ECE 333

Green Electric Energy

Lecture 24

PV Trends, Storage

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Slides Courtesy of Prof. George Gross

Announcements

- Last Lecture!!!
- Final on Monday, 5/11/20
  - Cumulative, weighted to solar questions
  - 24 hours to take it, should take less that 3 hours to complete
- ICES online for 333
- Today
  - Where to go from here?
  - Solar shading review
  - PV emerging trends
  - Storage

Where do we go from here?

- Intro to electric grid, electric machines, power electronics
  - ECE 330 (Schuh SMR 2020, Bose & Banerjee, FA 2020)
- Electric grid, power flow
  - ECE 476 (Dominguez-Garcia, FA 2020)
- Electric machines (lab course)
  - ECE 431 (SP 2021)
- Power electronics
  - ECE 464 (Stillwell, FA 2020)
- Power electronics laboratory
  - ECE 469 (Stillwell, FA 2020)
- Solar Cells
  - ECE 443 (SP 2021), ME 432 (FA 2020)

Solar Shading

Masters, Problem 5.10: Consider this very simple model for cells wired in series within a PV module. Those cells that are exposed to full sun deliver 0.5 V; those that are completely shaded act like 5-Ω resistors. For a module containing 40 such cells, an idealized $I-V$ curve with all cells in full sun is shown in Fig. 3.

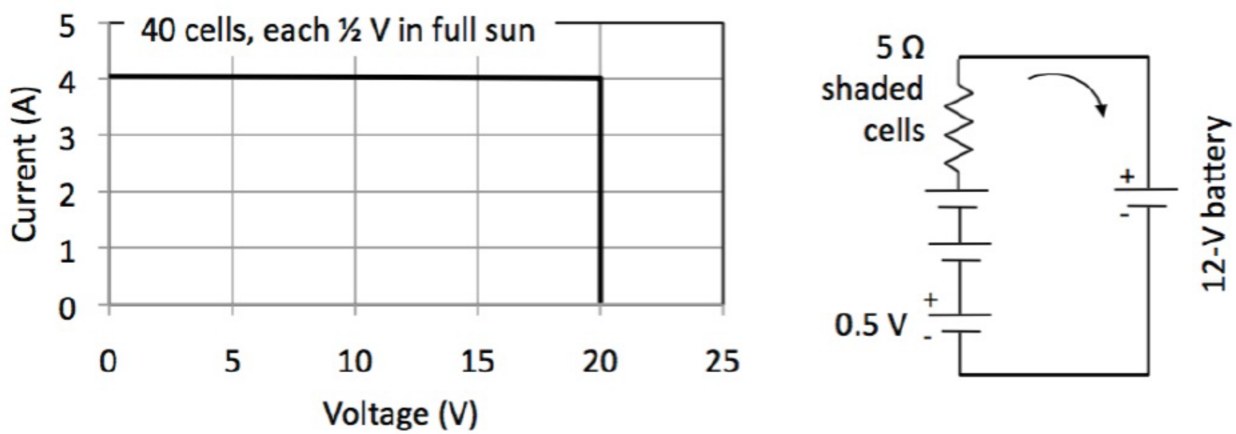


Figure P 5.10

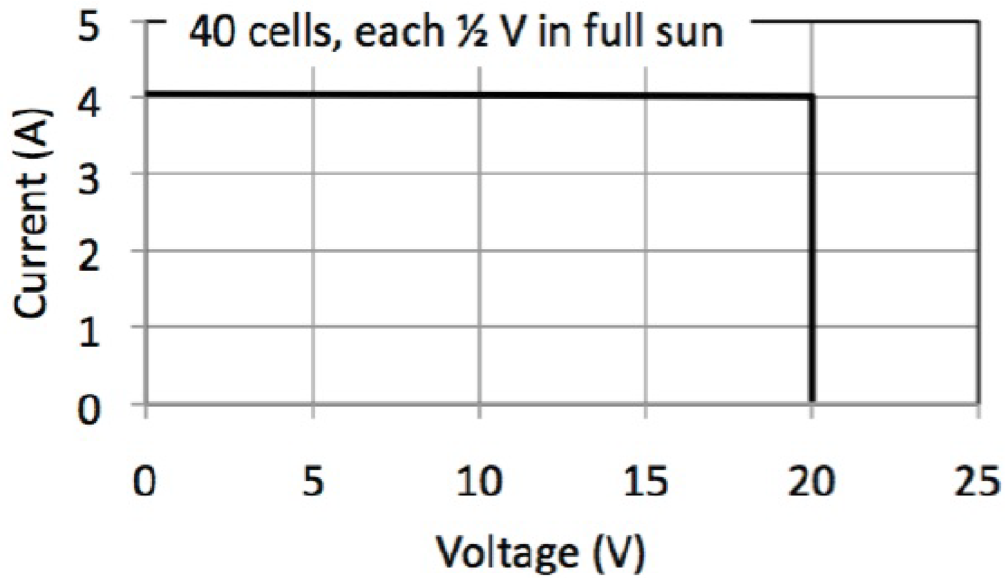
Figure 3: Figure P5.10 from Masters Text for Problem 1.

(a) Draw the PV $I-V$ curves that will result when one cell is shaded and when two cells are shaded (no battery load).

(b) If you are charging an idealized 12-V battery (vertical $I-V$ curve), compare the current delivered under these three circumstances (full sun and both shaded circumstances).

Solar Shading

Solar Shading



More Shading

Masters, Problem 5.11: An idealized 1-sun $I - V$ curve for a single 80-W module is shown below in Fig. 4.

(a) For two such modules wired in series, draw the resulting $I - V$ curve if the modules are exposed to only 1/2 sun, and one cell, in one of the modules, is shaded. Assume the shaded cell has an equivalent parallel resistance of 10 Ω.

(b) How much power would be generated at the maximum power point (MPP)?

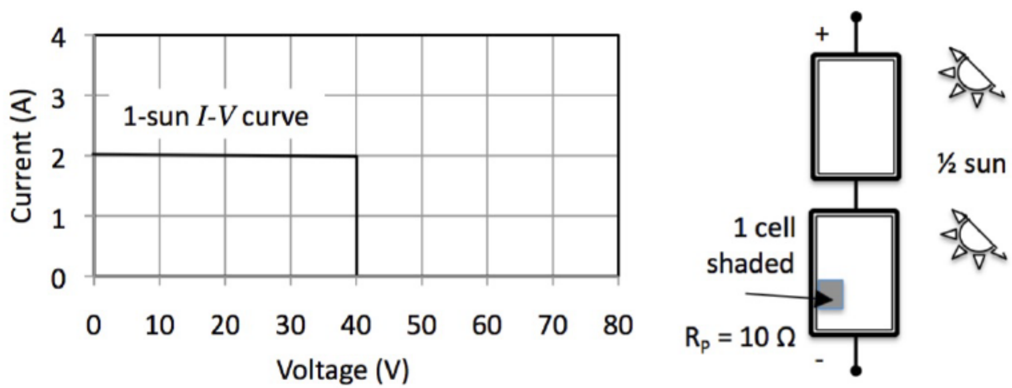
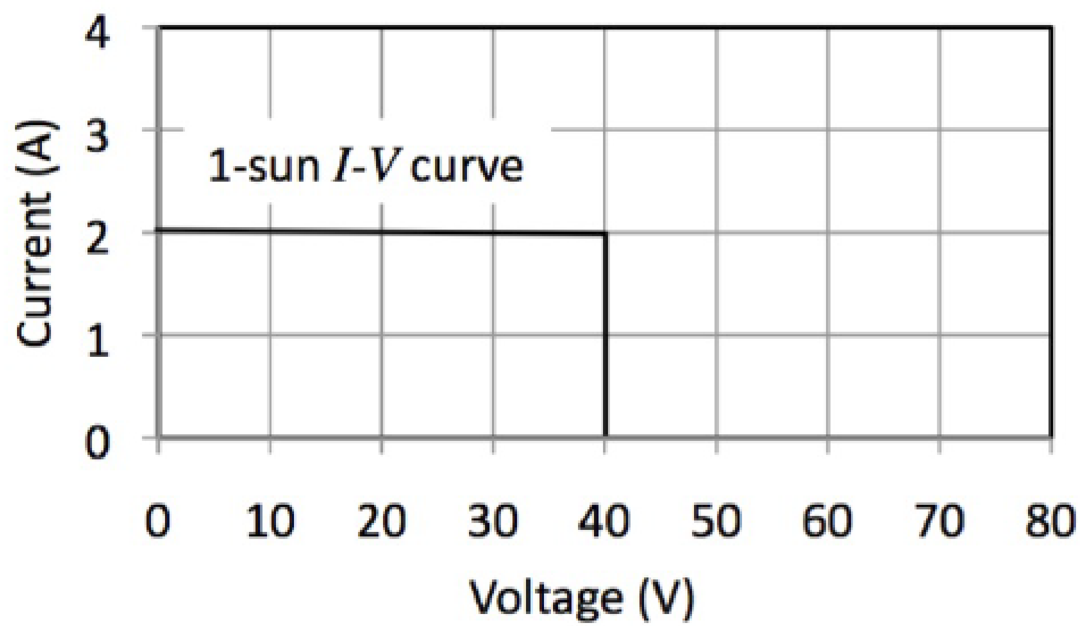


Figure P 5.11

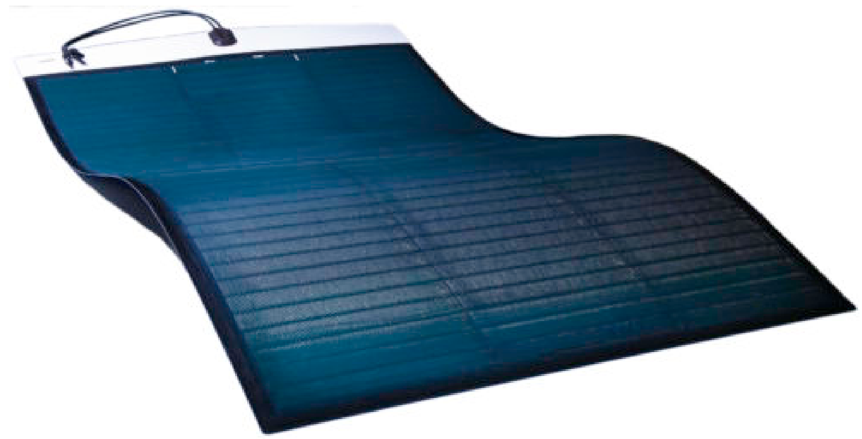
Figure 4: Figure P5.11 from Masters Text for Problem 2.

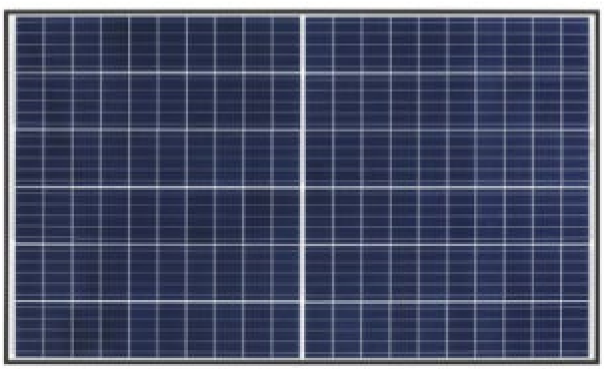
More Shading



PV Trends

- System: 1500 VDC
- Panel: Half Cells, Thin films
- System: Storage





1500 V Solar Inverters

- 2017 National Electric Code increase maximum voltage to 1500 VDC
- 1500 VDC installations projected to reach 50% of new installations by 2025 [*]

Photo Credit: Jinko Solar

Photo Credit: CPS America

[*] 2017 International Technology Roadmap for Photovoltaic (ITRPV)

Commercial Solar PV Costs

- Over 25% of system costs for 100 kW systems attributed to installation costs [*]
- Size of the enclosure is a cost driver in inverter [**]

[*] Fu, Ran, David Feldman, and Robert Margolis, "U.S. Solar Photovoltaic System Cost Benchmark: Q1 2018." Golden, CO: National Renewable Energy Laboratory
[**] P. Parker et al. "Dominant Factors Affecting Reliability of Alternating Current Photovoltaic Modules" IEEE PVSC 2015

1.5 kV Solar Inverters

[*]

[**]

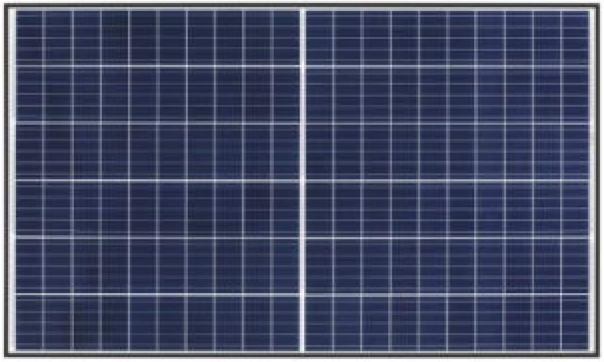
[†]

- 1.5 kV solar requirements
  - 50 kW - 2.5 MW
  - Input: 800 V – 1500 V DC
  - Output: 600 V_{AC} (L-L) 3-phase

[*] http://www.gepowerconversion.com/product-solutions/low-voltage-drives/lv5-solar-ehouse-solution
[**] http://solar.huawei.com/na/products
[†] https://www.solectria.com/pv-inverters/utility-scale-inverters/xgi-1500/

Solar Panels: Half Cells

- Traditional 60 and 72 cell panels => 120 and 144 cell panels
- Why?
  - Current is cut in half
  - Voltage is doubled
  - Smaller cell = less mechanical stress
  - Can treat each panel as two separate panels



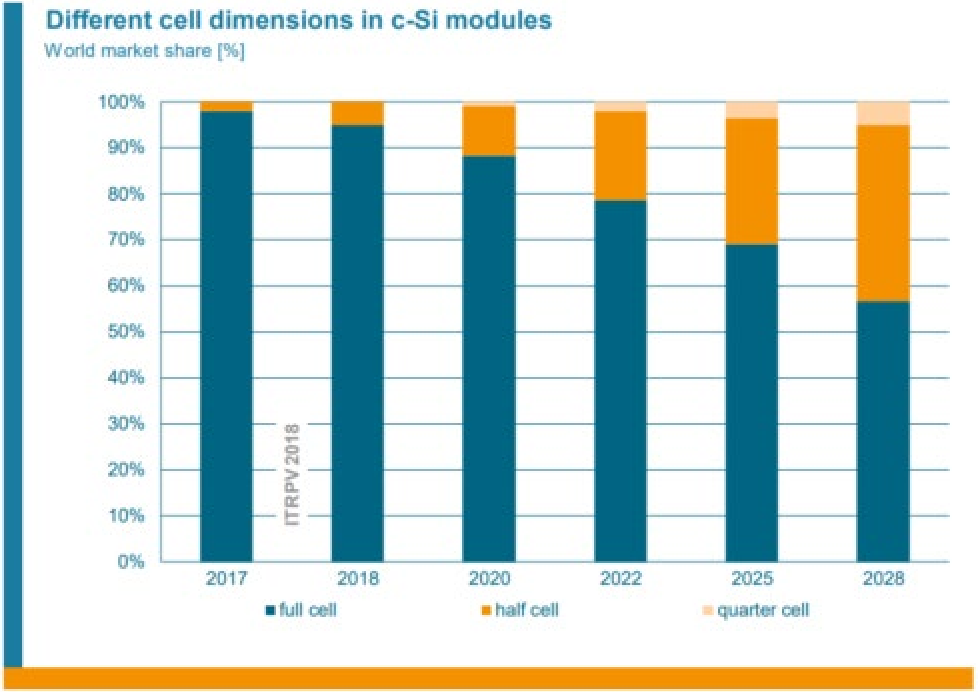


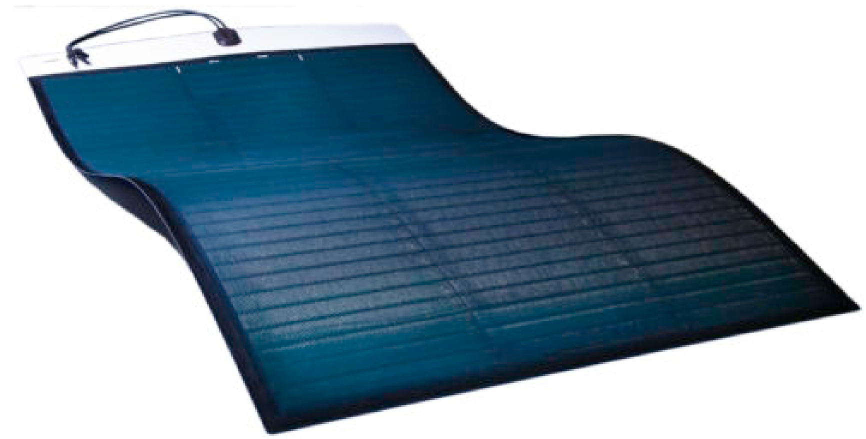
Fig. 46: Predicted market shares for modules with full, half, and quarter cells.

[Source: "What is a half-cell solar panel?" https://www.solarpowerworldonline.com/2018/10/what-is-a-half-cell-solar-panel/](https://www.solarpowerworldonline.com/2018/10/what-is-a-half-cell-solar-panel/)

Panels: Thin Film Solar Panels

Panels: Thin Film Solar Panels

- Advantages
  - Thinner – flexible and light weight
  - Flexible voltage operation
  - Possibly cheaper at scale
  - Not targeted in 2018 tariffs
- Disadvantages
  - Efficiency - ~17% - 18%
  - Lack of investment
  - Less developed technology



Panels: Thin Film Solar Panels

96 Cell

Electrical Data		
	SPR-E20-327	SPR-E19-320
Nominal Power (Pnom)[11]	327 W	320 W
Power Tolerance	+5/–0%	+5/–0%
Avg. Panel Efficiency[12]	20.4%	19.9%
Rated Voltage (Vmpp)	54.7 V	54.7 V
Rated Current (Impp)	5.98 A	5.86 A
Open-Circuit Voltage (Voc)	64.9 V	64.8 V
Short-Circuit Current (Isc)	6.46 A	6.24 A
Max. System Voltage	600 V UL & 1000 V IEC	
Maximum Series Fuse	15 A	
Power Temp Coef.	–0.35% / ° C	
Voltage Temp Coef.	–176.6 mV / ° C	
Current Temp Coef.	2.6 mA / ° C	

Vs.

Thin Film

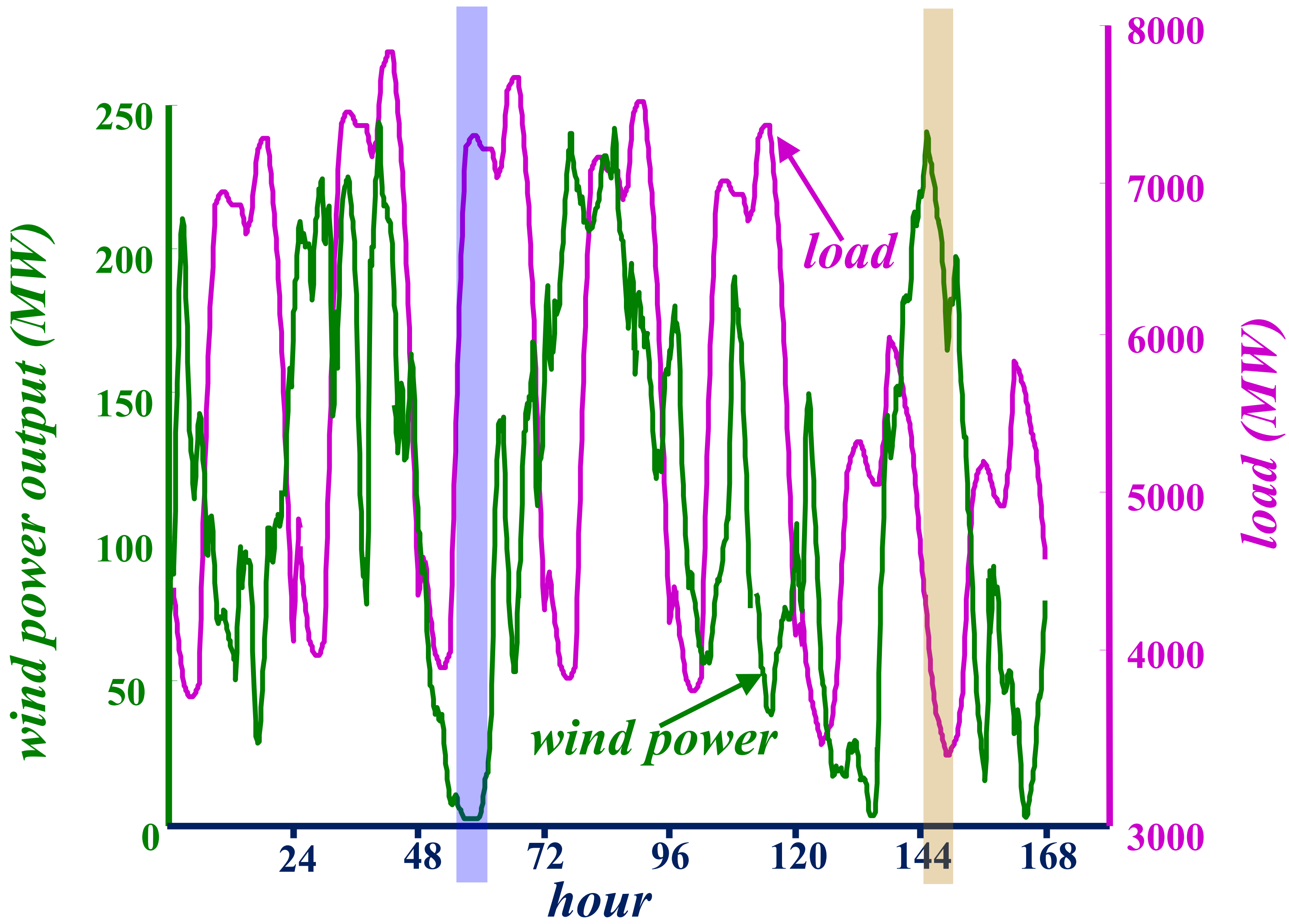
MODEL TYPES AND RATINGS AT STANDARD TEST CONDITIONS (1000W/m², AM 1.5, 25°C)[2]

NOMINAL VALUES		FS-6420 FS-6420A	FS-6425 FS-6425A	FS-6430 FS-6430A	FS-6435 FS-6435A	FS-6440 FS-6440A	FS-6445 FS-6445A	FS-6450 FS-6450A
Nominal Power[3] (-0/+5%)	P_{MAX} (W)	420.0	425.0	430.0	435.0	440.0	445.0	450.0
Efficiency (%)	%	17.0	17.2	17.4	17.6	17.8	18.0	18.2
Voltage at P_{MAX}	V_{MAX} (V)	180.4	181.5	182.6	183.6	184.7	185.7	186.8
Current at P_{MAX}	I_{MAX} (A)	2.33	2.34	2.36	2.37	2.38	2.40	2.41
Open Circuit Voltage	V_{OC} (V)	218.5	218.9	219.2	219.6	220.0	220.4	221.1
Short Circuit Current	I_{SC} (A)	2.54	2.54	2.54	2.55	2.55	2.56	2.57
Maximum System Voltage	V_{SYS} (V)	1500[5]						
Limiting Reverse Current	I_R (A)	5.0						
Maximum Series Fuse	I_{CF} (A)	5.0						

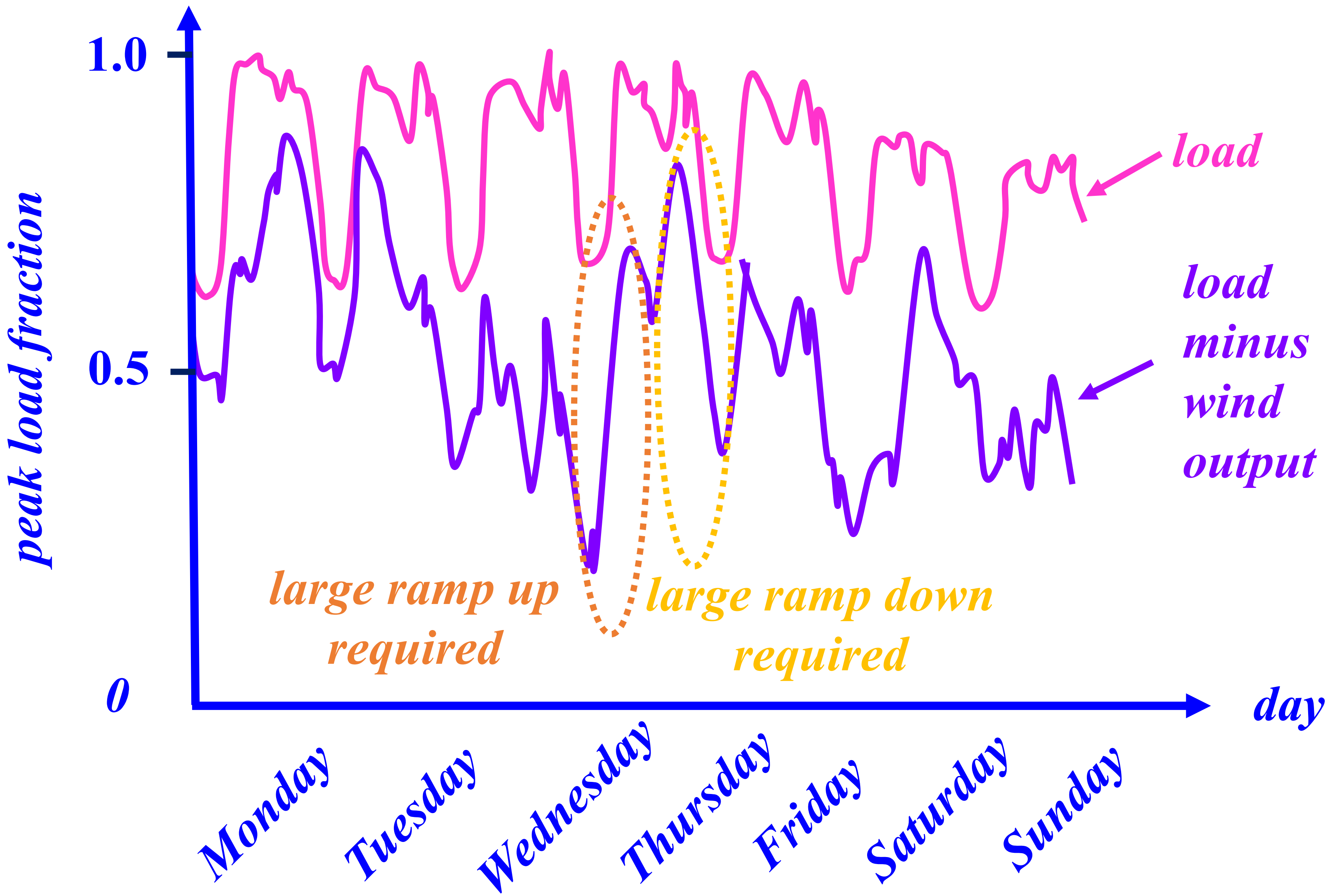
The Need for Energy Storage Resources (ESR)

- The *electricity business* is the only industry sector that sells a commodity *without sizeable inventory*
- The lack of utility–scale storage in today's power system drives electricity to be a highly *perishable* commodity
- The deepening renewable resource penetrations exacerbate the challenges to maintain the *demand–supply equilibrium* at all points in time
- Storage provides considerable, added flexibility to maintain demand–supply balance *around the clock*

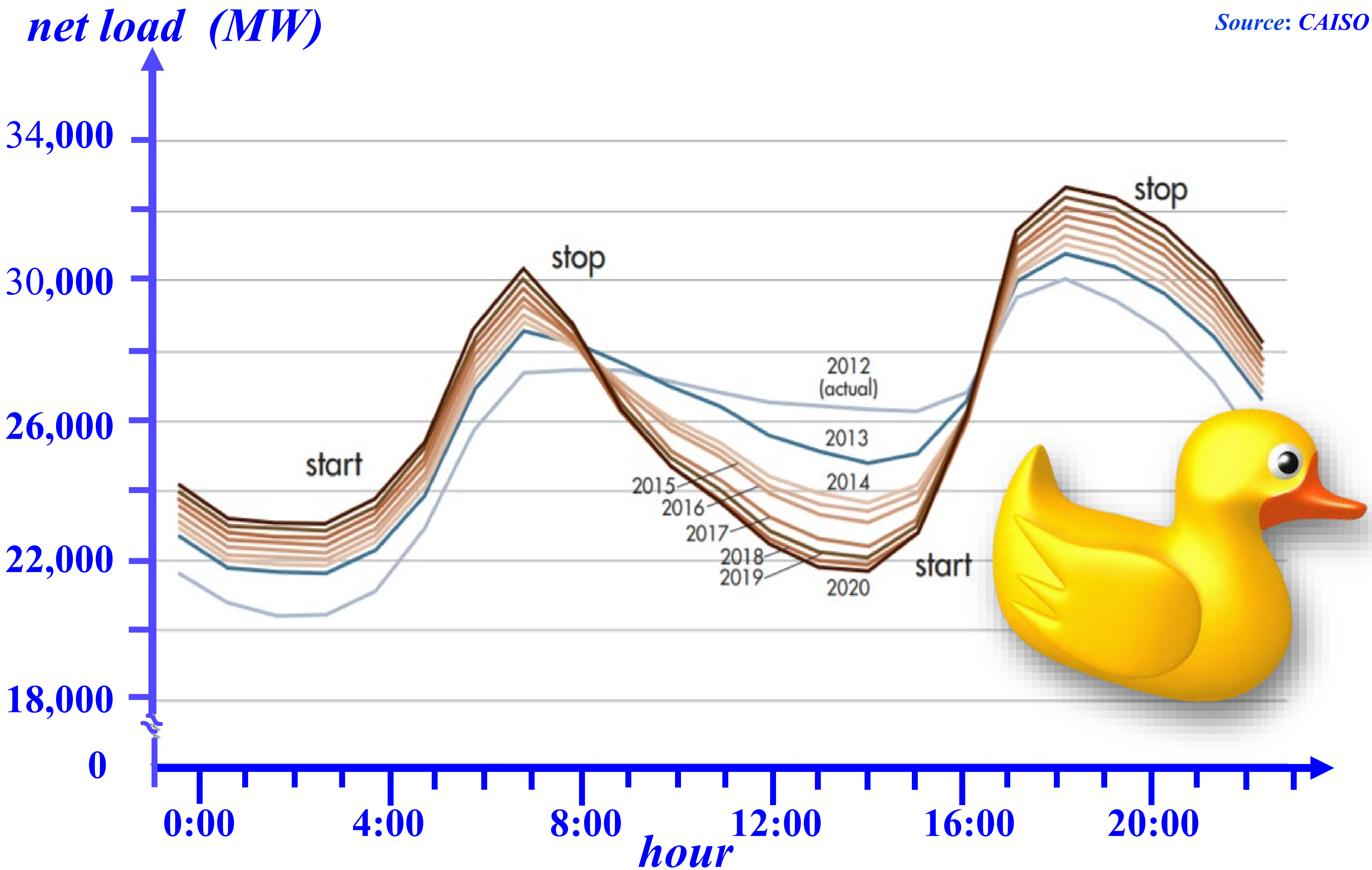
Misalignment of Wind and Load



Need for Larger and Faster Reserves

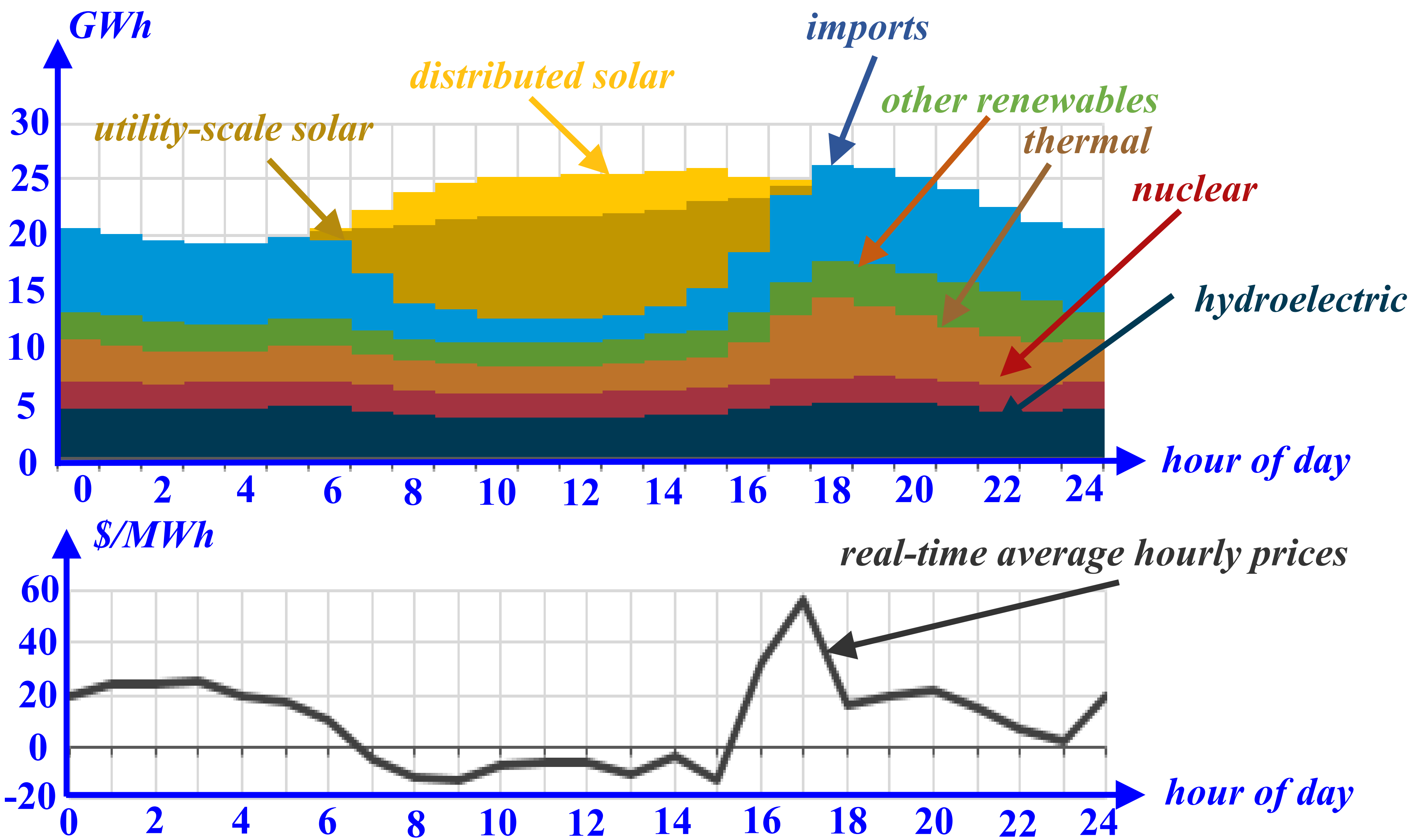


CAISO Daily Net Load Curve



Impacts of California Rooftop Solar

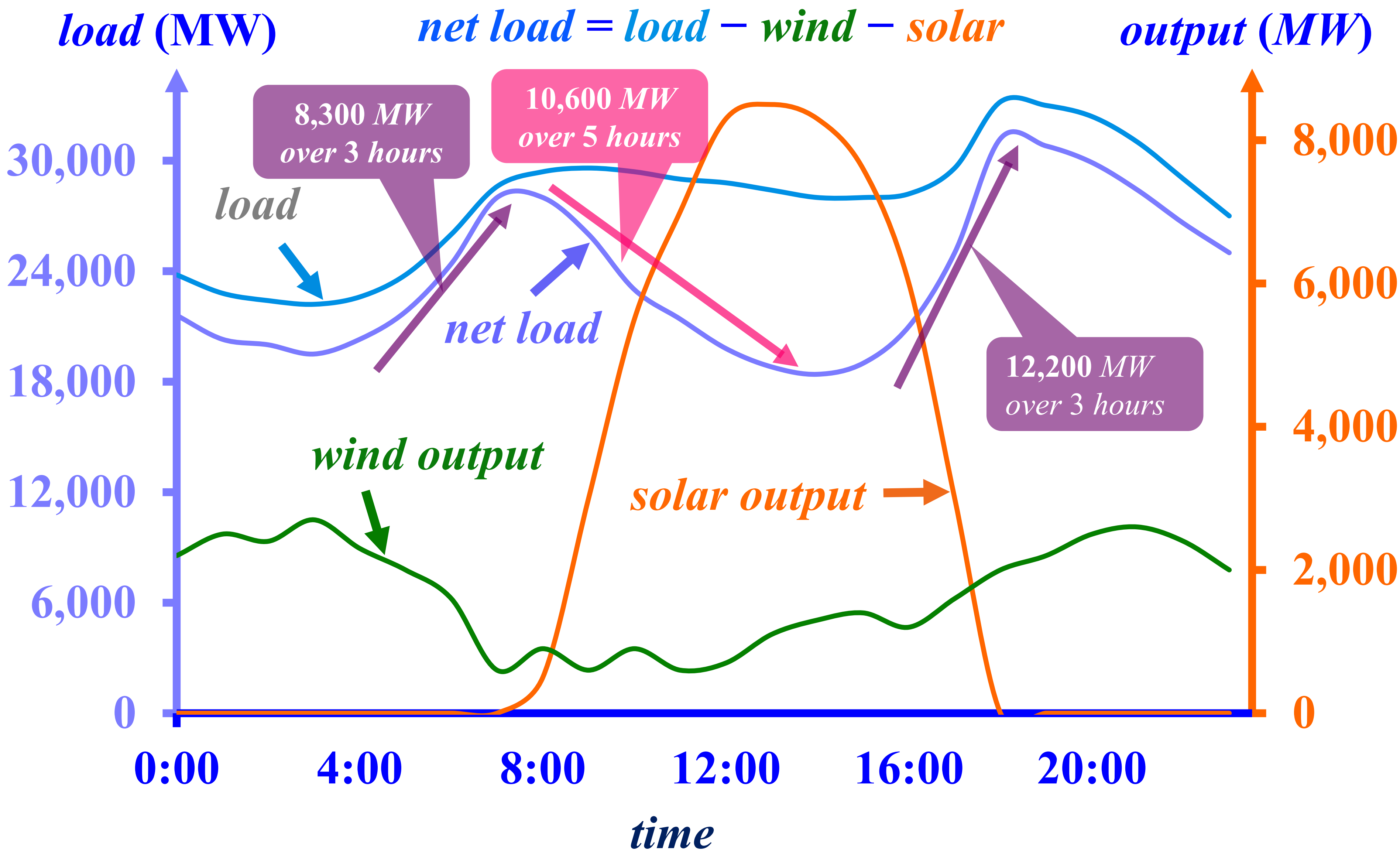
Source: US EIA based on https://www.eia.gov/electricity/data/eia861m/index.html and http://www.caiso.co



Net Load in California in Spring 2017

- *CAISO* recorded a 147 % increase in renewable curtailment from the first quarter of 2016 to the first quarter of 2017
- In the first quarter of 2017, about 3 % of the total potential wind and solar generation was curtailed, and about 1 % of the total potential renewable generation was curtailed
- On March 11, 2017, the solar curtailment exceeded 30 % of the solar production for an hour

Increased Flexibility Needs



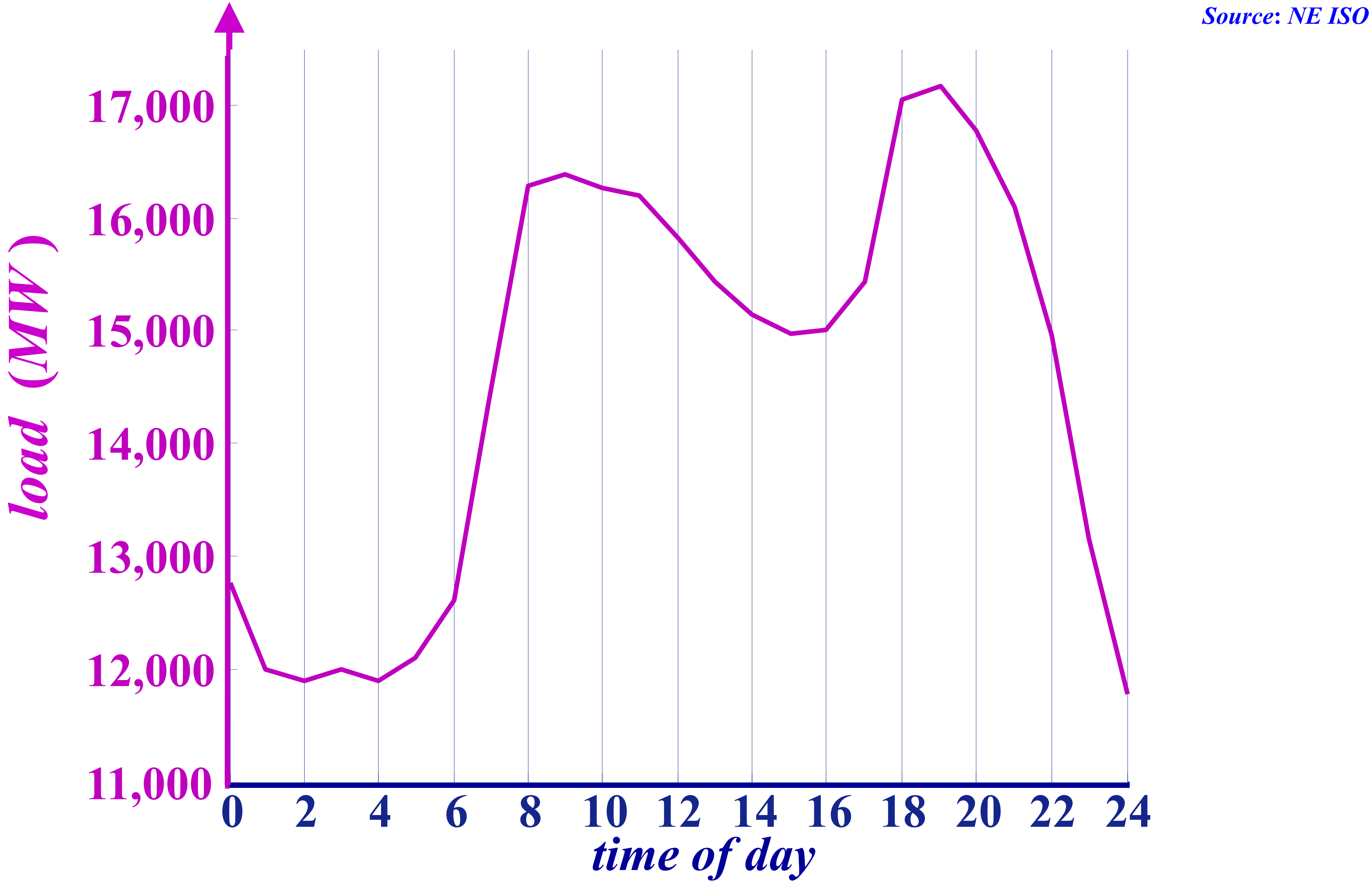
PRINCIPAL ROLES *ESR*s CAN PLAY

- Storage enables deferral of investments in:
    - **new conventional generation resources**
    - **new transmission lines**
    - distribution circuit upgrades
- Storage is key to the development of microgrids – in either grid–connected or autonomous systems

MORE ROLES *ESR*s CAN PLAY

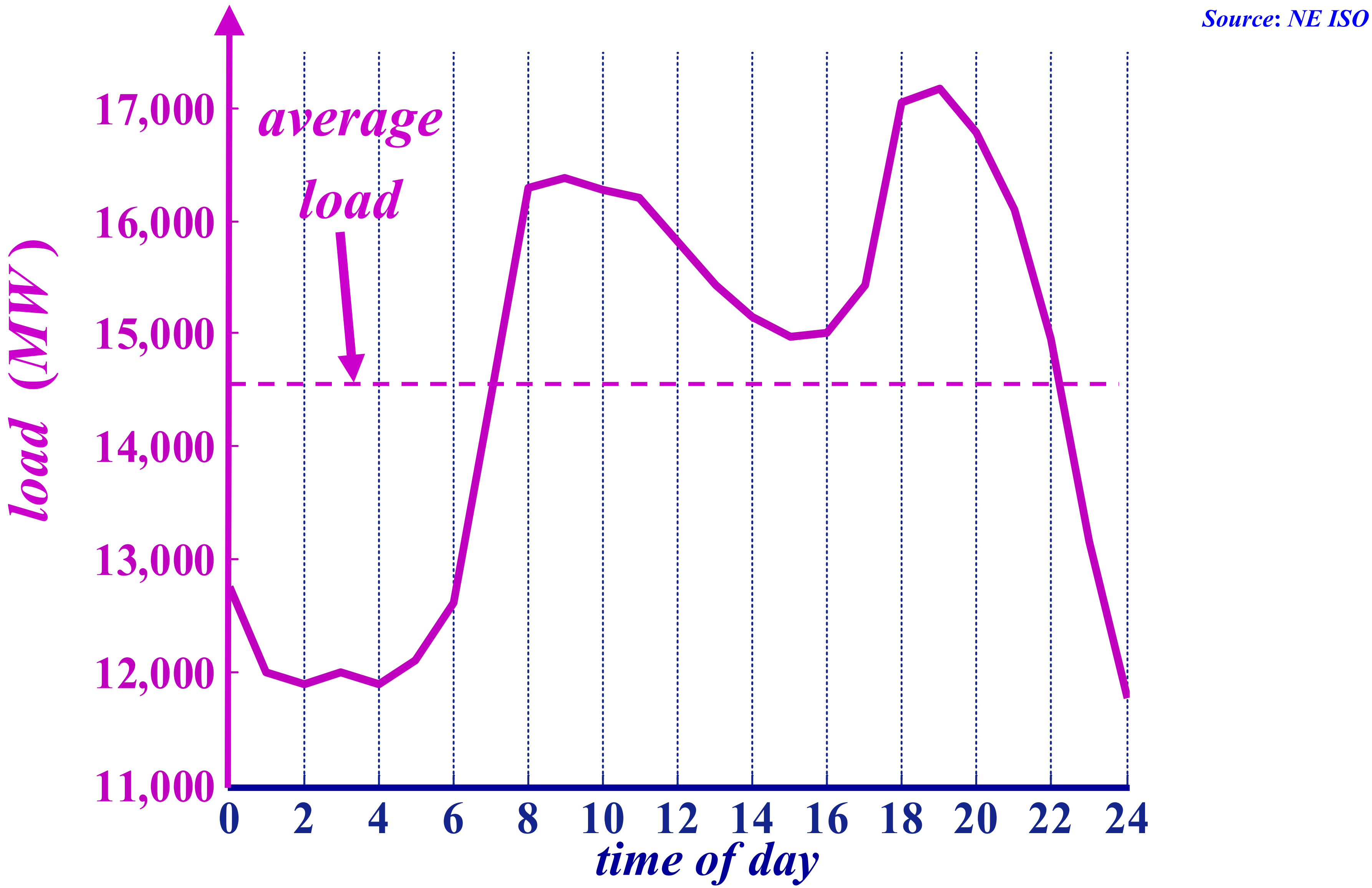
- In short–term operations, storage provides:
  - flexibility in time of energy consumption via **demand shift** and **peak–load shaving**
  - ability to delay the start up of cycling units
  - levelization of substation load
  - reserves and frequency regulation services
  - demand response action
  - capability to provide voltage support
- Storage can also provide *virtual inertia service* to replace part of the missing inertia in grids with integrated renewable resources – a major issue in grids with deep renewable resource integration

LOAD AND *LMP*



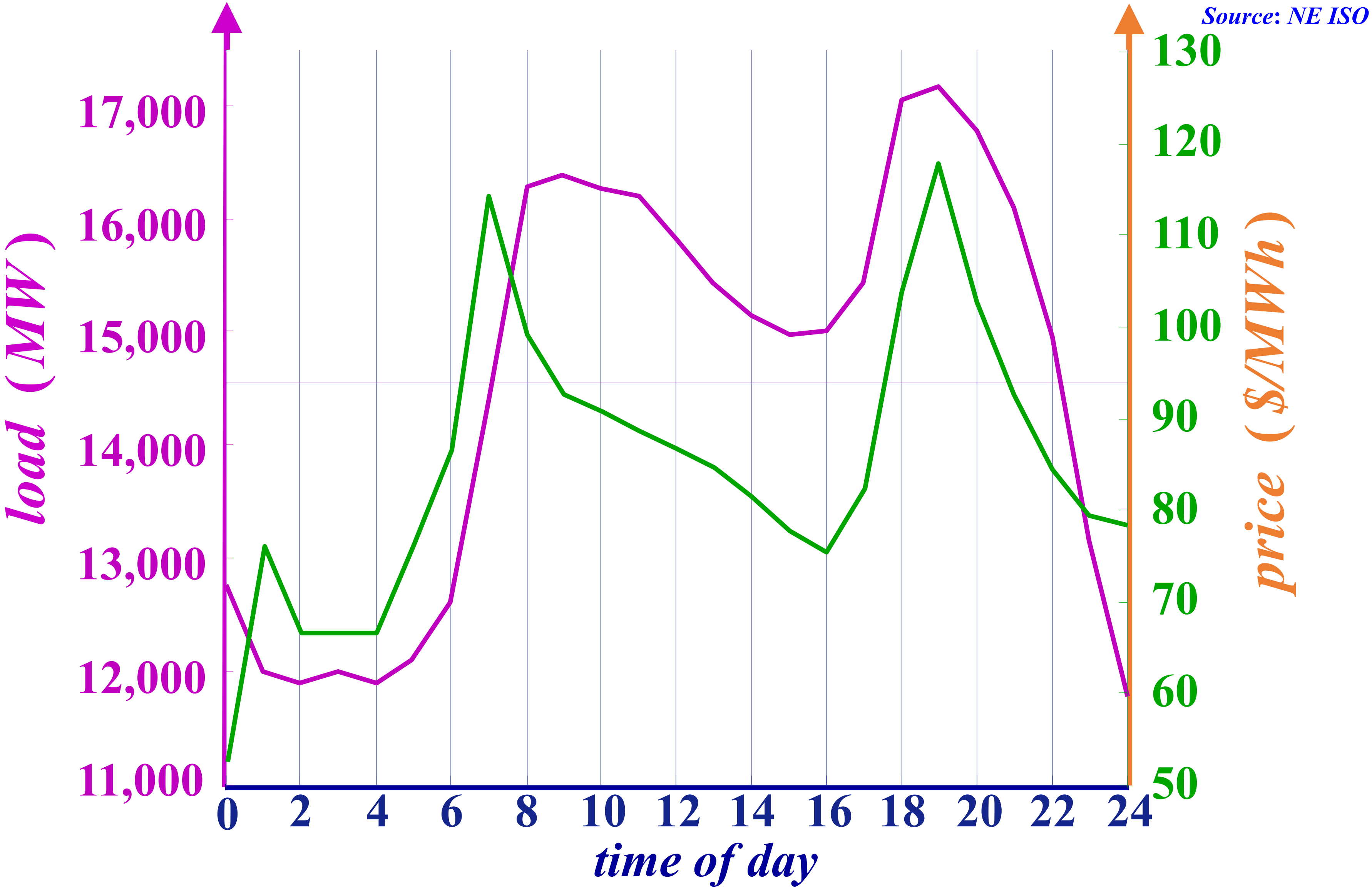
Source: NE ISO
load (MW)
17,000
16,000
15,000
14,000
13,000
12,000
11,000
0
2
4
6
8
10
12
14
16
18
20
22
24
time of day

LOAD AND *LMP*



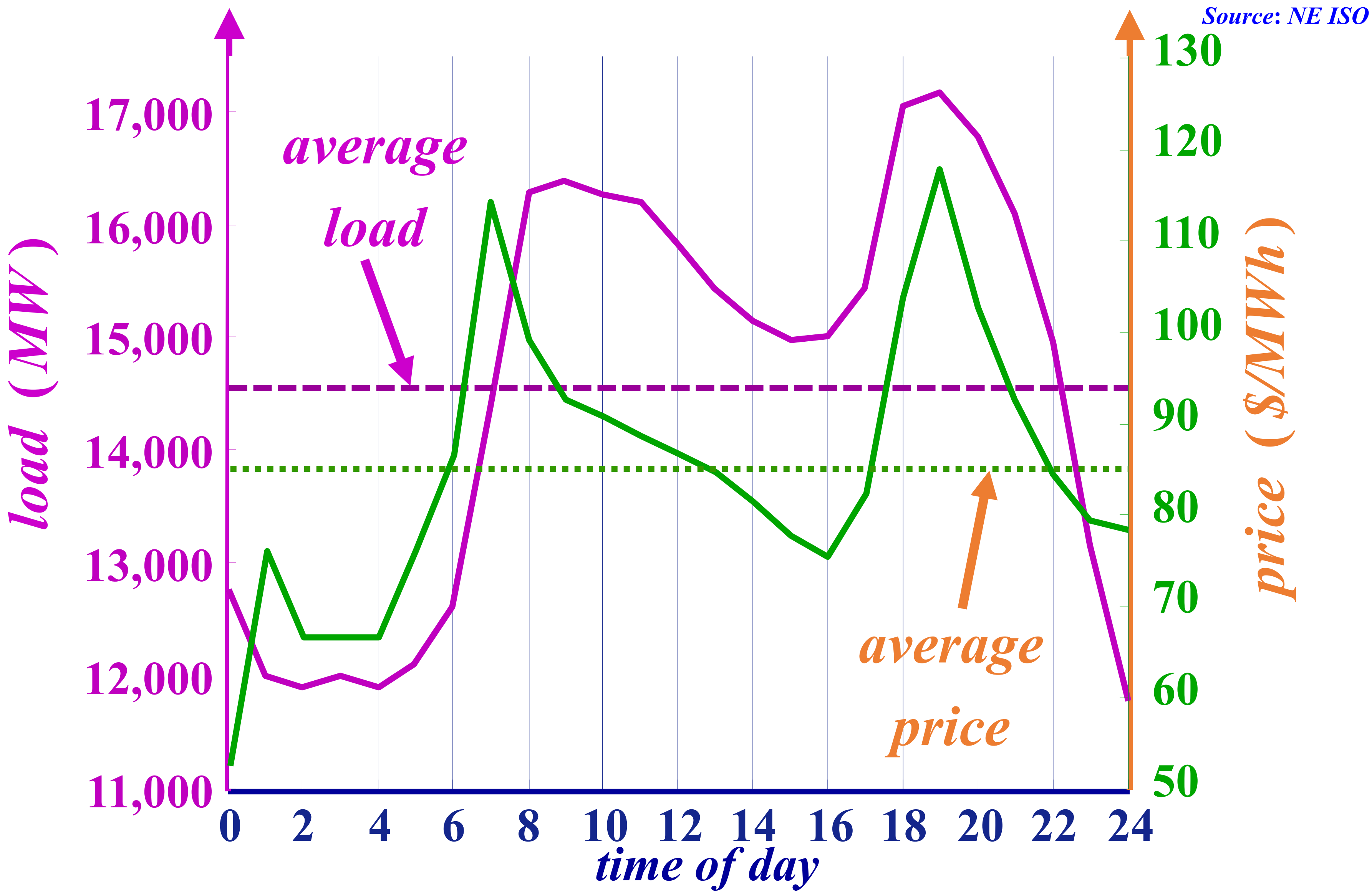
Source: NE ISO
17,000
16,000
15,000
14,000
13,000
12,000
11,000
average load
load (MW)
0
2
4
6
8
10
12
14
16
18
20
22
24
time of day

LOAD AND *LMP*

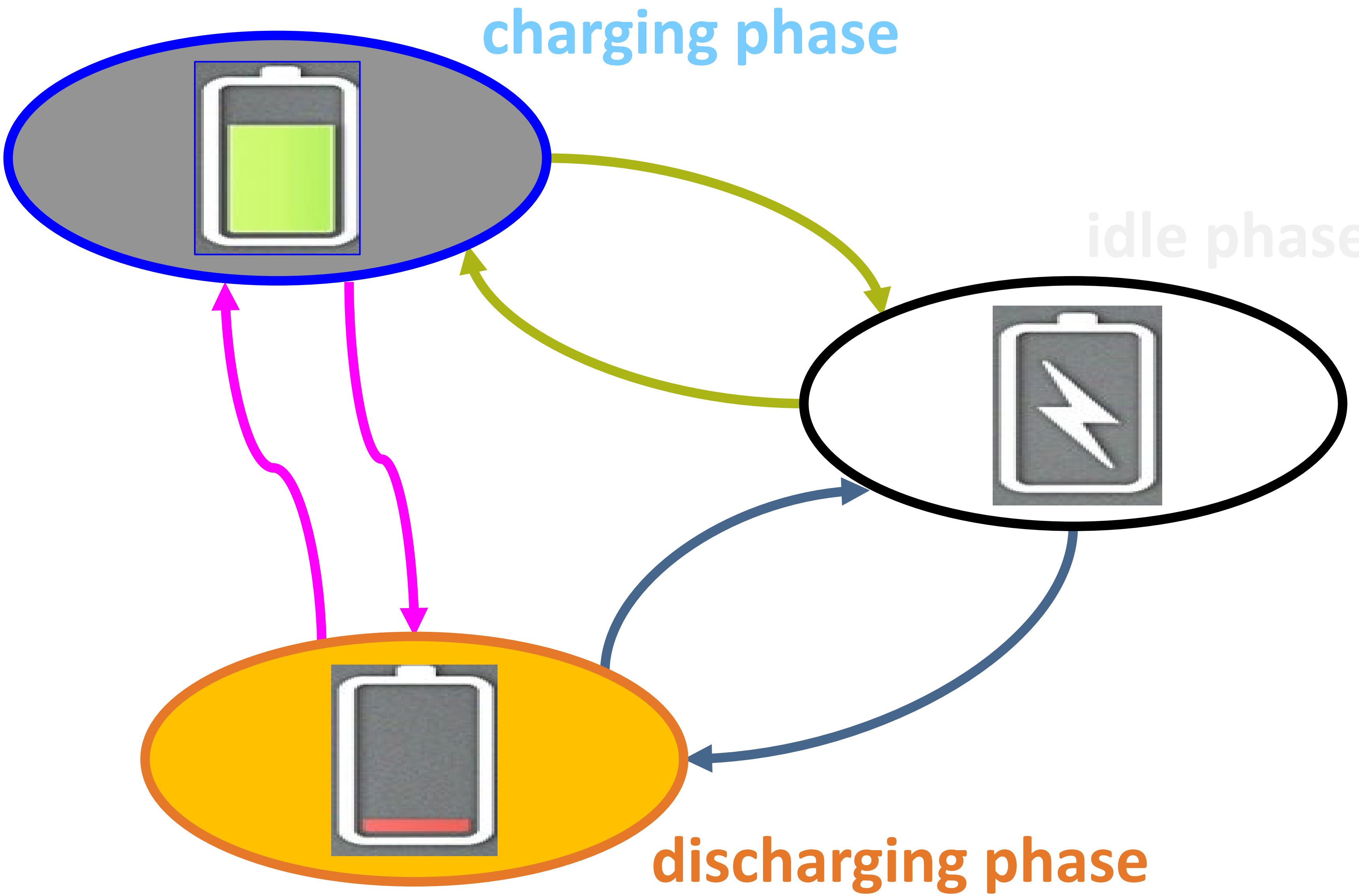


Source: NE ISO
load (MW)
17,000
16,000
15,000
14,000
13,000
12,000
11,000
130
120
110
100
90
80
70
60
50
price ($/MWh)
0
2
4
6
8
10
12
14
16
18
20
22
24
time of day

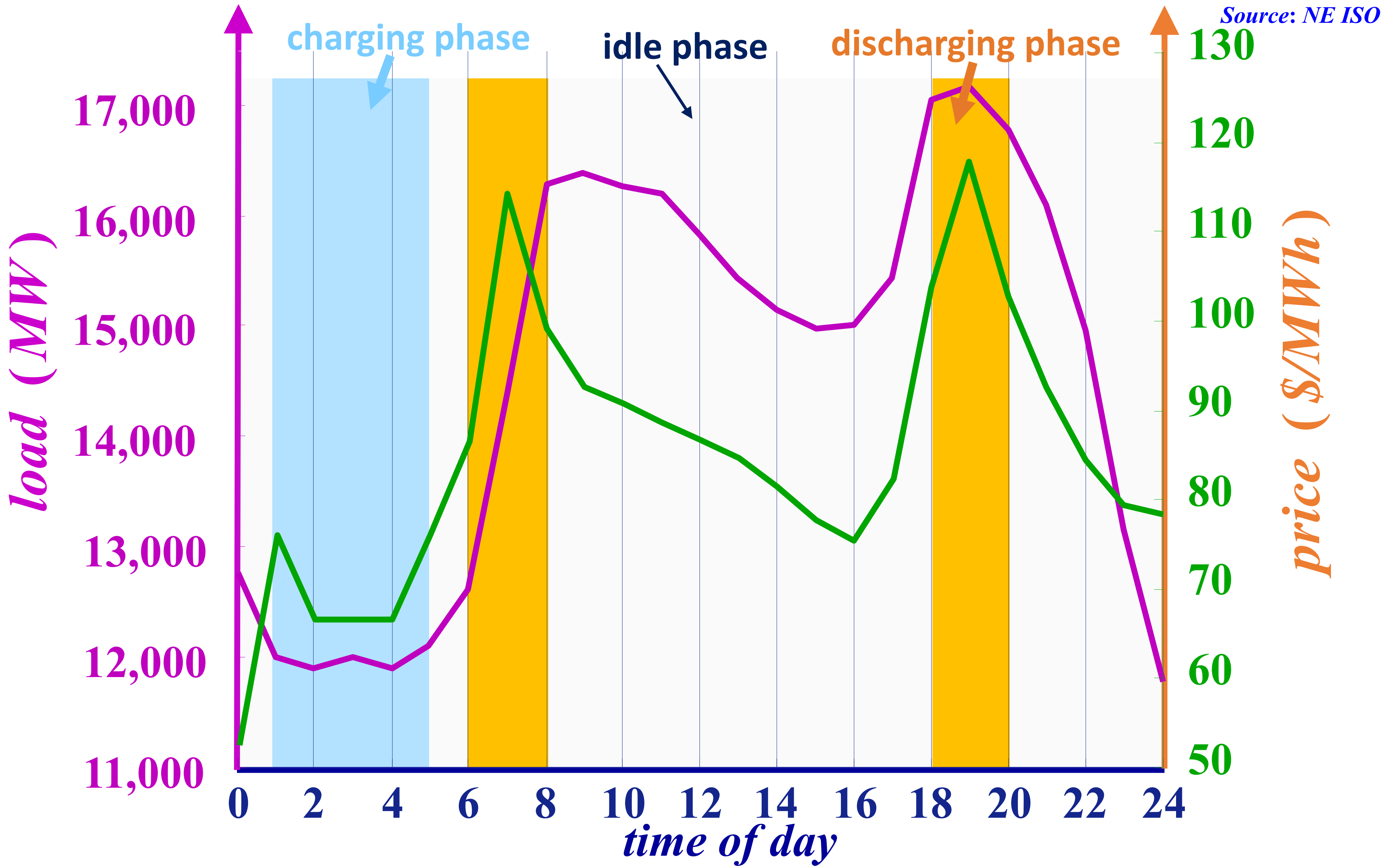
LOAD AND *LMP*


Source: NE ISO
average
load
load (MW)
17,000
16,000
15,000
14,000
13,000
12,000
11,000
130
120
110
100
90
80
70
60
50
price ($/MWh)
average
price
0 2 4 6 8 10 12 14 16 18 20 22 24
time of day

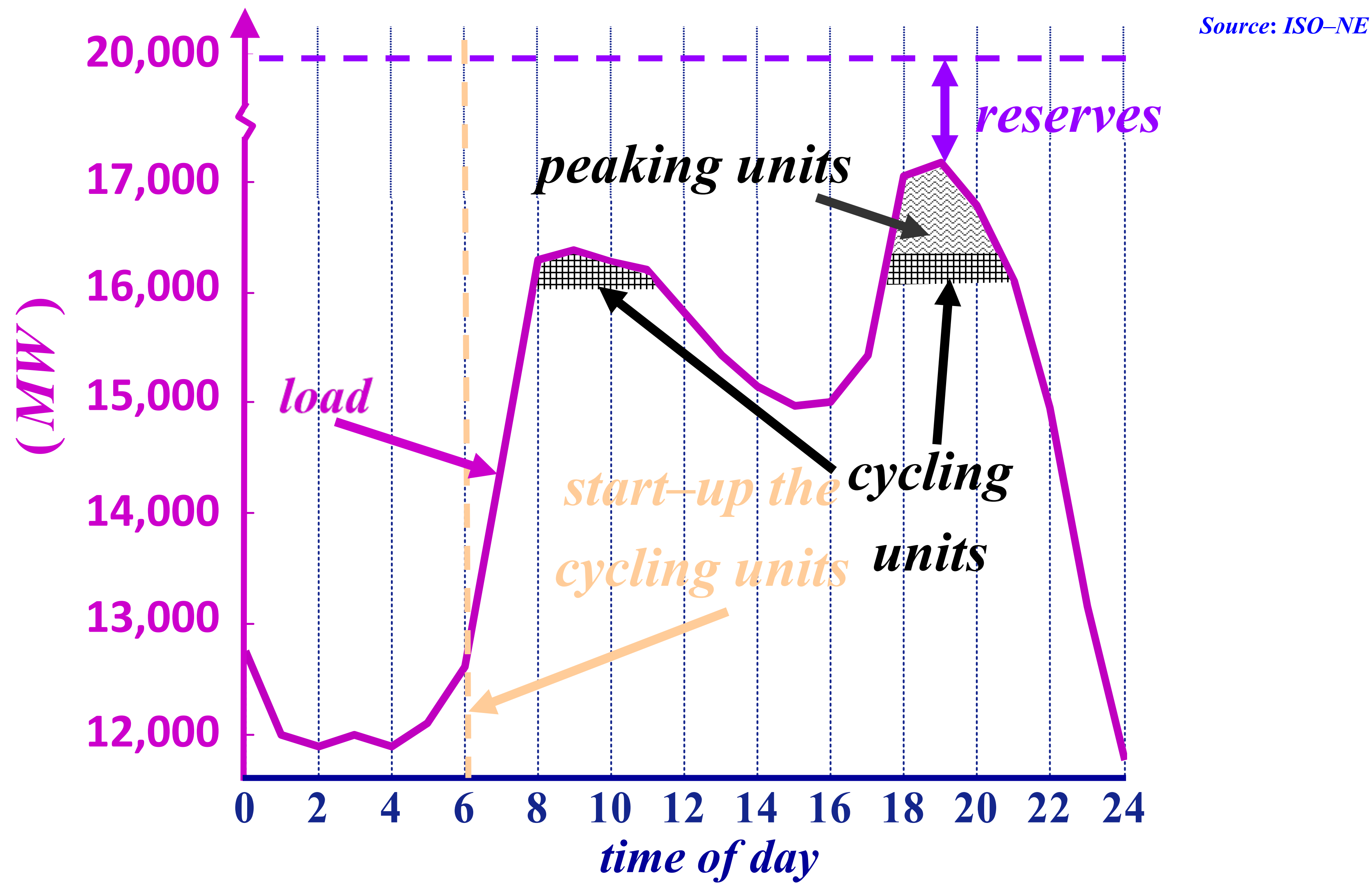
THE STORAGE RESOURCE PHASES



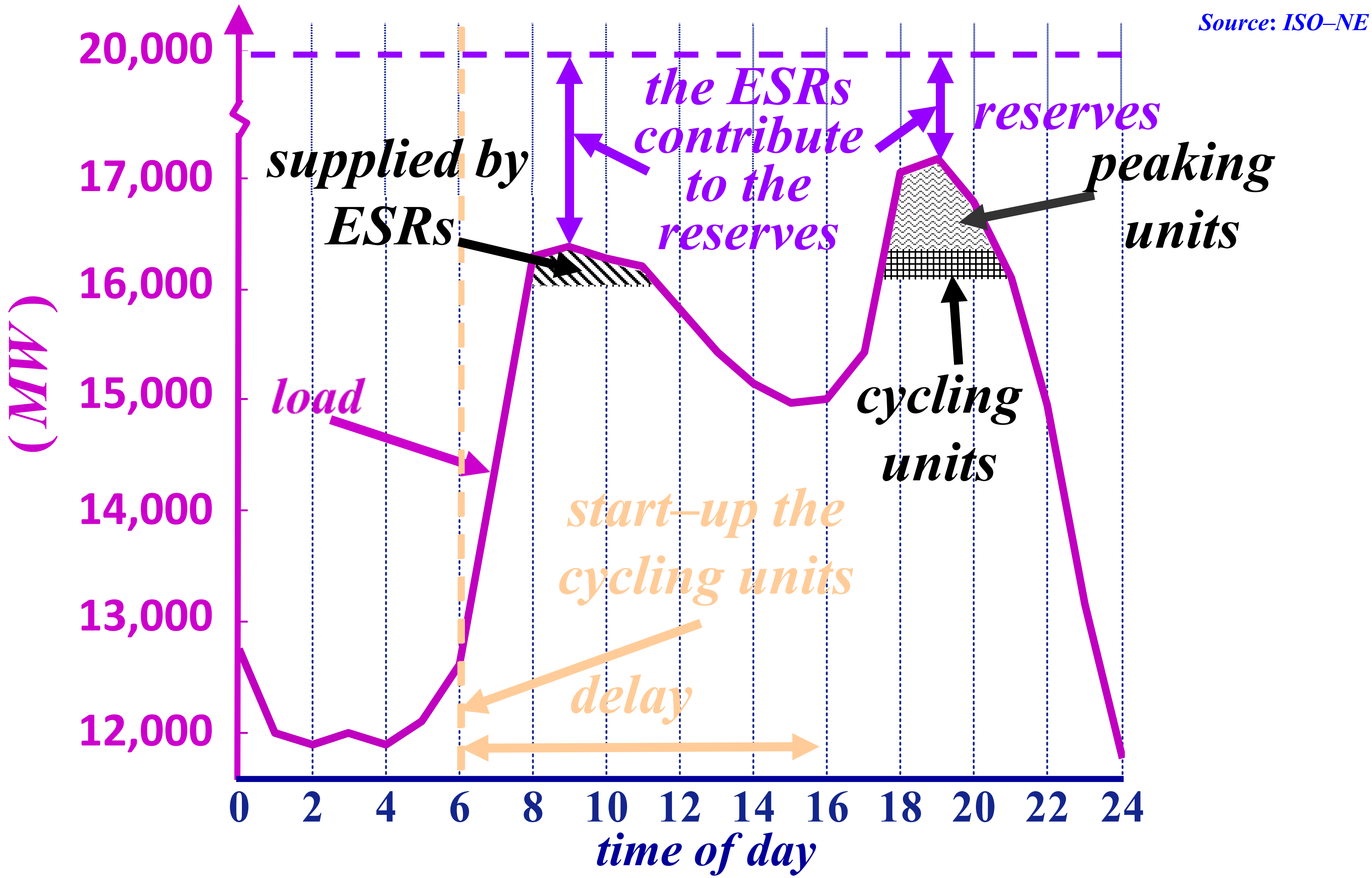
STORAGE UTILIZATION



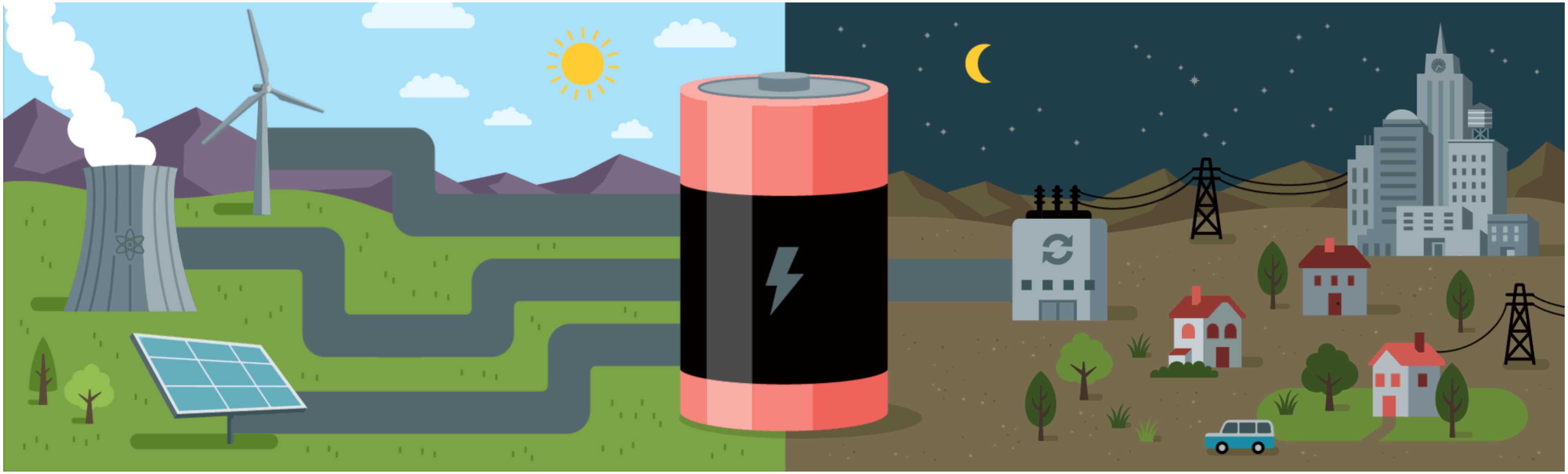
CYCLING UNITS WITHOUT *ESR*s



CYCLING UNITS WITH *ESRs*

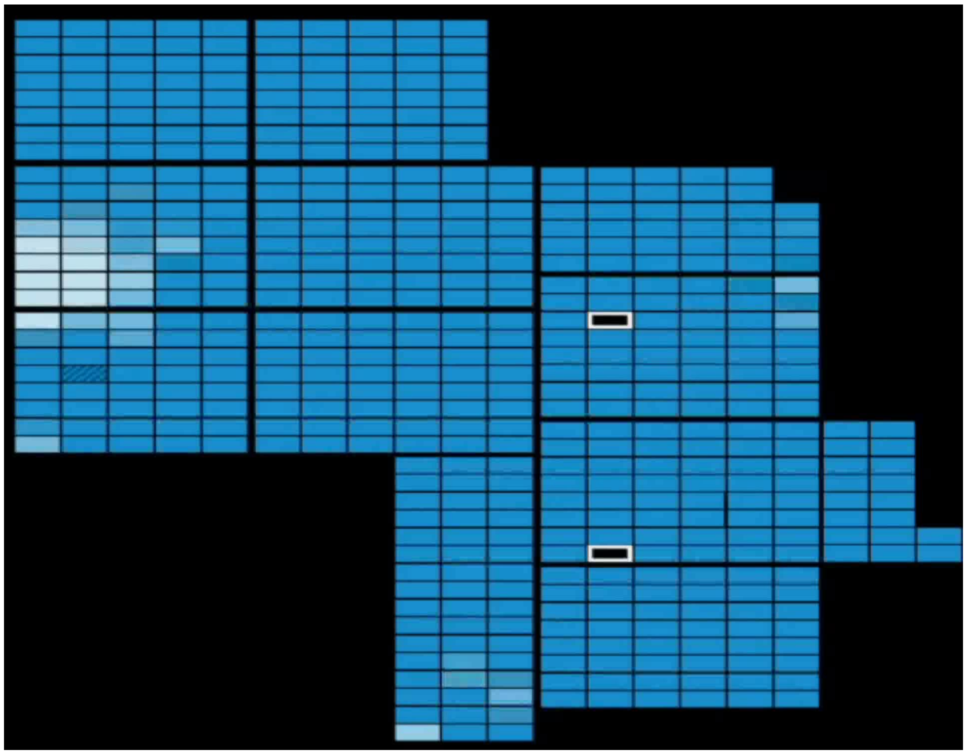


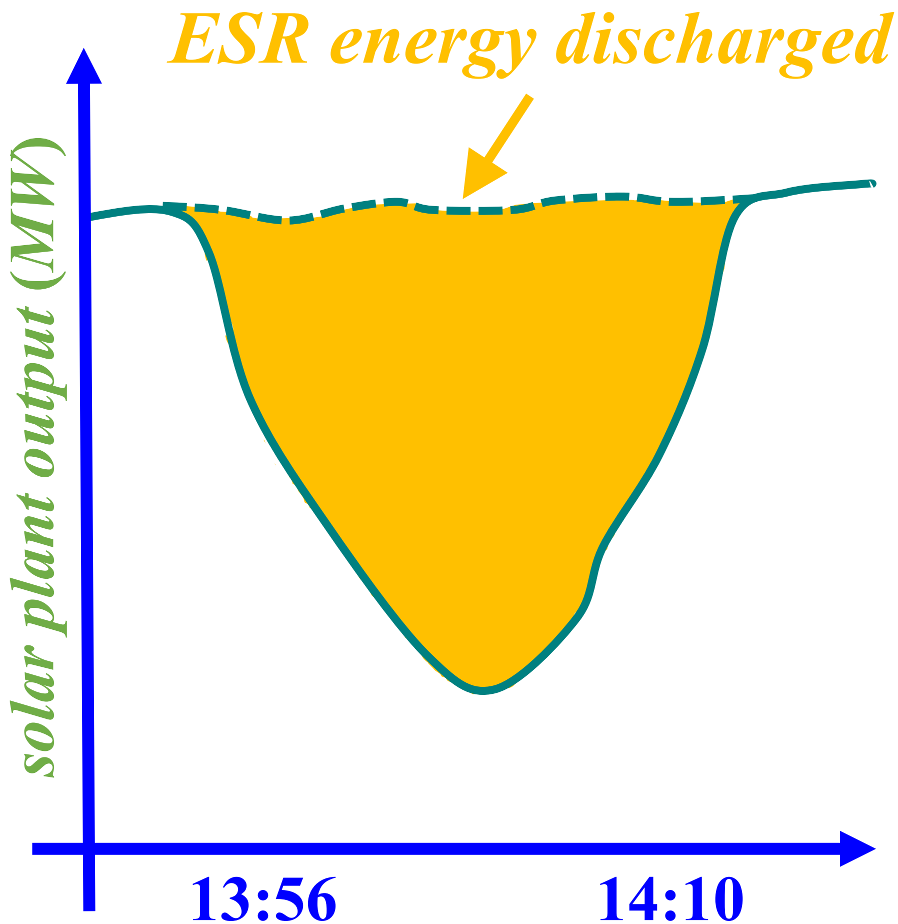
Battery Storage and *RER* Symbiosis



Source*: *The New York Times https://static01.nyt.com/images/2017/03/21/business/batteries-cover/batteries-cover-superJumbo.gif

INTEGRATION OF STORAGE WITH SOLAR RESOURCES

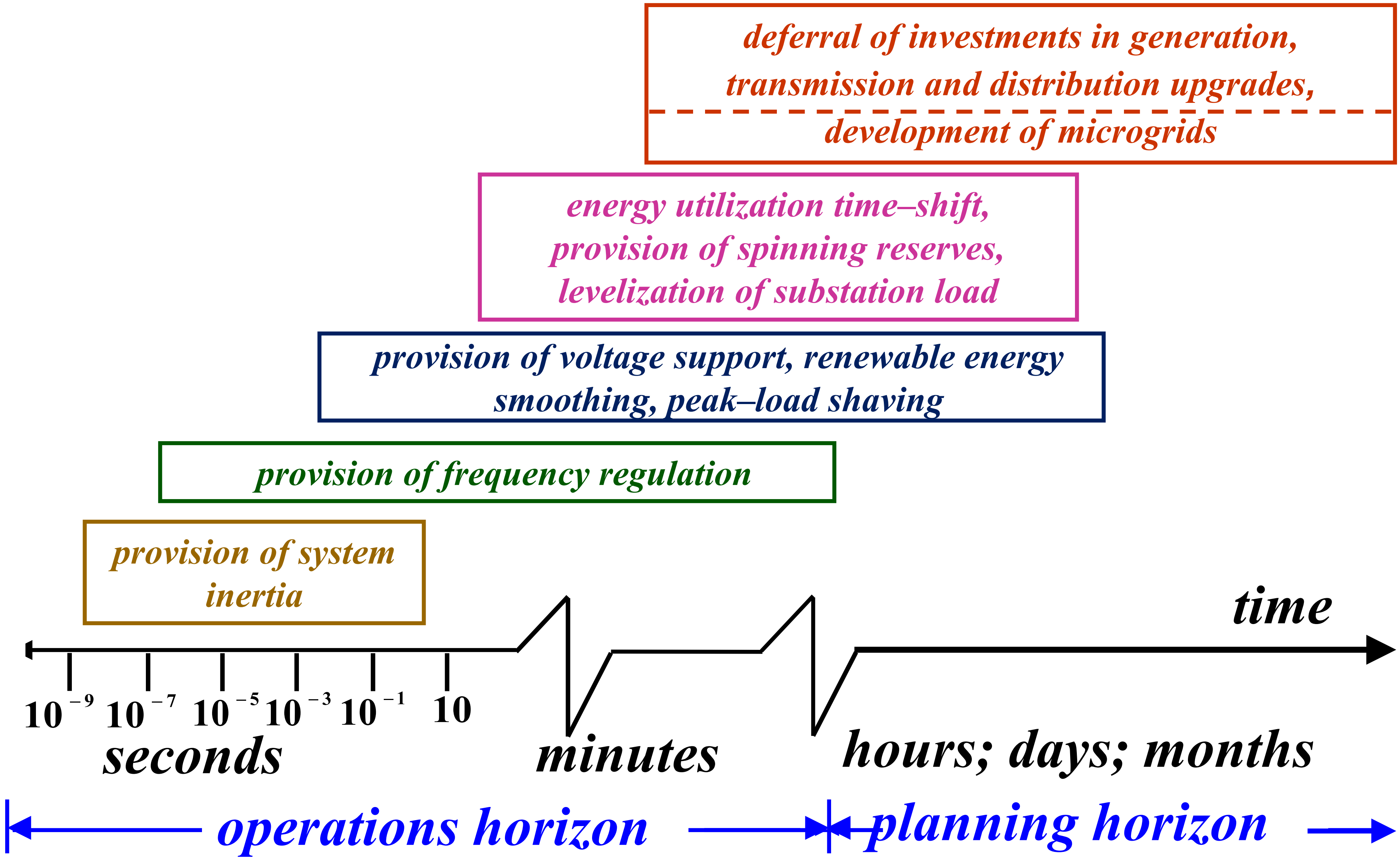




Demand Response Resources (*DRR*s) in Symbiosis with ESRs

- *DRRs* are demand–side entities which actively participate in the markets as both buyers of electricity and sellers of load curtailment services
- *DRR*s reduce the load during peak hours and/or shift the demand, in part or in whole, from peak hours to low–load hours
- The coordinated deployment of *ESR*s and *DRR*s can be symbiotic to further reduce the operational costs and emissions via reduced unit cycling and avoided delays in the start–up of cycling units

Energy Storage Applications

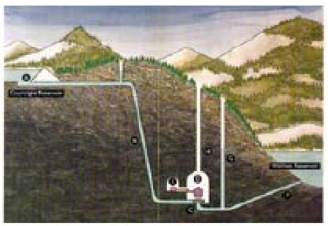


Key Benefits of Grid-Integrated ESRs

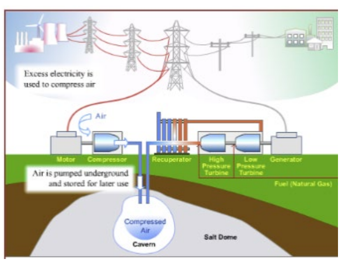
- Deployment of *ESR*s:
  - **raises** system reliability
  - **improves** operational economics
  - provides operators with **additional flexibility** to optimize grid operations and manage grid congestion
  - **raises** renewable output utilization
- Deployment of *ESR*s can reduce *GHG* emissions because *ESR*s:
  - **facilitate** renewable resource integration
  - **reduce** the system reserves requirements on the conventional fossil–fired resources
  - **displace** the generation of inefficient and dirty units used to meet peak loads

Energy Storage Technologies

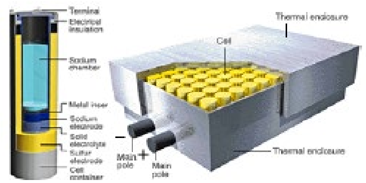
pumped storage



CAES



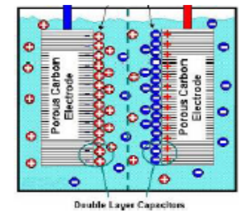
NaS battery



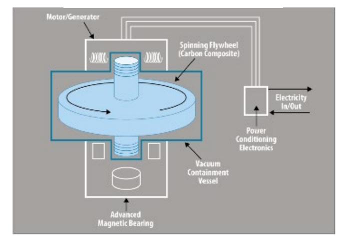
flow battery

advanced lead acid battery

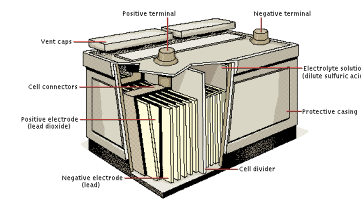
EC capacitor



flywheel



lead–acid battery



Li–ion battery

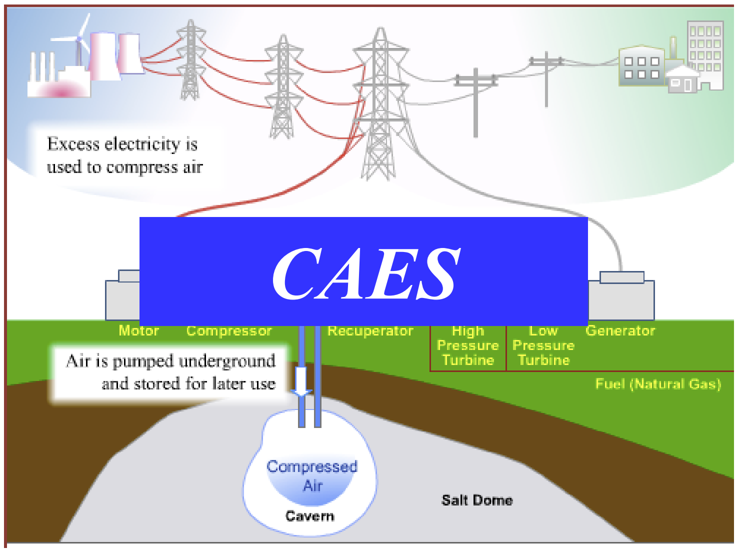
Ni–Cd battery

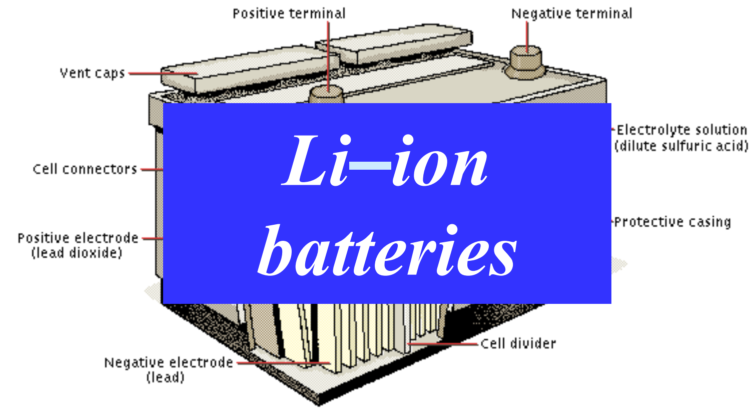
SMES

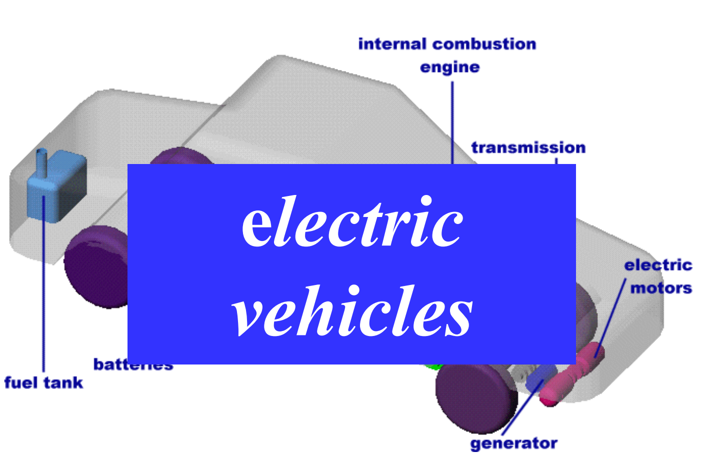
increasing capability ←

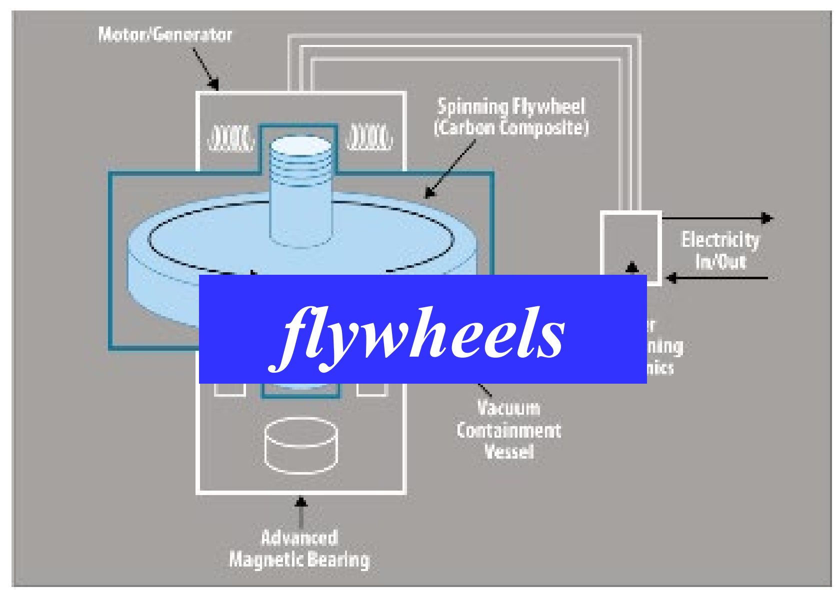
increasing capacity →

Storage Technology Advances



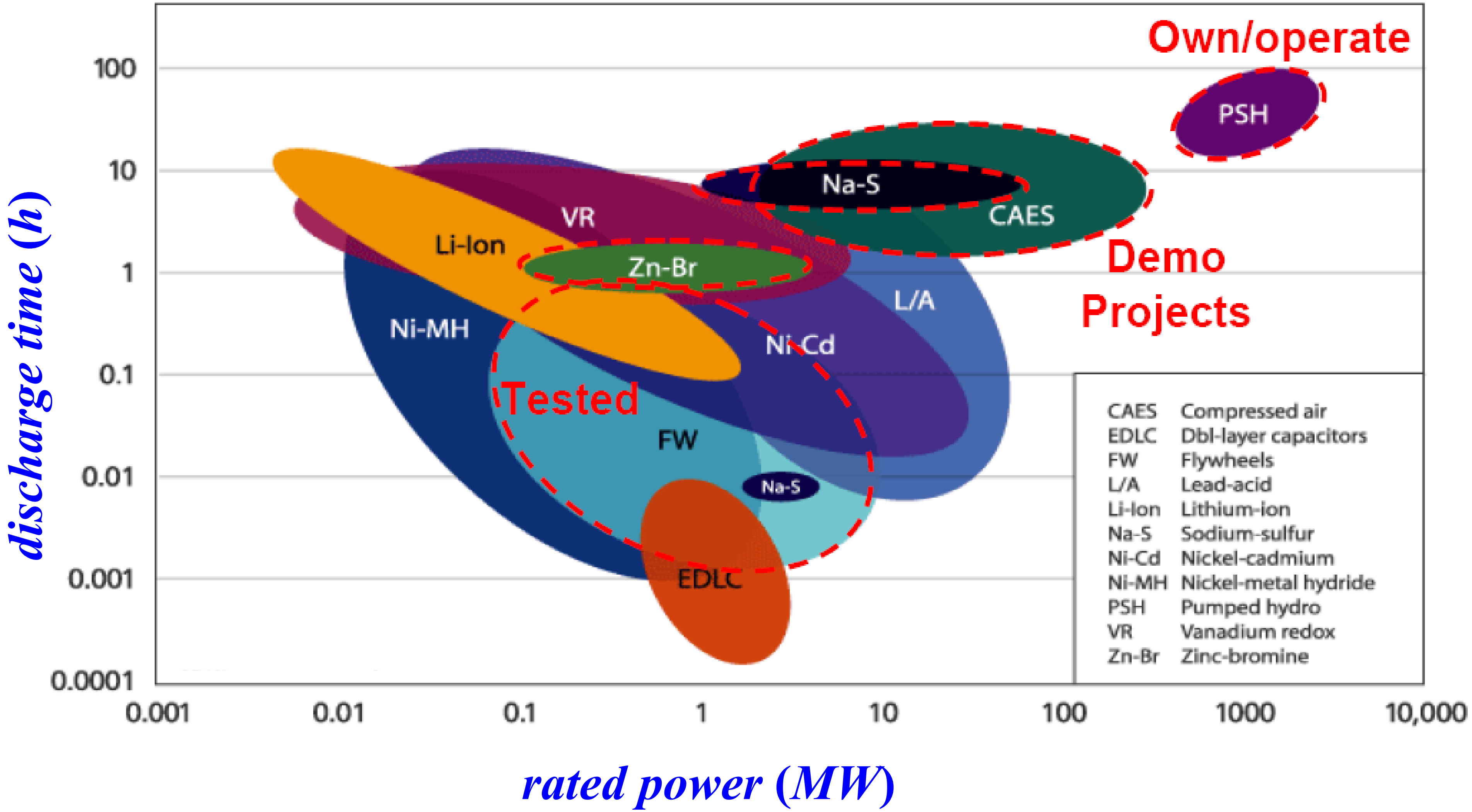






Energy Storage Technology Characterization

Source: Electricity Storage Association

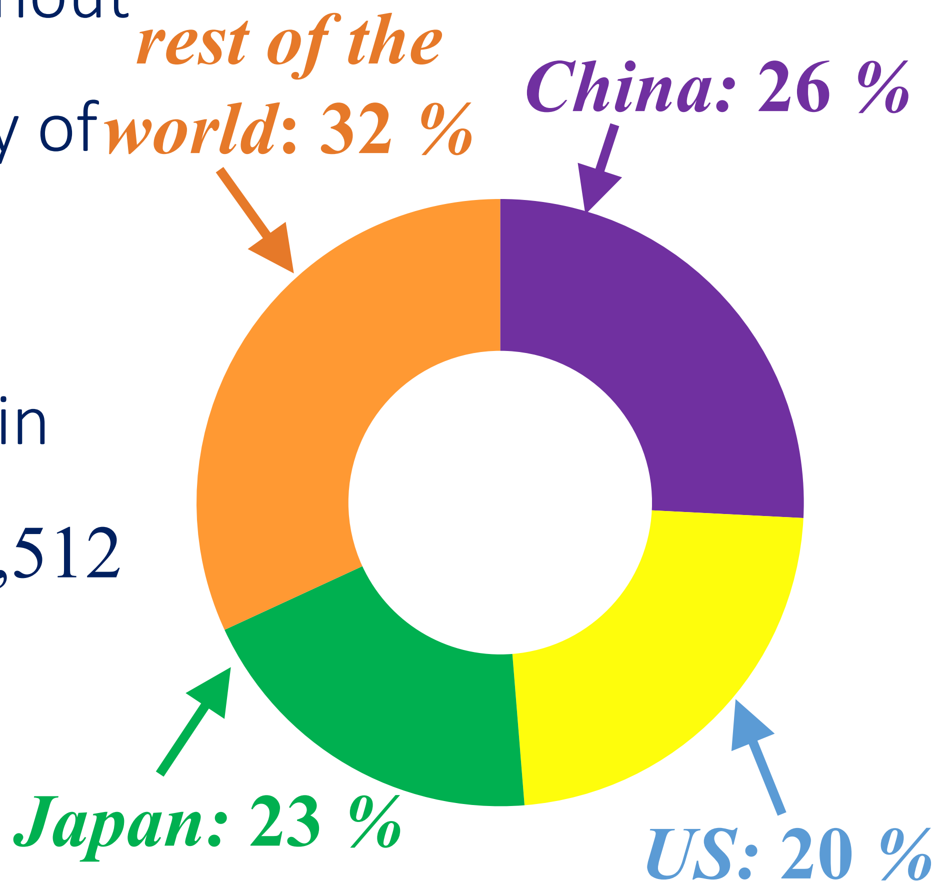


World Storage Status

Source**:** ***DOE Global Energy Storage Database,*** *http://www.energystorageexchange.org/projects/data_visualization*

- There are currently 1,737 *ESR* projects implemented throughout the world with a total capacity of 196,301 *MW*
- 288 out of these projects are in California with a capacity of 7,512 *MW*

global storage capacity

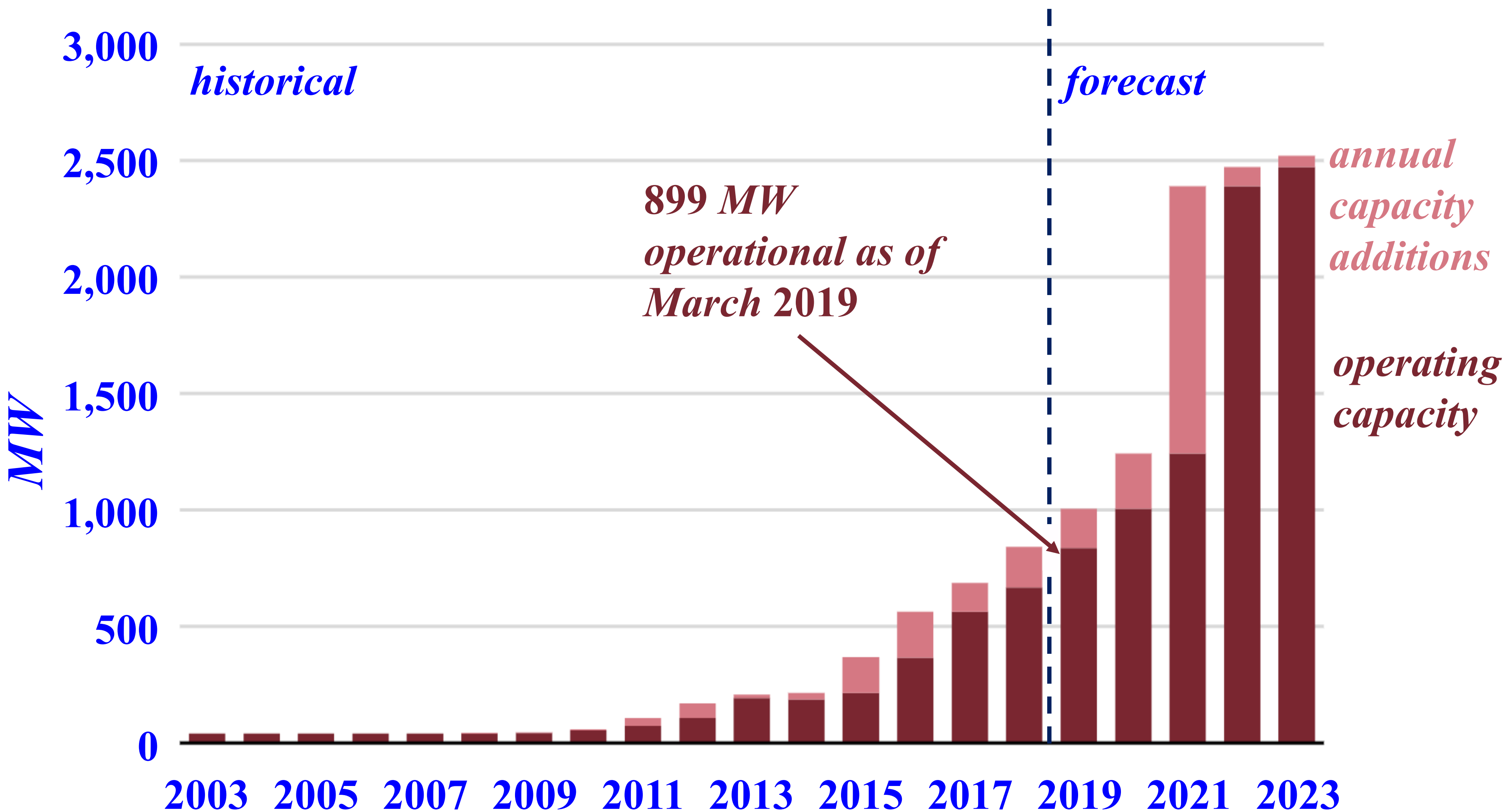


Battery Energy Storage Systems (BESSs)

- Many practitioners consider the installation of *BESS*s to most effectively address the challenges to integrate deepening penetrations of renewable resources – a game changer for *RER* integration
- *BESS*s can be highly efficient and discharge their stored energy at high ramp rates
- The development of *new, very large, highly efficient* batteries, appropriate for utility–scale storage, is predicted to grow into a huge business

EIA : US BESS Capacity and Forecast

Source*: *EIA, Annual Electric Generator Report and the Preliminary Monthly *Electric Generator; available at https://www.eia.gov/todayinenergy/detail.php?id=40072*



NOTREES PROJECT – *GOLDSMITH, TX* (36 *MW* / 23.8 *MWh*)

Source*: *http://www.energystorageexchange.org/projects

The ***advanced lead–acid battery*** system project was developed to reduce the output variability of the **153 *MW*** wind power plant

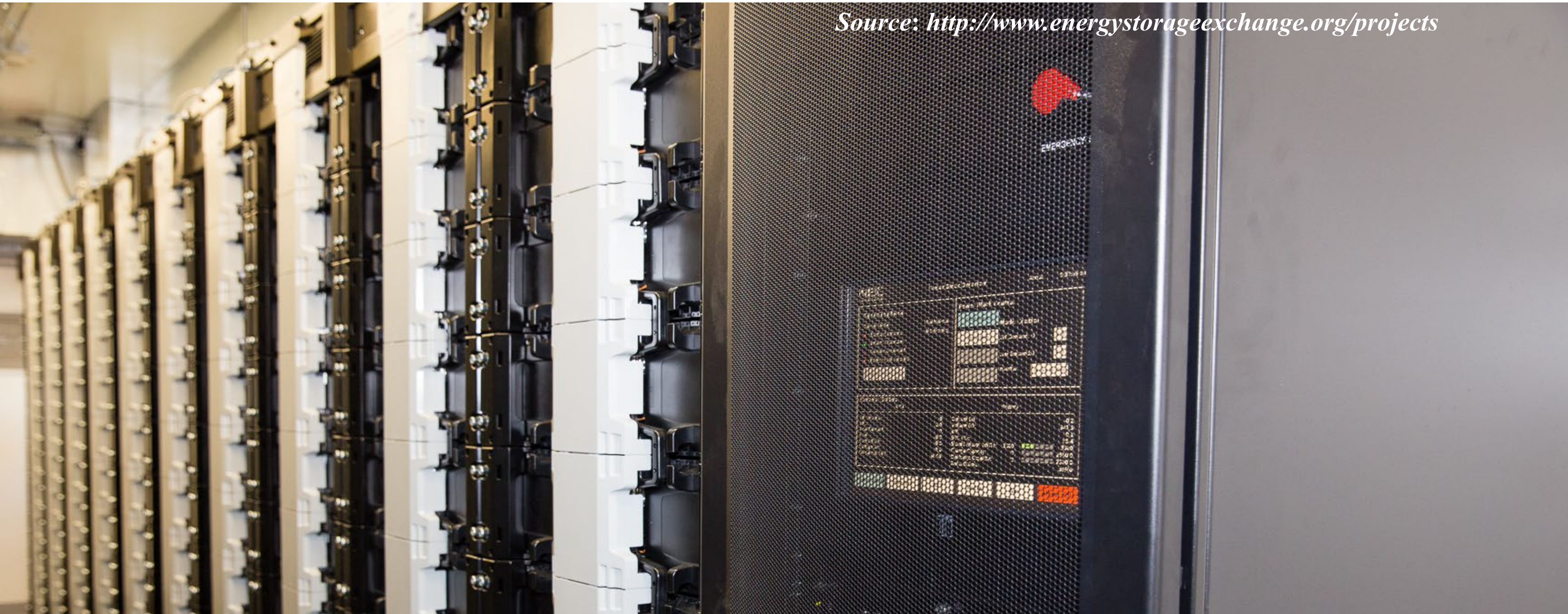
AES LAUREL MOUNTAIN – ELKINS, VA

(32 *MW* / 8 *MWh*)

Source*: *http://www.energystorageexchange.org/projects

The ***Li–ion*** batteries are installed in a ***98–MW*** wind farm to provide operating reserves and frequency regulation in the ***PJM*** system

SCE PILOT PROJECT – *ORANGE, CA* (2.4 *MW* / 3.9 *MWh*)



Source: http://www.energystorageexchange.org/projects

The set of ***Li–ion*** batteries relieves transformer overloads and defers distribution network upgrades to ensure summer–time demand peak loads are met

BUZEN SUBSTATION – *BUZEN, FUKUOKA PREFECTURE* (50 *MW* / 300 *MWh*)

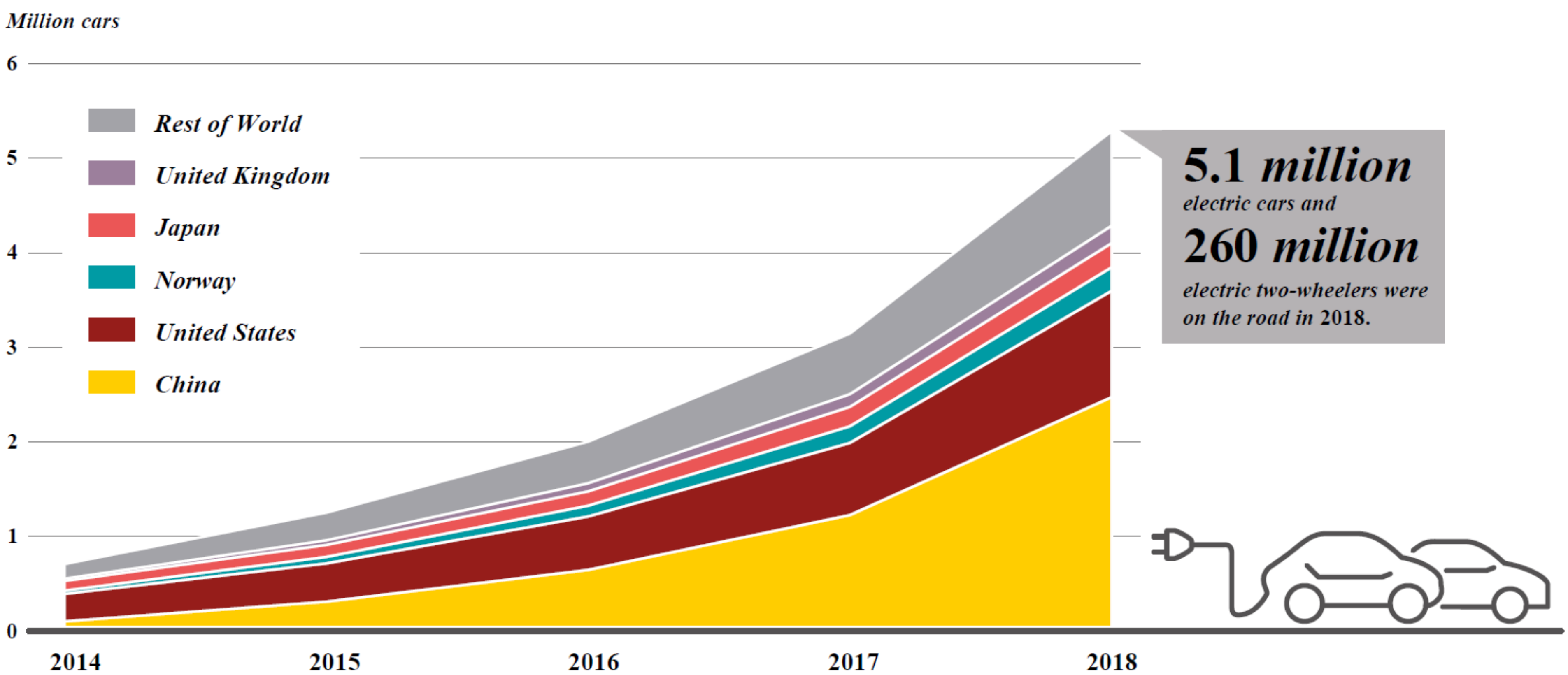
The world's largest *BESS* serves to provide demand – supply balance

BATTERY VEHICLES (*BV*s)

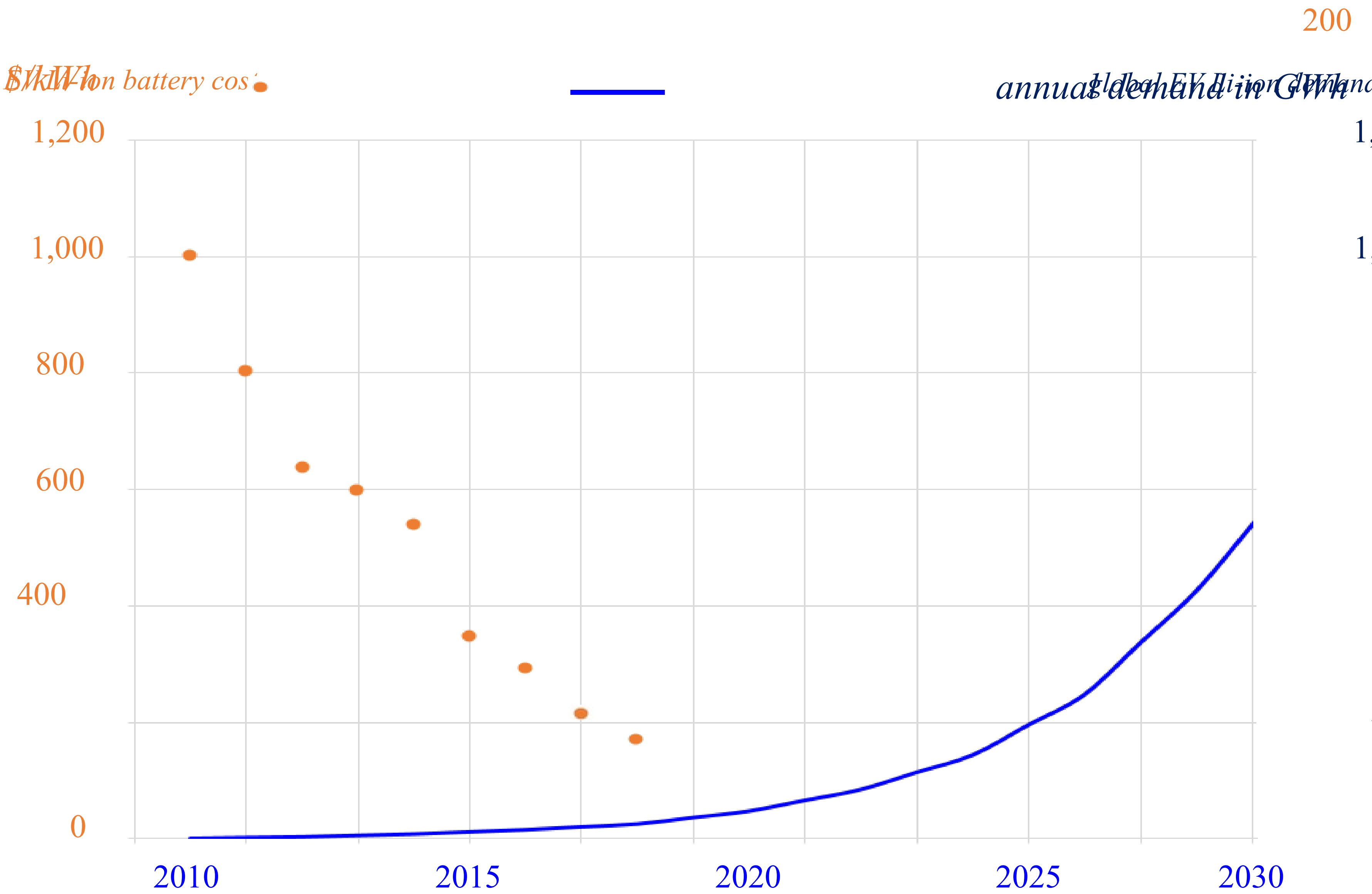
- Reduction in CO_2 *emissions* and *energy security* are the key drivers of initiatives aimed to promote the electrification of the transportation sector
- Consequently, the past decade has seen growing sales of ***BV*s** – *electric vehicles* (*EV*s), *hybrid electric vehicles* (*HEV*s) and *plug–in hybrid electric vehicles* (*PHEV*s) –fully/partially powered by batteries and without *internal combustion engines*, in some cases

GLOBAL *EVs* SALES AND MARKET GROWTH

Source: *REN* 21, *Renewables* 2019 *Global Status Report p.* 164; *available online at https://www.ren21.net/wp-content/uploads/*2019*/*05*/gsr_*2019*_full_report_en.pdf*



EV LI–ION BATTERY PACKS: PRICES AND DEMAND



Source: Bloomberg New Energy Finance https://www.bloomberg.com/news/articles/2016-06-13/batteries-storing-power-seen-as-big-as-rooftop-solar-in-12-years; *https://about.bnef.com/blog/behind-scenes-take-lithium-ion-battery-prices/*

BARRIERS TO LARGE–SCALE STORAGE DEPLOYMENT

- The pace of energy storage deployment has been very slow in the past, mainly due to the extremely high costs of storage
- The reductions in storage costs over the past decade have remained inadequate to stimulate the large–scale deployment of *ESR*s
- The high costs of storage present a *chicken and egg* problem: costs remain high due to low demand and the high costs impede any growth in demand