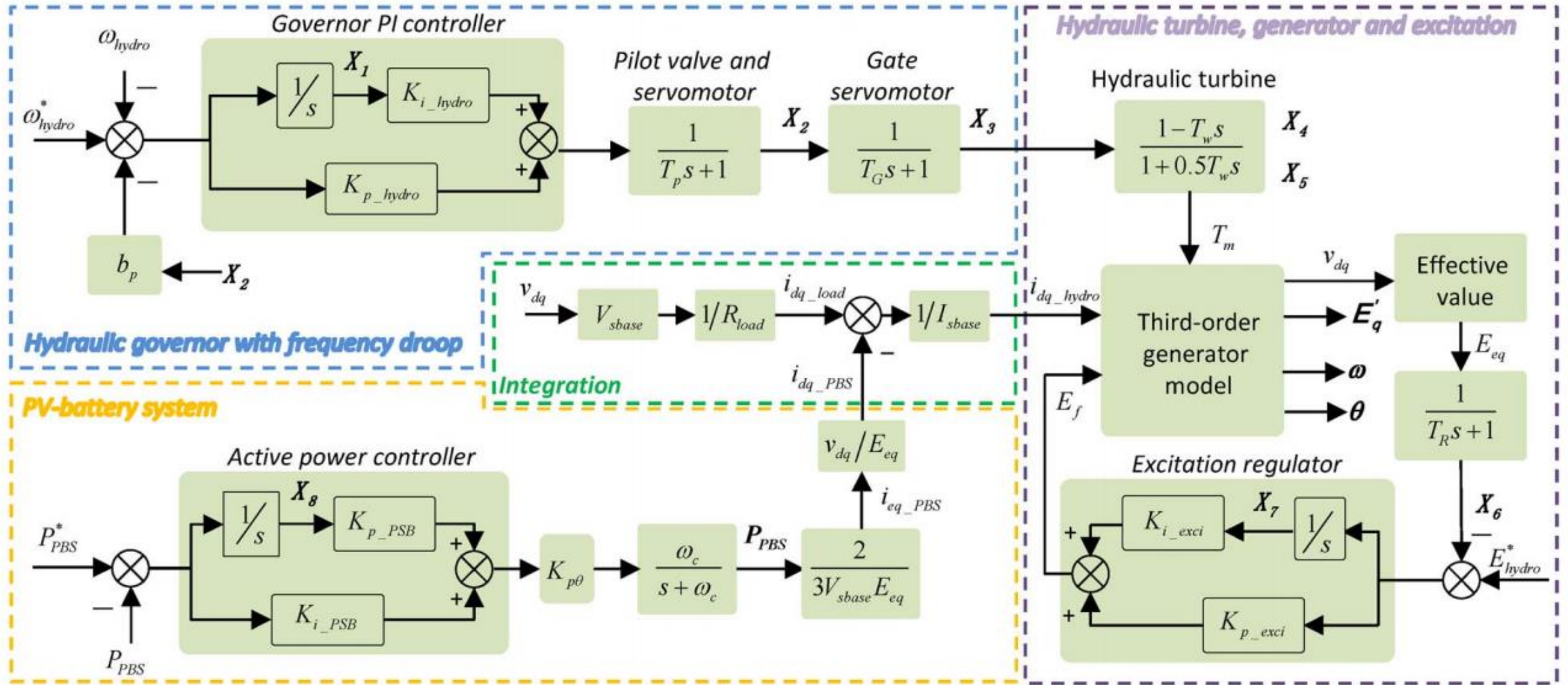
Energy Management System



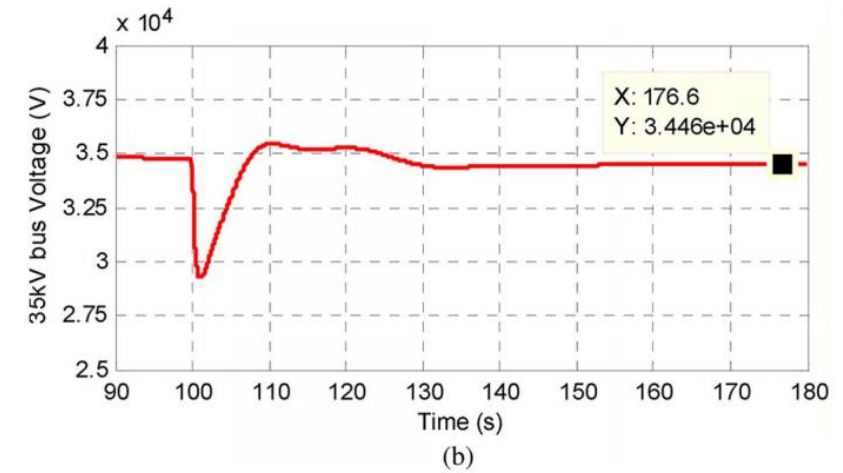
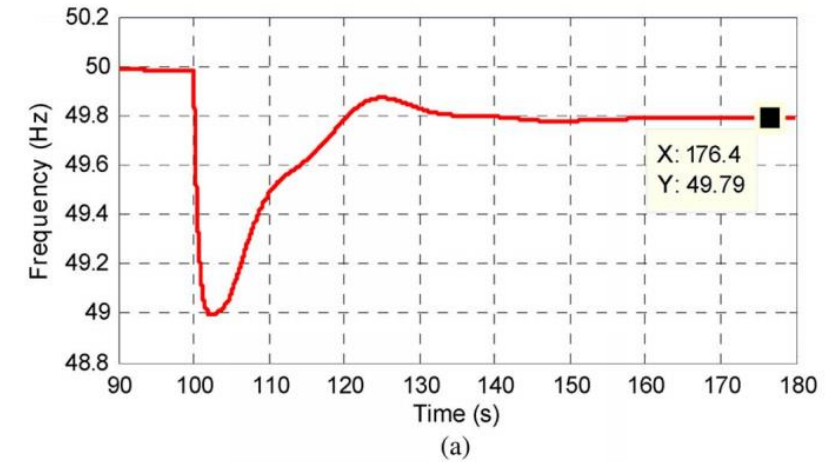
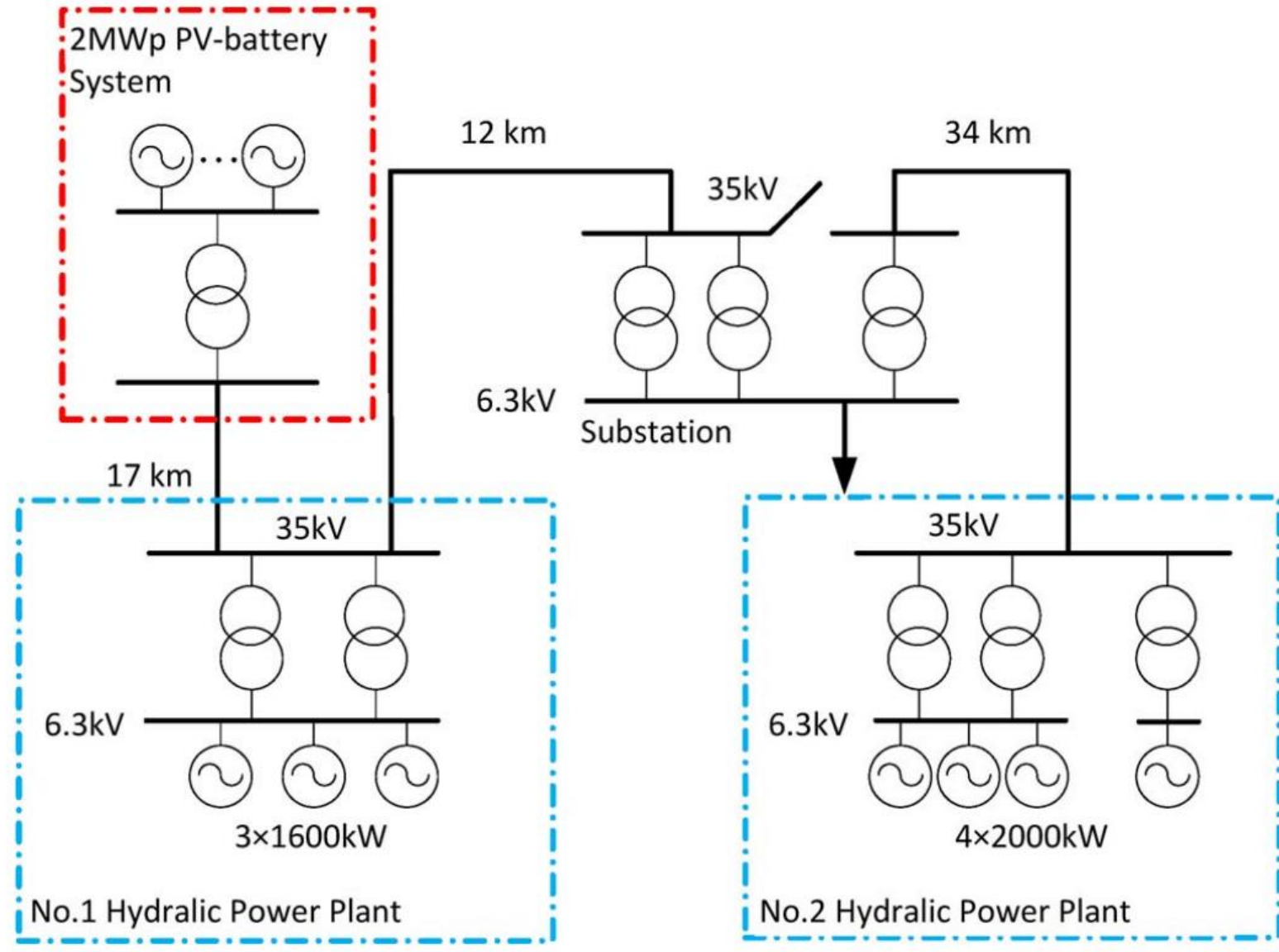
Hydropower and Microgrids



Hydropower and microgrids

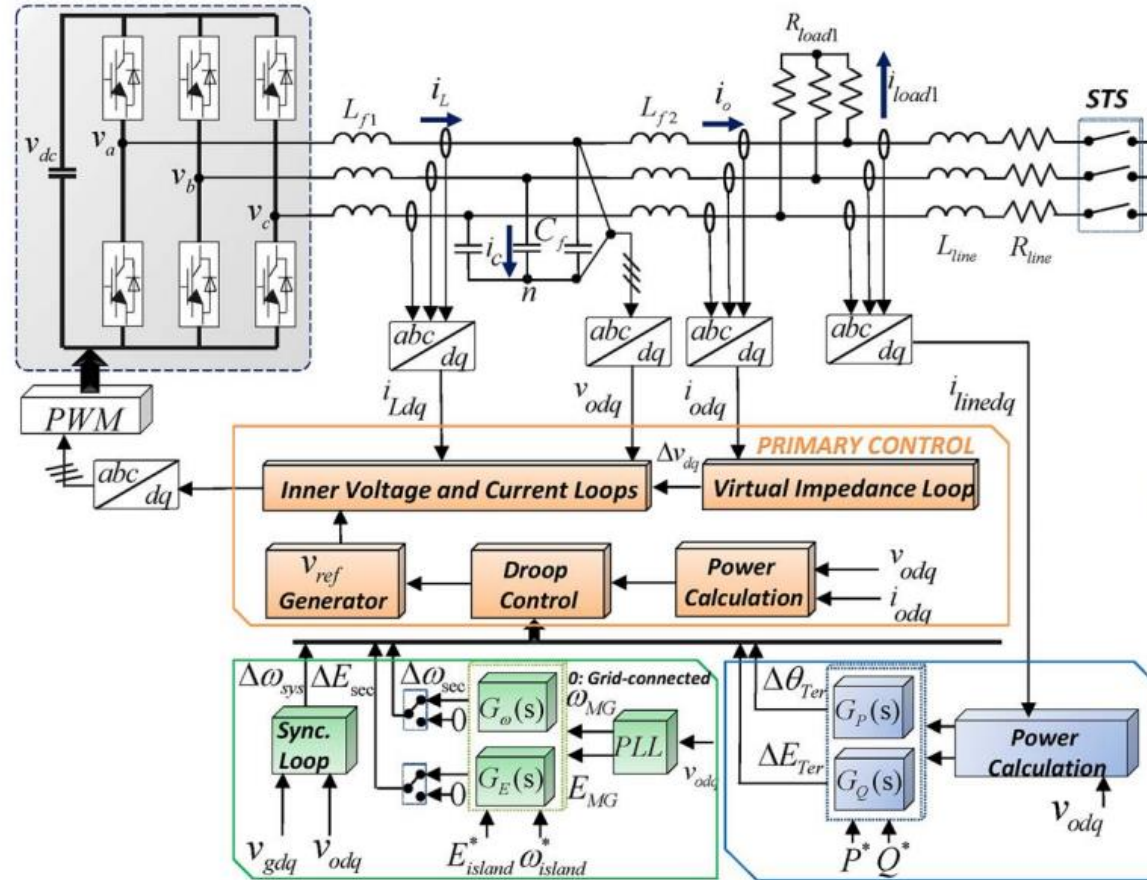


Hydropower and microgrids

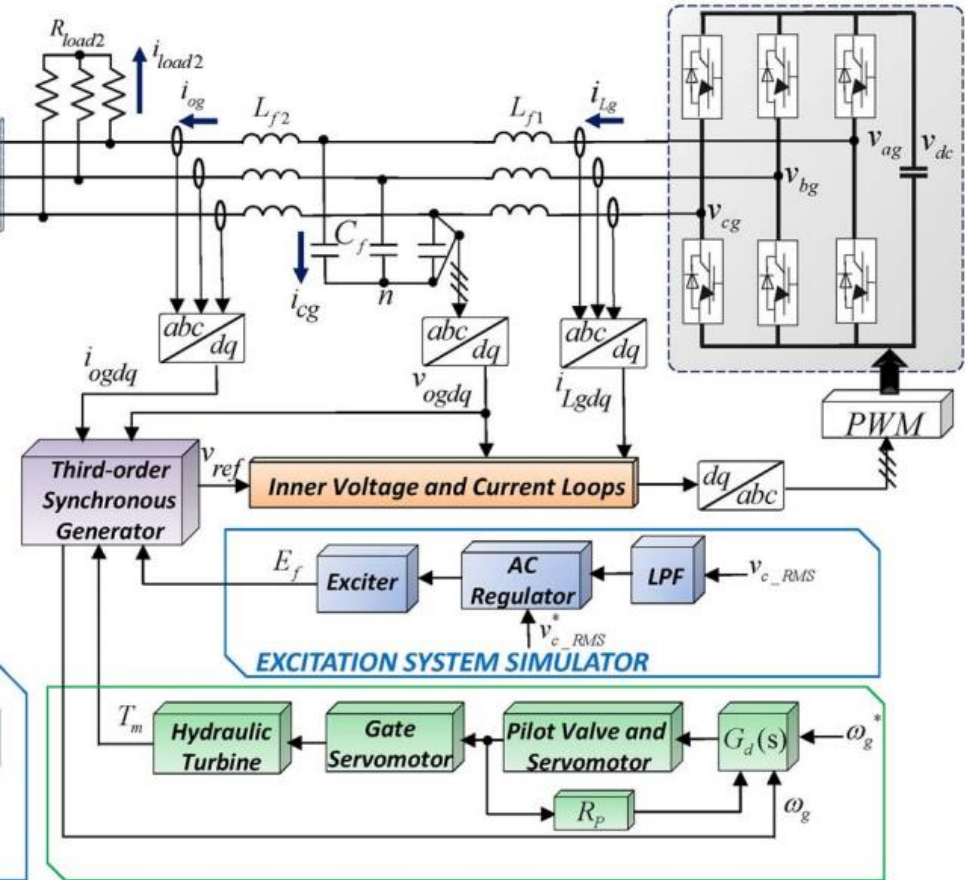


Hydropower and microgrids

INVERTER 2 (PV-battery system)

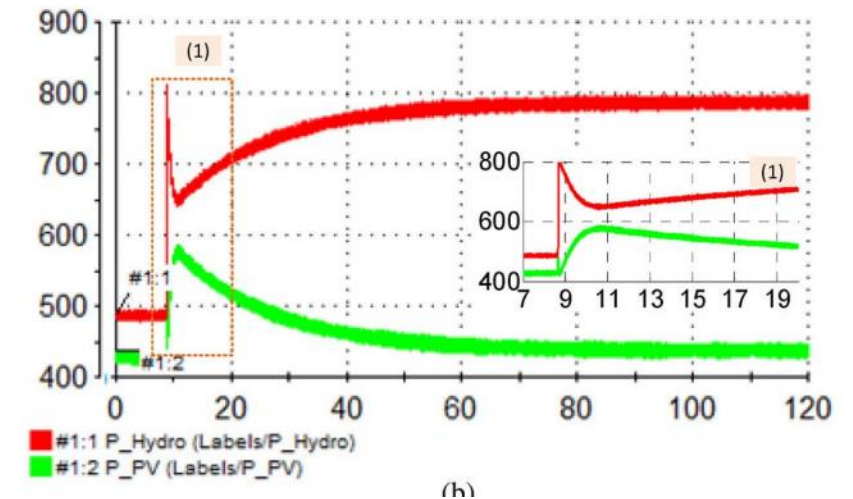
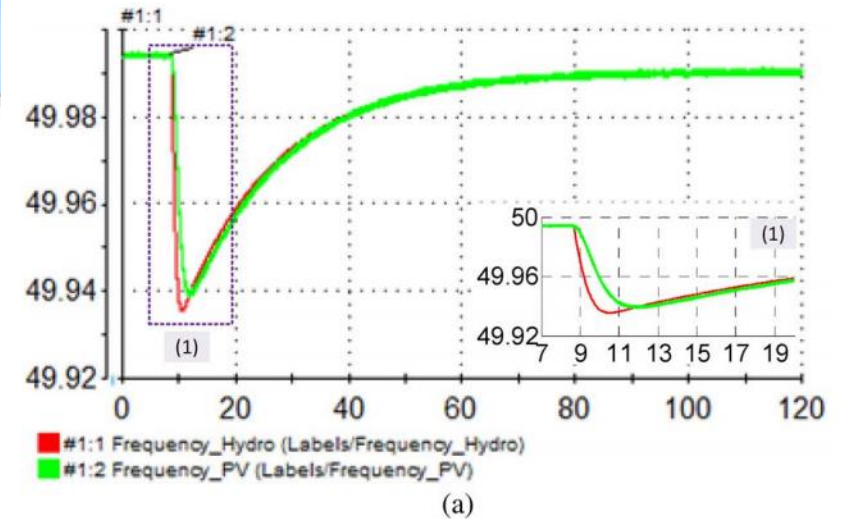
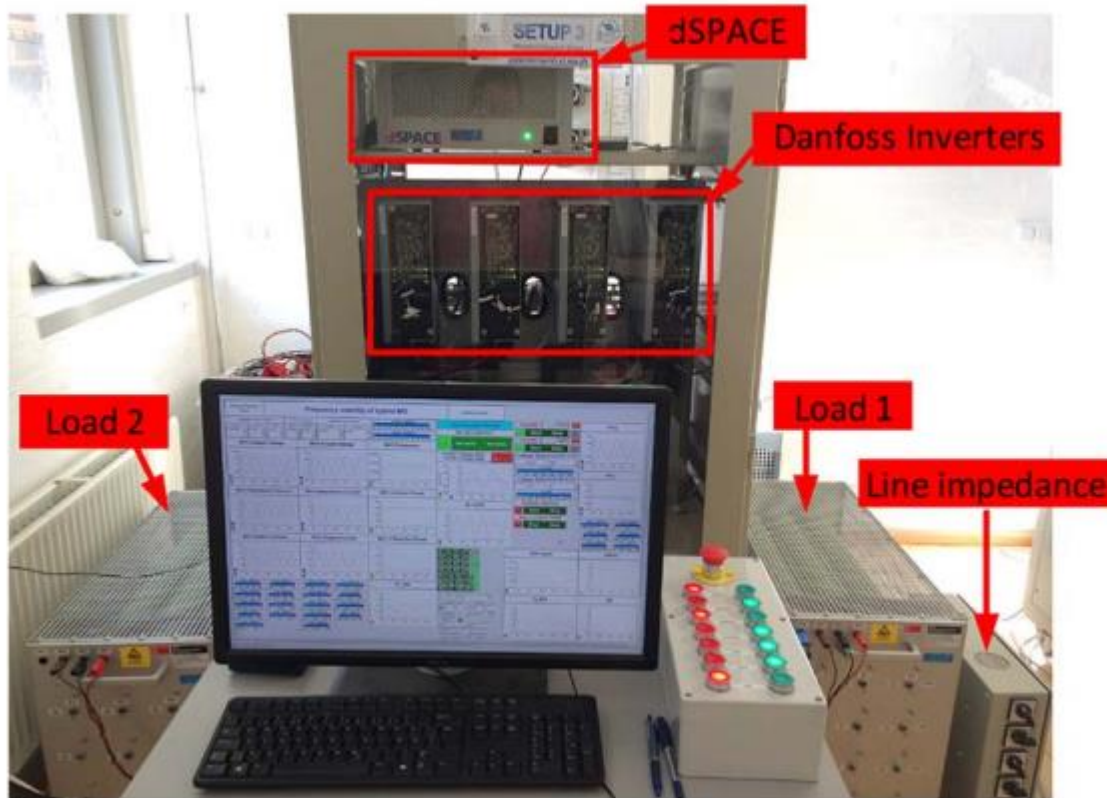


INVERTER 1 (Hydropower station)





Hydropower and microgrids

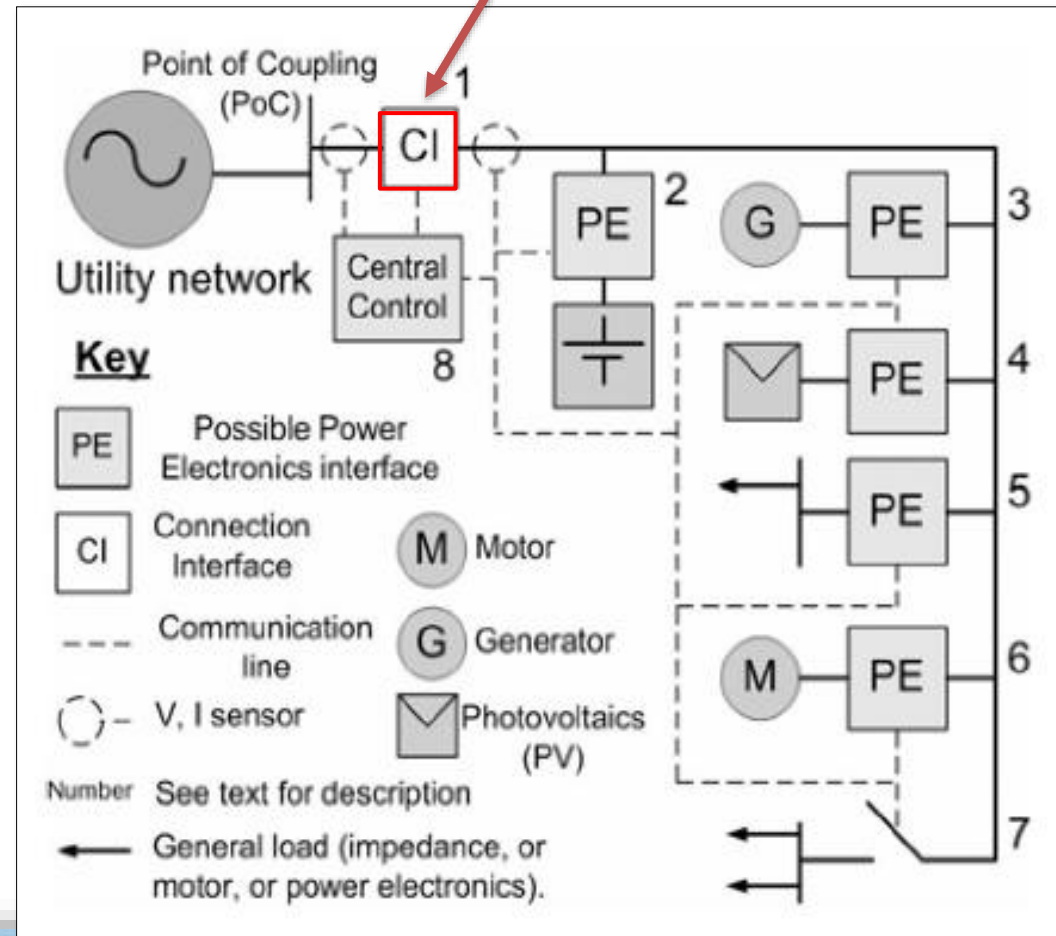


Y. Guan, J. C. Vasquez, J. M. Guerrero, Y. Wang and W. Feng, "Frequency Stability of Hierarchically Controlled Hybrid Photovoltaic-Battery-Hydropower Microgrids," in *IEEE Transactions on Industry Applications*, vol. 51, no. 6, pp. 4729-4742, Nov.-Dec. 2015.



Microgrid Configuration

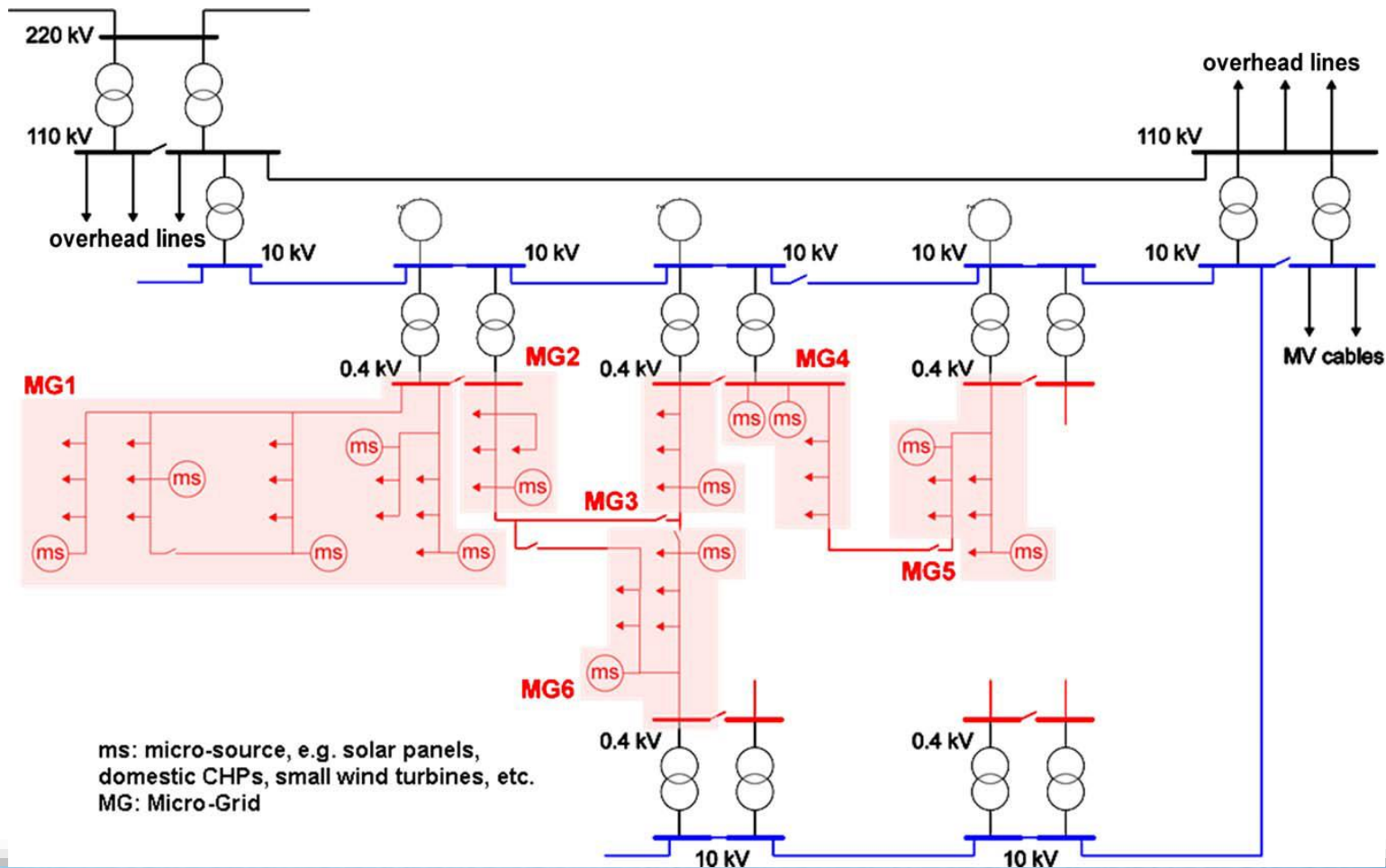
Connection interface (CI)





Microgrid Configuration

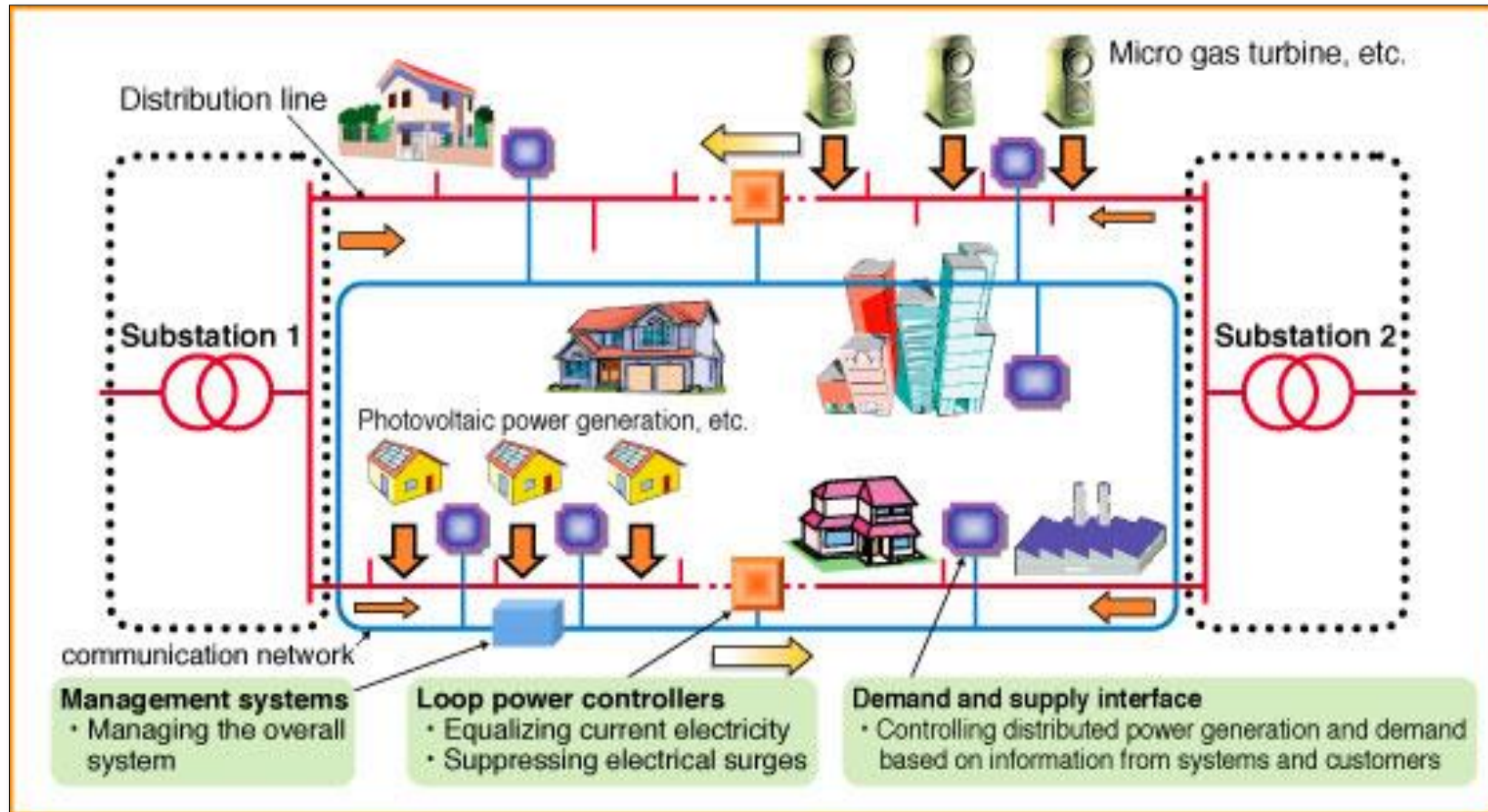
Distribution network with multiple microgrids





Microgrid Configuration

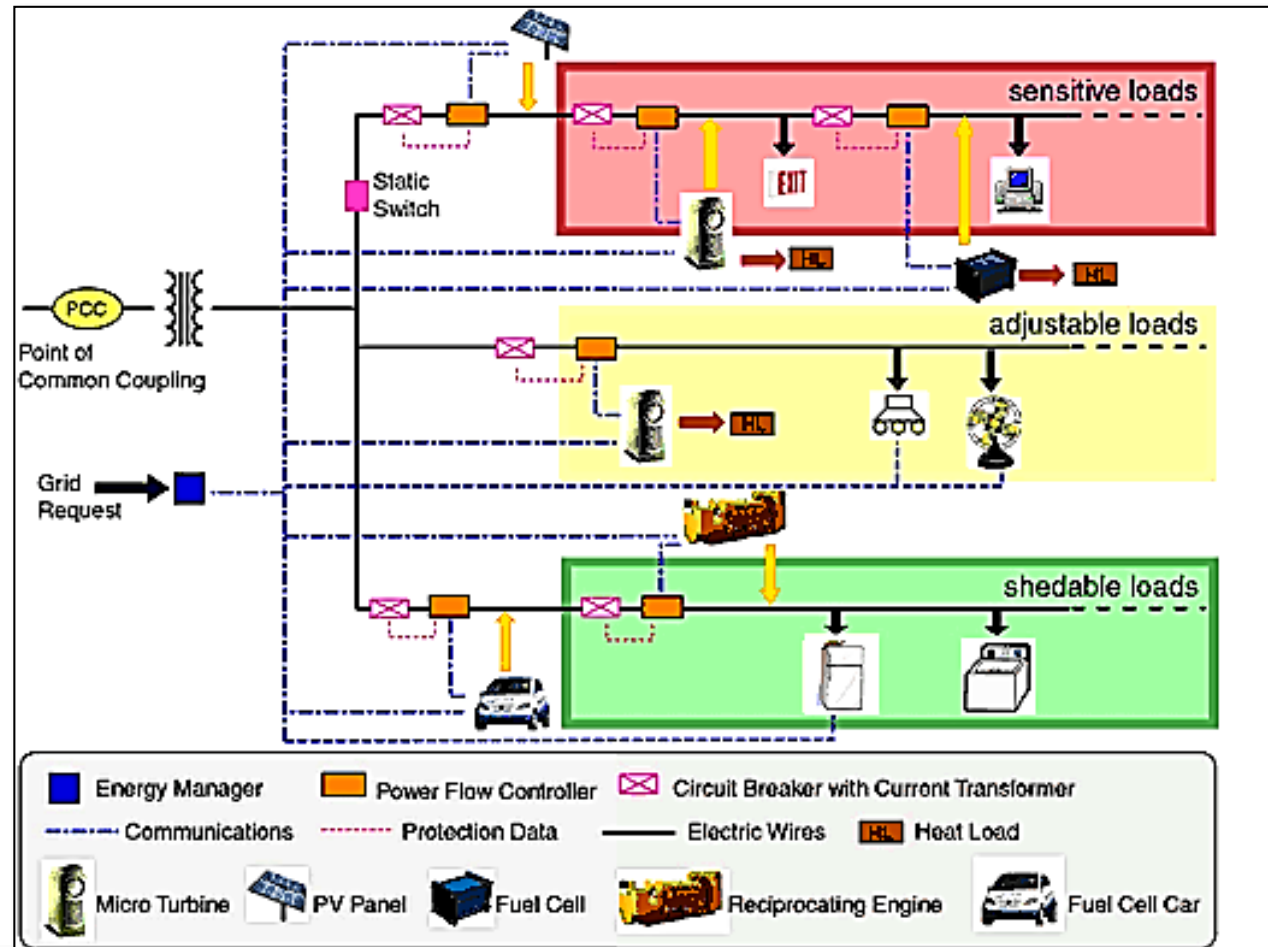
Distribution network with multiple microgrids





Microgrid Configuration

Microgrids with load management





Microgrid Configuration

Example: Jeju Island (S. Korea)

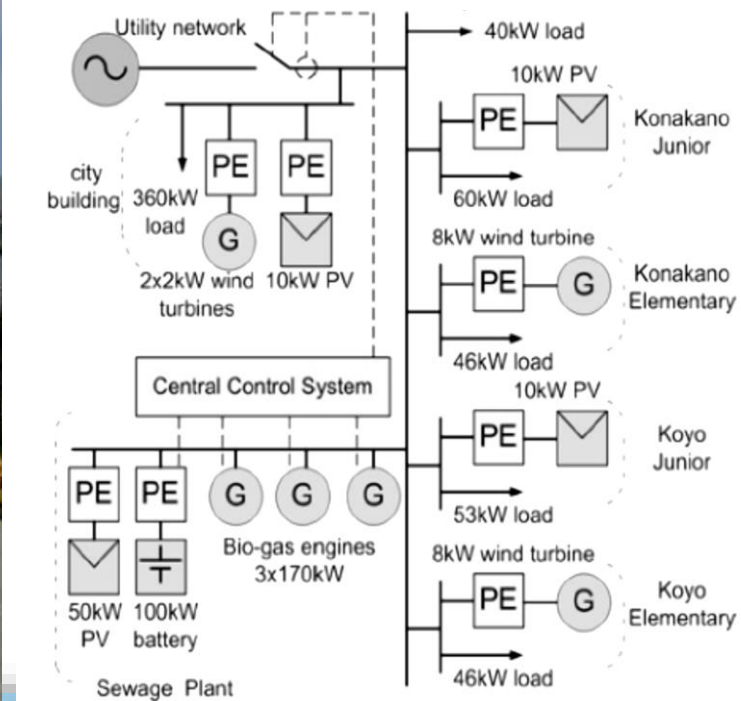




Microgrid Configuration

Example: Hachinohe Project (Japan)

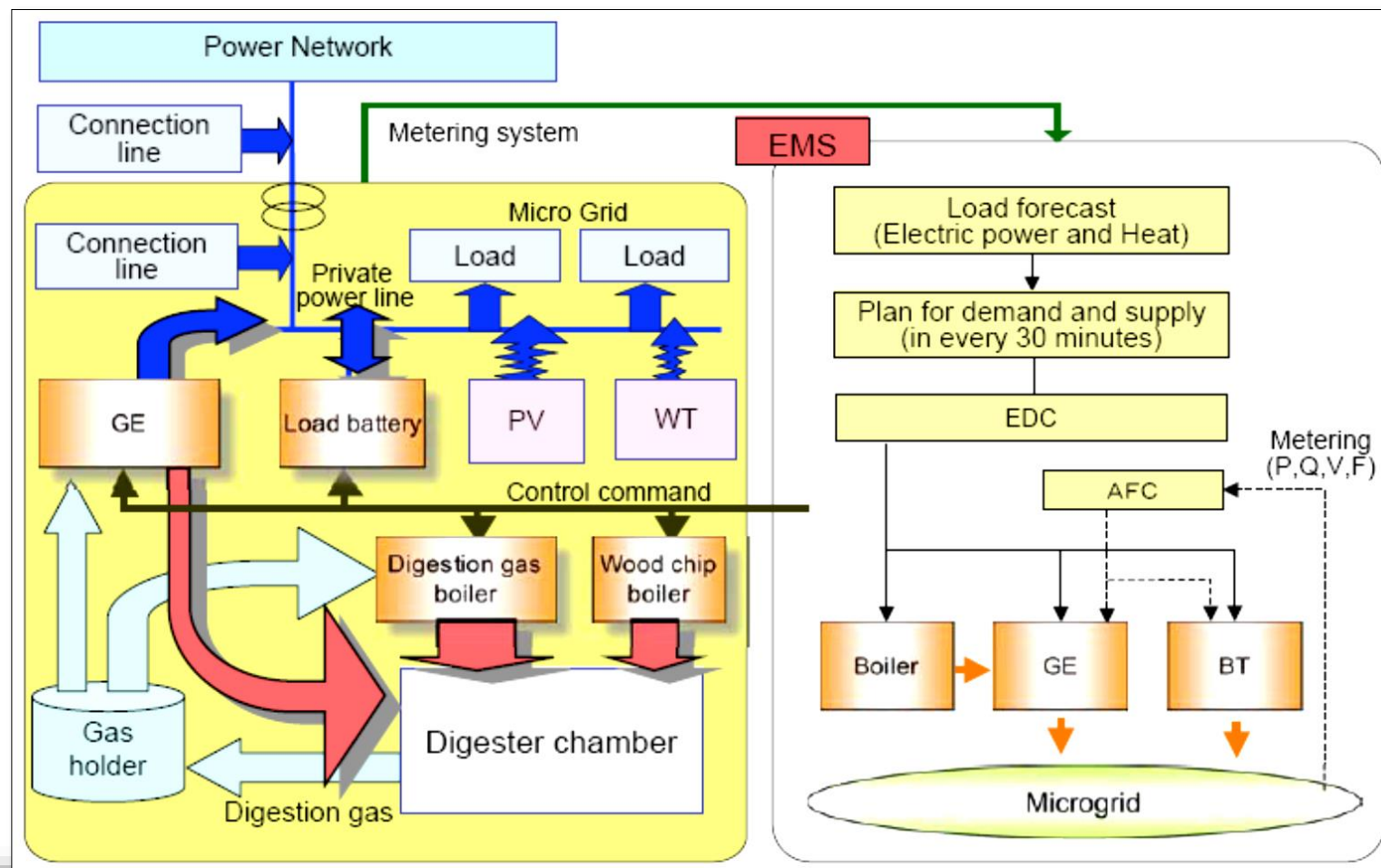
- Tecnnology demo
- GT+Biomass+PV+WT+BAT
- Load – 610 kW (Sewage Plant+Schools)





Microgrid Configuration

Example: Hachinohe Project (Japan)





Microgrid Configuration

Example: Sendai Project (Japan)

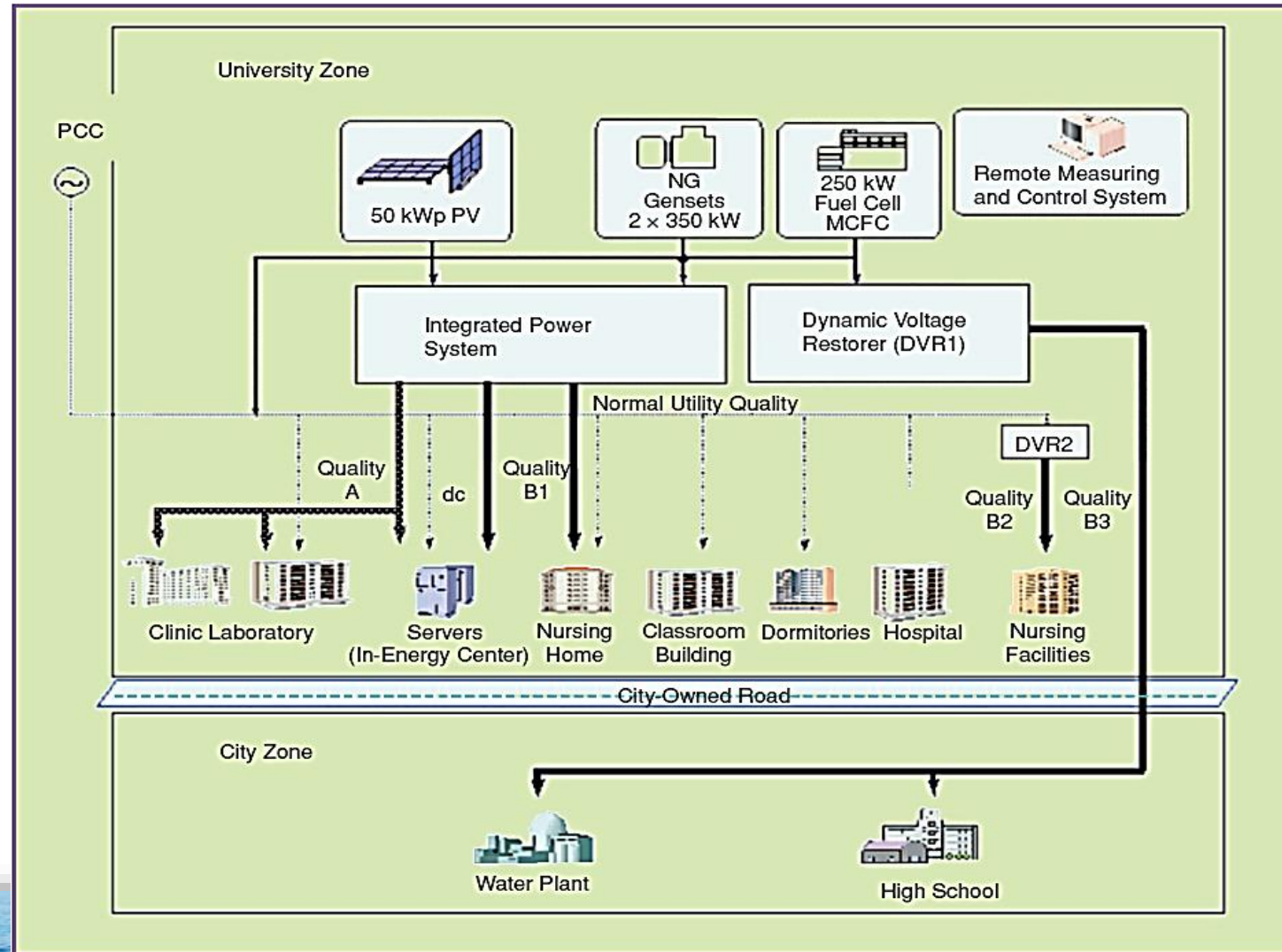
- 1 MW Microgrid with sensitive loads!





Microgrid Configuration

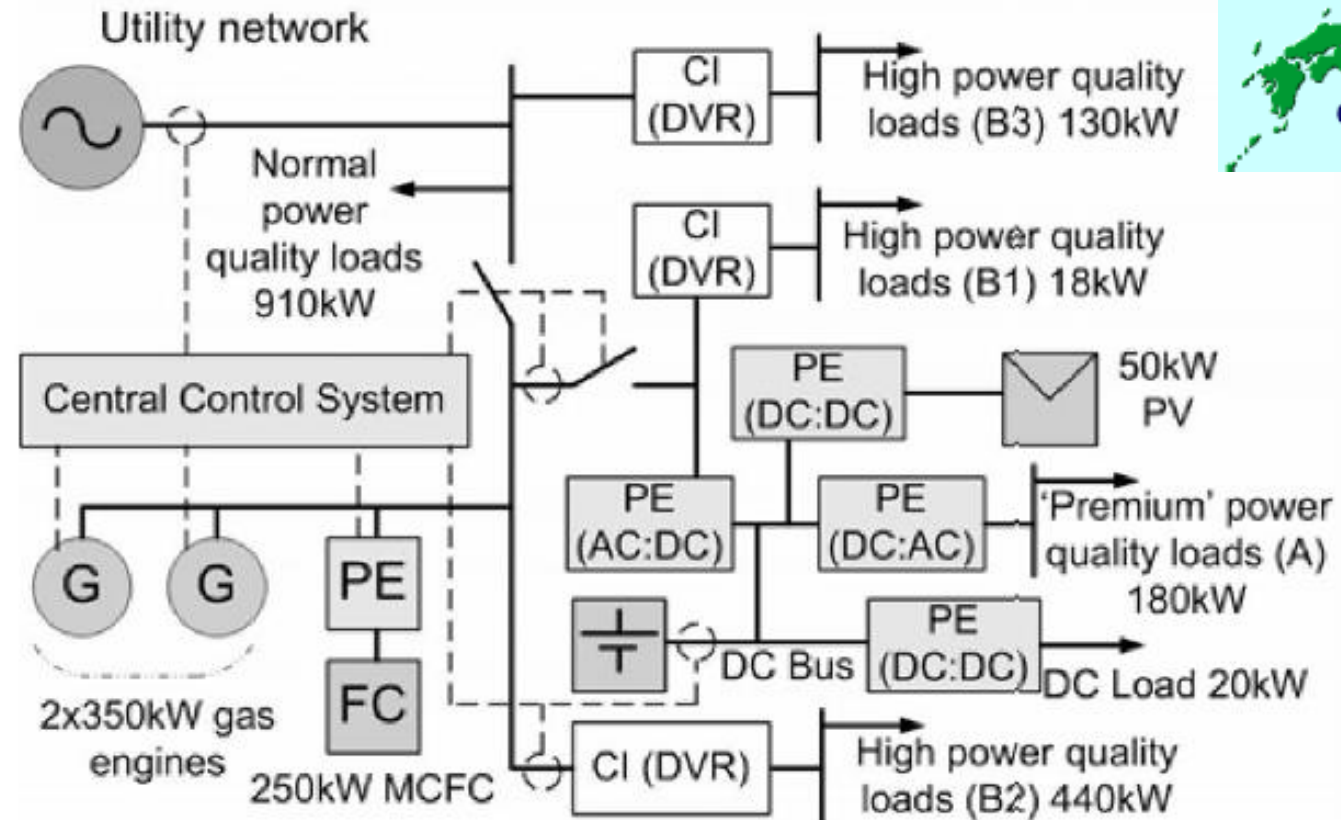
Example: Sendai Project (Japan)





Microgrid Configuration

Example: Sendai Project (Japan)





Microgrid Configuration

Fukushima



© 2011 IEEE Spectrum magazine





Microgrid Configuration

Fukushima

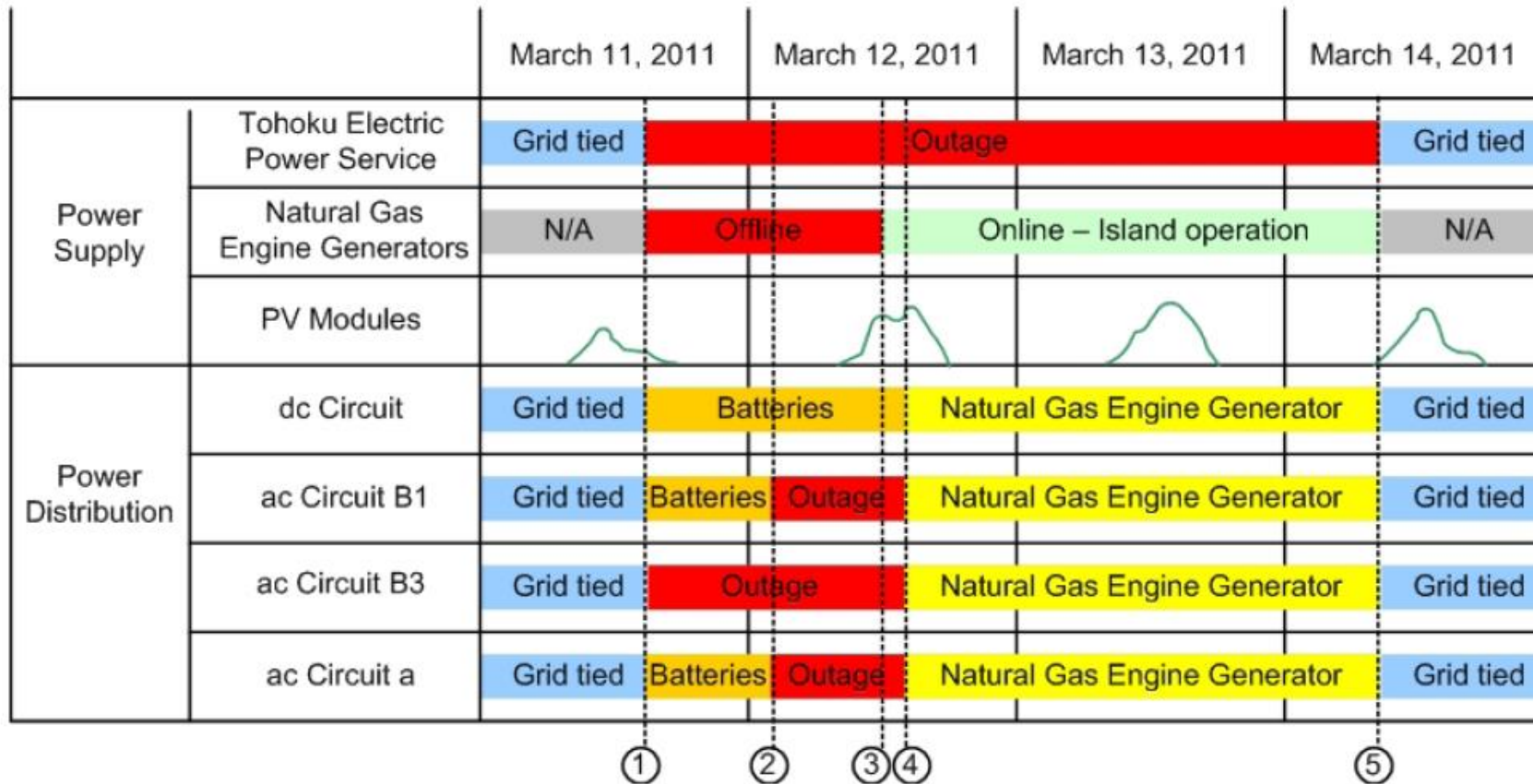




Microgrid Configuration

Example: Sendai Project (Japan)

Events timeline for the microgrid in Sendai, Japan, after the March 11, 2011 tsunami.



K. Hirose, "Performance of the Sendai Microgrid During the 2011 Earthquake and Tsunami"



AC Microgrids

- Definition
- Configuration
- Operation
- Control
- Conclusions



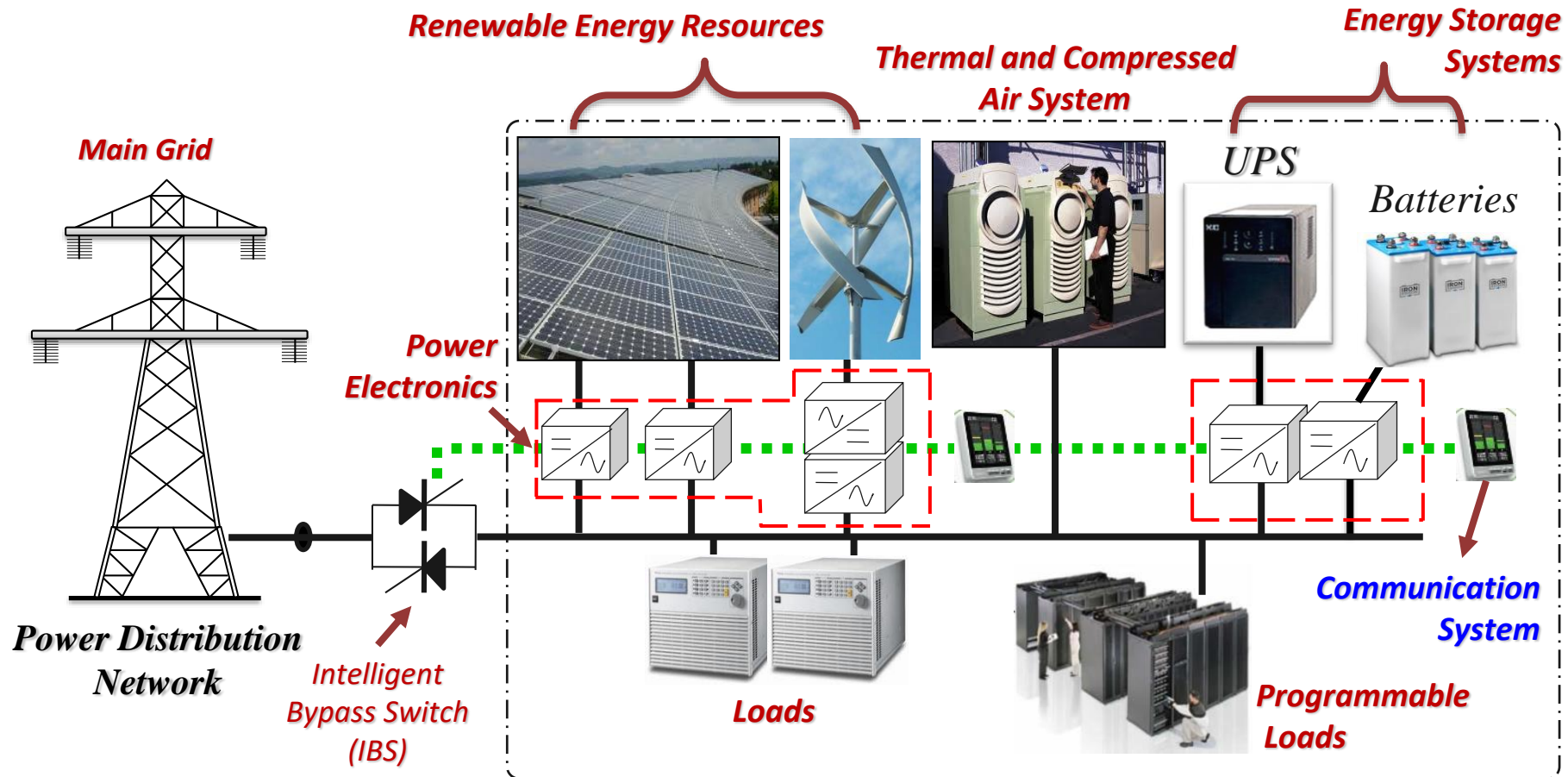
AC Microgrids

- Definition
- Configuration
- **Operation**
- Control
- Conclusions



Microgrid Operation

Typical structure of a microgrid

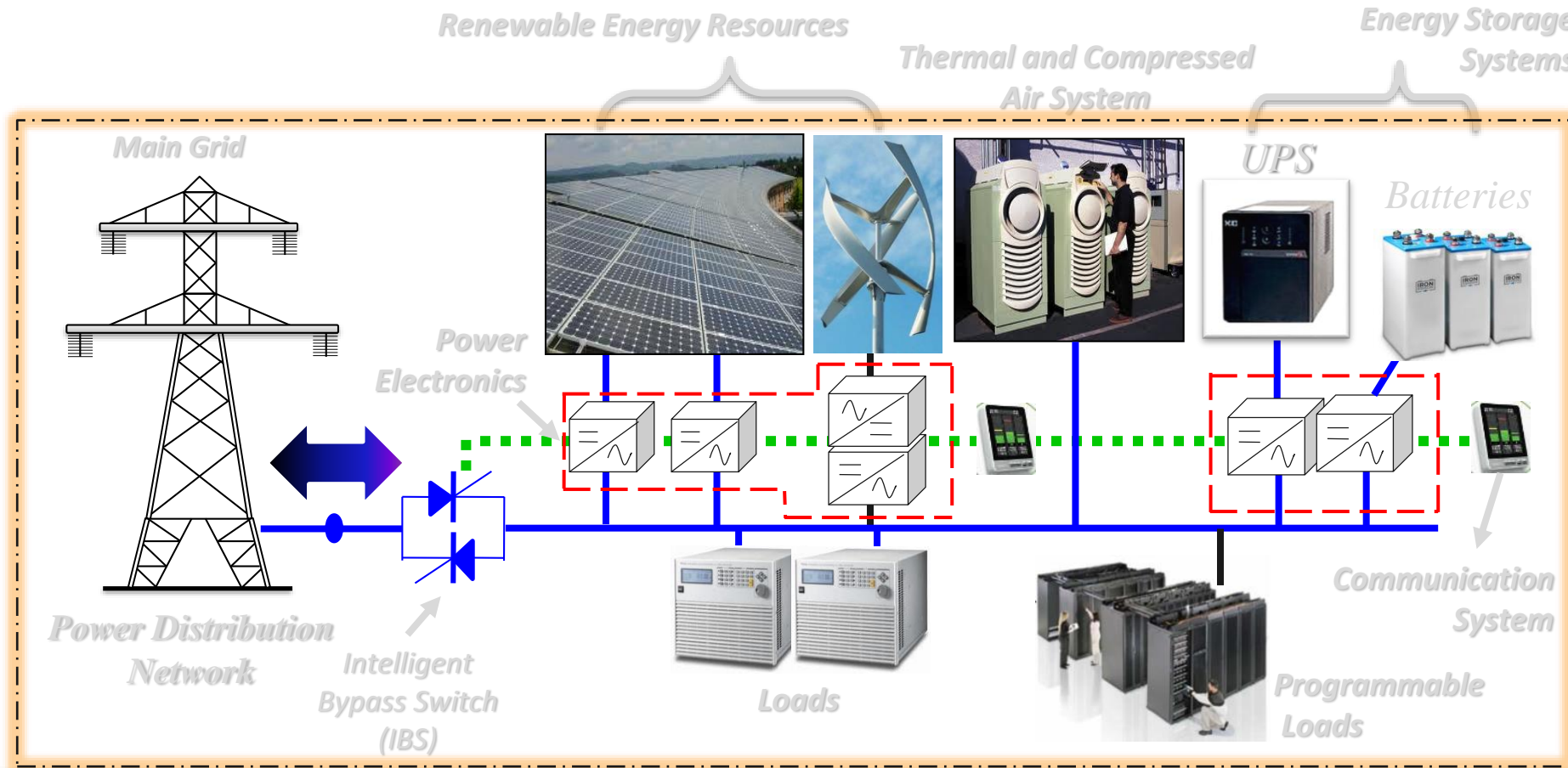




Microgrid Operation

Operation modes:

- Grid connected
- Islanded

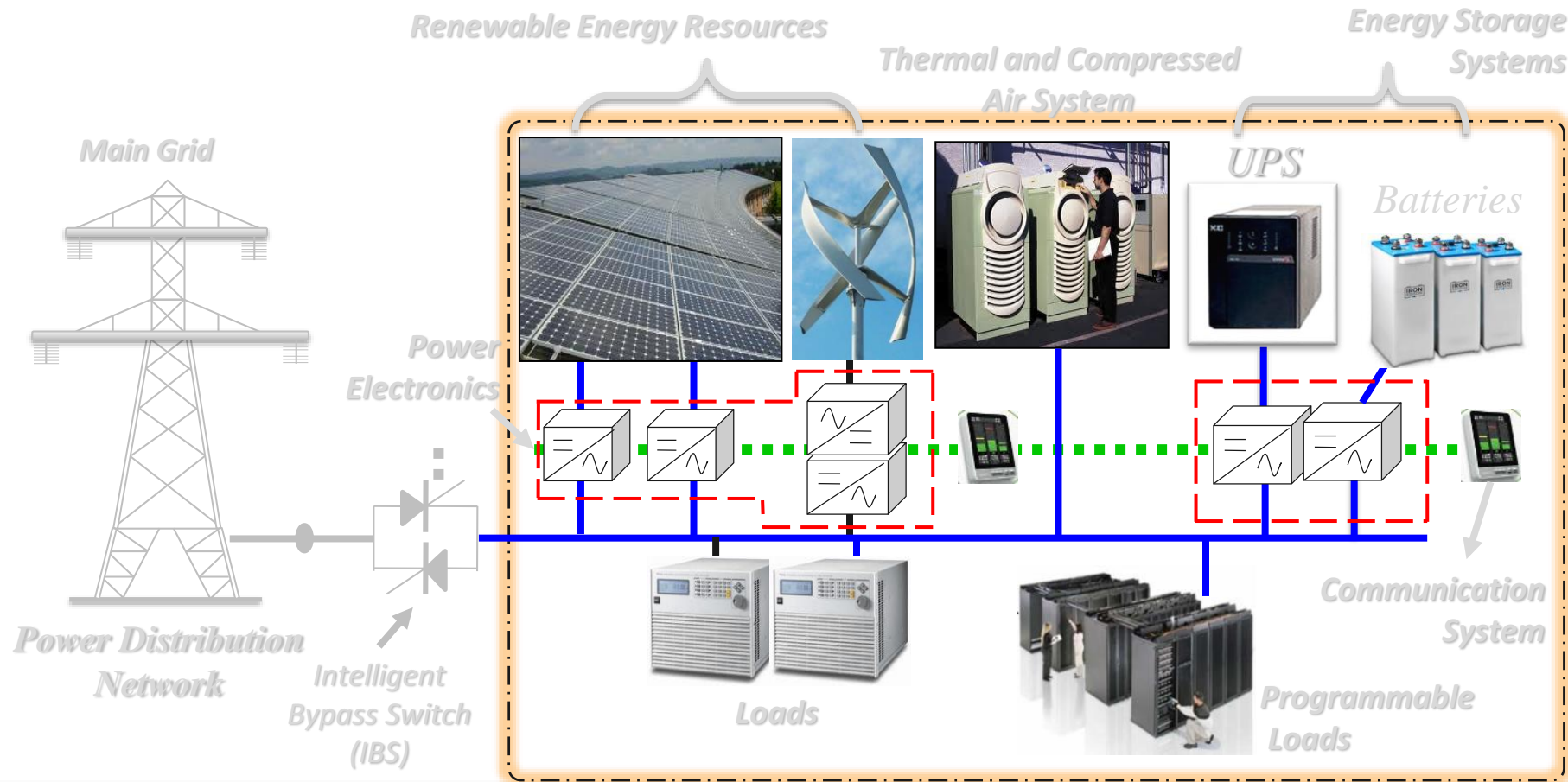




Microgrid Operation

Operation modes:

- Grid connected
- **Islanded**

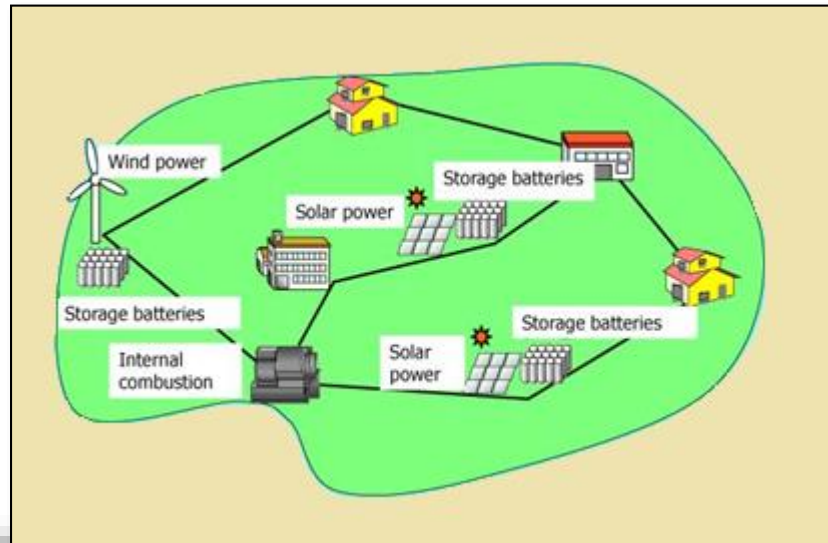




Microgrid Operation

Islanded operation modes

- Preplanned islanded operation: If any events in the main grid are presented, such as long-time voltage dips or general faults, among others, islanded operation must be started.
- Non-planned islanded operation: If there is a blackout due to a disconnection of the main grid, the microgrid should be able to detect this fact by using proper algorithms.



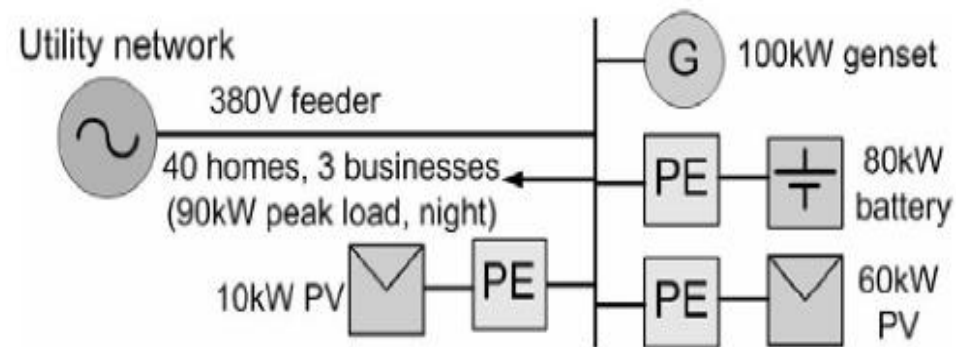


Microgrid Operation

Example: Rural electrification using microgrids

XingXingXia, XinJiang Province, China

星星峡, 新疆





Microgrid Operation

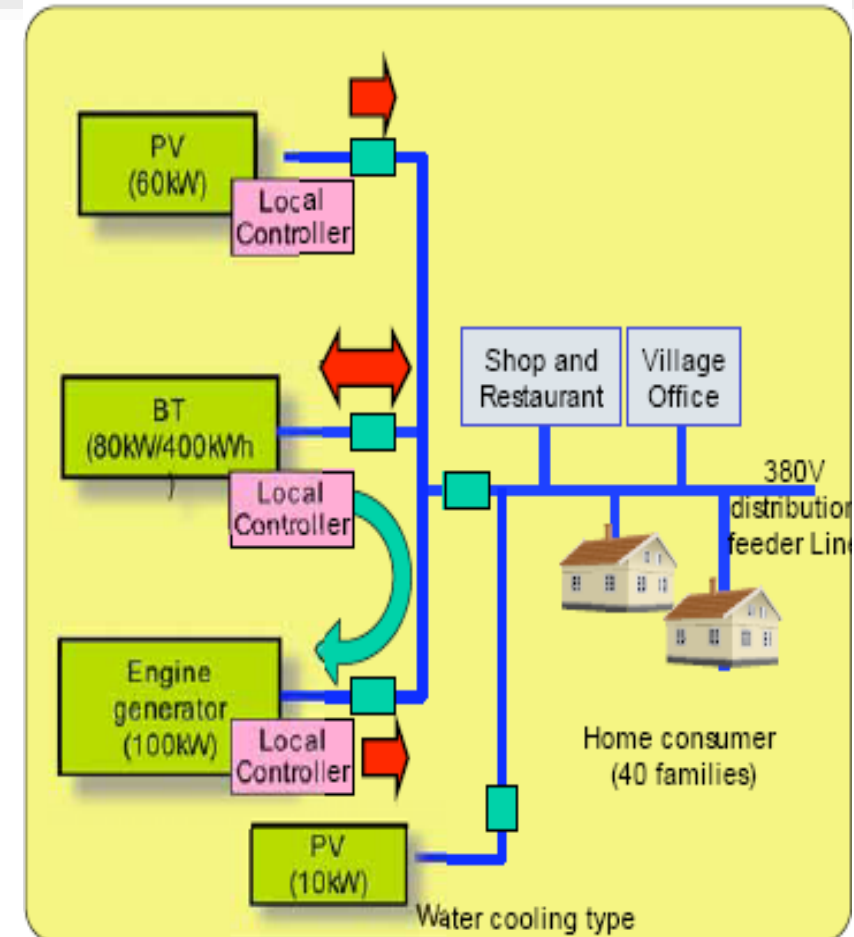
Power Balance

1. Electric Power Generation

Engine Generator	100kW
PV	70kW
Bateries	80kW (400kWh)
	250kW

2. Peak Load 90kW (at night time)

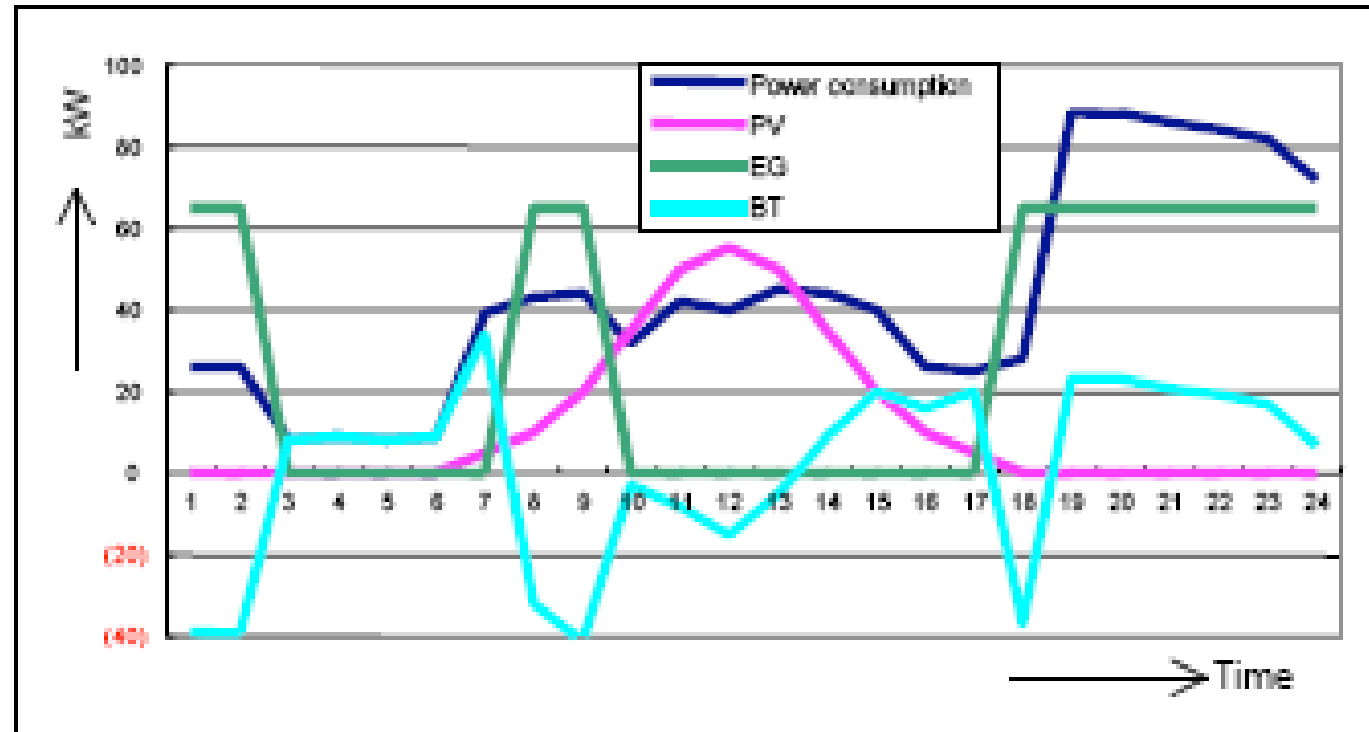
3. Distribution feeder 380V /500m





Microgrid Operation

Load and Generation Curves





AC Microgrids

- Definition
- Configuration
- Operation
- Control
- Conclusions

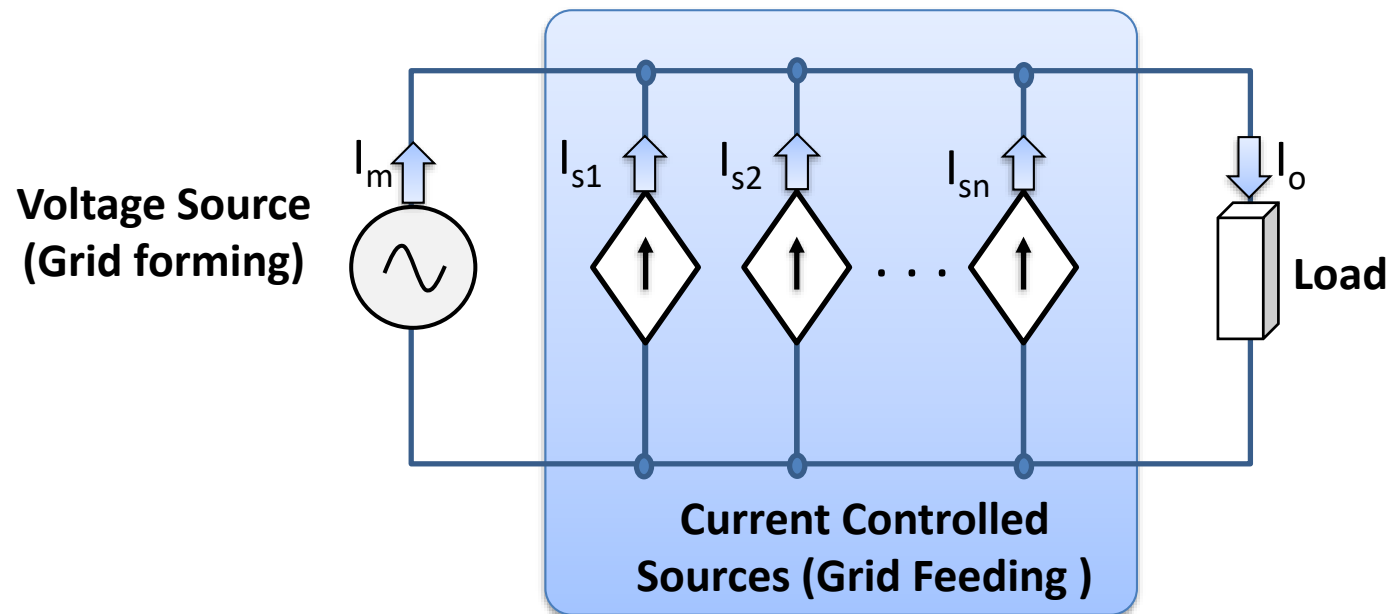


AC Microgrids

- Definition
- Configuration
- Operation
- **Control**
- Conclusions



Master-slave control

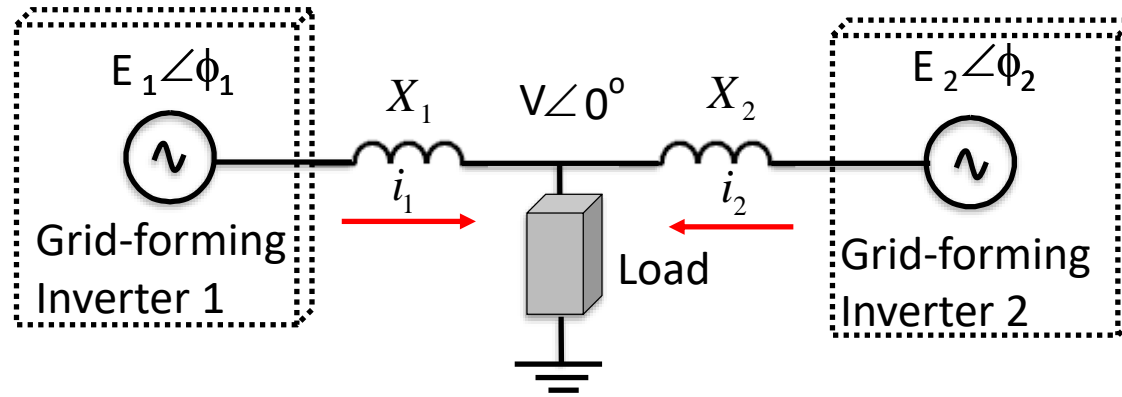


Source: Woo-Cheol Lee "A Master and Slave Control Strategy for Parallel Operation of Three-Phase UPS Systems with Different Ratings"

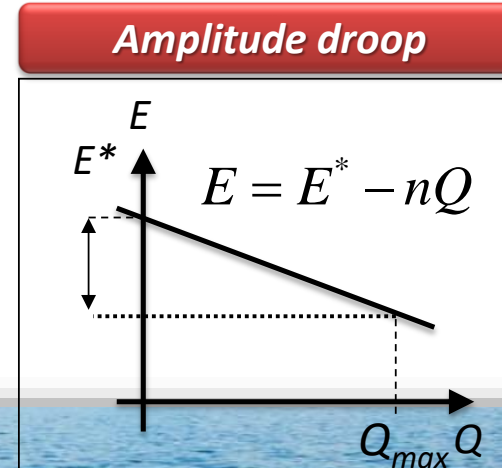
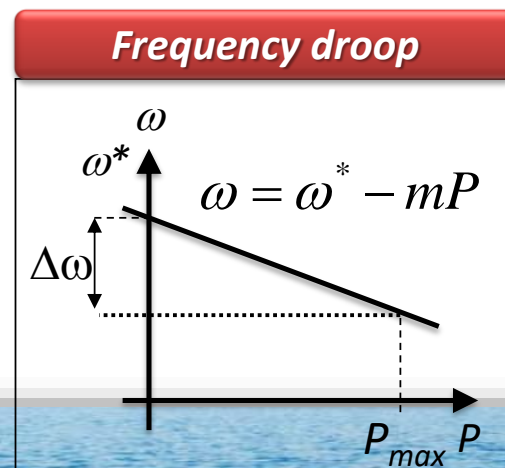


Microgrid Control

Droop control of AC systems



Active power $P = \frac{VE}{X} \sin \phi$ Reactive power $Q = \frac{EV \cos \phi - V^2}{X}$





Inertia principle

In a synchronous generator, energy conservation implies that

$$P_G - P_L = J \dot{\omega}$$

where

P_G is the generated real power,

P_L is the load power,

J is the system inertia, and ω is the frequency.

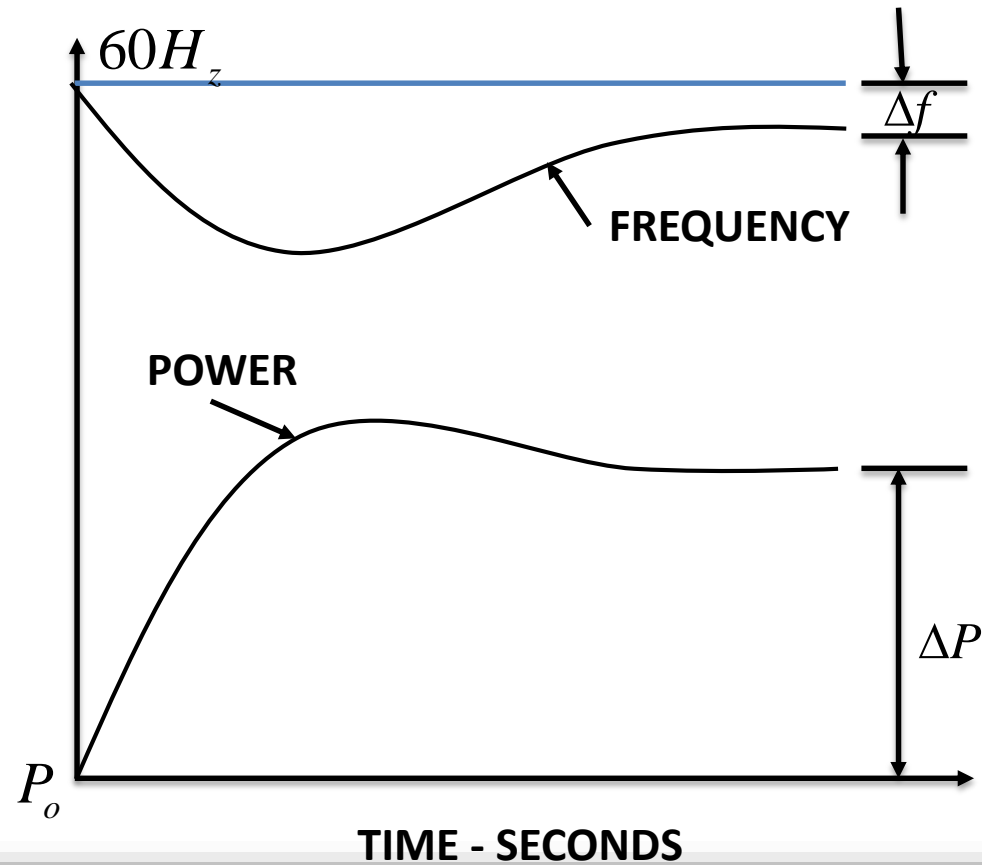
When $P_G > P_L$ the system frequency increases ($\omega > \omega_{nom}$).

When , $P_G < P_L$ the system frequency decreases ($\omega < \omega_{nom}$).



Inertia principle

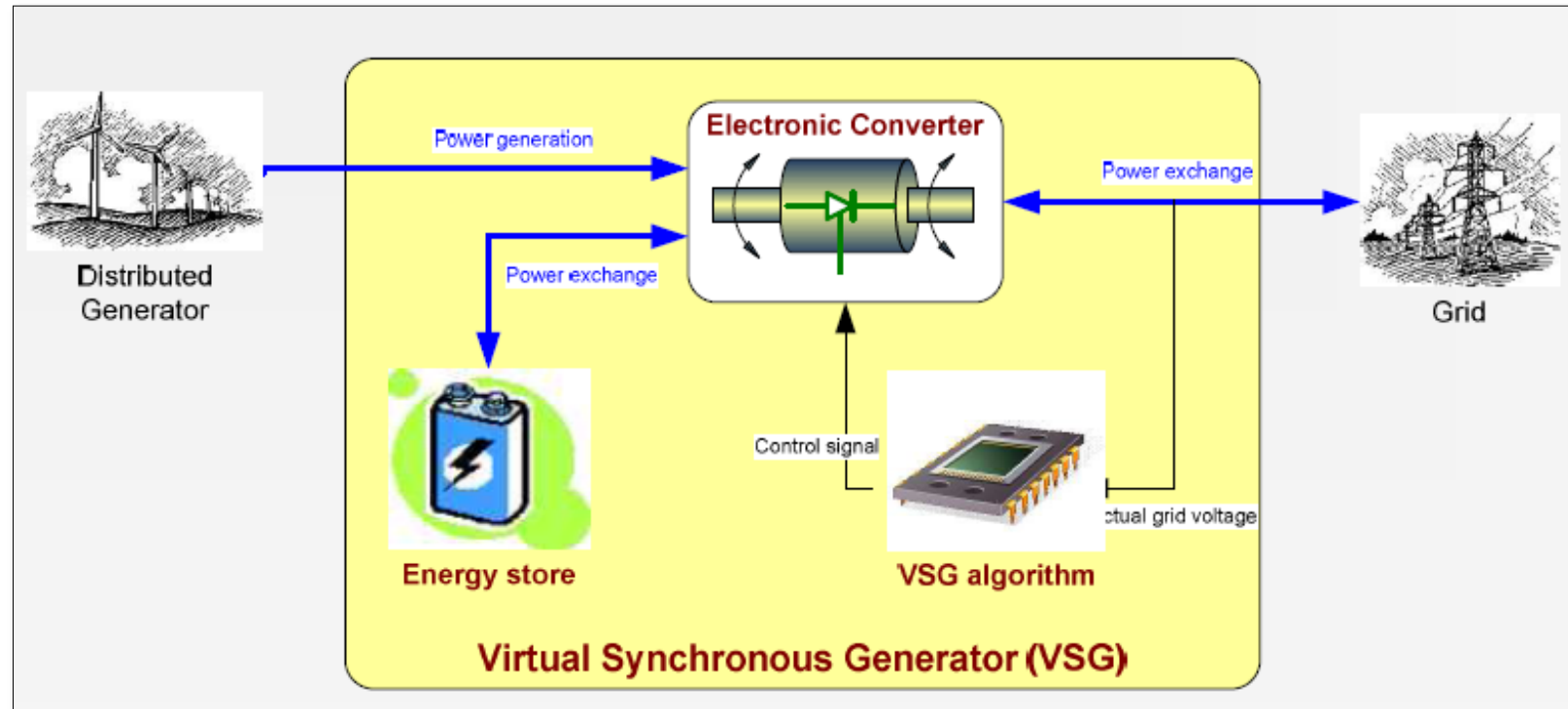
- Synchronous generator transient response



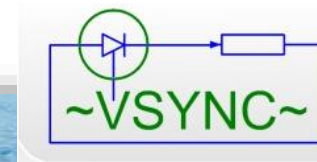


Microgrid Control

Virtual synchronous generators



*Inertias means not only load-dependent frequency (droops),
but also local storage energy system.*



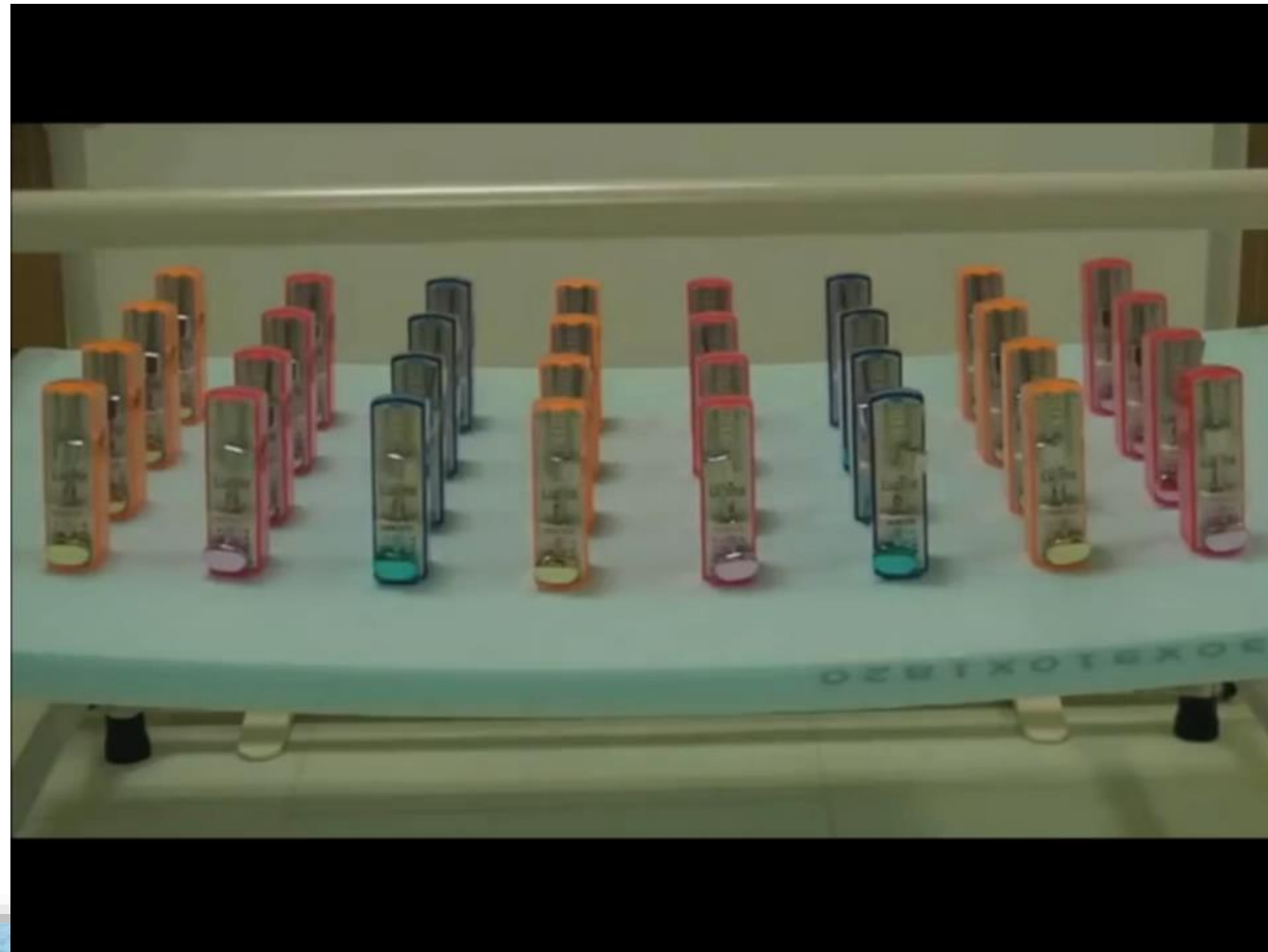
European Project VSYNC:

<http://www.vsync.eu>



Microgrid Control

Understanding how inertia helps synchronization



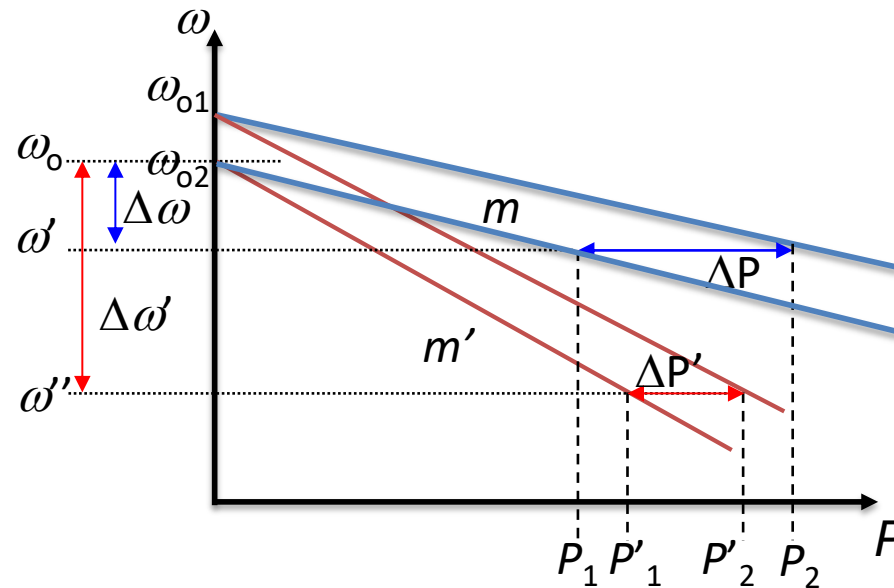


Droop control

- Trade-off power sharing / amplitude - frequency regulation

$$\omega = \omega^* - mP$$

$$E = E^* - nQ$$



$$\Delta\omega_{\max} = 2\%$$

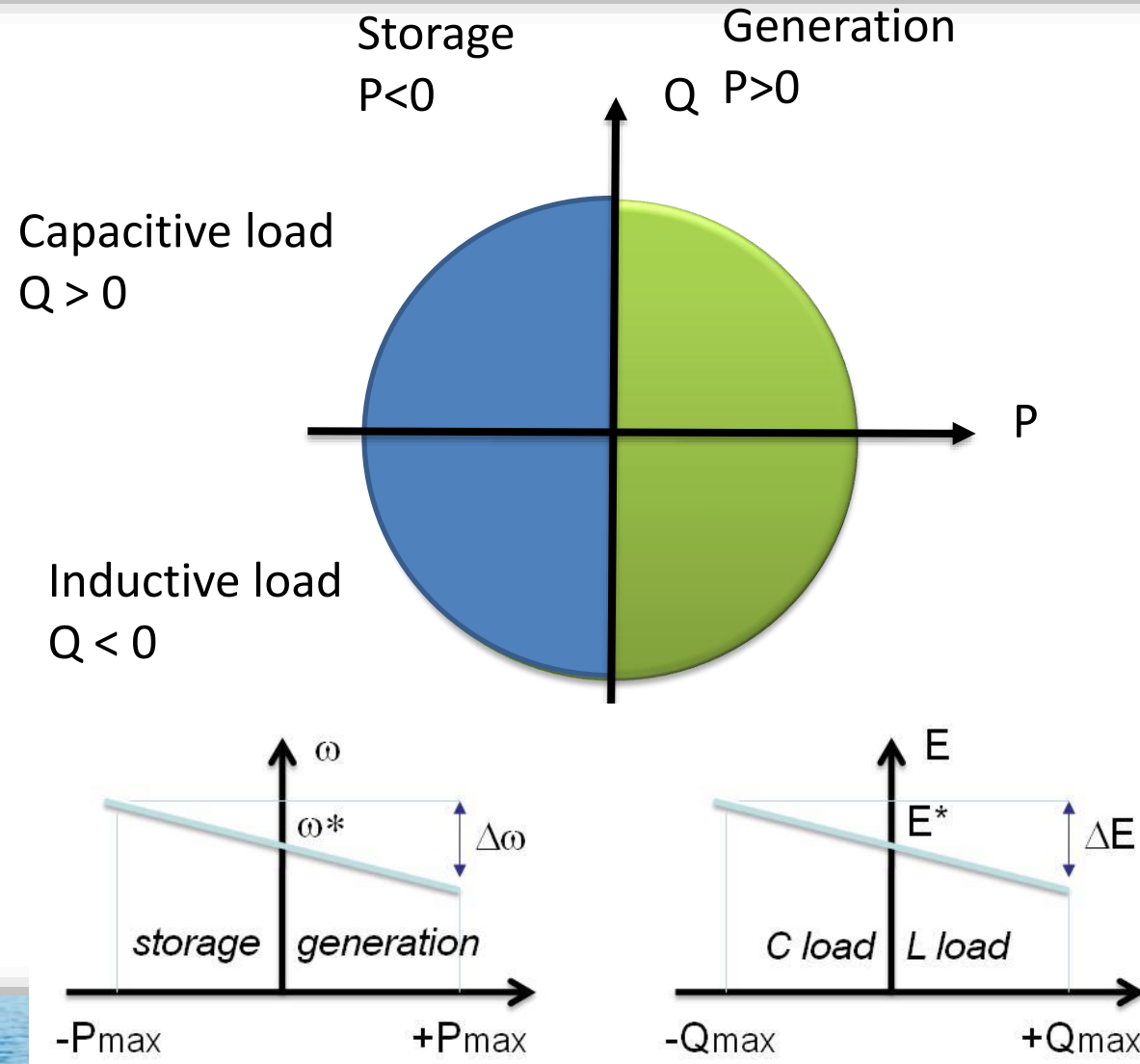
$$\Delta E_{\max} = 5\%$$

Phase droops are not feasible since the initial phase of each inverter is different!



Microgrid Control

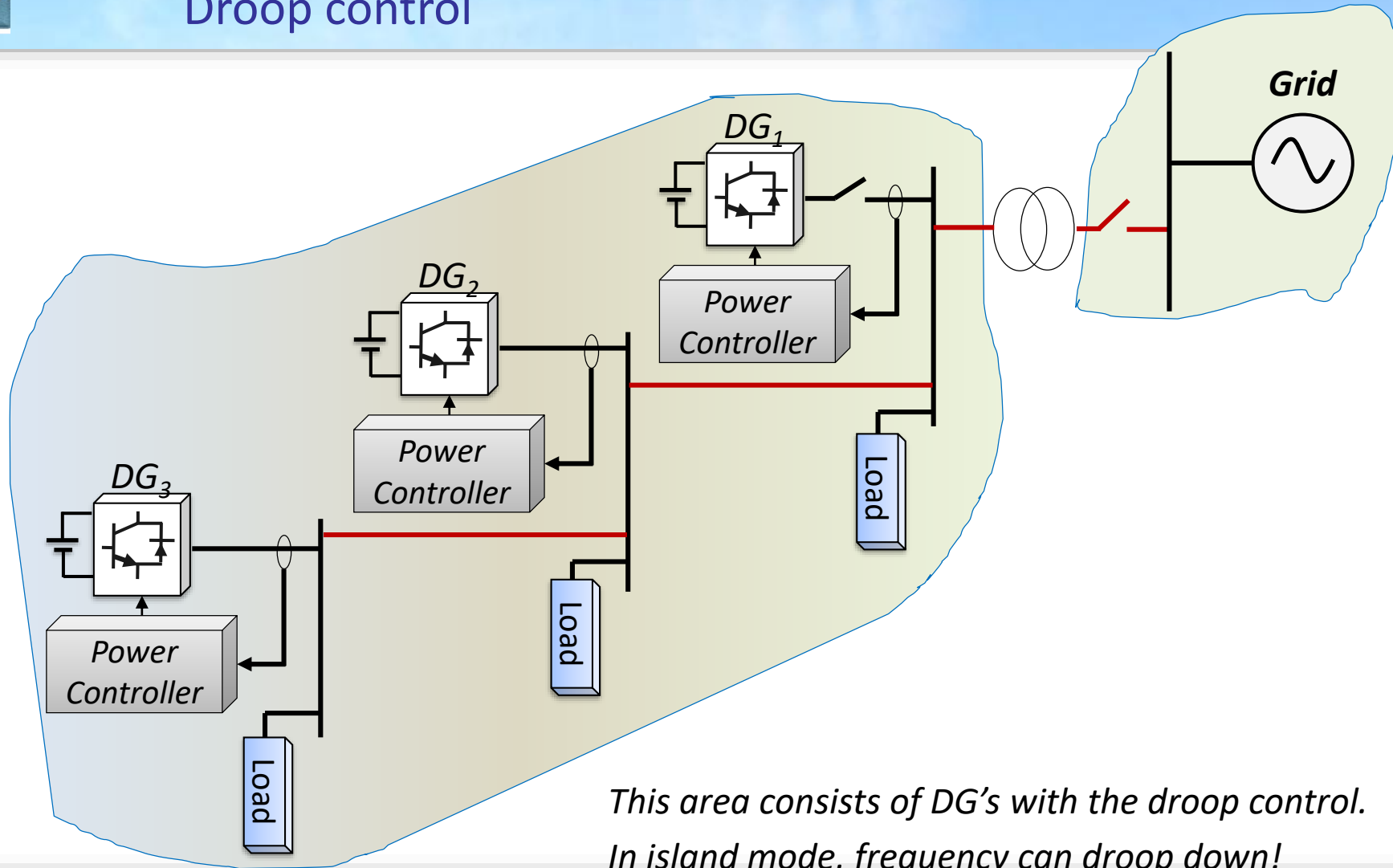
Droop control





Microgrid Control

Droop control

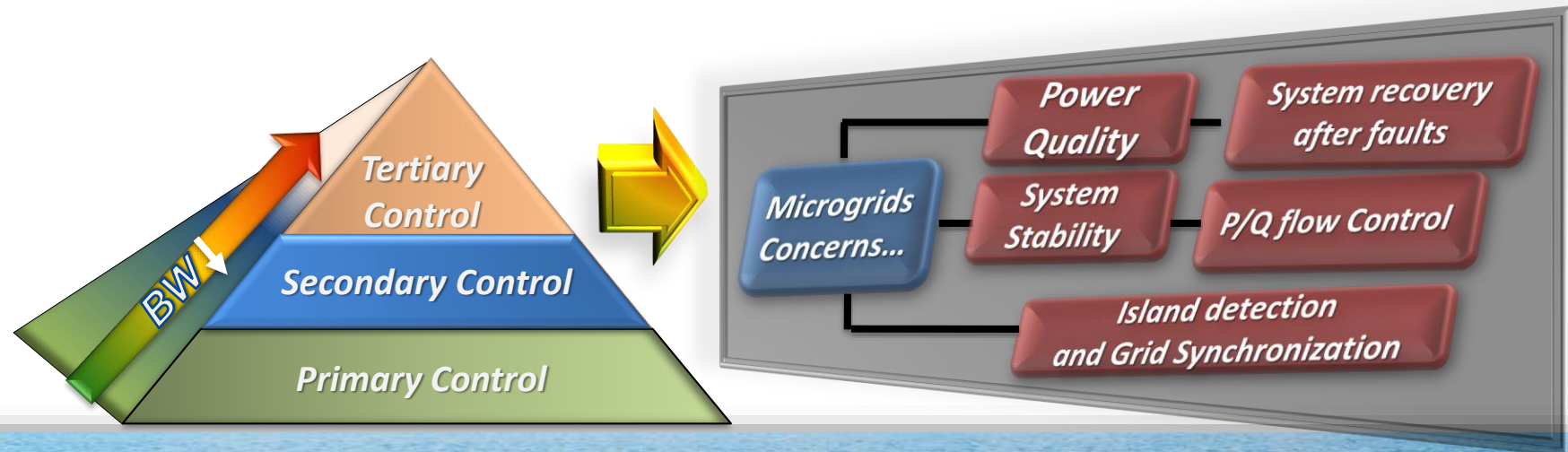


*This area consists of DG's with the droop control.
In island mode, frequency can droop down!*



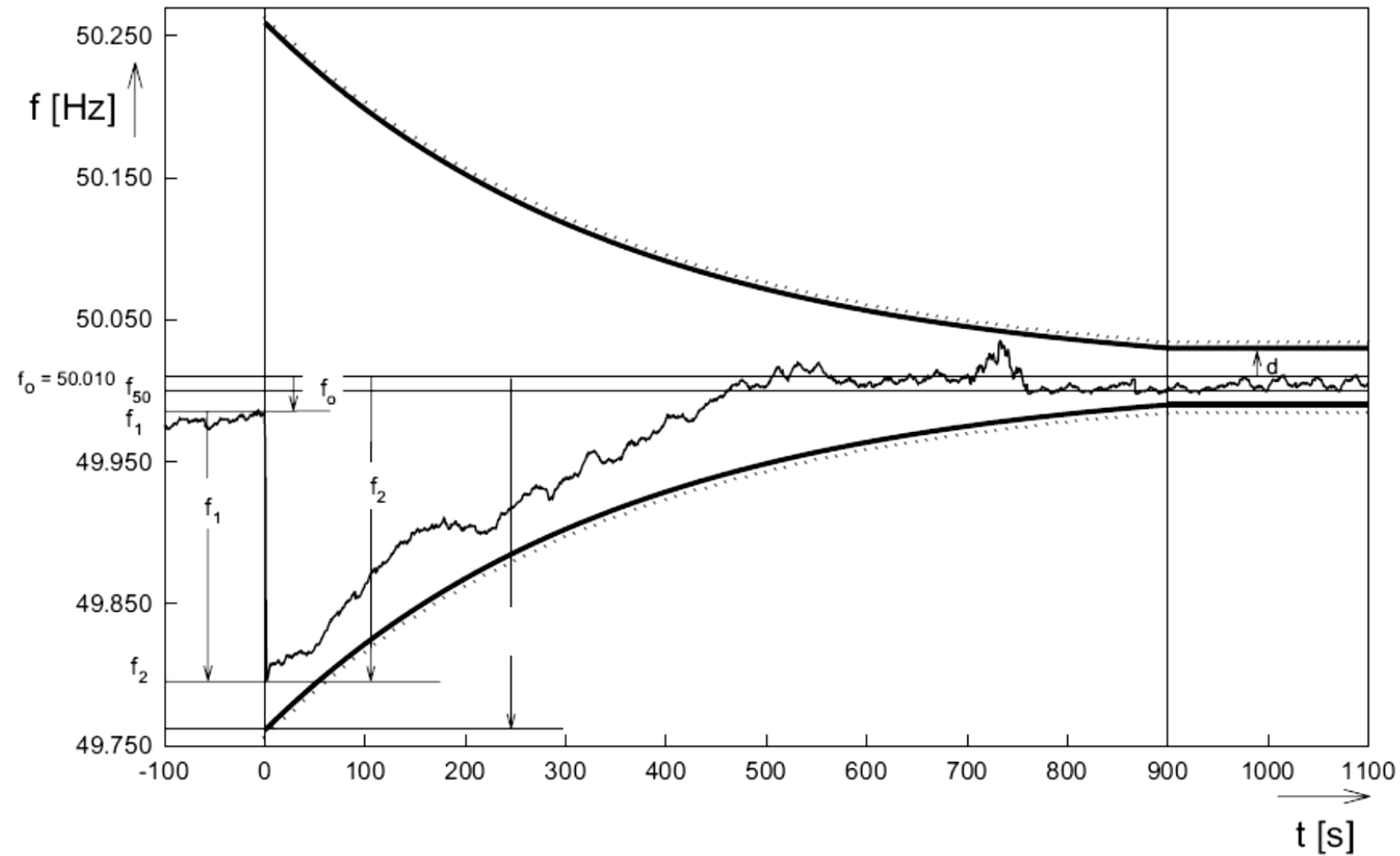
Hierarchical Control Principle

- Primary Control: Modeling + Inner loops + droop Control (P/Q Sharing).
- Secondary Control:
 - *f/V Restoration (Island)* : Set-points assignation from MGCC to the DGs .
 - *Synchronization (Island to grid Connected mode)*
- Tertiary Control: Power Import/export from/to the grid.





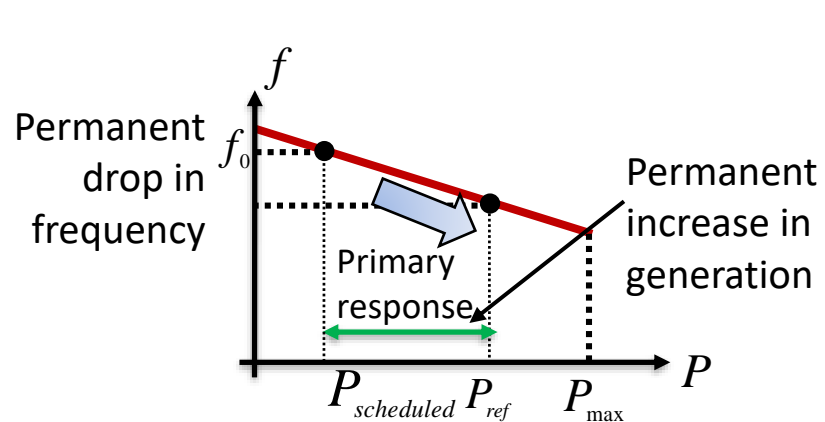
Secondary Control



Source: UCTE. A1 – Appendix 1: Load-Frequency Control and Performance

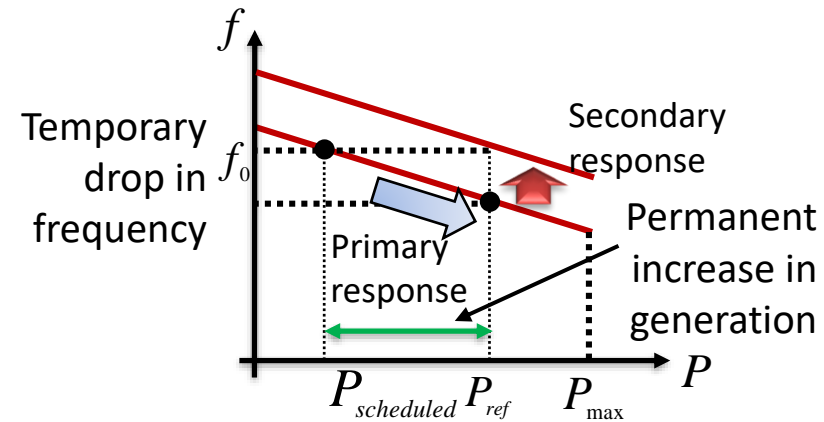


Secondary control



a)

No secondary control



b)

Using secondary control

Primary control ensures P sharing by drooping the frequency

Secondary control:

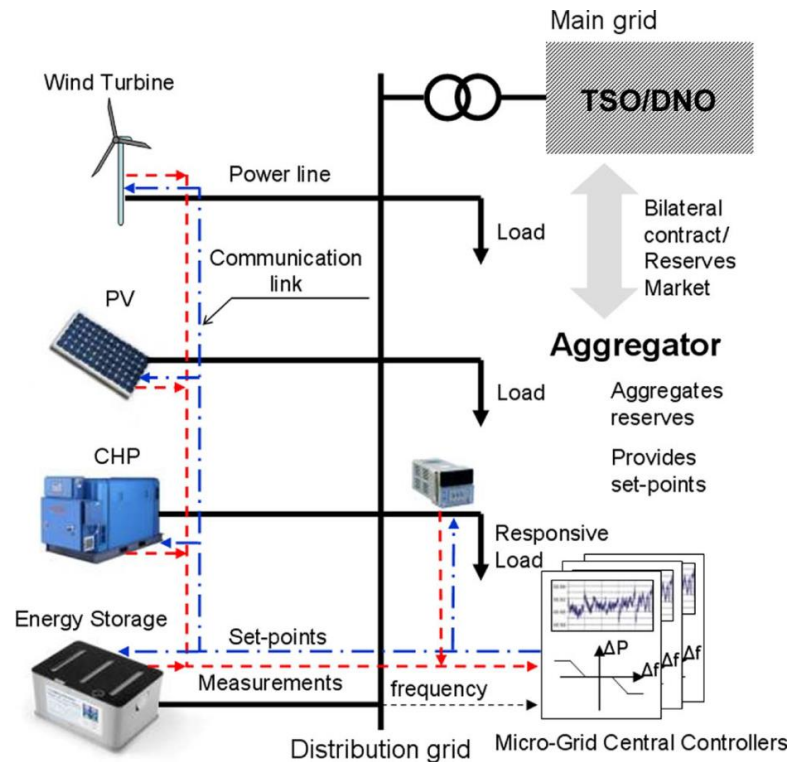
- Restore the nominal frequency
- Cannot work locally, it needs to be centralized.



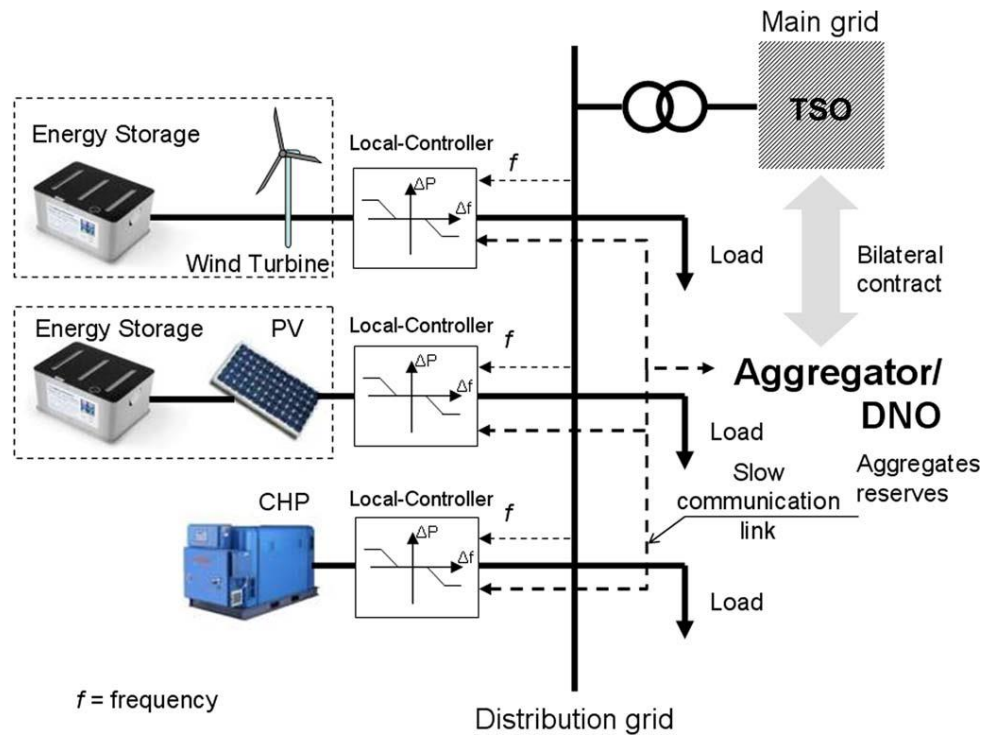
Microgrid Control

Centralized Vs Distributed Control

Centralized Control



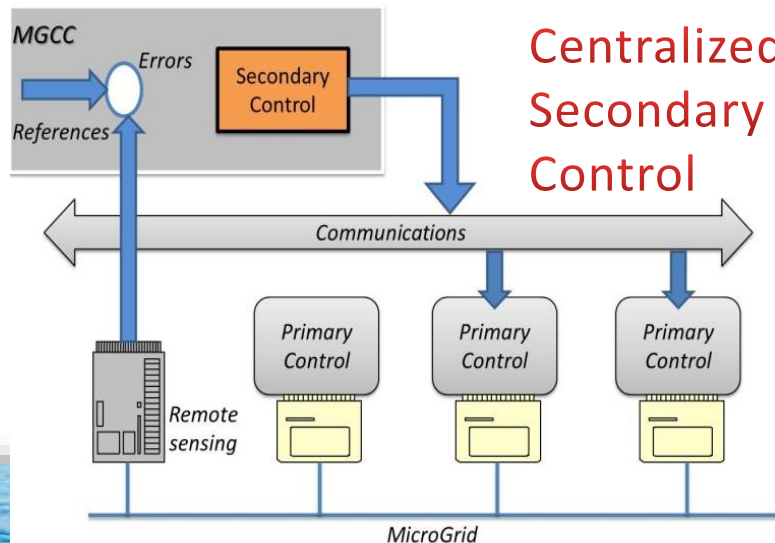
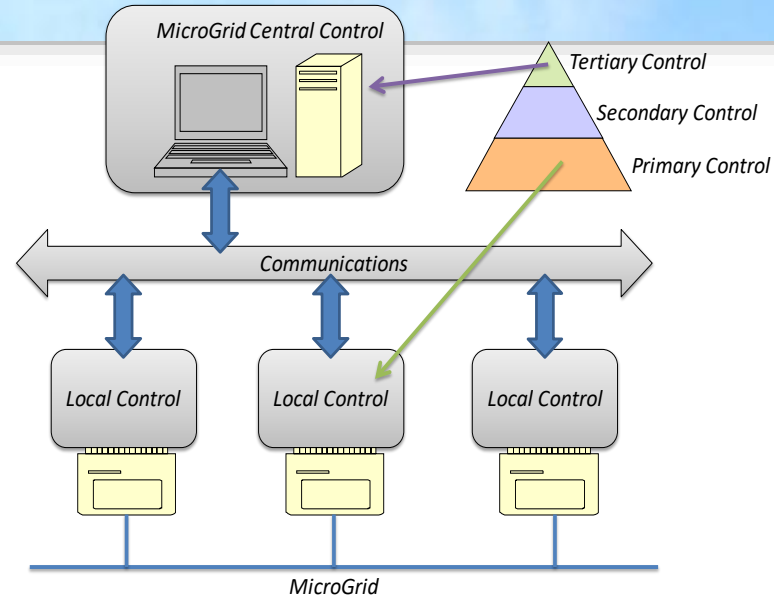
Distributed control



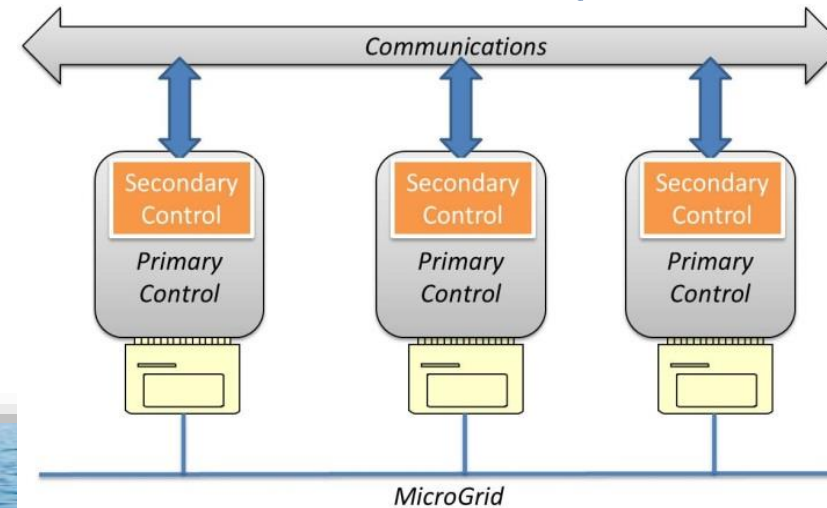


Microgrid Control

Microgrid
Local and Centralized
Controllers.



Distributed Secondary Control

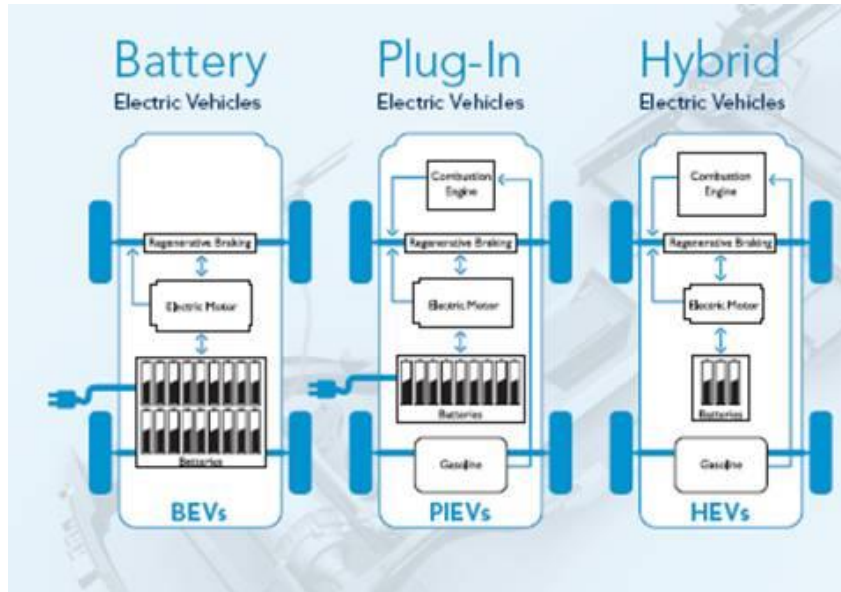




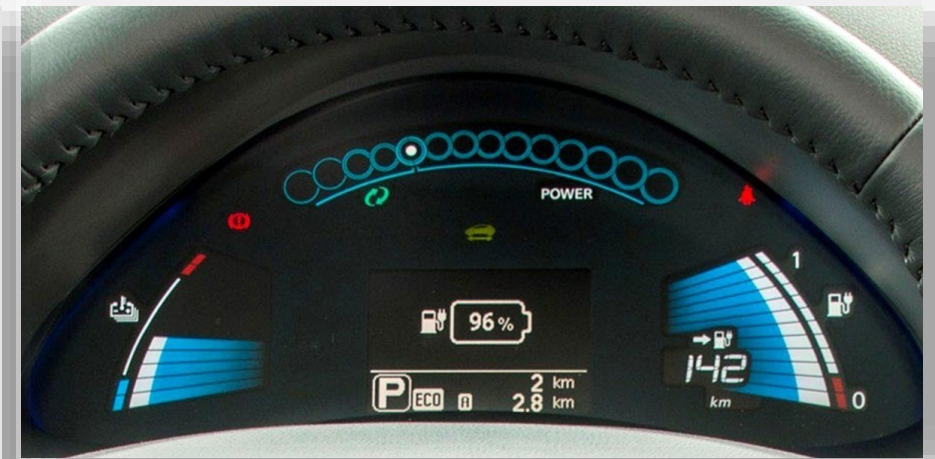
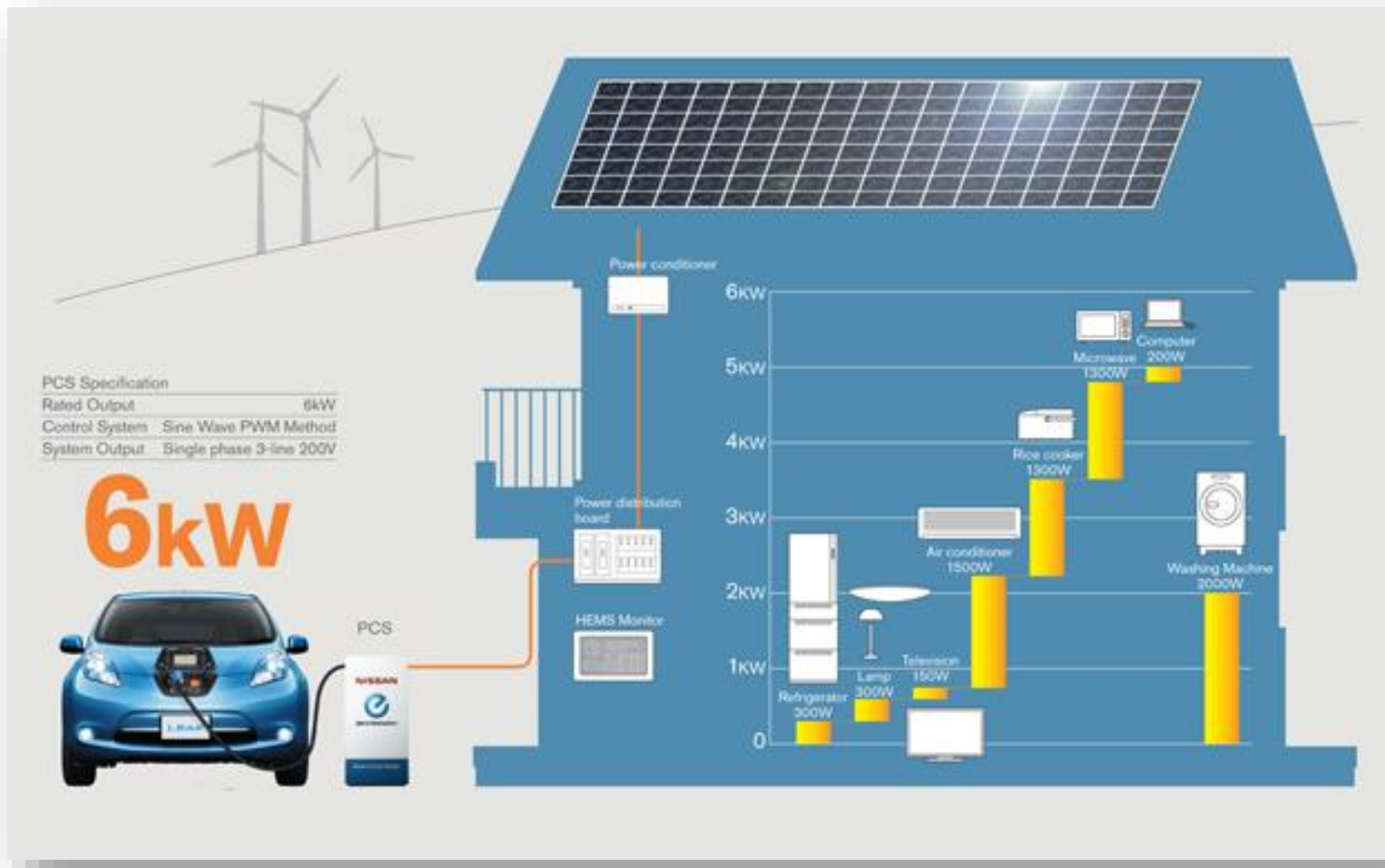
The diagram illustrates a hierarchical power distribution system. At the top, a **Stiff grid** (represented by a circle) is connected to a **Tertiary SG** (Secondary Generator, represented by a rectangle). The Tertiary SG is connected to a **Secondary SG** (represented by a rectangle) via a solid line. The Secondary SG is connected to a **Primary SG/Tertiary Cluster** (represented by a rectangle) via a solid line. The Primary SG/Tertiary Cluster is connected to a **Secondary Cluster** (represented by a rectangle) via a solid line. The Secondary Cluster is connected to two **Primary Clusters** (represented by rectangles) via solid lines. The Primary Clusters are connected to two **Microgrids (MG#1 and MG#2)** (represented by circles) via solid lines. Each Microgrid contains two **Distributed Generation (DG)** units (represented by circles). DG#1 and DG#2 are connected to MG#1, and DG#3 and DG#4 are connected to MG#2. The DG units are labeled **Primary**. The Primary Clusters are labeled **Tertiary** and **Secondary**. The Secondary Cluster is labeled **Secondary Cluster**. The Primary Clusters are labeled **Primary Cluster**. The Microgrids are labeled **MG#1** and **MG#2**. The DG units are labeled **DG#1**, **DG#2**, **DG#3**, and **DG#4**. The Primary Clusters are connected to the Secondary Cluster via **PCC#1** and **PCC#2** (Primary Cluster Connection points, represented by ovals). The Secondary Cluster is connected to the Tertiary SG via a **PCC** (Primary Cluster Connection point, represented by an oval). The Tertiary SG is connected to the Stiff grid via a **PCC** (Primary Cluster Connection point, represented by an oval). The Secondary SG is connected to the Tertiary SG via a **PCC** (Primary Cluster Connection point, represented by an oval). The Primary SG/Tertiary Cluster is connected to the Secondary SG via a **PCC** (Primary Cluster Connection point, represented by an oval). The Secondary Cluster is connected to the Primary SG/Tertiary Cluster via a **PCC** (Primary Cluster Connection point, represented by an oval). The Primary Clusters are connected to the Secondary Cluster via **PCC#1** and **PCC#2** (Primary Cluster Connection points, represented by ovals). The Microgrids are connected to the Primary Clusters via **PCC#1** and **PCC#2** (Primary Cluster Connection points, represented by ovals). The DG units are connected to the Microgrids via **PCC#1** and **PCC#2** (Primary Cluster Connection points, represented by ovals).

Cars also going to electric

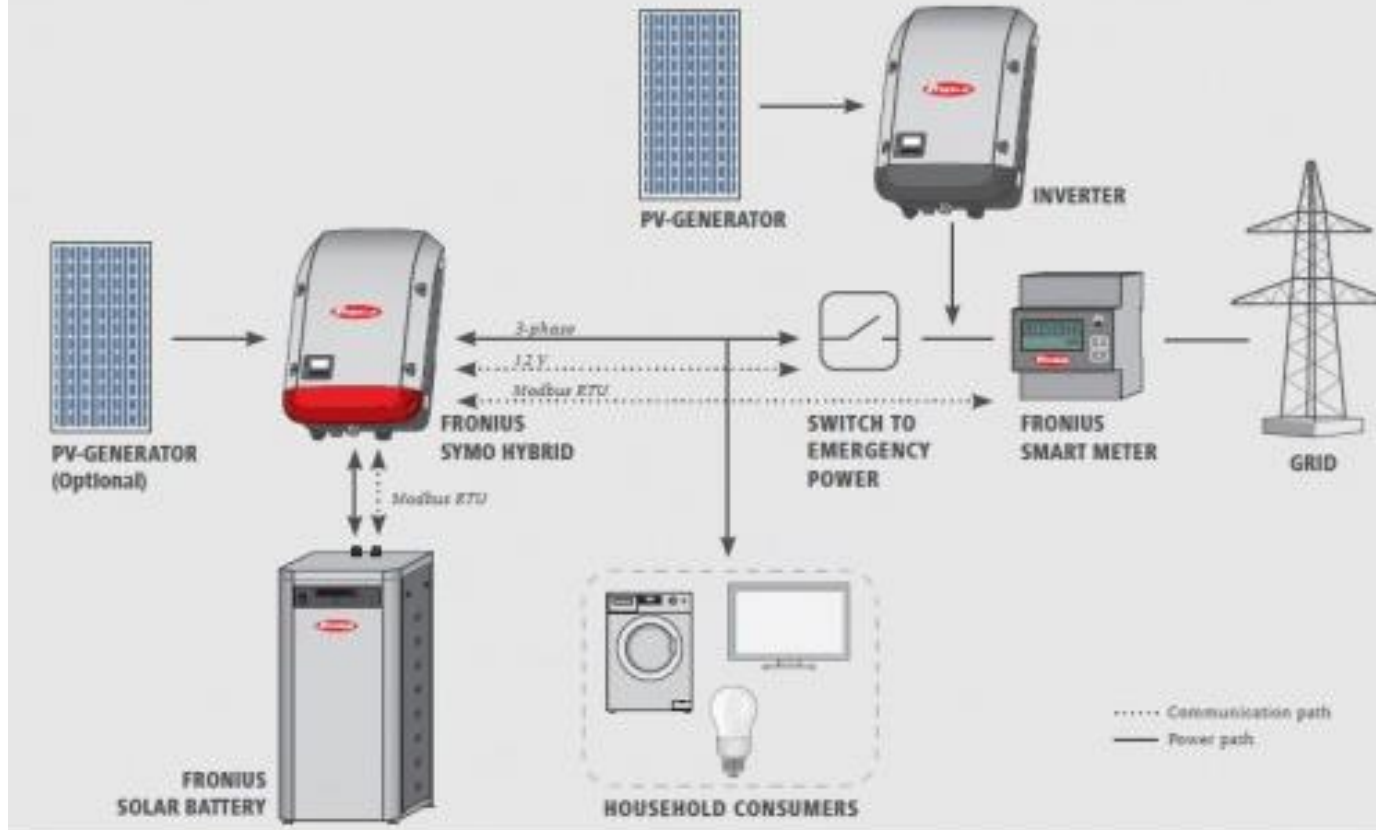
Leaf to home: bidirectional converter



Source: Nissan



CONFIGURATION DIAGRAM DC- & AC-COUPLING



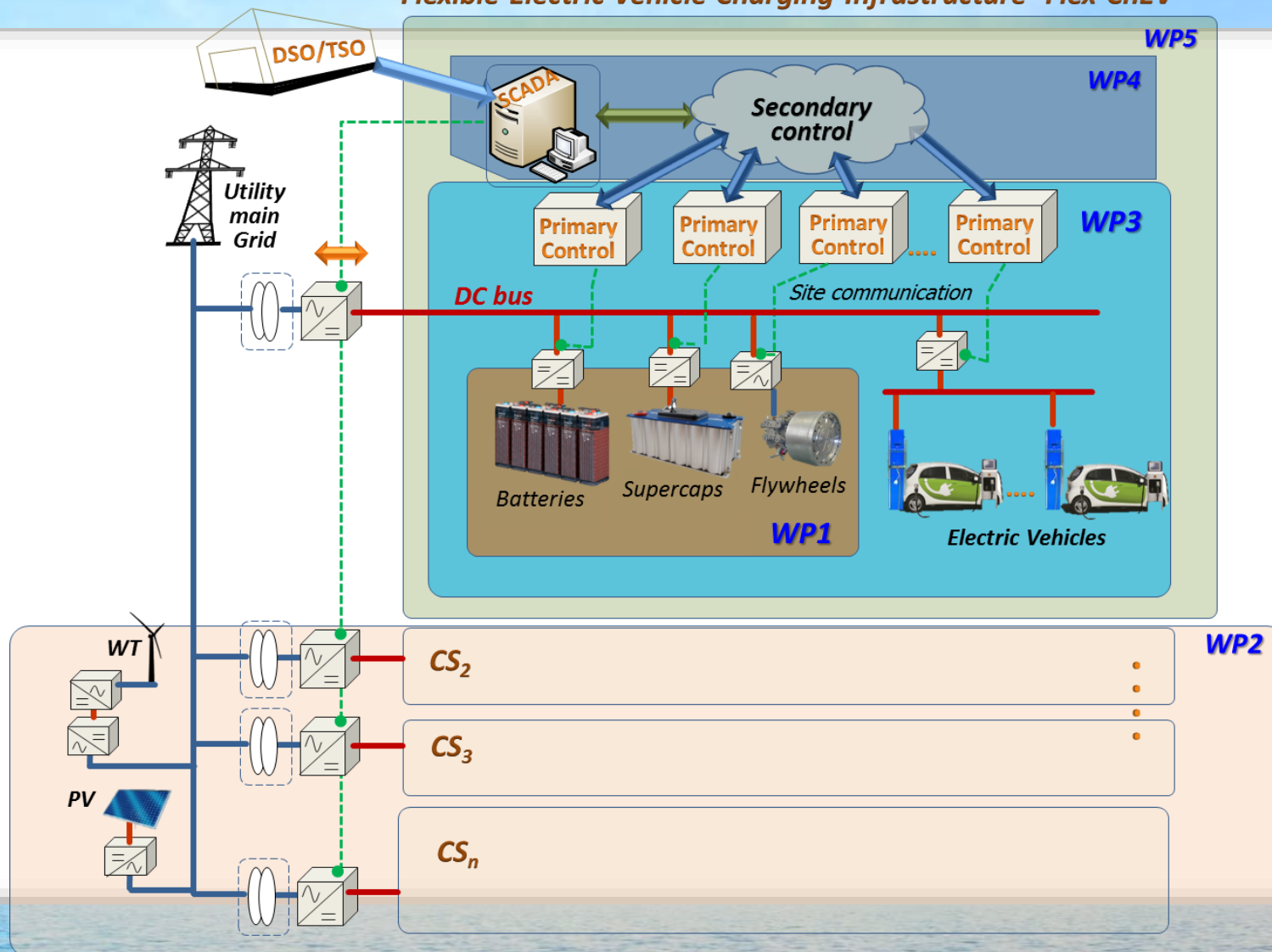
Home Batteries



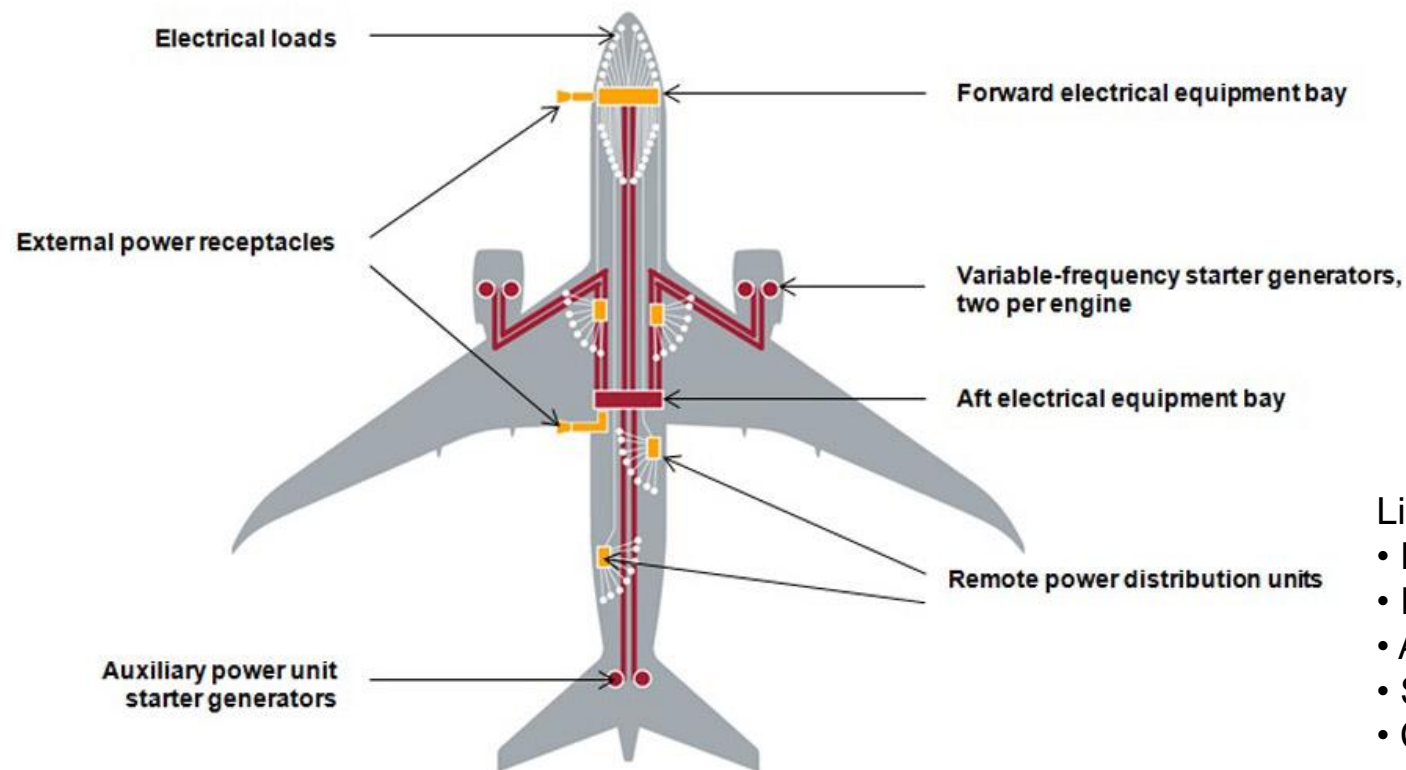
BYD 比亚迪

DC Electrical Vehicle Charging Stations

Flexible Electric Vehicle Charging Infrastructure Flex-ChEV



More electrical aircraft is here: Boeing 787

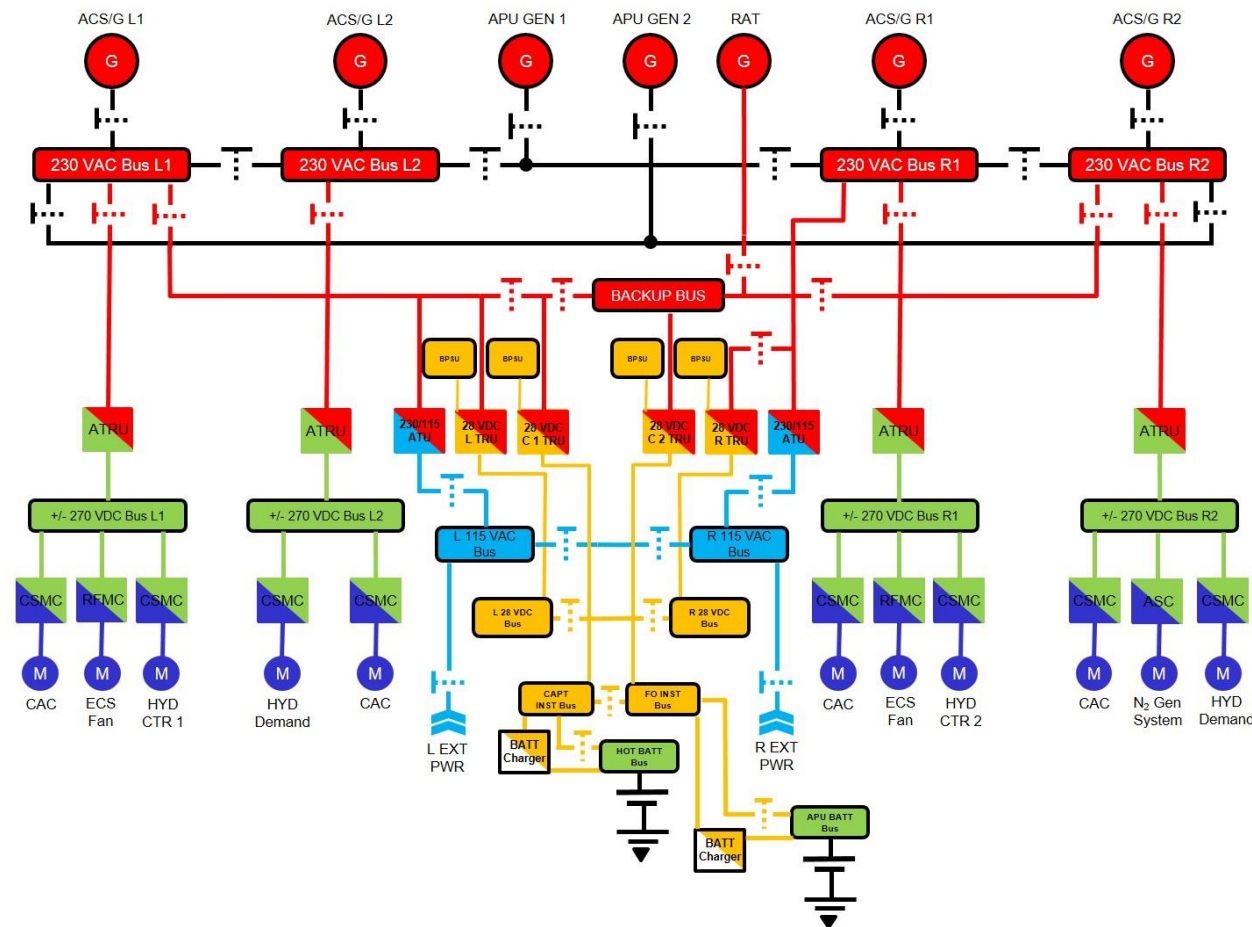
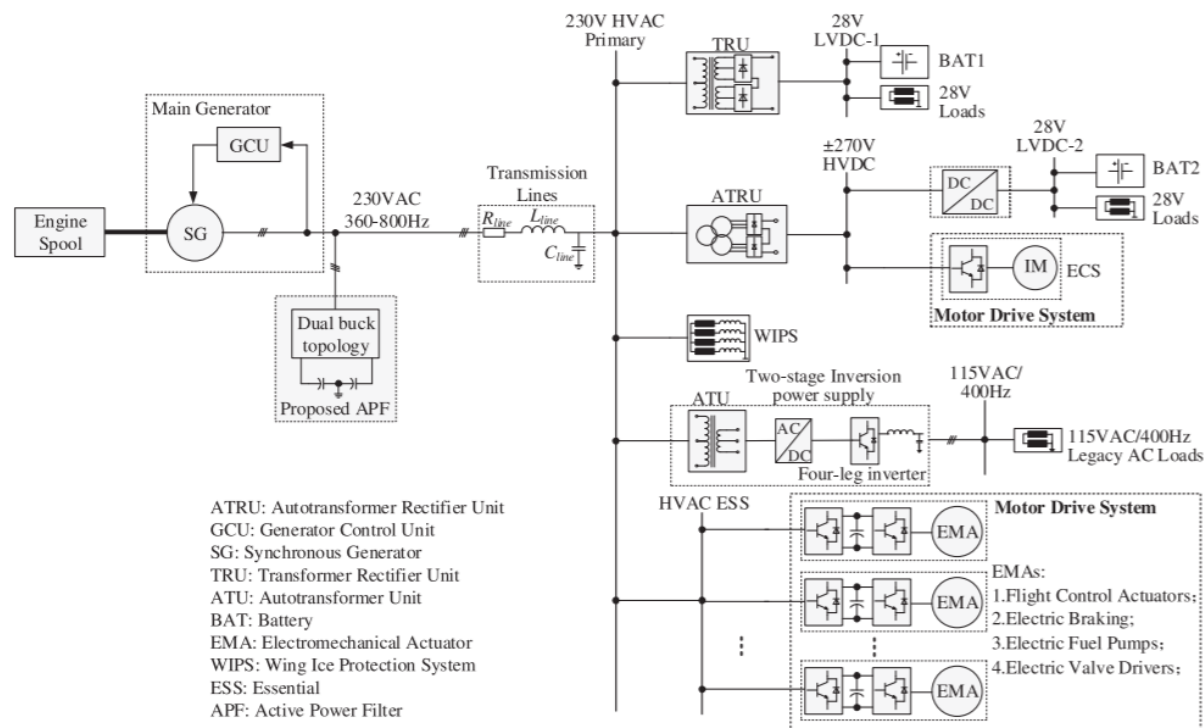


Li-ion batteries key advantages that suit it for modern jet application:

- Required high voltage and high current production
- Improved power quality
- An ability to recharge quickly
- Similar functionality than NiCd batteries, while weighing 30% less
- Compact – about the size of the average car battery

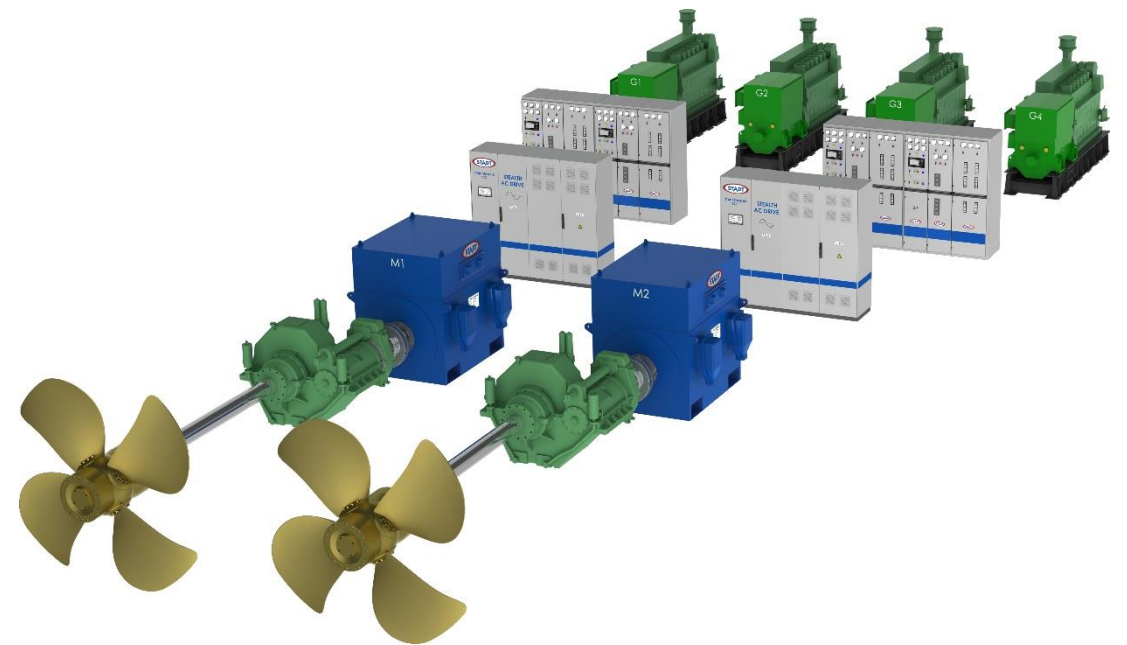
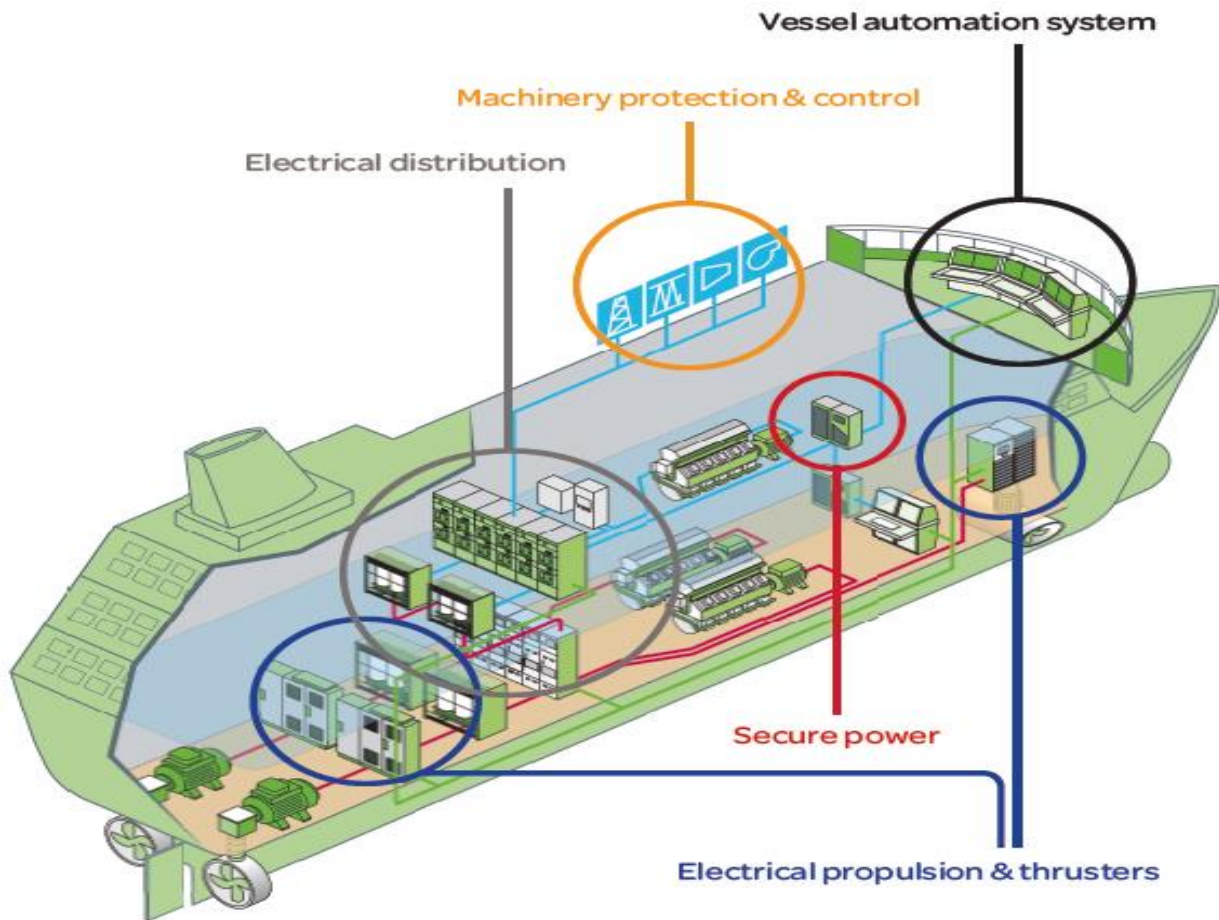
Source: Boeing

More electrical aircraft is here



CHEN et al.: HARMONICS ATTENUATION AND POWER FACTOR CORRECTION OF A MORE ELECTRIC AIRCRAFT POWER GRID

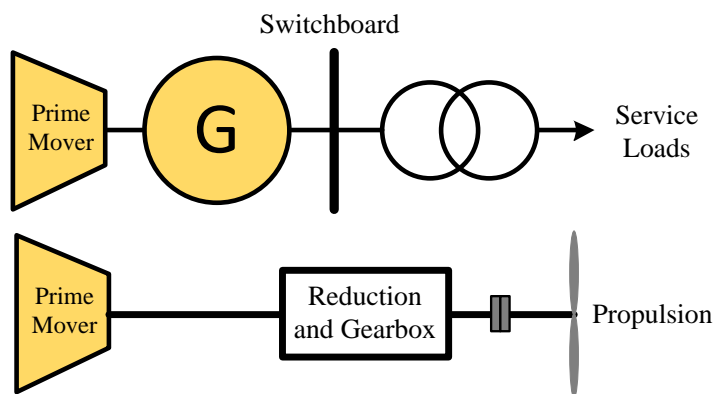
State-of-the-art of SPS



Source: Schneider Electric

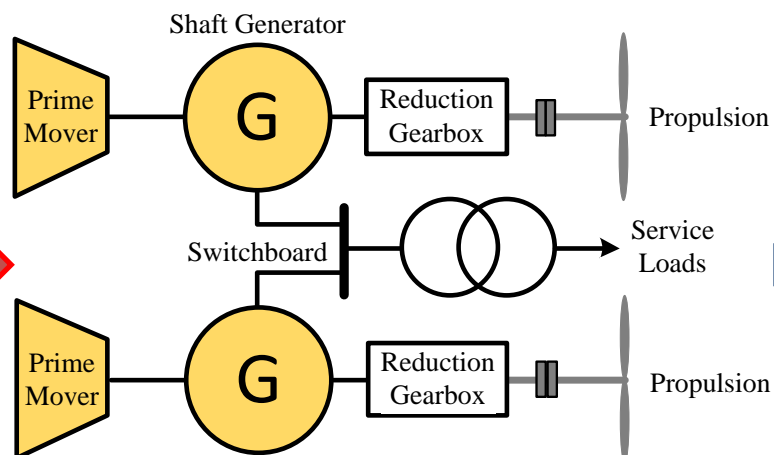
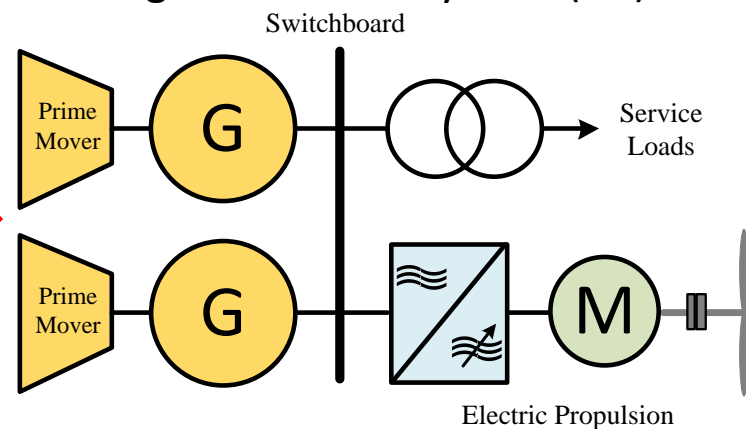
State-of-the-art of SPS

Game changer:
Growing demand of electricity



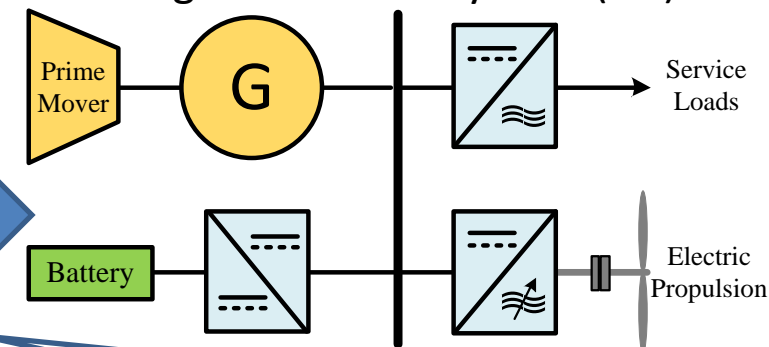
Conventional Ship

Integrated Power System (AC)

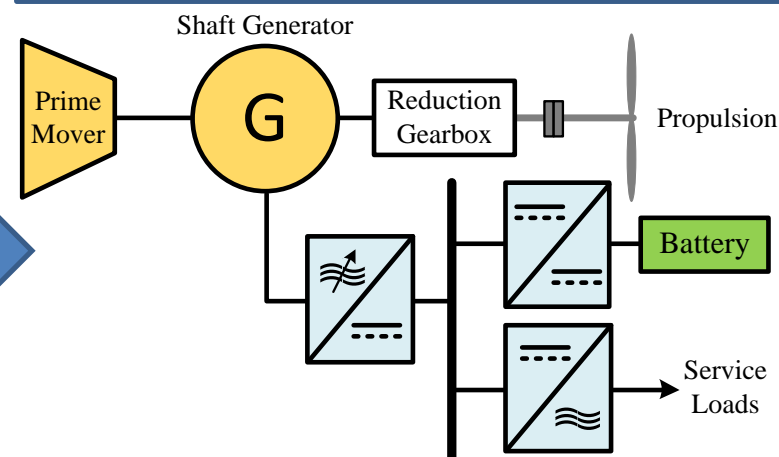


Shaft Generation Solution

Integrated Power System (DC)

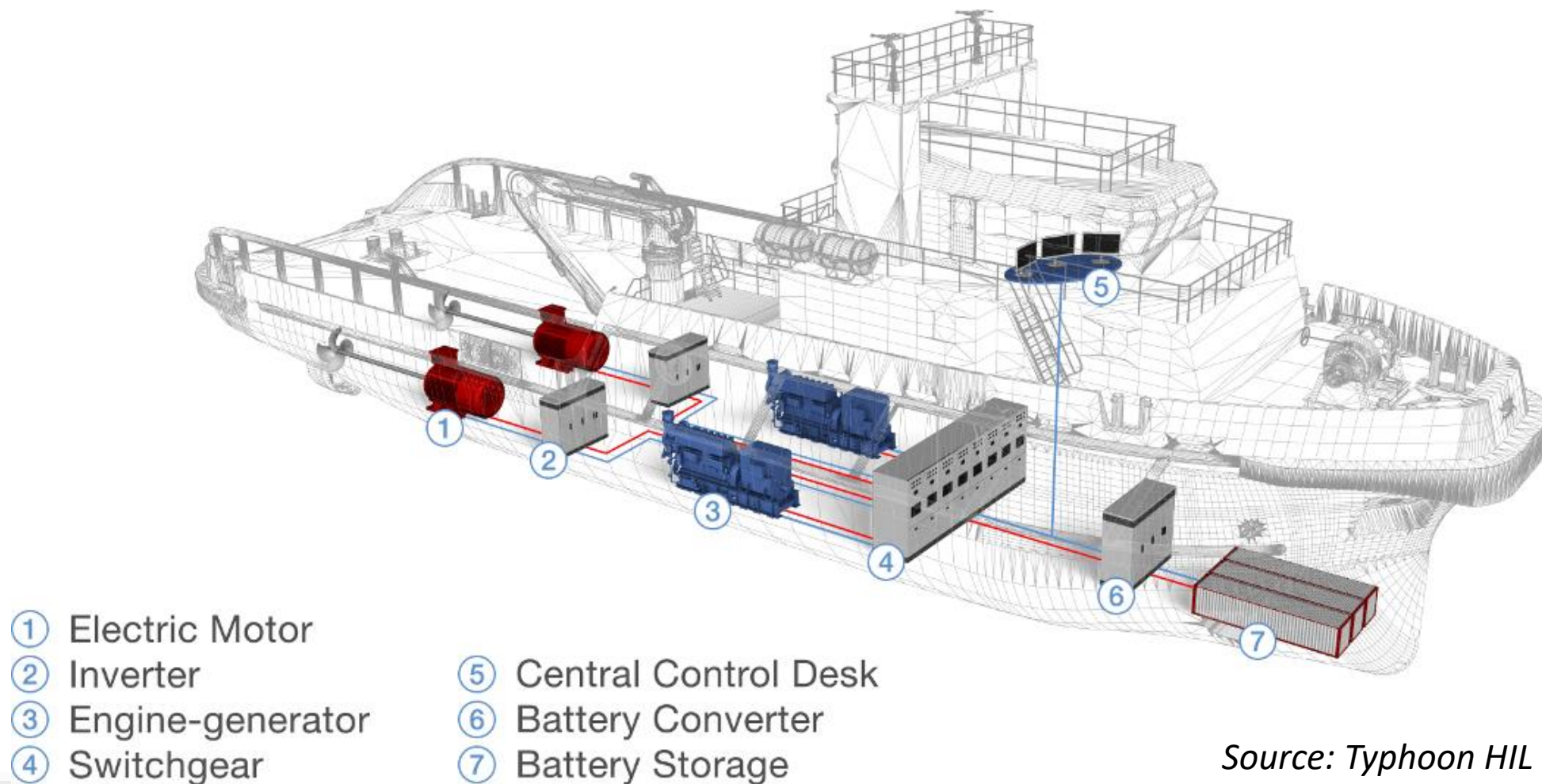


Game changer: Energy storage



(Parallel) Hybrid Propulsion Solution

Microgrids in Ships

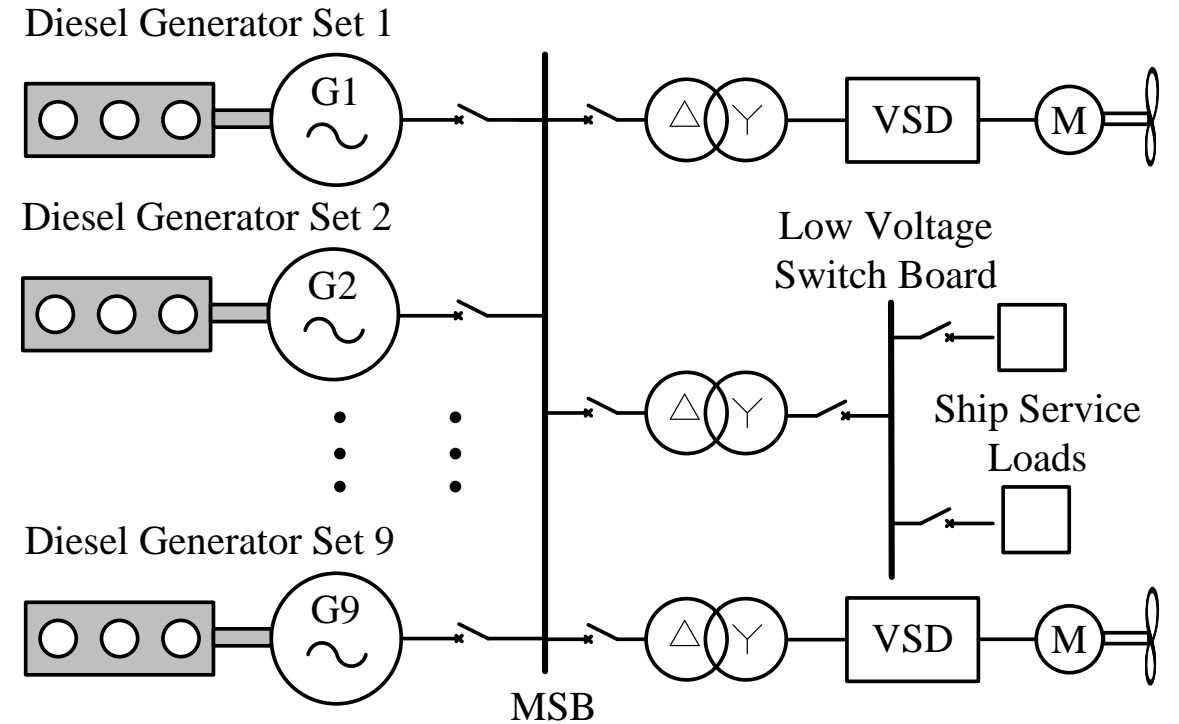


Source: Typhoon HIL

Queen Elizabeth II – cruise ship



Integrated electric propulsion configuration



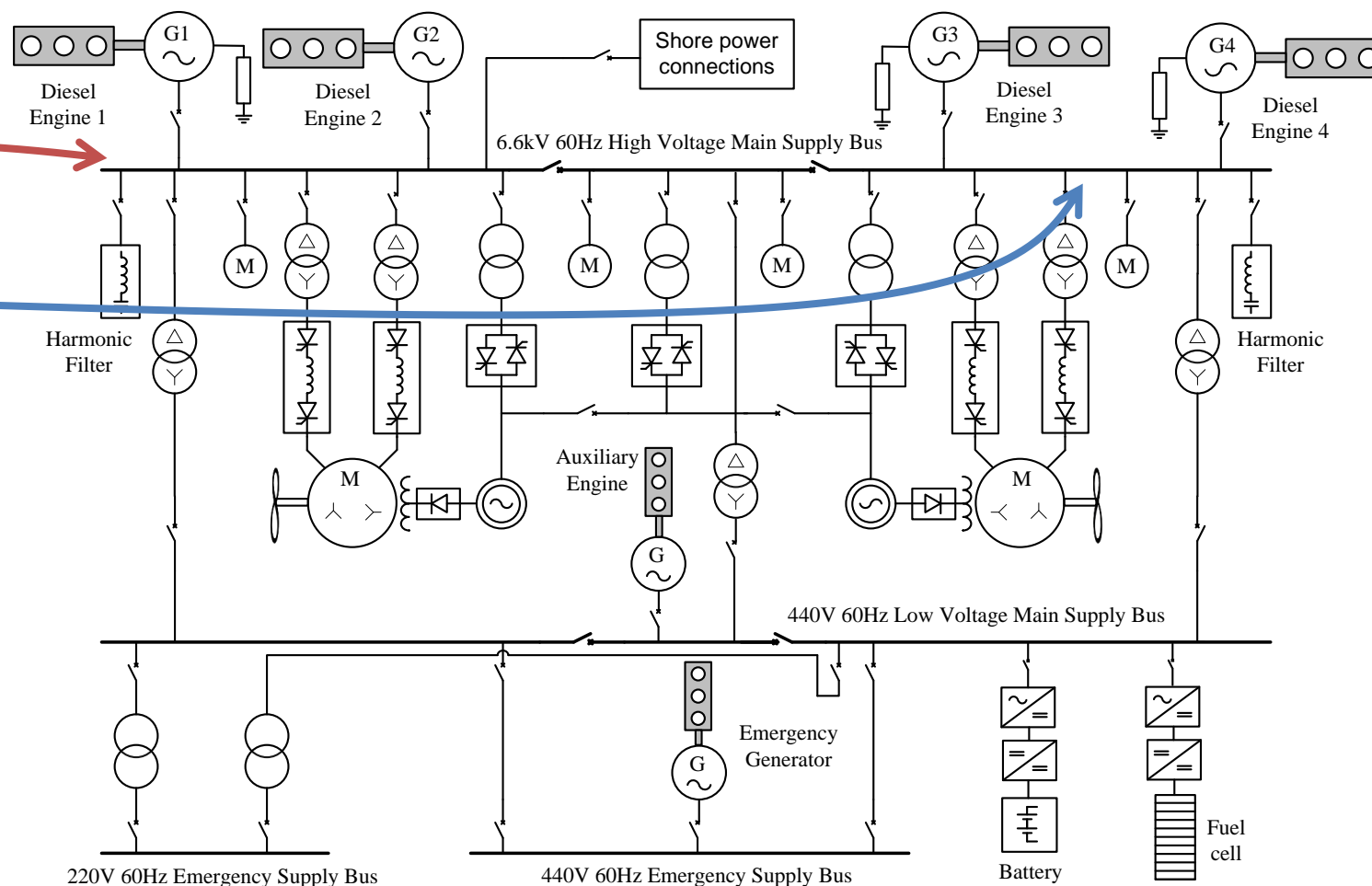
16-cylinder Wärtsilä 16V46CR EnviroEngine marine diesel engines, providing 67,200 kW (90,100 hp)@514 rpm
 2 General Electric LM2500+ gas turbines, total provide 50,000 kW (67,000 hp)

Radial AC distribution system

The 2 busses:

- port side bus
 - starboard side bus
- are linked with bus-tie switches.

These switches can be opened to disconnect the faulty bus from the healthy bus in the event of a fault and thus potential blackouts can be prevented

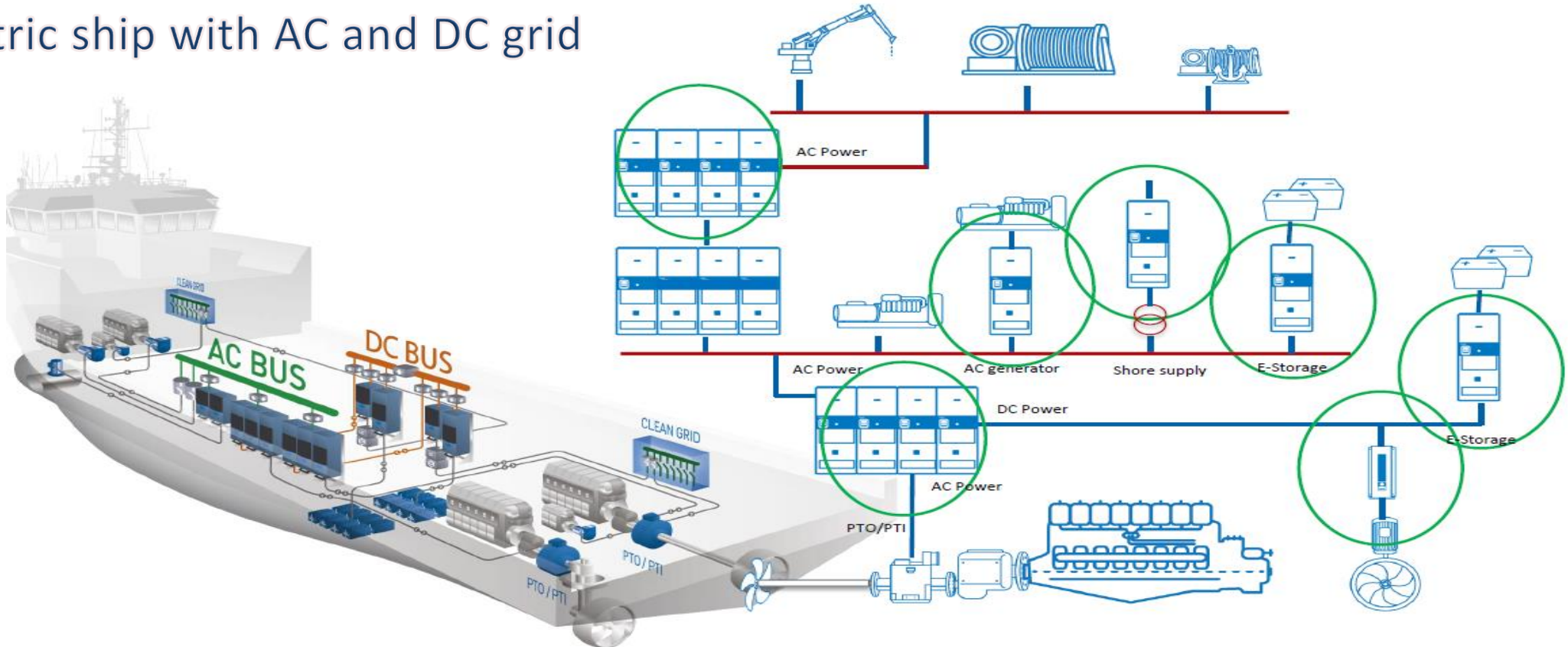


Huang, K.; Srivastava, S.K.; Cartes, D.A.; Sun, L.-H. Market-based multiagent system for reconfiguration of shipboard power systems. *Electr. Power Syst. Res.* **2009**, 79, 550–556.

Hall, D.T. *Practical Marine Electrical Knowledge*, 3rd ed.; Witherby Seamanship: Livingston, UK, 2014.

State-of-the-art of SPS

Fully electric ship with AC and DC grid

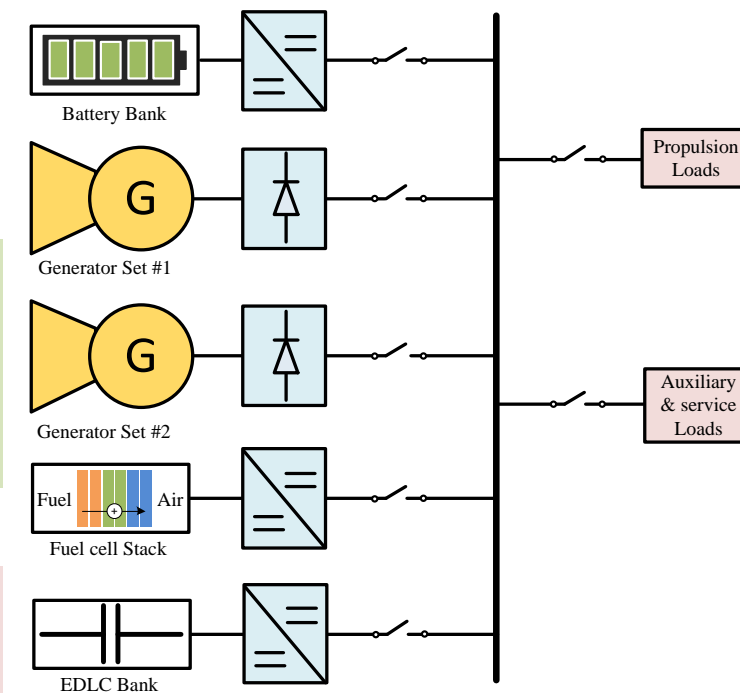
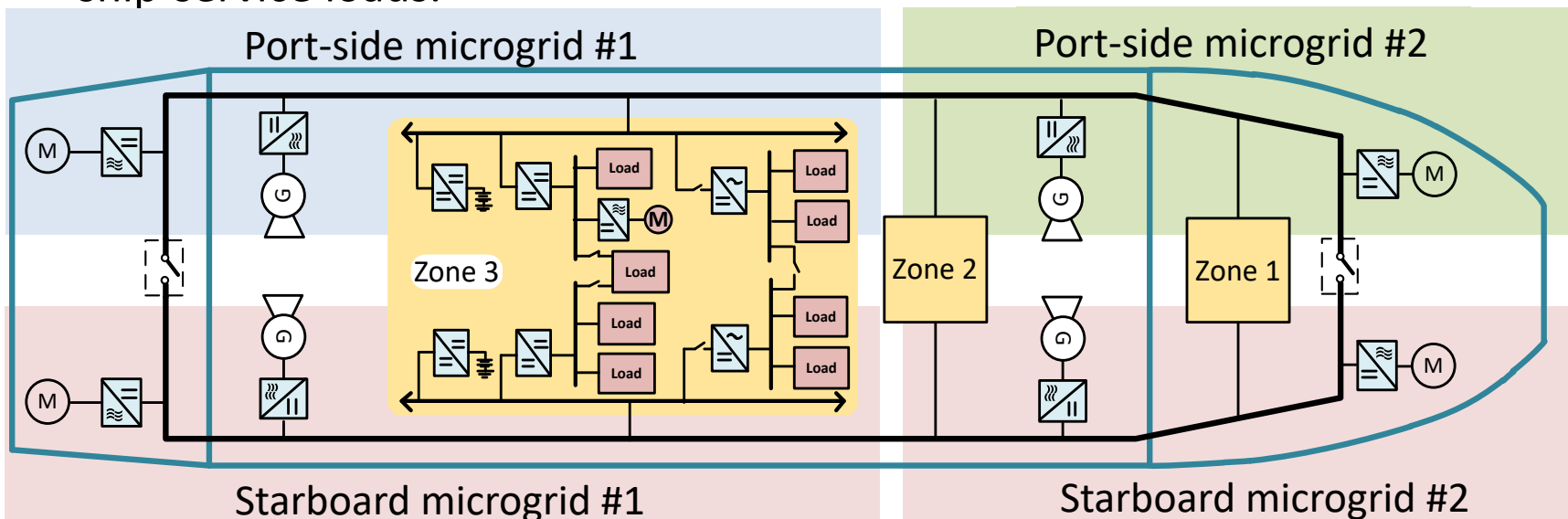


Source: Vacon Power / Danfoss

A Comparative Study of MG and SPS

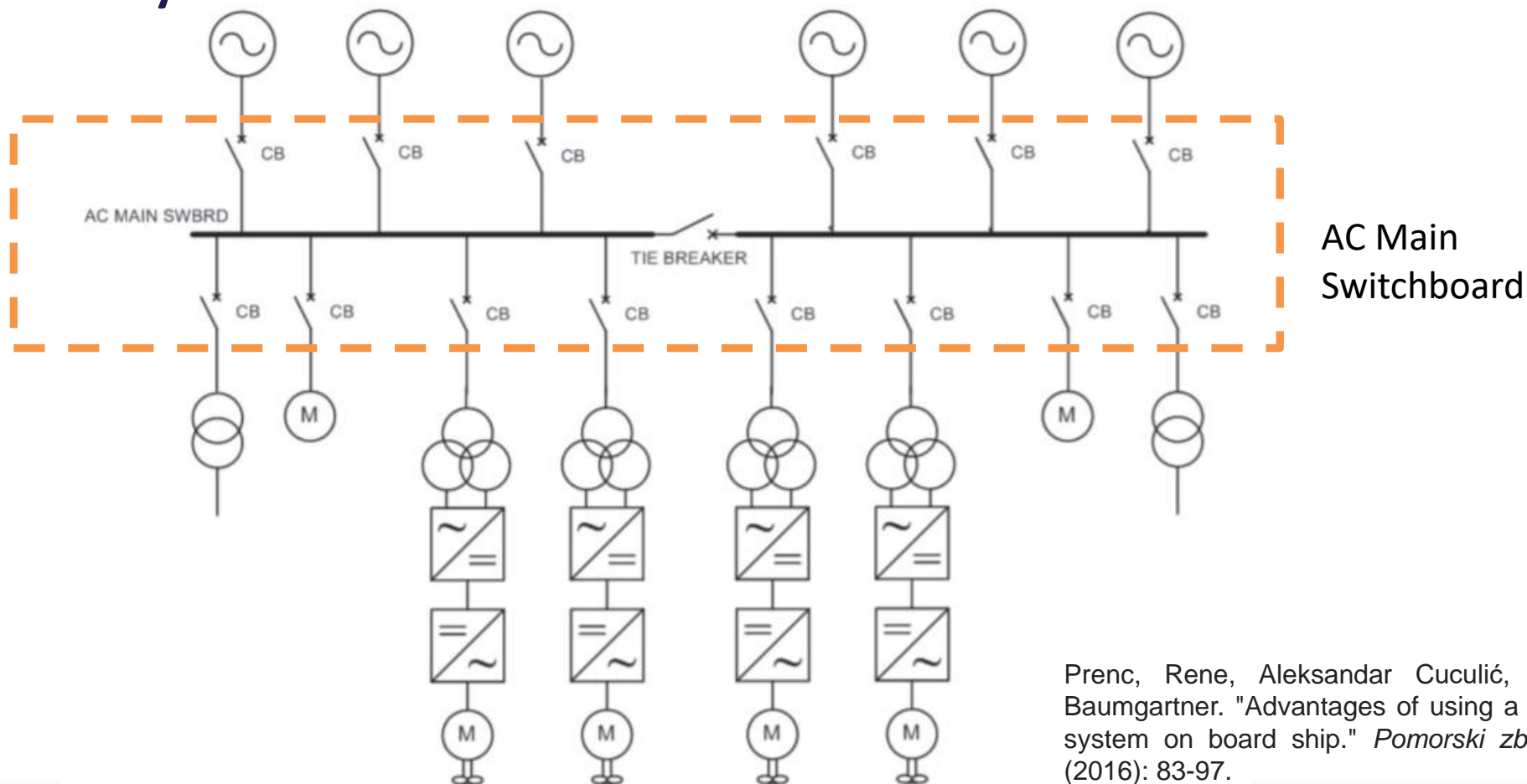
Defining Shipboard Microgrids:

Recommended by IEEE STD 1709-2010 [8], a DC shipboard MG is composed by gensets, centralized or hybridized ESSs, alternative power sources (APSS) [e.g. fuel cell and PV array], electric propulsion system and ship-service loads.



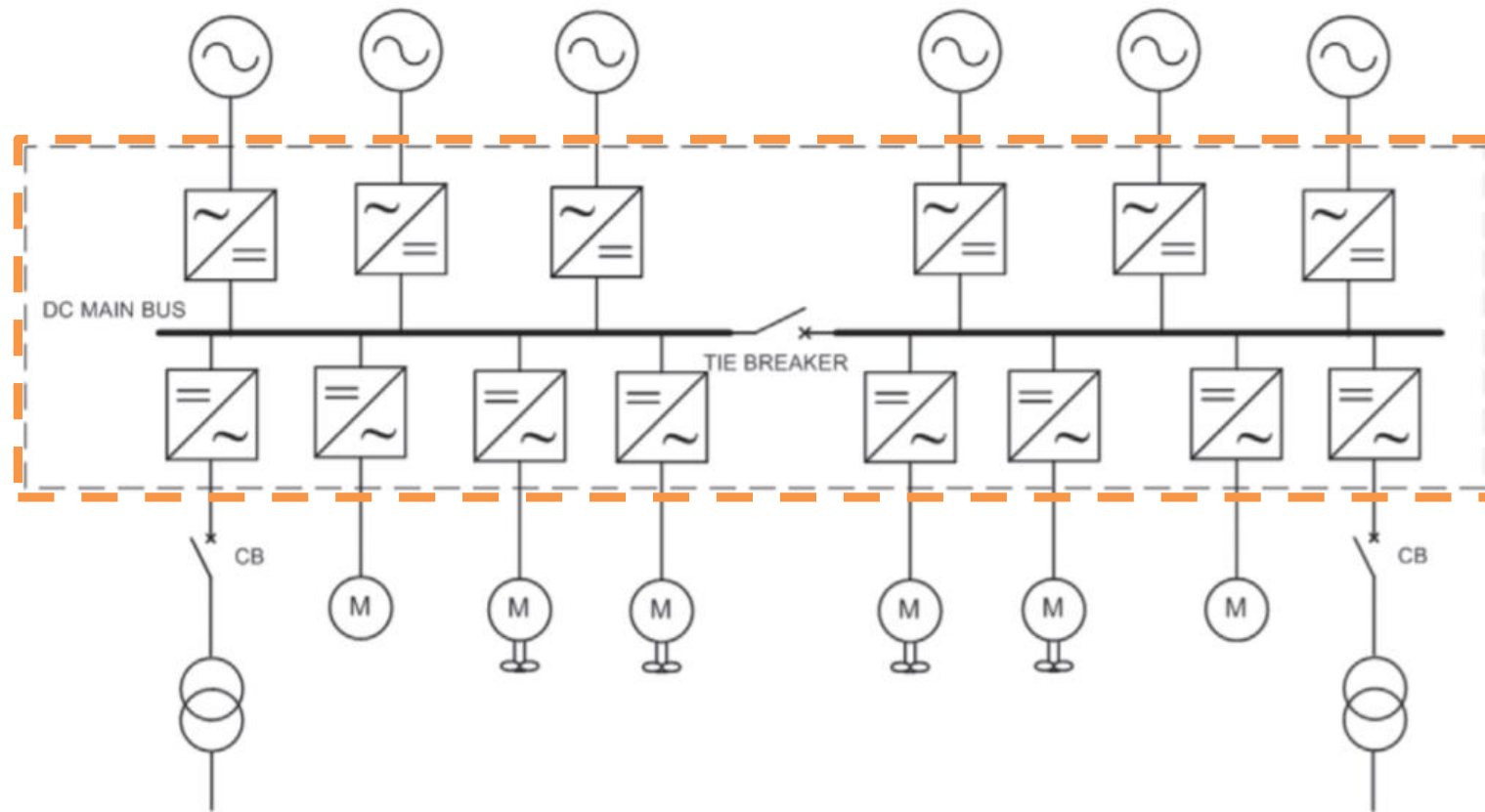
Single-Line Diagram of a sectionalized microgrid

AC Shipboard Power System



Prenc, Rene, Aleksandar Cuculić, and Ivan Baumgartner. "Advantages of using a DC power system on board ship." *Pomorski zbornik* 52.1 (2016): 83-97.

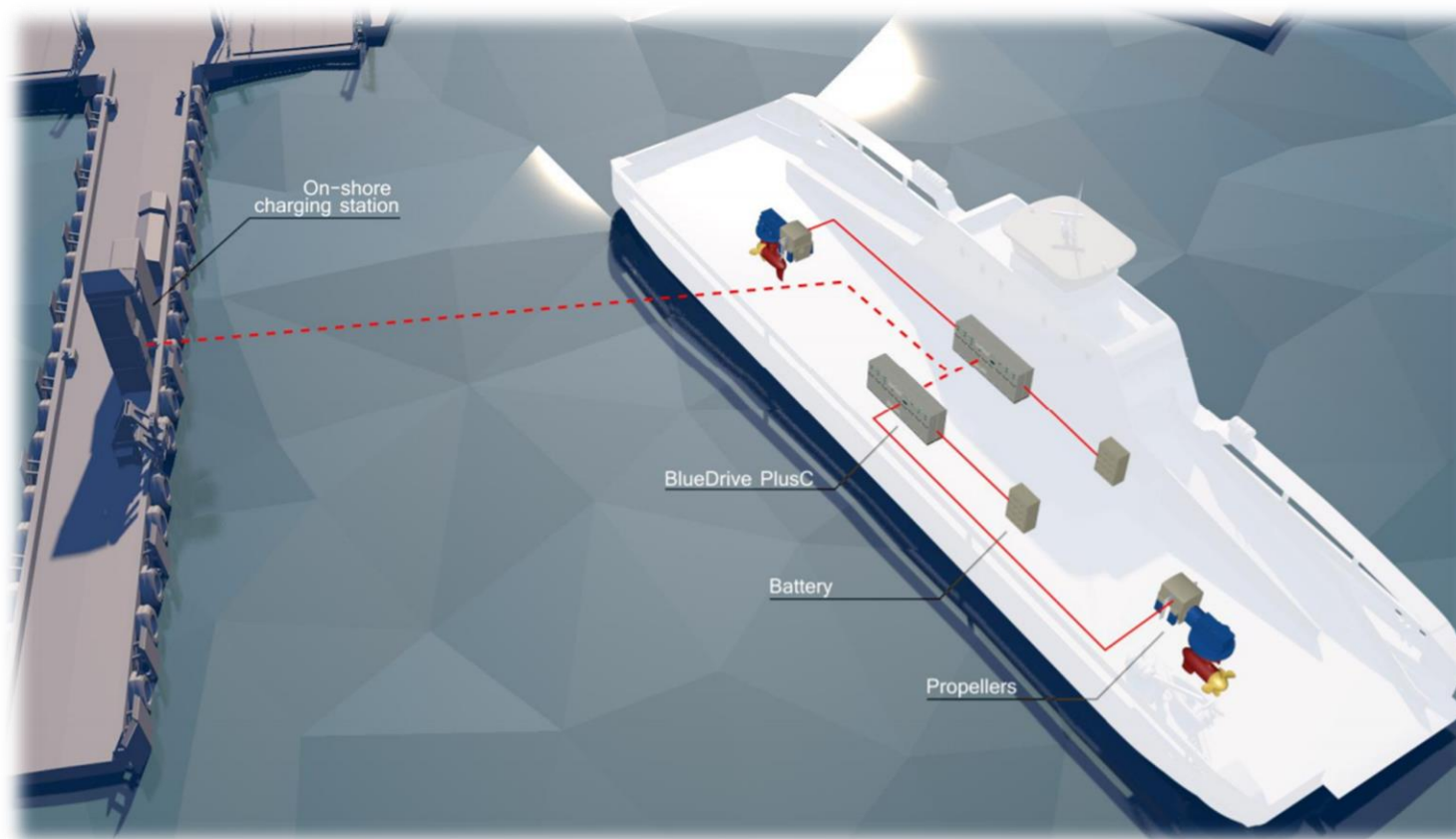
Onboard DC grid – Multidrive power system scheme



BlueDrive PlusC
from SIEMENS

<20MW

Onboard DC grid – Multidrive power system scheme



Source: SIEMENS

Onboard DC grid – Distributed power system scheme

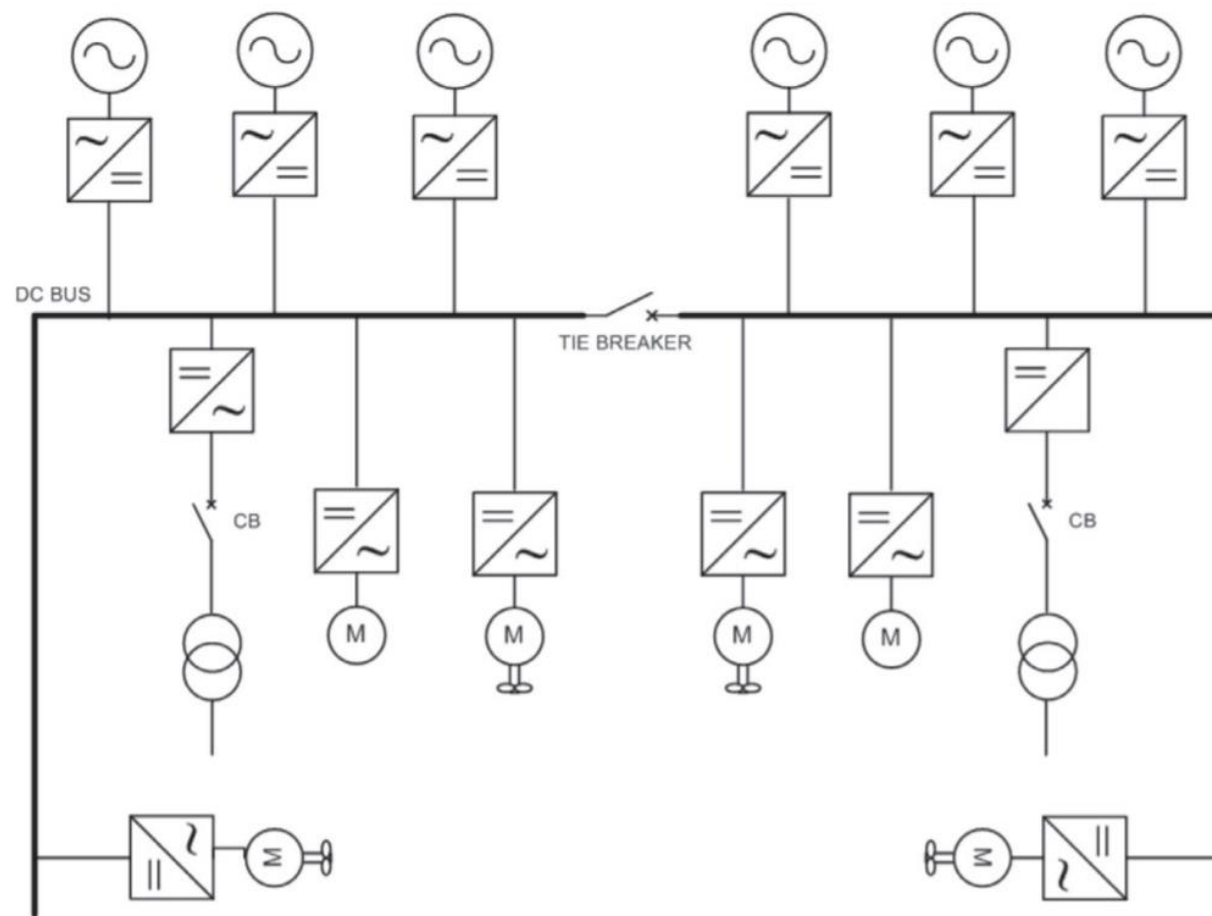
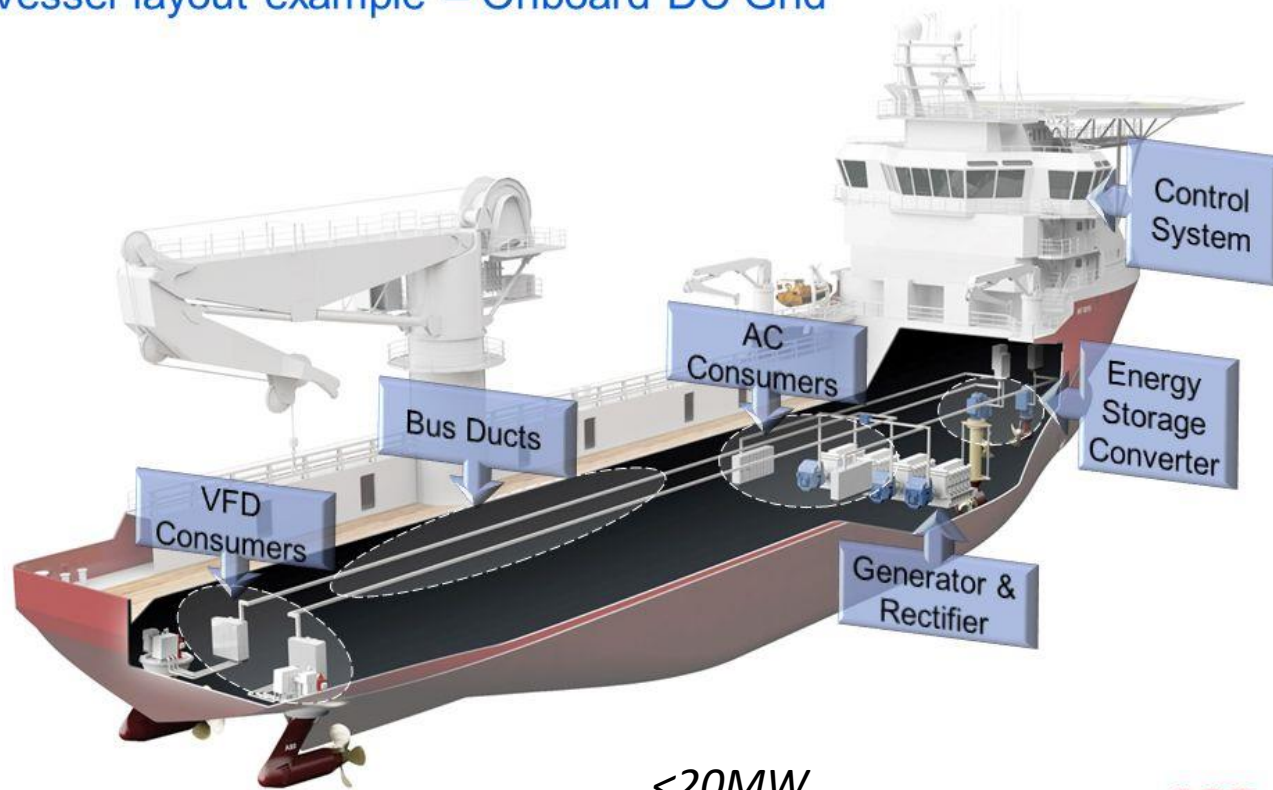


ABB Concept

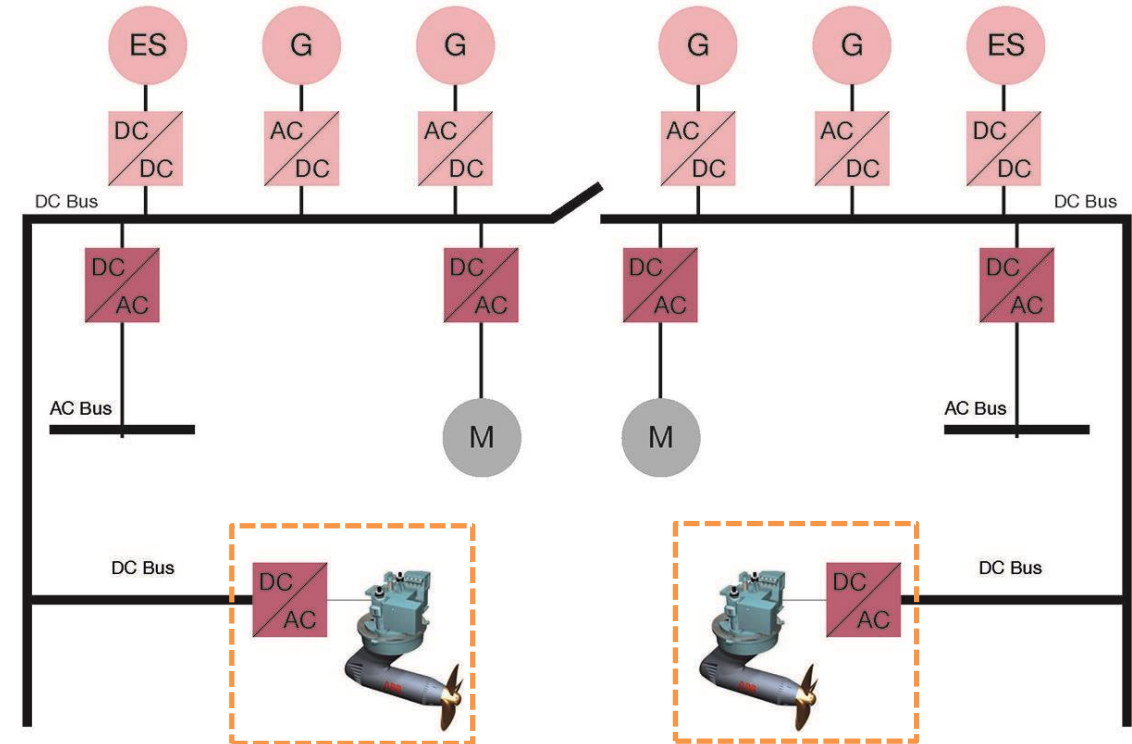
Onboard DC Grid

Vessel layout example – Onboard DC Grid



<20MW

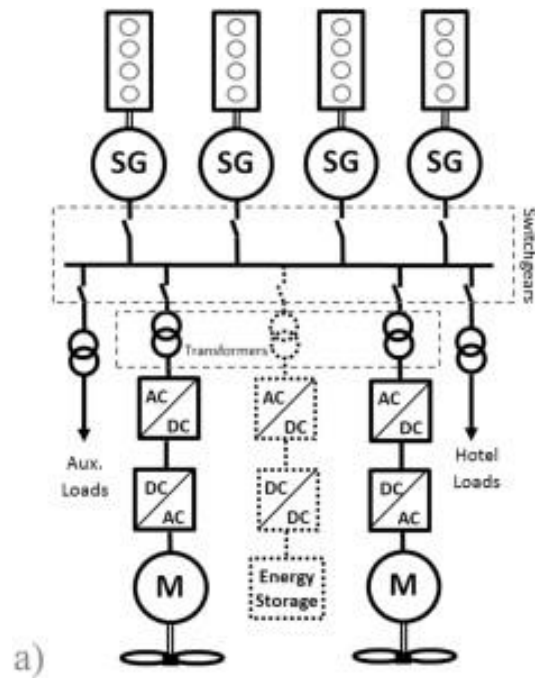
ABB



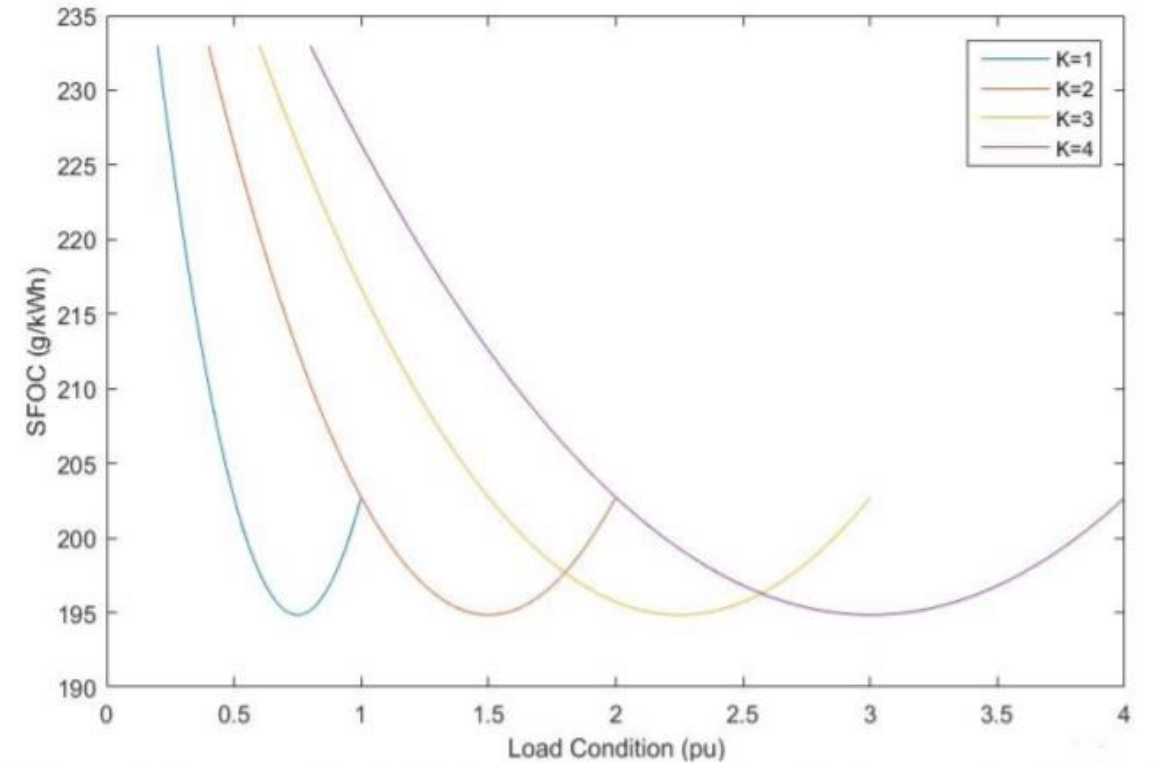
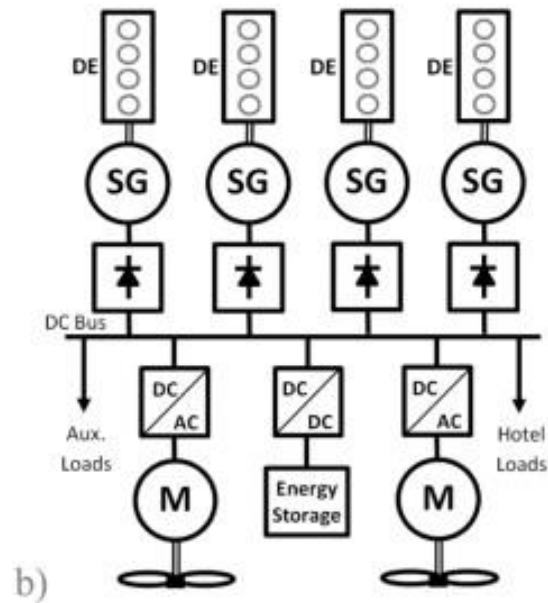
Source: ABB

State-of-the-art of SPS

AC SMG

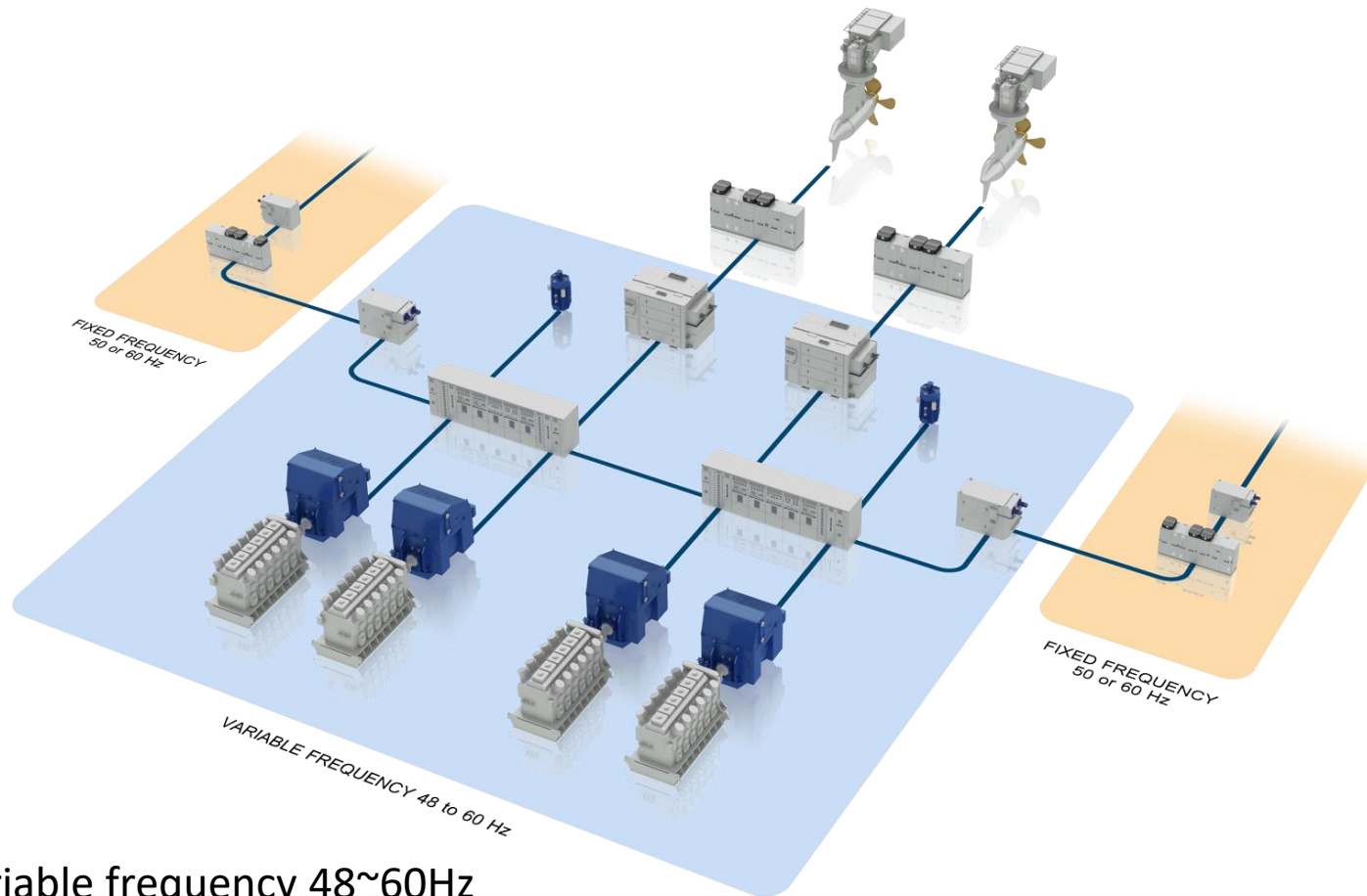


DC SMG

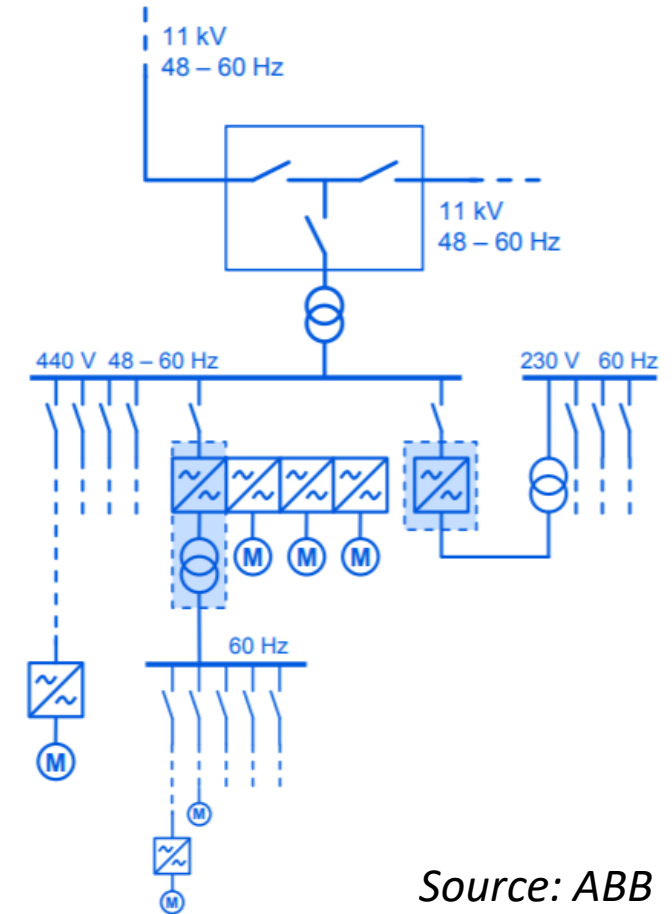


Schematic diagram of fuel efficiency characteristic for diesel generation (in fixed speed)

Dynamic AC concept – DAC by ABB

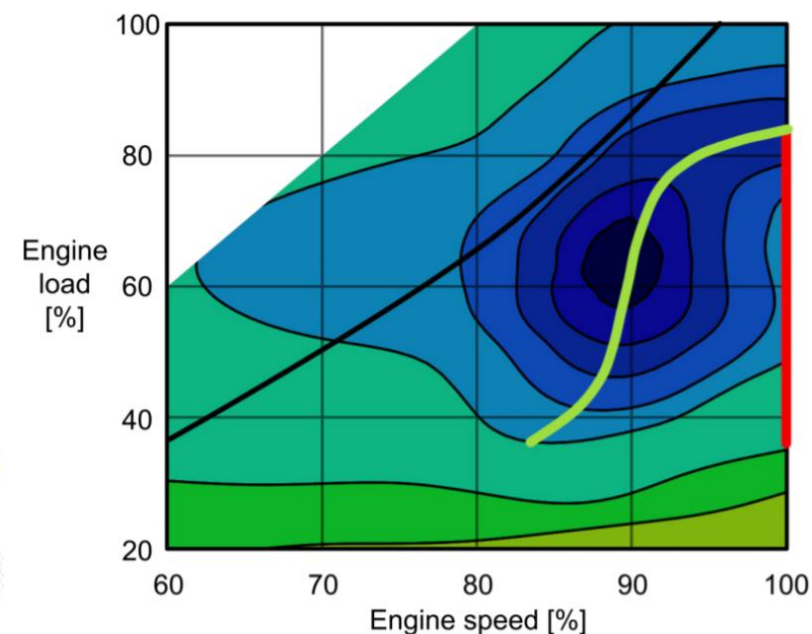
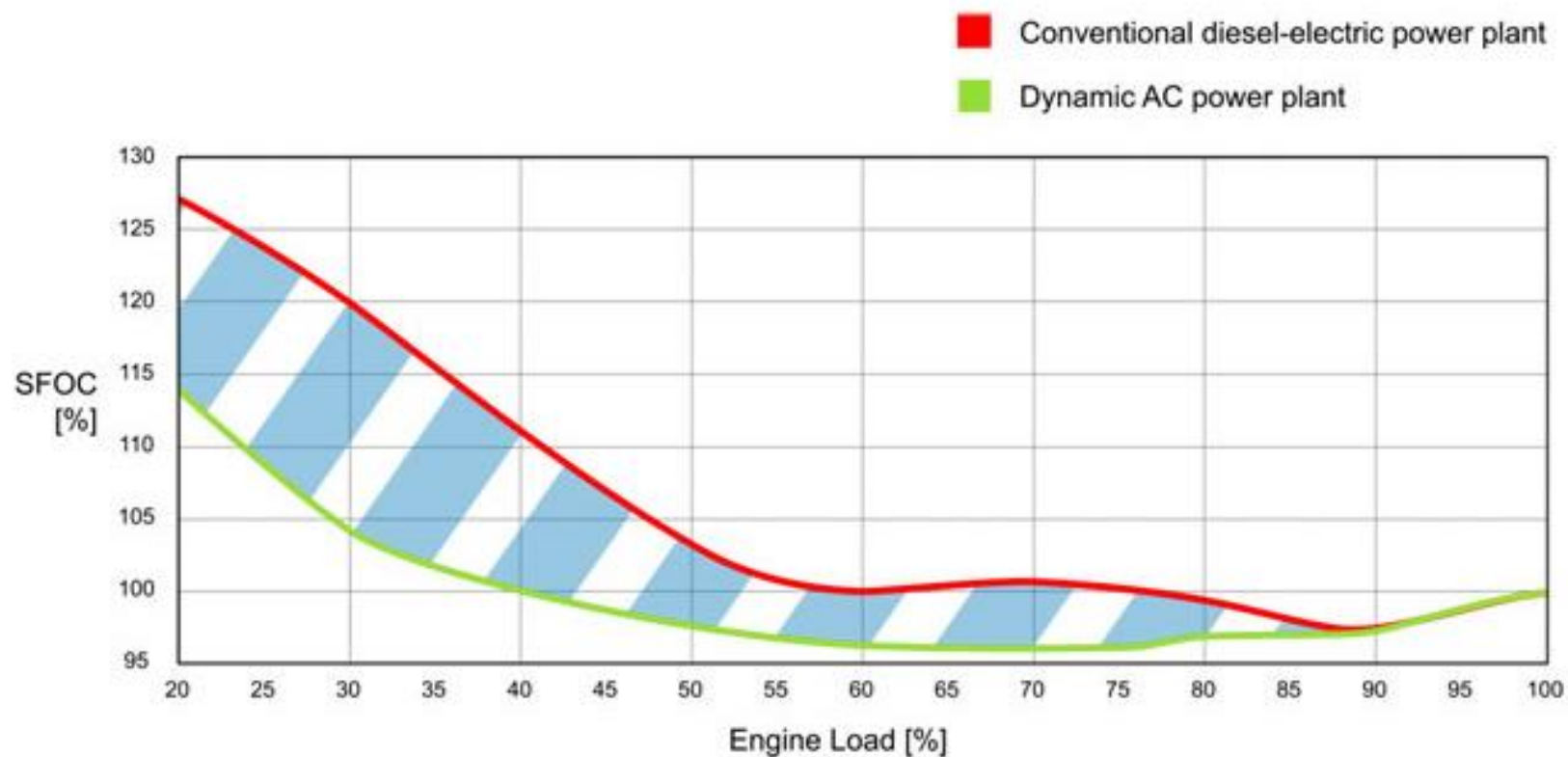


Variable frequency 48~60Hz



Source: ABB

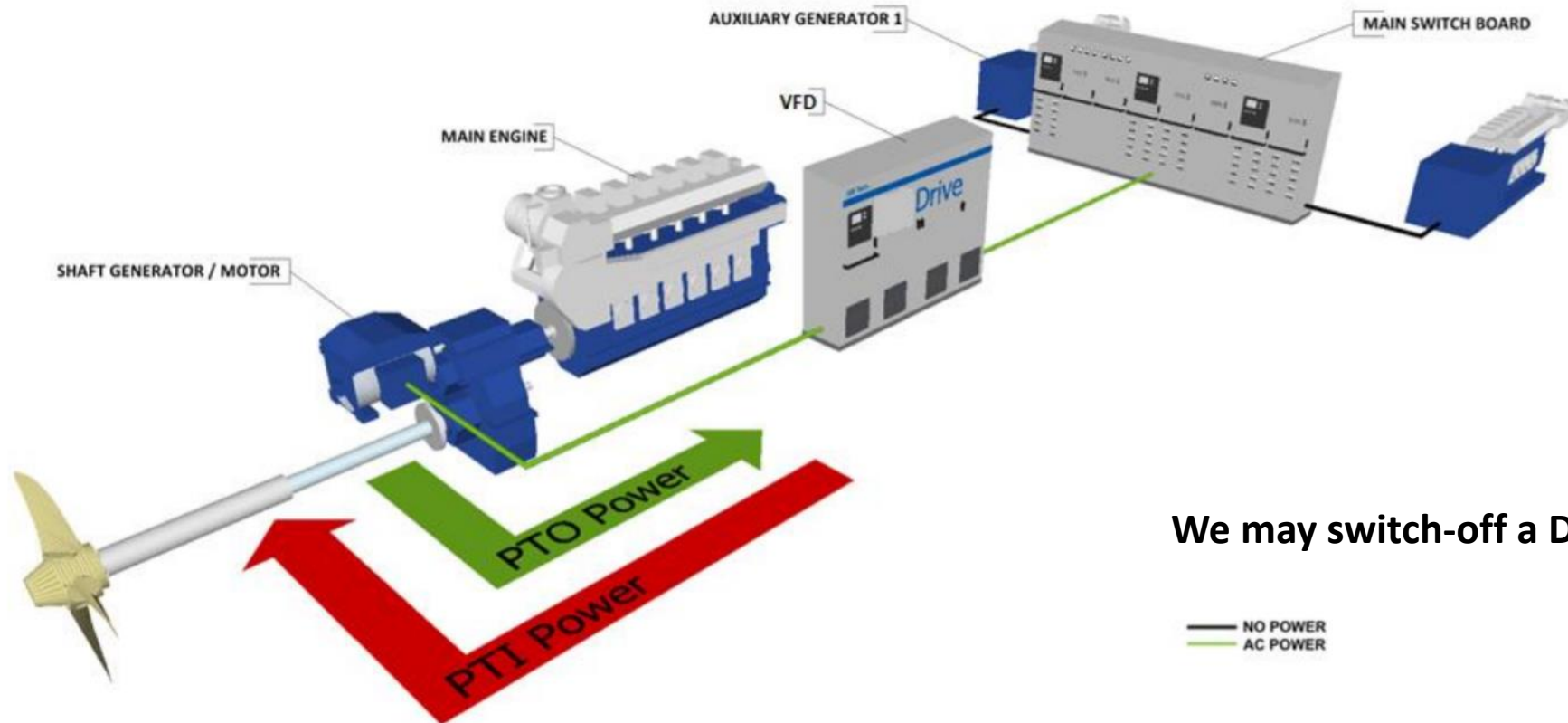
Dynamic AC concept – DAC by ABB



Benefits of Dynamic AC- Up to 6 % annual fuel savings for large cruise vessel (+20MW)

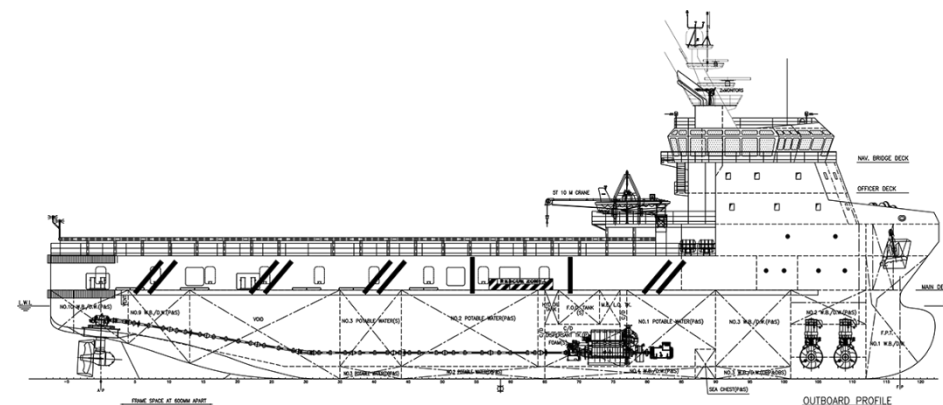
Source: ABB

Operating modes (PTO/PTI) of a shaft generator/motor system with VFD-



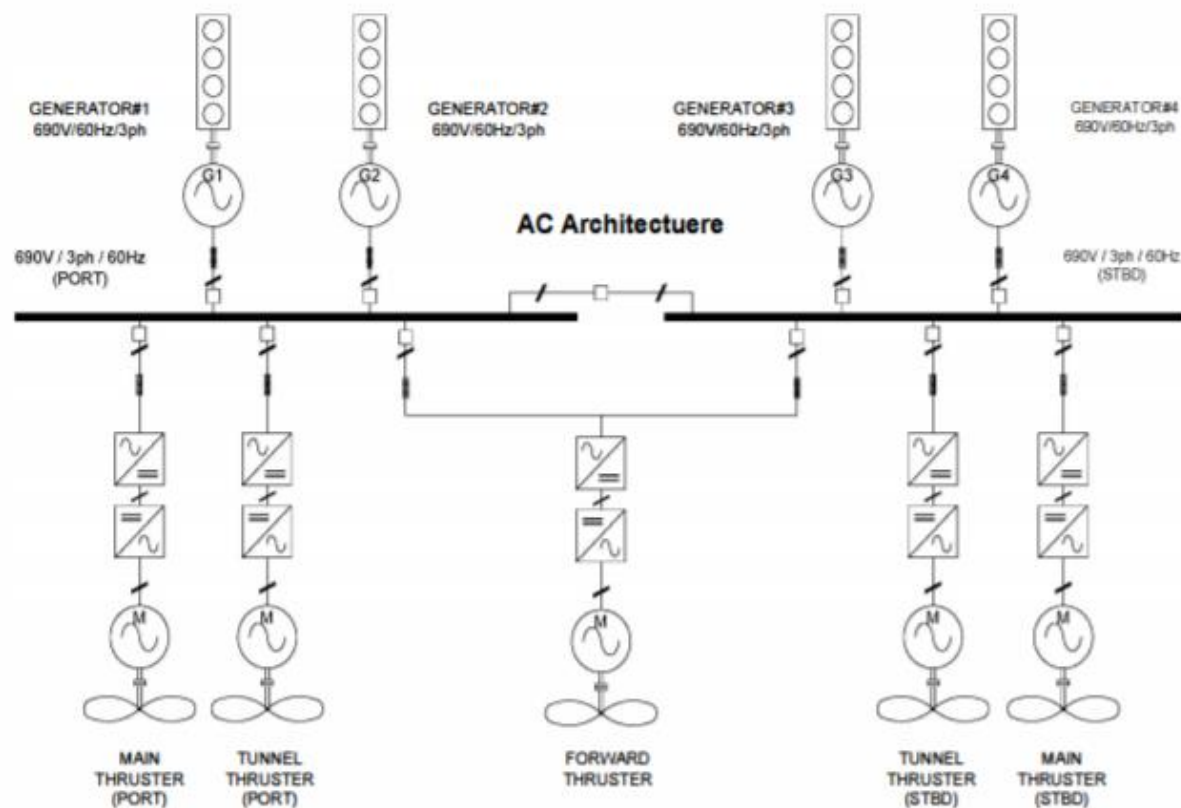
We may switch-off a DG!

Platform support vessel (PSV)

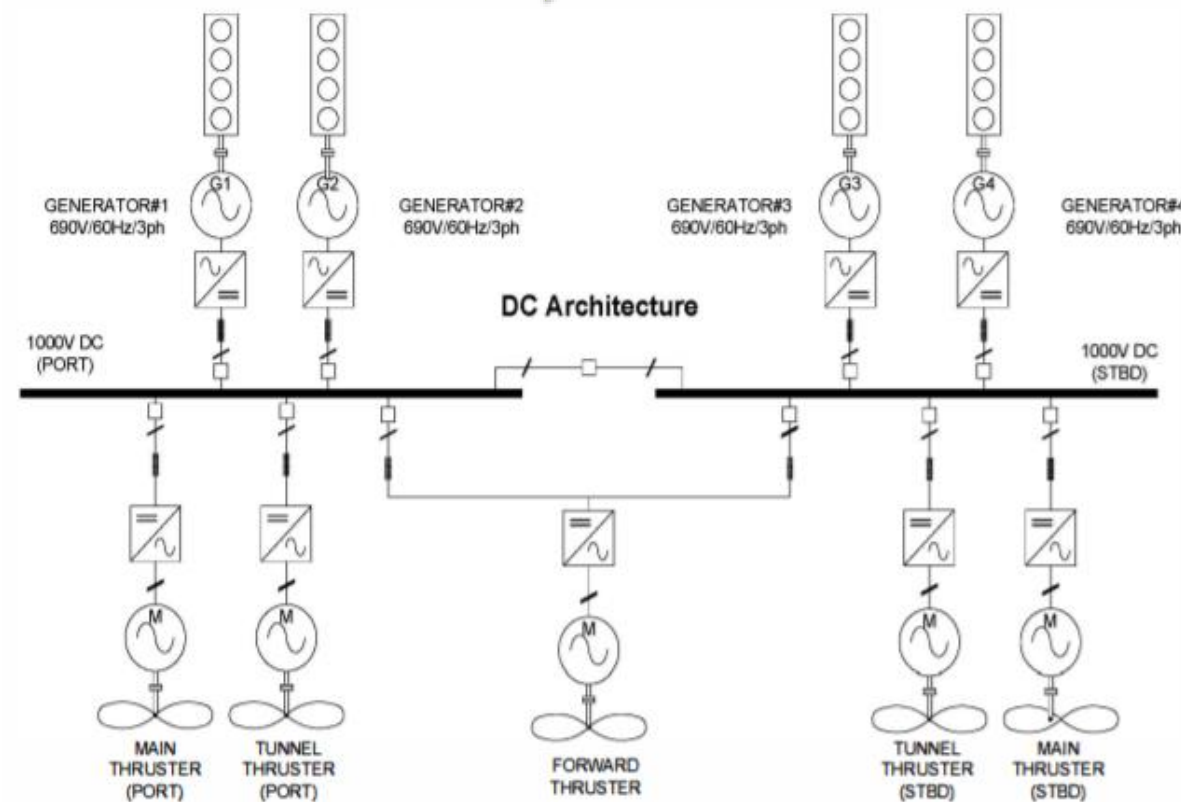


Platform support vessel (PSV)

AC

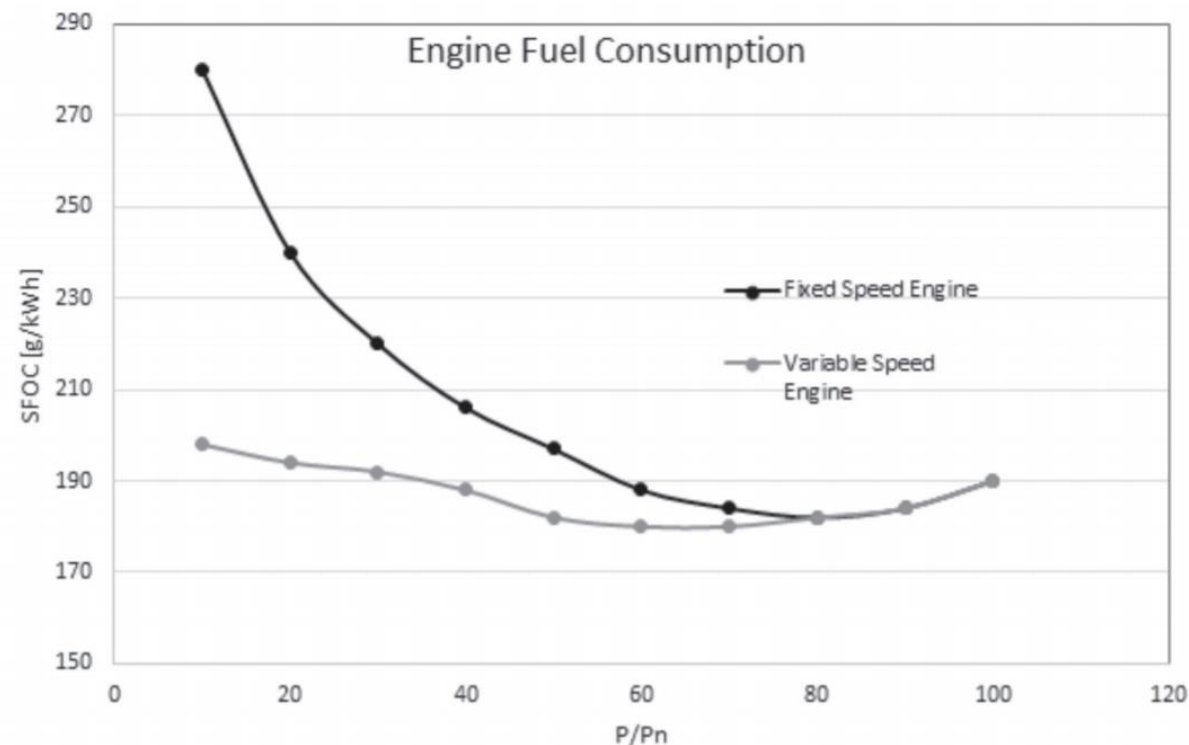


DC



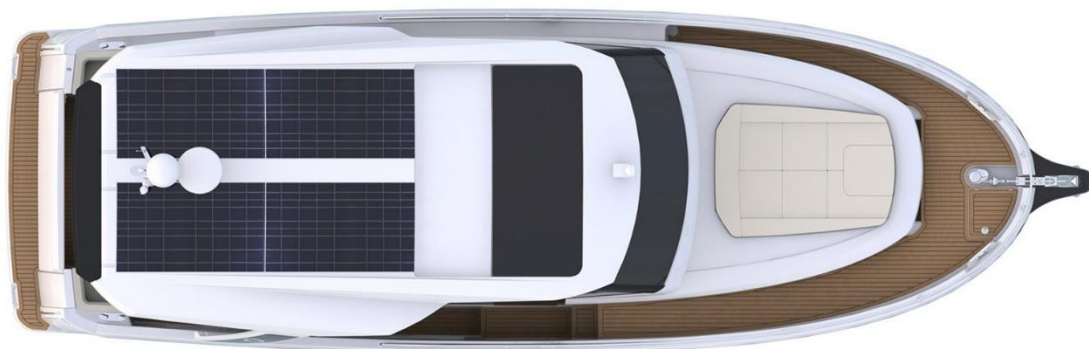
Benefits of using a DC ship power system

- Improvement of prime mover efficiency and reduction of fuel costs,
- Weight and space savings,
- Generators operating with a unity power factor,
- Lower transmission losses,
- Faster and simpler parallel connection of generators,
- Simpler implementation of energy storage.



Rao, Srinivasa, et al. "An exercise to qualify LVAC and LVDC power system architectures for a Platform Supply Vessel." *Transportation Electrification Asia-Pacific (ITEC Asia-Pacific)*, 2016 IEEE Conference and Expo. IEEE, 2016.

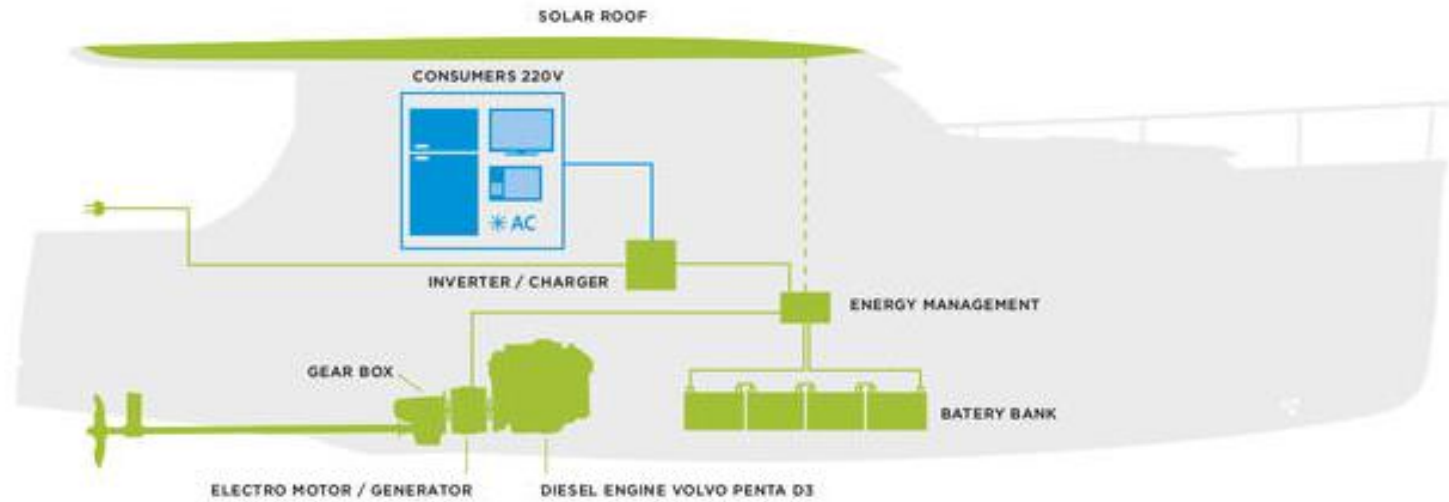
Hybrid Yachts



Lithium battery technology available: a 11,5 kWh on Greenline 33, 23 kWh on Greenline 40 and 46 kWh on Greenline 46 (battery pack with a permissible discharge of 100%).

www.greenlinehybrid.si

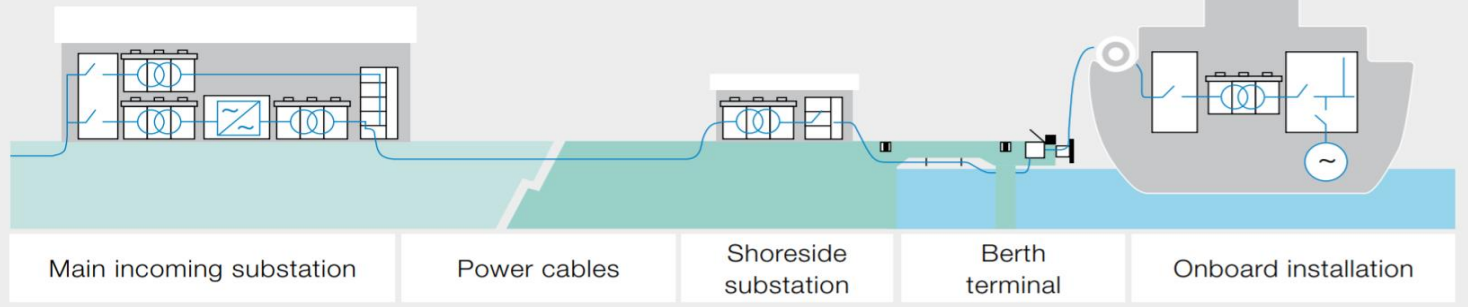
Hybrid Yachts



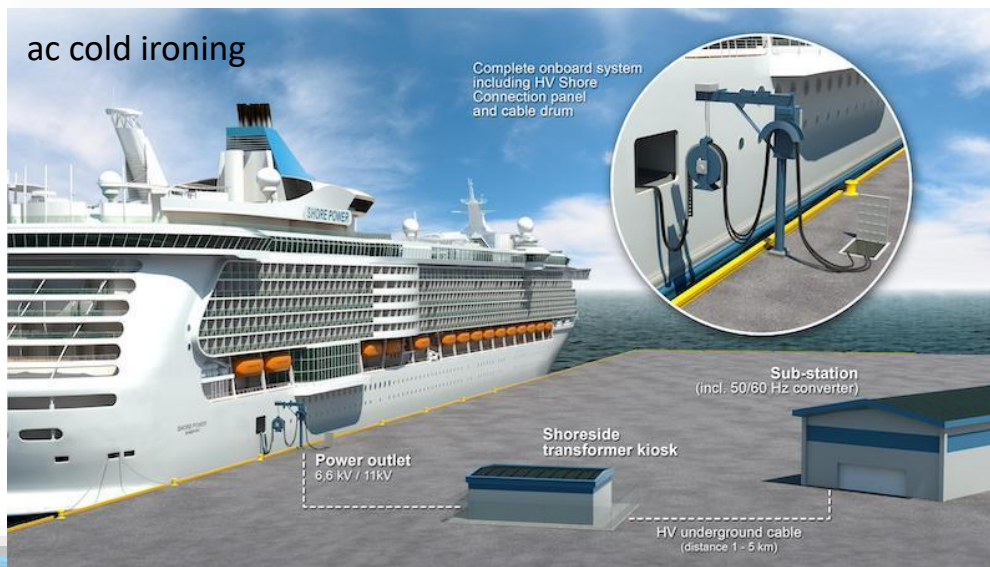
Cold Ironing



Overview of a ship-to-shore power connection

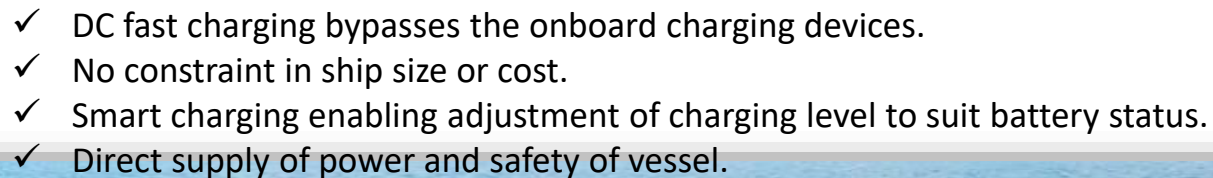


ac cold ironing



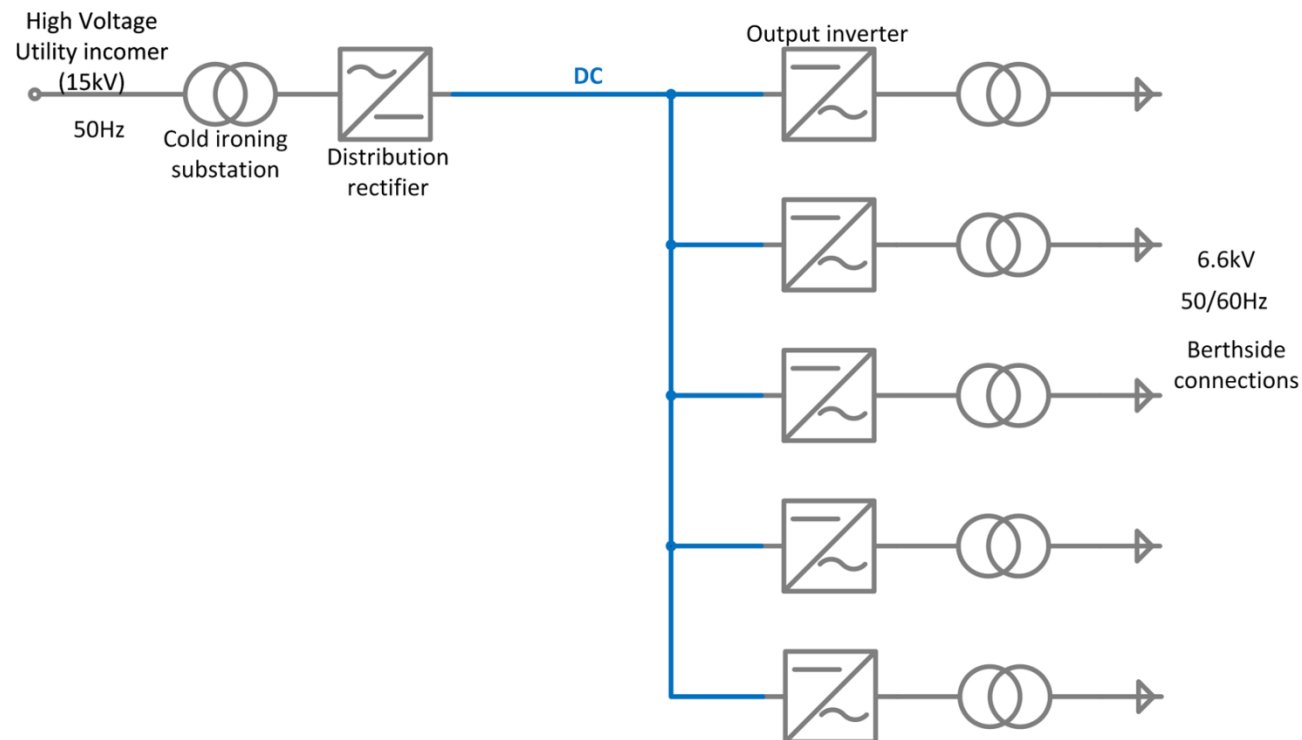
- High voltage shore connection (HVSC)
 - 1-20MVA, 6.6-11kV
- Low voltage shore connection (LVSC)
 - <1MVA, <1kVac, 1.5kVdc

dc cold ironing ?



Cold Ironing

DC distribution configuration



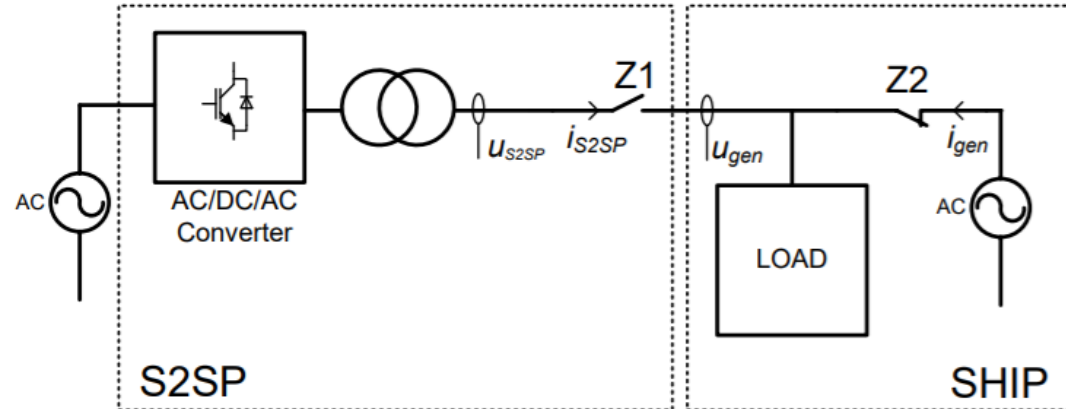
- By extending of two previous configuration with introducing DC bus.
- Easier to integrate with any energy storage device
- Able to use in small quay area

E. A. Sciberras, B. Zahawi, D. J. Atkinson, A. Juando, and A. Sarasquete, "Cold ironing and onshore generation for airborne emission reductions in ports," *Proc. Inst. Mech. Eng. Part M J. Eng. Marit. Environ.*, vol. 230, no. 1, p. 1475090214532451, 2014.

Synchronization

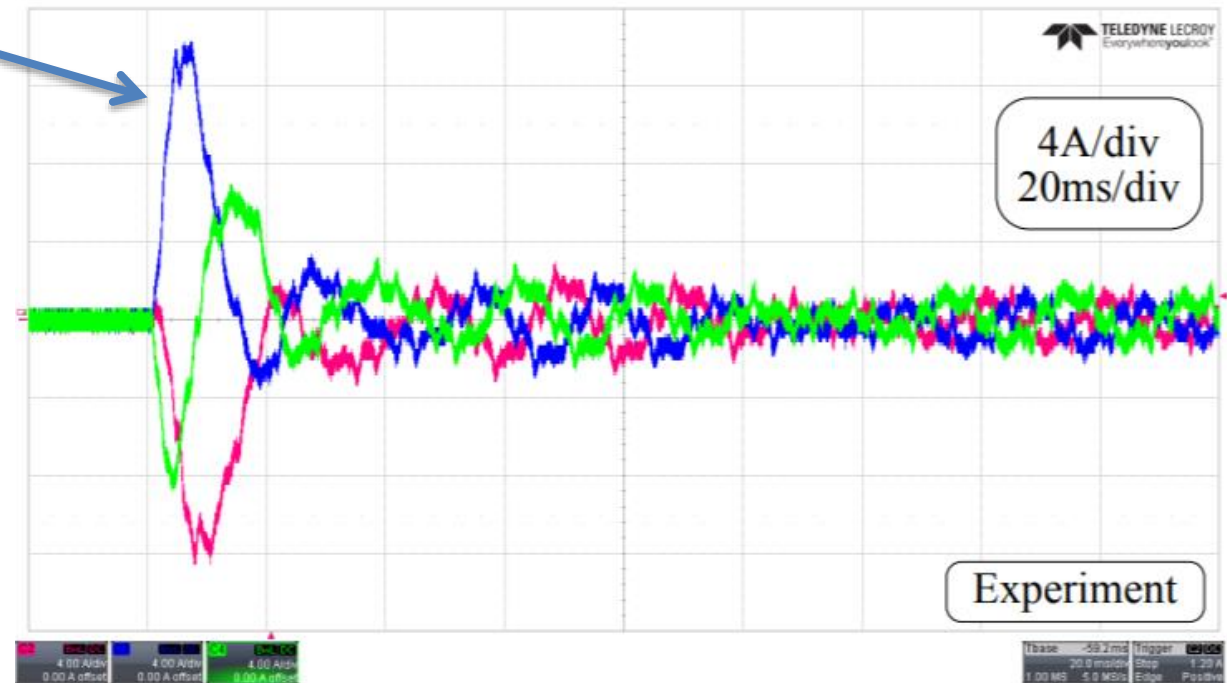
If Ship tries to synchronize bulky DG with the shore, huge inrush currents appear due to inertia

Simplified block scheme of S2SP system



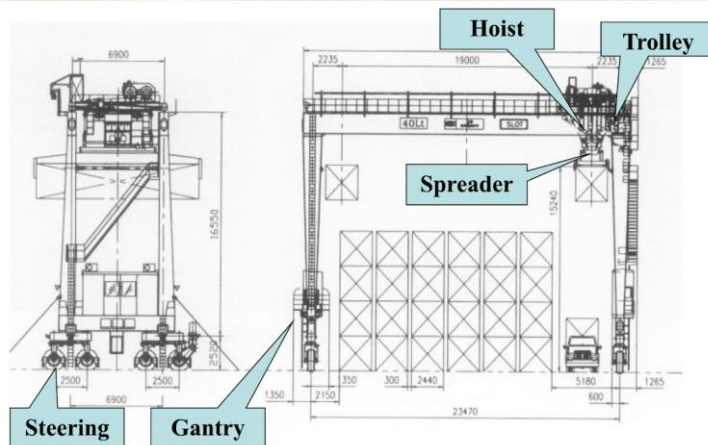
SP2S case

Phase currents of the synchronous generator during synchronization with low voltage AC grid

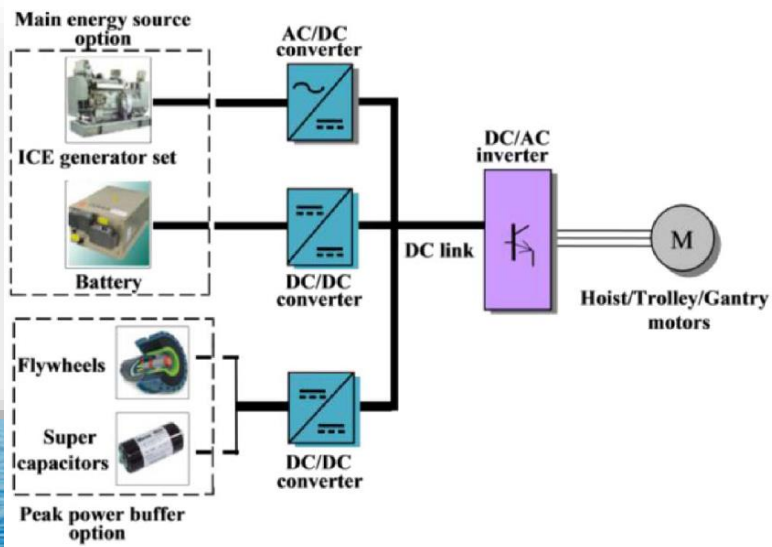
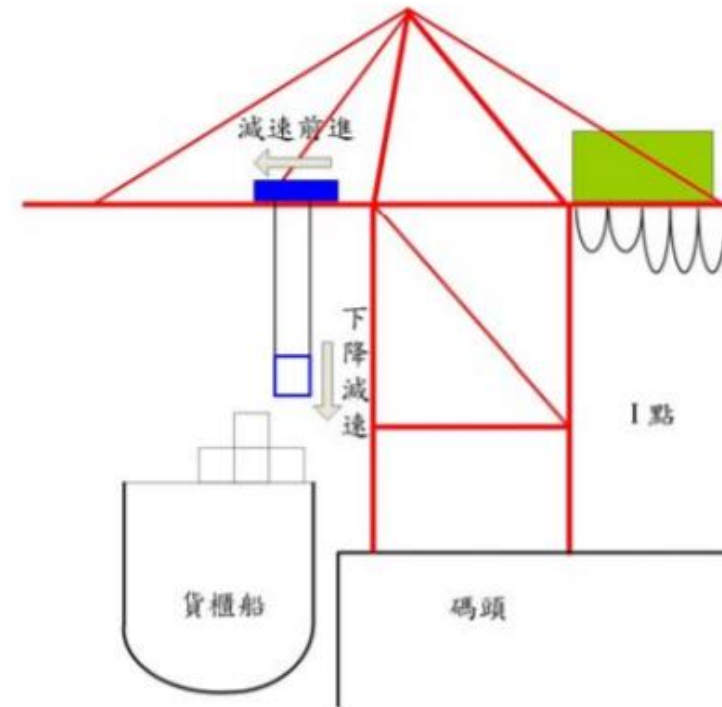
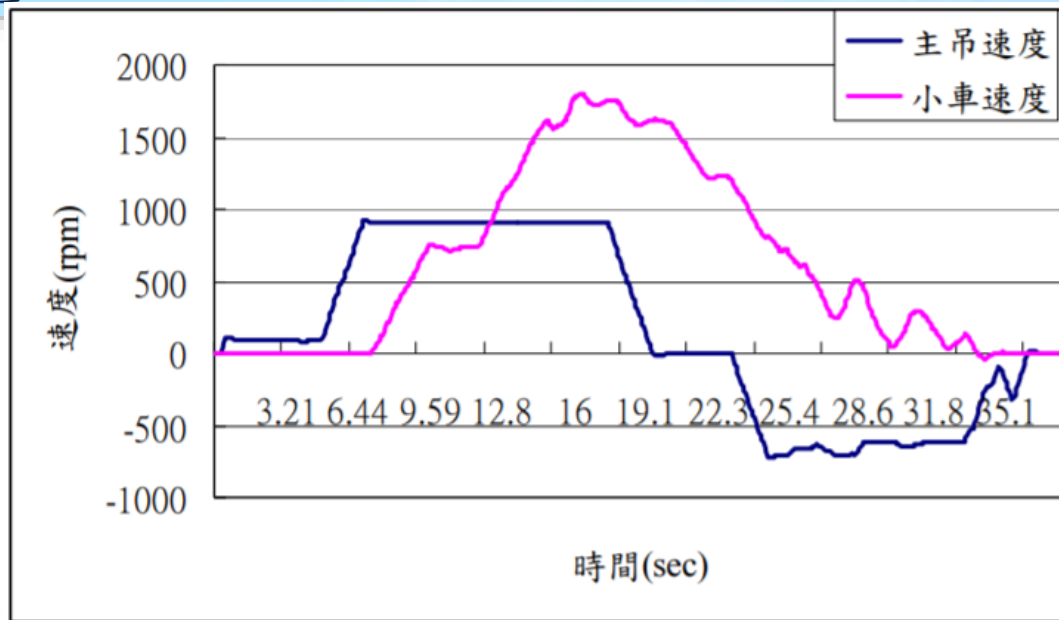


Source: Ship-to-Shore vs. Shore-to-Ship Synchronization Strategy, R. Smolenski, et al., IEEE TEC, 2018

Port Cranes

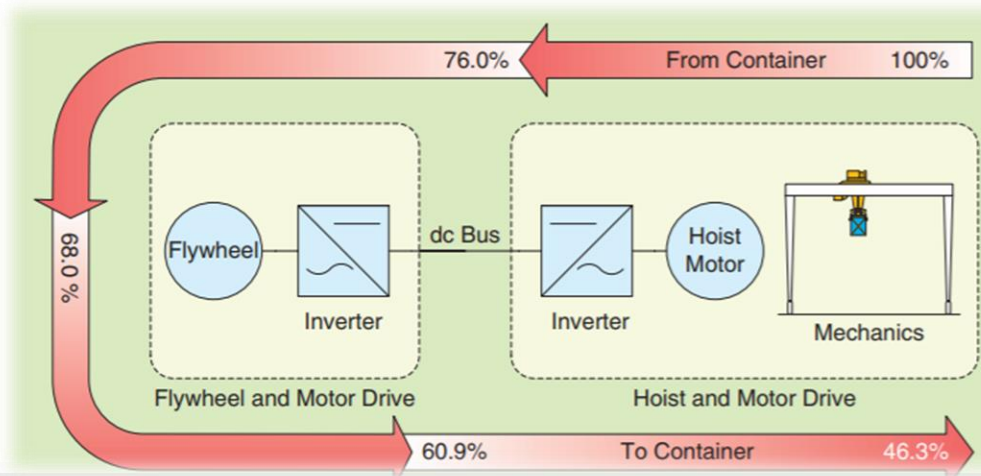
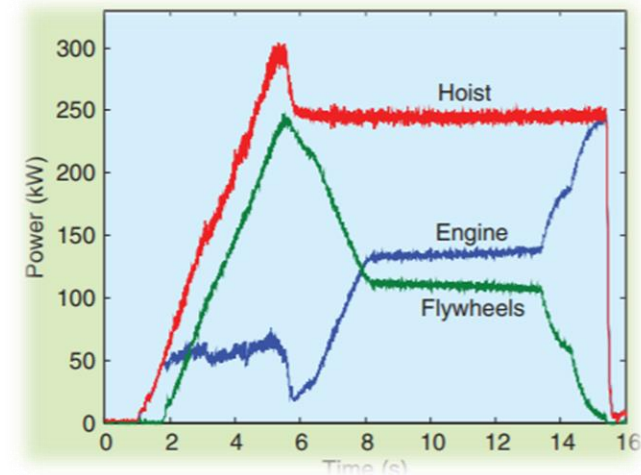
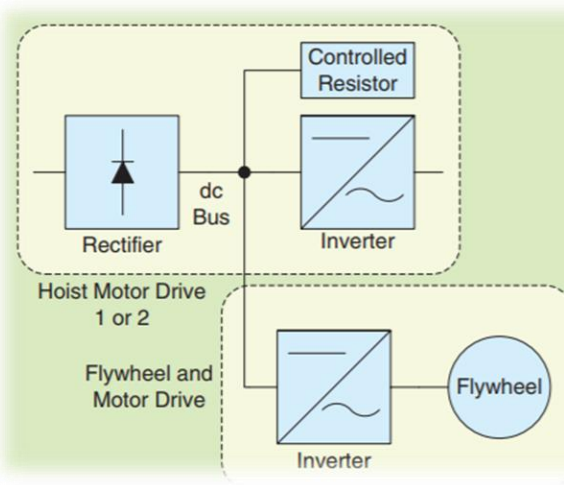
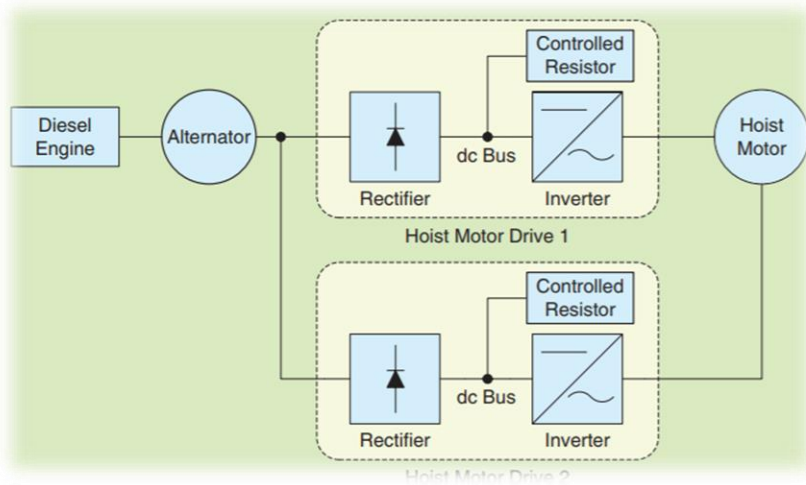


Port Cranes



Source: Nan Zhao, Nigel Schofield, and Wangqiang Niu
Energy Storage System for a Port Crane Hybrid Power-Train
IEEE TRANSACTIONS ON TRANSPORTATION ELECTRIFICATION, VOL. 2,
NO. 4, DECEMBER 2016

Port Cranes



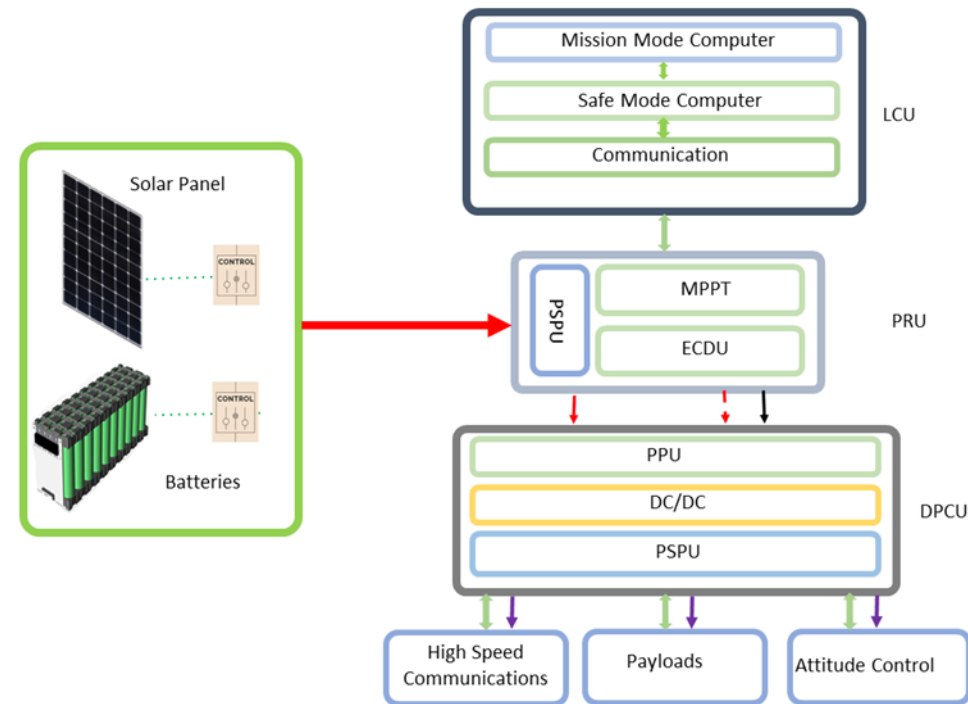
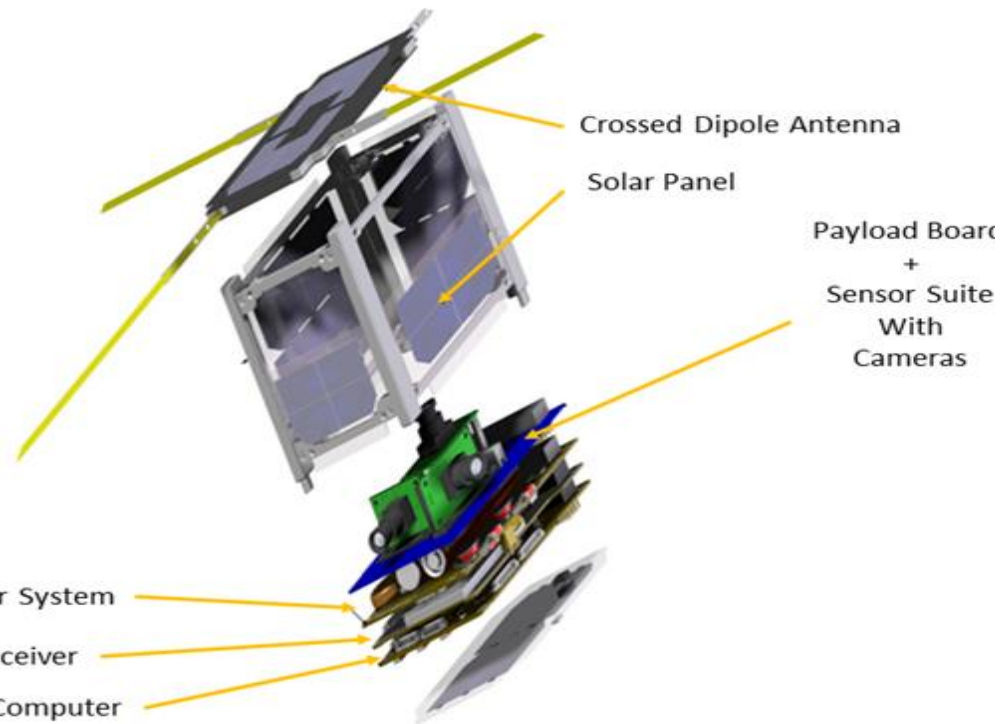
- +45% Energy recovery
- Possibly DC microgrid config.
- Coordination between FW
- Savings and...
- Power peak reduction

Source: Flynn, Mark M., Patrick McMullen, and Octavio Solis. "Saving energy using flywheels." *IEEE Industry applications magazine* 14.6 (2008).

Space Microgrids



Microgrids in Nanosatellites



LCU: Local Communication Unit

PRU: Power Regulator Unit

DPCU: Distributed Power Control Unit

MPPT: Maximum Power Point Tracking

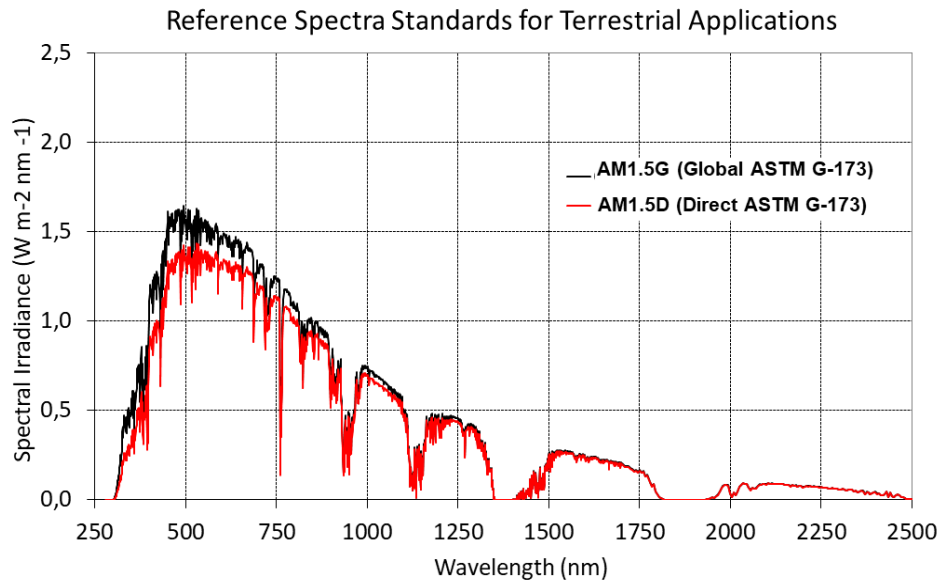
ECDU: ESS Charge Discharge Unit

PSPU: Power System Protection Unit

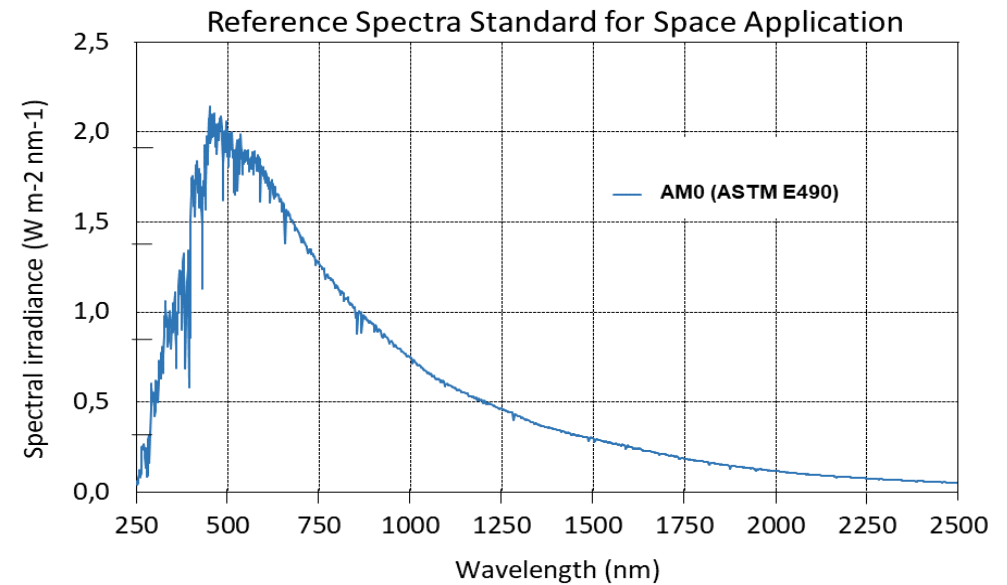
PPU: Power Processing Unit

Microgrids in Nanosatellites

AM1.5



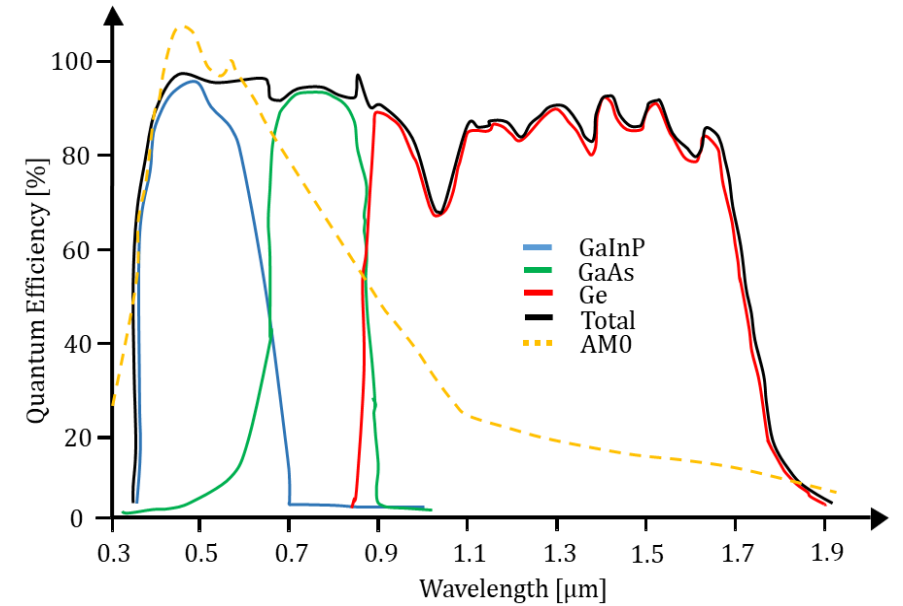
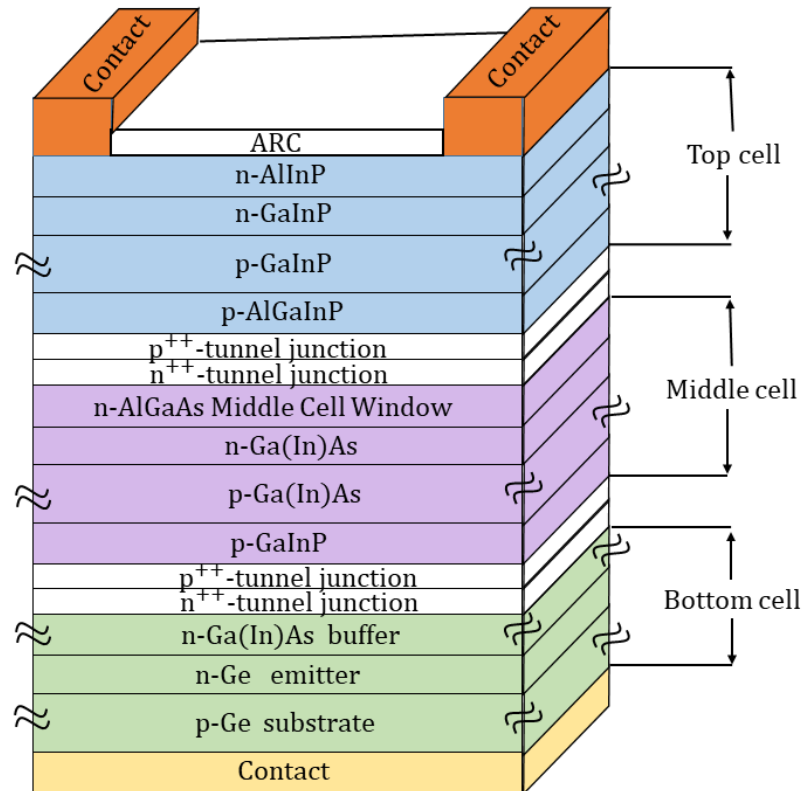
AM0



Standard sunlight spectrum for (a) terrestrial and (b) space solar cells.

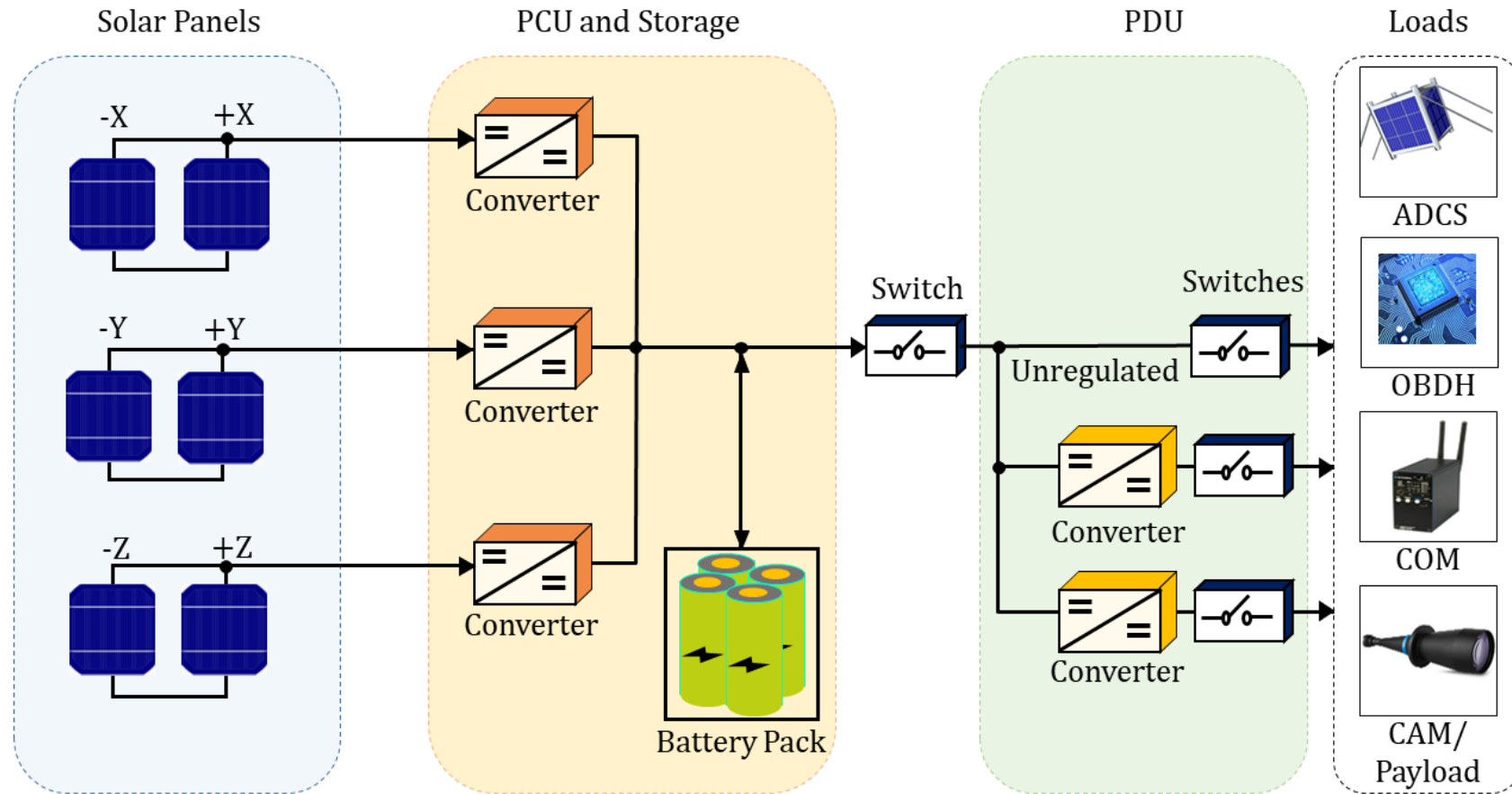
Microgrids in Nanosatellites

Design layers of 3-J Ge/GaAs/InGaP solar cells.

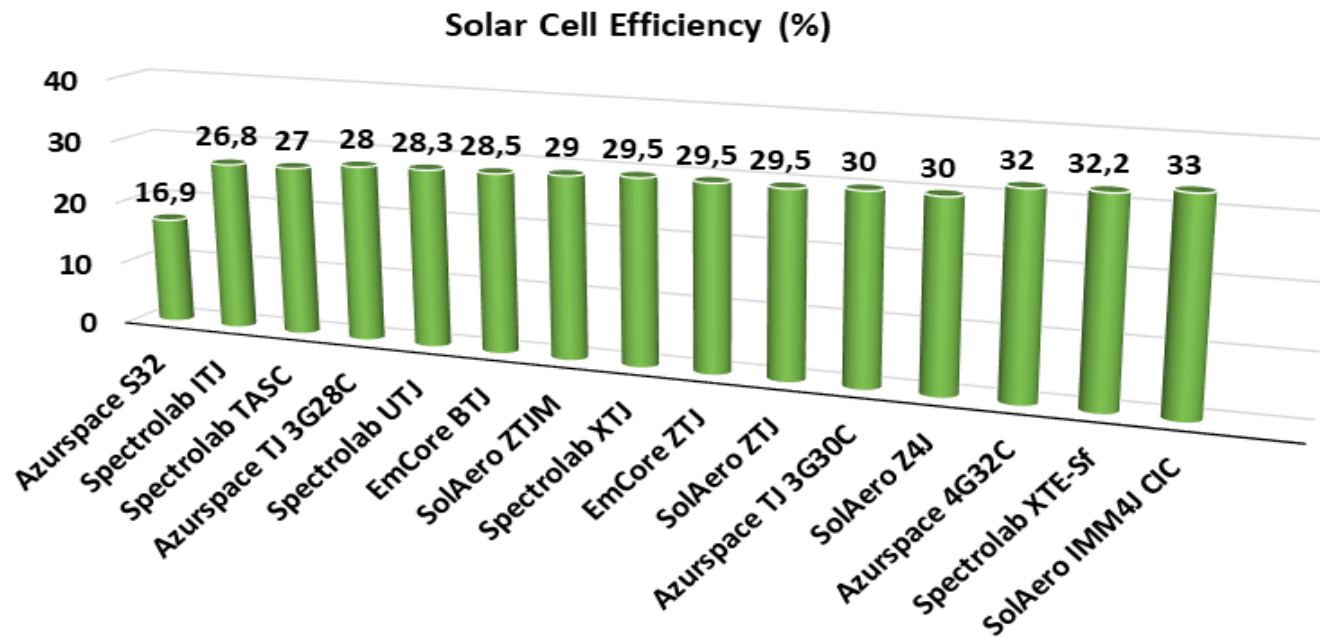


Wavelength spectrum covered by the base layers of the structure.

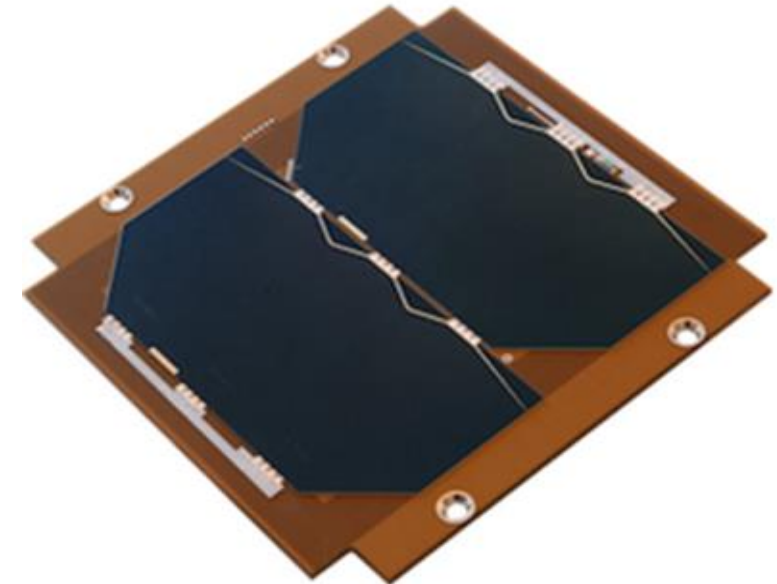
Microgrids in Nanosatellites



Microgrids in Nanosatellites



Space solar technologies and the efficiencies



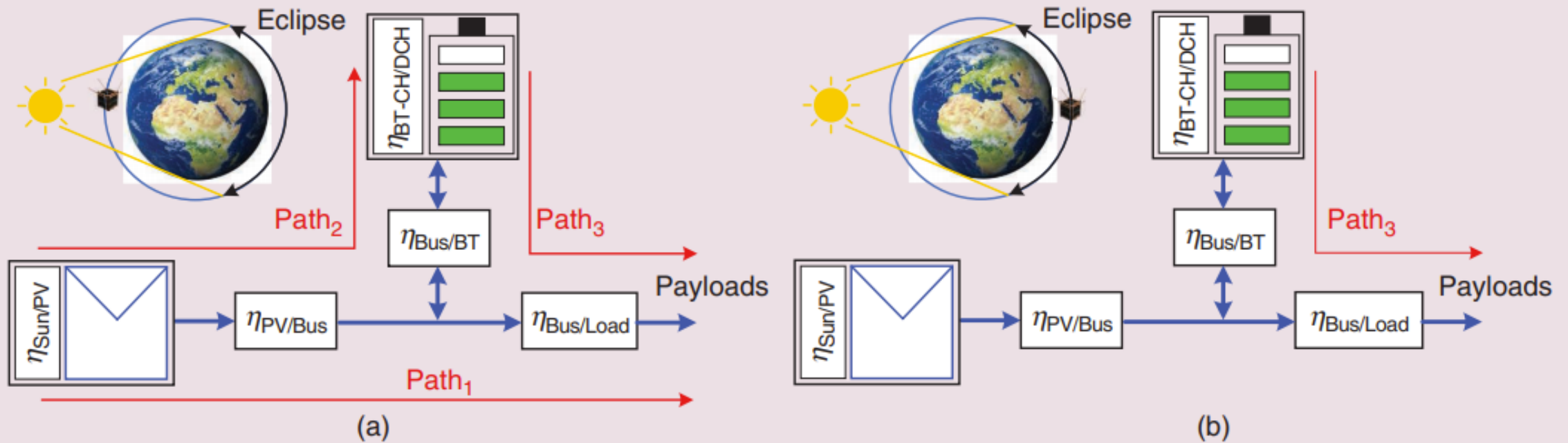
GomSpace NanoPower P110
[Courtesy GOMSpace].

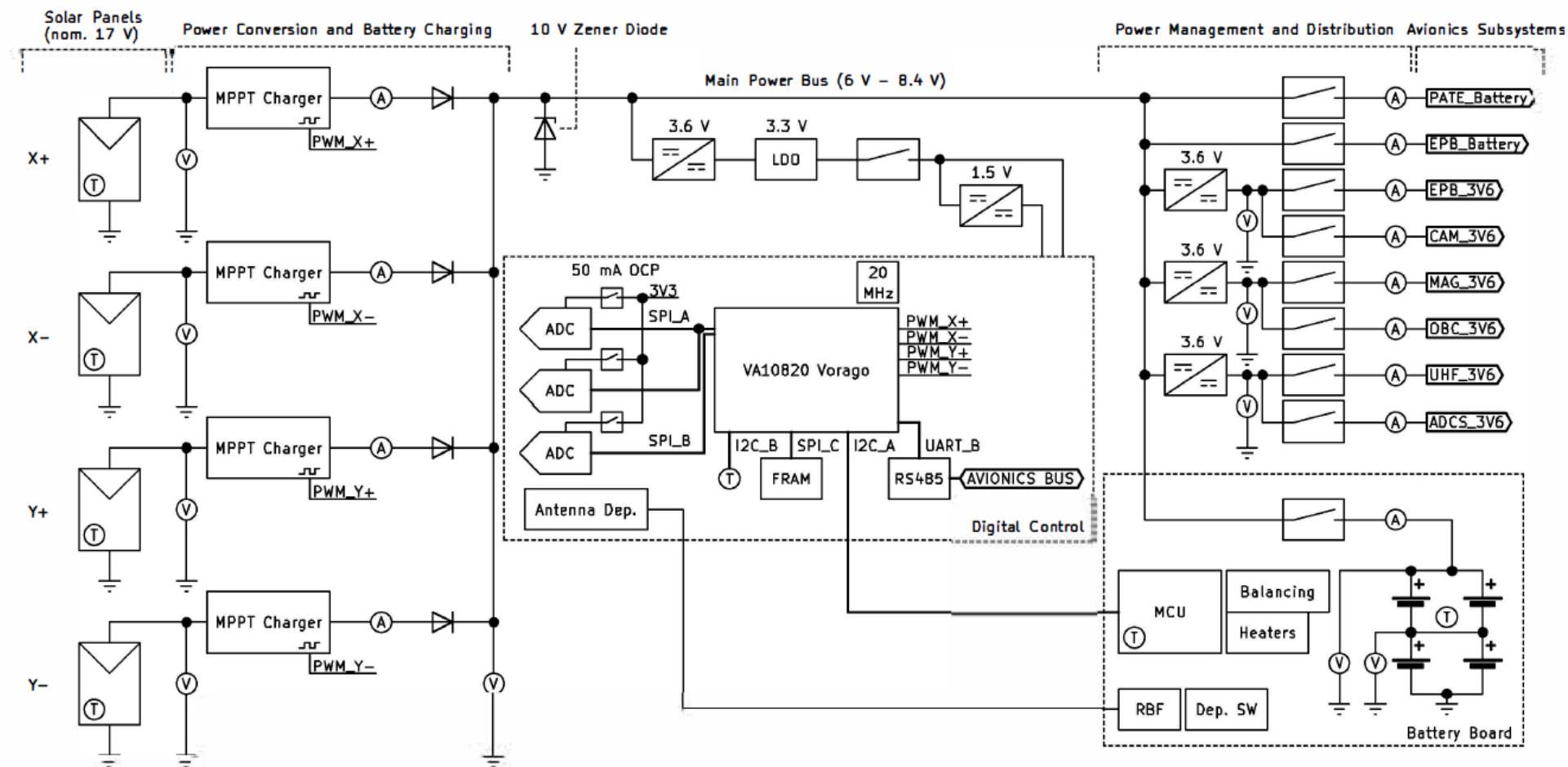


Microgrids in Nanosatellites

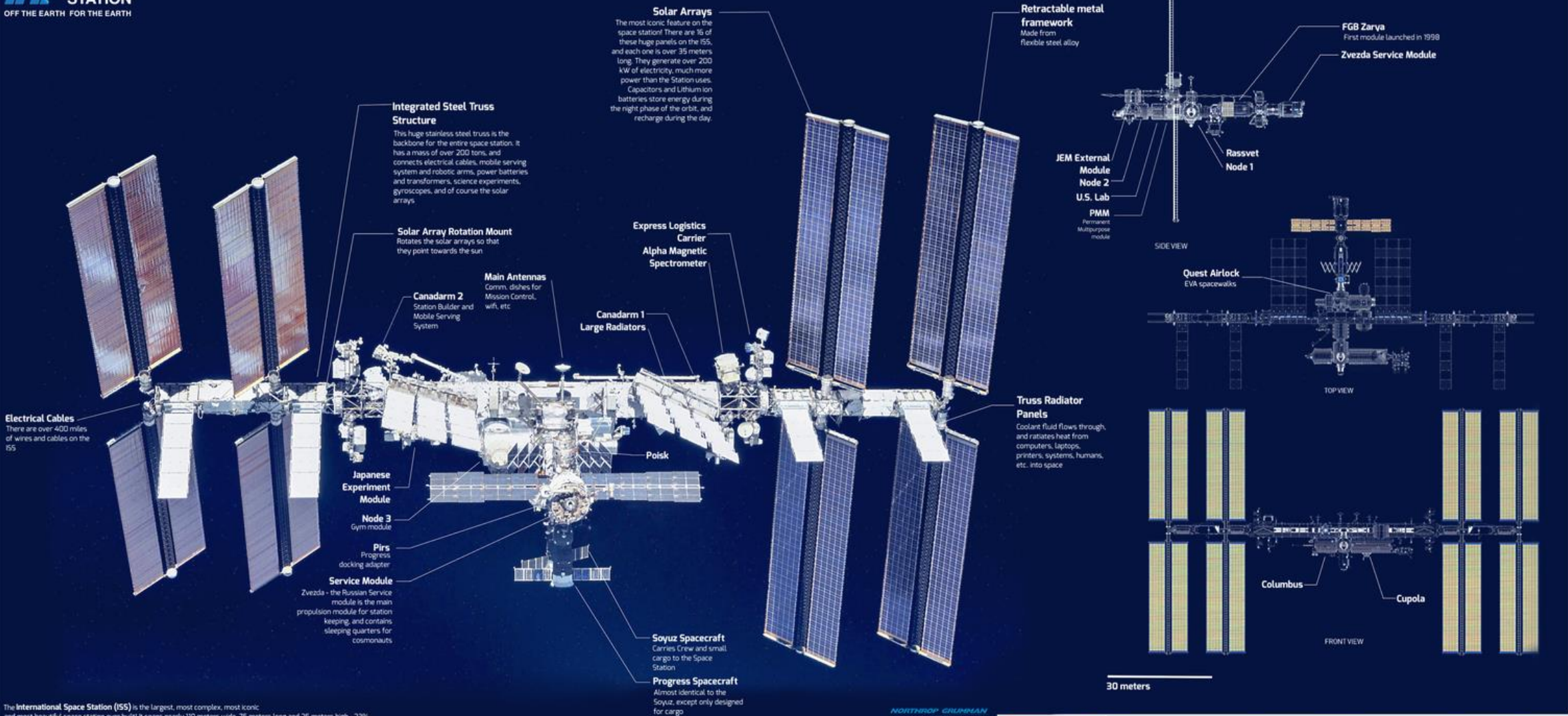


Microgrids in Nanosatellites





Block diagram of the Foresail-1 EPS.



The International Space Station (ISS) is the largest, most complex, most iconic and most beautiful space station ever built! It spans nearly 110 meters wide, 75 meters long and 25 meters high - 23% larger than a football field. It has mass of 419,455 kg, and internal volume equal to the cabin of a Boeing 747. It's home to currently 6 crew, and has a theoretical max capacity of around 30 astronauts. Hundreds of astronauts have visited or stayed aboard this amazing complex, and the station serves as a science and bio laboratory, earth observation, technology development and engineering outpost in space. Conceived in 1984, and launched in 1998, the International Space Station has been operating continuously to this day and beyond, hopefully to around 2030 onwards. Built by the primary users - the United States and Russia, and with the co-operation of 15 countries, it's truly the biggest international space project in history.

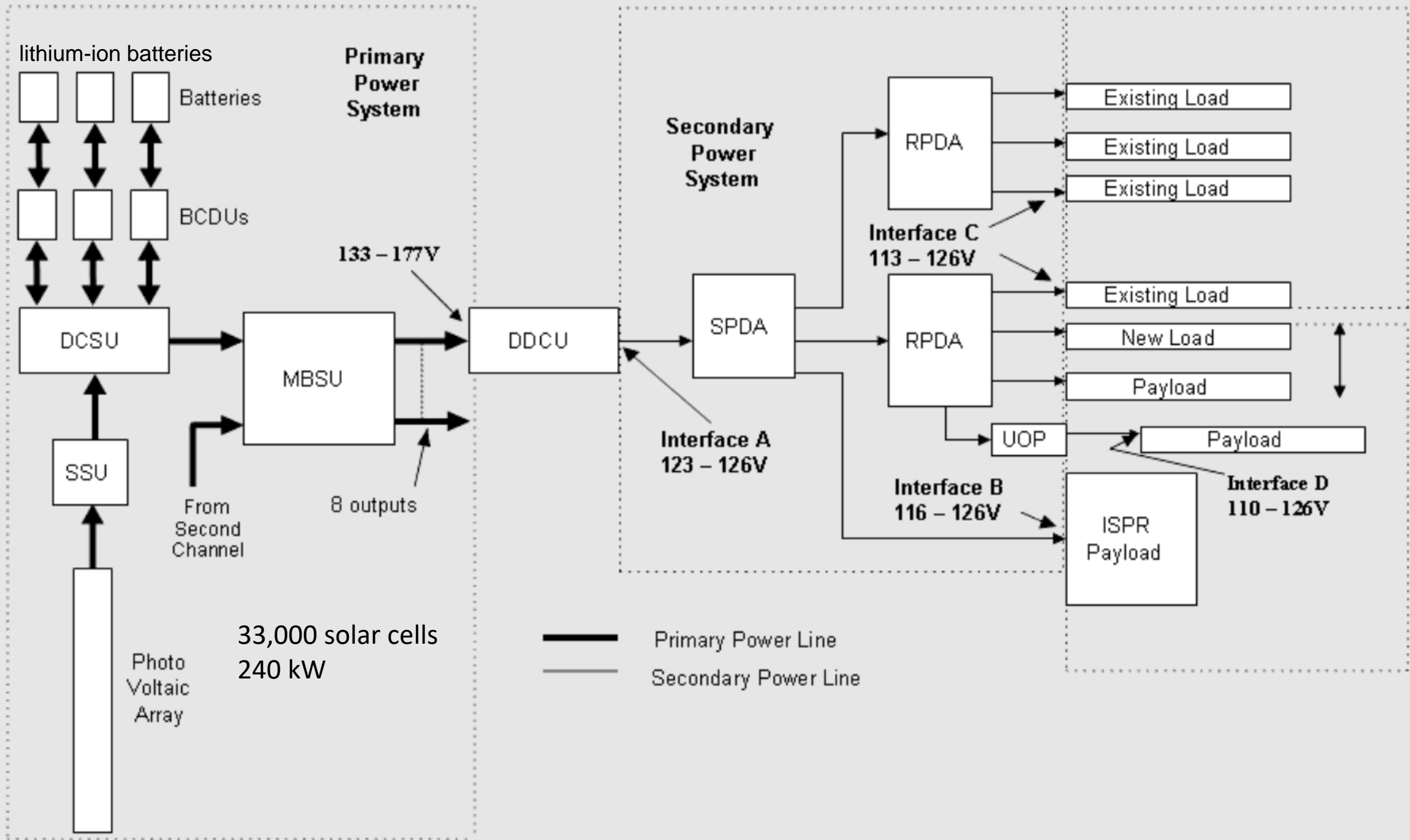


NORTHROP GRUMMAN

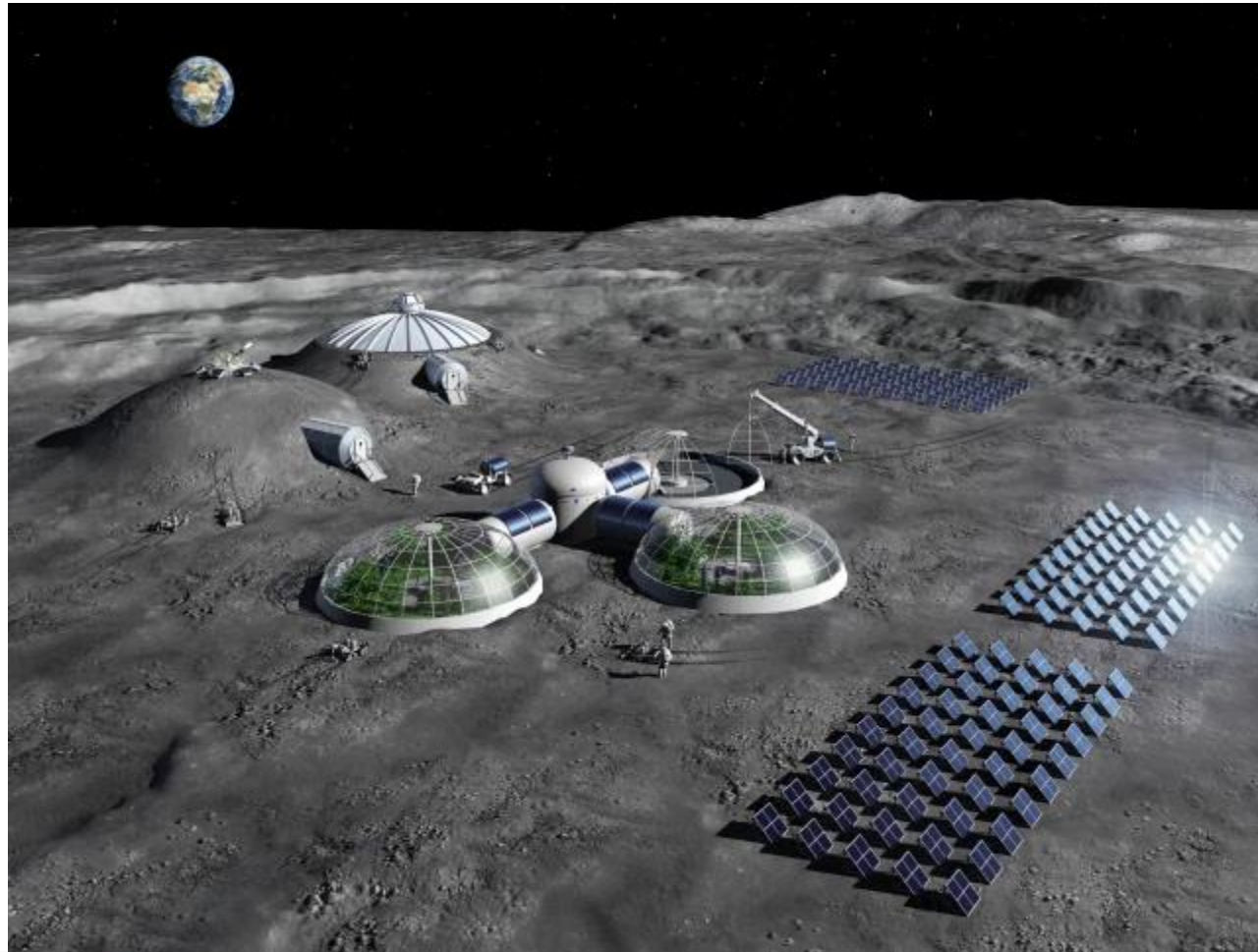


International Space Station	
Overview diagram	1998-037A
Blueprint no. 1	ISS-0419455





Lunar Base Microgrids





Lunar Base Microgrids

Lunar base construction period

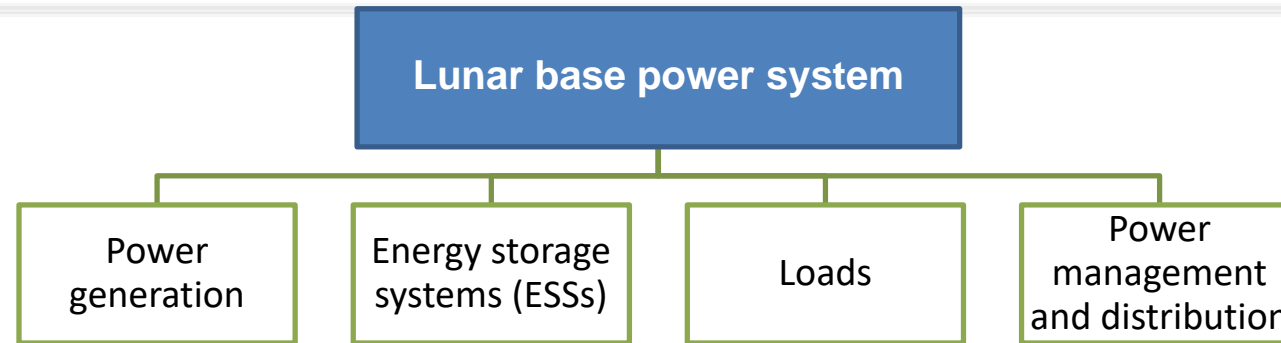
Phase	Purpose	Human presence	Stay period
0	Robotic site preparation	Minimum or no human presence	No stay
1	Deployment and initial phase	3 to 4 personnel	4 to 6 months
2	Growth phase	Approximately 10 personnel	1 year
3	Self sufficiency	10 to 100 personnel	Extended periods
4	Science and commercial	More than 100 personnel	Unlimited duration

In 15 to 20 years

[6] Z. Khan, A. Vranis, A. Zavoico, S. Freid, and B. Manners, "Power system concepts for the lunar outpost: A review of the power generation, energy storage, Power Management and Distribution (PMAD) system requirements and potential technologies for development of the lunar outpost," *AIP Conf. Proc.*, vol. 813, June, pp. 1083–1092, 2006.

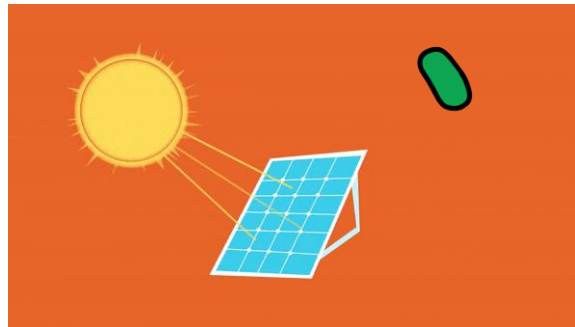
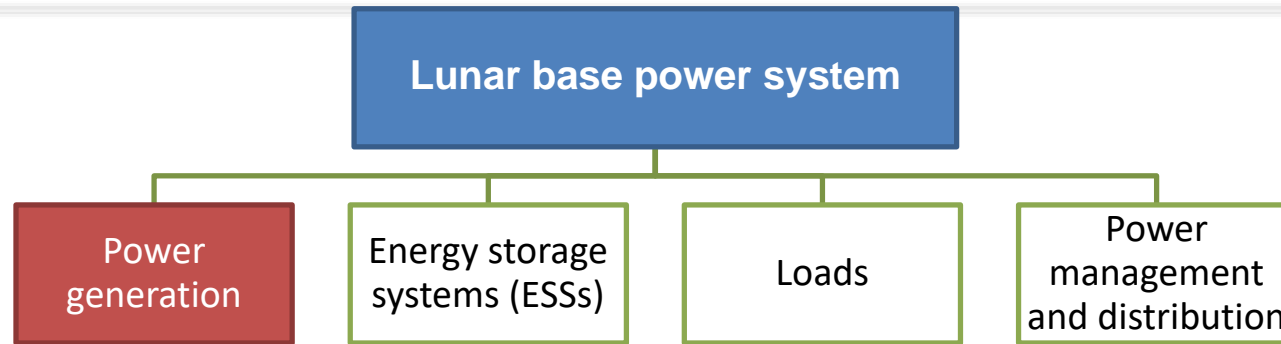


Lunar Base Microgrids



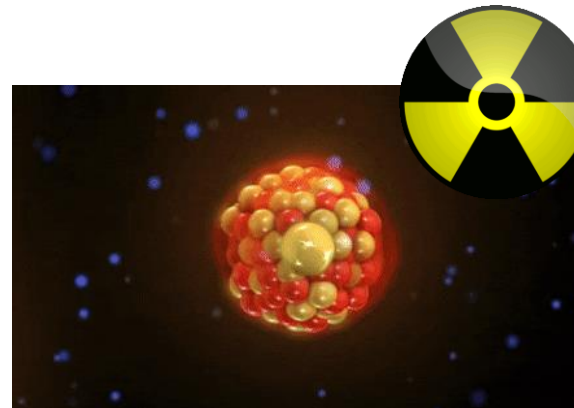
[6] Z. Khan, A. Vranis, A. Zavoico, S. Freid, and B. Manners, "Power system concepts for the lunar outpost: A review of the power generation, energy storage, Power Management and Distribution (PMAD) system requirements and potential technologies for development of the lunar outpost," *AIP Conf. Proc.*, vol. 813, June, pp. 1083–1092, 2006.

Lunar Base Microgrids



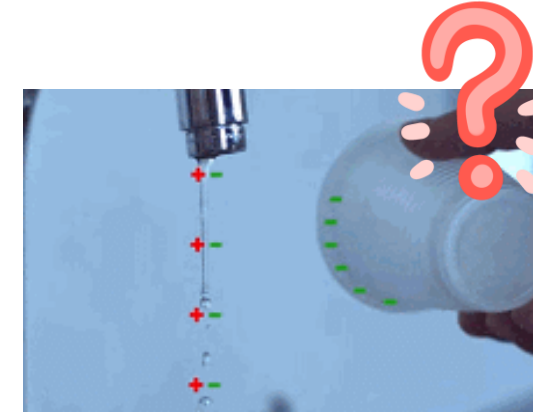
Solar energy

- Not hazardous
- Convenient
- Comparatively light
- Tested technology



Nuclear fission based “kilopower” reactor

- Hazardous
- Complex infrastructure
- More weight



Electrostatic charge

- LOW TRL – In laboratory

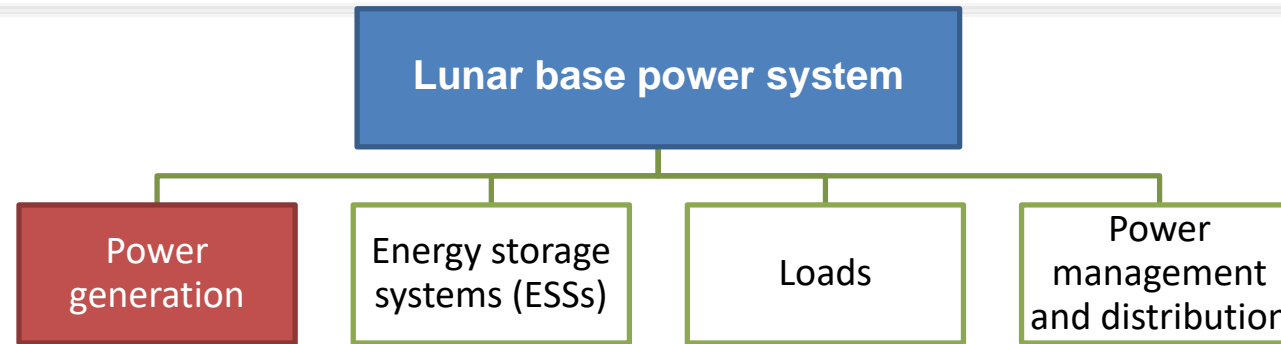


Less reliable!

[7] A. J. Colozza, “Small Lunar Base Camp and In Situ Resource Utilization Oxygen Production Facility Power System Comparison,” March, 2020.

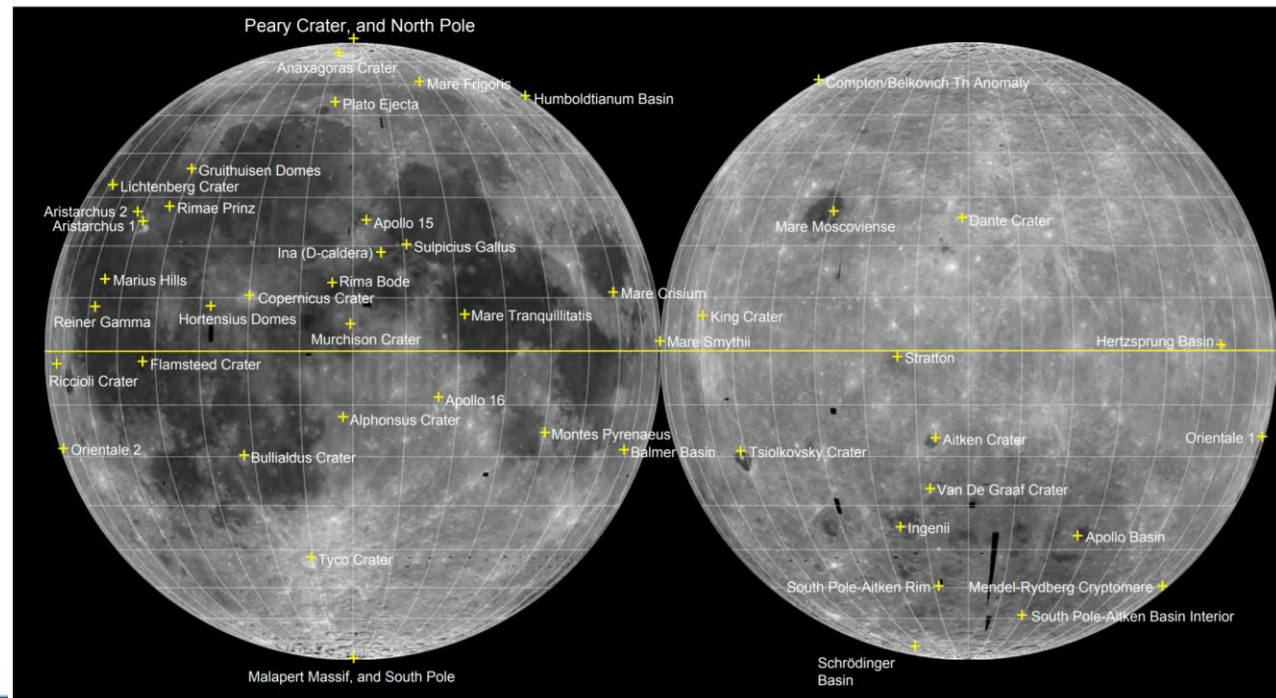
[8] S. H. Choi, G. C. King, H.-J. Kim, and Y. Park, “Electrostatic Power Generation from Negatively Charged, Simulated Lunar Regolith,” 2010.

Lunar Base Microgrids



Near Side

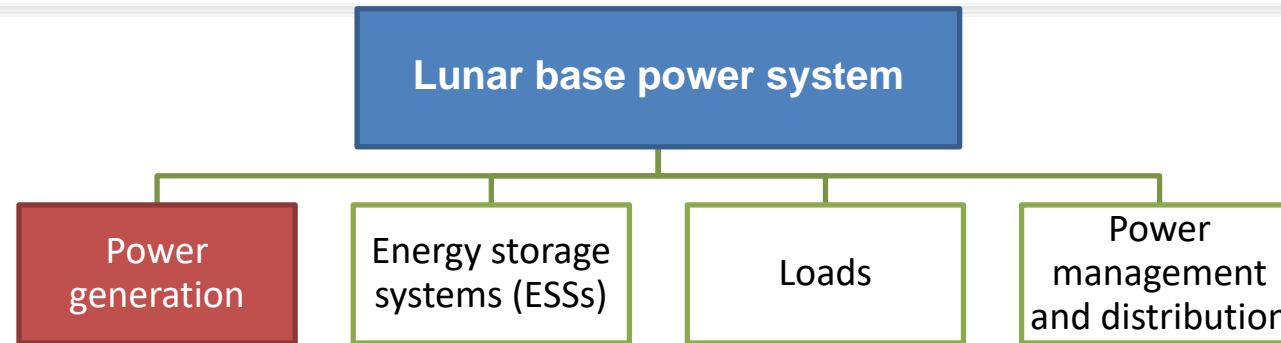
Far Side



[7] A. J. Colozza, "Small Lunar Base Camp and In Situ Resource Utilization Oxygen Production Facility Power System Comparison," March, 2020.

[9] H. J. Fincannon, "Lunar Environment and Lunar Power Needs," pp. 1–5, 2020.

Lunar Base Microgrids




Low declination angle
of 1.5°



Little variation in solar
elevation



Continuously available
throughout the year

- 
- Steep terrain at polar regions
 - Transition to sunlight regions
 - More than 15 days (high terrain)
 - Less than 15 days (low terrain)
 - At non-polar regions, sunlight and dark periods around 15 days each
 - Eclipse of about 5 hours twice a year due to earth
 - Polar region interests
 - South pole – Shackleton crater
 - North pole – Peary crater

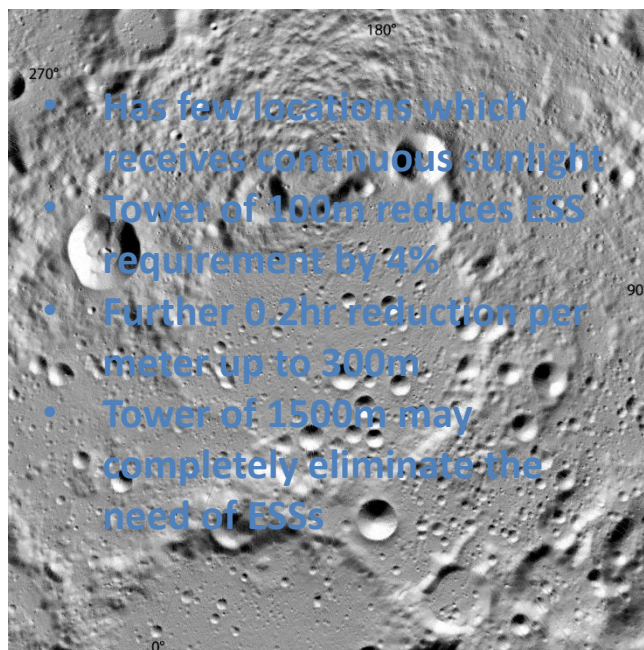
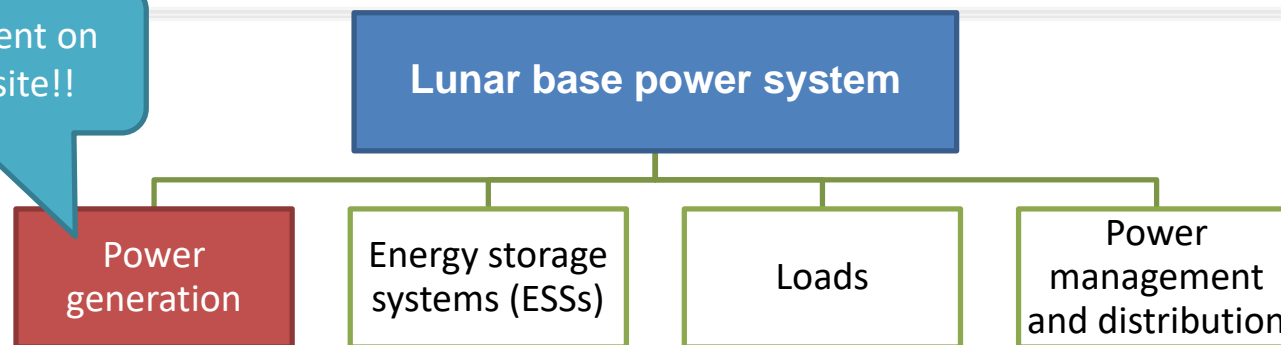
[7] A. J. Colozza, "Small Lunar Base Camp and In Situ Resource Utilization Oxygen Production Facility Power System Comparison," March, 2020.

[9] H. J. Fincannon, "Lunar Environment and Lunar Power Needs," pp. 1–5, 2020.



Lunar Base Microgrids

Highly dependent on location and site!!



- Has few locations which receives continuous sunlight
- Tower of 100m reduces ESS requirement by 4%
- Further 0.2hr reduction per meter up to 300m
- Tower of 1500m may completely eliminate the need of ESSs

North pole - Peary Crater



- Has most illuminated locations
- Average irradiance of 86%
- Receives continuous sunlight for 6 months
- Continuous darkness period of 71 to 120 hours
- Needs tower height of more than 3000m

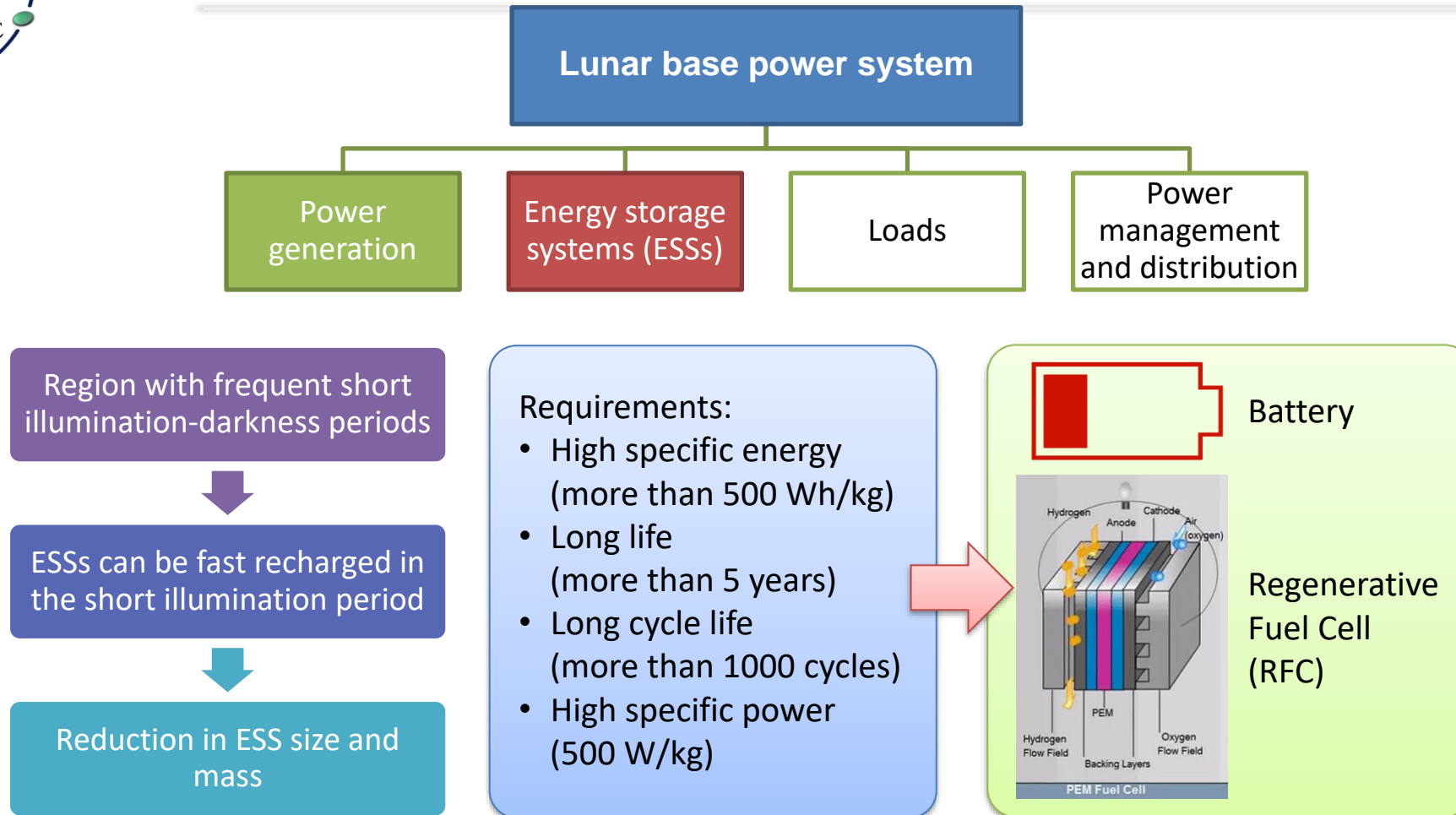
South pole - Shackleton Crater

[9] H. J. Fincannon, "Lunar Environment and Lunar Power Needs," pp. 1–5, 2020.

[10] A. D. Bintoudi, C. Timplalexis, G. Mendes, J. M. Guerrero, and C. Demoulias, "Design of Space Microgrid for Manned Lunar Base: Spinning in Terrestrial Technologies," in 2019 European Space Power Conference, ESPC 2019, 2019.

[11] J. Fincannon, "Characterisation of lunar polar illumination from a power system perspective," 46th AIAA Aerosp. Sci. Meet. Exhib., May, 2008.

Lunar Base Microgrids



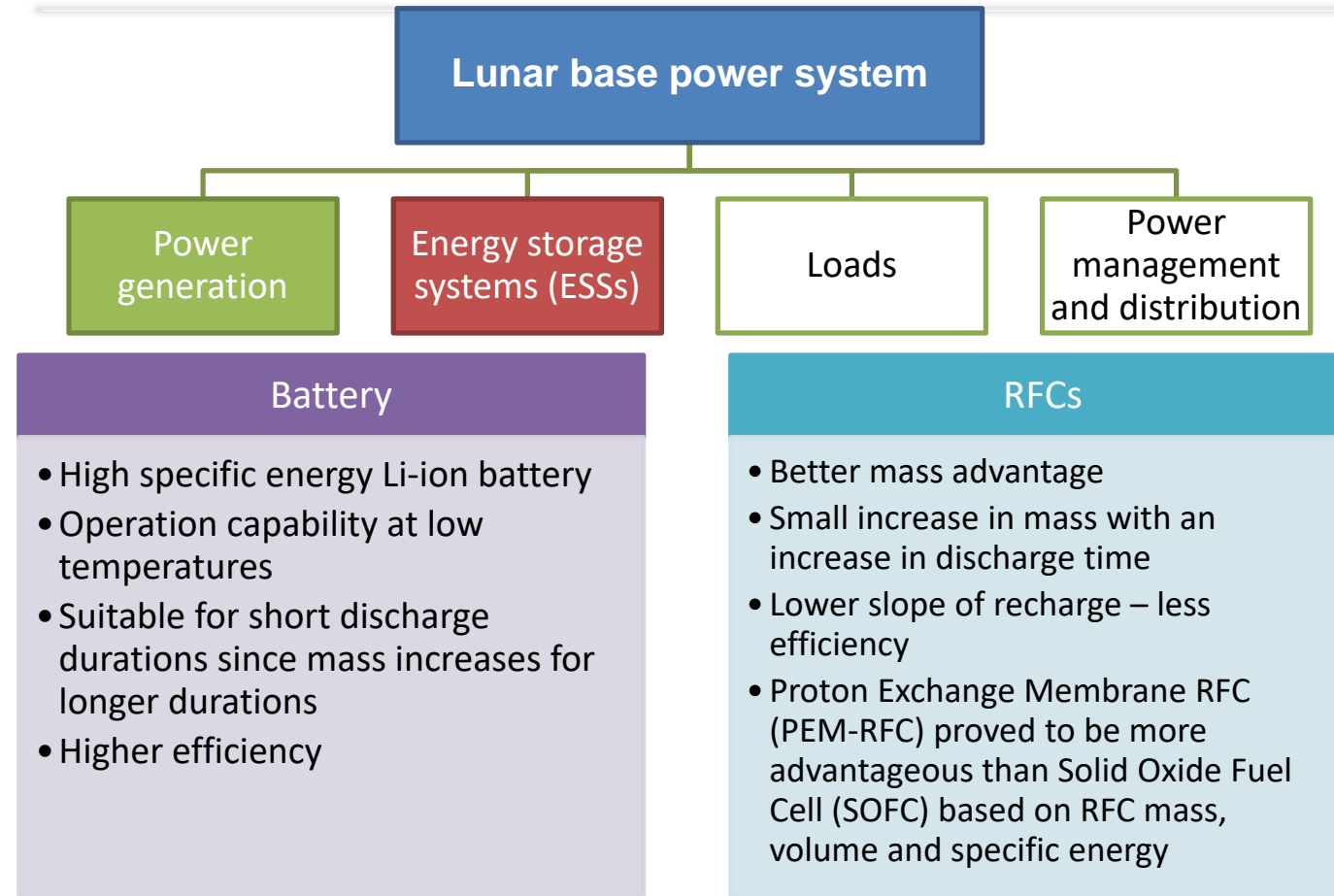
[7] A. J. Colozza, "Small Lunar Base Camp and In Situ Resource Utilization Oxygen Production Facility Power System Comparison," NASA Technical Reports Server (NTRS), March, 2020.

[11] J. Fincannon, "Characterisation of lunar polar illumination from a power system perspective," 46th AIAA Aerosp. Sci. Meet. Exhib., May, 2008.

[12] J. Blois et al., "Energy Storage Technologies for Future Planetary Science Missions Work Performed under the Planetary Science Program Support Task," December, 2017.



Lunar Base Microgrids



[7] A. J. Colozza, "Small Lunar Base Camp and In Situ Resource Utilization Oxygen Production Facility Power System Comparison," NASA Technical Reports Server (NTRS), March, 2020.

[12] J. Blois et al., "Energy Storage Technologies for Future Planetary Science Missions Work Performed under the Planetary Science Program Support Task," December, 2017.

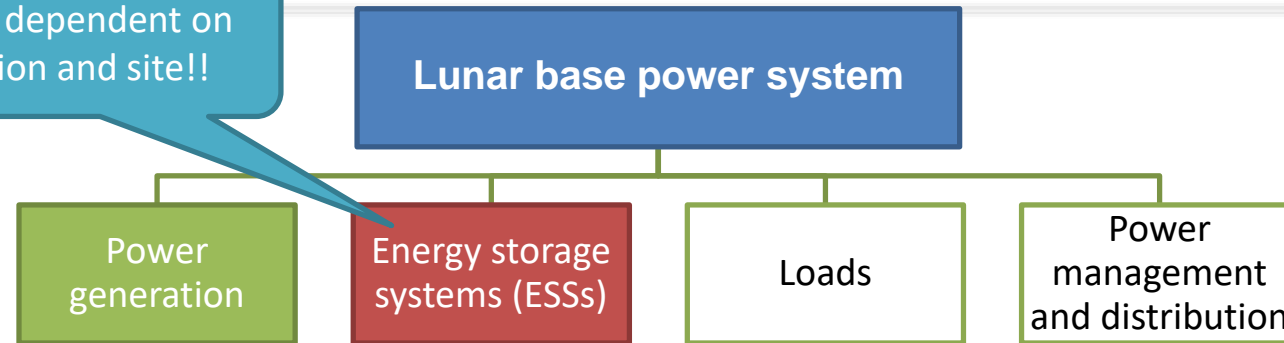
[13] M. C. Guzik, I. J. Jakupca, R. P. Gilligan, W. R. Bennett, P. J. Smith, and J. Fincannon, "Regenerative fuel cell power systems for lunar and martian surface exploration," AIAA Sp. Astronaut. Forum Expo. Sp. 2017, no. 203999, pp. 1–18, 2017.

[14] Mason and M. Rucker, "Common power and energy storage solutions to support lunar and Mars surface exploration missions," Proc. Int. Astronaut. Congr. IAC, vol. 2019-Octob, pp. 1–7, 2019.



Lunar Base Microgrids

Highly dependent on location and site!!



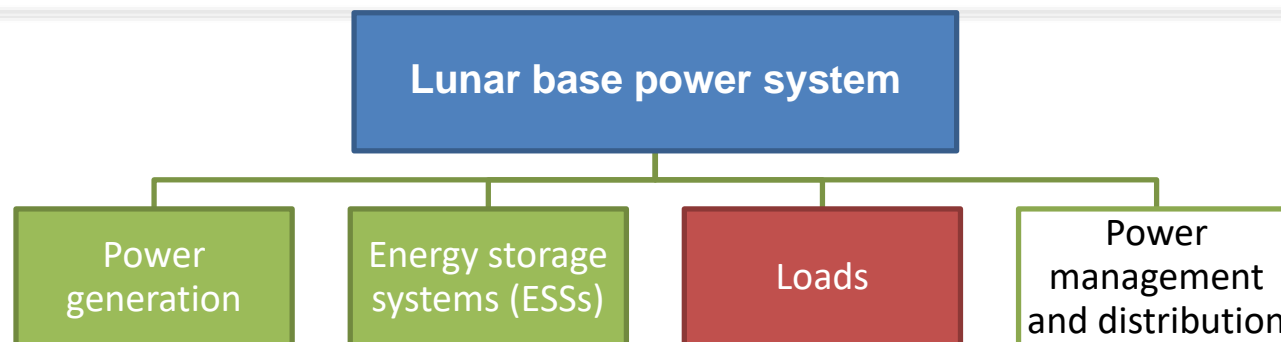
1 month illumination condition of the Shackleton crater

- ESS Mass and size depends on:
 - Base location
 - Solar power availability
 - Loads
- Reduce night-time load
 - Loads not at full power
 - Operate at ideal state (Low power state)

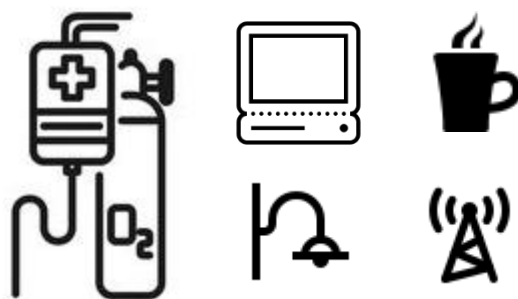
[7] A. J. Colozza, "Small Lunar Base Camp and In Situ Resource Utilization Oxygen Production Facility Power System Comparison," NASA Technical Reports Server (NTRS), March, 2020.

[10] A. D. Bintoudi, C. Timplalexis, G. Mendes, J. M. Guerrero, and C. Demoulias, "Design of Space Microgrid for Manned Lunar Base: Spinning in Terrestrial Technologies," in 2019 European Space Power Conference, ESPC 2019, 2019.

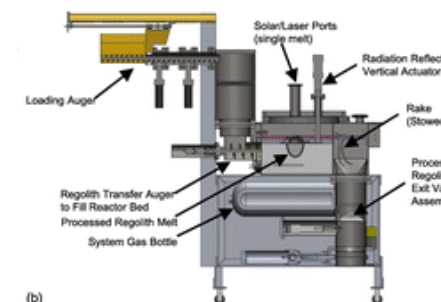
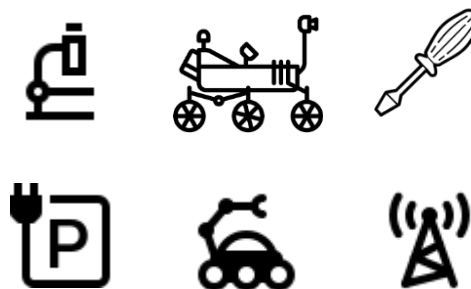
Lunar Base Microgrids



Crew habitat



Laboratory and exploration



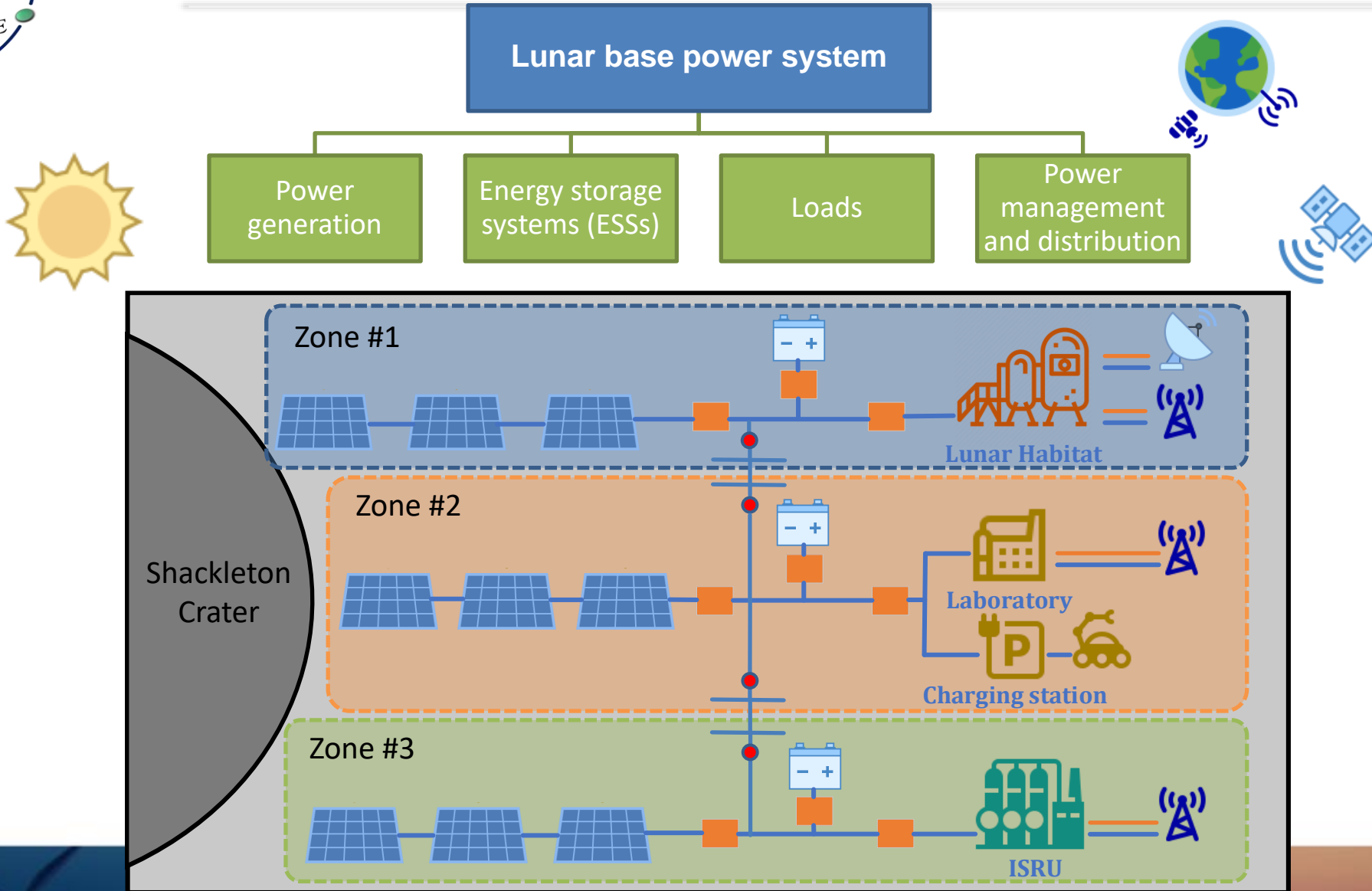
In-Situ Resource Utilisation



[7] A. J. Colozza, "Small Lunar Base Camp and In Situ Resource Utilization Oxygen Production Facility Power System Comparison," NASA Technical Reports Server (NTRS), March, 2020.



Lunar Base Microgrids



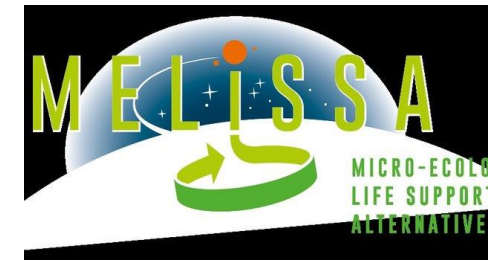


AALBORG UNIVERSITET



Universitat Autònoma
de Barcelona

Hierarchical Control of Space Closed Ecosystems – Expanding Microgrid Concepts to Bioastronautics





Closed Ecological Systems

Closed ecological systems (CES) are:

- Isolated Ecosystems without any matter exchange with outside environment
- Ecosystems rely on recycling and reutilization

Man-made CESs applications:

- Investigating fundamental processes
- Gaining insight into the function of the Earth's biosphere
- Studying interactions of ecosystems
- Creating space-based life support system for space explorations

Examples:

- BIO-Plex- NASA Johnson Space Research Center, Houston
- Biosphere 2- Oracle, Arizona
- BIOS 3- Krasnoyarsk, Russia
- CEEF complex- Japan
- MELiSSA - Barcelona, Spain - ESA



Biosphere 2, Oracle, Arizona

Source: M. Nelson, NS. Pechurkin, JP. Allen, LA. Somova, JI. Gitelson, "Closed ecological systems, space life support and biospherics," *In Environmental Biotechnology* 2010, pp. 517-565, Humana Press, Totowa, NJ.



Life Support Systems (LSS)

Advanced ecosystems capable of providing: food, water, and air for living outside the support of earth.

➤ **Space-based** closed LSSs:
Essential for deep space exploration missions

➤ **Ground-based** closed LSSs:
Improving life quality in earth extreme conditions (polar latitudes, mountains, deserts, undersea)



Human consumables and throughput values in kg/crew member/day

M. Nelson, NS. Pechurkin, JP. Allen, LA. Somova, JI. Gitelson, "Closed ecological systems, space life support and biospherics," *In Environmental Biotechnology* 2010, pp. 517-565, Humana Press, Totowa, NJ.
F.M. Sulzman, "Life Support and Habitability," *Space Biology and Medicine*, Volum II. University of Chicago: Abram Moiseevich Genin; 1994.

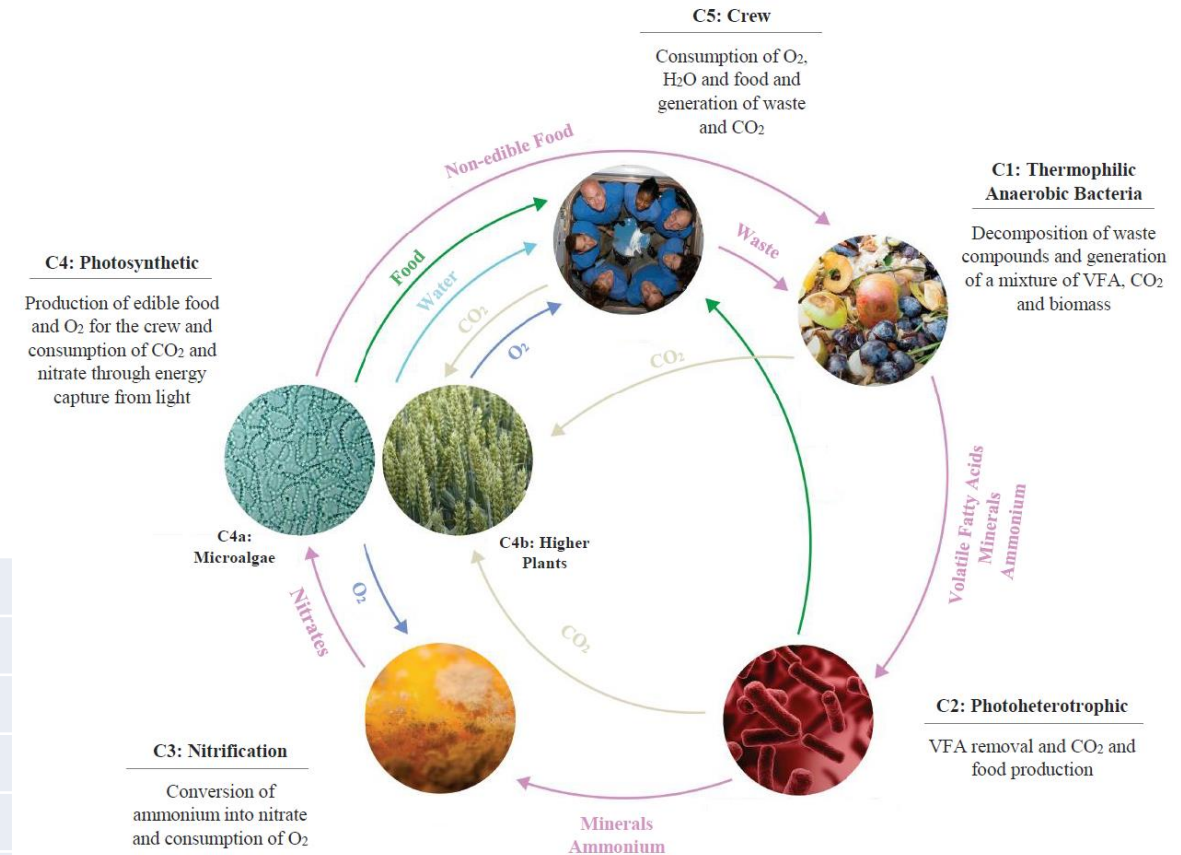


MELiSSA (Micro-Ecological Life Support System Alternative)

MELiSSA is an European pilot project that aims at developing a closed-loop regenerative Life Support Systems for long-term manned space missions

MELiSSA includes six specific microbiological compartments that reproduce the main functionalities of an ecological system in continuous modes of operation and under controlled conditions.

Symbol	COMPARTMENTS
CI	Thermophilic Anaerobic Bacteria
CII	Photoheterotrophic Bacteria Rhodospirillum rubrum
CIII	Nitrifying Bacteria Nitrosomonas/Nitrobacter
CIVa	Photoautotrophic Bacteria Arthrospira Platensis
CIVb	Higher Plant
CV	The Crew Compartment

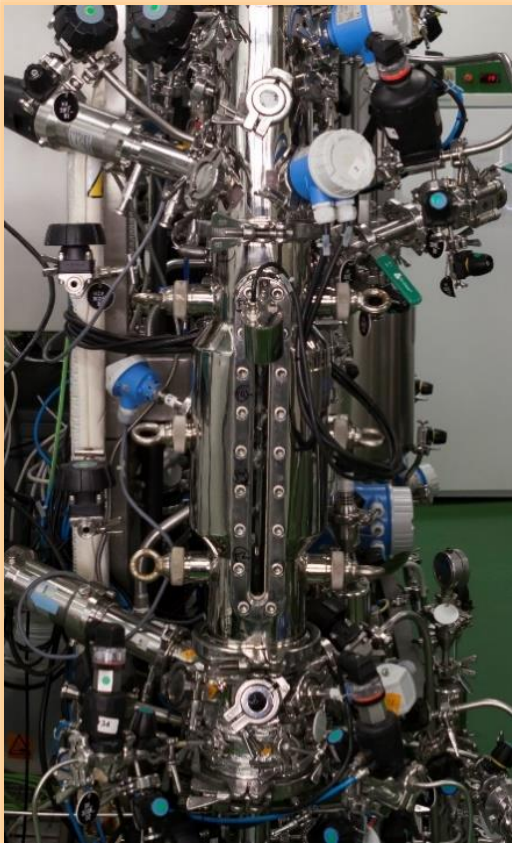




Microgrids Concepts in Closed Ecosystems

MELiSSA Pilot Plant (MPP)

Universitat Autònoma de Barcelona



CIII: Nitrification compartment



CIVa: Photobioreactor



CIVb: Higher plant compartment



CV: Crew compartment

MELiSSA (Micro-Ecological Life Support System Alternative)

www.ukem.eu/ajuk

MELISSA Integration Challenges

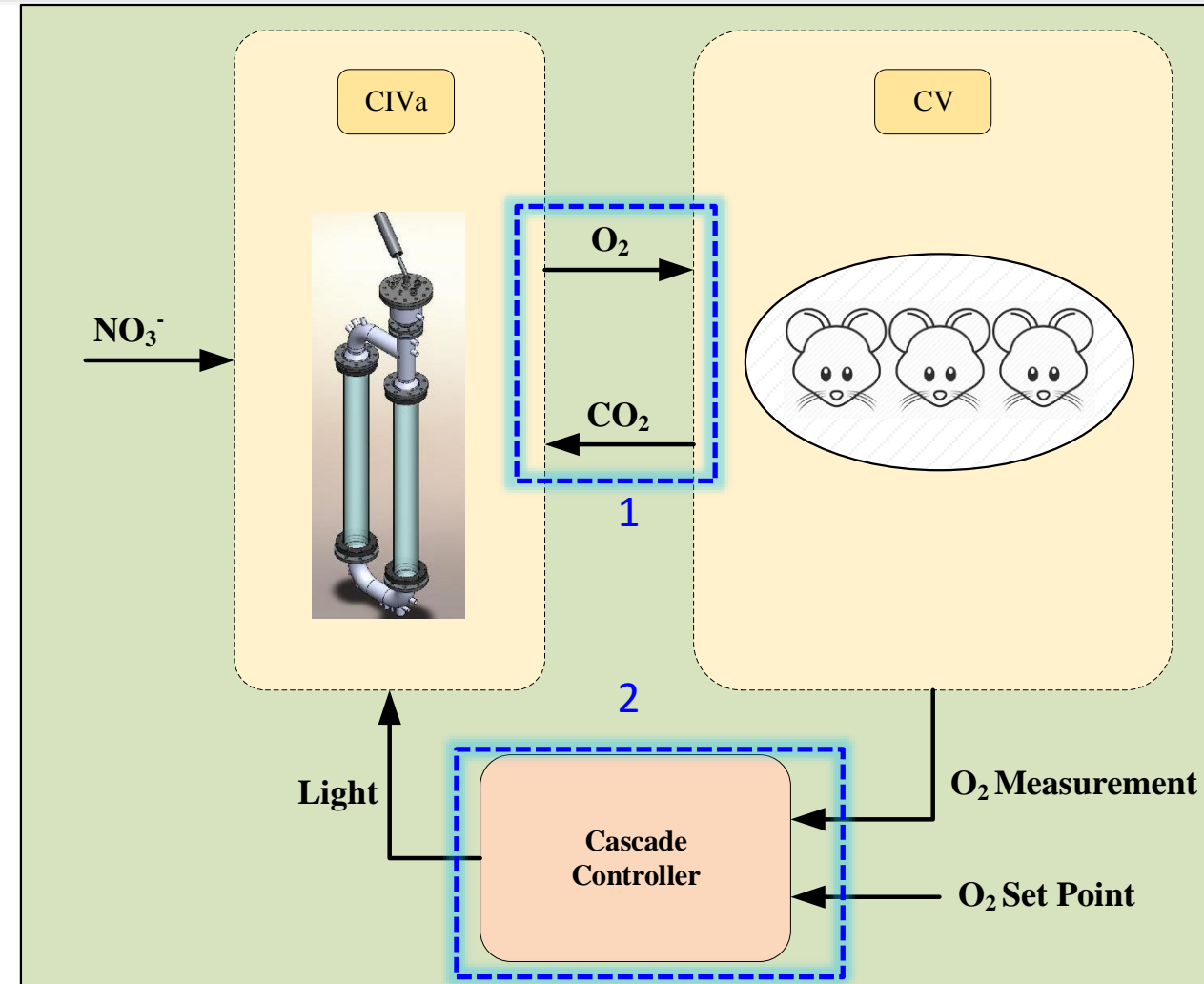
1. Integration goal: O_2 and CO_2 balance (life constraints)
2. Connection of individual compartments to have a complete operational loop.
3. Control **objective**: adjust illumination according to the O_2 demand of the crew needs

Main challenges on modelling and control:

- Highly complex system
- Highly-nonlinear dynamics and interactions

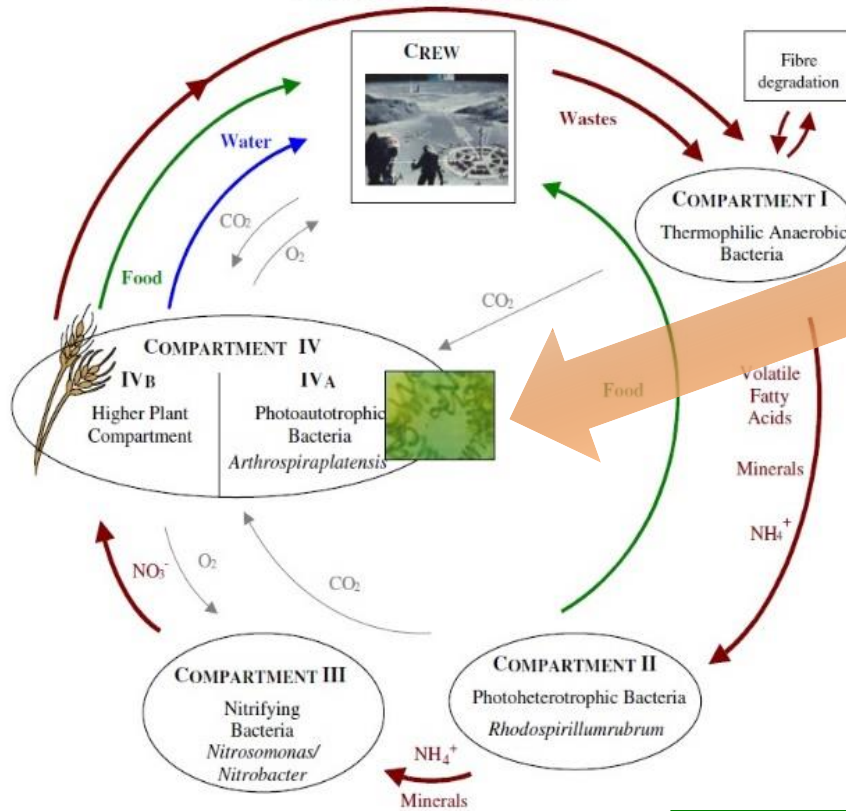
Final goal:

To achieve a closed liquid and gas loop fulfilling 100% of O_2 requirements and at least 20% of food requirements for one crew member.



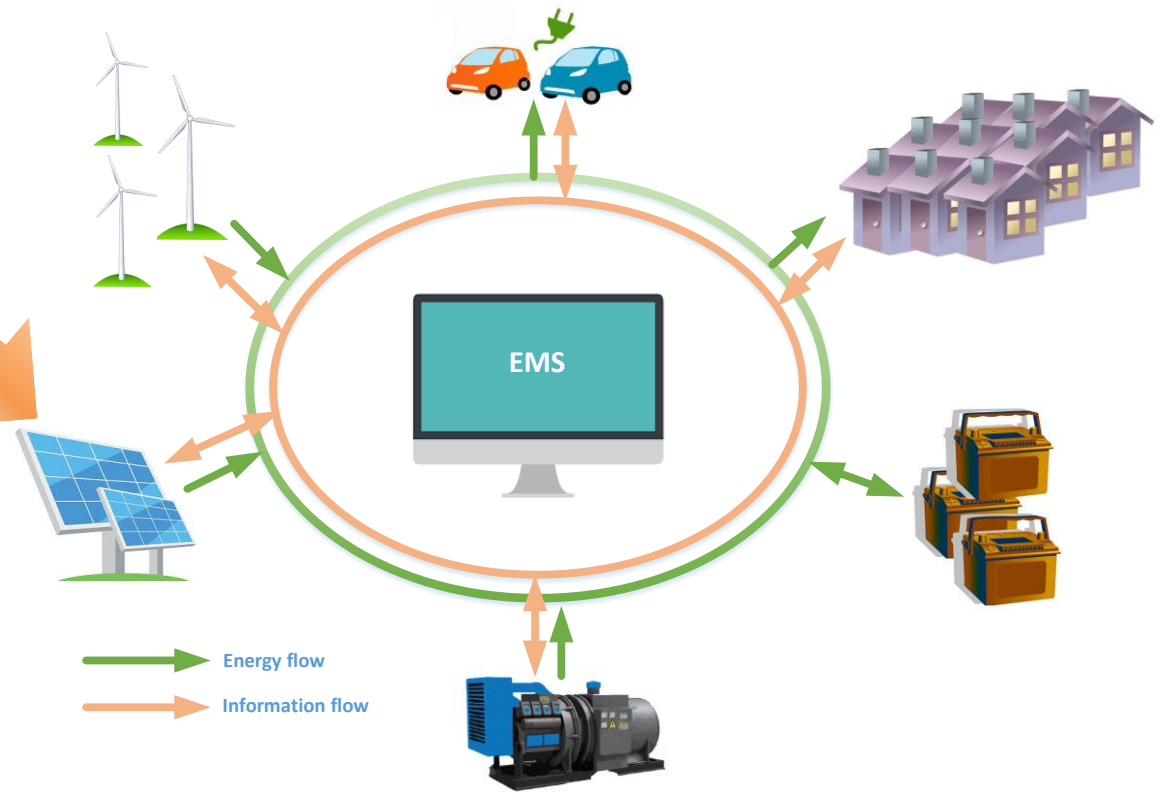
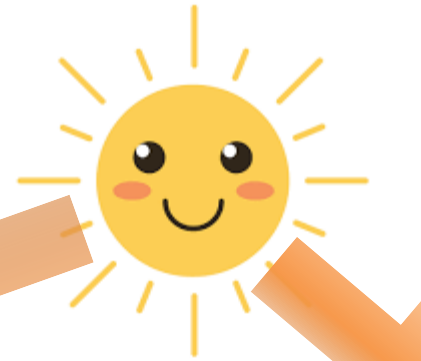
Parallelism between Closed Ecosystems and Microgrids

Non Edible Parts of Higher Plants



Closed Ecological Systems

- Photosynthesis
 - O_2 storage
- Microbial fuelcell



Microgrids

- Photovoltaics
- Energy storage
- Hydrogen fuel cell



Collaboration AAU - UAB

Aalborg University (AAU) Center for Research on Microgrids (CROM)
and

Universitat Autònoma de Barcelona (UAB) Department of Chemical, Biological and Environmental Eng.

Aim at bringing their expertise in **microgrids** and **biology** to establish a new **cross-domain research** and development framework.

AAU side: Advanced control and IoT knowledge applied in the microgrid areas

UAB side: Model and implementation of biological systems

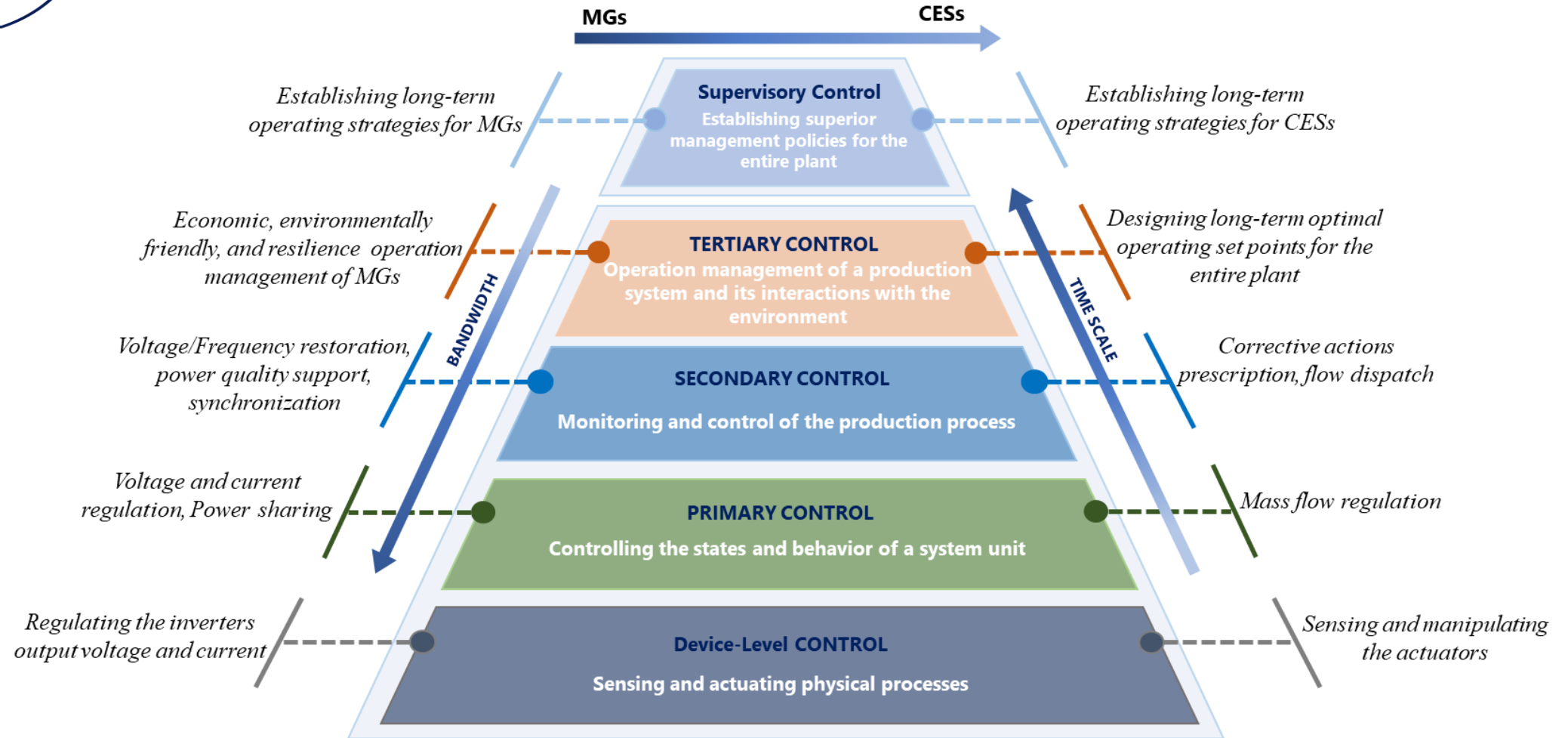
Final goal:

to control the operation of close ecological systems such as life support systems in space applications.

Midterm goals:

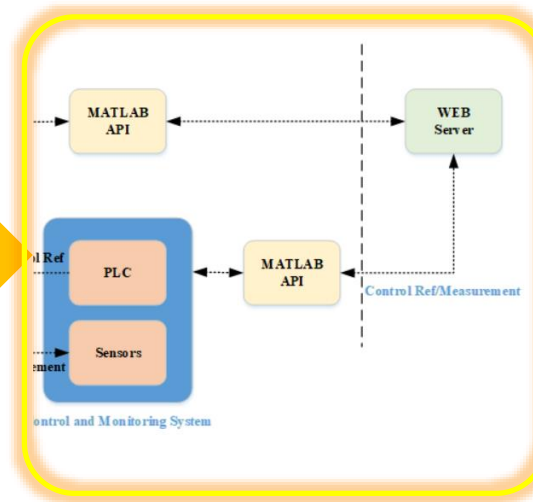
- Modeling of components and mutual interaction inside the biological ecosystem
- Real-time remote monitoring, supervision, and control **MELiSSA** laboratory from AAU-Denmark
- To develop a **Digital Twin** of the Space Biological Ecosystem

Multi-level hierarchical control structure of MGs and CESs





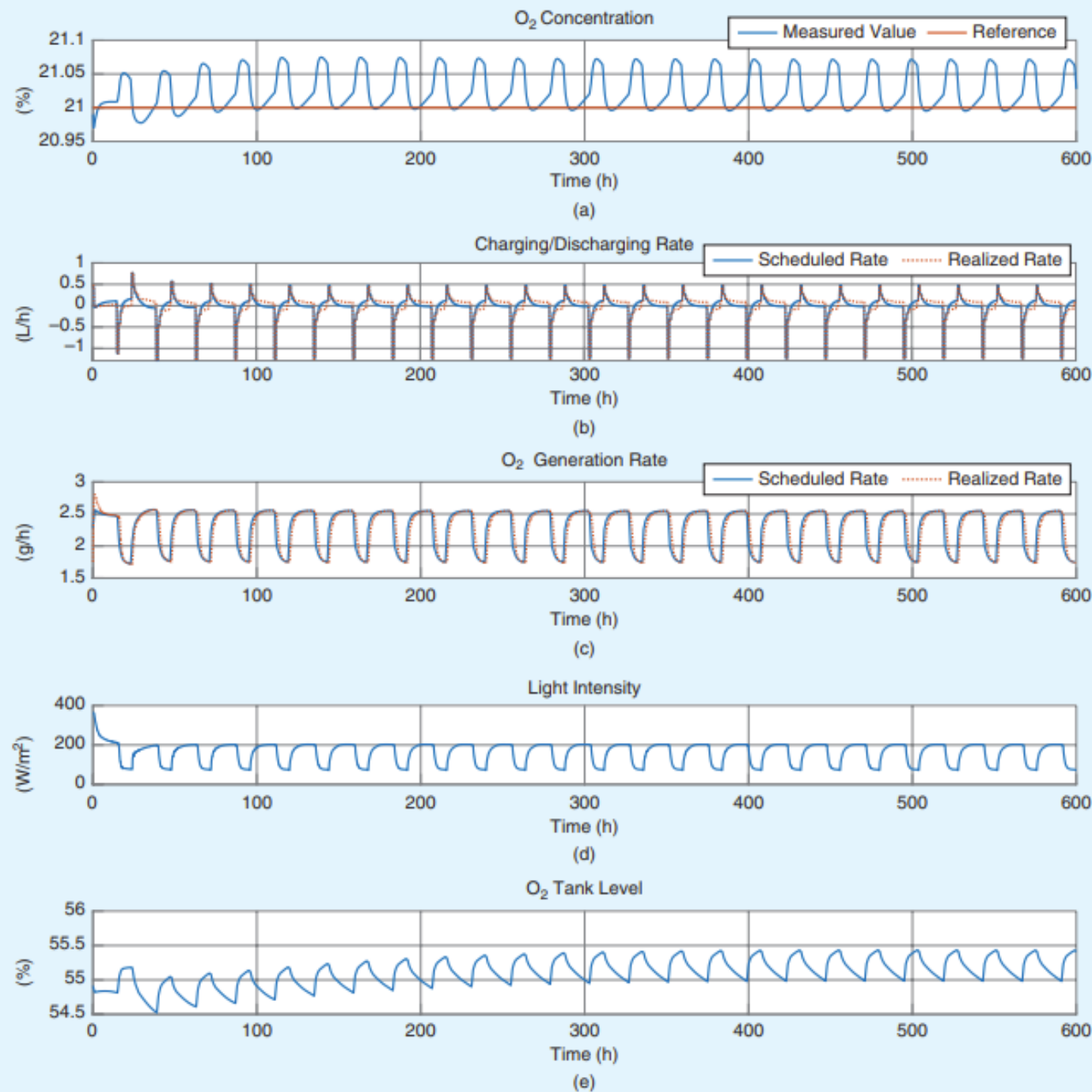
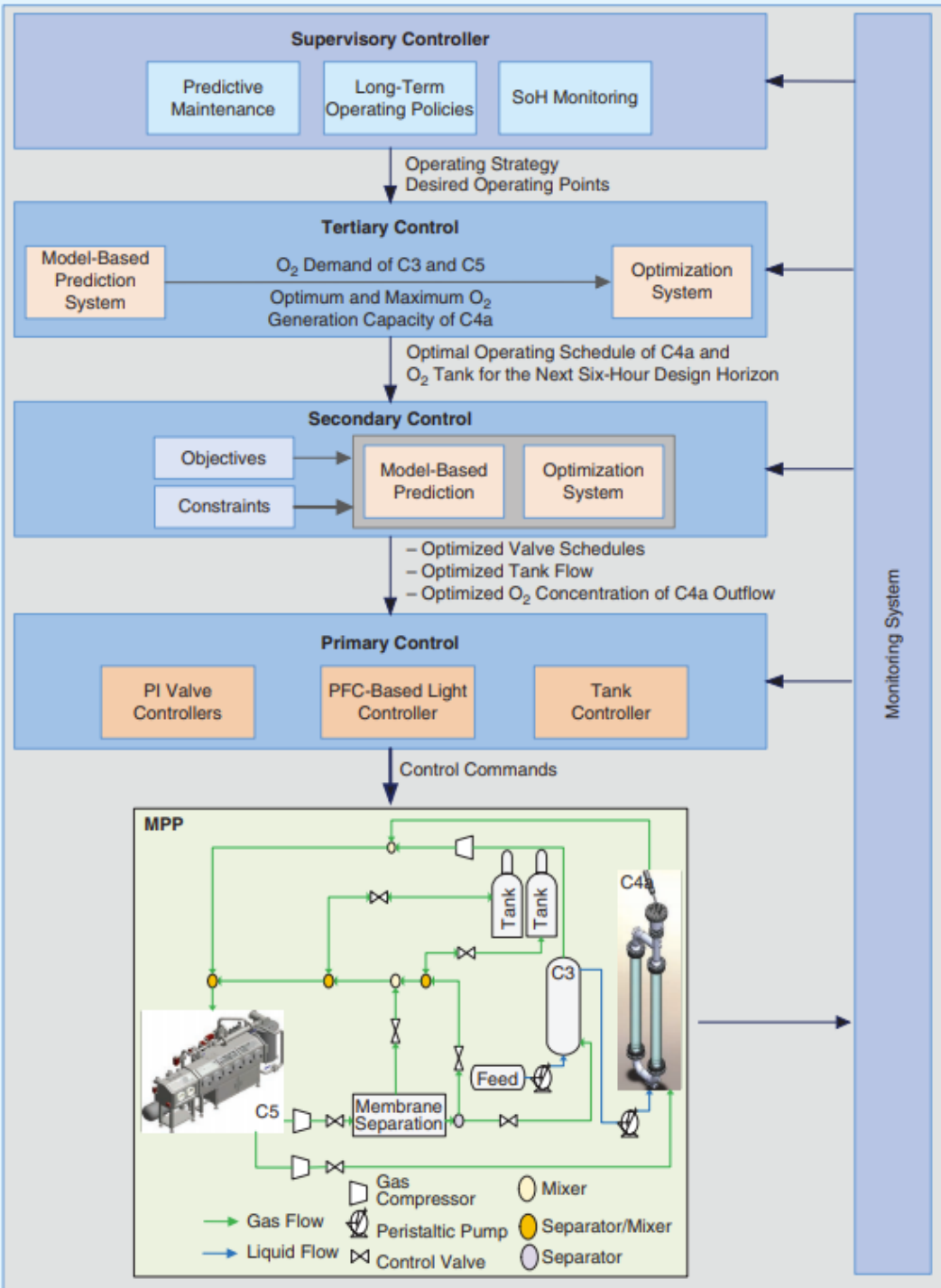
CROM FACILITIES (AAU)




- Real-time Communication Framework
 - Microgrid Control Architectures
 - Remote control and monitoring



MELISSA PILOT PLANT (UAB)





**“We can not solve our problems
with the same level of thinking
that created them”**

Albert Einstein