Slide 1

The Role of Energy Storage in Power Management

Edward Herbert
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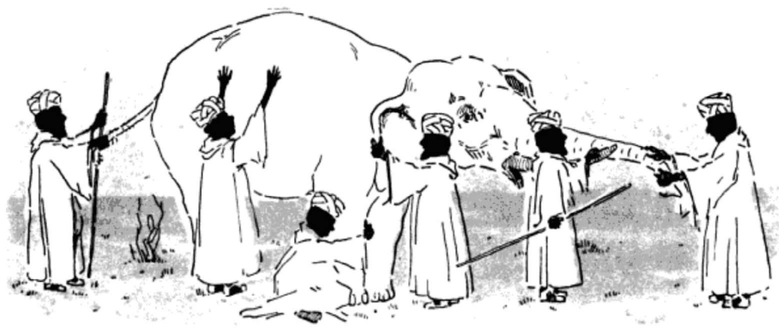
PSMA Energy Efficiency Committee

APEC2014
Ft. Worth, TX

Slide 2

EPRI-PSMA Workshop (prior to APEC2013)

"Are You Smart Enough for the Smart Grid?"



The Blind Men and the Elephant

John Godfrey Saxe (1816-1887)

They don't speak the same language!

Their physics give different answers!

EPRI and the PSMA Energy Efficiency Committee sponsored a workshop on the Smart Grid on the Saturday before APEC2013. We had eleven speakers discussing diverse topics of the Smart Grid.

A premise was that power converters could be modified to help The Grid, if only the utilities knew what to ask for. On the other hand, power converter designers do not know enough about The Grid to know what to offer.

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They don't speak the same language!

Transformer impedance:

Power converter Engineer:

$$Z = j\omega L_S + \frac{\omega^2 L_S L_L}{(j\omega L_L + R_L)}$$

Utility Engineer:

$$Z = 5\%$$

$$Z = 4.5\% R + 2\% X$$

% Impedance (%Z) is a sub-set of per-unit calculation. Power Converter Engineers should learn how to use per-unit calculation.

%Z is a normalizing function, and it is very useful.

%Z is normalizing for transformers with different VA ratings.

Two 5 % transformers in parallel each carry the same percentage of their rated current even if they are very different in VA rating.

Slide 4

They don't speak the same language!

VARs?? The power converter engineer knows vaguely that VARs stands for **Volt-Amps-Reactive**, but he has no idea how they work or how to apply them.

The Utilities apply VARs compensation within the distribution system to compensate for line and transformer impedances.

Our analysis shows that VARs compensation should be incorporated into the loads and distributed power sources, including energy storage.

This is a good business opportunity that is being overlooked. Adoption in new equipment would be very helpful to the Grid.

In the EPRI-PSMA workshop, we learned that VARs compensation with rapidly changing loads and distributed power sources is a serious problem for the Utilities.

Switched capacitors and other compensators that were designed to operate once or twice a day are switching much more frequently, and wearing out.

If the loads incorporated the correct compensation for the current being drawn, this would relieve the Utility of having to compensate them. Distributed power sources (including energy storage) should have compensation as well, and it will be complementary when power flow is reversed.

If new loads and power sources incorporate compensation, the problem will stop getting worse. Once a critical mass of new equipment is installed, there will be improvement.

VARs compensation should be mandatory for large loads such as EV chargers and large sources such as PV farms.

Slide 5

Their physics give different answers!

Ask a power converter engineer and a utility engineer what **Power Factor** is, and why it is important.

The difference in their answers is surprising and significant. The differences can be attributed to looking at different parts of the "elephant" ("The Grid.")

All perspectives are important, and all should be considered in managing energy in The Grid.

Power factor correction (pfc) circuits used in power supplies may provide a useful model for VARs compensation and load-line control.

Getting into the weeds about power factor and power factor correction (pfc) is beyond the scope of this presentation, but the difference is very instructive, not only to illustrate the problems of different perspectives but also to understand the reasons for the differences.

Phase shift, harmonics and phase imbalance have very different consequences in rotating machines and "solid state" power converters.

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Energy Storage: The inspiration for this PSMA Sponsored Industry Session.

The EPRI-PSMA workshop covered many interesting topics.

Energy storage stood out as an area of interest for
PSMA and the power converter industry,
prompting the PSMA Energy Efficiency Committee to sponsor
this Industry Session.

In workshop, the topic of energy storage was covered by
Dr. Satish Rajagopalan, Project Manager in the Power Delivery
& Utilization Sector at EPRI.

Dr. Rojagopalan talked way beyond his allocated time, but I would not have missed a minute of it.

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Dr. Satish Rajagopalan, EPRI, Important quotes:

- *"Energy storage is really expensive. Monetizing storage is one of our biggest challenges."*

- *"Energy storage applications are very divided as energy intensive applications or power intensive applications."*

- *"Frequency regulation from variable loads is a key problem. You need to balance the dynamic load versus the dynamic generating resource."*

- *"Large-scale energy storage systems are energy arbitrage systems, mostly pumped hydro."*

Dr. Rojagopalan talked mostly about battery systems and capacitor systems, thus the observation that energy storage is really expensive.

Pumped hydro is an example of less expensive energy storage, and this Industry Session will explore others.

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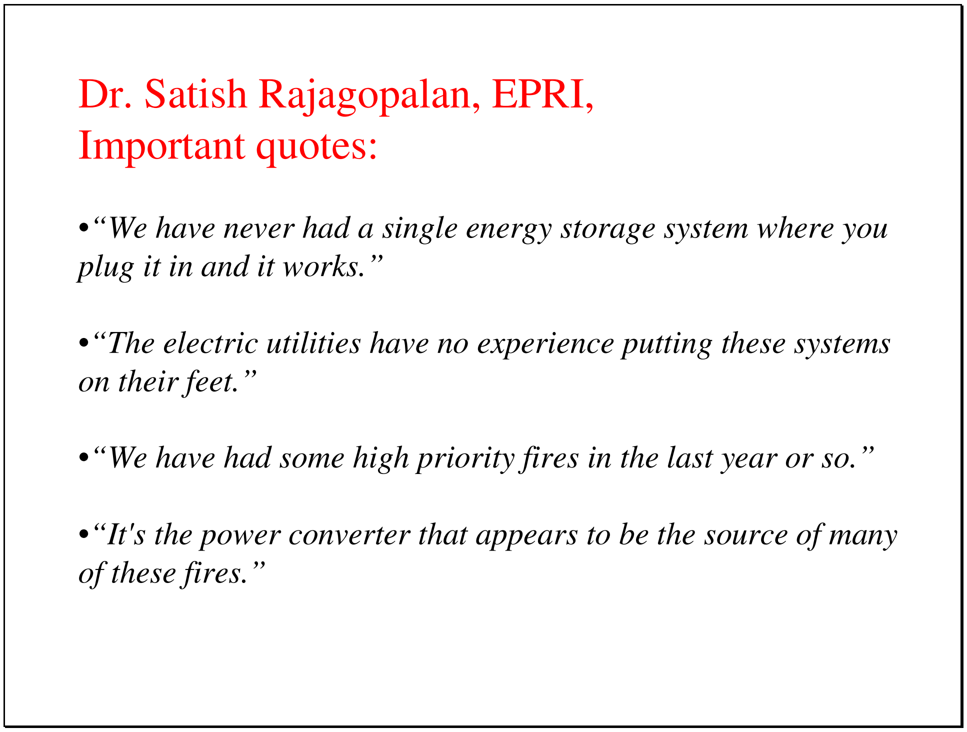

What is going on here? ? ?

Are too many projects going to low bidders? --- or to companies that are better at writing grant proposals than designing hardware?

Maybe it's that some companies know their batteries or capacitors very well, but have little idea how to specify or design the interface electronics.

In planning this Industry Session, we tried to find success stories, and invite people who had solved problems.

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Energy Storage in Power Management

- Power Quality --- PFC, phase balancing, harmonics.
- VARs compensation
- Regulation services
- Load leveling and load shifting

Energy storage in batteries and capacitors is very expensive, so we explore alternatives.

- Incorporate VARs compensation in "solid state" loads and distributed alternative power sources.
- Store energy in a form that is useful at a later time.
- Defer work until sufficient power is available.
- Modulate work and storage to complement power variations.

Slide 10

Frequency of Power

Line frequency usually is 50 or 60 Hz, 3-phase.

Power frequencies of interest may be from nHz to Hz.

3-phase power is “constant,” equivalent to DC. “Constant” does not mean that it doesn’t vary --- it does, in response to line and load variations. It means that he net power delivered by the three phases has no ripple (in a balanced system).

To study the dynamics of a power distribution system and energy storage, it is useful to define the frequency of power and explore the harmonic content of power variations over time.

Here is another example of dangerous semantics. “Constant power” has different meaning in different contexts. The jargon would be baffling to a lay person.

In the slide, we discuss the “constant power” of 3-phase ac power transmission. When applied to a motor or a well designed power converter, the total power flow has no ripple if the phases are balanced. It means that 3-phase power factor correction does not need large bulk capacitors for ripple smoothing, though they may be needed for hold-up time. “Constant power” in this sense is NOT invariant over time, it will vary as the load changes. With a resistive load, power will also vary as the voltage magnitude.

“Constant power” referring to a power converter has even more potential for confusion. It does NOT mean that the power does not vary. It does, in response to load changes. The meaning here is almost idiomatic, and means that the power does not change in response to line voltage variations. If the voltage goes up, the current goes down so that their product, power in Watts, stays the same.

If you are not sure that your reader or audience will understand what you mean, it is best to define it, with examples and equations.

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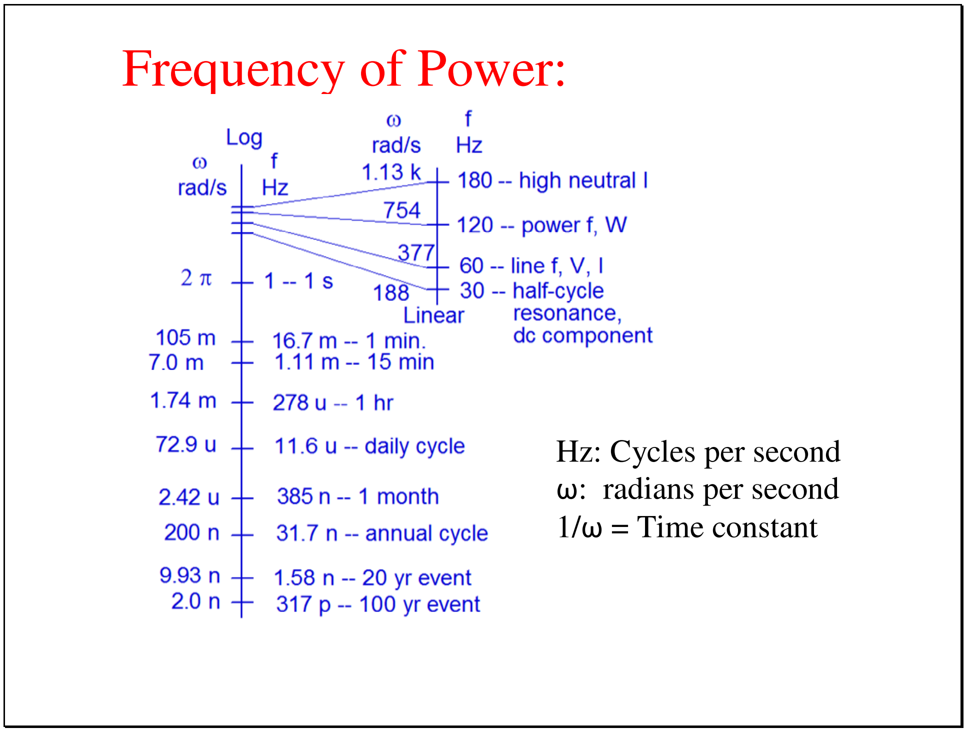

The frequencies of interest for power management cover many decades.

Above line frequency, it is a power quality issue. PFC correction is one solution, and we are familiar with the energy storage needed for PFC, the "bulk capacitors."

At line frequency, phase imbalance is an issue, but more important is VARs generation for compensation. It is beyond the scope of this presentation, but our analysis shows that compensation should be provided in the loads and distributed sources, including energy storage.

In this Industry Session, we will be discussing energy storage for regulation, about 1 to 20 mHz, and for load shifting, much of which is on a daily cycle, about 10 uHz.

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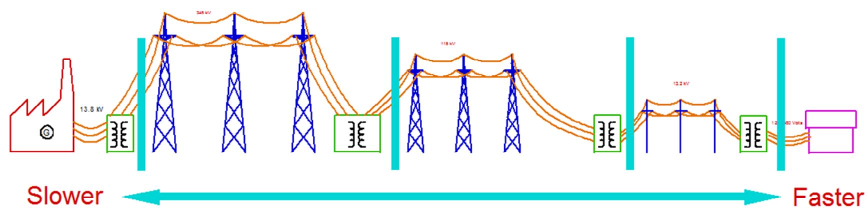

The large generators and bulk distribution are too slow in response to provide good regulation for rapidly varying loads and distributed power sources.

The customers' power converters, loads and distributed sources, with their fast dynamic response, can be modified to help The Grid --- a business opportunity for power electronics.

Customer equipment will come onto service much more quickly than utility equipment will be replaced.

A point was made in the workshop that much of the utility equipment is 40 years old, or more. However, it is well maintained, and may work reliably for another 40 years.

On the other hand, customer equipment will have a much shorter cycle life. If new equipment coming on line has modified characteristics that improve The Grid, worsening of the problem will be halted. Once a critical mass is installed, The Grid will be much improved.

VARs compensation at the loads and distributed sources may be the most important, but regulation services and load shifting will be very important as well.

It will be interesting to see if security concerns lead to short-cycle time recall and replacement of Smart Grid equipment such as Smart Meters.

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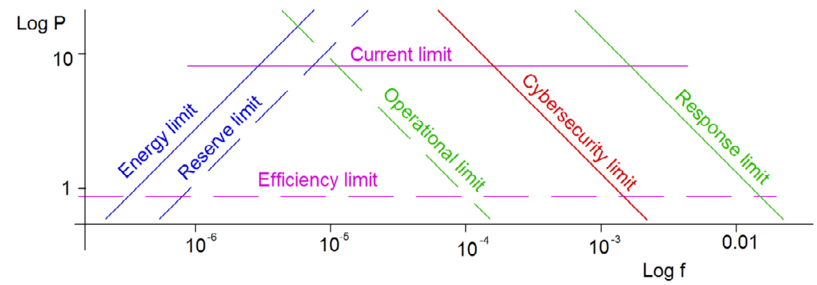
Energy Storage Frequency Characteristics

Energy storage frequency response graph



The frequency characteristics of energy storage can be plotted, Log P vs Log f.

The amount of energy that can be stored or returned is limited by the capacity of the storage medium, the solid blue line at the left. It may be preferred not to allow depletion to zero, so a higher reserve limit may be specified.

The upper limit is the frequency response of the equipment, the solid green line at the right. However, a much lower operational limit may be preferred. For example, battery cycle frequency may be limited to extend life. In an emergency, however, power could be applied rapidly, up to the response limit, particularly if it is a one-shot event that occurs infrequently, like a lost feeder.

The upper power limit may be a current limit. At some low power, it may be best just to turn the equipment off, if no-load losses dominate.

If hacking is a concern, there may be a cyber-security limit. Changes may have to be slow enough so that aberrant behavior can be detected and corrected before damage is done.

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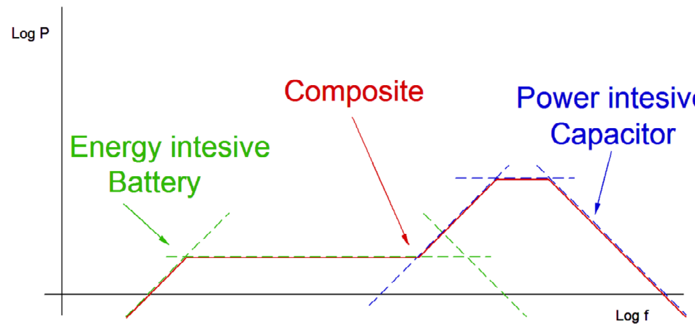
Composite Energy Storage



An energy intensive battery can be used with a power intensive capacitor to cover a broader frequency range.

The capacitor can provide higher currents for a short time, while the battery can provide lower current for a much longer time.

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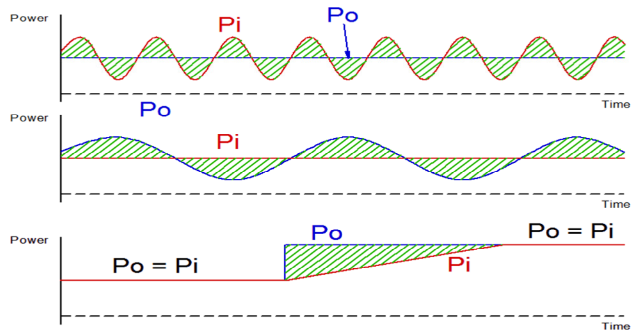
The energy of transients:



The amount of energy that must be stored and returned is the integral of the power difference.

More simply, if the input power and the output power are plotted vs time, the energy storage needed is the area between the curves.

Energy storage allows the input power and the output power of a system to differ, the difference being stored or recovered as needed to support the difference.

A higher magnitude of power difference or a lower frequency will require more energy storage.

Filtering high frequency power ripple as in PFC (1st curve), requires relatively little energy storage.

Keeping the input power relatively constant with a slowly varying load requires more energy storage (2nd curve).

It is preferred to keep higher frequency power noise off of The Grid. In the 3rd curve, a load is applied abruptly, but the input current *di/dt* is limited. Energy is supplied from storage to sustain the load as the input current soft-starts.

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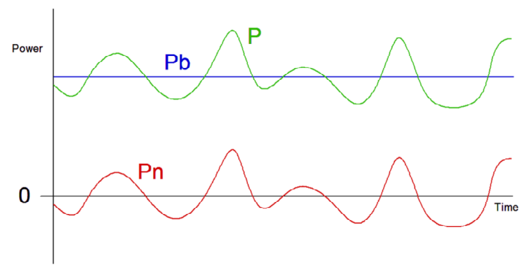
Power noise

$Pn = P - Pb.$



Power noise *Pn* is the variation of power *P* from the baseline power *Pb.*

Power noise is analogous to conducted EMI.

Power noise can originate in any connected device, irrespective of the direction of power flow.

Ideally, power is supplied and used at a steady rate, or at least it varies slowly.

Faster power transients can be characterized as "power noise." Its amplitude and harmonic content can be characterized.

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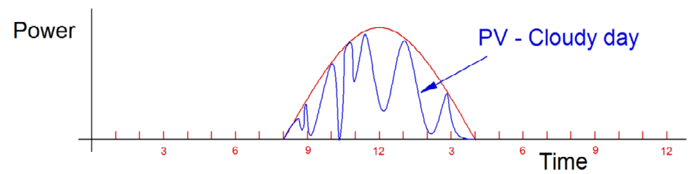
Power noise from a PV source:



"Alternative" energy sources are often cited as a source of power noise. A photo-voltaic source on a cloudy day is shown.

If the maximum power available is not captured, the energy is lost forever. It is good policy to use peak power tracking.

Positive *dP/dt* could be restricted, but if a cloud passes, large negative *dP/dt* cannot be avoided without using energy storage.

Alternative energy providers should be incentivized to incorporate energy storage to reduce power noise.

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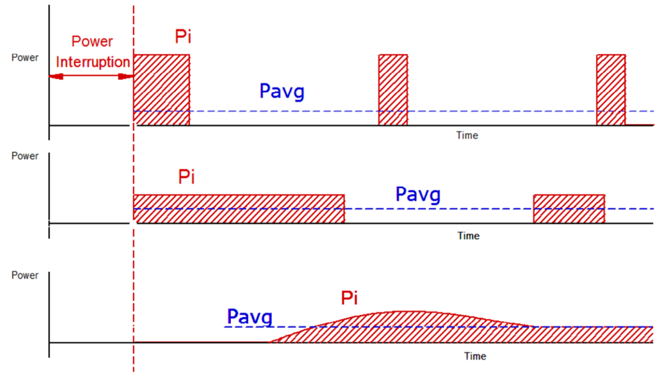
Power noise from loads



Most power noise comes from loads, particularly large on-off loads.

Proportional control has lower power noise. Proportional control with energy storage should be incentivized.

These graphs also show the problem of "on-off" loads when power is restored following an interruption. Many loads will be turned on and draw power immediately, being controlled by a thermostat or pressure regulator or the like.

Proportional control is preferred. It can be delayed when power is applied and soft-start. Power noise is minimized, but the proportional control would also enable power noise cancellation, as explained in later slides.

Proportional control is being used more often to maximize efficiency in a load. It can also be used to control energy storage and for regulation services. The needs of "The Grid" should be considered as well as the needs of the load.

Examples are variable speed heat-pumps and air-conditioners. Resistance heaters can have a power control, and PFC circuits can be modified to control throughput power as well as shape the current waveform.

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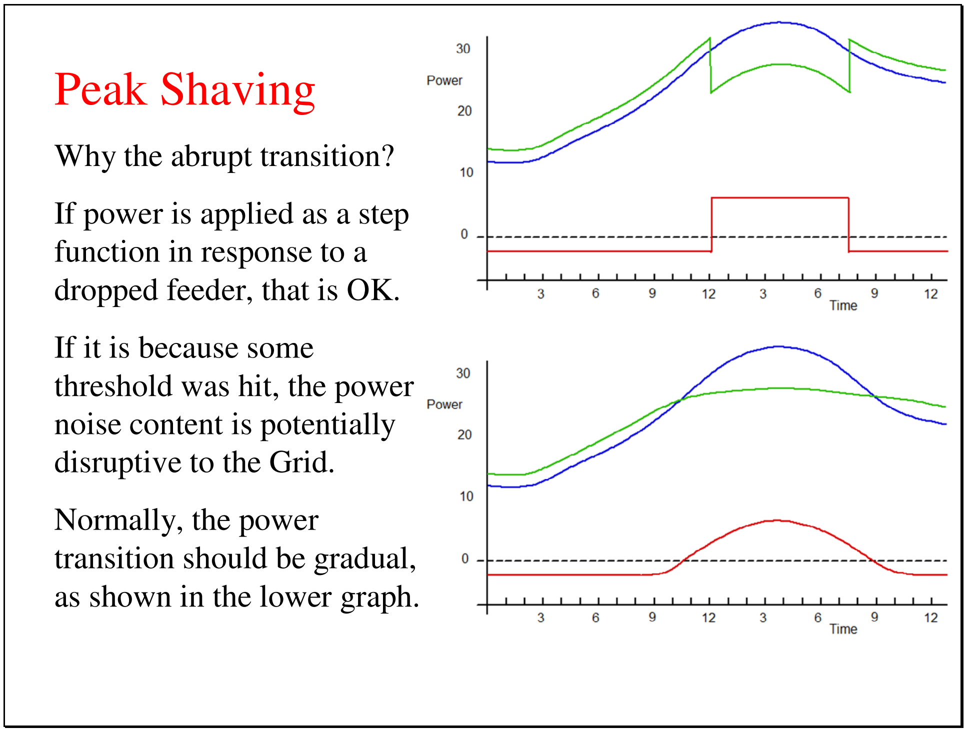

A graph like the one on the top is often shown as an illustration for peak power shaving.

Power noise is generated by any power source or load (including energy storage) that is switched in or out abruptly. The change may be more than the Grid can absorb, as it takes time to adjust the generators.

No significantly large source or load should be allowed to switch in or out abruptly. All transitions should be gradual, as shown in the lower graph.

Arbitrary thresholds should be avoided, and the response to them should be gradual.

Even non-electrical parameters may affect the Grid. A step rise in the spot price of power might result in a large number of loads disconnecting abruptly. If the reduced loading then results in a step drip in the spot price, the loads may reconnect abruptly, potentially causing a disruptive and destabilizing cycle.

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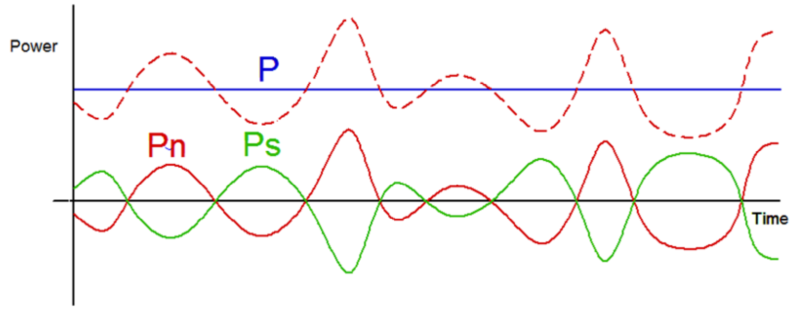
Power Noise and Regulation Services



Power noise from a source or load can be cancelled by <u>complementary energy storage</u>.

Power noise from a source also can be cancelled if a load has a <u>controlled complementary demand</u>, probably at much lower cost.

Regulation services is purposefully generated power noise that is out of phase with a source of power noise so as to cancel it. A familiar example in an audio context is noise cancelling ear phone.

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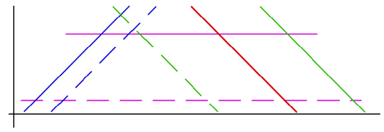
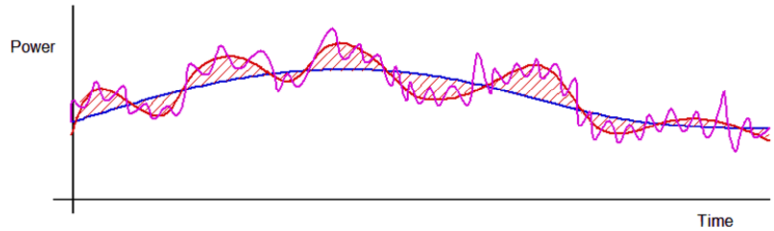
Regulation services





In a given system, the frequency response should be sand-boxed.

In the example, there is not enough energy to follow the low frequency profile, nor the frequency response to follow the high frequency power noise.

Frequency response is very important for designing and analyzing power noise cancelling equipment for regulation services.

At some upper limit, there probably will be phase lag through the detection circuits. Phase shift makes the cancellation less effective, if slight, and may make it worse if extreme.

On the other hand, trying to follow and correct low frequency variations may require more energy than is available. If the energy storage is depleted or over filled prematurely due to trying to follow low frequency power noise, then regulation services may be lost.

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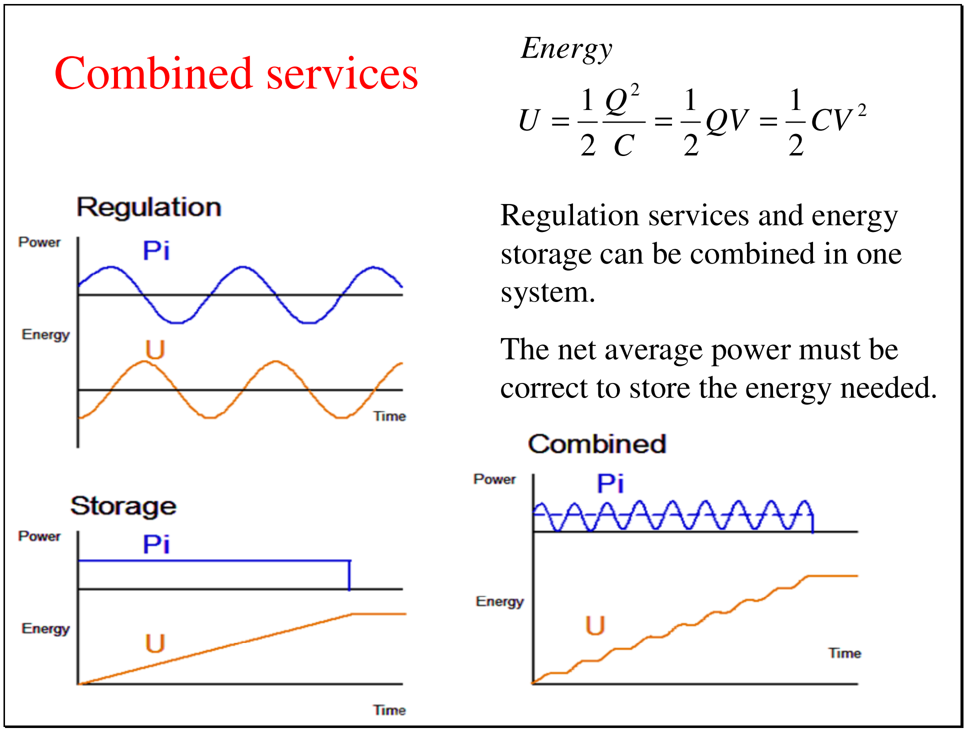

For regulation services, an energy storage device (capacitor, battery, etc.) is kept half full, on average.

The peak energy that can be supplied for smoothing is half the energy capacity.

For optimum storage for load shifting, the energy storage device is empty at the beginning of the storage period and should be full at the end. It may not matter if the storage device is full sooner.

For combined services, the average power must be controlled so that the energy storage device is full at the end of the time, but not sooner. If the average power is too high, it will fill too soon, and regulation services will be limited. If the average power is too low, it will not be full at the end.

Energy storage such as hot water cannot return electrical power, so the input power must be ≥ 0. It can, however, provide regulation services as a modulation of the power needed to heat the water over time.

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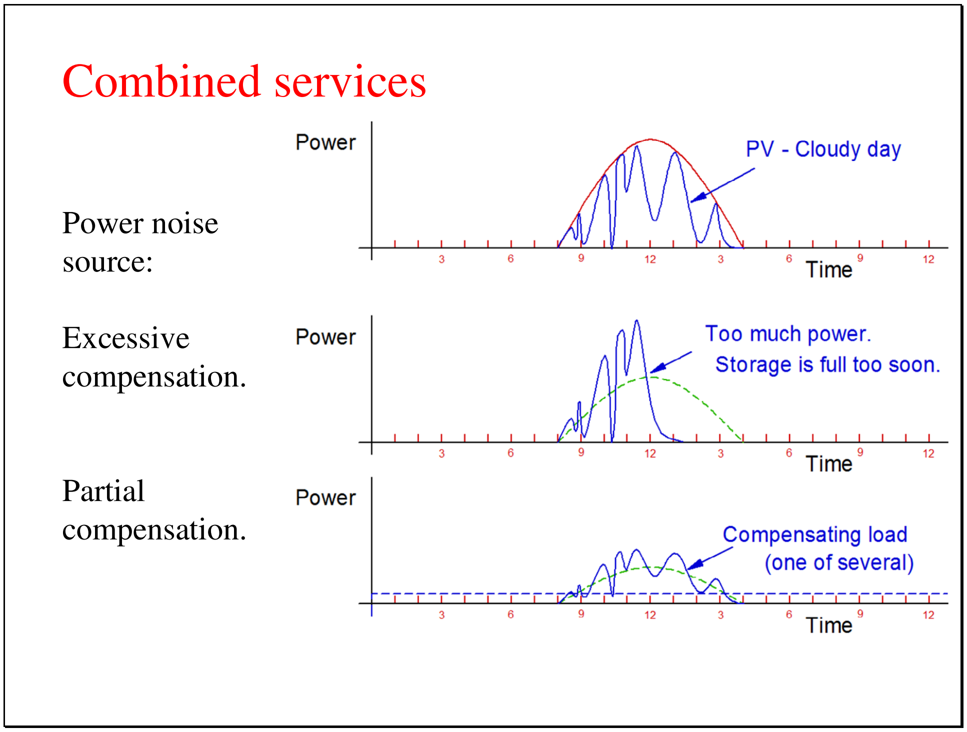

The first graph shows the power output of a peak-power-tracking PV panel on a cloudy day.

The red curve is the output on a cloud-less day, and defines the maximum that the power can be.

The second curve is the hypothetical input of a power storage device that is controlled for complementary power input so that it provides regulation services. Unfortunately, the average power is too high for the amount of storage so the storage is filled up by noon. Regulation services is ended.

So, if regulation services throughout the time period is required, the average power has to be matched to the energy storage capacity, and the energy storage must begin with enough reserve capacity so that it will not fill up too soon.

The third graph points out that one complementary load does not have to absorb the entire power noise output. It's power input has to be scaled to what it can hadle and what is needed. Note, as compared to a load that took only average power, a load with compensating power has to have double the peak current capacity.

This load could be one of several that collectively cancel all of the power noise. More likely, it will only partly attenuate the power noise, improving regulation but not trying to do more.

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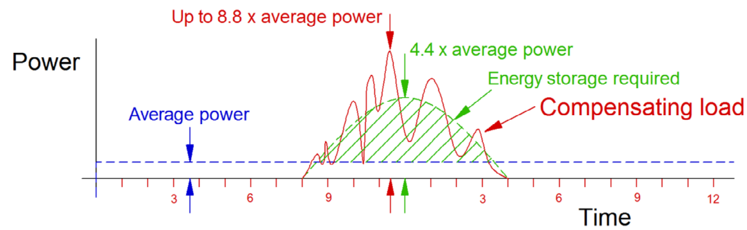
Peak power in a complementary load



Compared to a load that draws average power for 24 hours:

•Taking all of the energy during sunlit hours requires a peak power of 4.4 times the average.

•Adding complementary load regulation doubles that, to a peak power of 8.8 times the average.

This will require larger, more expensive equipment, in addition to the storage medium.

In the EPRI-PSMA workshop, "Are You Smart Enough for the Smart Grid?", regulation services was identified as being particularly valuable. As can be seen, much larger and more expensive power converters are needed as well as a much more sophisticated control algorithm.

So, rate compensation or some other consideration will be needed.

However, it is probably much less expensive to provide rate compensation to customers to provide regulation services that it would be to install large energy storage devices and their control in The Grid.

Except for needing to be larger, a small adjustment to the control algorithm of a power converter for very little cost may make it unnecessary to install Grid equipment.

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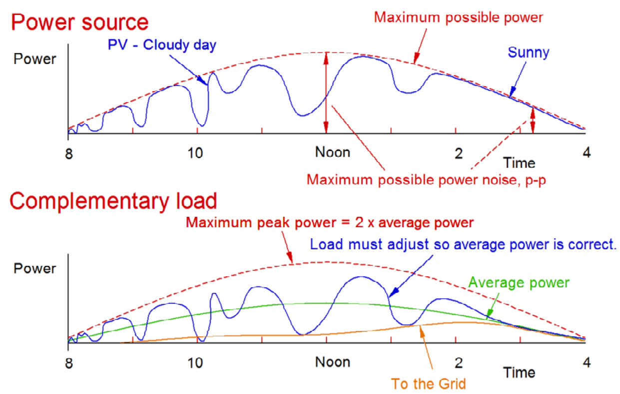
Complimentary load



At first, the load tracks the power noise closely.

Because the average power is too high, gradually the load is reduced, and more power goes to the Grid, with the power noise greatly attenuated.

Again, it is important that the average power schedule be correct if the combined criteria of sufficient energy storage and regulation services throughout the time period are to be met.

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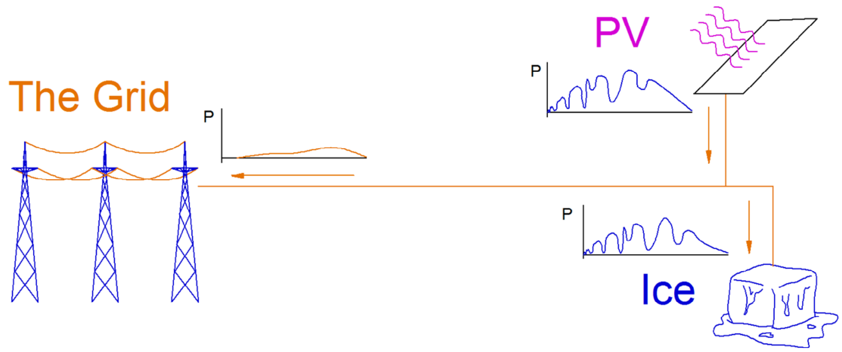
Complimentary load



By absorbing the higher frequency power noise locally, only the slowly varying power flows in the Grid.

The process of slowly varying the average power while following the higher frequency power noise profile has the effect of filtering the power noise to The Grid.

An objective should be to handle the higher frequency power noise near the source, in customers equipment. Just as in EMI, attenuating it at the source is most effective.

The large generators and slowly responding compensators should not be asked to handle fast transients.

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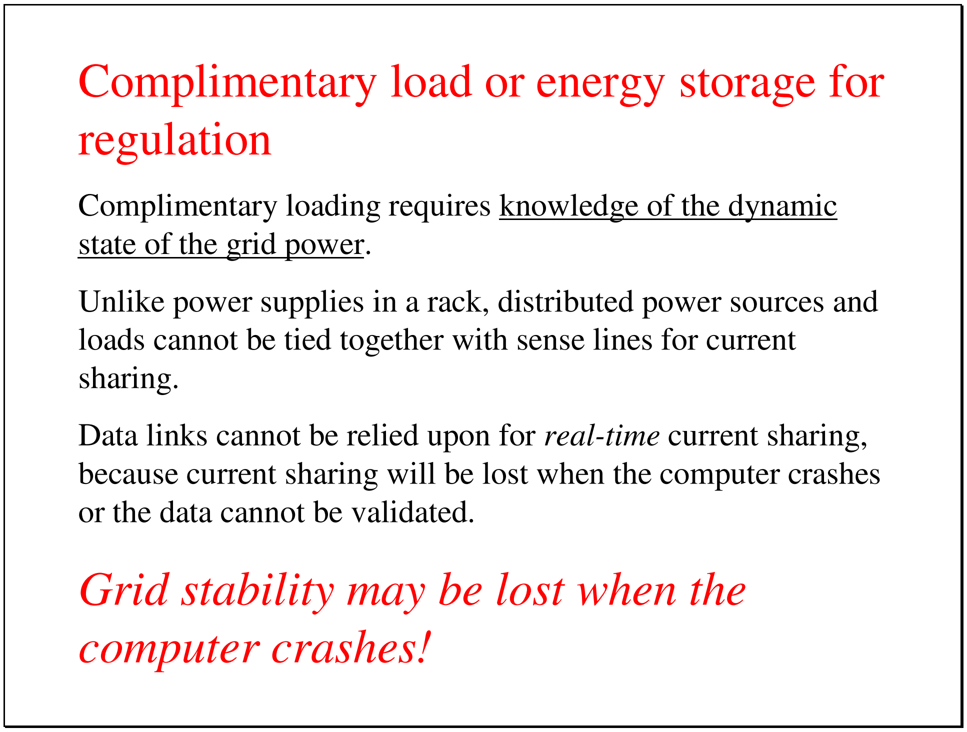

One of the more daunting challenges of power management is knowing the status of the Grid loading, to know when to modulate a load or storage for regulation services.

The simple answer is "the Internet of Things." The utility will get status and send commands to the various loads and sources telling them what to do.

This presents a problem when the computer crashes, or the data cannot be validated, particularly for equipment that must have a reasonably fast response time.

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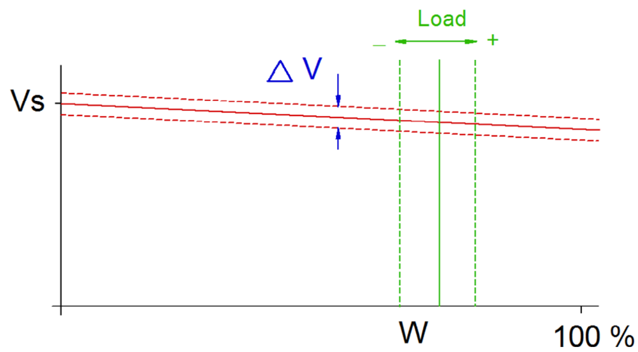
Power control by voltage sensing



The load can be modulated in response to voltage variations, as a higher voltage may indicate less loading.

However, this may be defeated by up-stream voltage controls.

The Grid needs a robust default mode for when the computer crashes or data cannot be validated. Also, the command/response lag may be appreciable, and made worse in an emergency or under certain hack attacks, just when a beneficial response is most needed.

It is much better if the response is to measured line variations. The drawing is a simple example of droop control, though that term, too, is a lexicographical mine field, having different meaning to different people in different circumstances and with different equipment.

Fundamentally, a “droop” in the voltage may very well mean an increase in load or a reduction in supply, and sensing that can tell equipment how to respond.

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Power control by frequency sensing

Frequency droop is sometimes used as an indication of Grid loading. However, as "solid state" sources and loads begin to dominate, this may become unreliable.

Even presently, frequency may not be a reliable indication of Grid loading. The ISOs need to keep the clocks as accurate as possible, so they may pour on the coal to speed up a lagging clock, leading to increasing frequency even when the Grid is heavily loaded.

We need to find alternatives to frequency sensing.

Proponents of DC power distribution often cite the problems of synchronizing as a reason to abandon ac power distribution.

Synchronizing is complex, but phase difference is a powerful tool. When well implemented, power flow can be controlled entirely by phase difference while maintaining constant voltage.

Maintaining the correct phase difference between equipment on the Grid is a daunting challenge, and poor control can lead to large current surges. This may well account for some of the problems seen bringing energy storage equipment on line.

The solution is beyond the scope of this presentation, but it is hoped that the reader will be encouraged to look for solutions.

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50.2 Hz problem

In Germany, frequencies to 50.2 Hz are seen.
400,000 inverters are being retrofitted to handle frequencies to 50.5 Hz.

Probably, they will have to upgrade again, as the underlying problem is not being addressed.

We need to find alternatives to frequency sensing.

The very large frequency variations seen in Germany are the result of poor frequency control in the distributed power converters.

It is not a solution to paper over the problem by changing the measurement limits. It is important to incorporate frequency control into all larger power converters, whether they control a source, a load or energy storage.

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Rotating machines

It is the large rotating machines and their angular momentum that stabilize the frequency of the Grid. The governors on large rotating machines control the frequency. When "solid-state" sources dominate, this control is overwhelmed.

Distributed sources and loads need "governors," emulating <u>ideal rotating machines</u>. We believe that this may lead to a clocked synchronized system. If this happens, frequency may be locked precisely. It would no longer vary with loading.

We need to find alternatives to frequency sensing.

The large rotating machines in The Grid stabilize the frequency at present, with their collective inertia making the Grid very resistant to speed variations. As the large rotating machines are overwhelmed by "solid state" loads with no inertia, large frequency swings as are seen in Germany are the result.

Power converters with any significant associated energy storage can and should emulate the inertia of large rotating machines, given a "governor," or clock, preferably synchronized to GPS signals, as are the Utility synchrophasors.

When frequency deviates, the connected equipment, collectively, should adjust their "governors" so as to tend to correct the frequency. When a sufficient number of such power converters come on line, a "critical mass," so to speak, the frequency will become locked.

This is possible within the control of the systems. The large power components should not be affected.

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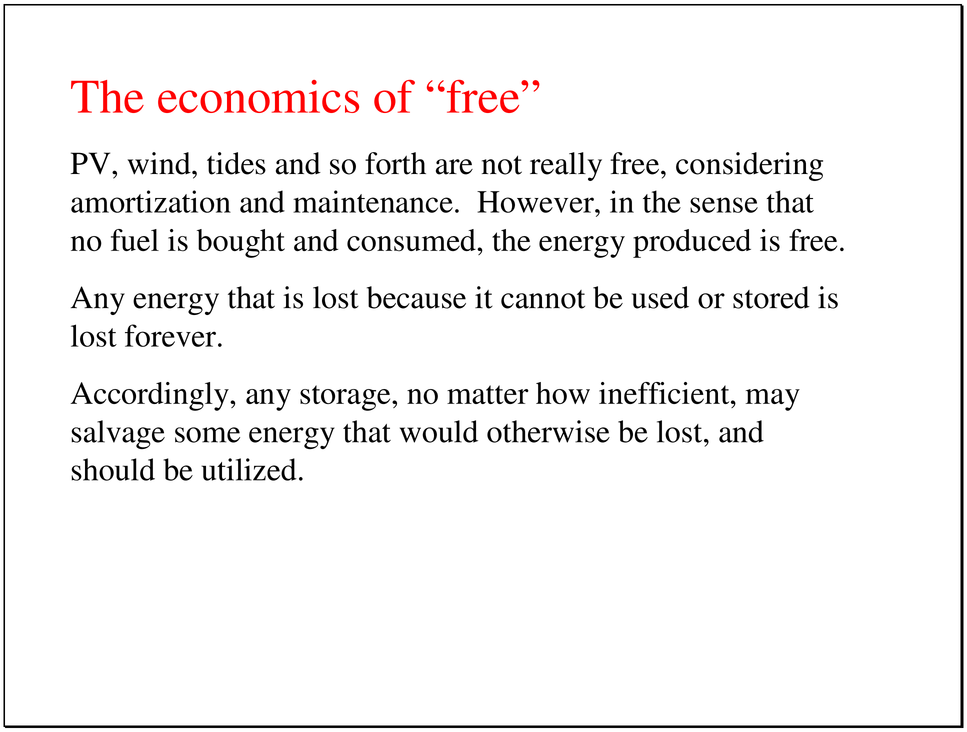

The likelihood of having significant "free" surplus energy is already being experienced in Europe on days of high production and low demand.

It stands to reason that if "zero-net-energy" buildings are encouraged, they very likely will be designed for days with higher demand and modest energy production, such as hot cloudy days when air conditioning demand is high and PV production is lower.

That same infrastructure may produce a lot of excess power on a bright sunny spring day when neither heat nor air conditioning are needed.

Any storage that can salvage some of this surplus energy is worthwhile, no matter how inefficient.

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"Leaky bucket" storage

For the same reason that inefficient storage of "free" energy is better than no storage, storage that leaks is better than no storage.

In northern latitudes, PV energy production is well matched to air-conditioning needs, but will do poorly in the winter. In the spring and fall, when neither heat nor air-conditioning are much needed, there may be a lot of wasted energy production.

Semiannual storage, ice in the spring, latent heat in the fall, may salvage some of this energy that would otherwise be lost.

An example of "leaky bucket" storage might be heating the earth, perhaps a salt dome or rocks. Much would dissipate, but if any could be salvaged later, it may be worthwhile.

Otherwise, PV panels and wind turbines may have to be shut down, loosing the power for ever. If left running, artificial loads may be needed to stabilize the Grid.

Heaters in the earth could serve that purpose, and some of the energy may be recoverable months later.

Annual energy storage

As recently as the 1950s, farmers in Vermont harvested ice from the lake and stored it in sawdust to cool their milk all summer. I helped with that when I was young.

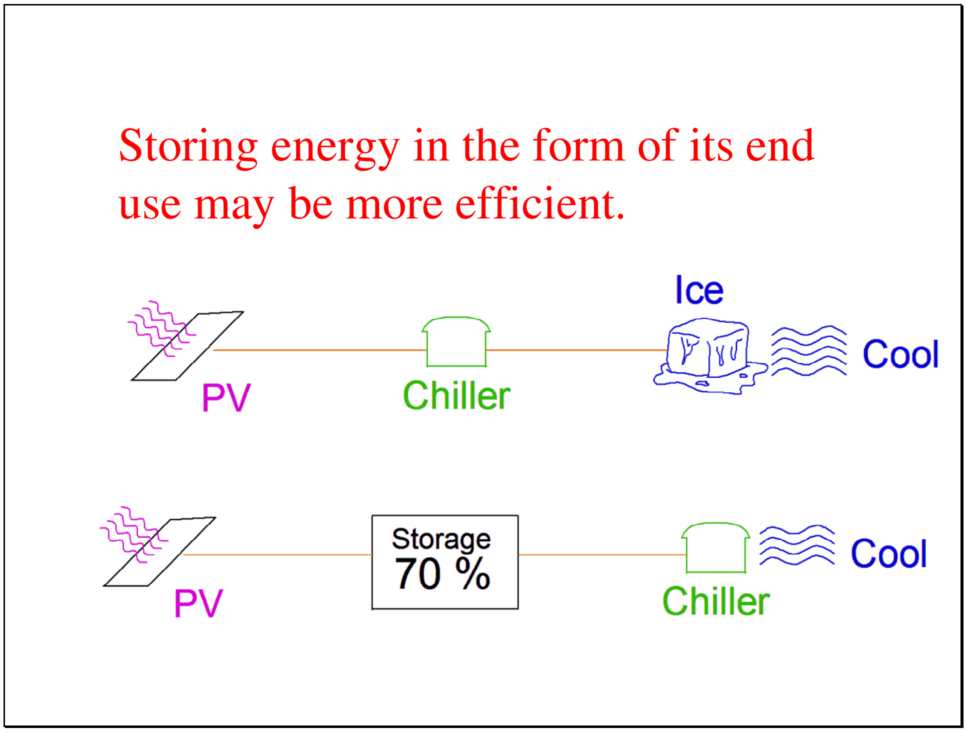
These same farmers still put up wood in the fall, and use it all winter for heat.

Can we do the same with excess solar and wind energy?

Can we save excess energy in the spring as ice for summer cooling? As building efficiency improves, it would take less.

Can we melt a large pile of salt in the autumn, for winter heating? It might provide warmth for an urban steam system.

Slide 35



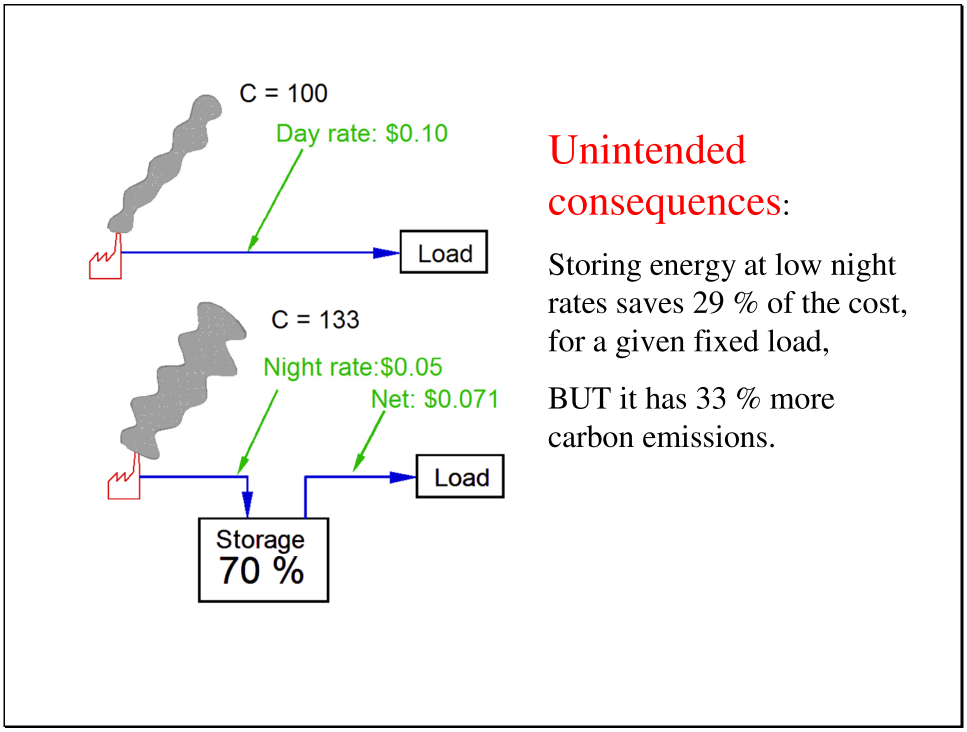
We usually think of energy storage as being batteries or capacitors, or at least some form that can return power to the Grid.

It is a very good battery that can return 70 % of the energy put into it. If energy is stored in a battery, the later used to run a chiller for air conditioning, the staring point is 30 % less. Then there are the inefficiencies of chilling.

If, instead, the PV powers a chiller directly, making ice that can be used later for chilling, the net air conditioning may be more, and ice storage may be much less expensive than comparable batteries.

Battery storage is more flexible, as the recovered electric power can be used for many more purposes, but the study is worthwhile.

Slide 36



It may be a very bad idea to use battery storage for power that has a carbon fuel source.

It is a problem with our rate structures that this may make economic sense.

It surely makes no sense if reduced carbon emissions are an objective.

Slide 37

Analysis, Design, and Performance Evaluation of Droop Current-Sharing Method Brian T. Irving and Milan M. Jovanović APEC 2000.

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Dealing with the 50.2 Hz Problem Modern Power Systems, 1 January 2013

Questions?

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