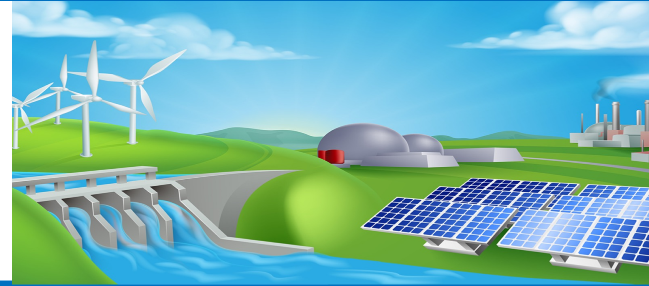


ECONOMICS OF MODERN POWER SYSTEMS

M4 – Challenges of DG integration / Solar Outlook

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Learning Goals

- Key Issues with DG Integration to Power Systems
- DG Optimization
- Solar Industry Outlook
- Duck curve and possible solutions

Key Issues with DG Integration to Power Systems

Challenges on DG Integration

- From distribution grid operation perspective

Operation and control
- Frequency and voltage regulation

Protection system requirements

Change on short-circuit capacity

Power Quality and stability

Challenges on DG Integration

- From distribution grid operation perspective

Operation and control • Frequency and voltage regulation	Protection system requirements
Change on short-circuit capacity	Power Quality and stability

Let's start with background…

Generation   Transmission   Distribution   Load   ⇒   Fundamental structure

Generators   Substations   Transmission circuits   Transformers
Circuit breakers   Metering   Load   ⇒   Physical devices

Voltage   Current   Power
Energy   Frequency   Impedance   ⇒   Fundamental variables

Operation & Control = coordinate devices such that fundamental variables remain within limits

Operation and Control

- DG output varies according to
  - local load variation
  - control modes if DG operation follow price signal
  - availability of natural resources like solar or wind (if RES)
- Challenges to traditional voltage, frequency and power control
  - Increase variations between max and min voltage level

Minimum voltage level remain the same → High load **without DG**

Maximum voltage level will increase → Low load **with DG** at maximum capacity

Operation of Power Systems: Voltage and Frequency Control

- Operational requirement
  - Follow the change in load demands
  - Supply electricity at minimum cost & environmental impact
- Power quality
  - Frequency
  - Voltage
  - Level of reliability
- Why constant frequency?
  - Frequency fluctuations are harmful to electrical appliances (speed of ac motors are proportional to the frequency)
  - Blades of steam and water turbines are designed to operate at a particular speed

Operation of Power Systems: Voltage and Frequency Control

- Why constant voltage?
  - Electric motors will run on over speed when fed with higher voltages (mechanical damage)
  - Over voltage may cause insulation failure
  - Lower voltage results in more current and therefore heating problems

Power = Voltage x Current

Frequency Control

- Load and generation balance
- Frequency is an indication
  - Balanced system 50/60 Hz

Net Power surplus ↑ **Frequency**

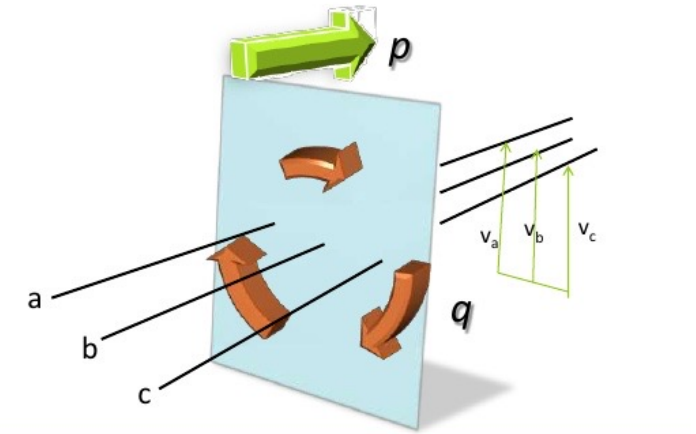
Net Power shortage ↓ **Frequency**

$$\Delta P \longrightarrow \Delta f$$

- Control reserves or load shedding

Voltage Control

- Control of voltage levels is carried out by monitoring production, absorption and flow of reactive power



p: instantaneous total energy flow per time unit
q: energy exchanged between phases without transferring energy

- Sources of voltage control
  - Synchronous generators can generate or absorb depending on excitation (regulator adjust excitation)
  - Sources or sinks of reactive power (capacitors or reactors)
  - Regulating transformer (tap changing)

Challenges on DG Integration

- From distribution grid operation perspective

Operation and control

- Frequency and voltage regulation

Protection system requirements

Change on short-circuit capacity

Power Quality and stability

Protection System Requirements

- DG will impact the protection scheme of the grid
- If protection system of DG is able to **detect a fault and rapidly disconnect** from the network, DG will not interfere with normal operation of protection system
- Nowadays distribution networks are automated and equipped with SCADA

  Supervisory Control And Data Acquisition

  - Provides access to a variety of local control modules
  - Elements: supervisory computers, remote terminal units, programmable controllers, communication infrastructure and human interface

Protection System Requirements

- If a circuit breaker opens could result in islanding of a DG unit
  - If DG is able to match active and reactive power of the load in the islanded system, system will continue operation
  - If not, large frequency or voltage variation will occur when DG tries to supply load
- Therefore most interconnection rules require a loss of main detection system that automatically disconnects de DG until grid is restored

Challenges on DG Integration

- From distribution grid operation perspective

Operation and control • Frequency and voltage regulation	Protection system requirements
Change on short-circuit capacity	Power Quality and stability

Change of Short Circuit Capacity

- New DGs increase the level of short circuit capacity (SCC)
- Increased SCC may be a problem
  - At the connection of the inverter of a HVDC line
  - Or in the presence of large loads with rapid varying demand

Challenges on DG Integration

- From distribution grid operation perspective

Operation and control • Frequency and voltage regulation	Protection system requirements
Change on short-circuit capacity	Power Quality and stability

Power Quality and Stability

- Usually DGs improve power quality
- But that are other issues
  - A large DG on a weak network may lead to power quality problems during starting and stopping
- Researchers are investigating the impact of high penetrations of wind and solar power on
  - Frequency response
    - Nonsynchronous or inverter-based generation do not participate in the regulation of grid frequency
  - Transient stability of electric power systems.
    - Transient is a momentary change in voltage or current that occur over a short period of time
    - Inverter-based generation have the potential to alter system stability as a result of changes in angle/speed swing behavior due to reduced inertia
    - Different power flow patterns

DG Optimization

Planning and Operation

DG Environment Optimization

- Key Issues regarding DG optimization
  - Optimal Location
  - Modeling Issues
  - DG Planning and Operation

Optimization Models Framework

- DG operation and planning objective
  - Minimize electricity production cost ensuring that load is served with reliability

- DG siting and sizing objective
  - Improve voltage profile
  - Reduce system losses

- Constraints
  - Supply = demand
  - Power balance at each node
  - Line and generation capacity

Optimal Location Challenges

- Several methods for finding best location of DGs (utility scale)
- Methods work well for current condition of the system
- But with network expansion, load concentration, regulatory changes, optimal location may not be optimal after years
- More specifically with growing penetration level of DGs, optimal locations keep changing

Modeling Issues

- As penetration level increases it will no longer be appropriate to model static load by the amount of active and reactive power being consumed

- Dynamic models for
  - fuel cell systems
  - micro turbines
  - induction machines and
  - generic loads

Optimization Models Framework

- Energy, environmental and economic analysis
  - Geographical Information Systems (GIS)
    - Store, organize and visualize spatial data
    - Perform spatial calculation
  - Accounting, simulation and optimization
    - Design DG system
  - Environmental and economic impact
    - Pollutant dispersion
    - External costs
    - Performing life cycle assessment (LCA)

Optimization Models Framework

- Energy Management System
  - Optimize operation of generation technologies under time varying operating conditions while satisfying technical and environmental constraints
  - Forecasting techniques are important
    - High levels of DG and RES
    - DG must be sized and dispatched starting from forecasted data
      - Loads
      - RES availability
      - Cost of fuels

Power Flow Analysis

- Considering power flow equation inside the optimization model poses additional challenges to finding the best solution
- OPF model itself challenges
  - Size of the problem
  - Problem is non-linear
  - Problem is non-convex
  - Some variables are discrete
- OPF solutions is usually obtained by
  - Iterative process
  - By linearizing the equations (approximation)

State-of-the-Art Techniques

- Metaheuristic algorithms have been used to solve the problem of optimal allocation of DG
  - Ant Colony Optimization (ACO)
  - Artificial Bee Colony optimization (ABC)
  - Tabu Search (TS)
  - Particle Swarm Optimization (PSO)
  - Simulated Annealing (SA)
  - Genetic Algorithms (GA)
- Multi-objective Programming
- Probabilistic Analysis

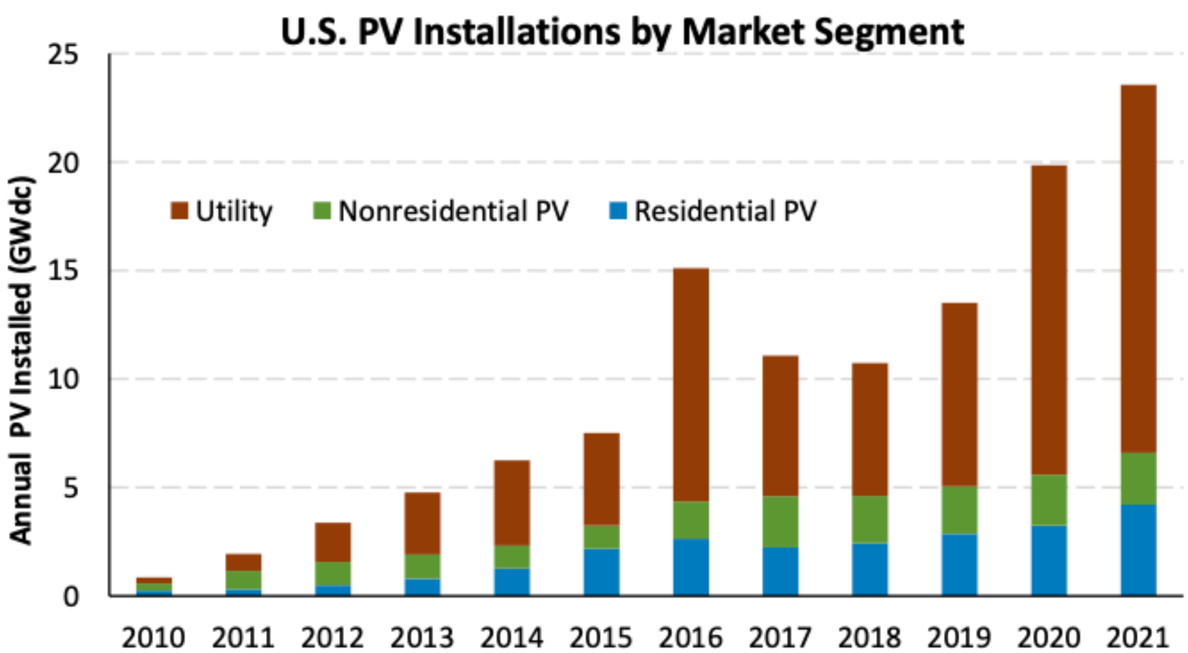
Summary of Techniques and Objectives

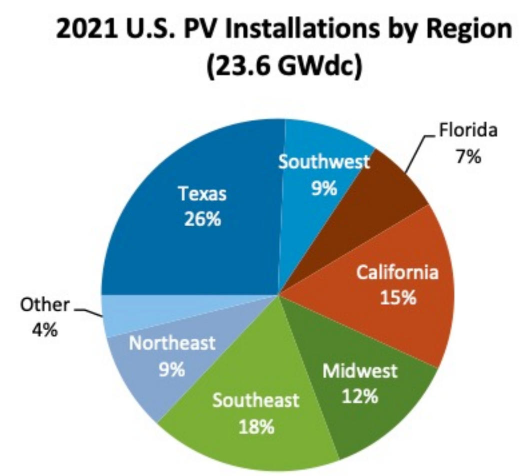
Techniques	Objectives
Analytical Analysis (one scenario)	Power losses
Exhaustive (explore most of the search space)	Multiple objectives (voltage rise and power losses)
Linear Programming (linearized power flow)	Minimize curtailment cost Maximize DG capacity
AC Optimal Power Flow	Power losses Maximize DG capacity
Metaheuristics (iterative process but uses intelligence to exploit search space)	Maximize DG Capacity Investment Planning
Probabilistic analysis	Improved reliability

Solar Industry Outlook

US Installation Outlook

- US installed 23.6 GW-DC of PV in 2021
  - Cumulative capacity reached 119.7 GW

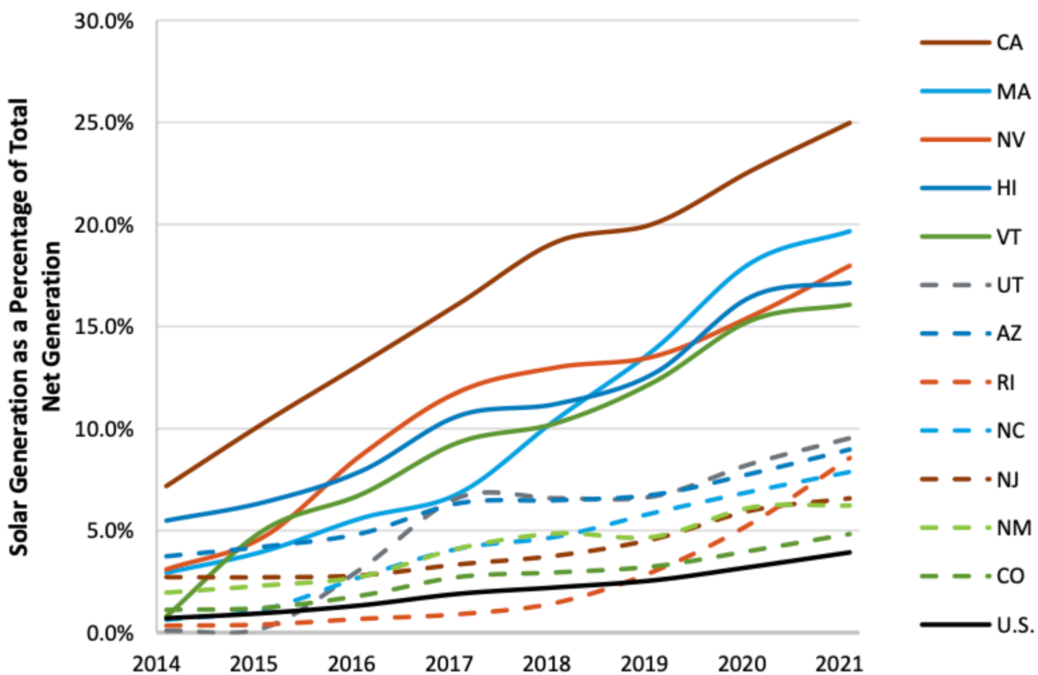




Source: NREL – Solar Industry Update , 2022

Solar Generation as % of Total Generation

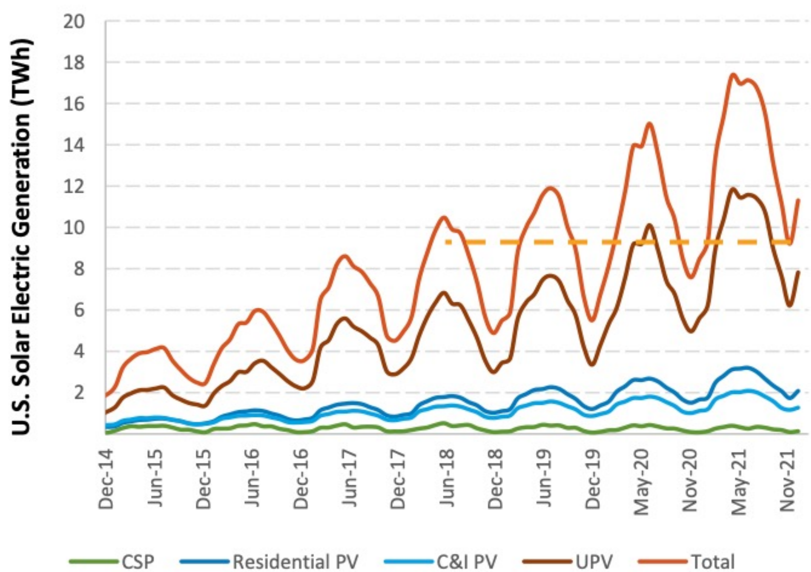
- 11 states with highest percentage generated at least 5% of their energy from solar in 2021,
  - California lead the way at 25%



Source: NREL – Solar Industry Update, 2022

Monthly US Solar Generation

- Total peak monthly U.S. solar generation increased by a factor of 5.7 from 2014 to 2021
- Utility-scale solar has generally dropped by approximately 53% from summer to winter
  - distributed PV systems dropped 47%



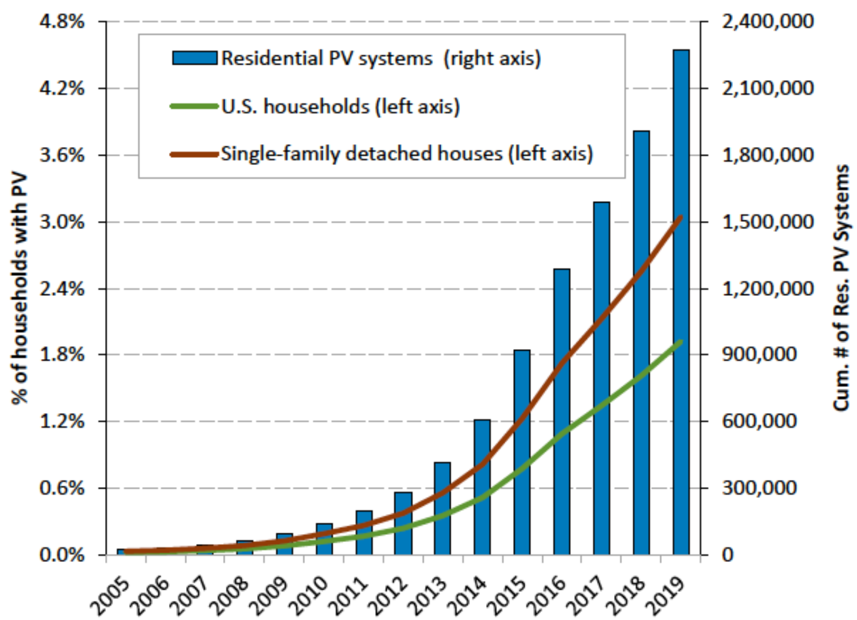
DPV = Distributed PV Installed Capacity (MW-AC)

UPV = Utility PV Installed Capacity (MW-AC)

Source: NREL – Solar Industry Update, 2022

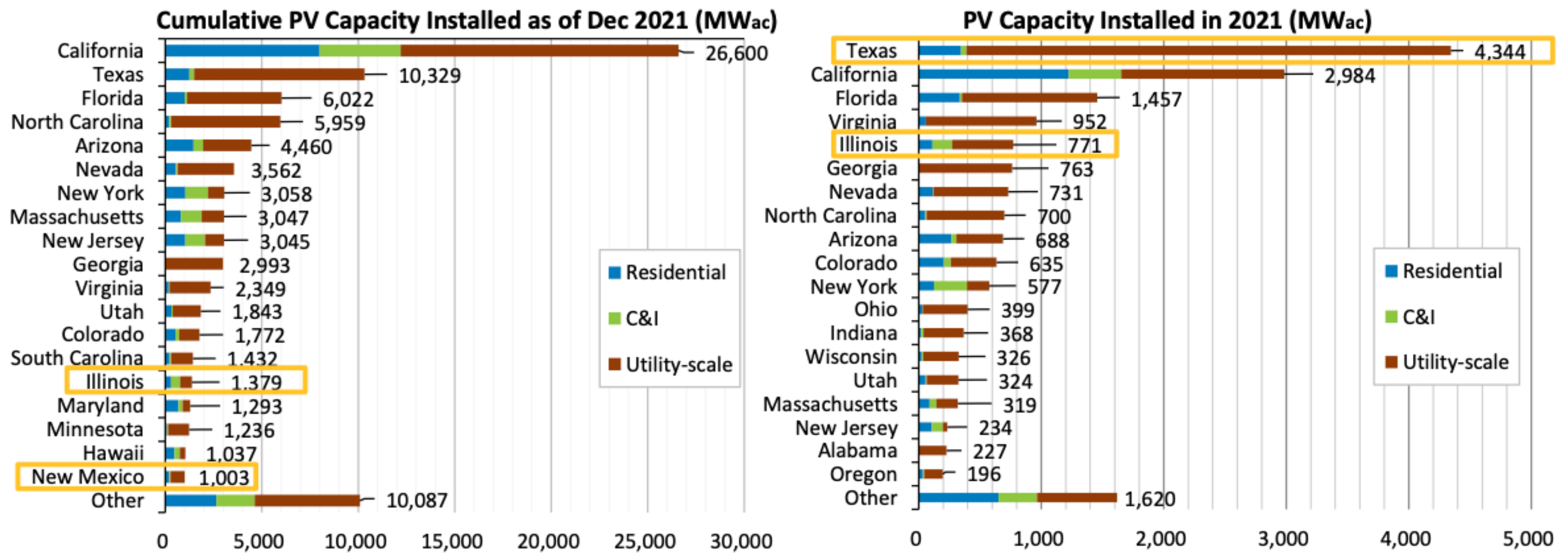
US Residential PV Penetration

- Since 2005 increase of 40% per year (100X)
- Still only 1.9% of households own a PV system
- Solar penetration varies by location: Hawaii (34%), California (15%) and Arizona (12%)



Source: NREL – Solar Industry Update, 2022

Installation Breakdown by State

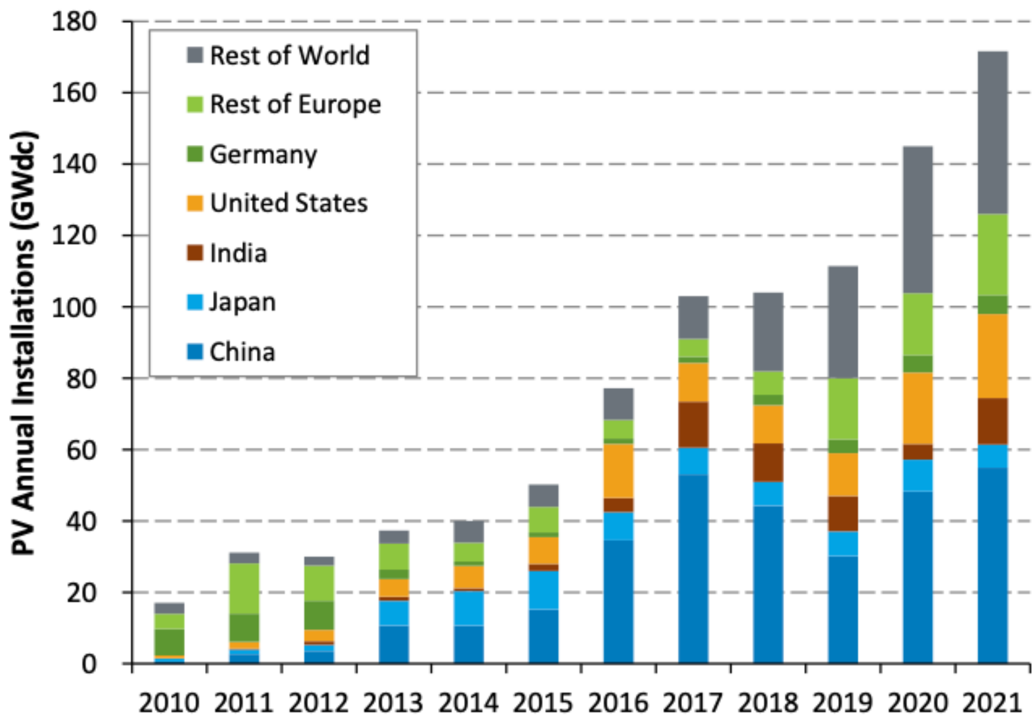


- 92.5 GW-AC of solar systems
  - 59.5 GW utility-scale PV, 21.0 GW residential PV, and 11.9 C&I PV

Source: NREL – Solar Industry Update, 2022

Top PV Markets

- Global PV installations reached 939 GW-DC
- Leading 5 markets: China, US, Japan, India & Germany

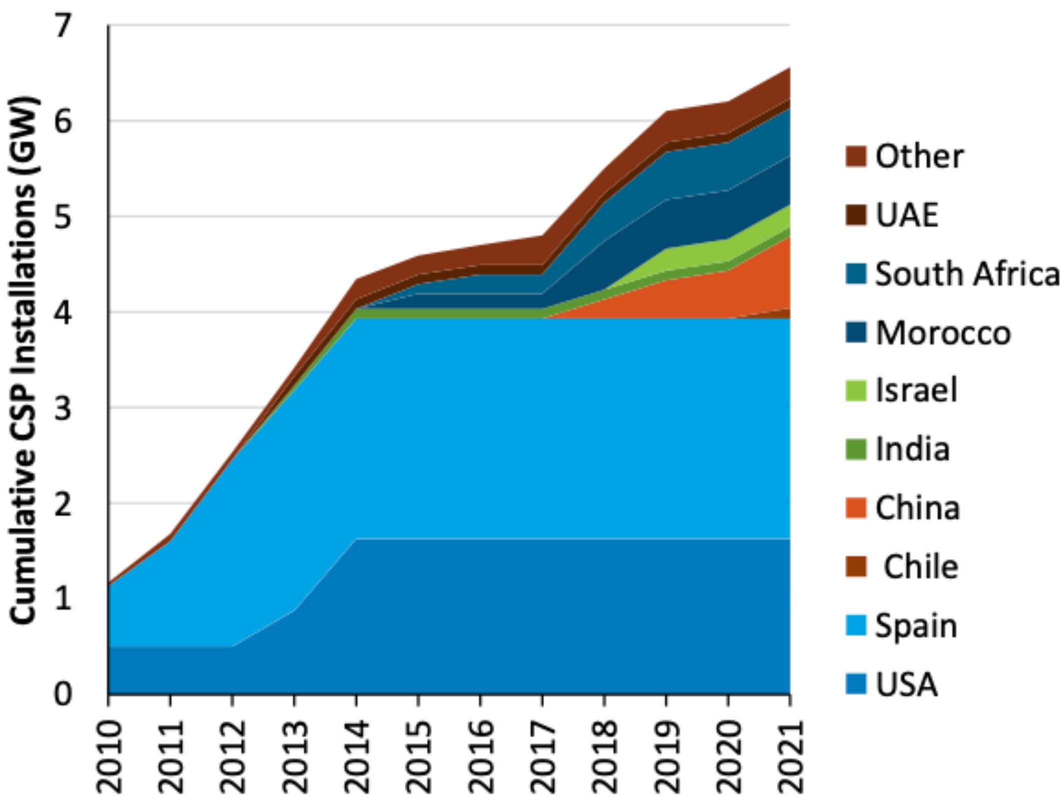


Annual increase of 172 GW-DC from 2020

Source: NREL – Solar Industry Update, 2022

Global CSP Installed

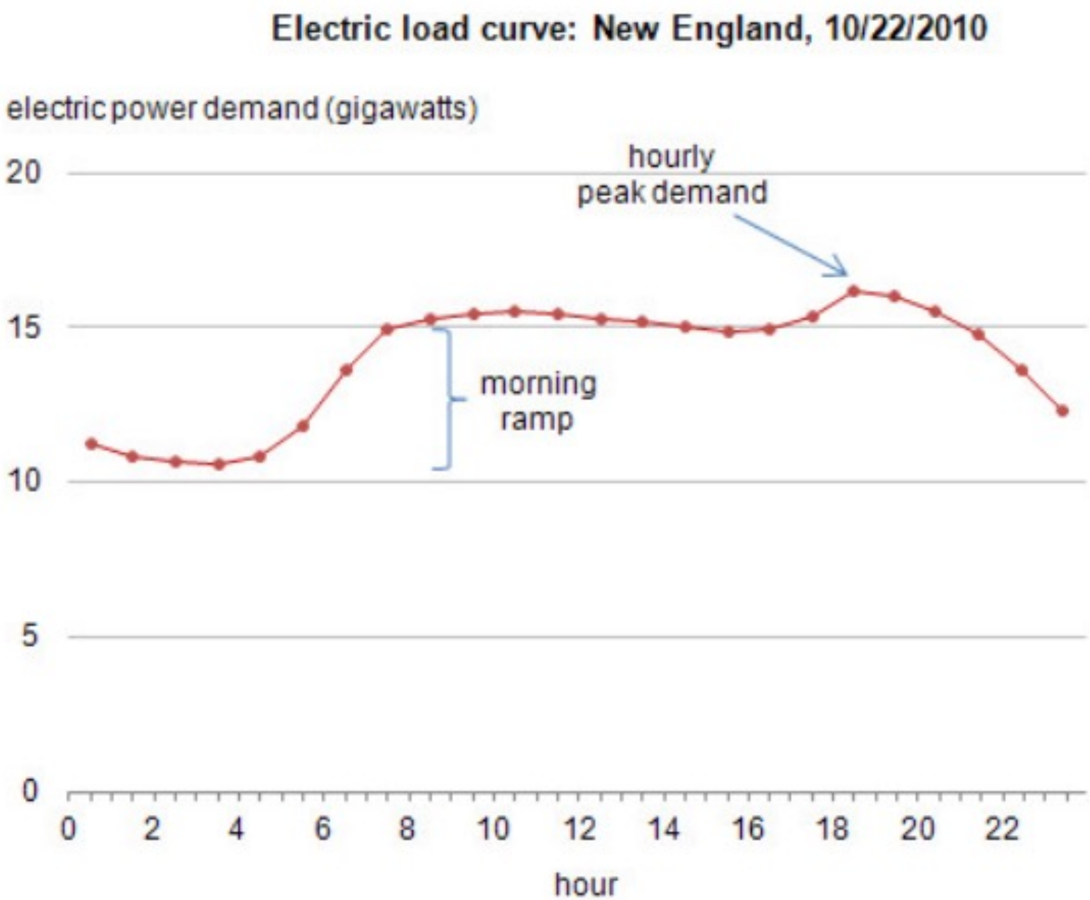
- Global CSP installations is almost at 7 GW
- Majority of CSP located on Spain and US



Source: NREL – Solar Industry Update, 2022

The Duck curve

Typical Load Curve

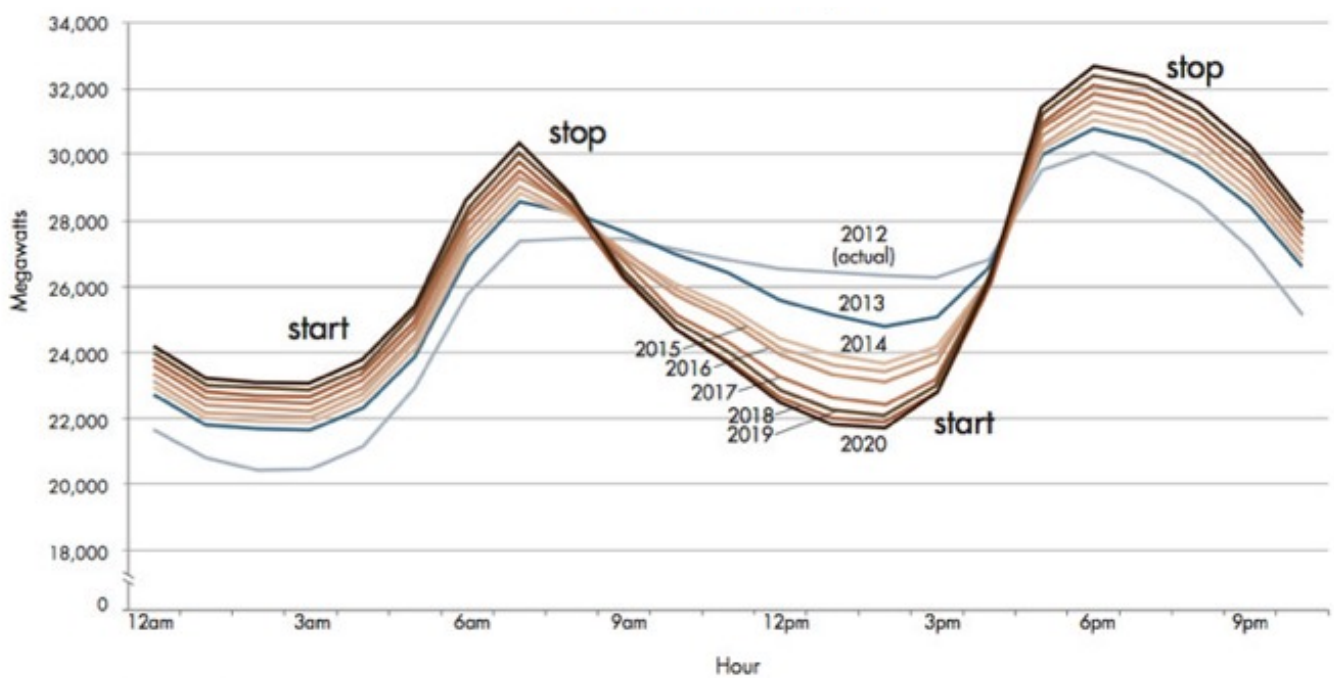


- Example from New England in the Fall
- Demand spikes in the morning and again in the evening before declining at night

Source: EIA

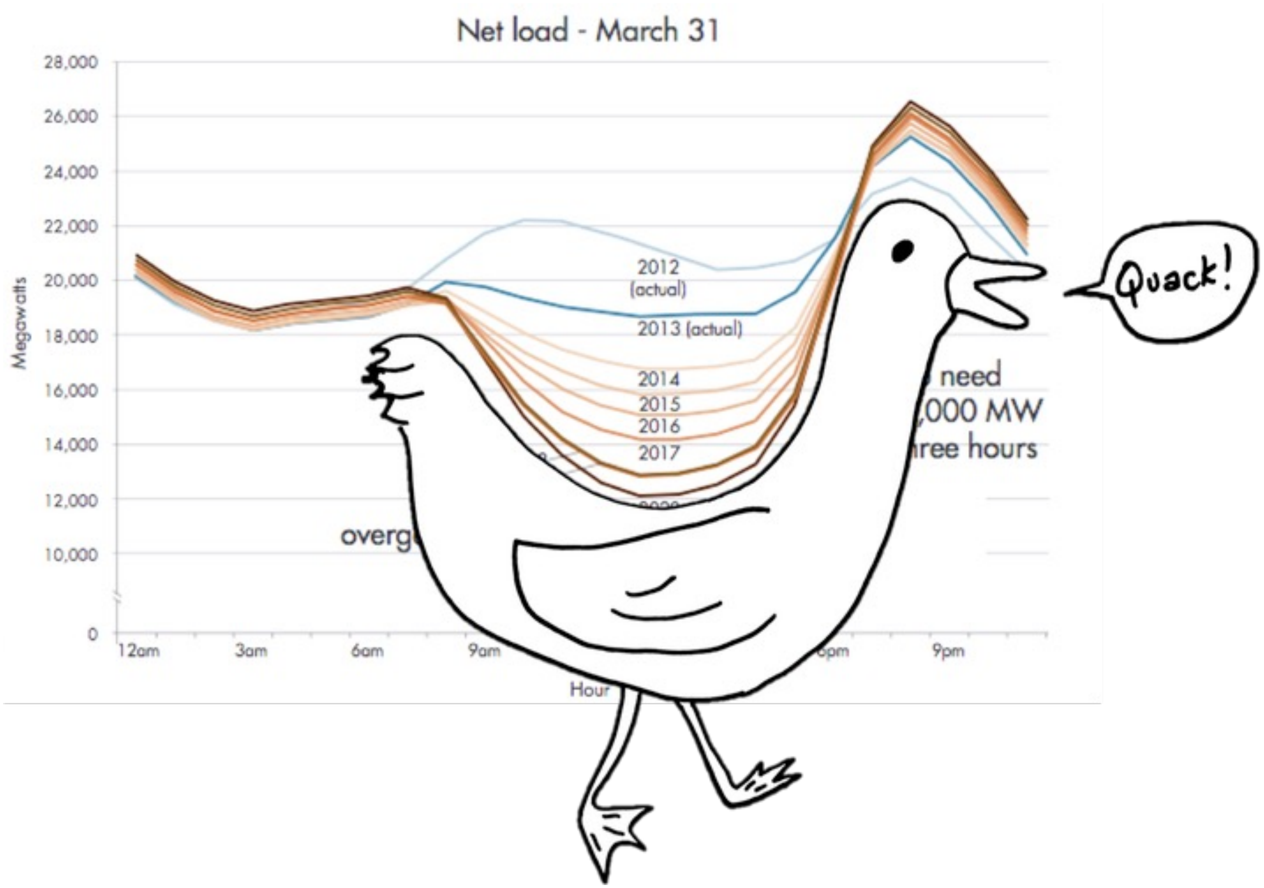
Then PV's come along

- Timing imbalance between peak demand and solar energy production
- PVs suppress net load during midday
- The duck is growing– ramp is getting more steep



Can’t see the duck??

Can’t see the duck??



Duck Curve Facts

- It was discovered around 10 years ago (first generated by modelers in Feb 2008)
- CAISO was the one to name it "duck curve"
- It is a serious threat to solar and clean energy community
- Utilities could be forced to
  1. Ramp up dispatchable plants for a morning peak,
  2. Scale back or shut down all those plants when sun is out
  3. Bring them all back online quickly when sun goes down
- All that ramping and stop-starting is expensive and unfamiliar

Solutions to Duck curve – flattening the duck

1. **Maximizing the inherent flexibility of the fossil thermal fleet**

- Ramp existing plants better technically and economically
  - Coal and NG
  - Nuclear can but there are concerns (debates about how flexible nuclear plants can be load following- safety issues, thermal stresses, age)
- Need dispatchable power plants that can ramp up and down relatively quickly.
  - Resemble today's medium and peak load (such as gas turbines)

Solutions to Duck curve – flattening the duck

2. **Covering a wider geographic area with renewables and energy markets**

- Spatial diversity - 3 to 4 hours of solar spatial diversity across the entire country, east to west
- Implementing markets!

3. **Demand Shifting**

- Move demand over underneath the belly to soak up some of that sun power
- Empower people to use electricity more efficiently

Solutions to Duck curve – flattening the duck

4. **Electric Vehicles (EVs)**

- Dispersed fleet of batteries could help soak up renewable energy during times of excess
- Need to send the right price signals
  - Get home: 5 to 6 pm worst time to charge, ideally hold off until midnight
  - Get to work: 8-9 am not quite solar yet, so hold off until 11 am
- They can help a lot!

5. **Energy Storage**

- Biggest hammer in the toolbox
- More on that later…

Renewable Curtailment

California Experience

- Wind and solar plants are being intentionally shut down
- These renewable resources produce a lot of electricity in the middle of the day (solar) and at night (wind)
  - But late afternoon or early evening is demand peaks
- Additional investment in renewable energy should expect lower returns from facilities that may not run at full capacity
- In 2017 renewable curtailment occurred in about 38 percent of hours

Combatting curtailment with a regional energy grid

- Change energy consumption patterns
- Store energy
- Improve forecasting of usage patterns
- Allow for more flexible operation of power plants are all necessary
- **Linking with other regional energy markets could give California an opportunity to export excess clean energy to neighbors**
  - California is already doing some energy trading on a small scale with its Energy Imbalance Market (EIM)

Main Conclusions on DG (M3 – M4)

Regarding Electricity Generation

- Many national differences in
  - Generation mix due to economic/geographical properties
  - Distribution system structure
  - Energy policy
- Global trends
  - More distributed generation
  - More renewable generation
  - Increased electricity demand
  - Objectives related to sustainability

Source: GSGF Global Smart Grid Federation

Regarding DGs

- Challenges
  - Power quality
  - Voltage and frequency management
  - Increased loads and lack of grid capacity
- Measures being taken
  - Public funding of R&D pilots
  - Grid reinforcement
  - Active demand / distributed storage
- Regulatory measures
  - Feed-in tariffs, tax benefits, subsidies

Source: GSGF Global Smart Grid Federation

Economic Findings Regarding DGs

- DG stimulates economic progress
- DG affects government spending and revenues
- DG positively impacts reliability of power systems
  - But new to be equipped with control systems
- DG lower international dependency, thus increase security of supply

Source: GSGF Global Smart Grid Federation


THANK YOU !

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