ECEN 460
Power System Operation and Control
Spring 2025

Lecture 25: Solar, Storage, Electric Grid Resiliency

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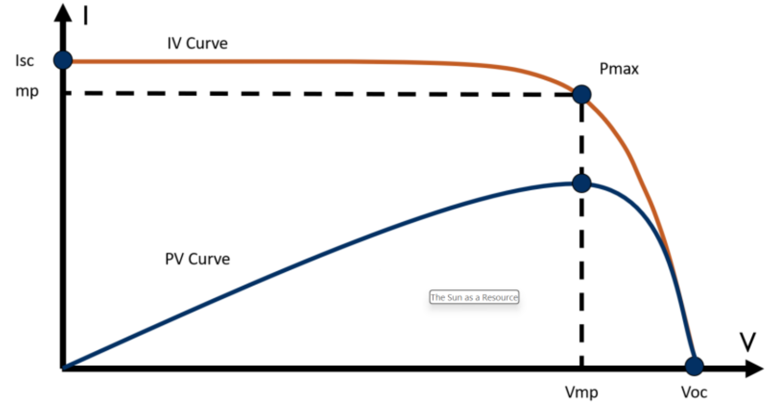
Announcements

- Schedule for the rest of the semester is
  - Lab 11 (project presentations) by the individual teams to their TA ideally before the end of classes (on or before April 29)
  - Exam 2 on Wednesday April 23 during class; comprehensive but more emphasis on material since the first exam; similar format to first exam, closed book, closed notes, but two 8.5 by 11 inch note sheets and calculators allowed
  - Design project due at 9:30 am on May 1 (i.e., at the end of our final slot; no final)
    - The syllabus in Canvas has been updated to show the May 1 date

Solar Photovoltaics (PV)

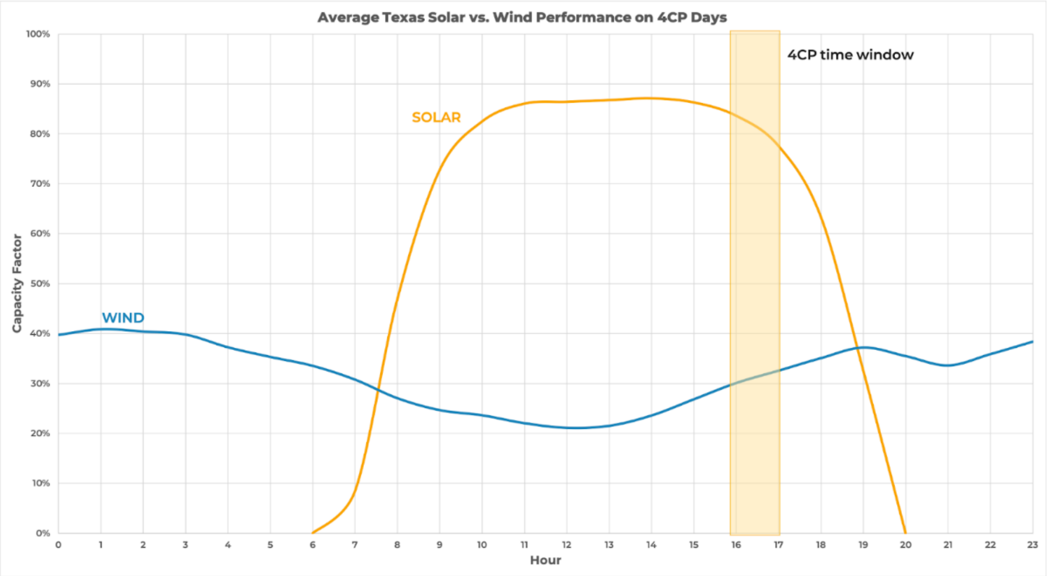
- Photovoltaics is the conversion of light into electricity using semiconductors known as solar cells
  - It dates back to 1883, but really got going in the late 1950’s, driven by NASA
  - Solar cells produce a dc output, with the right image showing an example IV curve



- Solar modules are groups of solar cells; a PV panel is one or more modules wired together ready to mount
- A PV system often includes an inverter to produce ac electricity
- PV panels can either have a fixed mount, or be on a tracker; trackers can be one-axis or two-axis

Solar Inverters and the Inverter Load Ratio (ILR)

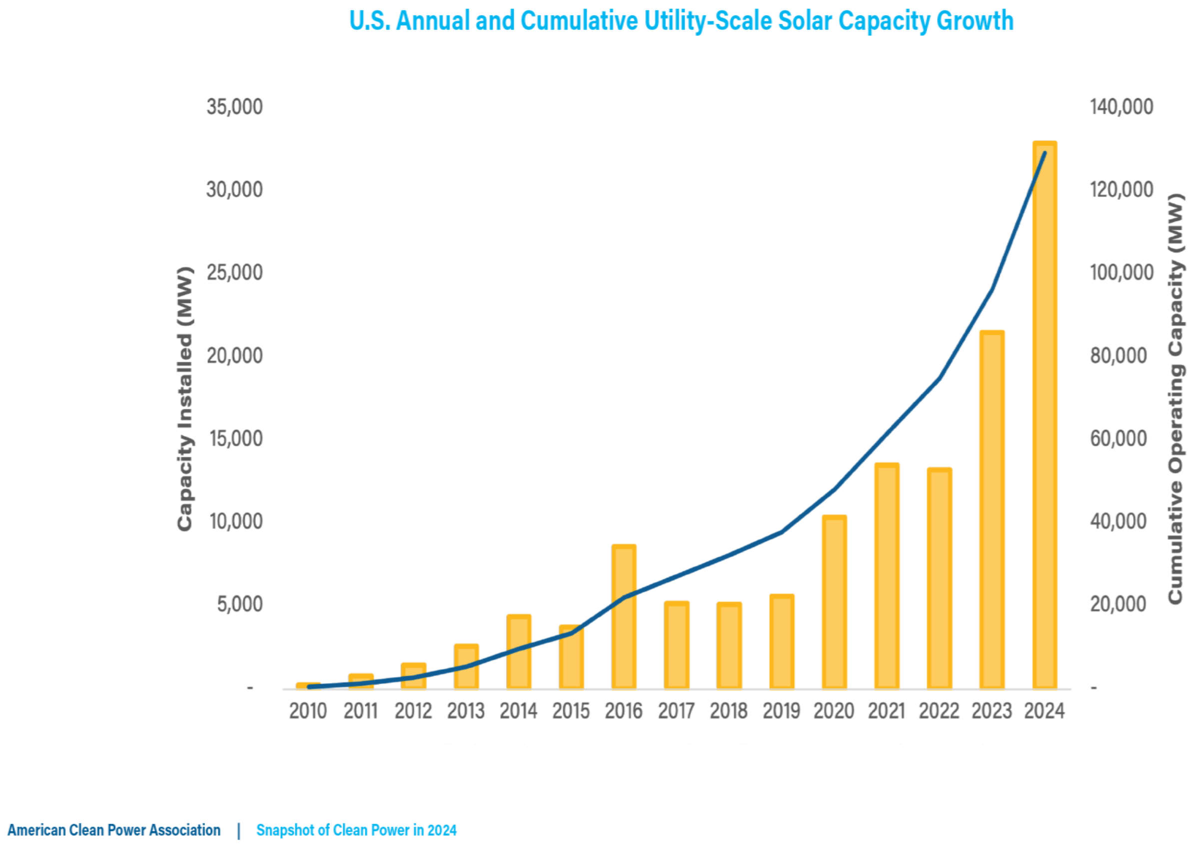
- The amount of dc electricity produced by a solar panel depends proportionally on the amount if solar irradiation
  - Because of atmospheric attenuation, the amount of irradiation varies
- Solar modules are rated based on the maximum power they could produce in full sun; however since this is seldom achieved, usually it makes economic sense to rate the inverter to be less than the maximum dc power
- The inverter load ratio (ILR) is the ratio of maximum dc power to the inverter's rating; typical values are on the order of 1.25



Worldwide Solar Capacity by Country, 2023

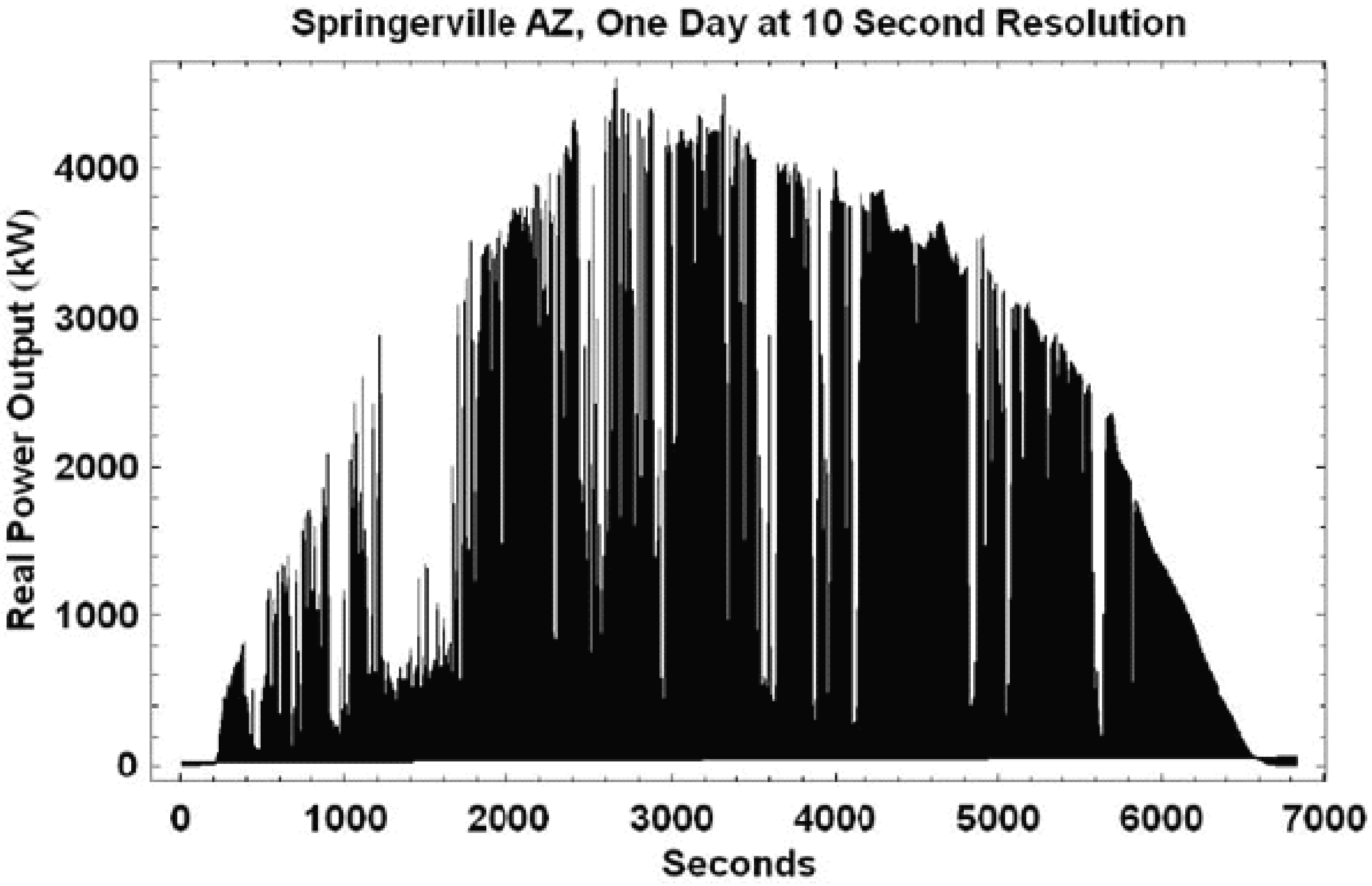
Solar statistics by country in 2023 (unless otherwise specified)

	Country	Gen (TWh)	% gen.	Cap. (GW)	% cap. growth	Cap. fac.
	World	1632.33	5.5	1419.0	32.2	13%
1	China	584.15	6.2	609.92	55.2	11%
2	United States	238.12	5.6	129.21	21.7	20%
3	India	113.41	5.8	73.11	15.3	18%
4	Japan	96.99	9.6	87.07	4.8	13%
5	Germany	61.22	12.1	81.74	21.1	9%
6	Brazil	51.48	7.3	37.45	46.7	16%
7	Spain	45.08	16.7	31.02	21.1	17%
8	Australia	44.99	16.5	33.68	12.4	15%
9	Italy	31.01	11.8	29.80	21.3	12%
10	South Korea	29.37	4.8	27.05	12.3	12%
11	Mexico	27.14	7.7	10.91	16.6	28%
12	Vietnam	25.70	9.3	17.08	2.3	17%
13	France	23.25	4.5	20.55	18.4	13%
14	Netherlands	19.99	16.6	23.90	21.2	10%



Source: en.wikipedia.org/wiki/Solar_power_by_country

Solar PV can be Intermittent Because of Clouds

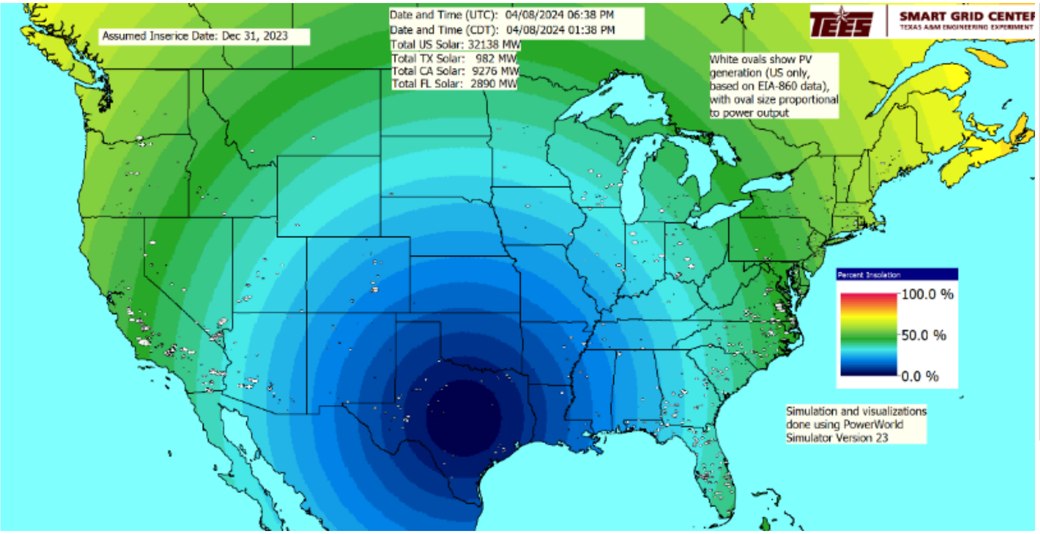


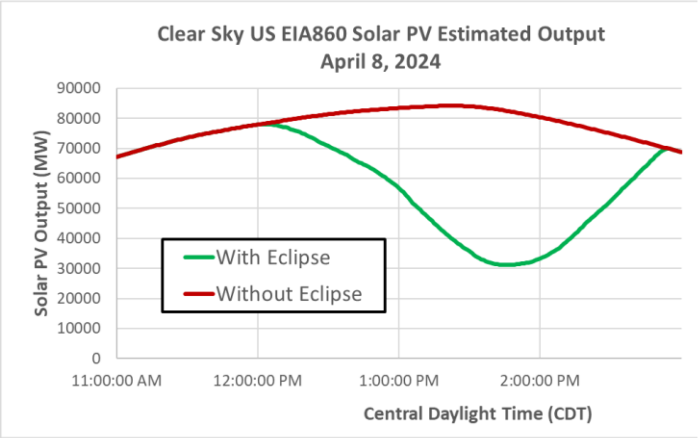
Intermittency can be reduced some when PV is distributed over a larger region; key issue is correlation across an area; also sometimes there is integrated storage

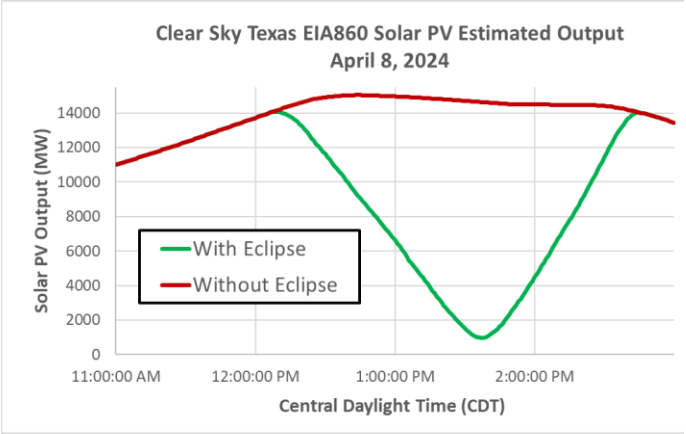
Image: http://www.megawattsf.com/gridstorage/gridstorage.htm

Impact of April 08, 2024 Eclipse on Solar Generation

- Solar generation is impacted by eclipses, with the total solar eclipse on April 08, 2024 and the annular one from October 14, 2023 great examples
- Unfortunately, these are quite rate events, with the next major one in the Texas area not due to occur until 2045







Modeling Solar PV

- Since a large portion of the solar PV is distributed in small installations in the distribution system (e.g., residential rooftop), solar PV modeling is divided into two categories
  - Utility Scale, which is considered a single generation plant
  - Small scale, as part of the load model
- For the US 28% is at small installations, but in California its is 41% while in Texas it is 11%; trend is towards utility scale

Table 1.17.B. Net Generation from Solar Photovoltaic
by State, by Sector, Year-to-Date through December 2024 and 2023 (Thousand Megawatthours)

	All Sectors						
	Estimated Generation From Utility and Small Scale Facilities			Generation at Utility Scale Facilities		Estimated Small Scale Generation	
Census Division and State	December 2024 YTD	December 2023 YTD	Percentage Change	December 2024 YTD	December 2023 YTD	December 2024 YTD	December 2023 YTD
New England	12,530	10,294	21.7%	4,673	3,577	7,857	6,717
Connecticut	1,962	1,659	18.3%	501	421	1,461	1,238
Maine	2,092	1,152	81.6%	1,077	523	1,015	629
Massachusetts	6,310	5,724	10.2%	2,246	2,015	4,064	3,709
New Hampshire	365	302	20.6%	4	3	361	299
Rhode Island	1,333	1,027	29.8%	623	423	709	603
Vermont	468	430	8.7%	222	192	246	239
Middle Atlantic	15,283	12,304	24.2%	6,361	4,141	8,922	8,163
New Jersey	5,189	4,710	10.2%	1,787	1,544	3,403	3,166
New York	7,905	6,205	27.4%	3,380	2,236	4,526	3,968
Pennsylvania	2,189	1,389	57.5%	1,195	361	994	1,029
East North Central	18,211	10,580	72.1%	14,682	7,694	3,530	2,887
Illinois	4,628	3,447	34.3%	2,703	1,911	1,925	1,536
Indiana	3,489	2,203	58.4%	3,102	1,854	387	349
Michigan	2,262	1,566	44.4%	1,916	1,269	346	298
Ohio	4,530	1,800	151.7%	4,021	1,382	509	418
Wisconsin	3,302	1,564	111.1%	2,939	1,277	363	287
West North Central	5,710	4,586	24.5%	3,834	2,997	1,875	1,589
Iowa	1,150	911	26.2%	671	521	479	390
Kansas	250	210	18.8%	83	81	167	129
Minnesota	2,758	2,417	14.1%	2,357	2,094	401	323
Missouri	961	867	10.9%	200	174	762	692
Nebraska	243	129	88.8%	185	79	57	49
North Dakota	3	2	25.0%	0	0	3	2
South Dakota	346	50	588.4%	338	47	7	4
South Atlantic	61,037	50,516	20.8%	51,244	42,375	9,792	8,141
Delaware	372	344	8.1%	167	155	205	189
District of Columbia	303	231	31.2%	46	25	257	206
Florida	23,302	17,804	30.9%	18,680	14,059	4,622	3,745
Georgia	9,348	8,069	15.9%	8,780	7,550	568	519
Maryland	2,603	2,325	12.0%	1,111	943	1,491	1,382
North Carolina	13,174	12,216	7.8%	12,267	11,459	907	757
South Carolina	3,591	3,351	7.2%	2,954	2,762	637	589
Virginia	8,076	6,129	31.8%	7,031	5,421	1,044	708
West Virginia	268	47	466.0%	207	0	60	47
East South Central	4,451	3,199	39.1%	4,156	2,950	296	248
Alabama	1,284	1,223	5.0%	1,257	1,201	27	22
Kentucky	406	286	42.0%	245	155	161	131
Mississippi	1,583	656	141.3%	1,553	633	30	23
Tennessee	1,178	1,034	13.9%	1,101	961	77	72
West South Central	49,294	34,353	43.5%	43,254	29,317	6,040	5,035
Arkansas	2,717	1,194	127.5%	2,200	798	517	397
Louisiana	1,546	592	161.2%	1,210	292	336	300
Oklahoma	526	242	117.0%	297	79	229	164
Texas	44,506	32,325	37.7%	39,547	28,150	4,959	4,175
Mountain	49,916	37,823	32.0%	38,173	27,614	11,743	10,209
Arizona	15,408	11,535	33.6%	9,958	6,663	5,450	4,871
Colorado	6,975	5,319	31.1%	4,939	3,616	2,036	1,704
Idaho	1,289	1,092	18.1%	1,013	854	276	238
Montana	474	316	49.7%	367	240	107	76
Nevada	14,279	11,209	27.4%	12,235	9,525	2,044	1,685
New Mexico	5,120	3,314	54.5%	4,319	2,613	801	701
Utah	5,915	4,835	22.4%	4,920	3,929	995	906
Wyoming	456	202	125.3%	423	174	33	29
Pacific Contiguous	81,266	70,376	15.5%	48,288	41,365	32,978	29,011
California	77,498	67,077	15.5%	45,775	39,100	31,723	27,977
Oregon	2,698	2,416	11.7%	2,076	1,901	621	515
Washington	1,070	883	21.2%	436	364	634	518
Pacific Noncontiguous	2,348	2,059	14.0%	752	653	1,596	1,406
Alaska	36	18	97.2%	16	0	20	18
Hawaii	2,311	2,040	13.3%	736	653	1,575	1,387
U.S. Total	300,046	236,090	27.1%	215,416	162,683	84,630	73,406

Image: EIA Electric Power Monthly, Feb 2025

Distributed PV System Modeling

- PV in the distribution system is often operated at unity power factor
  - There is research investigating the benefits of changing this
- IEEE Std 1547-2018 now allows both non-unity power factor and voltage regulation
  - "Constant power factor mode with unity power factor setting shall be the default mode of the installed DER unless otherwise specified by the Area EPS operator"
- A simple model is just as negative constant power load
- An issue is tripping on abnormal frequency or voltage conditions
  - IEEE Std 1547-2018 says, "For short-circuit faults on the Area EPS circuit section to which the DER is connected, the DER shall *cease to energize* and *trip* unless specified otherwise by the Area EPS operator (note EPS is electric power system)

Distributed PV System Modeling

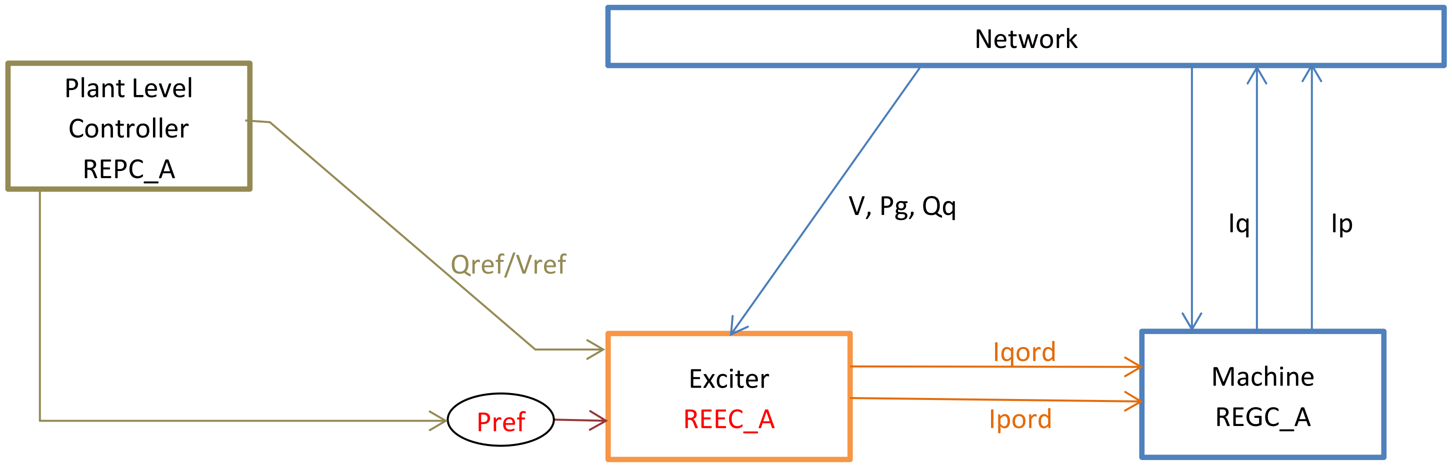
- An issue is tripping on abnormal frequency or voltage conditions (from IEEE 1547-2018
  - This is a key safety requirement!
  - Units need to disconnect if the voltage is < 0.45 pu in 0.16 seconds, in 1 second between 0.45 and 0.6 pu, in 2 seconds if between 0.6 and 0.88 pu; also in 1 second if between 1.1 and 1.2, and in 0.16 seconds if higher
  - Units need to disconnect in 0.16 seconds if the frequency is > 62 or less than 57 Hz; in 2 seconds if > 60.5 or < 59.5
  - Reconnection is after minutes
  - Values are defaults; different values can be used through mutual agreement between EPS and DR operator

In the News: California PUC Proposes Changes to State Net Metering

- One of the reasons for large amounts of residential solar PV in states such as California is their net metering interconnection agreements. For agreements signed before April 2023 household solar generation not only offsets the local electric load, but the utilities are required to buy excess power at retail rates
  - These retail rates would be paid for 20 years
  - Starting April 2023 the credits are only for wholesale rates (average change from \$0.30 per kWh to \$0.08 per kWh)
- In California AB 942 (evidently supported by the California PUC) would change existing customers to the new net metering
- Texas does not have state rules on net metering, though some utilities provide some form of solar buyback programs

Solar Stability Models

- The stability models for representing solar are very similar to those used for the wind machine and “exciter”

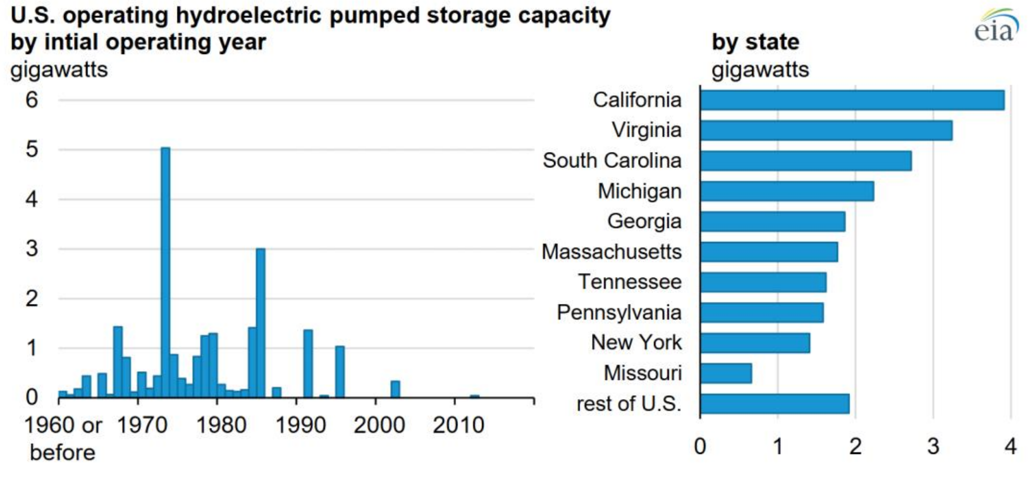


Grid Following and Forming Converter Models

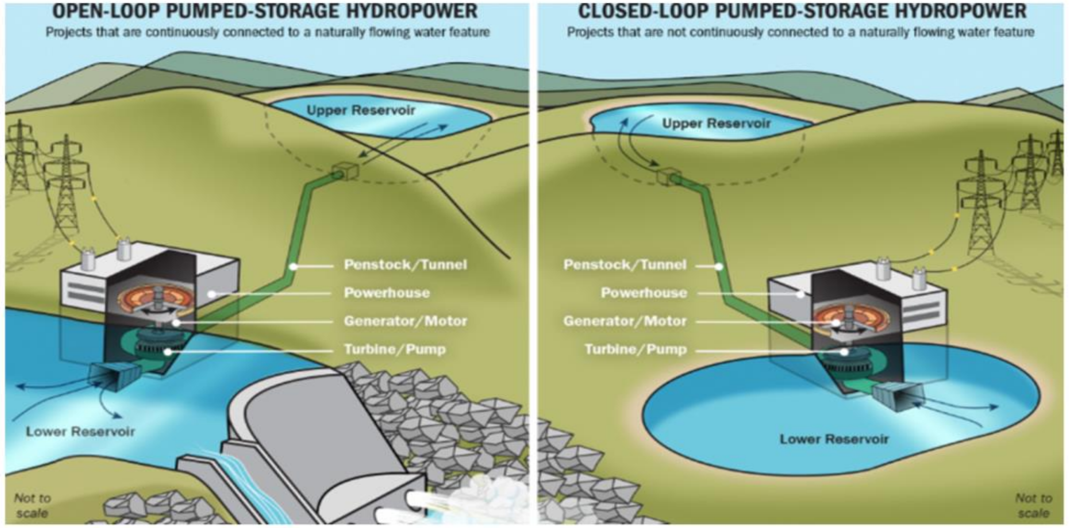
- All the IBR models presented so far are called "Grid Following Inverters"
- Some newer inverters are "Grid Forming Inverters"
  - These terms are very loosely defined
  - Terms refer to the hardware technology and the control system software that is driving that hardware
- Grid Following Inverters
  - Control algorithms assume the device is connected to an AC power system
  - Control *synchronizes* the inverter to this AC system
- Grid Forming Inverters
  - Control algorithms do not assume anything
  - Inverters can operate in an islanded power system as the only generator

Electric Energy Storage, Pumped Storage

- Traditionally electric grids have had little storage capability
- What did exist was pumped storage hydro, in which water is pumped up into a reservoir when electricity prices are low, and then run through hydro generators when the price was high; efficiency can be about 80%
  - US has 23,000 MW of capacity; largest pumped storage in US is 3000 MW at Bath County (VA) and a storage capacity of 24,000 MWh;



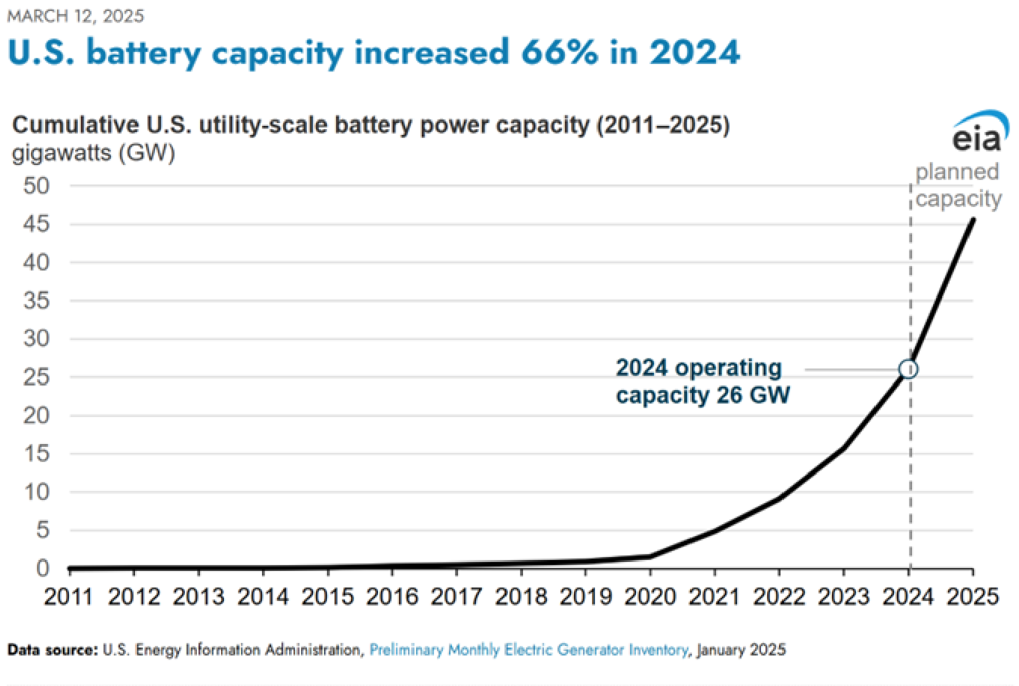
Source: U.S. Energy Information Administration, *Annual Electric Generator Report*



Source: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy

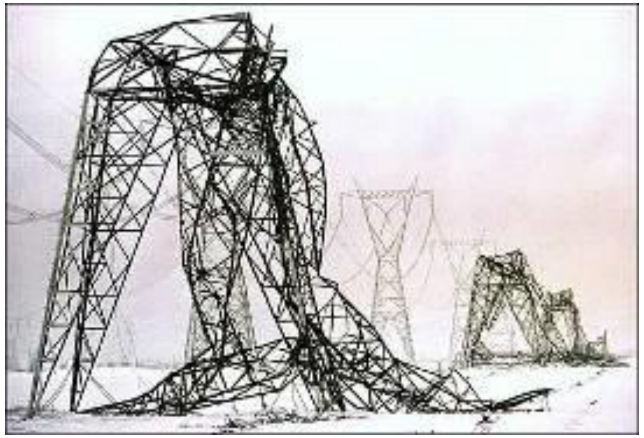
Electric Energy Storage, Batteries

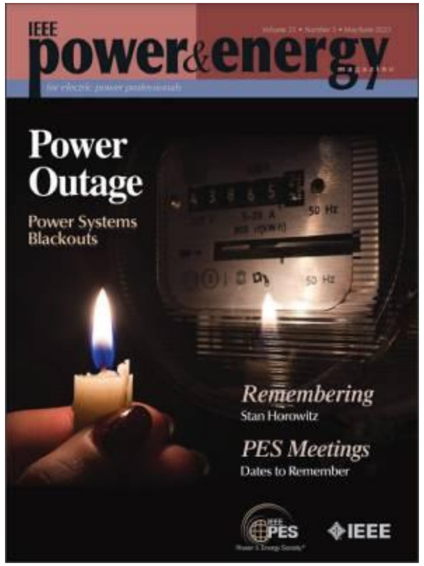
- Driven by the rapid decrease in battery prices, large amounts of batteries are now being deployed for storage; known as BESS (Battery Energy Storage Systems)
  - Lithium-ion batteries are the most common, offering a balance of energy density, power output and lifespan
  - BESS prices are currently about $150/kWh
  - Lifespan might be 5000 cycles
- BESSs can be used for peak shaving, load shifting, flexibility and improved resiliency
- A BESS is often included with new solar installations



Blackouts and Restoration

- Modern society depends on a reliable electric grid.
- Blackouts are costly, with some estimates of costs above $100 billion/year in the US.
- Blackouts can differ substantially in their impact, with most caused by local, lower voltage distribution issues.
- In May/June 2023 Jeff Dagle and I edited a special IEEE Power and Energy Magazine issue on blackouts
  – It is free for IEEE PES members





Upper right image: New York Daily News Archive

Electric Grid Operating States

- The goal of electric grid planning and operations is to prevent blackouts. Still, they do occur, and when they do the focus switches to restoration
- Blackouts come in all different sizes, with the vast majority local issues in the distribution system that can be quickly fixed with resources the utility already has
- There is a much greater challenge for large-scale blackouts, especially with equipment damage

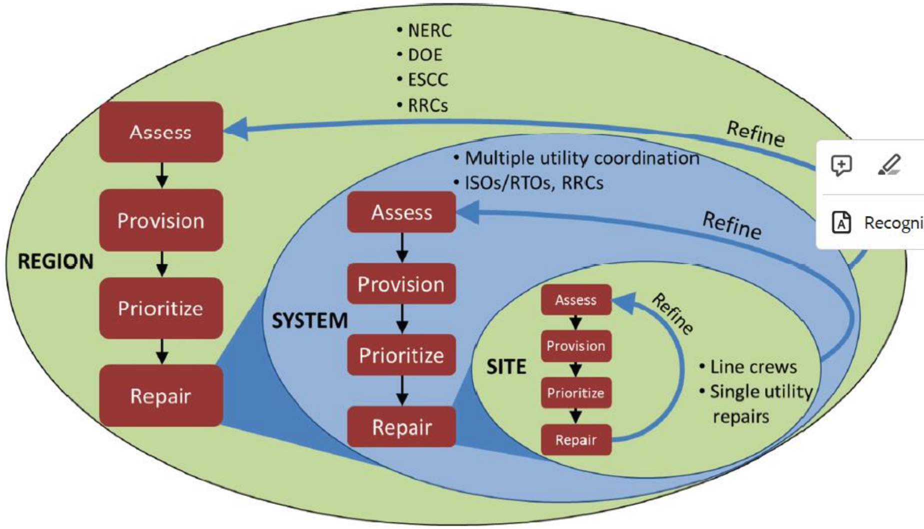


FIGURE 6.1 Illustration of the general processes of restoration that occur on multiple levels by different institutions with responsibility for electricity restoration.
NOTE: NERC, North American Electric Reliability Corporation; DOE, Department of Energy; ESCC, Electricity Subsector Coordinating Council; RRC, Regional reliability coordinator; ISO, Independent system operator; RTO, Regional transmission operator.

Image source: US National Academies 2017, Enhancing Resilience of US Electric Grid Report

The Real Cause of Most Blackouts!

Photo source: http://save-the-squirrels.com

Most outages occur in the distribution system, and many of those are caused by animals

And Sometimes It's the Trees

Standard Indices for Small Events (IEEE Std 1366-2022)

- System Average Interruption Duration Index (SAIDI) represents the average amount of time the supply to a customer is interrupted per year (expressed in minutes per year)
- System Average Interruption Frequency Index (SAIFI) represents the average number of times per year the supply to a customer is interrupted per year (expressed in interruptions per year)
  - Both are averages for a system, so some people have higher values, some lower

IEEE Std 1366-2022 Major Event Days (MED)

- A MED is a day in which the SAIDI exceeds a threshold; all indices are calculated with the MEDs removed
  - Typically one per year (give or take)
  - Purpose of removal is to allow indices to give good indication of normal operational and design stress
  - MEDs are analyzed separately
  - Just looking at standard indices doesn’t indicate what is really going on.

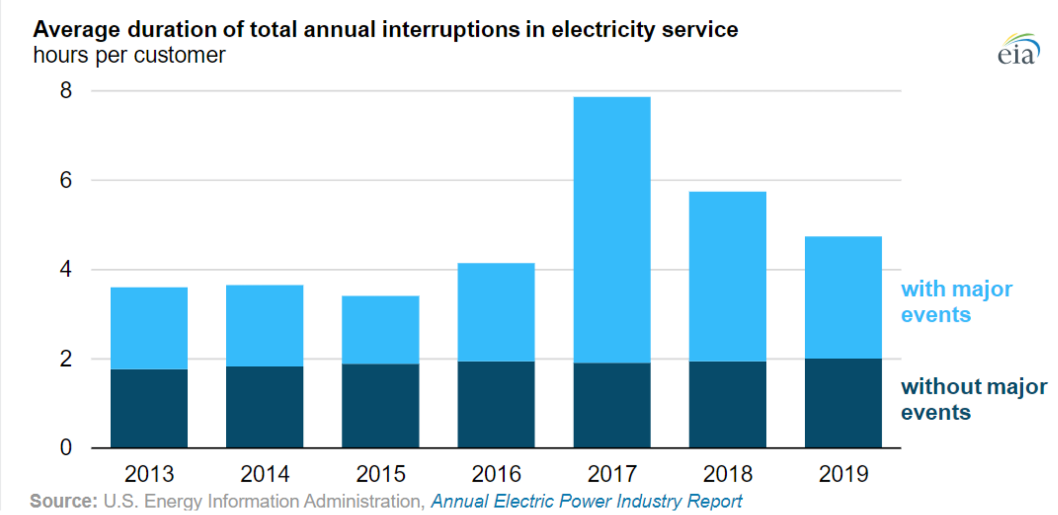
Comparison of International Reliability Indices

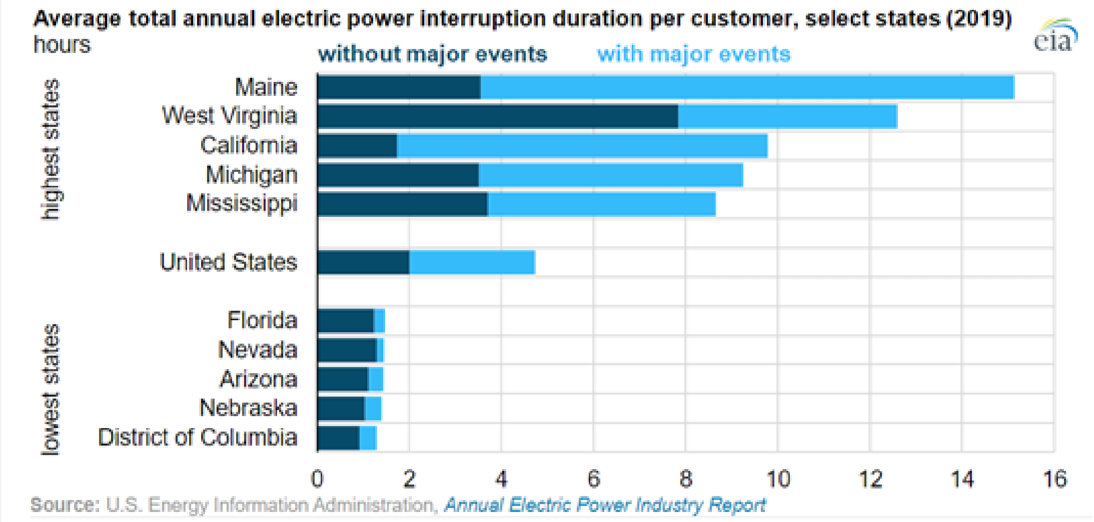
Country	SAIDI	SAIFI
United States	240	1.5
Austria	72	0.9
Denmark	24	0.5
France	62	1.0
Germany	23	0.5
Italy	58	2.2
Netherlands	33	0.3
Spain	104	2.2
United Kingdom	90	0.8

Source: Galvin Electricity Initiative, *Electric Reliability: Problems, Progress and Policy Solutions*. See http://www.galvinpower.org/sites/default/files/Electricity_Reliability_031611.pdf.

Source: Table 2 of http://www.fas.org/sgp/crs/misc/R42696.pdf

SAIDIs Without and With Major Events





Source: US EIA; a good IEEE report with more recent data is cmte.ieee.org/pes-drwg/wp-content/uploads/sites/61/2022-Benchmarking-Survey.pdf

A Good Source for US Power Outage Information

- https://poweroutage.us/