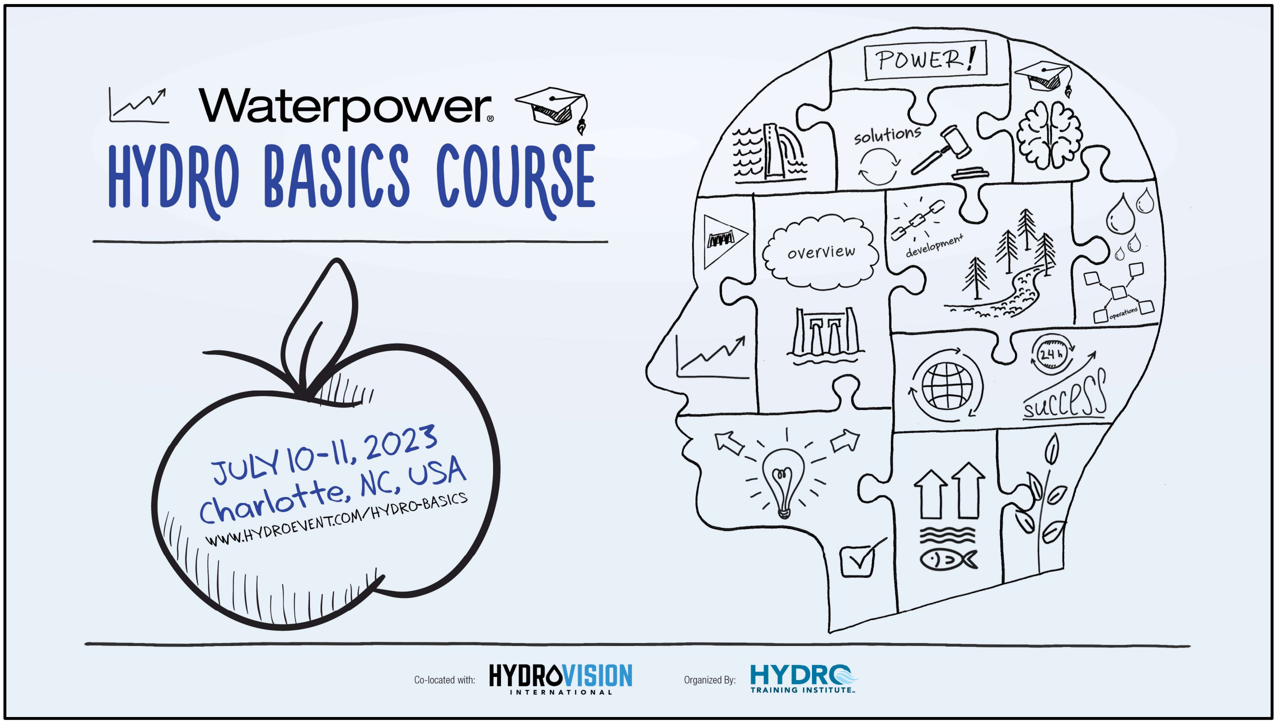
Waterpower
HYDRO BASICS COURSE
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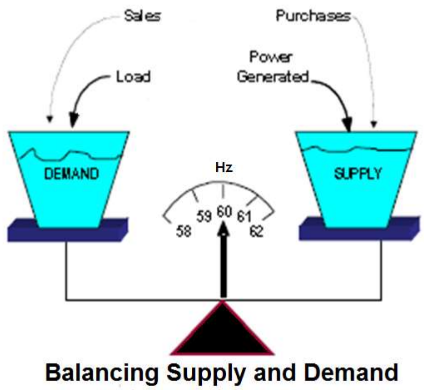
Session 5: Hydro in a Power System

Instructor
Steve Wenke
Senior Manager - Mana Consulting
Recently Retired as Chief Engineer for Avista

Session 5: Hydro in a Power System - Overview

- Power System Operation Basics
- Power System Controls
- Dispatch of Generating Sources
- Effects of Renewables on Power System Operations
- Capabilities of Generation Sources
- System Operations Planning
- River Operations
- Unique Capabilities of Hydro
- Impacts of Alternative Generation Sources

Balancing Power Systems
Frequency controlled by Real Power



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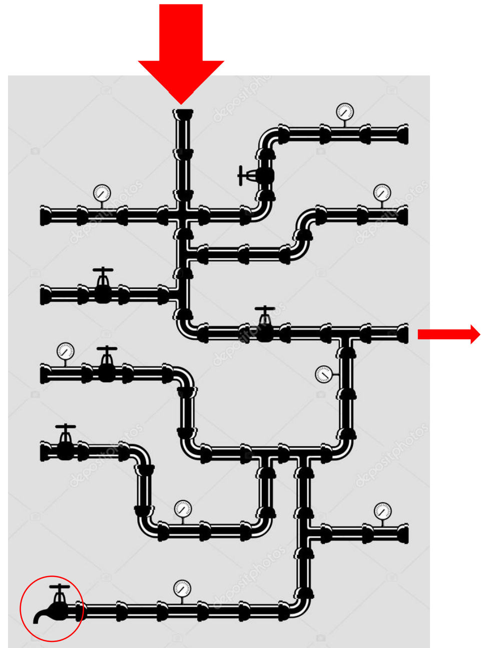
•System frequency is continually changing, it is only 60Hz momentarily
•Governor dead band is typically set so governors are inactive within ± 0.036Hz of 60Hz to prevent excessive operation or “hunting”
•Continual starting and stopping of loads, and to a lesser extent, of generation on and off the system results in varying frequency (speed)

Reactive Power

An analogous example can be a water system. With all the valves closed, it requires a certain amount of pressure to deliver a flow at the outlet of the system.

If you open a valve, the pressure will decrease in the system and you need to increase the source pressure to continue to deliver the pressure at the outlet.



A simple analogy for electricity and power system flow is water system flow. This is analogy is intended to provide the concept of reactive power. Voltage is the "pressure" that the system requires to deliver the Current the "flow" in an electrical sense.

If you have no valves open, you can easily control the flow that comes out the bottom. When another valve is opened, it effects how much flow comes out the bottom. You need to increase the pressure going in the system in order to keep the flow constant at the bottom.

This pressure increase in analogous to reactive power. Pressure needs to be adjusted constantly in order to keep the flow and pressure delivered at the end.

Power System Operation Basics

- Electrical energy cannot be stored
  - The original "just in time" process!
- Real and Reactive power loads are always changing
  - But there are patterns for similar types of loads
- Generation must be equal to load for stable operation
  - Continuous adjustments are required for balance
    - Manual, by operators
    - Automatic, by control systems like AGC
- **What happens if you don't always match source to loads?**

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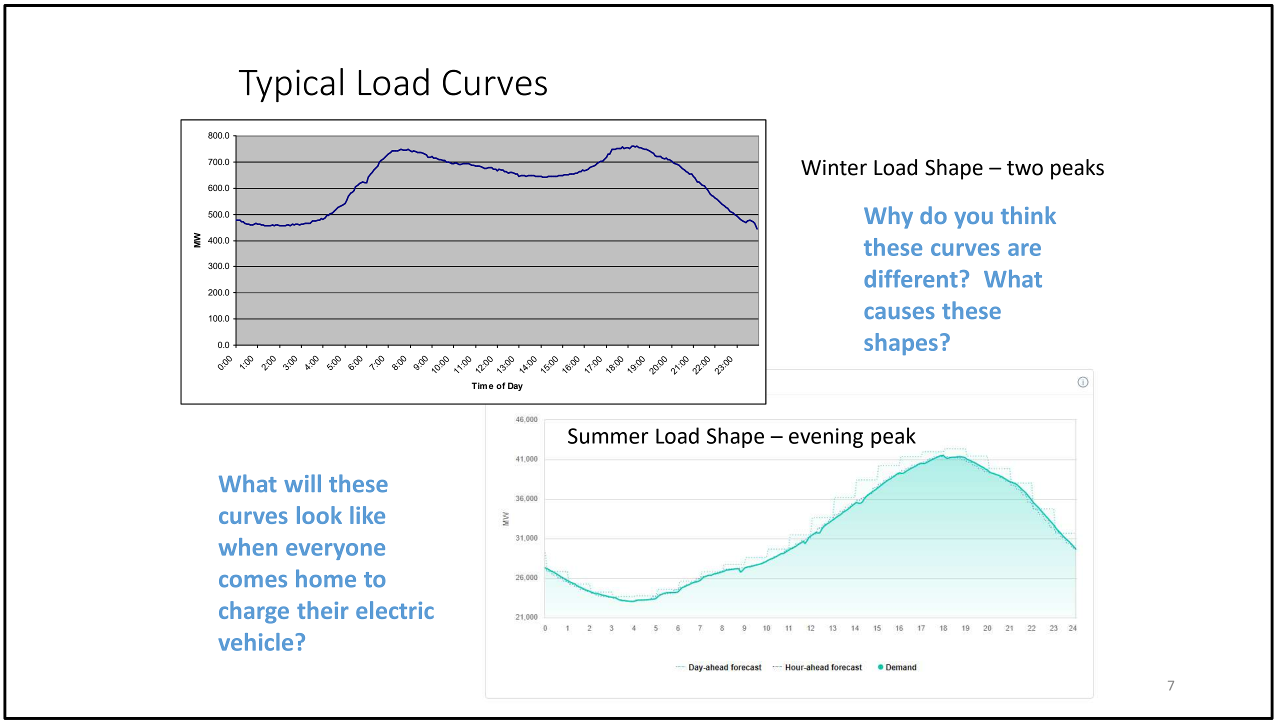
•Electrical energy cannot be stored in any meaningful amount using current practical technology
•Pumped storage plants allow electrical energy to be converted to another form (potential) for later conversion back to electrical
•Power generated must equal the power used plus losses to keep system frequency constant
•General trends for real and reactive power loads can be forecast based on historical data and forecast information.
•System loads can vary with time of day (lighting, working hours at businesses, etc.), day of week (factory closed on weekends), or month of year (ambient temperatures, weather, etc.)
  •Often one or two peaks a day
  •Peak can be two or three times minimum
  •Rate of change can be tens or hundreds of MW/minute on large systems
•The utility needs to be prepared for unanticipated load changes and have a plan to meet them.
•Should also plan maintenance outages around system peaks (and fuel/water availability) to minimize system operating costs
•If there are excursions because of inability to match loads, over or underfrequency events occur and burn up equipment, power supplies, etc. (over frequency – high voltage; underfrequency – high current)



•MW load on system versus hour of the day

•Winter Shape

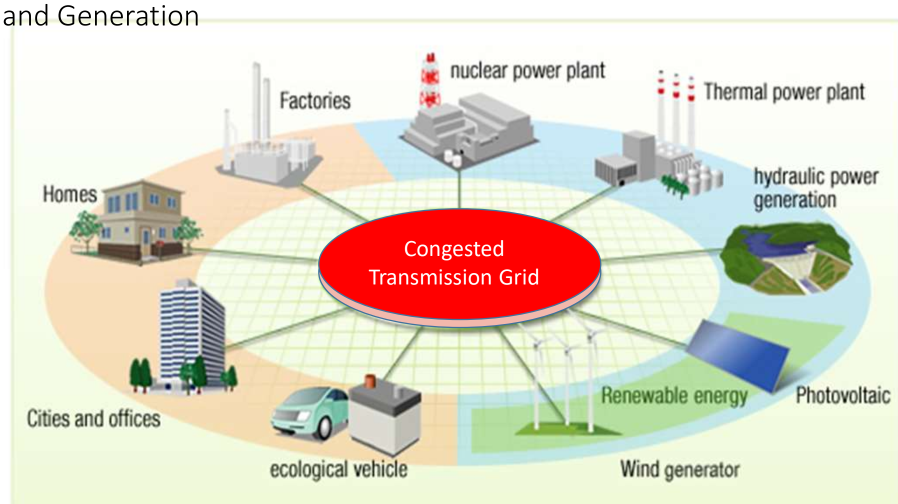
- •Two daily peaks
- •Difference between minimum to maximum: ~ 1.7
    - •Probably a moderate climate
- •Ramp rates approaching 20MW/min in this example, sudden weather changes can result in faster ramp rates (to 100MW/minute and higher)

•Summer Shape

- •Typically, would peak in the evenings as people come home, start cooking and turn up AC
- •If you are in an area with heavy irrigation pump load, this would be higher during daytime hours for peak

Power System Basics

Loads and Generation



Power moves from generator to load across the transmission grid

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Ideally, we want the least expensive resource serving the load. If a thermal plant is cheaper than a nuclear plant, you would want to use the thermal plant. Grid problems sometimes make that impossible.

The transmission path for the thermal plant output to reach the load may limit the ability of the thermal plant to deliver the power. If that happens then part, or all, of the energy to serve the load needs to come from other sources.

Dispatch is discussed later but these transmission constraints can cause more expensive resources to run so energy can reach the loads.

Transmission Congestion

- What might cause a transmission system to be congested?
- What happens if Transmission Constraints don't allow enough power to flow to loads?
- How do you know if the system becomes congested?

There are multiple causes for transmission congestion. They can include transmission lines that are out for maintenance, storm or other weather damage, high heat that limits the amount of current a conductor can carry (line sag); inadequate planning; a line gets overloaded for some reason.

If power flow cannot be met, it can lead to "brown outs" (i.e. low voltage but still energized) or "black outs" or "rolling black outs"

Transmission Operators are responsible for managing the transmission system and identifying if there are constraints. The have the authority to adjust generation as they see the need in order to not "crash" the transmission grid.

Power System Control

2 Basic Control Parameters

Frequency

Agreed upon value (60Hz in NA, 50Hz in EU)

Frequency Response at unit (governor action)

AGC Response (f_{error} term in ACE Equation)

Voltage

Set by Transmission Operator

Voltage Schedule

Reactive Power Schedule

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Bad things can happen if V or F drift too far from scheduled values.
Governors and AGC control Frequency. Automatic Voltage Regulators help with voltage control. Out on Grid there are Capacitor and Reactor Banks for V control.

- Electrical energy cannot be stored in any meaningful amount using current practical technology
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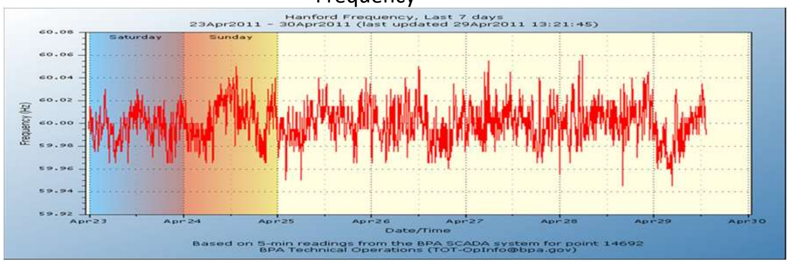
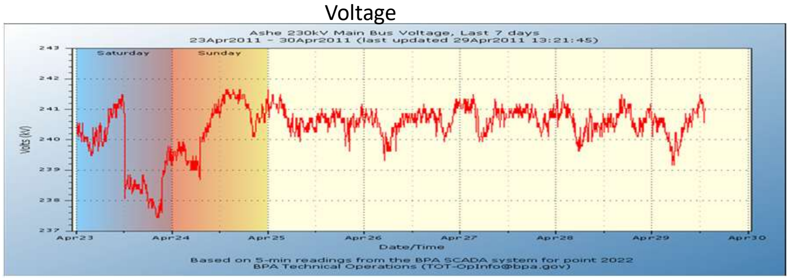
Power System Control

Frequency

[FNET/GridEye Server Map Gradient Display (utk.edu)]



Voltage



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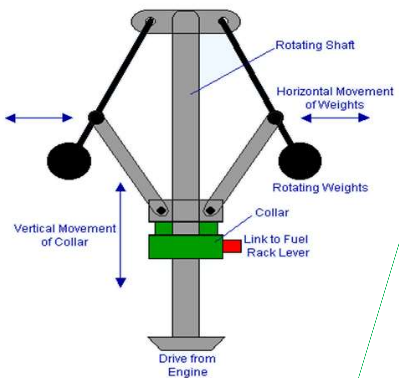
- Frequency and Voltage change constantly
- Automatic Systems are needed to balance the system in real time.
- Real and Reactive Power are needed for this balance

Balancing Power Systems
Real Power Balance

Unit Control



Governor Control

BA Level Control
(Balancing Authority)

Automatic Generation Control

Area Control Error (ACE)

ACE is a function of:

Interchange Error
and
BA share of Frequency Error

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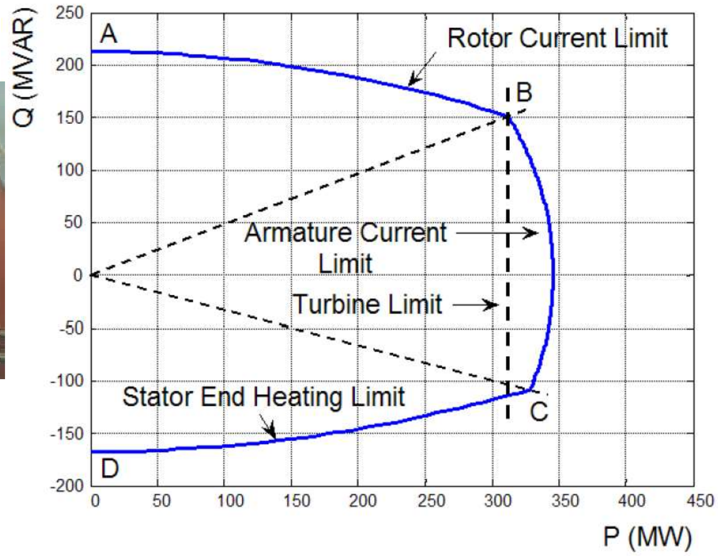
•Governor dead band is typically set so governors are inactive within ± 0.036Hz of 60Hz to prevent excessive operation or “hunting”
•Continual starting and stopping of loads, and to a lesser extent, of generation on and off the system results in varying frequency (speed)
•Error is Actual minus Schedule
•Area Control Error (ACE) is a calculation done by computers using telemetry from interchange points that measure all the power coming into a system against the power being produced by a system. The difference is the error. The computer than produces a signal that goes out to generators to adjust their output up or down to match the error and return everything to “zero”. This signal is call the Area Generation Control (AGC). This read and adjust cycle is generally done every four seconds.
•(the reality of this that things still change within the four second cycle time so the system never really sits at zero)

Balancing Power Systems
Voltage Controlled by Reactive Power



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Real and Reactive Power capability. This shows how much a reactive energy can be provided by a generator. What is important is that the reactive power (Q) is dynamic and is capable of adjusting automatically depending on what the system demands.
X axis is Real Power in MW
Y Axis is Reactive Power in MVAR (Volt Amps Reactive)
Resultant is Apparent Power in MVA (Volt Amps)

Balancing Power Systems

Reactive Power Balance - Some Transmission Reactive

There are transmission elements that can help control voltage. This is not a metered thing, so it does have allowed fluctuations.
Far Left: A synchronous condenser (this is a cutaway, the actual device is fully covered and not exposed like this.)
Center: A reactor bank
Upper Right: A capacitor Bank
Lower Right: A Static Var Compensator. This is a combination of smaller switched capacitor and reactor banks.

Interconnected System Operation

Benefits include

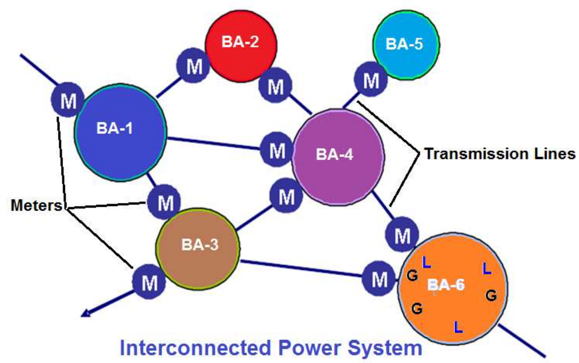
- Reserve sharing (Contingency, Frequency, Regulation)
- Diversity in transmission paths
- Sharing frequency error
- Access to wholesale energy markets
  - Economic Purchases or Sales

Disadvantages

- All systems “see” disturbances
- Other generation suppliers can sell to your customers

Makes Retail Power Markets possible

- Customers have choices



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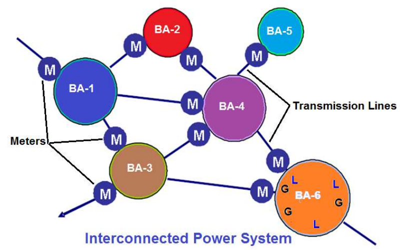
•NERC Functional Model BA = Balancing Authority – function: Balance supply and demand.
•Generators have governors and AVR and are also tied into the BA Area Generation
•Operation in parallel with neighboring systems allows planned and unplanned energy exchanges
  - •Can lower overall cost to provide energy to loads
    - •Reserve sharing
    - •Facilitates sales and purchases between systems
  - •Provides some protection against transmission path interruptions
  - •But all share in the impacts of an unplanned unit trip
    - •Good if you lost the unit
    - •Bad if you are located in the next system over

•Interconnected systems can set up power markets in which firm or interruptible power and energy can be bought or sold for the next hours, day, week, or longer
•Markets can contain conventional utilities, independent generation plants (merchant power – constructed to sell power to no one in particular)
•Markets pricing structures (determining how who gets paid for what power) can have dramatic impacts on daily generation mix, service reliability, and even plant siting
•Markets can greatly complicate the generation dispatchers job

Energy Interchange

- Excess generation can be sold to other entities, or
- Energy can be purchased from other suppliers
  - Neighboring (or distant) utilities
  - Power marketers
  - Independent generators



- Purchases are just another resource you use to meet your load demand.

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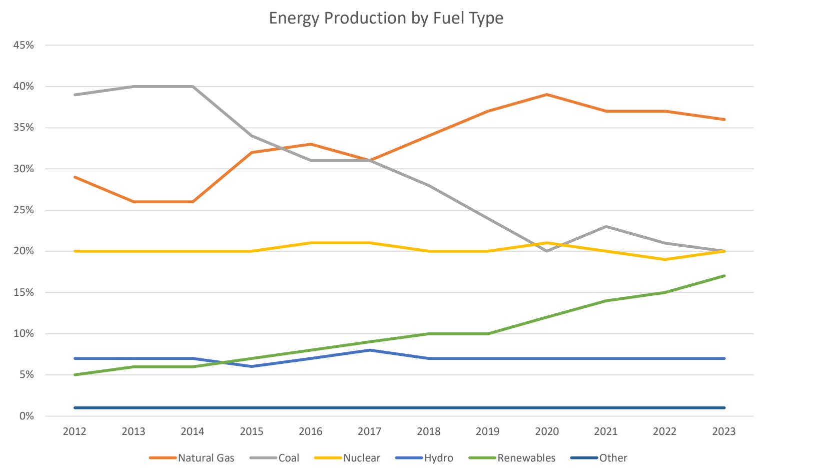
•Area load is internal generation less sales plus imports

•In many cases one utility may have extra generation available for a limited time and wish to sell the output to another utility. This could be because utility A started a large unit for the morning peak and wants to leave it on for the afternoon peak, but has no need for it during the mid-day lull.
•Purchased generation is treated like internal generation
•Sold generation is treated like a normal load

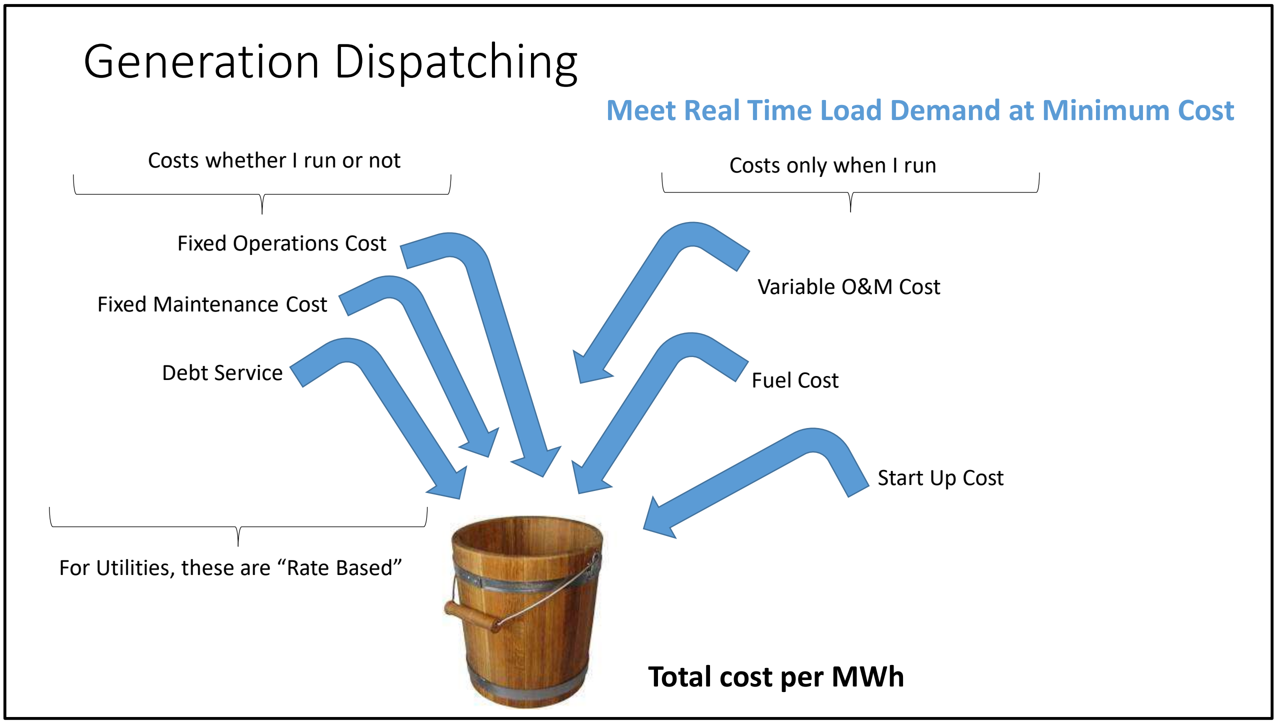
National Electric Resource Mix



Source: U.S. Energy Information Administration, Short-Term Energy Outlook, June 2022

You can see the declining output from Coal fired units and the increase in contribution with renewables

Of note is that currently Natural Gas fired generation is the dominant source of power in the US



Generator Dispatching – this is an economic decision in most cases. To determine the economics, there are several factors that contribute to the cost. This cost is divided by the MWh's produced and is use to determine the cost for generation. The lower the cost per MWh, the more economic the choice.

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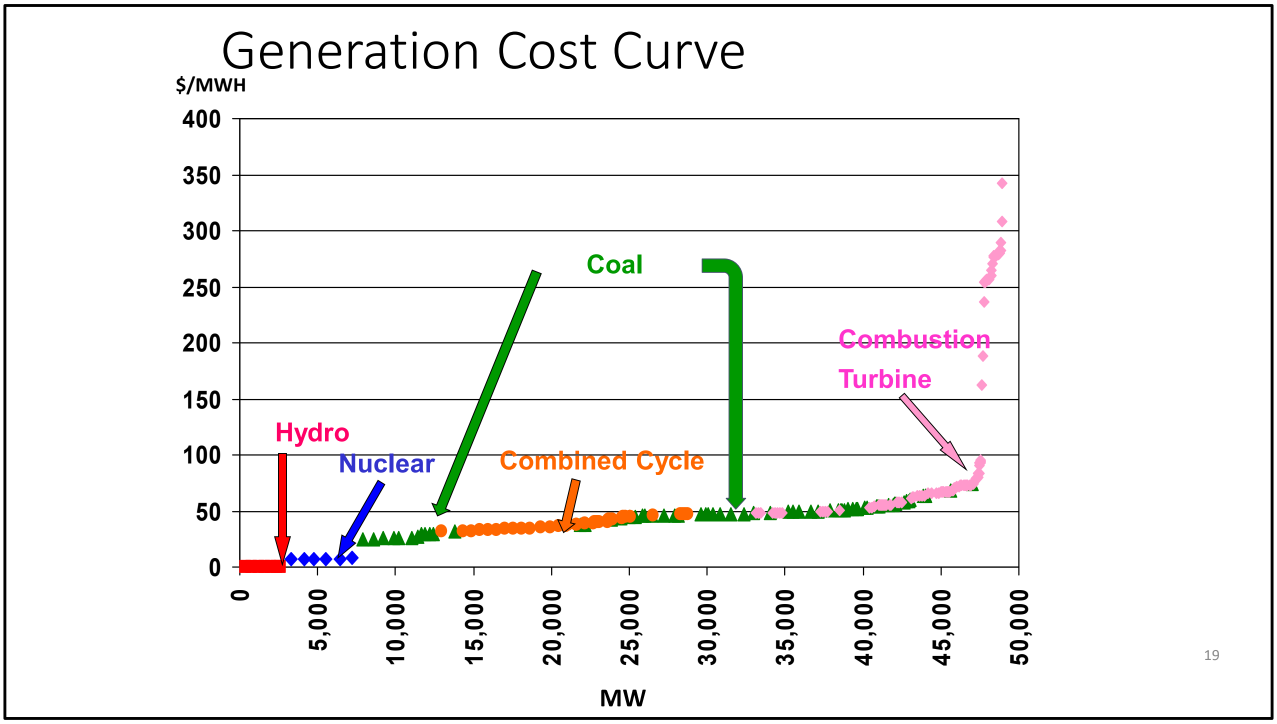
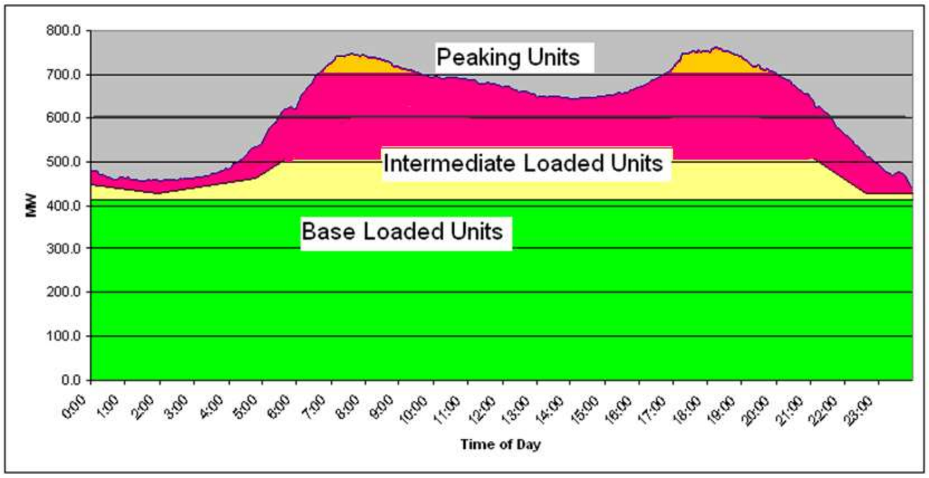


Sometimes this is referred to as the "stack" graph because it stacks up generating resources based on their cost.
Again, it is based on variable cost which changes each day based on the changing components of cost (e.g. gas).

You see there is a diverse mix of generation types – Starting with Hydro which is at a very low cost since the fuel is $0 but it is a limited resource. There are the Nuclear units which are also at very low variable cost. Then, Coal units and finally Combined Cycle units and Combustion Turbines.
So to give you a simplistic view of how a system is committed and dispatched – Assume every unit available, assume peak hour and hydro is operating and say there is a 47,500 MW demand. CT's are the required resources here at a cost of about $100. But, if energy can be bought from the Market at something less than that, then the cost to generate would be reduced relative to the Stack.
That's a high level look at how the electric system is operated both day ahead and intra day.
Obviously, dispatching on economics and with resources having varying cost types drives their operation to be weighted heavily toward the lowest variable cost.

Generation Dispatch



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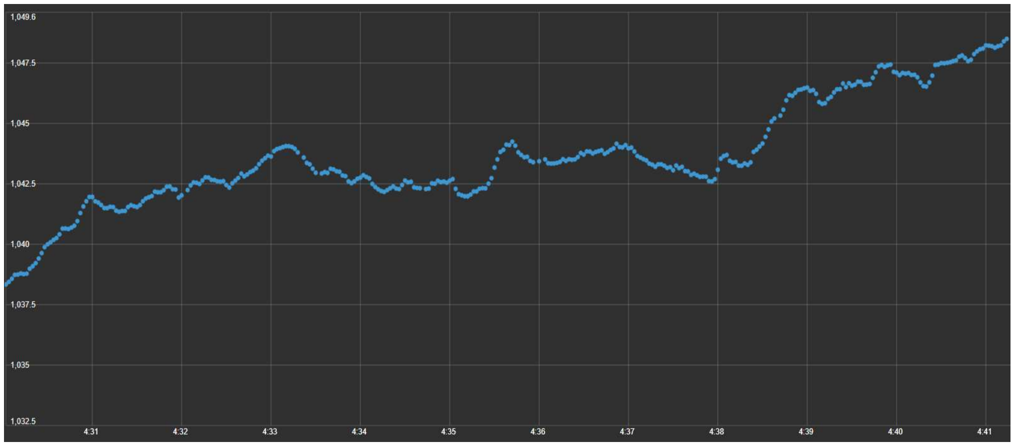
•One solution to the previously viewed load curve

•Base loaded units supply energy such that their loading is continuous where they are most efficient (lowest production cost). Some Hydro units must be base loaded for flat flows for environmental reasons.
•Intermediate units are used to follow the rough shape of the load curve
•Peaking units are usually the most expensive and are used for following the load curve excursions (could be hydro to avoid costly purchases)
•Note – regulating units, like hydro, may be used to follow the minute by minute variations in load and the base, intermediate, and peaking units may be used to keep the regulating units in range.

Deep Dive into Load Curve

Load
Increment
is 2.5 MW



Time Increment is One Minute

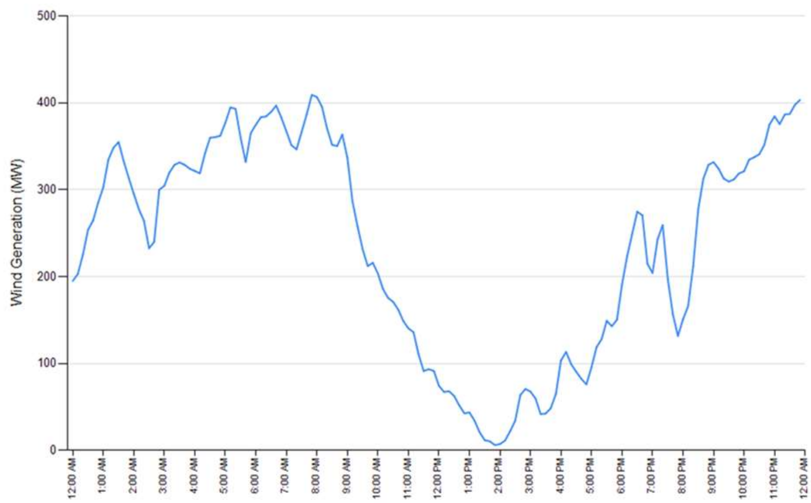
When you expand this down to the minute time increment, you can see how variable this is on a moment by moment basis.

New Additions to the Power System

•Alternative generation sources are often termed “intermittent energy” sources since they can provide a considerable amount of energy (kWh) over the course of a specific time period, but the timing of that delivery is never certain.
•From a system operations point of view, these could be treated as “negative loads”. The dispatcher cannot schedule them to be present at any particular time, and must, in fact, adjust other controllable resources around what these units are doing.

February 2012 – 1 day

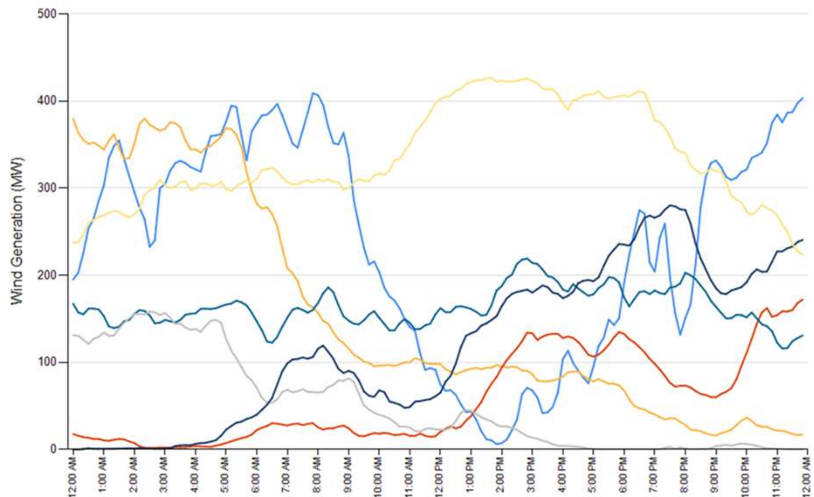
Wind Generation



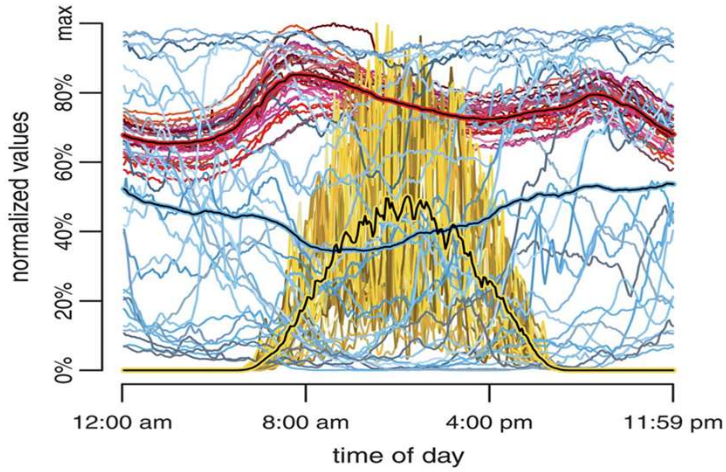
Want to explore the characteristics of intermittency with a wind farm output. This shows what happens over the course one day.

February 2012 – 7 days

Wind Generation



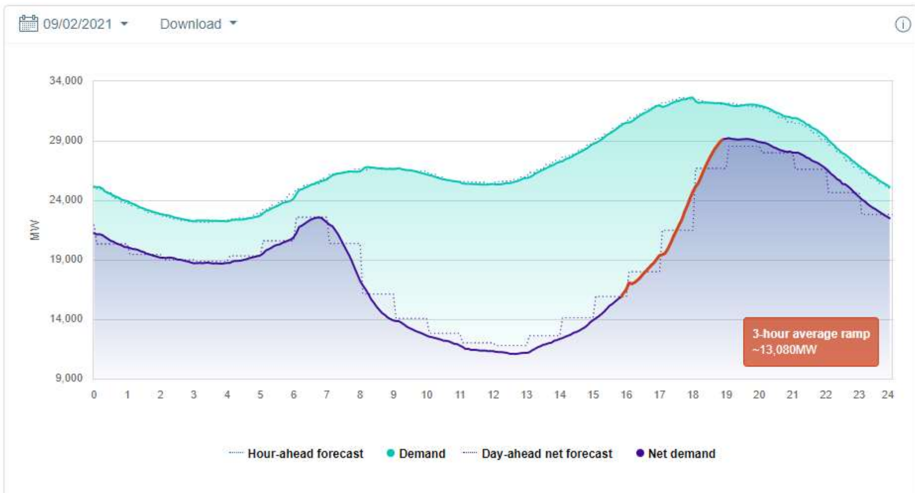
Flexibility for Short-Term Uncertainty



One month of wind farm, overlayed with one month of a solar field. How does this affect your planning?

Note that even though the output of solar does vary, it is pretty dependable as to when it shows up and when it leaves.

Generation Dispatch

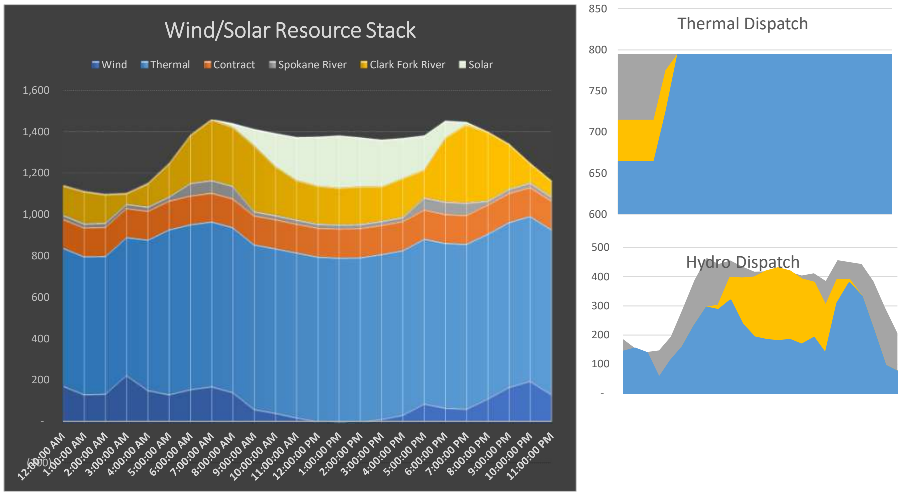


This is take from the California ISO. This shows the actual demand and the contribution of renewables to their grid. You can see the effects of solar.

This is the "Duck Curve"

Of concern is the amount of energy that needs to come on to meet the evening peak. You can see the ramp rate this day was 13,080 MW each hour. That is a lot and fast.

Impacts of Wind and Solar Penetration - Scenario



Shows effect if we have extensive solar penetration on our system. This is a possible future

Notice ramp on thermal dispatch

Notice how hydro would be reshaped – needed to compensate for solar, water management issues?

The yellow area on the thermal dispatch graph shows how much more the thermal would be backed off to adjust the addition of the solar contribution

The yellow area on the hydro shows how much less the hydro would be dispatched. You can see how much the impacts of the increased solar changes the hydro operation.

Other Considerations

Do you think a battery is a good thing or a problem thing?

This is a storage battery project. Demand Response resources have not yet been seen as a value in all regions of the country.

Working to integrate market ideas with micro grids and micro transactional grids

Current technology is about 1 MW / container size (8ft X 40 ft) or about 40MW /acre - allows for space between containers

Ancillary Services

- Non-energy services required to operate power system
- Six types as defined by FERC Order 888
  - Scheduling, system control, and dispatch
  - Reactive power supply and voltage control
  - Regulation and frequency response
  - Energy imbalance service
  - Spinning reserve service
  - Supplemental reserve service

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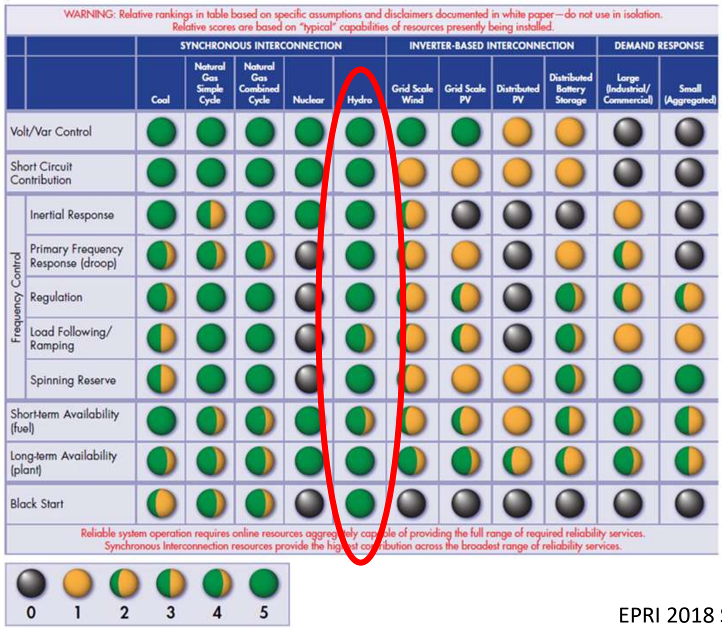
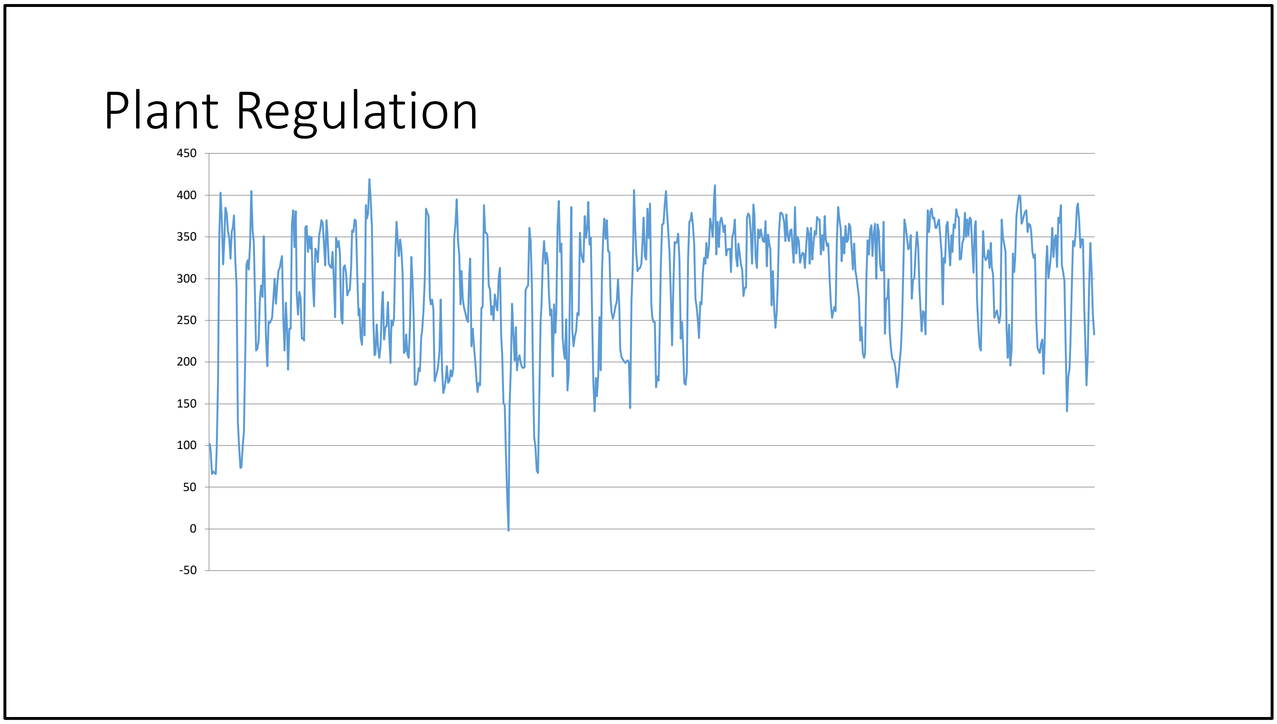
- When FERC opened up the transmission and generation markets, they defined 6 services that are required for reliable system operation. Many of these can be provided by hydro generators

Ancillary Services



EPRI 2018 System Reliability Services

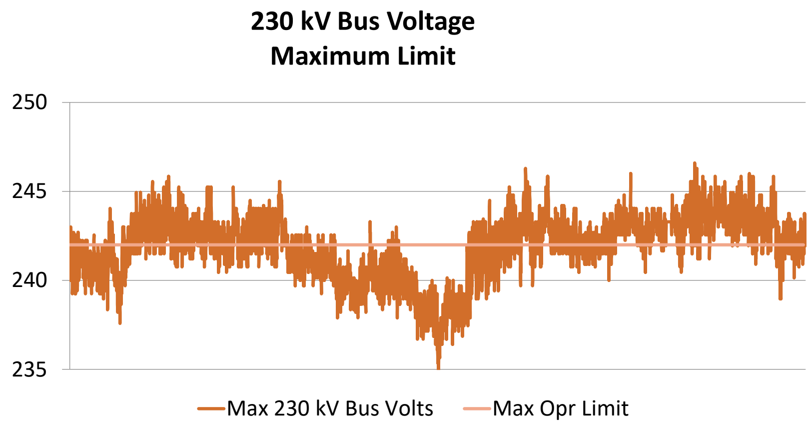
This chart is a good summary of most the services that are needed to assure a reliable transmission grid. Not surprisingly, conventional resources already possess most of these traits. The newer renewable resources do not have some of these characteristics and a system operator needs to make sure there are enough of these services with the resources that are on-line. If you don't, you may have to shut something down to get the services you need. That is a complicated by "must take" contracts, incentive contracts, transmission constraints, etc.



This shows this plant for the day and how it moves around. This movement would have been smoother and less magnitude before area operating restrictions, market opportunities, and intermittent resources have come on.

This graph is a composite of “Load Following”, AGC adjustments. These are all automated functions.

Voltage Support



The last item is the voltage support required at times in the system. This plant is located on a long, lightly loaded line during parts of the year due to water for hydro units. Forces units to operate at relatively high power factors and stability limits. More risk to machines by operating at fringes of design limits.

This also shows that rather than specific balance, voltage (i.e. reactive) is managed withing operating high and low limits.

Another reliability benefit: Inertial Response

Hydro turbines are massive and resist frequency change
Turbo Units create inertia with their speed

Hydro Turbines are massive – resistant to speed changes.

Steam or gas turbine generators (turbo generators) spin really fast.

Inertia = f(mass x angular velocity) = large mass x slow speed for a hydro unit = smaller mass x high speed for turbo unit

Plan for Contingencies

- You must leave room for unexpected events
- Types of contingencies
  - unplanned Unit outages
  - Loss of “fuel” (wind)
  - Loss of transmission lines (when power sales or purchases are being transmitted)
- BA’s Must have Reserve Generation (Operating Reserves) to reliably serve their load

What are some other contingencies that you might need to plan for?

• Generation reserves are required to maintain continuity of service to the system loads upon loss of generation

- Could be trips of utility units
- Could be trips of lines over which purchases were being delivered

•NERC and RRO (RE) requirements dictate either levels of reserves required or system performance on occurrence of a credible outage

•One of the big items is weather. Extreme heat and extreme cold create different problems. Another contingency that is becoming more of an issue is availability of natural gas during cold snaps. The gas may be diverted to consumer heating load and not available for generation.

Operating Reserves

- Increase generation – INC Reserve
  - Spinning reserves (already on-line but loaded at less than full capacity)
  - Supplemental (must start and load up in 10 minutes)
- Short term purchases
  - Buy on spot market for replacement power
  - Reserve sharing with connected utilities
- Reduce loads (Demand Response)
  - Drop interruptible loads
  - Drop other loads
- Reduce Generation – DEC Reserve
  - New problem introduced by wind and solar. If they unexpectedly come up something needs to back off to maintain a balanced system

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- Spinning reserve is on-line and automatically loads up based on governor response to system frequency decline (loss of power balance)
  - Unloaded capacity of generators on-line
  - Pump storage (doubly effective)
  - Unit in synchronous condense mode
- Non-spinning reserve is that which can be available in 10 minutes or less (starting reliability is important here)
  - Units on standby
  - Quick start units
- Replacement generation is that which the utility places on-line to unload the spinning and ten minute generation to prepare for the next contingency
  - Other, more economical, units come on to allow non-spinning to come off or to re-establish spinning reserve
- Utilities can reserve power on machines operated by another utility
  - Use tie lines to transmit energy
- Multiple utilities can form a “pool” and agree to share spinning reserve obligations and costs among the pool members
  - Each systems largest credible generation loss is unlikely to happen at the same time, so pooling can reduce overall reserves to be carried (lower costs)
- Loads can be spinning reserves
  - Large industrial customers can exchange low power rates for agreeing to be tripped off line for utility system generation shortages (works on other end of real power balance)

Generation Reserves
NERC Reliability Standards

- Bal 001 – Control Performance Standard
  - How well does a BA maintain frequency, follow load, and minimize Area Control Error (ACE)
- Bal 002 – Disturbance Control Standard
  - Must recover ACE within 15 minutes of a contingency event.
  - Must restore reserves before end of the Disturbance Recovery Period (60 – 105 min)
- Bal 003 – Frequency Response Standard
  - How well does a BA respond to large frequency, frequency deviations.

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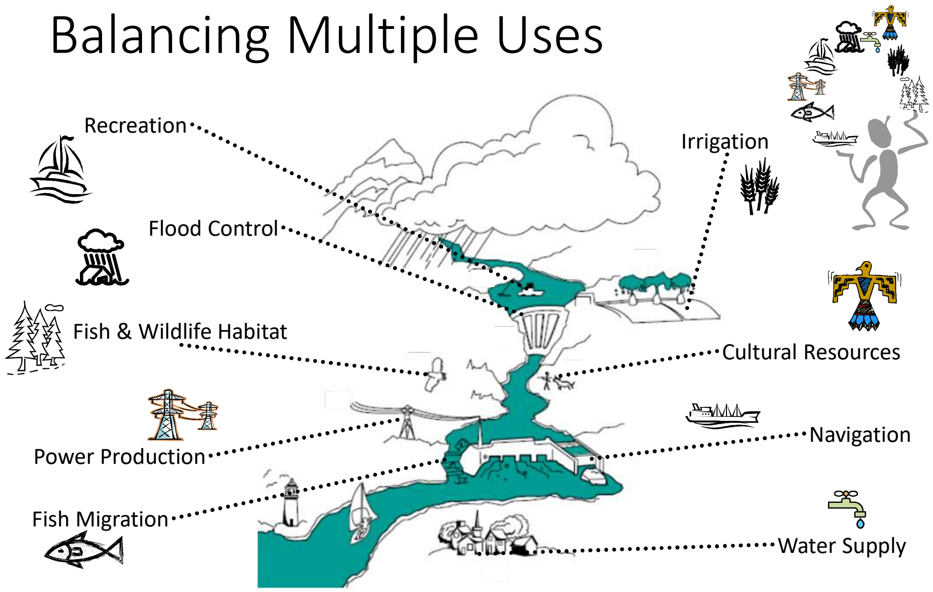
Balancing Multiple Uses



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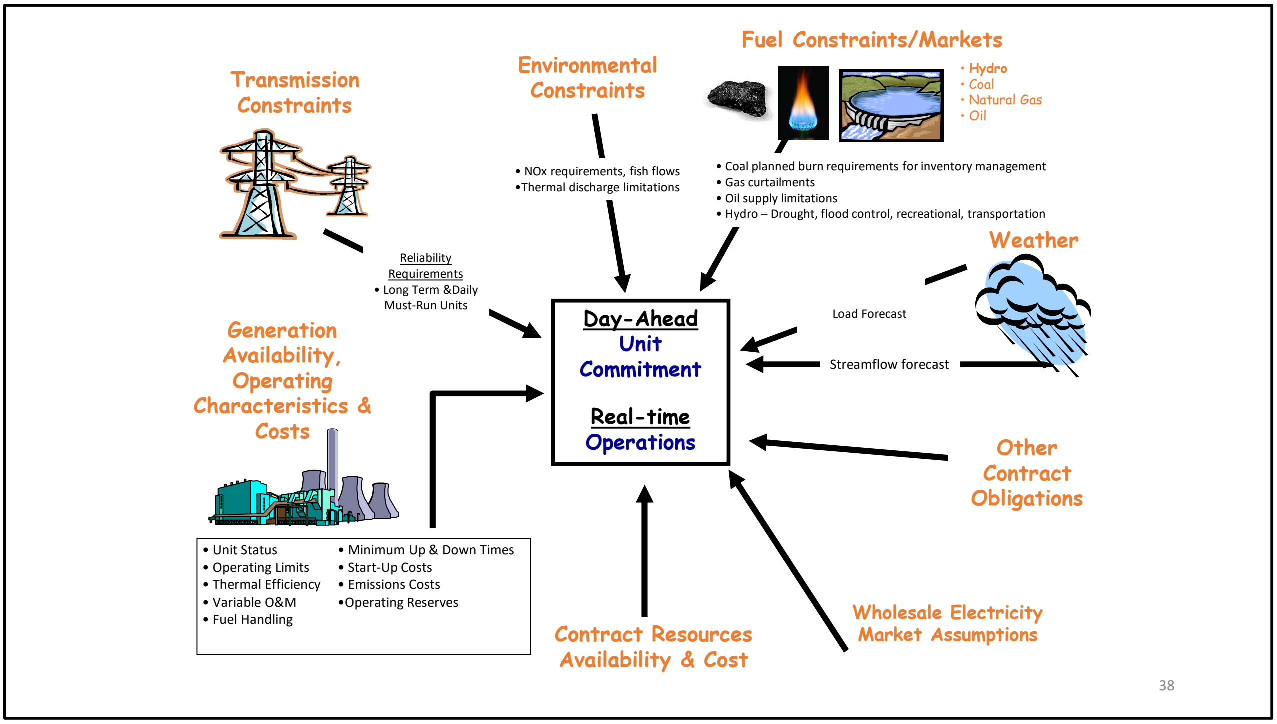
Power Production does not happen independently. It happens in the context of all the other competing uses.



Factors that you need to consider for planning purposes

Planning for Operations

- Fuel Supply
  - Thermals
    - Purchase your gas, coal oil, uranium
    - Consume in real time
  - Wind and Solar
    - Hope for windy sunny days
    - Wait until real time to see how it unfolds
  - Hydro
    - Use Historic Hydrology Records
    - Statistical Analysis
    - Hope for lots of rainy days and a little luck

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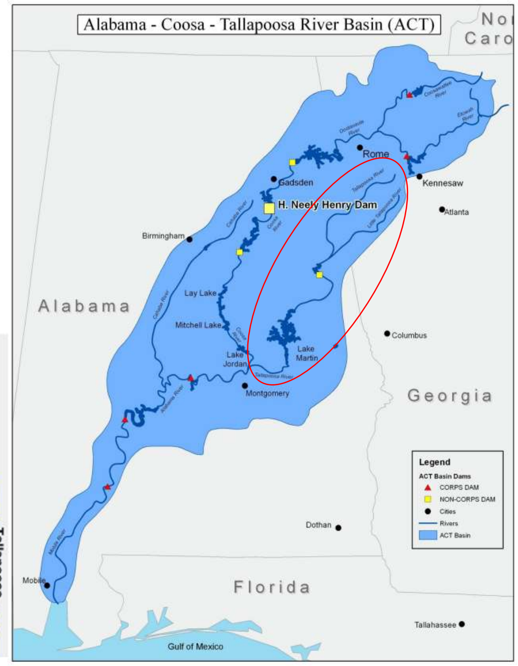
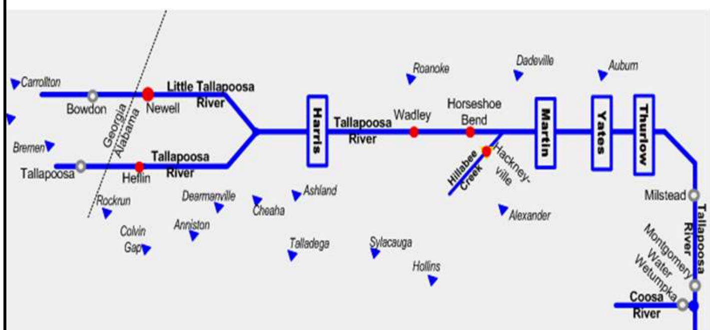
Depending on the resource type you have available to you, you need to consider the different characteristics of the resource types.

Drainage area of Alabama River, Coosa River, Tallapoosa River



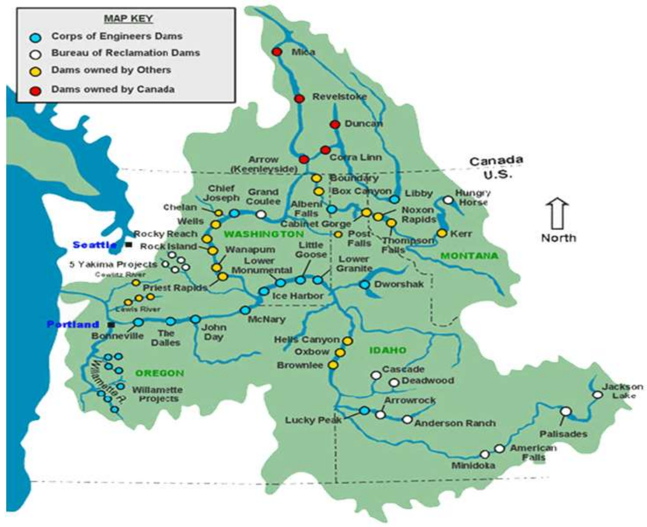
Tallapoosa River Schematic



Planning and dispatching hydro resources

An hydrologist's view of a river system.
Rivers – Little Tallapoosa, Tallapoosa, Hillabee Creek, Coosa
Dams – Harris, Martin, Yates, Thurlow
Rain Gauges – Carrolton, Bremen, Rockrun, Colvin Gap, Anniston, Dearmanville, Cheaha, Talladega, Ashland, Roanoke, Dadeville, Alexander, Auburn
Stream Gauges – Tallapoosa, Bowdon, Milstead, Montgomery Water, Wetumpka
Rain and Stream Gauges – Newell, Heflin, Wadley, Horseshoe Bend, Hackneyville

Hydro plants have a Dynamic Fuel Supply



Upstream outflow = downstream inflow
Lots of planning and coordination is required for reliable operations

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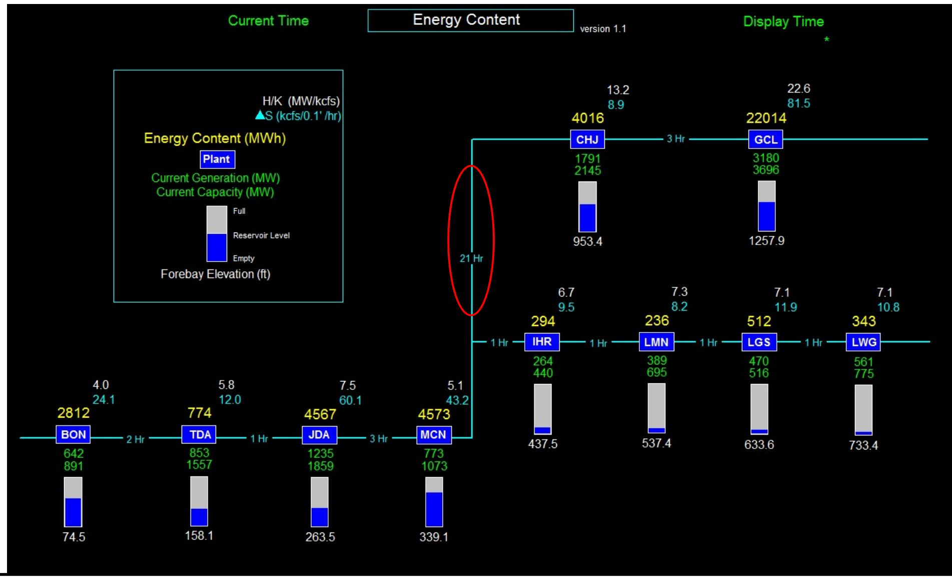
- Storage Reservoirs vs Run of River
- Geographic and Geologic Locations
- Time Factors and Lag Times
- Reservoir and Turbine Characteristics

Real Time Considerations

10 kcfs increase at LWG

Generate or Store Today??   Sell ???   What about tomorrow?



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A 10 k increase at LWG.

If we could store it we could deal with it some other day. But we can't store because of 1 ft. FB limit.

Moving it all the way through the system means 500 MW of excess power each hour for the rest of the day.

We could back off GCL but what about tomorrow? What if We HAD to draft GCL that amount?? To keep things the same out of GCL we would have to sell 500 and put all that load across LSN and LCOL

GCL – Grand Coulee   CHJ – Chief Joseph   LWG – Lower Granite

LGS – Little Goose   LMN – Lower Monumental

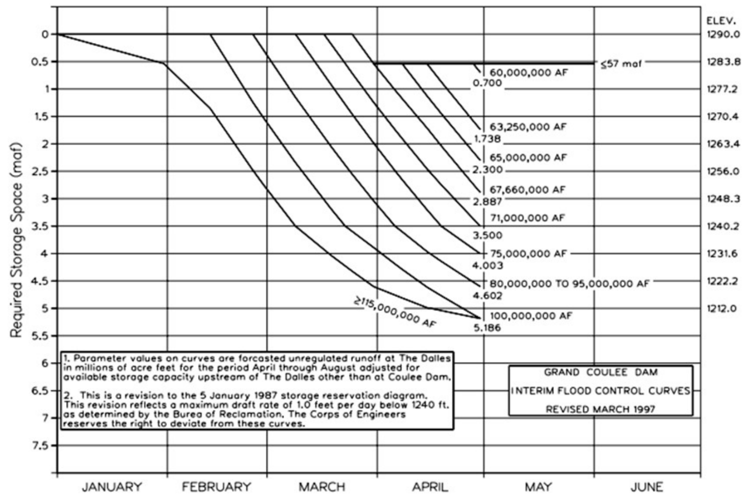
IHR – Ice Harbor   MCN – McNary   JDA – John Day

TDA – The Dalles   BON – Bonneville

The times in hours represent the water travel time. For example, it takes 2 hours for a release from The Dalles (TDA) to reach Bonneville Dam (BON)

Another perspective, a release from Grand Coulee (GCN) takes (3+21+3+1+2=) 30 hours to reach Bonneville Dam. Think about it – more than a day.

Rule Curves



Rule Curves force operations for flood control

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To help operations, often rule curves are developed based on historical information, changes in unit operation, and other water demands.

Unique Capabilities of Hydro

- Black start (start without off-site power)
  - Simple auxiliaries can be started by engine-generator set, or even batteries
- Energize dead lines
  - Salient pole rotor construction results in higher line charging limits
- Ride-through disturbances
  - Hydro turbine and generators relatively insensitive to frequency deviations

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- Black start
  - Due to the simplicity of the auxiliary systems, hydro units are often used as black start projects. The few auxiliaries that are required can be carried by local engine generators or even batteries until the main unit(s) have started up.
- Energizing transmission lines
  - The relatively high capacity of the salient pole machine in the underexcited region allows the hydro machine to energize longer lines than an similarly sized cylindrical rotor machine
- Ride-through disturbances
  - Steam turbine blades are subjected to pressure pulses related to operating speed. Blades are designed and built to avoid natural resonant frequencies at normal operating speed. Operation at off-nominal frequency (real power balance problems) results in pressure pulse frequency changing. Turbine must be tripped before resonant frequencies of turbine blades approaches pressure pulse frequency due to reduced or increased speed.
  - High efficiency large frame industrial gas turbines have tight tolerances on blade temperature. Reduced shaft speed due to reduced frequency results in higher blade temperatures at the same load level, so some turbine controls will reduce load on the machine as frequency drops. Since this aggravates the real power balance, the frequency decline is worsened by this action.
  - Hydro units have neither problem and are less sensitive to frequency excursions in either direction

Unique Capabilities of Hydro

- Spinning Reserves
  - Capacity above current operating point due to max Efficiency below full capacity
- Regulation
  - Kaplans are best because of flat Efficiency curves
- Dec Reserve
  - Kaplans again are best
  - Short term storage utilized to prevent spill
- Inc Reserve

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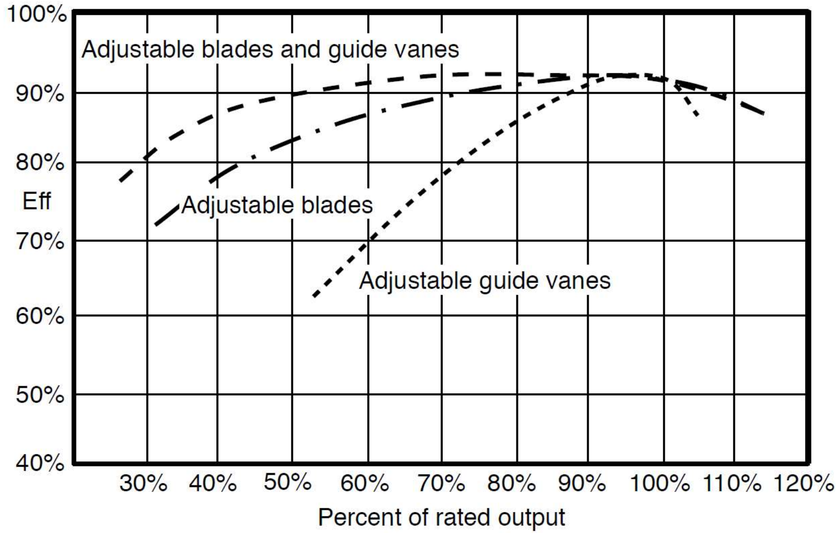
- Spinning Reserves (also called Active Reserves)
  - These are both units that are on-line but not producing power and any power between actual output level and Pmax.
- Voltage Regulation
  - The relatively high capacity of the salient pole machine in the underexcited region allows the hydro machine to energize longer lines than a similarly sized cylindrical rotor machine
- Dec Reserve
  - Hydro can easily incrementally increase or decrease their output at minimal increment impact in efficiency. Even then, there is not incremental fuel cost. Inc Reserves can be limited based on forebay limits if the reservoir is full.

Efficient Hydro Operations

= Operating Reserves



Indicates the relative efficiency of different types of hydro units. (adjustable guide vanes is the same thing as wicket gates)

Impacts to Hydro Units Due to Integrating Alternative Sources

- Increase in start stop cycles can accelerate aging of generator
  - Cyclical loading and heating
- More frequent maintenance may be needed to minimize effects
  - Possibly more wear in wicket gates, bearings, actuators, other moving parts

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Hydro’s Role in the Future

- Continues to be very flexible resource in generation mix (provided there’s water)
- Capable of marketable ancillary service and reserves support
- Expanded need for pumped-storage hydro to “store” or shift timing of output from alternative variable energy sources

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Some climate change studies are showing dramatic shifts in rainfall distribution and timing even in the next 50 years.

The Shift in Fundamentals

- Traditionally, energy has been stored in the fuel (i.e. the coal pile, the gas pipeline, the reservoir)
- Traditionally, energy has been delivered “just in time”
  - If more energy was needed, we just added more fuel.
- Now with intermittent renewables, the energy being created is only available for consumption when it is created
  - This has increased the value of storage

What other factors might be different in the future?

Other factors would likely be the shift to electric vehicles
The use of Distributed Resources
Advances in battery storage technologies
Development of small nuclear plants.

CONCLUSIONS

- Hydro generation provides easily controllable and flexible source of real and reactive power
- Fast startup and ramp rates
- Low operating costs
- Few moving parts means greater reliability
- Proven technology and a renewable fuel
- Lots of uncertainty but still well suited to meet the anticipated needs of the future.