


Energy Storage Applications

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EE6509 – “Renewable Energy Systems in Smart Grids”

Lecture Objective

1. **Review typical applications of energy storage systems in power systems**
2. An in-depth look at load shifting application from the utility perspective
3. An overview of some issue in energy storage applications

Real world energy storage facilities and their applications

Name/Location	Rating	Application
BES/Australia	30 MW/ 8 MWh	Fast frequency response
BES/USA	8 MW/ 2 MWh	Frequency regulation
BES/Germany	8.5 MW/ 8.5 MWh	Frequency control, spinning reserve
BES/Puerto Rico	20 MW/ 14 MWh	Frequency control, spinning reserve
BES/Japan	34 MW/ 244.8 MWh	Wind power fluctuation mitigation
BES/USA	10 MW/ 40 MWh	Spinning reserve, load leveling
BES/Ireland	2 MW/ 12 MWh	Wind power fluctuation mitigation
SCES/China	3 MW/ 17.2 kWh	Voltage sag mitigation
SCES/Spain	4 MW/ 5.6 kWh	Frequency stability
FES/USA	20 MW	Frequency regulation, power quality
FES/Japan	235 MVA	High power supply to nuclear fusion furnace
SMES/Japan	10 MW	System stability, power quality

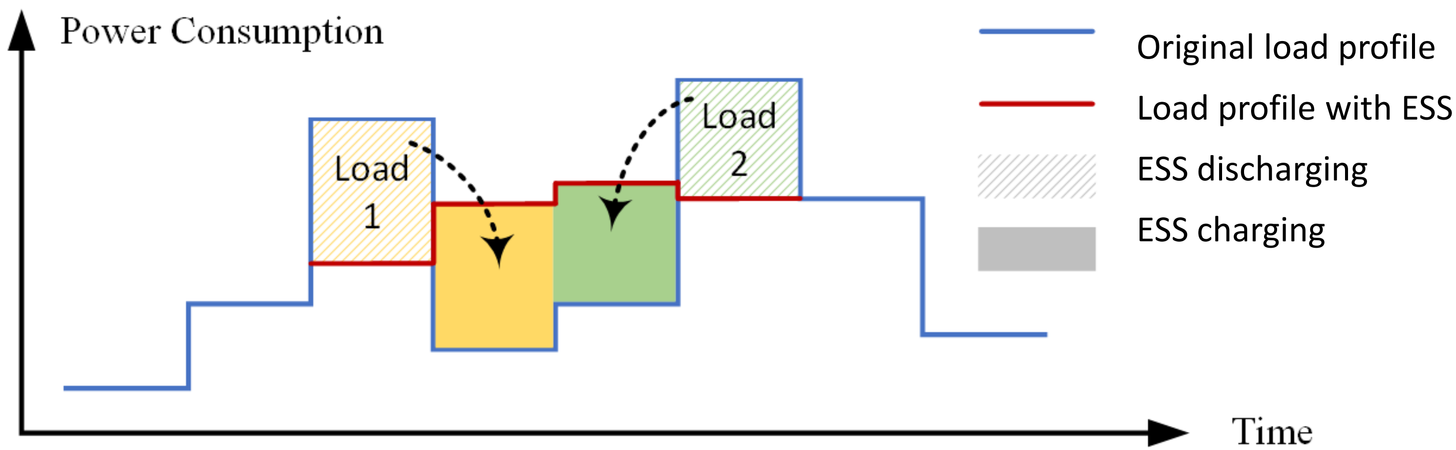
Umer Akram, et al "A review on rapid responsive energy storage technologies for frequency regulation in modern power systems," *Renewable and Sustainable Energy Reviews*, 2020.

1. Typical Applications of ESS

1) Load shifting
2) Frequency control
3) Electric vehicle (EV)
4) Uninterruptible power supplies (UPS)
5) Thermal energy storage

1) Load shifting

- **Stores** energy when demand is low and **returns** it to grid when demand picks up.

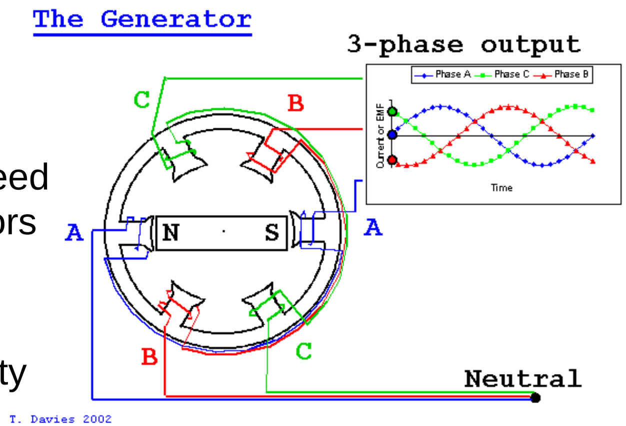


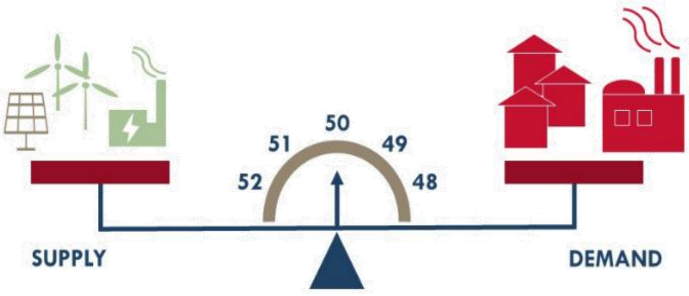
- **Longer** time window (eg, 30mins to hours)
- Requires **high energy capacity** storage.
- Can provide additional **operating benefits** (part 2)

2) Frequency Control

➤ **Frequency**
- AC power system
- Reflection of rotation speed of synchronous generators

➤ **Importance**
- Grid: system stability
- Consumers: power quality





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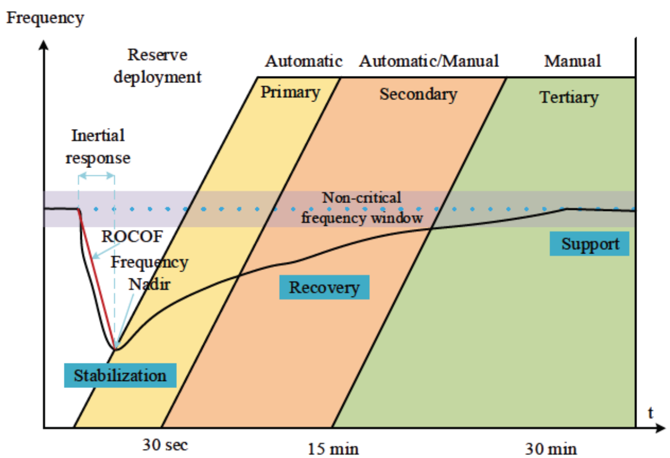
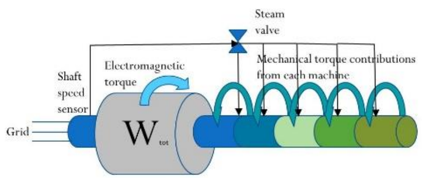


- **Inertia Response (IR):** the inherent releasing of energy at the rotor of synchronous machines.
- **Primary control:** mitigate frequency variation (seconds)
- **Secondary control:** eliminate frequency deviation (seconds to minutes)

Country/Region	Australia	Europe	Singapore
Nominal frequencies (Hz)	50	50	50
Normal operating frequency bands (Hz)	Interconnected system: ±0.15 Islanded system: ±0.5	±0.2	±0.2
Emergency frequency tolerance bands (Hz)	±1 Extreme frequency tolerance band: 47−52	±0.8	Under-frequency load shedding: 49.7

2) Frequency Control

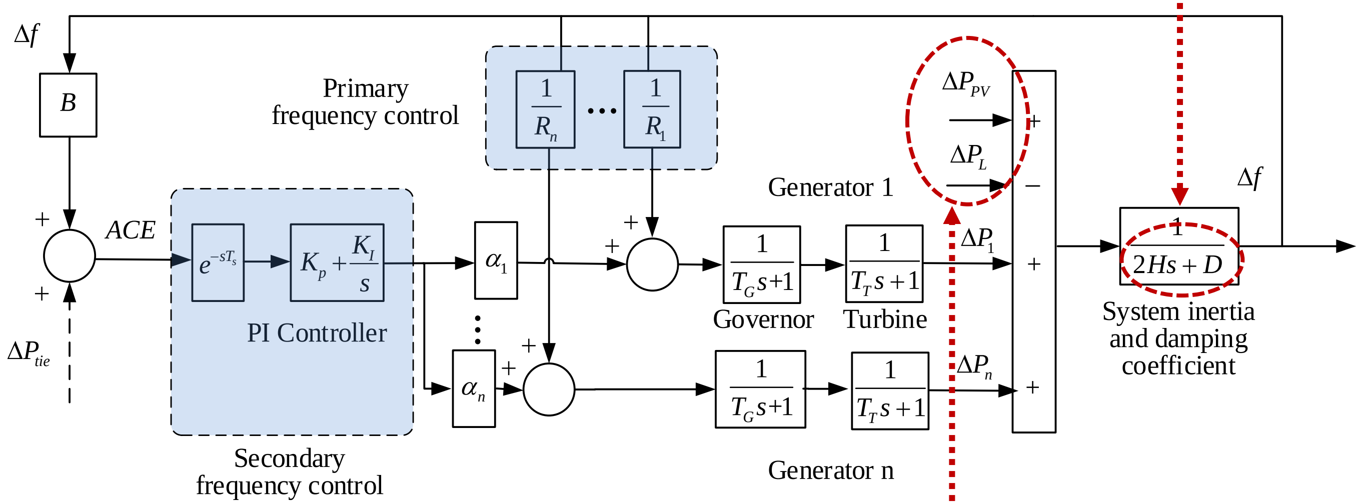
➢ **Lower inertia and load damping:**



Generation side: power-converter interfaced generators (wind, solar).

Transmission side: asynchronous interconnection through HVDC links.

Load side: inverter-based loads.

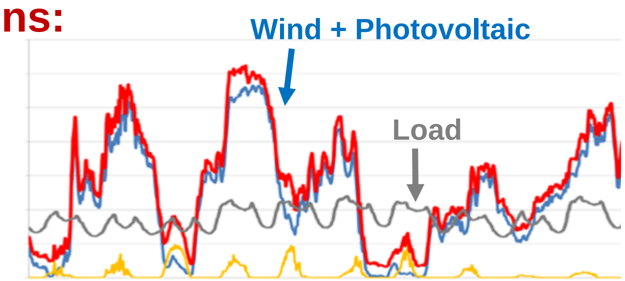


New frequency regulation (FR) resources and methods are needed!

➢ **Larger and faster power fluctuations:**

Generation side: intermittent renewable power generation

Load side: demand response program, EV charging load, etc.



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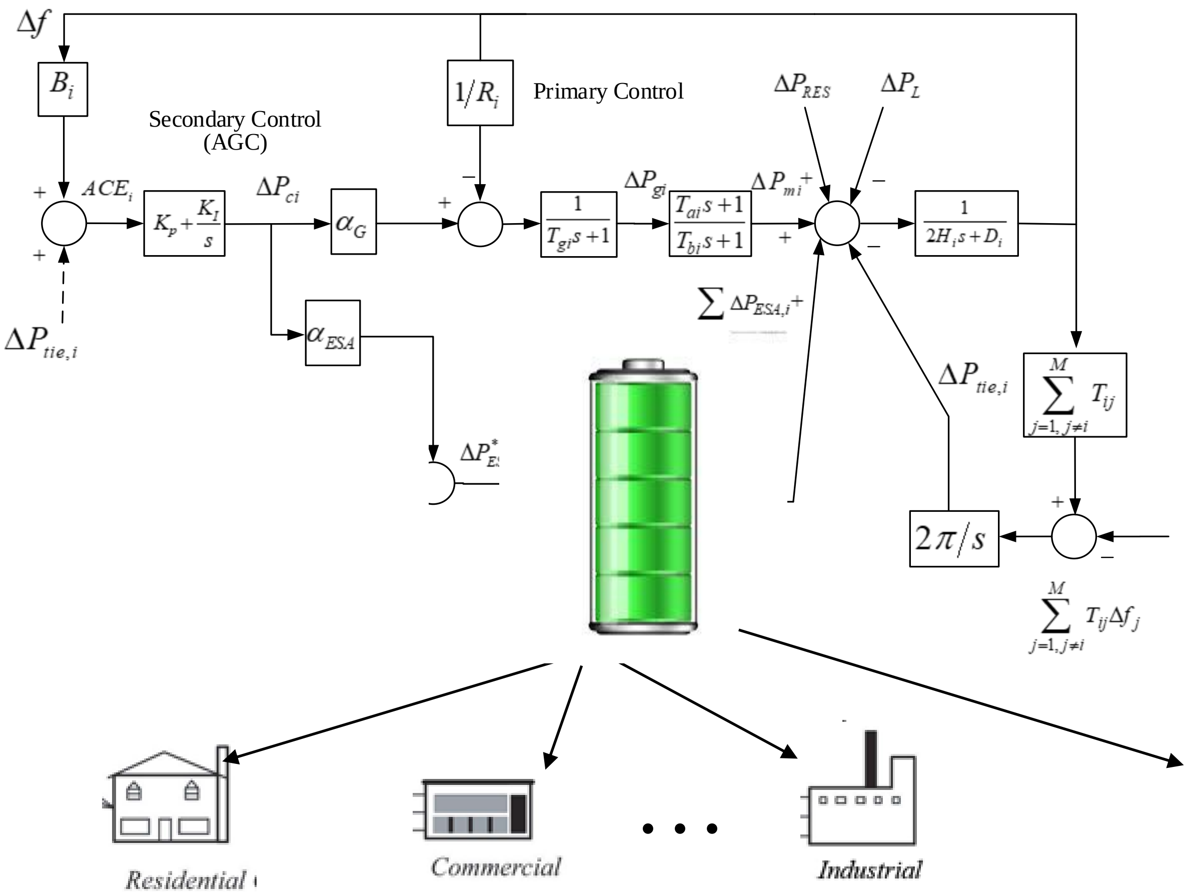
2) Frequency Control



Key challenges:

1) Sizing → what's optimal size of the ESS?
2) Controller design → how to charge and discharge?

Can be an aggregation of widespread small-scale ESS units, large in number but small in capacity (kWh)

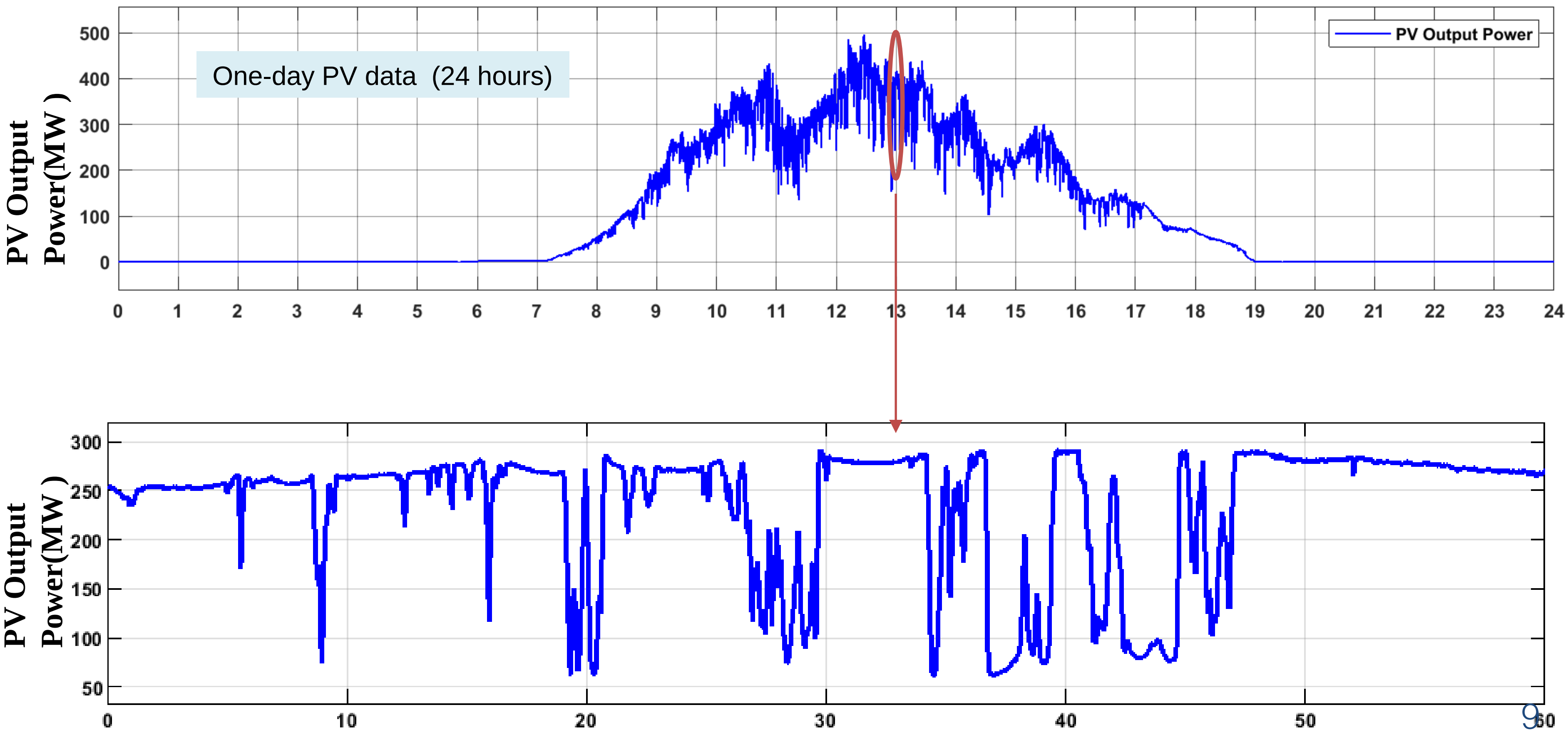
Y. Wang, Y. Xu, Y. Tang, et al "Aggregated Energy Storage for Power System Frequency Control: A Finite-Time Consensus Approach," ***IEEE Trans. Smart Grid*, May 2018.**

Or be large-scale grid ESS in MWh level

Z. Yan, Y. Xu, et al, "Data-driven Economic Control of Battery Energy Storage System Considering Battery Degradation," ***IET Generation. Transmission & Distribution, 2020.***

2) Frequency Control

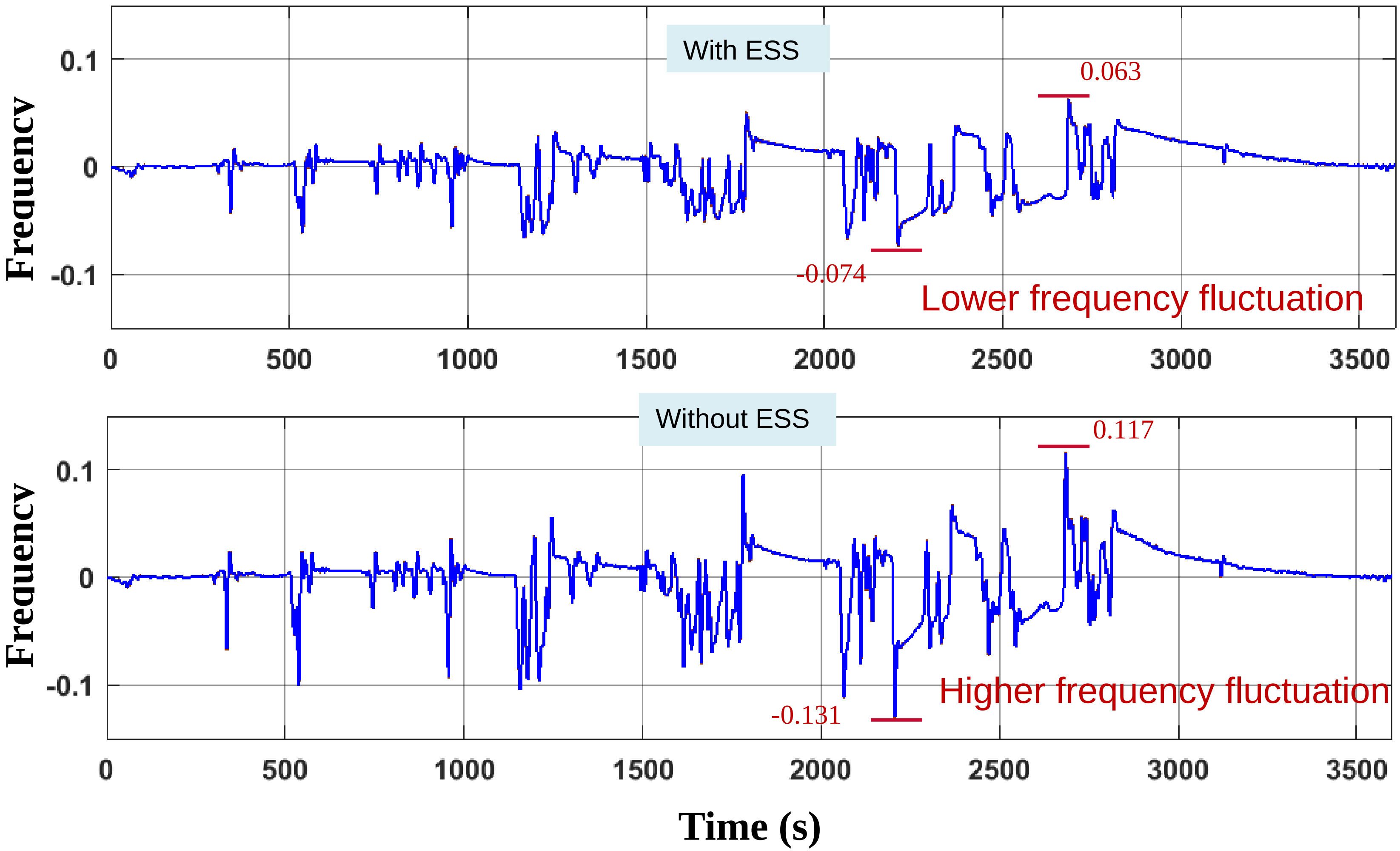
Simulation tests: considering solar PV fluctuations



One-hour PV data (60 mins)

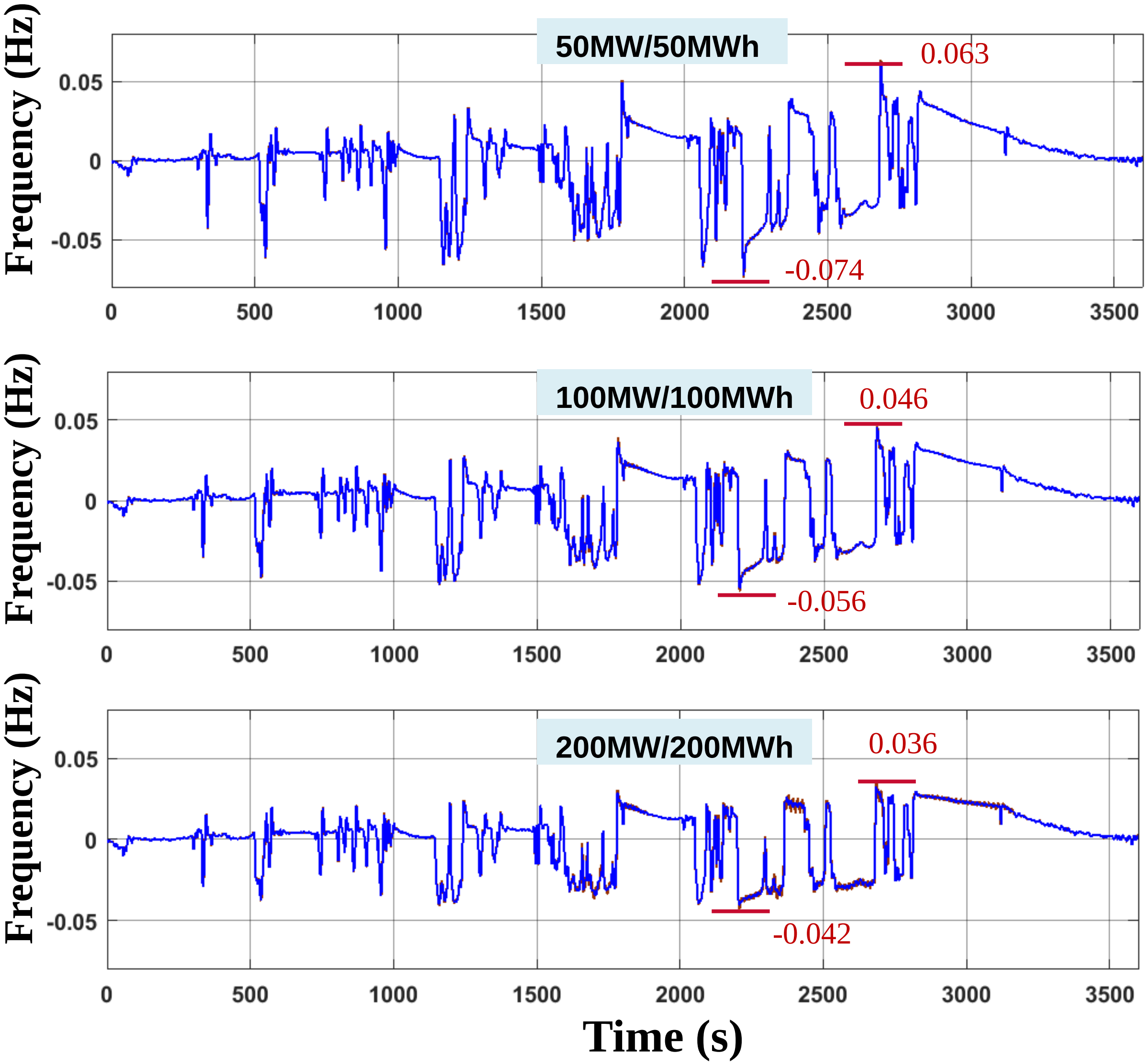
2) Frequency Control

Frequency fluctuations: With ESS VS Without ESS



2) Frequency Control

Comparison with Different ESS Power Rating & Capacity

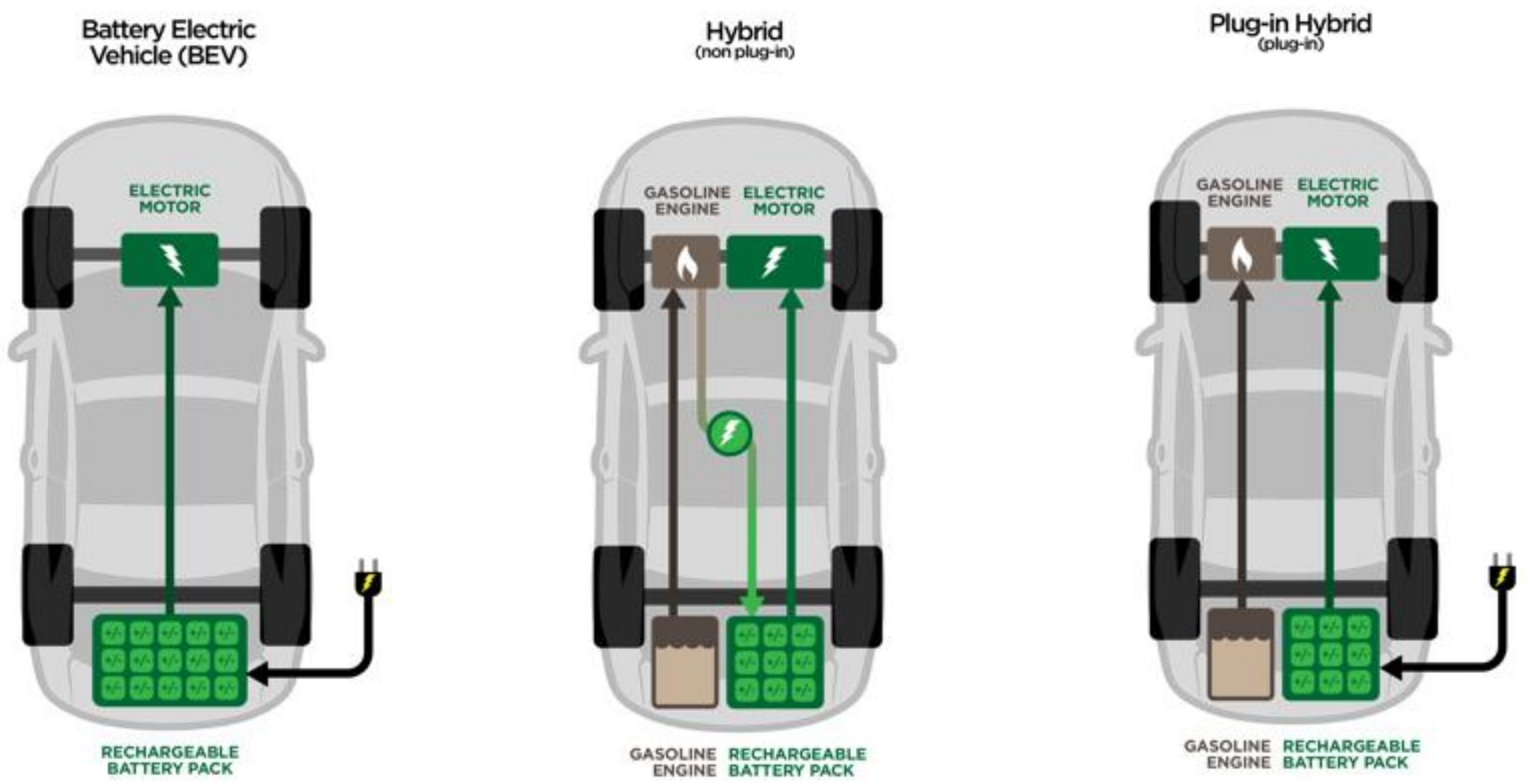


A larger power and capacity of ESS achieves better frequency regulation performance.

But what is the optimal cost-effective size?

3) Electric Vehicle

- Unlike internal combustion engine (ICE) vehicles, electric vehicles consumes electricity that can be generated from a wide range of sources besides fossil fuels, such as clean **renewable sources**.
- **Pollution** from fossil fuel power plants is easier to control compared to that emitted by ICE vehicles.
- The biggest challenge to EV technology is the **energy storage system**.



https://www.google.com.sg/search?q=hybrid+electric+vehicle&source=lnms&tbm=isch&sa=X&ved=0ahUKEwjNwfbdmprXAhVMp48KHdvABZIQ_AUICigB&biw=1920&bih=989#imgrc=vLj8g2P6QJpiWM:

3) Electric Vehicle

Battery Electric Vehicle (BEV)

- Current research focuses on **fuel cells** and **batteries**.
- **Flywheels** and **super-capacitors** are also being considered, though usually not as primary
- Issues in BESS for BEV include insufficient energy capacity, long charging times, high costs, safety, reliability, difficulties in determining state of charge and health, and effects on charging infrastructure.

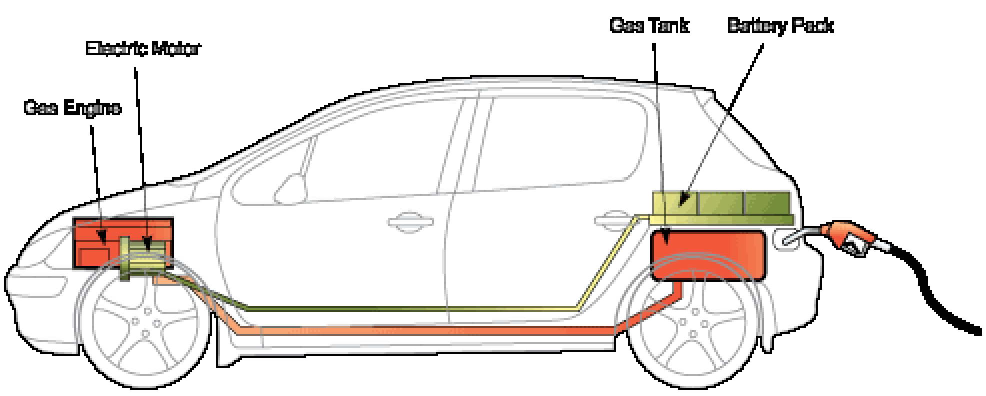
www.greencar.com

www.tva.gov

3) Electric Vehicle

Hybrid Electric Vehicle (HEV)

- Unlike BEV, hybrid electric vehicles uses smaller ESS to aid in energy recovery from regenerative braking and to allow the ICE to operate more efficiently over wider range of road conditions.
- Because HEV technology is already in commercial readiness, the impact in near future applications is quite certain and significant.
- It is possible all automobiles sold worldwide in near-future will be some degree of HEV.

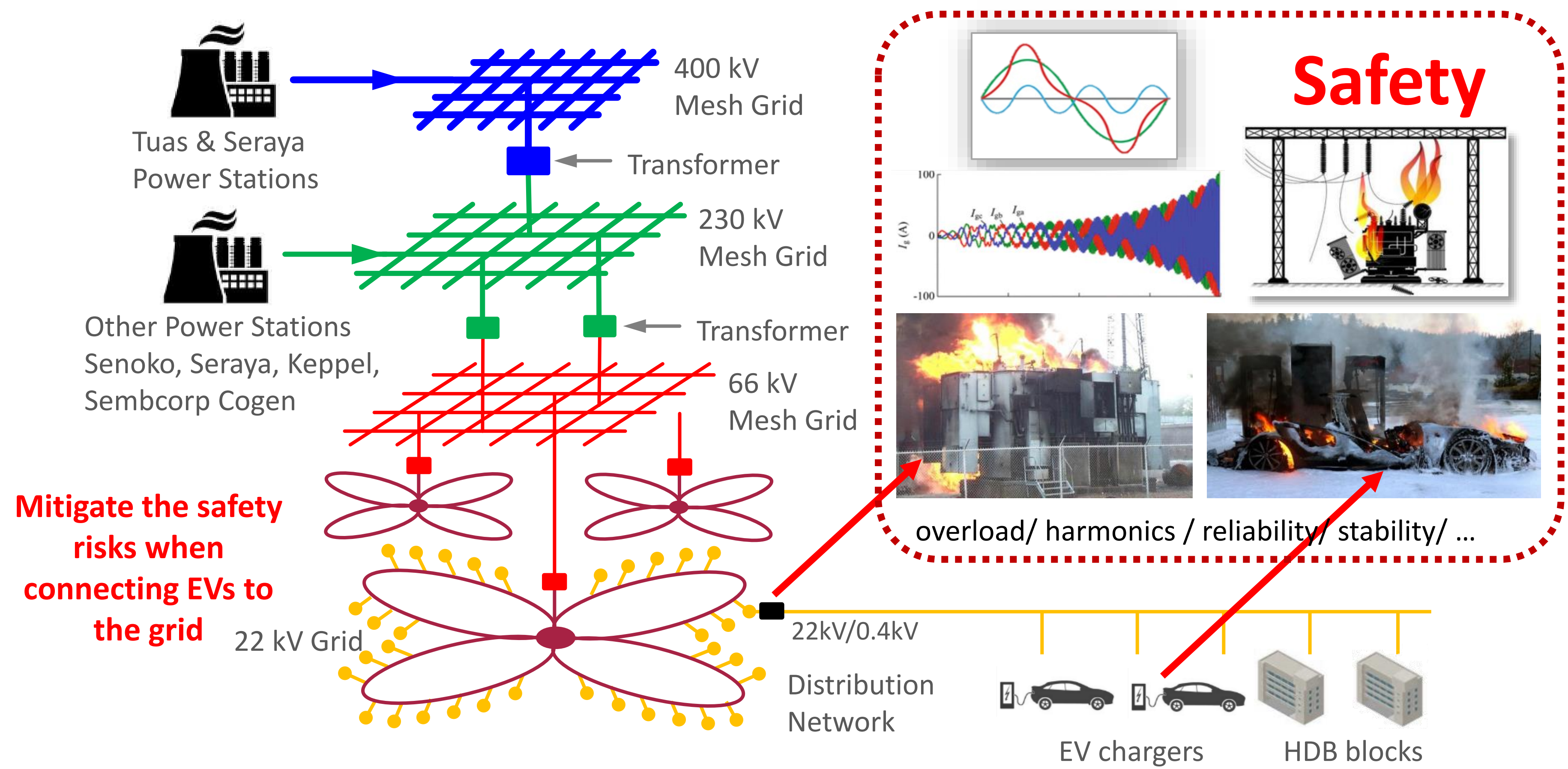


3) Electric Vehicle

Plug-in HEV (PHEV)

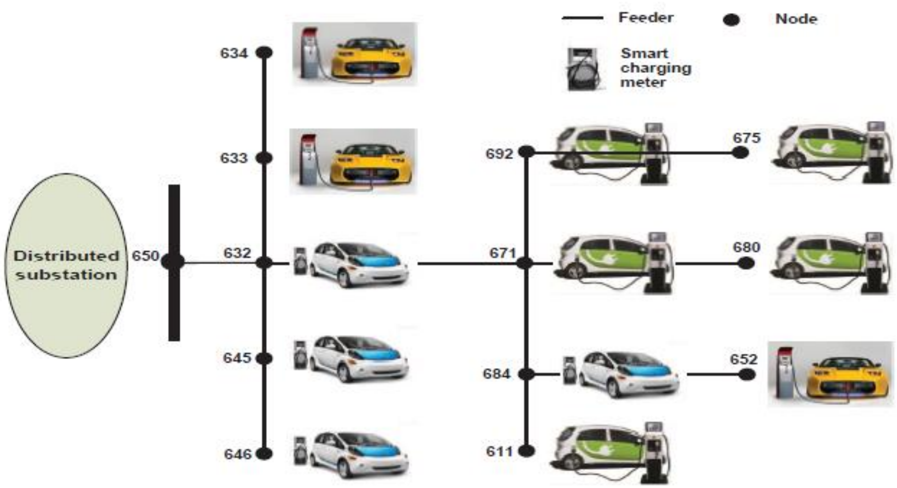
- Allow the vehicle ESS to be charged from EV charging point, is perhaps a further incremental step to help in the eventual adoption of full EV future.
- Most HEV ESS are based on NiMH batteries, with trials going on with Li-ion batteries.
- The main challenges to HEV technology is the higher initial costs. The need for **power electronics to coexist with high temperature ICE** require more research into high-temperature electronics

3) Electric Vehicle



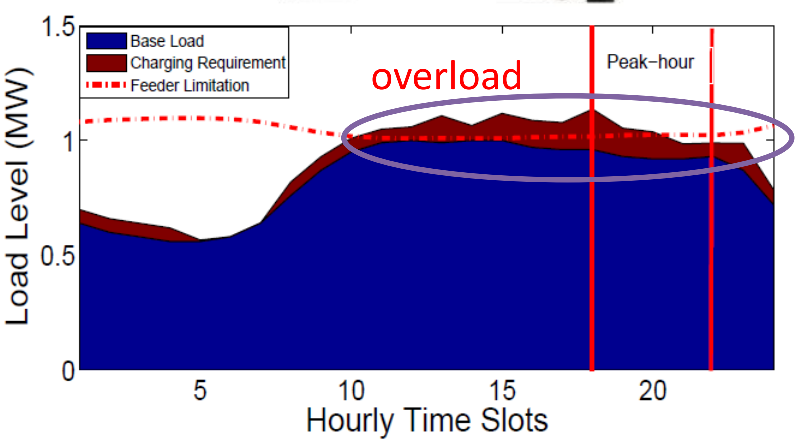
3) Electric Vehicle

Controlled EV charging/discharging

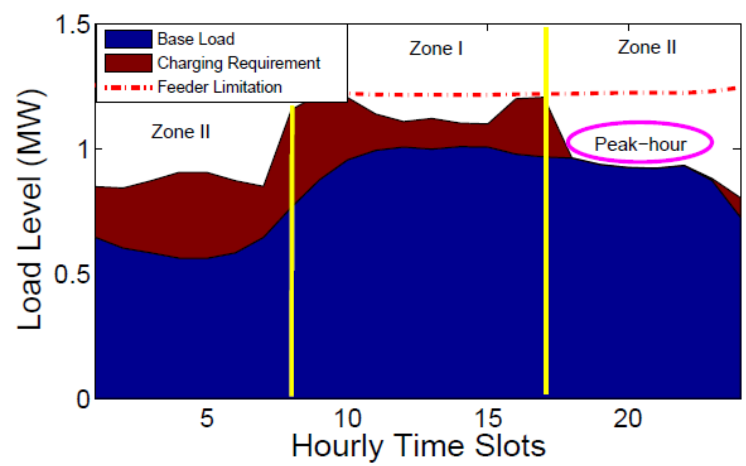


Optimally controlling the EV's charging/discharging to:

1) Ensure the charging load does not violate power grid security limit;
2) Support the power grid operation



Uncontrolled charging



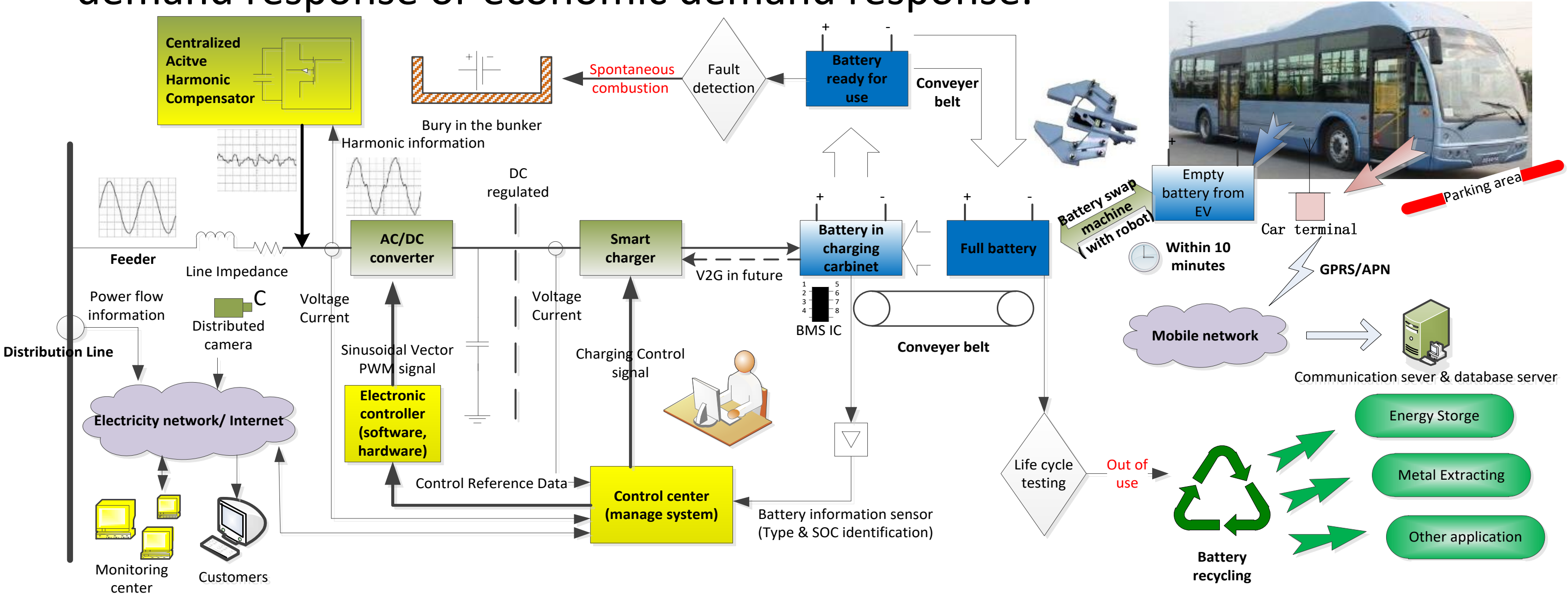
Controlled charging

J. Li, C. Li, **Y. Xu**, et al, "Noncooperative Game-based Distributed Charging Control for Plug-In Electric Vehicles in Distribution Networks," *IEEE Trans. Industrial Informatics*, 2016

3) Electric Vehicle

Vehicle to Grid (V2G)

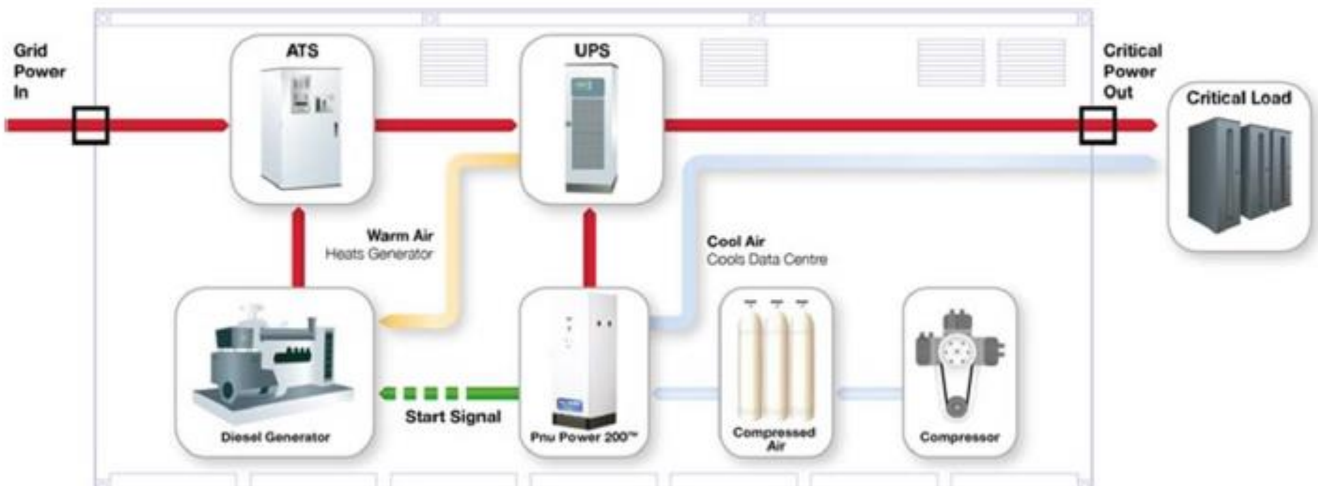
- Sufficiently large number of EV simultaneously connected to the charging infrastructure for this concept to work.
- EV owners must also be willing to participate in the scheme.
- The individual ESS of every EV shall collectively become a massive ESS to supply the grid with power to meet certain objectives, be it load leveling, emergency demand response or economic demand response.



Y. Zheng, Z.Y. Dong, **Y. Xu**, et al, "Electric vehicle battery charging/swap stations in distribution systems: comparison study and optimal planning," *IEEE Trans. Power Systems*, vol. 29, no. 1, pp.221-229, Jan. 2014.

4) Uninterruptible Power Supplies

- Uninterruptible power supplies (**UPS**) have conventionally been based on **lead-acid batteries**, particularly for data centers and many other installations e.g. wind turbines backup,
- One newly commercialized solution is based on **compressed air** to generate the initial burst of electric power to keep systems supplied while the back-up generator starts.
- Another offer is based on flywheel ESS.



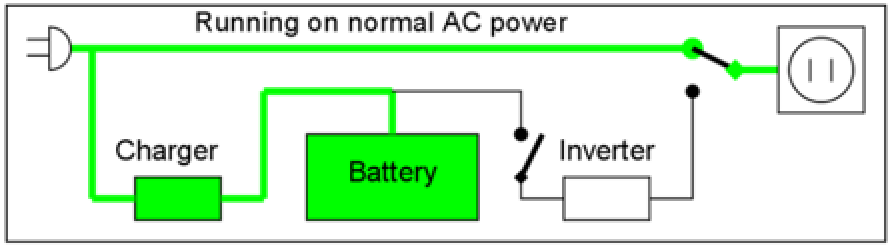
www.pnu-power.com

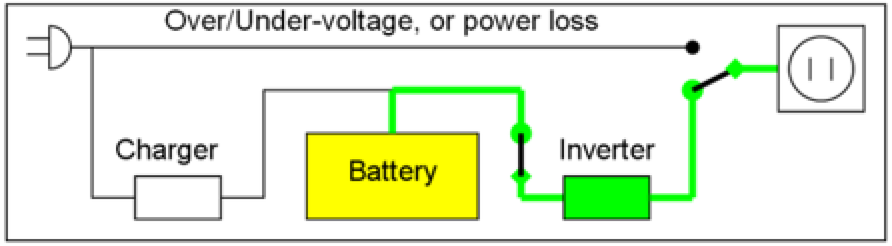
4) Uninterruptible Power Supplies

- Above: large lead-acid BES based UPS for data centers
- Left: small lead-acid BES UPS for one or two desktop computers

4) Uninterruptible Power Supplies

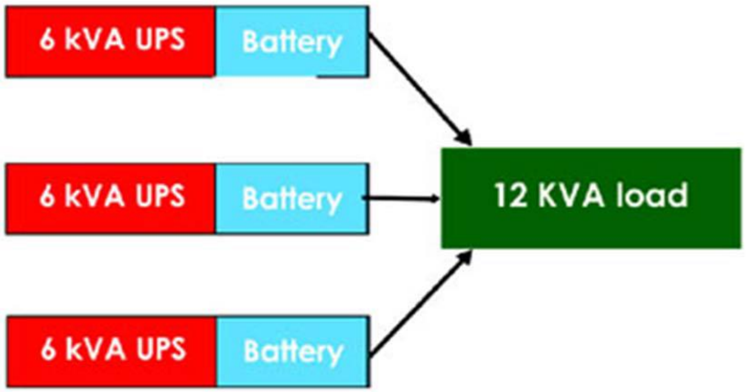
- Offline/standby UPS provides only surge protection and energy backup.
- Protected equipment is normally connected directly to incoming utility power.
- When the incoming voltage falls below or rises above a predetermined level the UPS turns on its internal DC-AC inverter circuitry, which is powered from an internal storage battery.
- The UPS then mechanically switches the connected equipment on to its DC-AC inverter output.
- The switchover time can be as long as **25 milliseconds** depending on the amount of time it takes the standby UPS to detect the lost utility voltage.





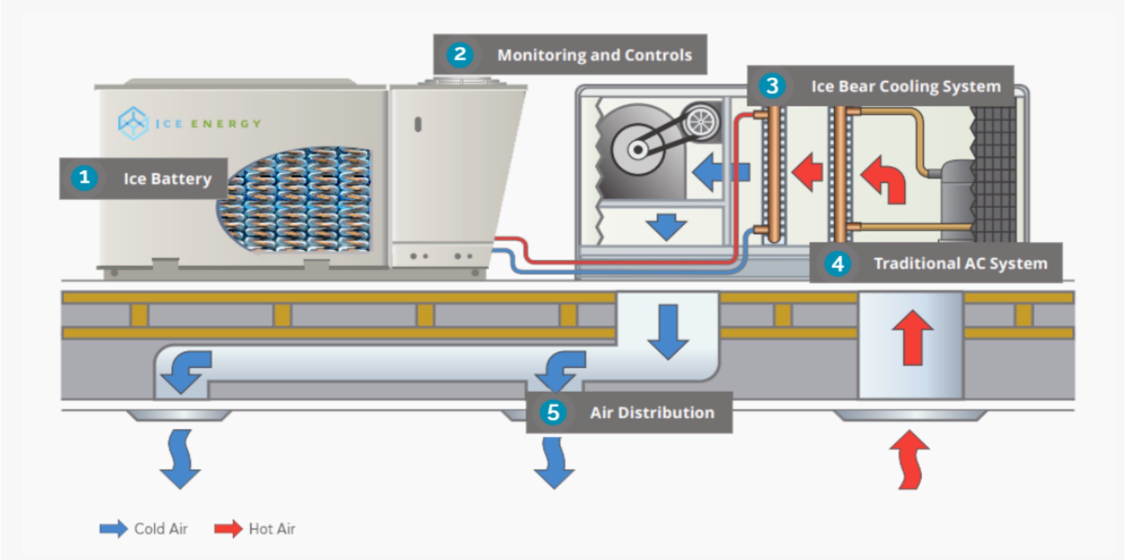
4) Uninterruptible Power Supplies

- In environments where reliability is of great importance, a single huge UPS can also be a **single point of failure** that can disrupt many other systems.
- To provide greater reliability, multiple smaller UPS modules and batteries can be integrated together to provide redundant power protection equivalent to one very large UPS.
- "**N+1**" means that if the load can be supplied by N modules, the installation will contain N+1 modules. In this way, failure of one module will not impact system operation.



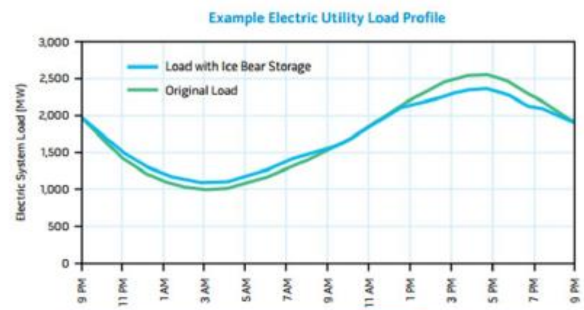
5) Thermal Energy Storage

- **Heating, ventilation and air conditioning (HVAC)** accounts for major portion of energy consumed in buildings.
- ESS can help in reducing energy requirements in HVAC.
- Energy can be **stored thermally** in building walls and in chilled or heated water.
- By using ESS for thermal/cooling load leveling, HVAC can be made to operate more efficiently.



5) Thermal Energy Storage

Converting cheap electric energy at night to cooling energy in making ice, which may then be used to cool a building when electricity is expensive in the day.



2 modes: Ice cooling (day) & Ice charging (night)

Ice Evaporator coil added to the Air-conditioning unit

Heat Exchanger

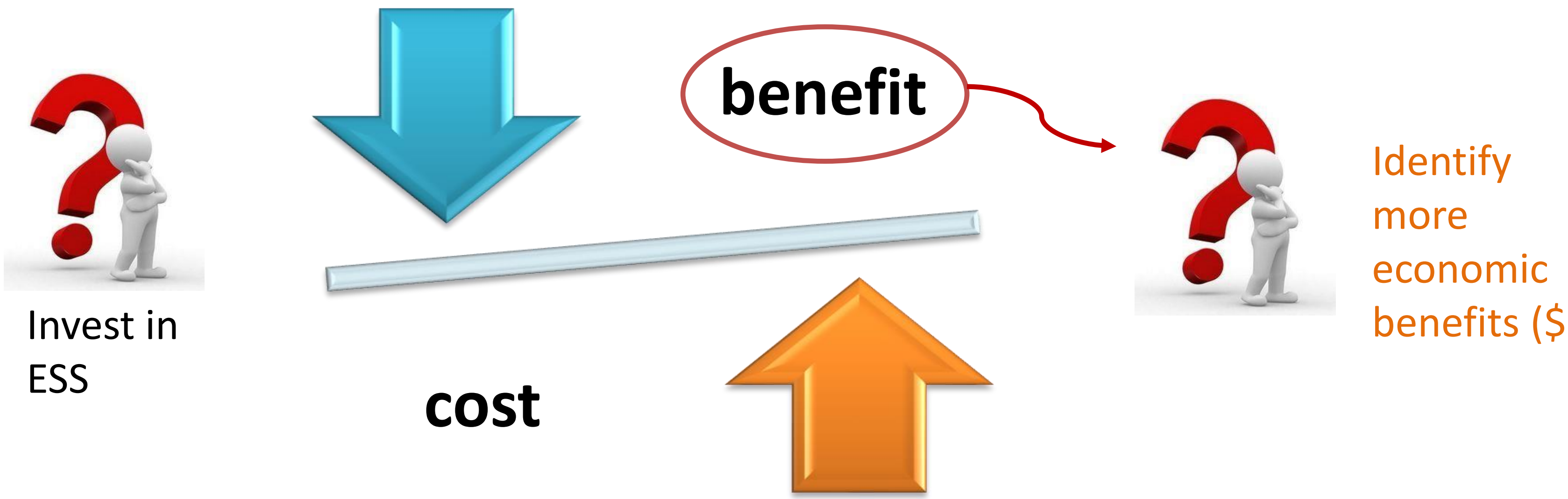
:www.ice-energy.com

Lecture Objective

1. Review typical applications of energy storage systems in power systes
2. **An in-depth look at load shifting application from the utility perspective**
3. An overview of some issue in energy storage applications

2. Load Shifting from Utility Perspective

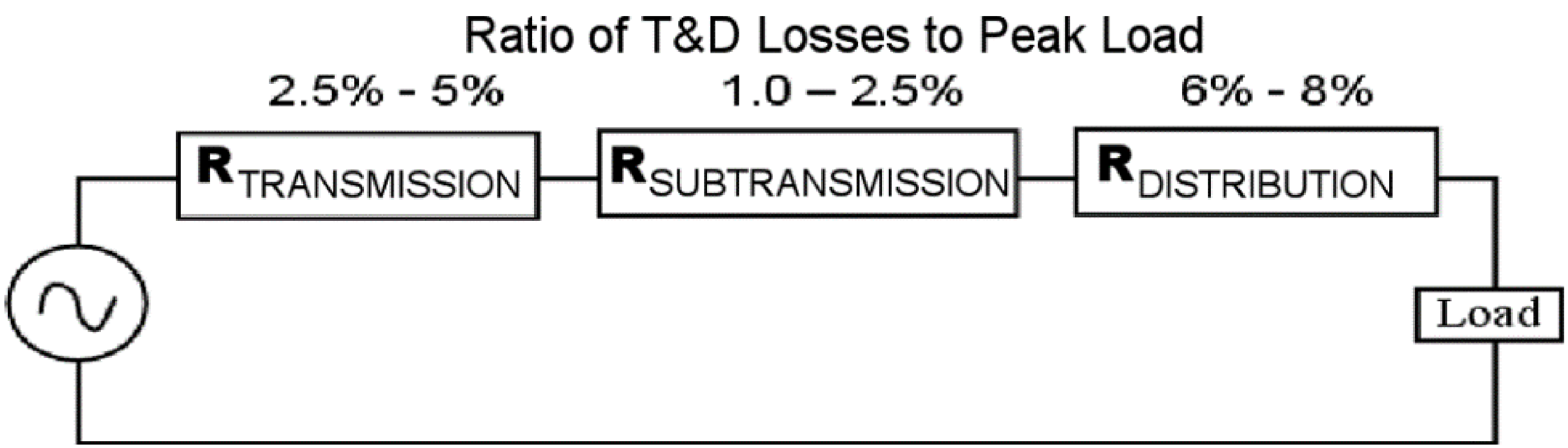
The benefit of load shifting from the peak to the off-peak period to **defer grid defer investment** on generation, transmission, and distribution assets is well known.



1) Load leveling to reduce transmission and distribution (T&D) power loss
2) Load leveling to regulate the bus voltage of distribution networks

1) An In-Depth Look at T&D Losses

- The impact on reducing **transmission and distribution (T&D) losses** is often ignored or lightly mentioned.
- However it is possible to identify the key parameters and **quantify** the saved T&D losses as a function of the size or power of the energy storage.
- This is an **added benefit** of utility-scale energy storage that is not fully recognized.



Ali Nourai, V. I. Kogan and Chris M. Schafer, "Load Leveling Reduces T&D Line Losses," IEEE Trans. Power Delivery

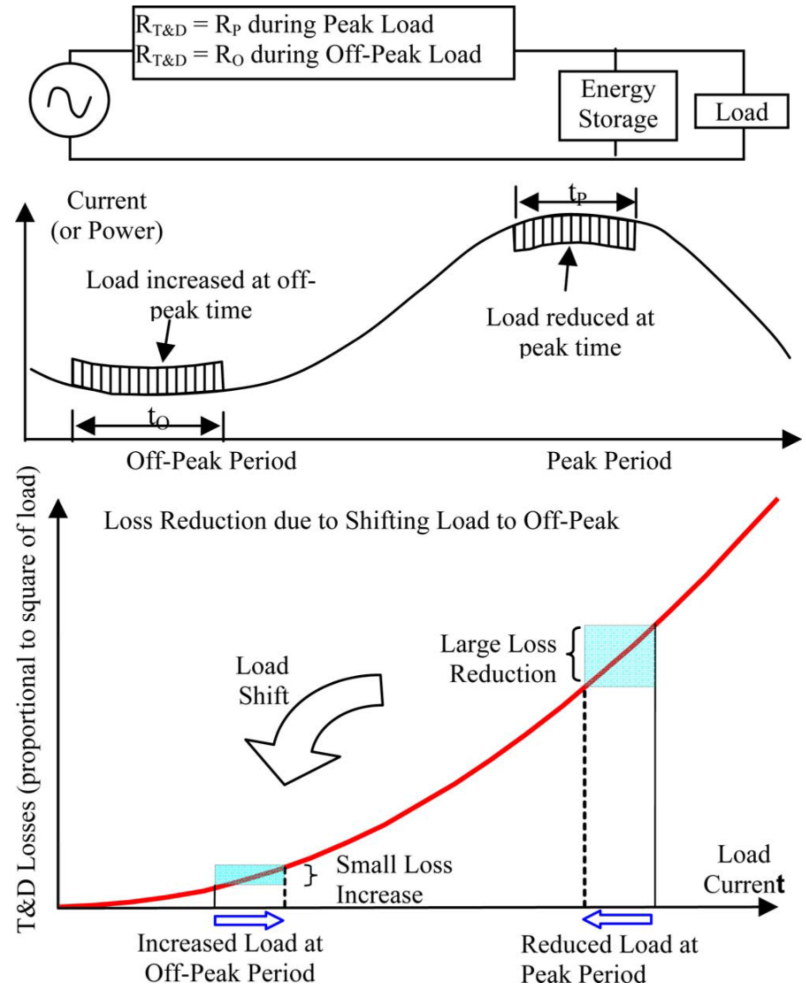
1) An In-Depth Look at T&D Losses

- Power losses are proportional to the square of the current flow (**$P=I^2*R$**), using energy storage to shift some of this current or load from the peak period to off-peak period decreases the net resistive losses, which can offset some of the storage losses.
- Two other factors also enhance this loss reduction and increase its value.
  - The **resistance** of T&D wires and transformers is lower at off-peak periods (lower temperature).
  - The **price** of the energy (and losses) is generally lower during off-peak periods.

1) An In-Depth Look at T&D Losses

Principle

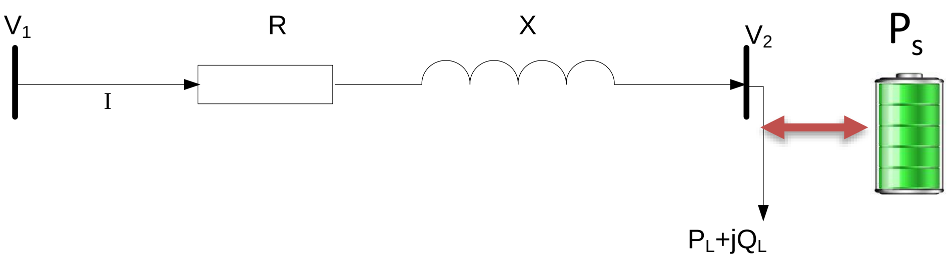
- This calculation of T&D losses is based on a simplified (Thevenin equivalent) circuit as seen by a single load center with local energy storage to shift load from peak to off-peak periods.
- Other parameters that can impact on the calculation of the T&D losses
  - storage efficiency;
  - ratio of peak to off-peak loads (before load leveling);
  - equivalent total T&D resistance (derived from known T&D losses);
  - variation of the total T&D resistance from peak to off-peak periods.



Ali Nourai, V. I. Kogan and Chris M. Schafer, "Load Leveling Reduces T&D Line Losses," IEEE Trans. Power Delivery

1) An In-Depth Look at T&D Losses

- The total (peak and off-peak) T&D loss for a time period with and without load shifting may be approximated respectively as



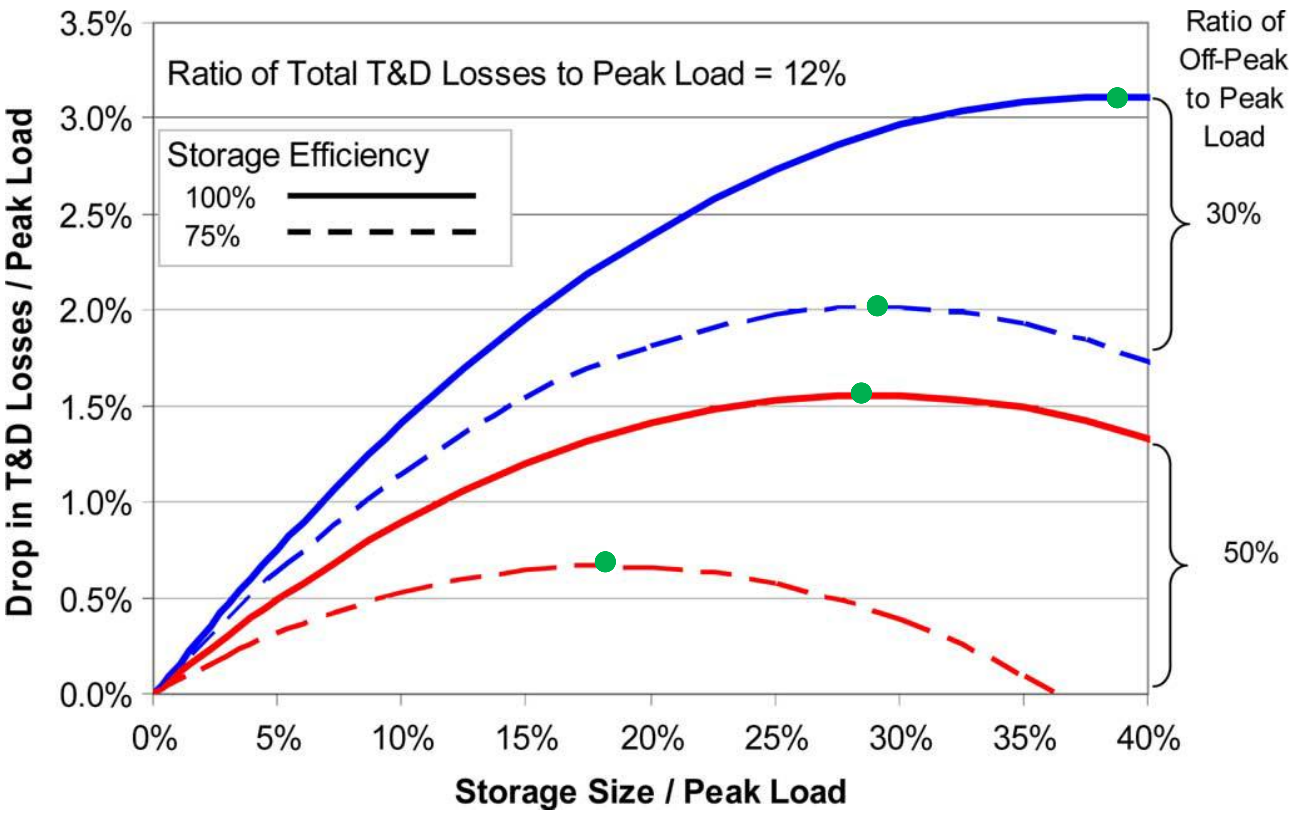
$$L = I_P^2 R_P t_P + I_O^2 R_O t_O$$

$$L_S = (I_P - I_S)^2 R_P t_P + (I_O + I_S)^2 R_O t_O$$

reduced V.S. increased

L	T&D losses without any load shift;
L_S	T&D losses with shifted load (energy storage);
R_P R_O	equivalent T&D resistances during peak and off-peak periods, respectively;
I_P, I_O	load current during peak and off-peak periods, respectively;
I_S	current provided locally by the storage device;
η	net ac energy efficiency of the storage system;
t_P	storage discharge time during the peak period;
t_O	t_P/η = storage charge time longer than discharge time due to the storage inefficiency.

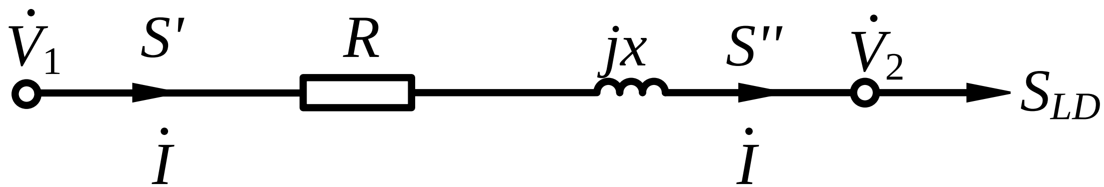
1) Impact of Load Shifting on T&D Losses Conclusion



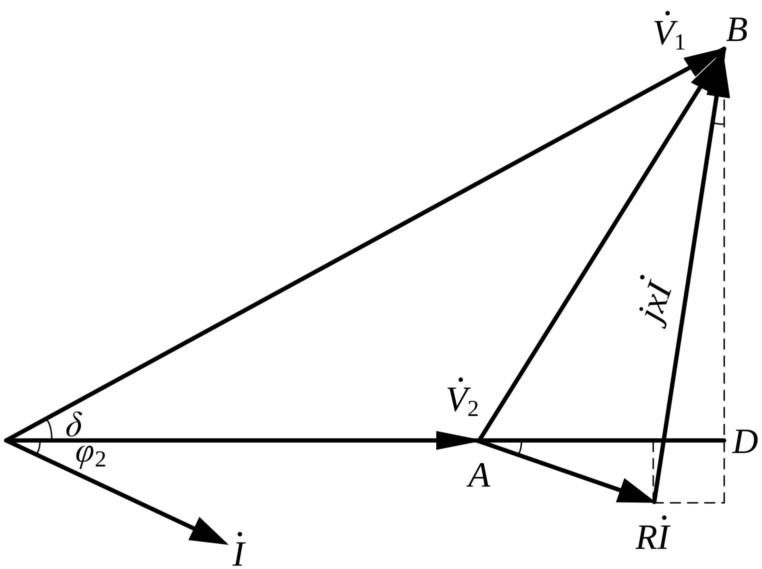
Another observation is the savings in the T&D losses is sensitive to the **ratio of the off-peak to peak loads**.

The savings in T&D losses increases (losses decrease) with the storage size **up to a maximum value beyond which the losses increase again**.

2) Voltage Regulation of Low-Voltage Distribution Networks



$$\dot{V}_1 - \dot{V}_2 = (R + jX)\dot{I} = \Delta\dot{V}_2 + \delta\dot{V}$$



$$\left.\begin{aligned} \Delta V_2 &= RI\cos\varphi_2 + XI\sin\varphi_2 \\ \delta\Delta V_2 &= XI\cos\varphi_2 - RI\sin\varphi_2 \end{aligned}\right\}$$

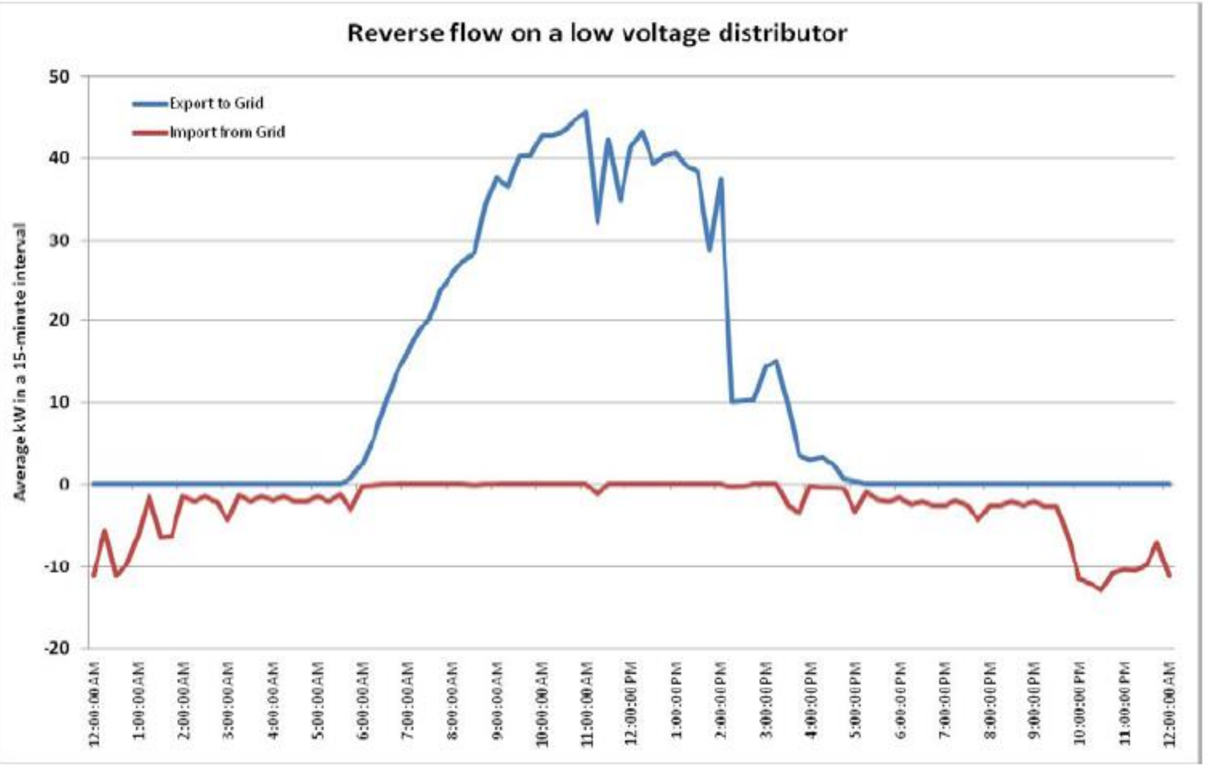
$$\left.\begin{aligned} \Delta V_2 &= \frac{P''R + Q''X}{V_2} \\ \delta\Delta V_2 &= \frac{P''X - Q''R}{V_2} \end{aligned}\right\}$$

- For high-voltage transmission network, **R<<X**, so voltage mainly depends on **Q**;
- But for low-voltage distribution network, **R≈X**, so voltage depends on both **P and Q**.

2) Voltage Regulation of Low-Voltage Distribution Networks

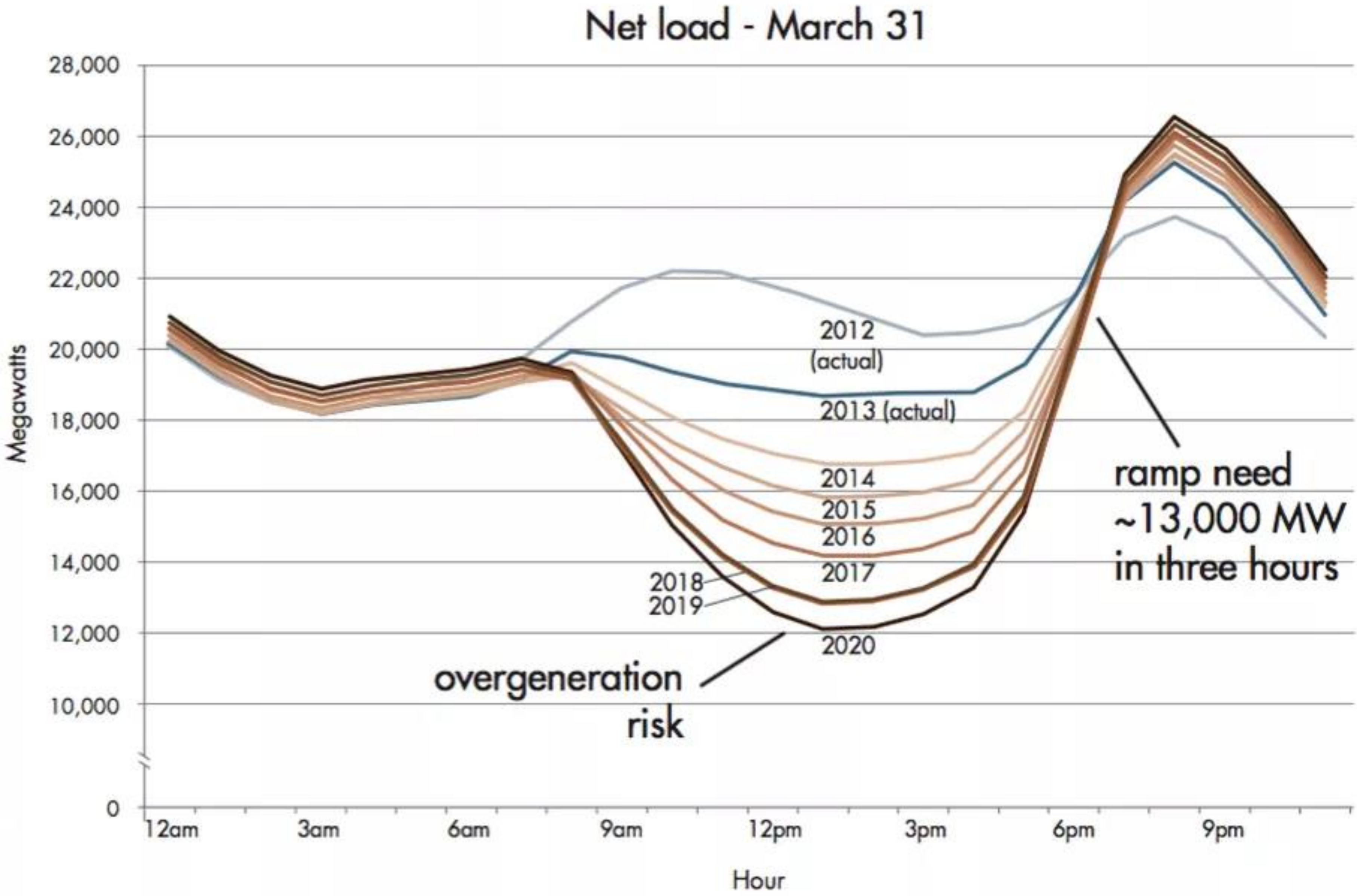
❑ <u>Impact of high PV penetrations on feeder voltage</u>

- **Reverse power flow → voltage raise**



Export of electricity of a residential feeder to the grid

Figure 2: The duck curve shows steep ramping needs and overgeneration risk

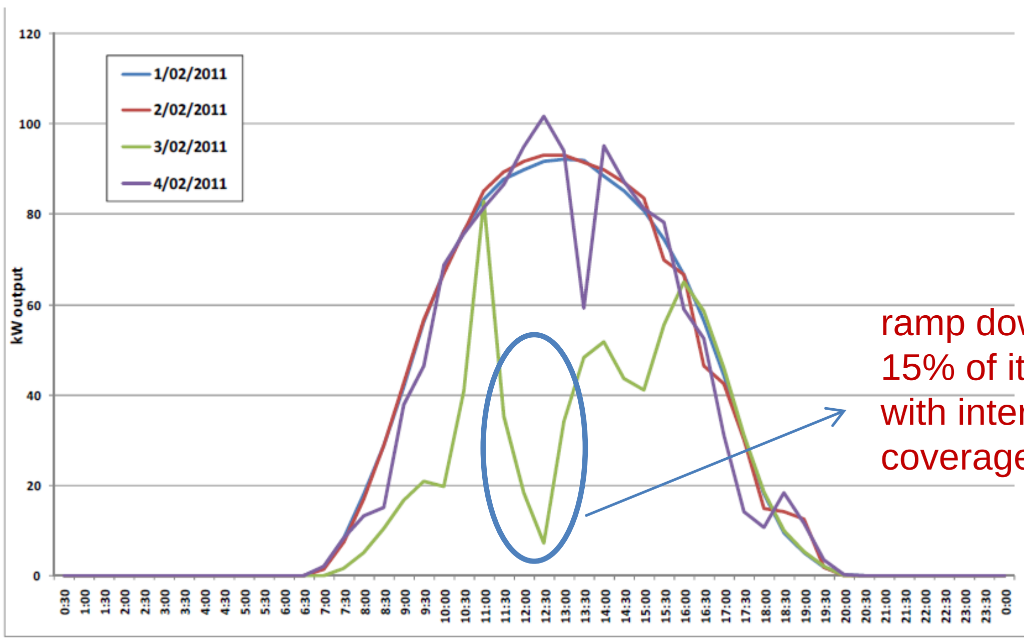


https://www.vox.com/2018/5/9/17336330/duck-curve-solar-energy-supply-demand-problem-caiso-nrel

2) Voltage Regulation of Low-Voltage Distribution Networks

❑ <u>Impact of high PV penetrations on feeder voltage (cont’)</u>

- **Volatile and fast PV output variation → transient voltage fluctuation**



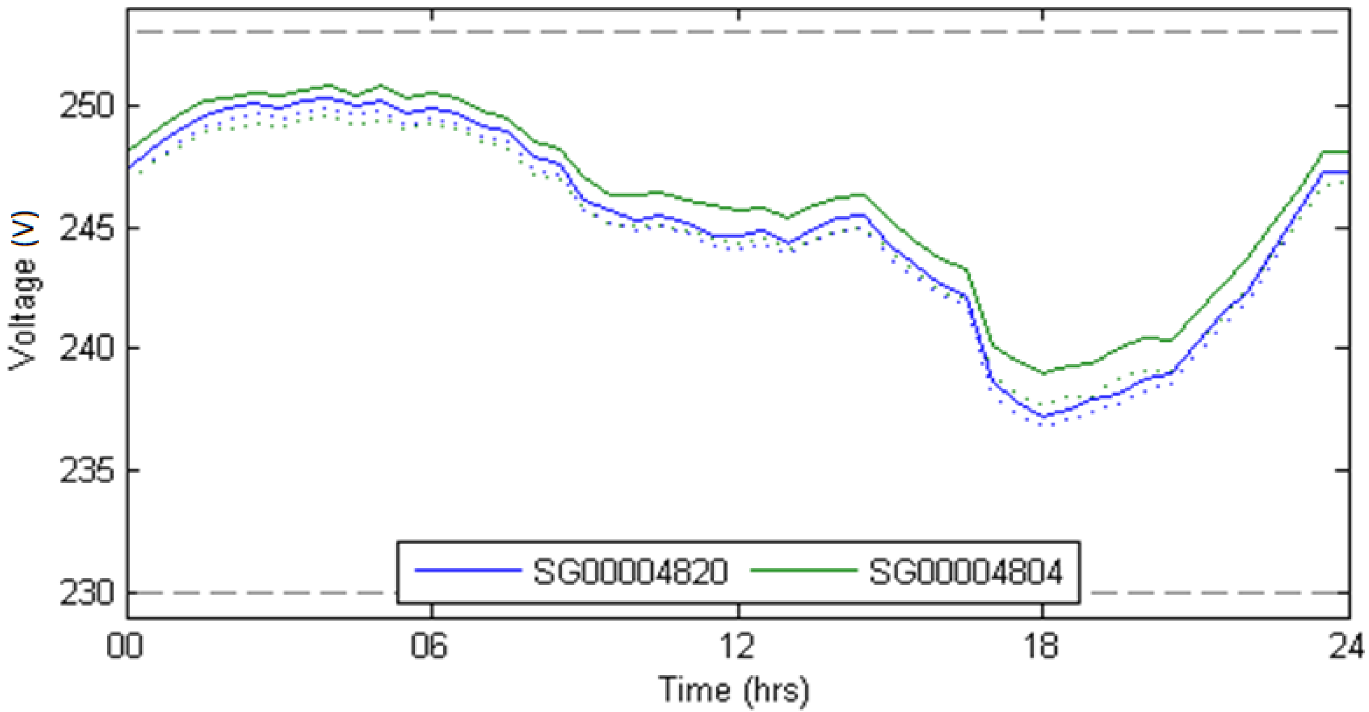
ramp down/up on the order of 15% of its capacity per minute with intermittent cloud coverage

Solar profiles for four days during a summer peak week in a residential feeder

2) Voltage Regulation of Low-Voltage Distribution Networks

❑ <u>Impact of high PV penetrations on feeder voltage (cont')</u>

- **significantly increased difficulty for Volt/Var control (VVC)**



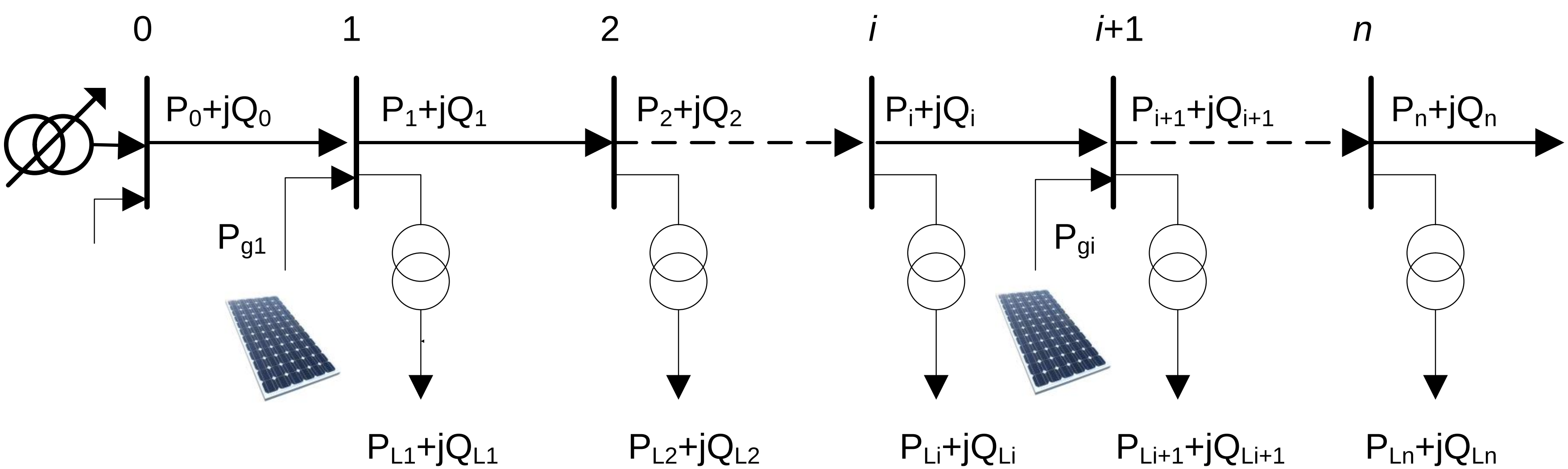
Voltage profiles of two substations in a residential feeder on 11 June 2012

2) Voltage Regulation of Low-Voltage Distribution Networks

❑ Possible solution to mitigate voltage violation problems

Method	Advantages	drawbacks
Lower down the set-point of OLTC	easy to implement, no additional cost	cannot ensure the voltage thorough the whole feeder;
Network reinforcement	decrease line resistance and thereby reduce line voltage drop	costly; the installed capacity of PV usually increases at a much higher speed rate than the network upgrading.
Curtail real power feed-in from PV units at times of low demand	easy to implement	spilling of solar energy; "costly" and not economically attractive to the PV panel owners;
Use energy storage devices to manage PV variations	fast-speed (compensate the PV variations)	costly; the battery is difficult to be widely installed: limited space, obstruction from local residents, etc.
Distribution static compensators (DSTATCOM)	fast-speed (provide rapid and continuously variable reactive power support)	costly
PV inverters to provide/absorb reactive power	fast-speed (absorb and inject reactive power)	against grid code and utility rules; decrease PV's real power capacity; not attractive to PV owners

2) Voltage Regulation of Low-Voltage Distribution Networks



$$P_{i+1} = P_i - P_{Li} + P_{gi}$$

$$Q_{i+1} = Q_i - Q_{Li}$$

$$V_{i+1} = V_i - \frac{R_i \cdot P_i + X_i \cdot Q_i}{V_{ref}}$$

Charge/discharge ES to regulate the bus voltage

$$\Delta V_{i,i+1} = V_i - V_{i+1} \approx \frac{R_i \cdot \left(P_{i+1} + P_{Li} - P_{gi} + P_{ESi}\right) + X_i \cdot \left(Q_{i+1} + Q_{Li}\right)}{V_{ref}}$$

Lecture Objective

1. Review typical applications of energy storage systems in power system networks
2. An in-depth look at load leveling application from the utility perspective
3. **An overview of some issue in energy storage applications**

Safety and Reliability

- An ESS with large energy density is similar to an explosive device. The former provides controlled release of energy while the latter provide uncontrolled release of energy in a burst mode.
- Safety and reliability issue in ESS is thus very important to ensure it does not explode or catch fire. Lithium-ion batteries have been known to catch fire, making it a concern for EV applications. There have also been concern of high-speed flywheel breaking apart.
- The U.S. National Highway Traffic Safety Administration has been working with all automakers to develop postcrash procedures to keep occupants of electric vehicles and emergency personnel who respond to crash scenes safe.

https://www.cnbc.com/2021/07/30/tesla-megapack-caught-fire-at-victorian-big-battery-site-in-australia.html

Impact on Ecological Environment; Materials, Disposal and Recycling

- To ensure energy storage really contributes to a greener environment, issues of raw materials used in ESS must considered. Many ESS require materials which are rare in nature or the mining of the materials may result in serious environment damage.
- Many ESS materials may also be toxic to humans and animals.
- The disposal of ESS, particular electro-chemical batteries has always been of concern. Harmless chemicals should be prevented from leaking into the environment. Toyota has placed a bounty on every of its HEV batteries to encourage proper disposal and recycling.