JOURNAL OF
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From the Editors

We are excited to present the first 2020 issue of the SCTE ISBE Journal of Energy Management. Our Journal is intended to spur creative thinking, drive new standards and, encourage participation in discussions to optimize our energy portfolio in the cable industry.

In this edition we present four articles. The first is centered on powering the industry's focus – 10G how we will ensure that bandwidth expansion and next generation architecture does not stress power availability and reliability since power is a cornerstone of reliability for our industry. Next, we present a primer and cost analysis on what flywheel technology can do for alternate approaches to traditional battery energy storage. The third paper will address the 30% of critical facility power load: airflow and cooling optimization. This detailed paper sets the stage for a possible industry standard on how to address the challenge of rightsizing cooling equipment. The last paper is intended for the cable industry energy procurement professionals. This paper analyzes the impacts loads have on the utility grid and how to target optimal rates. Including detailed reports on a Texas based case study which revealed how the grid could react and/or behave both cost and CO_2 wise if load optimization could be a realization.

We are thankful for the individuals who contributed to the Journal of Energy Management. We hope to spark some new ideas during your enjoyable read. If you have feedback on this issue, have a new idea, or would like to share a success story please let us know at journals@scte.org.

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Rightsizing Network Cooling - Getting Ready For 10G

Rightsizing – Part 1: Optimizing Equipment Heat Removal - Simply a ratio of kW heat per Ton of cooling?

A Technical Paper prepared for SCTE/ISBE by

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1. Introduction

As networks move to become 10G capable the increase of required network bandwidth will result in an associated increase in power and heat load created by the production equipment. Will this require a significant investment in cooling?

Surprisingly the answer is: NO.

Why?

Related industry surveys of experts indicate the following facts for IT Loads:

- Cooling capacity was found to be over 2 times what was required to meet the IT load.
- Only 40% of the cooling air was used to cool IT equipment with 60% effectively wasted capacity caused by mismanagement of airflow and cooling capacity.
- Poor use of cool air results in 15 – 25 % loss of cooling unit capacity.

The net result is millions of dollars spent over and above what is required to cool production loads. On the other hand, managed properly, this can be used as additional capacity. How can this capacity be harvested? The solution: Rightsize the cooling system.

Air conditioning "rightsizing" should be approached from two perspectives. These are the physical device calculations (for each kW of production equipment heat load a kW of cooling is required) and space airflow optimization with the end goal to provide enough cooling resources with efficient heat removal strategies. This document is intended to provide guidance to achieving rightsizing and challenges the conventional thinking that more heat means more cooling units without looking at airflow optimization. Airflow optimization is the way to reclaim cooling capacity. More heat can be removed without additional air-conditioning units - that is "rightsizing".

Prior to purchasing new cooling units, a psychrometric balancing and room airflow optimization program should be performed. If additional cooling is required after airflow optimization, then topics detailed in this paper should be closely reviewed, including the influence of a new cooling unit(s) on redundancy, future growth, building expansion and/or mechanical infrastructure cooling capacity.

2. Rightsizing

2.1. Rightsizing Defined

In critical facilities providing cooling to remove the heat produced by the production equipment is key to reducing production equipment failures. Cooling energy costs in a critical facility that has not taken steps to optimize airflow can be as much or more than the energy costs for the production equipment. The evolution to 10G capable networks will result in much greater bandwidth requiring faster response times with massive amounts of data being transported. This translates to high heat generation from the production equipment which if not properly managed will drive cooling costs to increase exponentially.

Rightsizing of cooling equipment is not just the calculation of how many kW or tons of cooling is required to match the heat load being produced. It is the exercise of optimizing the critical facility

environment to ensure airflow is adequate, but not excessive and airflow is being provided throughout the facility, to meet the needs of the production equipment. In addition, there is a balanced return airflow and temperatures through the cooling units themselves to ensure they operate efficiently.

2.2. Key Performance Metric

The overall basic metric to be used for rightsizing should be the "Cooling Ratio": kilowatts (power) required for a cooling system to remove a thermal ton (or 3.5 kW) of heat, see Figure 1. This number needs to be minimized to ensure the lowest amount of cooling system kWh is being used to achieve the highest amount of heat removal.

A facilities overall cooling ratio can be determined first from thermodynamics and then from the facility conditions which can greatly affect cooling unit performance.
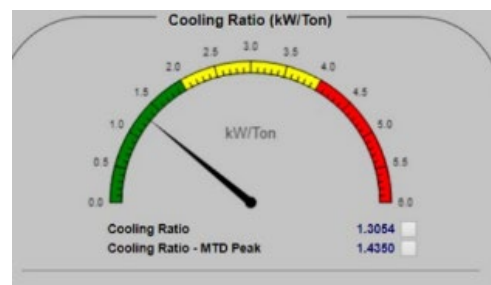
Figure 1 – The Cooling Ratio: kW Load/Ton Cooling

If airflow and temperatures are not optimal for a site, the best thermodynamic performance of a cooling unit cannot be reached. Each will be less efficient with the result that more power is used to run cooling units for a given amount of heat removal.

3. Operating Conditions

Maintaining proper temperature and humidity conditions for production equipment operation should be the main goal in determining cooling system sizing in any critical facility. Too little cooling capacity will lead to production equipment running too hot and eventual failure. Excess cooling capacity results in unnecessarily high energy costs.

ASHRAE's publication, TC9.9 2015 Thermal Guidelines for **Data Center Networking** Equipment is the guide that is typically used to establish environmental conditions for Network Facilities of all types.

3.1. Temperature and Relative Humidity Recommendations

The ASHRAE TC9.9 guidelines were updated in 2015 to reflect the new recommended and allowable temperature and humidity ranges due to the more resilient operating conditions of equipment provided by manufacturers.

The ASHRAE recommended temperatures are optimal for the hardware environment and allow for the maintenance of appropriate moisture levels. Temperature and relative humidity cannot be viewed in isolation. The recommended temperature and relative humidity levels for the hardware take this relationship into account. Relative humidity at the recommended levels is appropriate only if it is maintained in conjunction with appropriate temperatures. Lowering the temperature set points without regard to the relative humidity (RH) levels can lead to dangerous conditions.

Table 1 - ASHRAE Equipment Environment Specifications for Air Cooling (Imperial)

Class [a]	Equipment Environment Specifications for Air Cooling						
	Product Operation[b,c]					Product Power Off[c,d]	
	Dry-Bulb Temperature[e,g], °F	Humidity Range, Noncondensing[h, i, k, l]	Maximum Dew Point,[k] °F	Maximum Elevation[e, j, m], ft	Maximum Rate of Change[f], °F/h	Dry-Bulb Temperature, °F	Relative Humidity,[k] %
Recommended (Suitable for all four classes; explore data center metrics in this book for conditions outside this range.)							
A1 to A4	64.4 to 80.6	15.8°F DP to 60% rh and 59°F DP					
Allowable							
A1	59 to 89.6	15.8°F DP and 8% rh to 80.6°F DP and 80% rh	62.6	10,000	9/36	41 to 113	8 to 80
A2	50 to 95	10.4°F DP and 8% rh to 80.6°F DP and 80% rh	69.8	10,000	9/36	41 to 113	8 to 80
A3	41 to 104	10.4°F DP and 8% rh to 80.6°F DP and 85% rh	75.2	10,000	9/36	41 to 113	8 to 80
A4	41 to 113	10.4°F DP and 8% rh to 80.6°F DP and 90% rh	75.2	10,000	9/36	41 to 113	8 to 80
B	41 to 95	8% to 84.2°F DP and 80% rh	82.4	10,000	N/A	41 to 113	8 to 80
C	41 to 104	8% to 84.2°F DP and 80% rh	82.4	10,000	N/A	41 to 113	8 to 80

Table 2 - ASHRAE Equipment Environmental Specifications for Air Cooling (Metric)

Class[a]	Equipment Environmental Specifications for Air Cooling						
	Product Operations[b,c]					Product Power Off[c,d]	
	Dry-Bulb Temperature[e,g] °C	Humidity Range, Non-Condensing[h,i,k,l]	Maximum Dew Point[k] °C	Maximum Elevation[e,j,m] m	Maximum Temperature Change[f] in an Hour (°C)	Dry-Bulb Temperature °C	Relative Humidity[k] %
Recommended (Suitable for all 4 classes)							
A1 to A4	18 to 27	-9°C DP to 15°C DP and 60% RH					
Allowable							
A1	15 to 32	-12°C DP & 8% RH to 17°C DP and 80% RH[k]	17	3050	5/20	5 to 45	8 to 80
A2	10 to 35	-12°C DP & 8% RH to 21°C DP and 80% RH[k]	21	3050	5/20	5 to 45	8 to 80
A3	5 to 40	-12°C DP & 8% RH to 24°C DP and 85% RH[k]	24	3050	5/20	5 to 45	8 to 80
A4	5 to 45	-12°C DP & 8% RH to 24°C DP and 90% RH[k]	24	3050	5/20	5 to 45	8 to 80
B	5 to 35	8% to 28°C DP and 80% RH[k]	28	3050	NA	5 to 45	8 to 80
C	5 to 40	8% to 28°C DP and 80% RH[k]	28	3050	NA	5 to 45	8 to 80

The air conditioners should be set to maintain production equipment intake air conditions within the ASHRAE 2015 recommended temperature range of 64.4°F – 80.6°F (18 - 27°C) and dew point range of 15.8°F – 59°F (-9 - 15°C) (max 60% RH). These guidelines allow the Network Facility to achieve efficient use of power while maintaining hardware availability.

Most computer hardware manufacturers provide two sets of recommendations. The "recommended" conditions represent the target conditions at which the hardware environment should be maintained for optimal reliability and performance. The "operating" or "allowable" specifications are generally very wide and are designed as the maximum limits beyond which the intake conditions of the production equipment should never be allowed to exceed.

To attain these conditions and maintain energy efficiency the settings on the cooling systems can vary as there are many influencing factors including room airflow, control design, control scheme, sensor placement, sensor calibration, equipment design, equipment placement and room design.
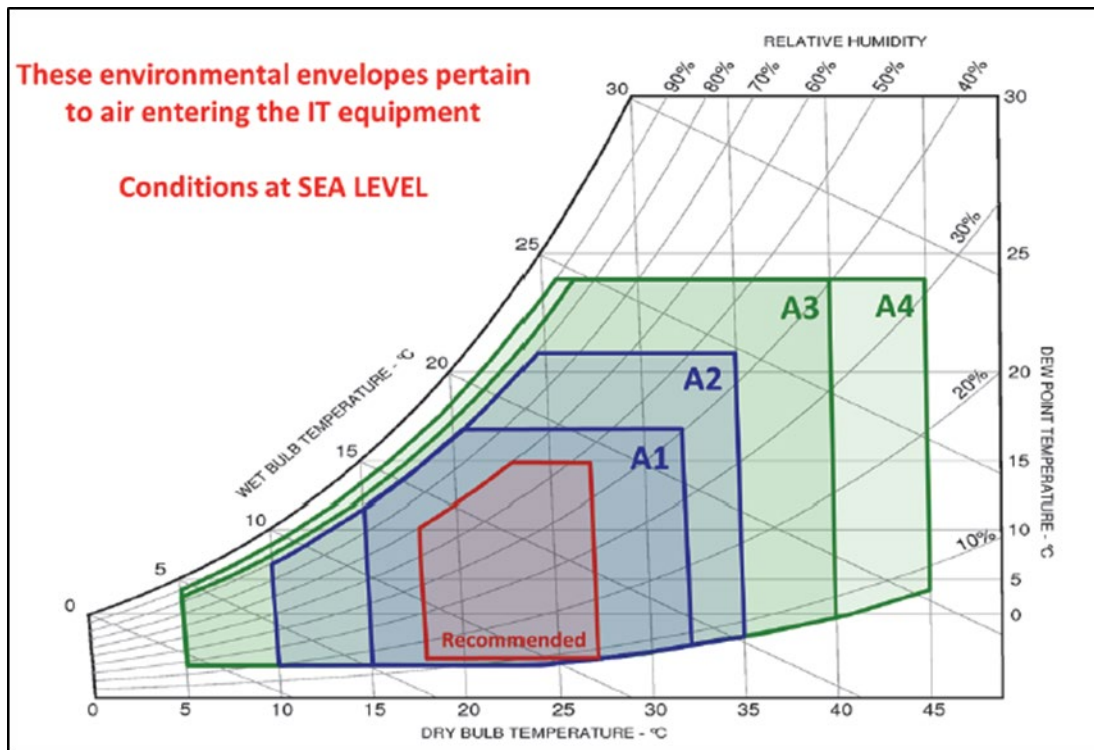
Figure 2 - ASHRAE Psychrometric Chart

Extremely high temperatures or extreme fluctuations in temperature can affect the functioning of production equipment or degrade performance. These conditions can affect the physical properties of the components, degrade performance and cause production equipment alarms resulting in possible equipment failure, increased customer impact hours and truck rolls.

Maintaining unnecessarily low temperature conditions can not only lead to associated high humidity issues, but it is also an inefficient power utilization for cooling.

Relative humidity control is also important for both availability and efficiency considerations. Cooling system humidity operation can consume significant energy if improperly designed or implemented. Ignoring the need for the maintenance of controlled humidity levels can carry comparable costs in equipment damage and lost productivity. Dust is ubiquitous and dust has deliquescent relative humidity levels that must be avoided otherwise hardware reliability can be affected. Typical RH levels below 60% will avoid this problem. Maintaining a balance between these driving considerations is important but can be challenging.

4. Airflow Optimization

Optimization of the air distribution systems should be done prior to deciding if additional cooling is required.

Airflow "rules of thumb" for the required CFM (cubic feet per minute) at the server and at the cooling unit are given in the Appendix.

The two airflow situations that will be considered are:

- raised floor, see Figure 3, and
- slab on grade, see Figure 4.

Both ideally have an aisle that is designated as a cold aisle (supply air, equipment inlet) and on designated as hot aisle (return air, equipment exhaust).

In raised floor environments, adequate underfloor pressure must be calculated and provided to accommodate the space thermal load. All penetrations should be properly sealed to reduce un-intentional leakage, allowing strategic perforated tile sizing and placements. Ideally the cooling units are placed at the end of a hot aisle and not facing the equipment. ASHRAE publications and manufacturer's information show appropriate subfloor pressure between 0.030" and 0.045" WG (Water Gauge). The number and location of perforated tiles or air grilles will be calculated to maintain appropriate subfloor pressure. Calculations are based on the cooling unit(s) specifications and perforated tile specification. That is underfloor pressure is a proxy for adequate room airflow.
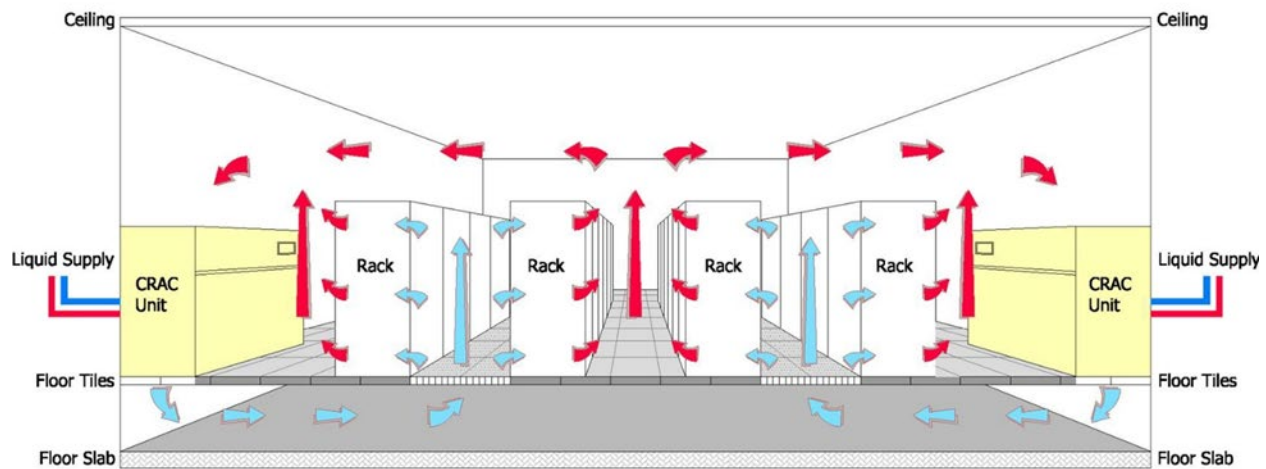
Figure 3 - Raise Floor Airflow (©ASHRAE Used with permission. (2015))
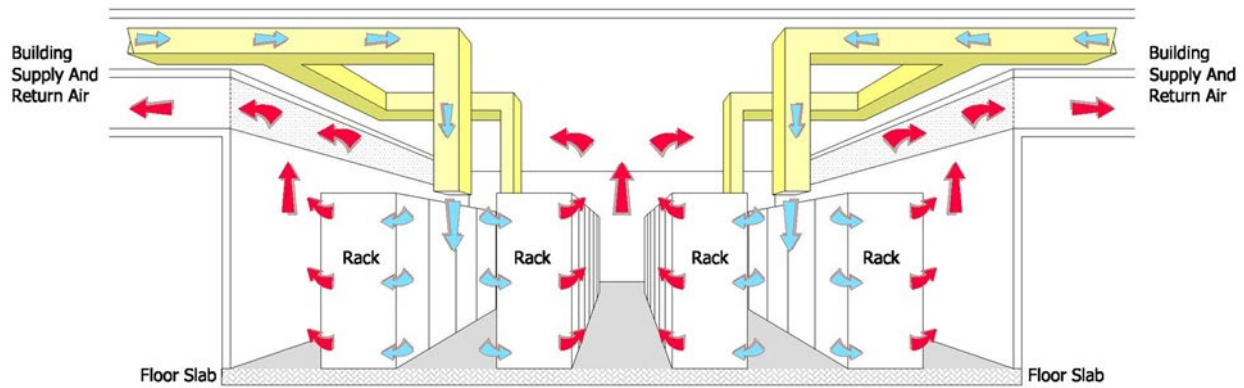
Figure 4 - Airflow Slab on Grade (©ASHRAE Used with permission. (2015)).

Overhead cooling in a slab floor environment presents unique challenges including ensuring duct sizing is appropriate for the volume of air supply and minimizing elbows in duct work which can significantly reduce air flow. Hot aisle cold aisle configurations will facilitate improving cooling efficiency. If the cooling units are in the white-space with the production equipment they should be placed at the end of the hot aisle to minimize the return air path.

All key airflow paths to be considered for airflow optimization are shown in Figure 5.
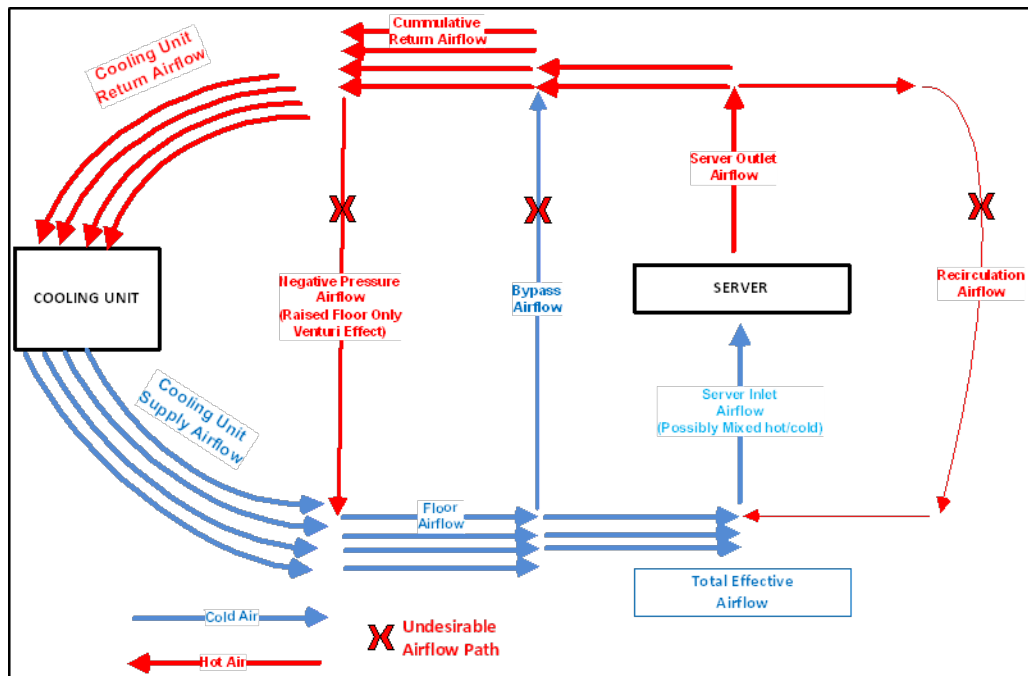
Figure 5 - Airflow Paths

Note that negative pressure, indicated by the red arrow, shown in Figure 6 is only in a raised floor environment. This occurs because the floor tile may be too close to the cooling unit and the velocity of the air under the tile causes air to be drawn down into the tile (Venturi effect, usually at greater that 530 f/min).
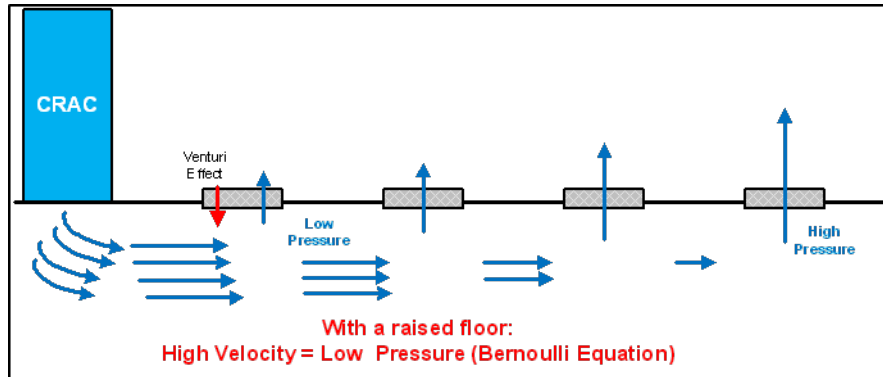
Figure 6- Raised Floor Only, Negative Pressure

Bypass air is a short circuit of cold air in a raised floor resulting in the air returning to the cooling unit without being used to cool a server. For both raised floor and slab on grade recirculation can occur if there is not enough air to feed the server and it draws its own exhausted and mixed air in to meet its own airflow requirements. It can be caused by excess air volume, HVAC locations and lack of blanking panels resulting in the server exhaust being drawn back to the server inlet. This is shown in Figure 7.
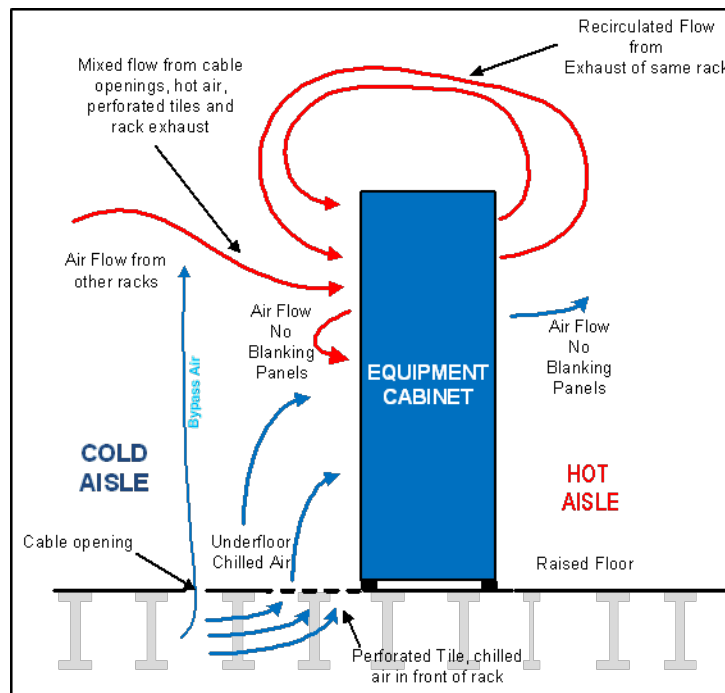
Figure 7 - Bypass and Recirculation

Other considerations in a raised floor environment are underfloor obstructions to airflow. Although power cables, network cables, fire systems and associated equipment trays are generally found under floor these must be minimized. Most cabling should be routed under the hot aisle leaving the plenum under the cold aisle as free from obstructions as possible.

4.1. Air Flow Optimization at the Server

Regardless of whether there is a raised floor or slab on grade, baseline measures of temperature and humidity should be done at the rack inlets to create a profile of conditions in the site. This can be accomplished using basic temperature and humidity gauges on every third rack or by implementing a monitoring system to collect and display data on a continuous basis as shown below.

The objective of optimizing airflow is to ensure adequate airflow is available to meet the production equipment air intake requirements at acceptable temperature ranges and to minimize the variation of inlet temperatures in the site. In the Figure 8 the inlet temperature range in this aisle is from 69°F (20°C) to 86°F (30°C) with the top end temperatures being in excess of the ASHRAE recommendation of 80.6°F (27°C). Airflow optimization should be conducted to close the gap between the lowest and highest inlet temperatures.
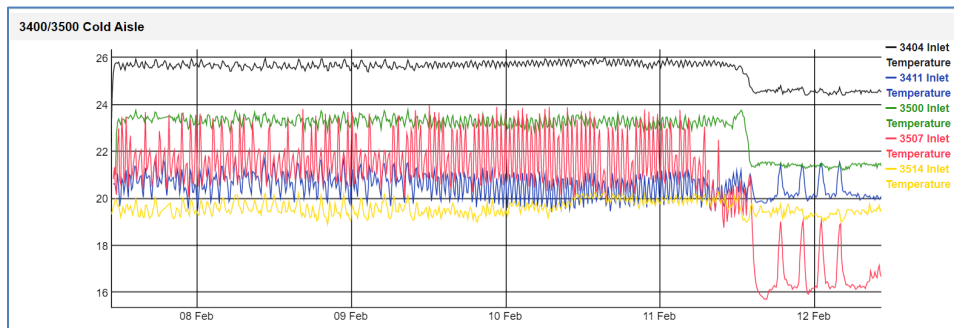
Figure 8 - Rack Airflow Temperatures

Figure 9 - Rack RH%

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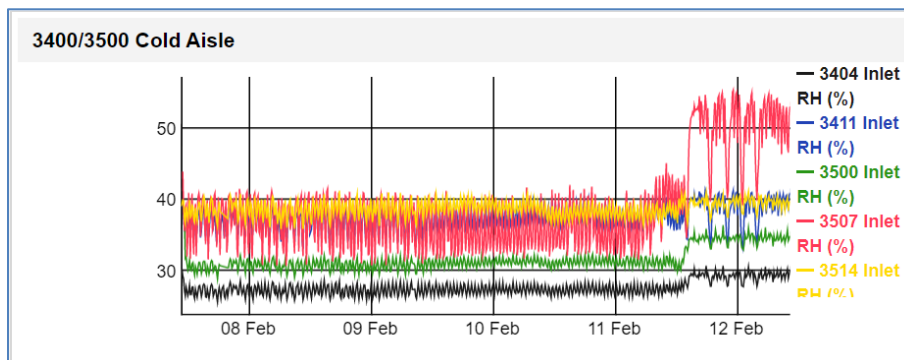
Figure 9 shows how relative humidity levels can vary depending on temperature. As the inlet temperature goes down, for example rack 3507 in figure 8, humidity levels for rack 3507 in figure 9 increase from less than 40% relative humidity to over 50% relative humidity. Monitoring relative humidity conditions helps to ensure conditions do not creating condensation.

In a site with a raised floor airflow through the perforated tiles to should be measured determine if adequate airflow is being provided to meet the cooling needs of the rack heat loads.   As a rule of thumb (see appendix for formulas) for every 1 kW of production equipment power draw, 150 CFM (cubic feet per minute) of airflow is required. For a rack with a 3 kW power draw, 450 CFM should be provided. If less airflow is being supplied, then the equipment inlets may pull warm air from the back of the equipment exhausts or from the room causing the equipment inlet temperatures to be recorded as too high. Using the guideline above a site with 80 kW of production power draw would require the cooling systems to supply at least 12,000 CFM. Even though this level of supply air is being provided it does not necessarily mean airflow distribution in the site is good. Differing heat load densities in racks, reverse airflow racks, lack of blanking panels or congestion in the supply plenum will all impact the air distribution and how well the production equipment cooling needs are being met.

In a slab floor environment, airflow from the ducts can be measured to determine if adequate supply is available. Similar to the raised floor environment, if adequate airflow is not provided equipment may pull warm air from the back of the rack creating the perception of hot spots when in fact adequate cooling and airflow is available.

Cooling needs of low heat load racks, less than 2 kW, can typically be met by ensuring there is enough air supplied in the room to meet the overall cooling needs of the equipment. Once rack heat loads begin to exceed 3 kW for example placement of a few high-density racks in an otherwise low-density site more attention to airflow distribution is required.

Providing excess airflow in a site is equally bad in a site as the excess air causes the return air temperature to the cooling system to be low, resulting in the unit's operating efficiency to be lowered. Ideally the temperature difference between the return air temperature and supply air temperature measured at the cooling unit should be on the order of $\Delta20°F$ ($\Delta10°C$). Lower temperature deltas are an indication of excess air supply and air mixing in the site.

The location and installation of the cooling units, floor space configuration, rack locations and other variables and obstacles in the site have a significant effect on the operating efficiencies of the cooling systems. A focus on these variables and airflow obstacles can identify optimization opportunities that improve the long-term efficiency of the space and can cost significantly less than new cooling units.

The conditioned air must be distributed to the areas in need of heat removal and the heat must be returned to the air conditioners for reconditioning. Furthermore, balancing the airflow capacity provided by the air conditioners with the distribution of conditioned air in the subject area is critical to both hardware availability and energy usage efficiency.

4.2. Airflow Optimization at the Cooling Unit

Once airflow is optimized to and from the production equipment, the cooling unit must be optimized. As mentioned earlier the ΔT from return air to supply air temperature directly affects the capacity of the cooling unit. An example of this is shown in Figure 10. As can be see if the return air temperature is

increased from 75°F (24°C) to 85°F (29°C) for a Direct Expansion CRAC (computer room air conditioner) there is a 30% increase in sensible cooling capacity.
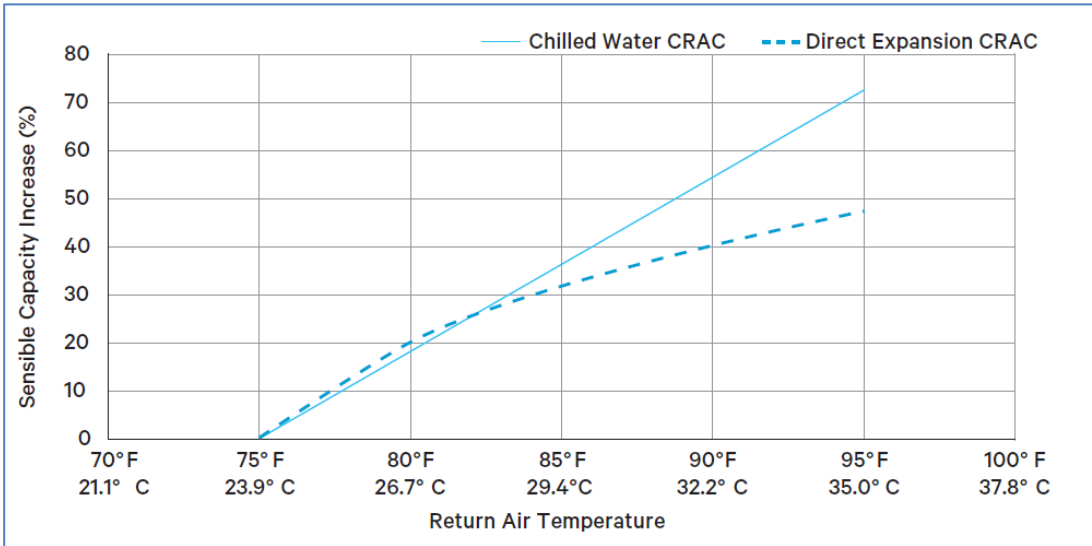
Figure 10 - Sensible Capacity Increase with Return Air Temperature

("Focused Cooling Using Cold Aisle Containment", SL-24636(R02/09), ©2017 Vertiv Co.))

Not only must airflow be optimized to ensure return temperatures are high, but the set point of the cooling unit must be properly adjusted. This is dealt with in detail in **SCTE 253 2019: Cable Technical Facility Climate Optimization, Operational Practice: Understanding Set Point Values, Part 1.**

4.3. Cooling Optimization Process

Adjustments to the air distribution system, whether it's air distribution tile placement, overhead duct vent adjustments, or actual modifications to the duct system, is part of the optimization process and are necessary to fine tune to meet ASHRAE inlet air conditions. This process is typically iterative as shown in the figure below, between air balancing (changes to the air distribution network) and changes in cooling system set points (and sensitivities) until goal conditions are met.
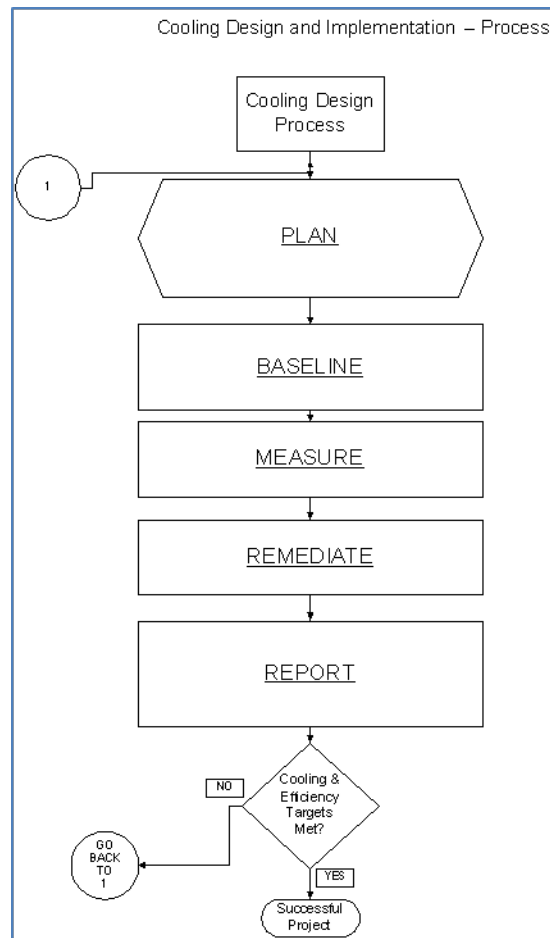
Figure 11 - Cooling Process (with permission from Rogers)

While many good design practices have gone into the building of hub, headends and data centers, many other additional steps should be conducted to ensure optimal operating conditions. It is recommended that an ongoing monitoring and optimization program be enacted. This program will aid in addressing the ever-changing heat load configuration typical in the normally dynamic lifecycle of the critical space. Doing so will aid in balancing air distribution to the room heat load and allow for increased cooling efficiency.

5. Estimating Cooling System Capacity

It is important to accurately assess the cooling capacity of the air conditioning equipment in order to ensure that there is adequate capacity to meet the needs of the production hardware. For example, the net total cooling capacity of a cooling unit may be listed as 270,300 BTU (22.5 tons or 79.2 kW at 85°F (29.4°C) dry bulb at 30% RH.

The cooling unit model number generally contains the nominal tonnage (BTU) or kW ratings. In the example above the unit would be referred to as 22 ton unit (270,300 BTU/12000 # of BTU's per ton = 22.5 tons). This can be misleading as total capacity refers to the sensible and latent cooling combined at a specified return air temperature, where sensible cooling is accomplished through the removal of heat and latent cooling through the removal of moisture. Critical facilities typically do not create humidity therefore the sensible heat removal component is the most important. The temperature referred to in the above example is the return air temperature to the cooling unit and not the supply air temperature. Lower return air temperatures can reduce cooling capacity by 25% or more.

The number of air conditioning units required depends on the sensible cooling capacity and the desired temperature and relative humidity conditions at which the room is to be maintained. At a set point of 72° F (22.2°C) and 50% RH, the net sensible cooling capacity of the same unit falls to 17 tons or 59.7 kW, a reduction of 24.6% as it is operating less efficiently at the lower return air temperature. This dramatic decrease in cooling capacity demonstrates the importance of taking the operating conditions of the room and heat loading into account when determining the cooling capacity.

Air conditioning systems, such as split-systems or self-contained refrigerant-based air conditioning systems typically have a much lower sensible heat ratio (SHR). This low SHR forces the removal of significant amounts of moisture from the air. In effect, these units will act as large dehumidifiers for which moisture will needs to be re-introduced into the space in order to maintain appropriate levels. This is an inefficient process and will increase the energy usage of the facility.

6. Calculating Critical Facility Heat Load

Production equipment in a critical facility is the main contributor to the total site heat load. Depending on the site, lighting can account for 2 - 3% to the total heat load however with upgraded LED lighting systems this value will be much less. Additional equipment in the facility such as the power plant and the cooling units themselves will add to the total heat load. A representation of typical heat distribution is shown in Figure 12.
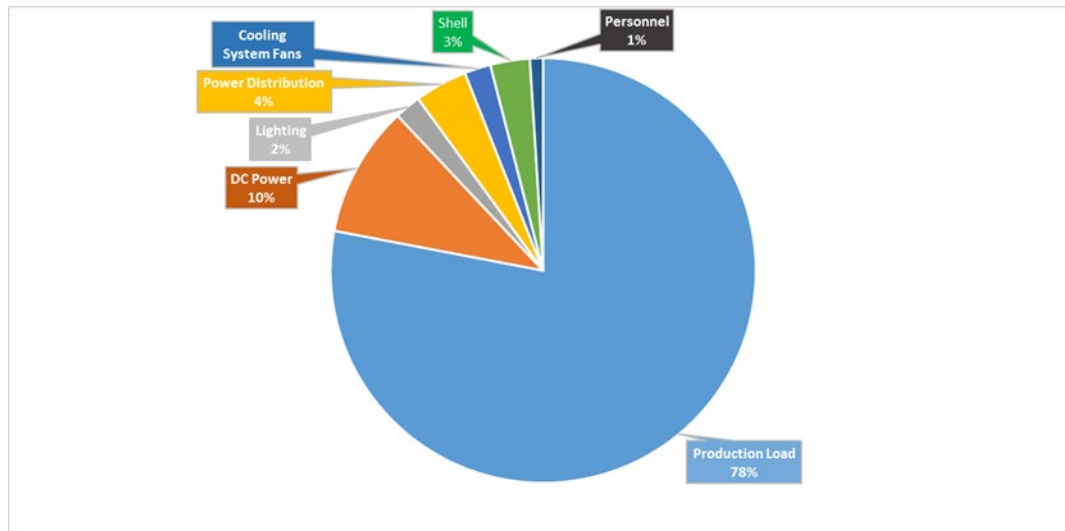
Figure 12 - Typical Heat Loads

6.1. DC equipment Heat Load

If the production equipment is all powered by a DC plant, then the simplest methods for calculating the heat load is by readings directly off the rectifiers. For each kW of power used to power production equipment, one kW of heat is created.

6.2. Rectifier Efficiency

If the rectifier bays are in the white space of the site then the addition of the DC plant efficiency losses, which generate heat in the conversion from AC power to the rectifier DC voltage, should be added. Newer rectifiers can have efficiency levels of 95% however older models can be as low as 88%. It is best to look up the specifications of the rectifier and use the published efficiency rating.

If all rectifiers and batteries are located in a separate enclosed power room then they will typically be served by cooling systems dedicated to the power room and any heat load should not be included.

6.3. Heat Loads other than DC plant

If there is additional equipment that is not powered by the DC plant and the equipment is inside the white space the power it consumes turns into heat and should be accounted for in the heat load calculations.

Some examples of AC loads found in cable operator facilities

- Direct to battery load: Inverters going from DC to AC only if these are running off the battery (not the DC plant/rectifier bay)
- Transformers in the room: Connecting to prime power.
- Humidifiers: This will vary over time between full power and idle. Estimating at full power will provide additional margin on most days.
- Floor fans

6.4. Heat Load contribution from lighting

All lighting from old style florescent bulbs to the more efficient LED bulbs will have a listed wattage of power consumed. The power consumed represents the heat load. Add up all the power for each bulb and this will provide the heat load contribution of the lighting.

In "unmanned facilities" where the lights are only on a few hours per month the heat load contribution of the lighting will be negligible and can be ignored.

6.5. Heat load from Cooling Units

If the HVAC equipment resides inside the facility there will be a contribution to heat load from the unit fan or blower motor, or evaporator fan power. This can be ascertained by either isolating the fan power measurement while the blower is at full speed or can be estimated by the maximum fan power from the HVAC equipment cut sheet. If the HVAC equipment resides in a CRAC gallery or roof top units then there is no additional heat load contribution.

Newer HVAC equipment designed for critical facility cooling applications is now being certified to net sensible capacity, meaning fan power contribution has already been removed from the system cooling capacity.

7. Other Consideration

There are two other main considerations when undertaking rightsizing, particularly as the industry moves to 10G:

- Reliability (availability)
- Resilience.

Reliability (availability) is determined by measuring the number of racks where ASHRAE inlet conditions are met under normal operating conditions. This is called Thermal Conformance in Figure 13.

The resilience is determined by measuring the number of racks where the ASHRAE inlet condition are met under a cooling unit failure. This is required to make sure that N+1 cooling units does provide protection from a failure of one cooling unit. Airflow changes may result in inlet conditions not being met when using N units and this must be addressed to ensure proper redundancy. This is called Thermal Resilience in Figure 13.

This is particularly important when increased set point temperatures are used to increase return air temperature.
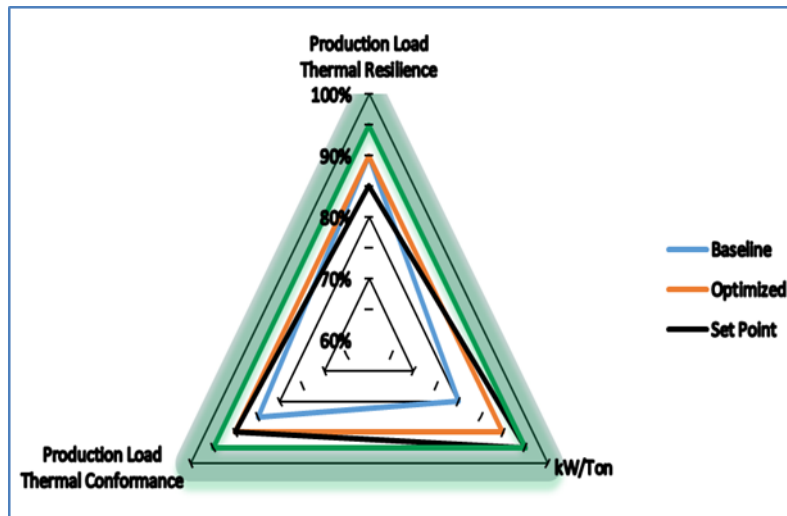
Figure 13 - Rightsizing Reliability and Resilience

8. Conclusions

Rightsizing cooling is the key step to prepare for future heat loads including 10G.

Operating under the condition of excess cooling capacity is not viable in the long run, especially as heat loads continue to increase.

The key 'levers' to success are:

- Using standard operating conditions (ASHRAE)
- Airflow optimization at the server
- Airflow optimization at the cooling unit
- Understanding the heat loads at network sites
- Using appropriate set points for temperature and humidity

Metrics for success are maximizing the cooling capacity of each cooling unit, measured by kW of power used for every ton of heat load.

In addition, care must be taken to ensure reliability(availability) and resilience of the cooling system.

Further information regarding environmental requirements, climate optimization and energy management can be found in the following documents:

- SCTE 186 – Product Environmental Requirements for Cable Telecommunications Facilities
- SCTE 219 – Technical Facility Climate Optimization Methodology
- SCTE 234 – ISO50001:2011 Energy Management Systems, Energy Metrics with Guidance for Use.

9. Appendix – Airflow Formulas

The following formulas determine the basic airflow requirements. These can be considered "rules of thumb" for the required CFM (cubic feet per minute) at the server and at the cooling unit.

Server Cooling Formula for CFM for 1 kW of heat removed:

$$CFM = 3412/(1.08 * \Delta T)$$

For a ΔT of 20°F(10°C) the resulting CFM is:

$$CFM = \frac{3412}{1.08 * 20} = 150$$

For the Cooling Unit CFM:

$$CFM = (\frac{BTU}{hr})/(1.08 * \Delta T)$$

Given that 12,000 BTU/hr = 1 Refrigeration Ton of cooling, then at a ΔT of 20°F resulting CFM is:

$$CFM = \frac{12000}{1.08 * 20} = 555$$

10. Abbreviations and Definitions

10.1. Abbreviations

10G	10 gigbit
AC	alternating current
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BTU	British thermal unit
BTU	British Thermal Units
CFM	cubic feet per minute
CFM	Cubic Feet per Minute
CRAC	computer room air conditioning
DC	direct current
HVAC	heating ventilation air conditioning
ISBE	International Society of Broadband Experts
IT	information technology
kW	kilowatt
kWh	kilowatt hours
LED	light emitting diode
RH	relative humidity
SCTE	Society of Cable Telecommunications Engineers
SHR	sensible heat ratio
WG	Water Gauge, imperial measure for small pressure differential
10G	10 Gigs

10.2. Definitions

Air Bypass	Conditioned air that does not reach computer equipment, escaping through cable cut outs, holes under cabinets, misplaced perforated tiles or holes in the computer room perimeter walls.
Air Recirculation	Supply airflow returning to cooling units without passing through production equipment, also referred to as short cycling
Deliquescent Relative Humidity	The relative humidity at which dust absorbs enough water to become wet and promote corrosion.
Hot Spot	An area, typically related to a rack or set of racks, where ambient air temperature is above acceptable levels, typically caused by heat generation exceeding cooling equipment capacity.
Production Equipment	All Network Equipment associated with delivering any service to customers…
Rightsizing	Process not just involving the calculation of how many kW or tons of cooling is required to match the heat load being produced. It is the exercise of optimizing the critical facility environment to ensure airflow is adequate, but not excessive and airflow is being provided

	throughout the facility, to meet the needs of the production equipment. In addition, there is a balanced return airflow and temperatures through the cooling units themselves to ensure they operate efficiently.

11. Bibliography and References

- SCTE 186 – Product Environmental Requirements for Cable Telecommunications Facilities
- SCTE 219 – Technical Facility Climate Optimization Methodology
- SCTE 234 – ISO50001:2011 Energy Management Systems, Energy Metrics with Guidance for Use.
- SCTE 253 2019: Cable Technical Facility Climate Optimization, Operational Practice: Understanding Set Point Values, Part 1
- TC9.9 2015 Thermal Guidelines for Data Center Networking (ASHRAE)

Flywheel Energy Storage Replacement
For Lead - Acid Batteries in CATV Network Stand
- By Power Supplies

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1. Introduction

The need for highly reliable access networks has never been greater and will continue to grow as our Cable Networks provide greater and greater Internet throughput. The Cable Television Internet access network has dominated the last mile connectivity market for many years. This service demand has driven amazing creativity in the design of innovative ways to use the installed cable infrastructure to meet these needs.

The distributed powering design of our network is an area in great need of improved reliability. We have used lead-acid batteries as the primary energy storage device to provide continued operations when commercial power is lost. The struggle is that lead-acid batteries degrade in high temperatures, have reduced capacity in low temperatures, require significant maintenance and are not environmentally friendly.

This paper examines the use of flywheels as a direct replacement for the lead-acid batteries. Flywheels are a mechanical battery. Using a heavy mass spinning at high RPMs, the flywheel can store energy in the form of mechanical or kinetic energy. When grid power is lost, the flywheel becomes a generator providing a replacement of the lost power. Flywheels provide consistent power, independent of temperature, over a very long life with little to no maintenance ... the exact shortcomings of lead-acid batteries.

2. Flywheels

2.1. Flywheel History

Flywheels were first introduced to the Cable Industry during the mid 1990s. The CableLabs Telecom Subcommittee was looking into switched telephony and how to meet the telephony standard of no more than 53 minutes of system downtime per year, with the distributed powering network of a cable system. It was determined that replacing the lead acid batteries in the 60v/90v standby power supplies, in use at that time and often still in use, would allow the cable systems to meet the 53 minute unavailability standard.

The first flywheel was installed in 1999 in Harrison NE for Windbreak Cable. This wheel was used as a true field test to understand what improvements would be needed for a final design. A production 5KWh flywheel was installed in Lyman NE for the same cable operator in 2001 and after 19 years is still operating.

The two most asked questions regarding the use of flywheels were 1) would they operate for 20 years with little or no maintenance as claimed by the manufacture and 2) would they explode if something went wrong. The installed flywheels in the Windbreak Cable systems answered both questions, having operated for 19 years with no major problems.

2.2. Flywheel Technology

The flywheel is, an essence, a mechanical battery. It stores energy by spinning a heavy mass at high speeds and when grid power is removed the mass continues to spin, generating power for the connected load.

Flywheel stored energy is calculated as follows:

$$E = \frac{1}{2} k M R^2 w^2$$

where:

k = shape constant

M = mass

R = radius

w = rotational speed

Flywheels can be designed in different ways using different materials for the mass, depending on the application. The particular design of the Beacon Power flywheels installed at Windbreak Cable use a mixture of fiberglass and graphite for the mass mounted on a steel hub. To reduce loss, the wheel is mounted on frictionless magnetic bearings and is all contained in a vacuum chamber as represented in the Figure below.
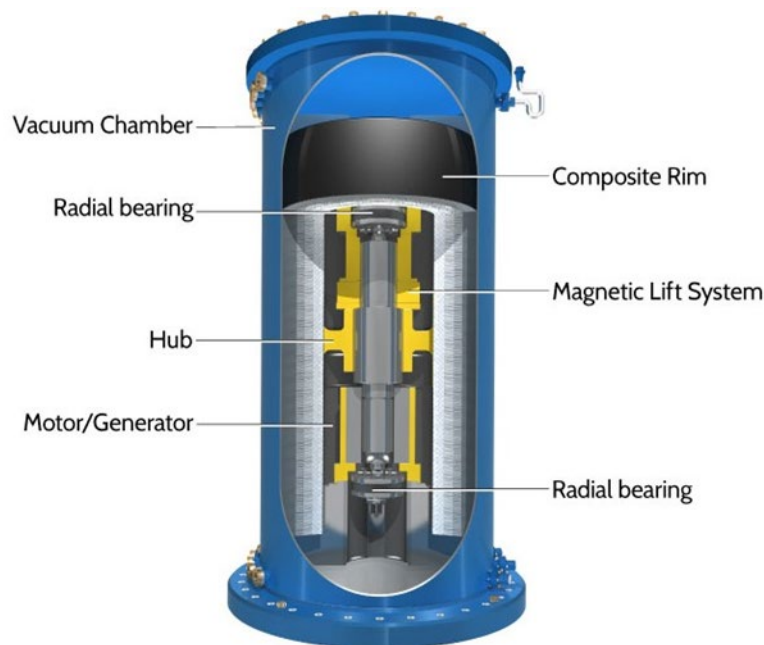
Figure 1 - Beacon Flywheel Cross Section

A flywheel has 3 modes of operation: Power Up, Standby and Power Generation. In the Power Up or "Charge" Mode, the flywheel's motor/generator draws power from commercial power to spin up the rotor. In Standby or "Float" Mode, the flywheel spins in a vacuum on magnetic bearings. The vacuum and magnetic bearings provide a high efficiency, low loss, operating environment. In this mode the flywheel needs less than 100 watts to maintain the high speed of the rotor.

The Power Generation or "Discharge" Mode occurs when utility power is lost. The motor transitions into a generator and converts the kinetically stored energy, contained in the spinning mass, into electric energy for use by the connected load. This power generation continues until either utility power is restored or the flywheel speed slows to a point that the generator can no longer produce power at the level required by the load. Since the load and the motor/generator are connected to the same bus, see Figure 2, there is never an interruption of power to the load.
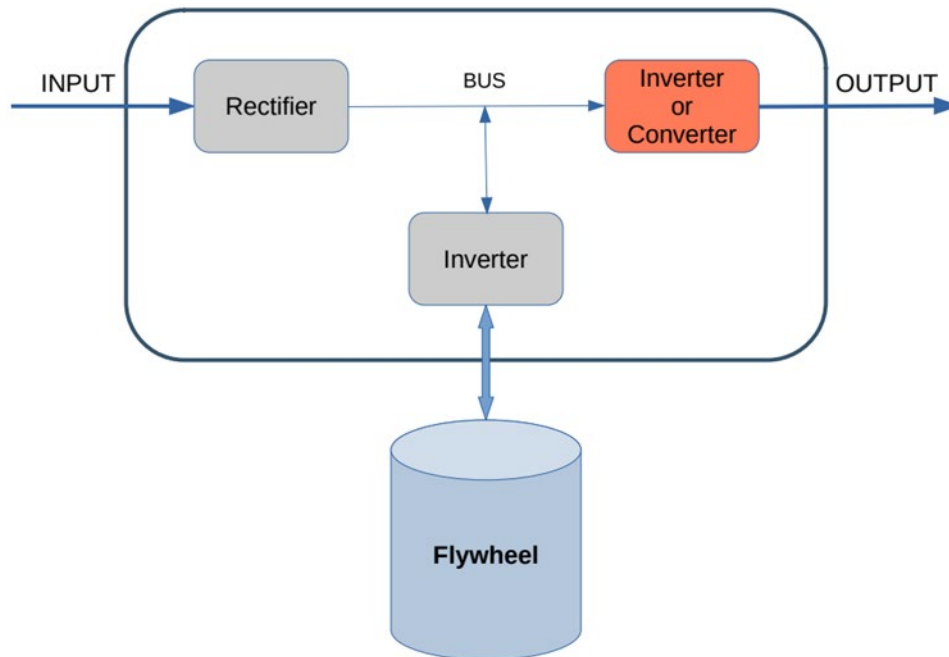
Figure 2 - Flywheel Connection Diagram

Table 1 - Duration of Flywheel Standby Power vs Load

	Flywheel
Source	Beacon Power
Brand / Model	BHE-2
Capacity Rating (Kwhr)	2.00

Output Voltage (VDC)	Load (Amps)	Duration of Standby Power (Hours)
36	8	6.9
36	9	6.2
36	10	5.6
36	11	5.1
36	12	4.6
36	13	4.3
36	14	4.0
36	15	3.7
36	16	3.5
36	17	3.3
36	18	3.1
36	19	2.9
36	20	2.8

3. Facts about Lead-Acid Battery Technology

The real world characteristics and performance of Lead-Acid batteries are influenced by many factors, such as: local environmental temperatures, method of usage, rate of discharge and recharge, storage, etc. Lead-Acid batteries of all types are considered by manufacturers to be expired when their Capacity drops to 50%, regardless of rated Amp Hours, Voltage, or Cold Starting Amps. The effects on battery performance by these factors are illustrated in the following sections.

3.1. Effects of Temperature Ranges on Battery Capacity and Battery Life

Battery Capacity and Battery Life are two factors usually compared together and they behave opposite each other as temperatures increase or decrease from a rated nominal temperature. Manufacturers typically consider a battery to be operating at 100% when the temperature is around 25°C / 77°F.

In Figure 3, we see that battery capacity reduces by approximately 10% and battery life increases by 20% for each temperature decline of 10°F below nominal 77°F. Correspondingly, when ambient temperatures rise above 77°F, the opposite happens to both capacity and life.
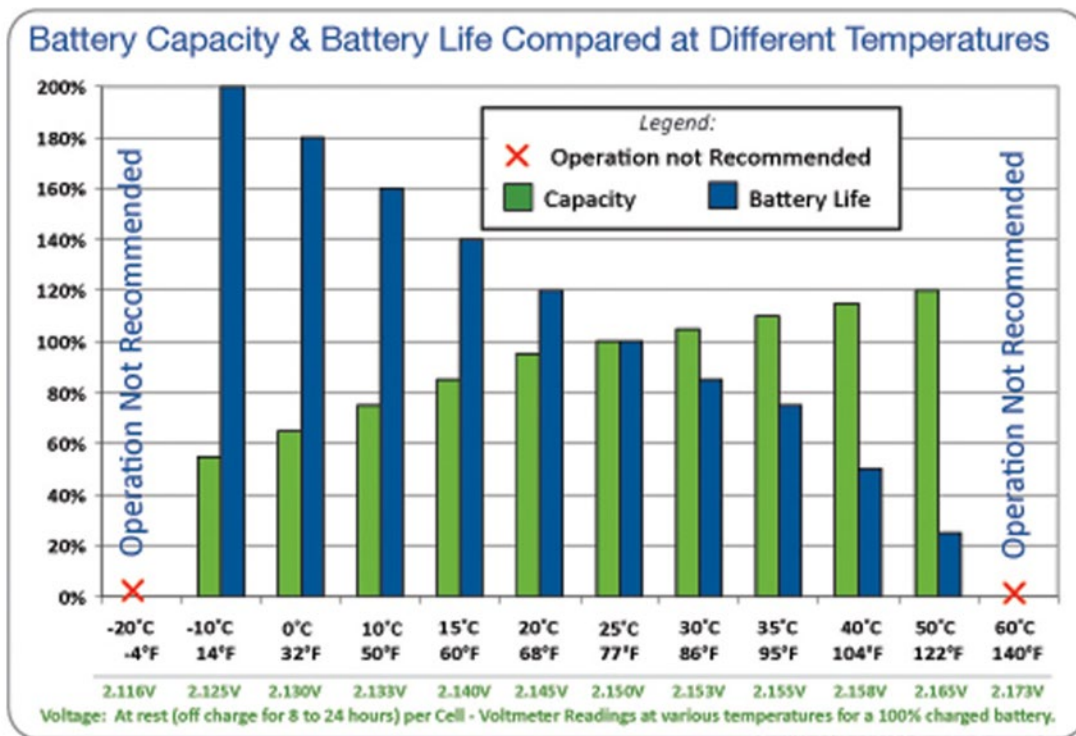
Figure 3 - Battery Capacity and Battery Life at Different Temperatures

3.2. Effects of Temperature on Cycle Life

One discharge and recharge of a battery is termed a cycle. The projected maximum number of Cycles in any given battery, regardless of Depth of Discharge, is the rated Cycle Life of the battery.

Battery Cycle Life, like battery Capacity and Life, is adversely affected by temperature excursions outside an ideal working range. Figure 4shows the degradation patterns affecting Cycle Life, below 10°C / 50°F and above 60°C / 140°F, with the rate of decrease in Cycle Life much steeper in hotter temperatures versus colder temperatures.

Cycle Life and Temperature

Slow drop off below +1O °C due to anode plating
Fast drop off above 60 °C due to chemical breakdown

Actual life will depend on the cell chemistry and
the percentage of time spent at the upper and
lower temperature limits

Ideal working
temperature range

Too wide means lower cycle life
Too narrow means wasteful thermal management

Cycle Life (Cycles)

Cell Operating Temperature (Constant (°C))

Figure 4 - Battery Cycle Life and Temperature

3.3. Effects of Discharge Time vs Capacity

Batteries discharged at a slow rate will deliver a higher amount of rated battery Capacity than those
discharged at a fast rate. The example in Figure 5 shows that the discharge of a battery (with Pasted
Plate) in five hours can discharge almost 100% of its rated Capacity, whereas when that same battery is
discharged in one hour, it will only discharge 55% of its rated Capacity.
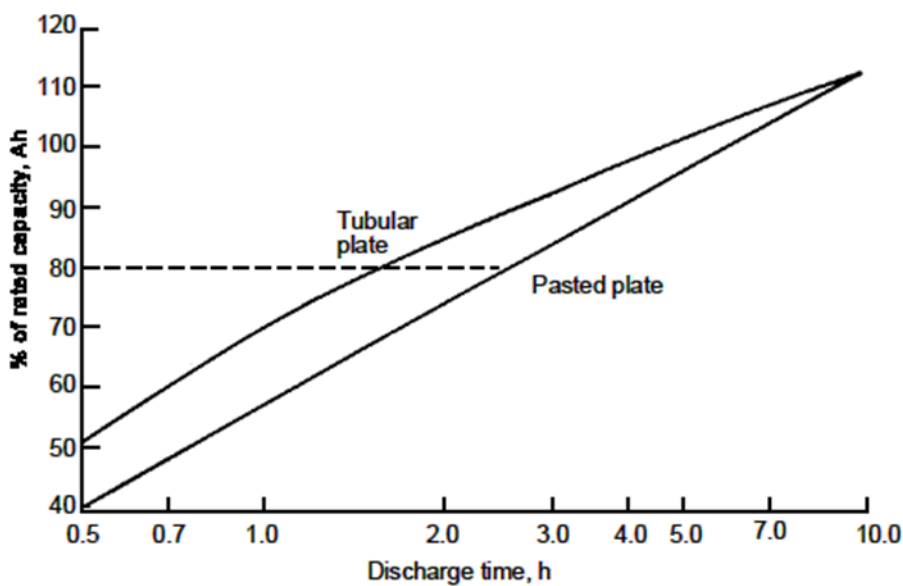
Figure 5 - Rate of Discharge vs. Capacity

3.4. Effects of Temperatures above 20⁰C / 68⁰F on Battery Aging

In this example, Table 2 shows the effect of accelerated aging on a battery when ambient temperatures are above 20^oC / 68^oF. Month 12 has an average temperature of the nominal 20^oC / 68^oF, with the battery aging an equivalent 30 days over the month. However, month 6 shows the battery aging an equivalent 46 days over that 30 day period, due to that month's average temperature being 26oC / 79oF.

The final effect of elevated temperatures over this sample 12-month period is the battery aging an equivalent 437 days over the actual 360 day period.

Table 2 - Effects of Temperature on Battery Aging

Month	Average Temperature	% of Nominal Life	Calculation (100% / Temp %)	Aging Effect	Aged days in the Month
1	20.5	95	100/95	1.05	31.58
2	21	92	100/92	1.09	32.61
3	22	87	100/87	1.15	34.48
4	23.2	80	100/80	1.25	37.50
5	25.3	70	100/70	1.43	42.86
6	26	65	100/65	1.54	46.15
7	25.2	70	100/70	1.43	42.86
8	23.8	77	100/77	1.30	38.96
9	22.5	85	100/85	1.18	35.29
10	21.5	90	100/90	1.11	33.33
11	20.5	95	100/95	1.05	31.58
12	20	100	100/100	1.00	30.00
TOTAL AGED DAYS PER CALENDAR YEAR					437.21

3.5. Effects of Storage on Battery Capacity

When a new battery is unused and in storage, even though the ambient temperature might be around 68^oF, the battery Capacity will decrease. Figure 6 shows that a battery's Capacity will drop by as much as 20% when just sitting idle for 12 months.

TYPICAL STATE OF CHARGE v STORAGE TIME
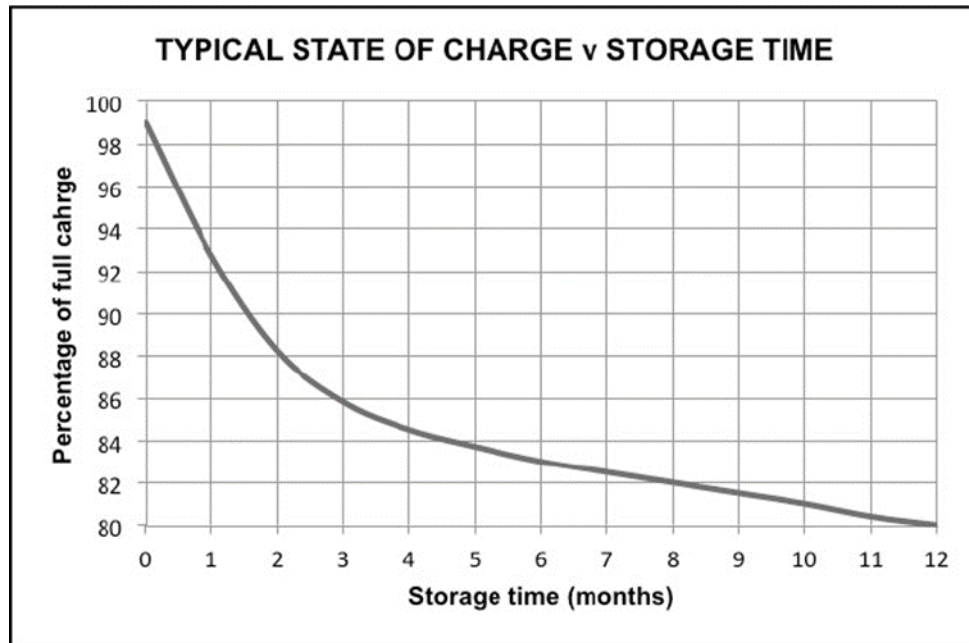
Figure 6 - Battery Capacity vs Storage Time

4. Flywheel Business Case

Flywheels are designed to operate for 20 years with little to no maintenance and the experience of the flywheel installed at Windbreak Cable has shown this is truly possible. A device that is designed to operate for 20 years in the Cable Industry is very rare, so for the business case study we must look at Life Cycle costs in comparison to Lead-Acid batteries. The short answer is that the Life Cycle costs of flywheels are much lower than Lead-Acid batteries.

As explained in the last section, Lead-Acid batteries have widely varying costs of operation due to many factors, from ambient temperature of operation to observing the manufacturer's recommended Quarterly Preventive Maintenance schedule. Over a 20-year life span, the batteries will be replaced several times due to Capacity dropping below 50%. Also, since temperature variations have such wide ranging effects on the life of a battery, Figure 7 shows how batteries age differently depending on location in the US (Battery Life Expectancy Zones). We then use these Zones to build a cost comparison table for batteries vs flywheels over the 20-year period.

During this same 20-year period the Flywheel does not require maintenance, can be charged and discharged over 100,000 times, with no change in capacity and is not affected by any of the problems described for batteries in Section 3.

Battery Expectancy Zone

	Extreme Cold 51 Months	Cold 56 Months	Mild 47 Months	Heat 41 Months	Extreme Heat 30 Months
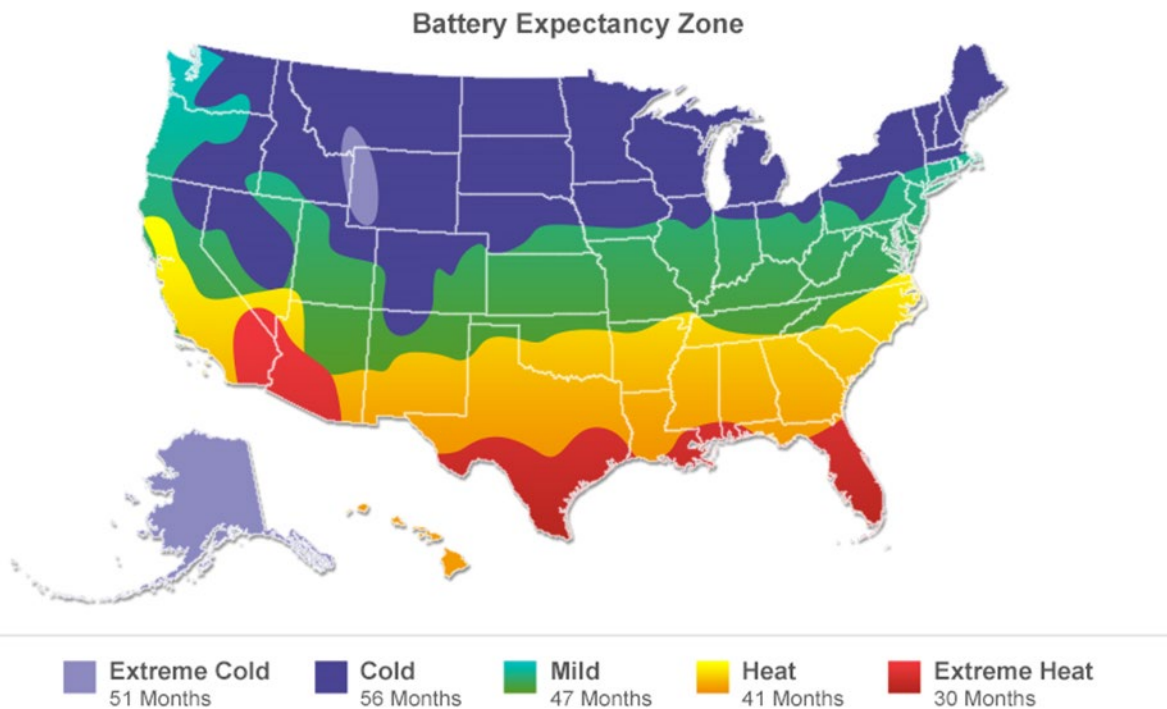
Figure 7 - Battery Life Expectancy: US Zones

Table 3 below compares the purchase cost and operational expenses of two brands of Lead-Acid batteries and a 2KWhr flywheel, for each of four Battery Life Expectancy Zones, over the 20-year life span.

The financial assumptions for this table are as follows:

- The flywheel is purchased on Day 1 with available funds and is not financed over the 20-year period.
- We did not use a Net Present Value method of calculating the costs of multiple battery replacements during the 20-year period.

In summary, this table shows that the total cost of a flywheel over the 20-year life span is much lower than multiple sets of Lead-Acid batteries in all 4 Life Expectancy Zones.

Table 3 - Cost Analysis of Lead-Acid Batteries vs Flywheel

Source / Brand / Model	Batteries (3 batteries per Power Supply = 1 Set)								Flywheel
	Alpha — AlphaCell 4.0HP				Universal Power — UB121100				Beacon Power BHE-2
Capacity Rat	2.95				2.85				2.00
Life Span (mo)	56 @ Cold	47 @ Mild	41 @ Heat	30 @ Extreme	56 @ Cold	47 @ Mild	41 @ Heat	30 @ Extreme	240
Discharge / R	100	84	73	54	100	84	73	54	100,000
Total Sets of	4.3	5.1	5.9	8.0	4.3	5.1	5.9	8.0	
Cost per Set									
Purchase ($1	$654.24	$654.24	$654.24	$654.24	$616.74	$616.74	$616.74	$616.74	$15,000.00
Labor / Perso	$200.00	$200.00	$200.00	$200.00	$200.00	$200.00	$200.00	$200.00	$2,000.00
O & M (Qtty	$3,733.33	$3,133.33	$2,733.33	$2,000.00	$3,733.33	$3,133.33	$2,733.33	$2,000.00	None
Total Cost pe	$4,587.57	$3,987.57	$3,587.57	$2,854.24	$4,550.07	$3,950.07	$3,550.07	$2,816.74	
* Total Cost p	$5,271.30	$4,474.80	$3,966.86	$3,073.15	$5,228.21	$4,432.72	$3,925.40	$3,032.77	
* Total Cost p	$6,056.93	$5,021.56	$4,386.25	$3,308.85	$6,007.42	$4,974.34	$4,340.41	$3,265.37	
* Total Cost p	$6,959.65	$5,635.13	$4,849.98	$3,562.63	$6,902.76	$5,582.14	$4,799.29	$3,515.81	
* Total Cost per Set of Batterie		$6,323.67	$5,362.74	$3,835.87		$6,264.20	$5,306.69	$3,785.46	
* Total Cost per Set of Batteries (5th replace)			$5,929.71	$4,130.07			$5,867.73	$4,075.79	
* Total Cost per Set of Batteries (6th replace)				$4,446.83				$4,388.39	
* Total Cost per Set of Batteries (7th replace)				$4,787.88				$4,724.96	
Total Cost ov	$22,875.45	$25,442.73	$28,083.11	$29,999.52	$22,688.46	$25,203.47	$27,789.59	$29,605.29	$17,000.00
Cost per Kwh	$18.09	$20.12	$22.21	$23.73	$18.60	$20.66	$22.78	$24.27	$0.09
* Rate of Inf	3.00%								

An important performance factor to note is that during the life of a Lead-Acid battery, capacity does not remain constant as the battery ages but instead declines constantly. This table cannot take into account subjective comparisons, such as reduced battery Capacity due to multiple discharge - recharge cycles and temperature aging. This decline can only be measured by performing a load based test of the battery throughout its life cycle. This load based test has not been factored into the analysis, as it would be conducted at the discretion of the operator. There is also a disposal cost for Lead-Acid batteries that has not been included in the analysis.

Another view of this analysis is to compare total capital and operating costs on an annualized basis. For example, Table 4 shows these average annual costs for batteries in each of the four Life Expectancy Zones vs a flywheel.

Table 4 - Annual Cost of Batteries vs Flywheels

	Batteries (3 batteries per Power Supply = 1 Set)				Flywheel
Life Span (months)	56 @ Cold	47 @ Mild	41 @ Heat	30 @ Extreme	240
Average Total Cost (20 years)	$22,736.00	$25,322.00	$27,936.00	$29,802.00	$17,000.00
Annual Total Cost	$1,136.80	$1,266.10	$1,396.80	$1,490.10	$850.00

5. Conclusion

The need for highly reliable access networks has never been greater and that need will become more severe as our Cable Networks provide greater and greater Internet throughputs. As Cable Operators move to 10G, our distributed power network must improve as well. Replacing Lead-Acid batteries in our

standby power supplies with flywheels will provide a long term and dependable improvement. Flywheels are the reliable, lower cost and environmentally sound solution for standby power.

6. Bibliography and References

Internet Public Domain for Figures 1 – 7 and Table 2

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Flywheel Energy Storage, William D. Bauer, Presentation to SCTE · ISBE Energy 2020

The Value of Optimum Electric Load Shaping

A Guide for Energy Procurement and Policy Decision Makers

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1. Abstract

A simulation framework and calibrated simulation study estimated the impact, in terms of variable generation costs and CO_2 emissions, attributable to optimally shaping electric load across large geographic areas for increasing renewable energy scenarios. This study used actual historical load and renewable energy generation data, individual generator constraints, and fuel costs as inputs to quantify the value of optimal load shaping toward the objective of raising the efficacy of the generation-to-load power system. While automatic and continuous power balance is not new, its holistic consideration is becoming tractable with modern computing and pervasive Internet communications, necessitating "smart demand" that responds to variable and uncertain renewable energy supply. In simulations, electricity retailers created load flexibility by calculating and broadcasting forecast optimum load shapes, i.e., shapes designed to encourage electric loads to track and favor generation with the lowest costs. Through reception and processing of optimum load shapes, future residential, commercial, industrial, and transportation energy management systems can orchestrate storage-capable end uses of electricity to optimize their own on and off operation to minimize deviations from optimum load shapes. Results from a case study of Texas indicate that continuous load shaping has the potential to significantly reduce costs and emissions, supporting the case for further research and development in carbon-free generation and grid optimization enabled by the Internet of Things. Results indicate a potential 1/3 reduction in annual generation costs and a 1/5 reduction in CO_2 emissions at high renewable energy penetrations.

2. Introduction

Recent geopolitical initiatives to reduce carbon emissions have encouraged research and development focused on clean and inexpensive energy sources [1,2]. Initiatives have resulted in a series of policies and mandates designed to drive socio-economic trends to increase the penetration of renewable energy sources (RES) and raise the efficiency of existing power generation [3]. Despite these initiatives, greater than 75% of the world's electricity is generated using thermal technology that is, on average, only 35-40% efficient [4,5]. Thermal power plants cost billions of dollars to operate on an annual basis [6]. Furthermore, they are the largest consumers of fresh water on the planet and are among the largest producers of heat, creating nearly twice as much heat as they do electricity along with greenhouse gases that trap heat [7,8]. The transition to clean energy is not straightforward, and challenges exist in maintaining the security of supply as electricity providers seek to provide the most effective mix of generators, which include the highest penetration of RES [9].

Electric load is forecast with ever-increasing accuracy [10] but traditionally has not provided continuous demand flexibility. Instead, loads are typically operated as needed without regard for the transmission or distribution constraints in a given geographic area or for the time-varying costs and CO_2 emissions that result from generating electricity in thermal power plants. On the contrary, this research assumes end-use loads, including air conditioning, hot water heating, and battery charging, are considered flexible due to the thermal and electrochemical storage ability of their inherent internal energy reservoirs. Through load modulation, thermostats and other future controllers of end uses can achieve varying levels of energy storage and release, subject to the

constraint that the systems they control remain sufficiently charged to maintain occupant comfort and meet expected needs.

To determine the maximum theoretical benefit of load shaping, a daily optimum load shape (OLS) 'flattens' (i.e., holds constant) the output of thermal generation over time to provide a best-case scenario for reducing variable generation costs. The OLS consists of the flattened thermal generation plus the time-varying RES generation. Ubiquitous internet connectivity enables energy retailers to broadcast the OLS to allow the distributed storage in end-uses—and the operation of generation resources—to be orchestrated over time. The purpose of the OLS is to continually modulate loads in concert with the lowest-cost generation to jointly optimize supply and demand by minimizing the production cost of electricity [11]. To explore the value of the OLS across generation and load, simulation models account for variable electricity production costs, emissions, and the flow of electricity. In addition to varying by generation mixtures, i.e., the mix of generators and fuel types, the production costs of electricity are impacted by weather, which simultaneously influences loads and, to a more significant extent, certain forms of RES generation. For example, during summer, higher wind speeds from a cold-weather front can simultaneously decrease the cooling loads in buildings and increase the output of wind power generation. At times, electricity production cost can be relatively low, such as when wind and solar RES generate most of the required power. At other times, the production cost can be high, such as when marginal power is provided by expensive peaking generators designed to operate for only a few hours a day, or from thermal generators operating at a partial load with lower heat rate efficiencies [12].

In the joint optimization of electricity supply and demand, one objective of the OLS is flattening the load met by thermal generators in order to raise the overall heat rate efficiency across the generation fleet and thus minimize variable production costs, particularly fuel burn costs. Another objective of OLS is reducing the curtailment of low-cost RES by modulating loads to match in-time the forecast availability of RES. The overarching goal of this work was to advance current trends to modernize the generation of electricity. Introducing OLS created load flexibility and elasticity and allowed for higher RES utilization, more efficient operation of existing thermal generation, and more effective management of distributed energy resources (DERs), including thermal and battery storage.

A simulation framework was designed based on time-synchronous load and RES generation data, generation fleet constraints, and fuel costs. Once calibrated using historical data, inputs to the simulation framework could be modified to support past- or future-based analysis. While necessary for optimizing the transmission and distribution portions of the electric grid, spatial variations in the production cost of electricity were not considered in this study though should be considered in future work. The novelty of this work is the ability to provide estimates of the impact of the OLS on variable generation costs and CO_2 emissions anywhere in the world using a relatively small set of input variables.

Section 3 describes the methodology, Section 4 discusses the results, and Section 5 presents conclusions and suggestions for future work.

3. Simulation Methodology

The simulation framework utilized a two-step process to estimate the impacts in costs and CO_2 emissions attributable to generating electric power with and without the OLS. First, an electricity production cost model (PCM) based on the Generic Algebraic Modeling System (GAMS) [11] simulated the costs and emissions of the thermal generators that met the historical net load (i.e., the total load less RES generation) without load shaping. Next, a second GAMS model simulated the costs and emissions based on the daily optimum 'flat' net generation shape.

In each simulation, the PCMs performed a generation unit commitment optimization to minimize the variable cost of generating electricity per day by choosing the lowest cost mix of generators each hour, subject to the following individual generator operating characteristics and constraints:
- Marginal heat rate[1] [MMBTU/MWh][2], the fuel burned to produce electrical output
- Maximum generation capacity [MW], the maximum electrical output
- Minimum generation capacity [MW], the minimum electrical output
- Maximum upward and downward ramping [MW/hour], the maximum increase or decrease in the output in a single hour (note: thermal generators ramp slowly in comparison to gas turbines)
- Variable operation and maintenance cost, VOM [$/MWh] which increases with electrical output
- Startup cost [$/start], related to the type of fuel and time required to start, typically from a cold-start condition
- Fuel price [$/MMBTU], cost of each fuel type
- Minimum down time [hours], the amount of time required to go offline and back online again
- CO_2 emission rate [lb/MMBTU], the emission rate per unit of fuel consumed.

3.1. Key Performance Metrics

In addition to variable generation cost and CO_2 emissions, *Ls*, the amount of load shaped, is defined as the sum over the simulation interval of the absolute values of the deltas between the shaped and unshaped load and has units of energy. As a percentage, *Ls*, is a normalized value when divided by the sum of energy delivered in the unshaped case.

3.2. Texas Case Study

The simulation framework was applied to a case study of the serving area of the Electric Reliability Council of Texas (ERCOT), responsible for approximately 10% of U.S. and 2% of world electricity production [13]. Texas was suitable for this study as it is a multi-climate, large geographic area that can be modeled as an electrical island due to its limited imports and exports of electricity. In addition, time-synchronous load and RES data are available for Texas as well as generator sizing and constraints [14]. The area simulated includes over 24 million residential,

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[1] Marginal heat rate is defined as the amount of additional heat required for the next unit of electricity produced.
[2] MMBTU uses Roman numeral M twice to denote a million, whereas MWh uses the S-I unit M to denote a million.

commercial, and industrial electricity customers across 200,000 square miles. Figure 1 depicts the eight colored ERCOT weather load zones [15] along with climate regions 3, 4, and 5, as defined by the Pacific Northwest National Laboratory [16].
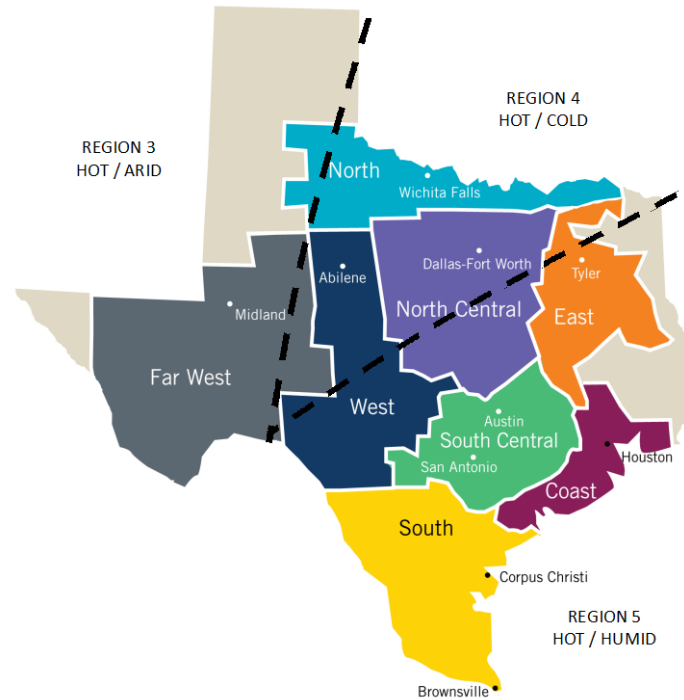
Figure 1 - ERCOT operating area with weather zones and climate regions.

The case study consisted of unshaped and optimally shaped cases for actual ERCOT load and three scenarios of increasing RES penetration. Also included were the operating characteristics and constraints of 263 utility-scale thermal generators that closely represent the ERCOT generation fleet [14], an excerpt of which is listed in Table 1.

Table 1 - Sample ERCOT generator characteristics and constraints.

Unit	County	Fuel	Prime Mover	Capacity (MW)	Marginal HR (MMBtu/MWh)	Base Heat Rate (MMBTU)	Co2Ems(lb/MMBtu)	VOM($/MWh)	MinLoad(MW)	StartCost($)	MinDownTime(hrs)	RampRate(MW/hr)	FuelPrice($/MMBtu)
BRAUNIG_AVR1_CT1	bexar	GAS	CC	533.0	9.3	154.5	117.0	3.7	213.2	49690.0	4	169.5	3.3
ATKINS_ATKINSG7	brazos	GAS	GT	18.0	12.8	0.0	117.0	15.7	7.2	419.5	1	6.2	3.3
DG_WALZE_4UNITS	bexar	LFG	LFG	9.8	13.8	0.0	117.0	8.9	3.9	456.8	4	3.4	0.0
CALHOUN_UNIT1	calhoun	GAS	ST	44.0	12.3	102.7	117.0	4.5	17.6	4102.0	7	10.2	3.3
COLETO_COLETOG1	goliad	COAL	ST	655.0	10.4	1284.1	214.3	4.5	327.5	61063.7	12	117.2	2.2
CPSES_UNIT1	somervell	NUCLEAR	ST	1205.0	10.5	0.0	0.0	2.2	1084.5	561693.2	20	96.4	0.7
WT-ercot1	kinney	WIND	WT	20200.8	0.1	0.0	0.0	0.0	0.0	0.0	0	20200.8	0.0
PV-ercot1	presidio	SOLAR	PV	1003.8	0.0	0.0	0.0	0.0	0.0	0.0	0	1003.8	0.0

Note that generators were, for the most part, individual line items, though in some cases were grouped into a single line meta generator, e.g., utility wind and solar generators were grouped by technology. Prime movers[3] include Combined Cycle (CC), Gas Turbine (GT), Landfill Gas (LFG), Steam Turbine (ST), Wind Turbine (WT) and Photovoltaic (PV) generators. Not shown but also included are Internal Combustion (IC) and Combustion Turbine (CT) generators.

3.3. Estimated Texas production cost and emissions

For Case 1, Actual load, production costs, and emissions were estimated for the 2005 hourly load reported by ERCOT less the time-synchronous production of electricity from all utility-scale wind and solar generators [16]. For simplicity, 745 MW of Texas utility-scale hydroelectric generators was excluded from the analysis[4]. The hourly GAMS PCM took as inputs the net load along with the generator characteristics and constraints. The PCM simulated the time-varying unit costs, marginal costs, and CO_2 emissions based on a constraint of fossil-based thermal generation equaling net load for each hour. Consistent with best practices, the simulated variable production costs were compared to the actual production costs for the same period to check for general agreement [17, 18].

For Case 2, Actual load with daily optimum load shape, a significant assumption was made to support the calculation of a) the minimum theoretical variable generation cost based on the daily optimum thermal generation shape, and b) the daily optimum load shape. The assumption was that all load could be shaped with negligible losses and penalties. While unrealistic due to the efficiency losses of thermal and electrical storage, this assumption allowed the daily-based GAMS PCM to relax the constraint of thermal generation equaling net load for every hour---to thermal generation equaling aggregate net load for an entire day. This always resulted in a constant output `flat' thermal generation shape with no generator starts, stops or ramping of electrical output. The flat thermal generation shape had the lowest variable generation cost and thus was considered the daily optimum net generation shape. As a final step in Case 2, the *hourly-based* PCM was re-run using the flat daily optimum net generation shape and returned the variable generation costs and emissions.

4. Results

In simulations of generation across the ERCOT serving area, production cost and CO_2 emission estimates for actual unshaped and simulated shaped loads quantified the impact of various penetrations of utility wind, utility solar, and distributed solar photovoltaic generation. The load, RES generation, thermal generator properties, constraints, and fuel costs were combined to estimate electricity production cost based on the optimized daily unit-commitment of the generation mix. Comparing the daily electric power production costs and emissions for unshaped and optimally shaped load, yielded a range of costs and CO_2 emissions, as shown in Table 2.

---

[3] A prime mover is a mechanical or solid-state source of power.
[4] With nearly 70 GW of generating capacity in Texas, removal of 745 MW of hydropower did not significantly skew results.

Table 2 – Full-year 2005 range of variable generation costs and CO_2 emissions for unshaped load and optimally shaped load in scenarios of increasing RES penetration.

Scenarios →	A. Low RES Penetration uWind22, uSolar1, dSolar0			B. Medium RES Penetration uWind30, uSolar3, dSolar5			C. High RES Penetration uWind38, uSolar5, dSolar100		
↓ Cases	Cost $ [B]	Cost $/MWh	CO_2	Cost $ [B]	Cost $/MWh	CO_2	Cost $ [B]	Cost $/MWh	CO_2
1. Unshaped Load	5.36	17.96	252	3.75	12.58	146	3.22	10.77	94.7
2. Optimally Shaped Load	5.31	17.80	257	3.23	10.83	148	1.92	6.44	77.9

Notes to Table 2:
1. Curtailment of utility-scale wind (uWind) and solar (uSolar) is required during some hours in Scenario B and many hours in Scenario C in order to prevent over generation.
2. Entries for uWind and uSolar denote penetration relative to total ERCOT annual electricity production, e.g., uWind22 denotes utility wind providing 22% of total ERCOT annual production in 2005.
3. Entries for distributed solar, e.g., dSolar50, denote the percent of houses with solar PV.

Table 2 summarizes annual costs and CO_2 emissions for the ERCOT serving area. Rows depict different cases, and columns are grouped into three scenarios of (A) low, (B) medium, and (C) high penetrations of RES. In each group, the daily optimal load shape is applied to flatten net generation in order to determine the theoretically lowest possible variable generation cost. The difference between the load with and without the application of the OLS determines the upper bounds of possible reductions in variable costs and CO_2 emissions.

Results from all Scenarios indicate a reduction in costs when the OLS was applied. Scenario A savings were 1%, Scenario B savings were approximately 10%, and Scenario C savings were approximately 40%. Scenario B and C savings are particularly important as they reflect the additional annual savings expected from the deployment of OLS. Savings in Scenarios B and C are attributable to OLS modulating load to better match in time the available RES, which results in decreased curtailment of RES and reduced operation of thermal power plants.

With respect to CO_2 emissions, there is a 2% to 3% increase from Scenario A to Scenario B; this is due to increased use of lower-cost but higher CO_2-producing coal steam turbines, which displaced the use of cleaner natural gas combined cycle generation. Most notably, Scenario C provided an approximate 20% reduction in CO_2 attributable to the OLS increased use of RES.

4.1. Unshaped Actual Load versus Optimally Shaped Load

For Cases 1 & 2, Scenario A, variable generation cost and CO_2 emissions were calculated for the unshaped *actual* hourly load and for the hourly load had it been *optimally* shaped over seven days as shown in Figure 2 (a) and (b). As expected, the daily optimum minimum cost generation was achieved when the net load was a constant, depicted as a flat line for each hour of 20--26 Aug 2005 in Figure 2 (b).
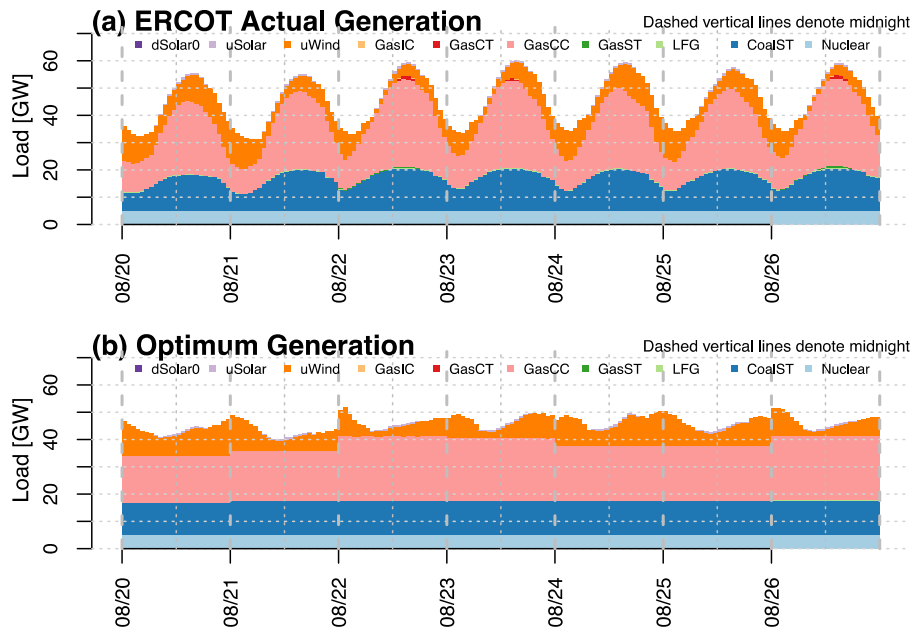
Figure 2 - ERCOT hourly actual and optimal generation on 20-26 Aug 2005

Figures 2-5 are known as generation stacks that depict the contributions of individual generation technologies that together meet the time-varying load. Zooming into Figure 2 (a), there are peak hours of dark red (GasCT) in-between the bands of orange (uWind) and light red (GasCC) on 22, 23, and 26 August, and there are peak hours of dark green (GasST) above dark blue (CoalsST) on 22 and 26 August. Barely visible are a) the smallest generation contributions in the midday diurnal signature of light purple (uSolar) at the very top of each graph, and b) a continuous thread of light green (LFG) atop the dark blue (CoalST) depicting the output from coal-fired steam-driven turbine-coupled generators. As depicted by the colors in the legends of Figures 2-6, a total of 10 generation types may be used to meet the load. The week of 20-26 August is particularly interesting as it is the hottest week of 2005 with over a TWh of energy delivered each day and many of the 263 thermal generators having high capacity factors[5].

In Figure 2 (a), note the up and down ramping of net generation (depicted by seven humps) in shades of blue, green, and red as the Texas generation fleet varied its production of electricity to meet the net demand. As expected, after calculating the daily optimum net generation shape, the ramping of net generation in (a) is removed, resulting in a smooth load in (b). Specifically, there is no intra-day ramping in the dark blue (CoalST) and light red (GasCC), which results in an impact on variable generation cost and CO_2 emissions of individual generators. Summing across all generators and intervals, the total energy delivered in the week in (a) and (b) is the same. Said differently, the areas under and including the topmost curves in (a) and (b) are the same.

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[5] Capacity factor describes how intensively a generator is run. A capacity factor near 100% means a generator is operating nearly all of the time. It is the ratio of actual generation to maximum potential generation over a given time period. Low annual capacity factors for peak-load plants result in high generating costs for units that operate only a few hours a year. Conversely, high capacity factors, e.g. for nuclear plants, result in low generating costs.

As depicted in Figure 2 (b), calculation of the daily optimum generation sometimes resulted in greater than typical step changes (i.e., discontinuities) on day boundaries at midnight, e.g., between midnight on 22 August and 1 AM on 23 August 2005. These atypical discontinuities were the result of adjacent days having a different aggregate energy use. As expected, discontinuities were minimal between days with similar meteorological conditions. Typical discontinuities in load at midnight were defined as those observed in (a) and were compared and contrasted to the discontinuities in (b). Methods for reducing midnight discontinuities in generation can be addressed through modifications to the GAMS PCM to manage daily boundaries, though were beyond the scope of this research and should be explored.

4.2. Low/Medium/High Renewable Energy Scenarios

Hourly generation from the Texas fleet of RES and non-RES generators were compared and contrasted for the low, medium, and high RES penetration cases (Scenarios A, B, and C). Sample visualizations of the generation that met the load for each hour of 23 August 2005 are shown in Figures 3, 4, and 5. Cases and Scenarios are denoted with an abbreviated notation, e.g., C1SA denotes Case 1, Scenario A. In Figure 3, both the (a) and (b) visualizations are a zoomed view of 23 August 2005 from the weekly view in Figure 2.
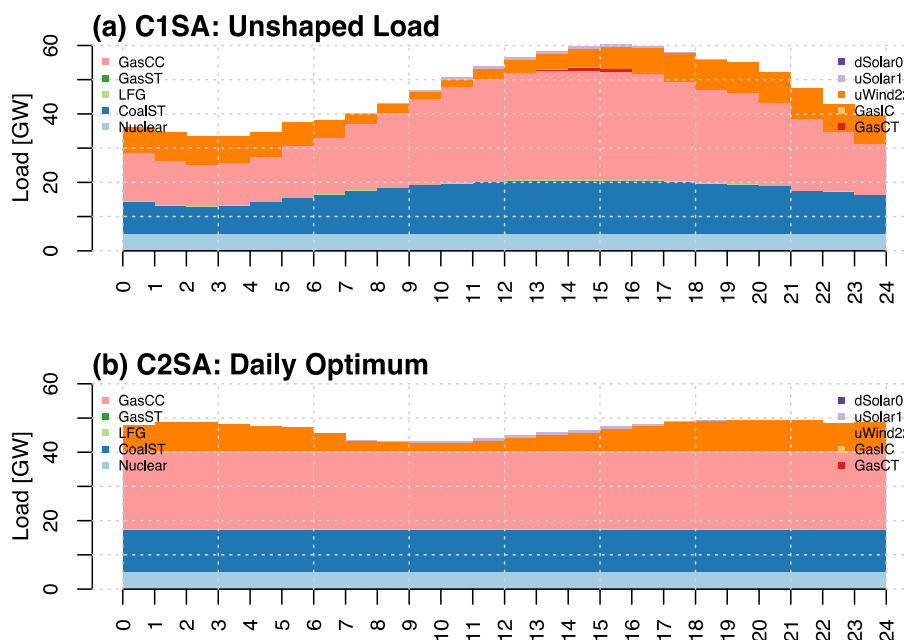
Figure 3 - Cases 1 & 2, Scenario A, ERCOT actual and optimal generation on 23 Aug 2005

Figure 3 (a) depicts the variability in load and generation in 24 hourly intervals. The variability in the utility wind resource (uWind22) is denoted by the changing height of the orange bars, which was lowest from after sunrise through hour 11. Note that GasCT generation (in dark red) was required for hours 14, 15, and 16 to ramp up and meet the daily peak load.

The top line in Figure 3 (b) provides a visual insight into calculating the daily optimum load shape. First, the non-RES generation in (a) was flattened by equally distributing daily production needs across all 24 hours, in this case, starting with the light blue (Nuclear) fleet at the bottom up to and including the light red (GasCC) fleet. Second, the hourly RES generation was added atop the flattened non-RES generation resulting in a somewhat concave optimal load shape in (b). In Figure 3, the percent of load shaped, Ls, between (a) and (b), is 21%.

As shown in the legend of Figure 4, Scenario B introduced a) increased uWind from 22% to 30% of total ERCOT annual production, b) increased utility uSolar from 1% to 3% of total ERCOT annual production, and c) distributed net-zero solar PV on 50% of homes.

Figure 4 - Cases 1 & 2, Scenario B, ERCOT actual and optimal generation on 23 Aug 2005

The impact on the non-RES generation fleet of increasing RES is visible by comparing Figures 3 (a) and 4 (a). Note that Figure 4 (a) shows an increase in ramping of net generation to accommodate the increase in RES. For the Daily Optimum, comparing Figures 3 (b), and 4 (b) provides insights into the impact on the non-RES generation fleet of increasing RES. In Figure 3 (b), the top of the non-RES generators is a flat line at 40 GW. In Figure 4 (b), the top of the non-RES generators is a lower flat line reduced to 30 GW, representing a one-quarter reduction in the non-RES generation between Scenarios A and B. Any reduction ensures existing generation assets are available for future growth in demand without construction of new thermal power plants. In Figure 4, the percent of load shaped, Ls, between (a) and (b), is 29%.

As shown in Figure 5, Scenario C further increased a) uWind to 38% of total ERCOT annual production, b) uSolar to 5% of total ERCOT annual production, and c) dSolar to 100% of homes.
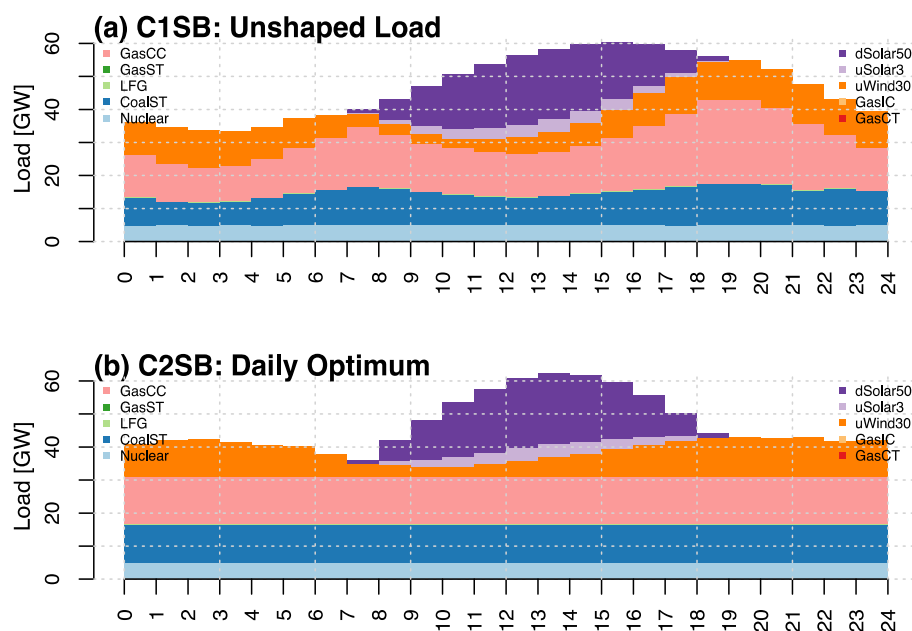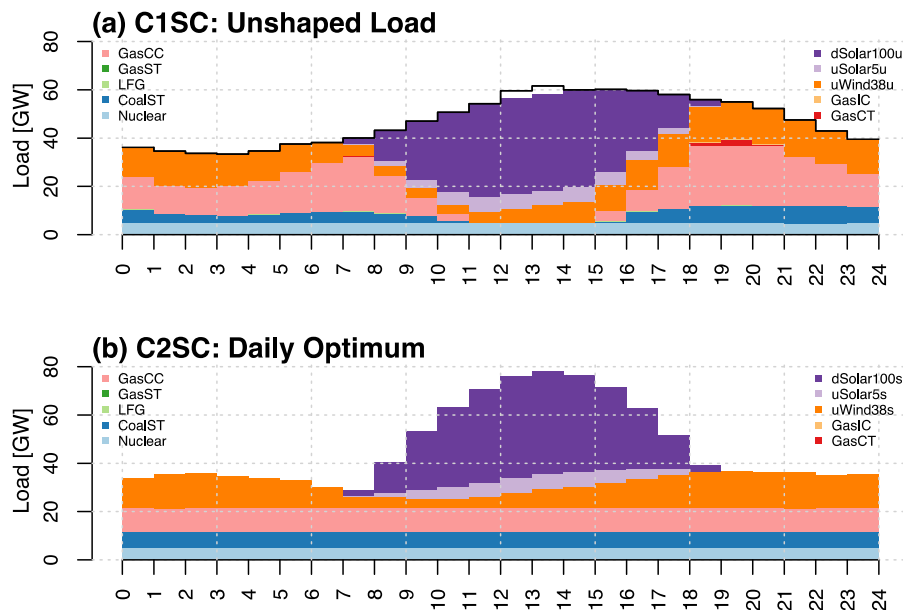
Figure 5 - Cases 1 & 2, Scenario C, ERCOT actual and optimal generation on 23 Aug 2005

The additional impact on the non-RES generation fleet of further increasing RES is visible by comparing Figures 3 (a), 4 (a), and 5 (a). Note that Figure 5(a) shows a further increase in the ramping of net generation to accommodate the increase in RES. During daylight hours, the massive contributions of the distributed solar generation required downward ramping through noon to prevent over-generation, and then upward ramping through hour 19 in order to ensure supply would meet demand at sunset. Approaching noon, the required downward ramping was so great that the GasCC and CoalST fleets were completely shut down by hour 11. During hours 12 and 13 the top back line depicts renewable energy that had to be curtailed (i.e., could not be used and was thrown away). The four nuclear power plants in light blue remained operational as they cannot shut down for short intervals. During the afternoon, the generators in the CoalST and GasCC fleets ramped up, and in hours 18-20, production was supplemented by fast-starting and fast-ramping GasCT generators. For the Daily Optimum, comparing Figures 3 (b), 4 (b), and 5 (b) provides insights into the impact on the non-RES generation fleet of further increasing RES. In Figure 5 (b) the top of the non-RES generators is a lower flat line reduced to just over 20 GW, representing a nearly half reduction in non-RES generation between Scenarios A and C. In Figure 5, the percent of load shaped, Ls, between (a) and (b), is 59%.

5. Conclusions and Suggestions for Future Work

This research developed a simulation framework and calibrated study for creating a broad geographic assessment of the impact of load flexibility on variable generation costs and CO_2 emissions for decision and policymakers. Unique to this research was the use of an electricity production cost model to estimate the impact of flexible load on the generation of electric power for the state of Texas, which accounts for approximately 10% of the $50B annual cost of electric

power production in the United States [17]. The methodology estimated the monetary savings that electricity producers would realize by optimizing the mix of generation in various renewable energy penetration scenarios, which is an essential metric in deciding whether OLS is worthy of further research and implementation [13]. The framework only requires knowledge of historical or forecast load, RES generation, generator constraints, and fuel costs. It should be routinely applied to create scorecards that track the untapped value of OLS in the U.S. and world geographies. In addition, the framework can be extended to consider the physical constraints due to congestion in transmission and distribution networks.

Throughout its 138-year history, electric power generation has typically been optimized only to meet the anticipated inflexible load and required reserves at the lowest possible cost [11]. By including flexible load as an additional dimension of optimization, OLS introduced a new paradigm in the traditional supply-demand relationship by enabling storage-capable loads to shift forward or backward in time in order to follow and use the least costly forms of generation. The effect of time-shifting load was twofold: a) to reduce electric power production costs and CO_2 emissions by shaping load to increase the efficiency of thermal generation, and b) to decrease the curtailment of RES. The OLS allows society's demand for electricity to seek and follow the least costly forms of supply—while providing for user needs and maintaining user comfort.
With the ability of OLS to move generation away from more costly generators towards less costly generators, the Texas-wide annual opportunity for reduction in production costs increased as a function of RES penetration. The maximum opportunity for savings in the high RES Scenario C, based on daily optimum load shapes, were a 1/3 reduction in annual generation costs, from $3.2B to $1.9B, and a 1/5 reduction in annual CO_2 emissions, from 95B to 78B tons. The enormity of the generation changes implies gross errors are possible in modeling the behavior of the bulk power system. That said, in the presence of highly penetrated RES, as fossil-fueled baseload, mid-merit, and peaking power plants run less often, their marginal cost of generation will increase, resulting in cost calculations that increasingly support the business case for OLS as existing thermal generation becomes less competitive.

6. Abbreviations and Definitions

6.1. Abbreviations

CC	combined cycle generator
CoalST	coal steam turbine generator
CO_2	carbon dioxide
CT	combustion turbine generator
DER	distributed energy resource
ERCOT	Electric Reliability Council of Texas
GAMS	Generic Algebraic Modeling System
GasCC	natural gas combined cycle generator
GasST	natural gas steam turbine generator
GT	gas turbine generator
GW	gigawatt
IC	Internal combustion generator

ISBE	International Society of Broadband Experts
LFG	landfill gas generator
Ls	Load shaped
OLS	Optimum Load Shape
MMBTU	million British thermal units
MW	megawatt
MWh	megawatt-hours
PCM	production cost model
PV	photovoltaic generator
RCA	Robert Cruickshank Associates
RES	renewable energy sources
SCTE	Society of Cable Telecommunications Engineers
ST	steam turbine generator
TWh	terawatt-hours
VOM	variable operation and maintenance cost
WT	wind turbine generator

6.2. Definitions

dSolar	Distributed net zero solar penetration expressed as percentage of homes with solar. Net zero refers to the annual production of electricity from photovoltaics being equal to the annual electricity consumption of the home.
uSolar	Utility-scale solar generation expressed as a percentage of total annual production from all power plants.
uWind	Utility-scale wind generation expressed as a percentage of total annual production from all power plants.

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Powering the future 10G access networks
- An End to End Perspective

A Technical Paper prepared for SCTE•ISBE by

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1. Abstract

The quest for 1G and 10G networks is forcing cable operators to innovate both in the outside plant (OSP) and the inside plant (ISP) technologies. Some of these are OSP levers such as extending the spectrum, fiber deep technologies etc. Similar evolution is happening on the ISP through the introduction of DOCSIS 3.1, 4.0 and talk about the future DOCSIS 5.0 technologies. Different architectures are being evaluated to carry the petabytes of data being generated on these access networks – including the enhanced optical access to virtualizing the CMTS.

These access strategies are being analyzed from the long-term planning points of view to support the customer demand and to support a competitive product offering. In this paper we evaluate the impact of these access evolution strategies on key operational factors points of view that are often overlooked during initial analysis. In an earlier paper [1] we proposed a framework to evaluate transformation options for Outside Plant (OSP) network access powering solutions from an architectural, financial and operational perspective. In this paper we extend the framework to also include Inside Plant (ISP) operational factors such as power, cooling and rack-space requirements. In addition, we propose some of the metrics that can be used to compare different end-to-end solutions.

Our goal in this paper is to develop a framework that can be used by network operators to evaluate the end-to-end operational impacts of their access network evolution strategies.

2. 10G goal is pushing the envelope on the access operational factors

Broadband access demand has been growing at a rapid pace. In order to keep up with the demand the Cable industry has developed a new set of technologies that can deliver data rates targeting 10 Gigabits per second over the coming years [2]. Some of the new technologies include N+0 (fiber deep), Extended Spectrum DOCSIS (ESD), and Full-Duplex DOCSIS (FDX). The Extended Spectrum DOCSIS technology itself has numerous implementation options – mid-split, high-split, ultra-high-split etc. In addition to the full line-up of options in the OSP, operators have to optimize the corresponding ISP explosion through Centralized Access Architecture (CAA), Distributed Access Architecture (DAA) and Virtualized CCAP architectures.

Architecture	ISP Options	OSP Options
CAA	I-CCAP (D3.1) + Optical Aggregation	Node Split, Mid-split
DAA	CCAP Core + CIN V-CCAP + CIN	All of the above +N+0, Full Duplex, 1.2/High-split, 1.8/High-split

We will not go into details of these technology options, but suffice to say, each of these technology options has significant impact on the HFC access network both in the OSP and ISP. Furthermore, operators are challenged to figure out the best way to transition their existing network – which is in different stages of evolution depending on the markets and legacy approaches– to the new 10-Gig capable state. The table above illustrates the complex transition options that are possible. Operators are faced with the above capacity related transitions to keep up with the access demand. This itself is a marathon task. Hence, looking into the end-to-end operational impacts (power, space, cooling) is often overlooked. In this paper we focus on these operational impacts.

3. Recap of the OSP power analysis framework and recommendations

In [1] we developed a framework to analyze different access transformational upgrades from only the OSP point of view. These upgrade options included different OSP access levers such as Node Splits, N+0, Full Duplex, Spectrum Upgrades and backhauling some of the wireless solutions. We provided a framework to analyze different powering solutions from the architectural, operational and financial points of view as mentioned below.

Architectural measures: These measures evaluate a powering solution in the context of supporting the current access architecture and the future planned upgrades.

- Feasibility: How feasible is this upgrade in their current network?
- Ease of upgrade: How easy is it to extend to future needs?
- Lifetime of the solution: How often does one need to upgrade?

Operational measures: The operating metrics determine how a powering solution meets, at a minimum, the committed service level agreements (SLAs) and offer a simpler maintainable solution.

- Reliability: What level of reliability needs to be considered to meet the SLAs?
- Complexity: What are the maintenance complexities?
- Failure recovery: How long does it take to recover from failure?

Financial measures: The financial measures provide the investment overlay (total and time-adjusted) views of the solution over a long-term transformation.

- Long-Term CapEx: What is the 5/10-year capital expenditure of the solution?
- Long-Term OpEx: What is the 5/10-year operating expense of the solution?
    - o   Including the obsolescence and disposal costs
- Total cost of ownership (TCO) NPV: What is the net present value (NPV) costs over 5/10 years?

In the previous paper we recommend the operators and the standards forums to –

- **Align with your company's access strategy:** As a powering solution cannot be an afterthought or a point solution. It needs to align with the transformation strategy being developed by the team.
- **Consumption is not the only metric you need to optimize:** Albeit, consumption reduction is one of the main goals of the NextGen energy strategy, we propose to follow the framework.
- **Plan long-term powering solutions before making the short-term next steps:** Gaining a clear vision on the long-term powering needs is essential to make the short-term decisions.

In this paper we extend the above framework and recommendations to evaluate different access upgrade solutions from an end-to-end (both ISP and OSP) perspective.

4. Operational factors influenced by ISP architectures

OSP changes have direct impact on ISP operational factors. As operators get ready to upgrade their networks for the next generation technologies, they have an opportunity to re-architect their ISP. The inside plant has traditionally faced numerous challenges – chief among them are powering, cooling, and rack space availability. Note that we do not consider elements in ISP that are relevant for the access upgrades, such as voice switches that are getting phased out, in this paper.

- **Powering**: The inside plant hosts a range of active networking devices that support the cable HFC network. Key among these include the CMTS, the optical transmitters/receivers, Ethernet aggregation network and any relevant access routers. As the demand for cable access network has grown, it has driven the need for changes in equipment in the ISP. In addition, the equipment has been upgraded to support higher performance and density that leads to changing powering needs.
- **Cooling**: The challenges on the powering side outlined above also manifest into similar challenges on the equipment cooling needs. Legacy HVAC systems are facing significant capacity challenges trying to meet the needs of the new power-hungry equipment.
- **Rack Space Constraints**: The need for additional equipment in the ISP due to access changes outlined above requires additional equipment rack space. Many ISPs have run out of the rack-space capacity they were originally designed for, and have little room left for expansion. Increased density in the CMTS equipment and commoditizing the aggregation network reduces the footprint.

As outlined above, ISP is facing several challenges on the powering, cooling, and rack space front. As operators plan to upgrade their networks to support the new 10G technologies, they have an opportunity to re-architect their ISP environment to solve some of these vexing problems. As the focus of this paper is on the access network, we will mainly focus on the access related components in the ISP. The access network architectures can be classified in two broad categories – centralized and distributed. We have summarized in the coming sections the major architecture options being considered by most network operators below. For a expanded discussion on this topic the reader should refer to [3].

Centralized Access Architectures (CAA): Traditional cable access network architecture is based around the Cable Modem Termination System (CMTS) in the ISP. All the CMTS functionality is centrally located in the ISP Hub. The CMTS generates and receives the DOCSIS RF signal which is sent to the Optical transmission equipment co-located in the hub. The video signal is also modulated by the Edge QAM (EQAM) device and sent to the Optical transmitter. The analog optical signal is sent over fiber to optical nodes in the field.

Distributed Access Architectures (DAA): Distributed Access Architectures (DAA) were

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Different CMTS variants

Centralized Access Architectures (CAA): The Centralized Access Architectures have two implementation options – Modular CMTS and Integrated CMTS (CCAP).

- Modular CMTS: In the Modular CMTS implementation the downstream modulation for Data and Video signals is handled by a separate Universal Edge QAM device.
- Integrated CMTS: In case of the Integrated CMTS implementation, the CMTS integrates all functions within the CMTS. The integrated CMTS is also known as a Converged Cable Access Platform (CCAP).

Distributed Access Architectures (DAA): Depending on the CMTS functionality moved from the hub, there are three major variants.

- CCAP Core with Remote Phy: In this case only the DOCSIS Physical Layer (Phy) is move to the optical node. The rest of the CMTS functionality remains in the CCAP Core located in the Hub.
- CCAP Core with Remote Mac-Phy: In this case both the DOCSIS Physical (Phy) as well as Media Access Control (MAC) layer functionality is moved to the optical node.
- Virtualized CCAP: In this case in addition to the Phy and MAC layers being moved to the optical node, the remaining CCAP Core functionality is virtualized. As such, the CCAP Core functionality is implemented as a software module in an upstream data center. This eliminates the CMTS functionality from the Hub.

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developed specifically to address the power, cooling, and rack space challenges in the ISP. The idea is to move part of the CMTS functionality – at least the DOCSIS Physical Layer (Phy) - to the optical node.

In the following sections we evaluate the framework introduced in [1] for both ISP and OSP impacts and potentially expand the framework. At the end we introduce different metrics to succinctly evaluate different access upgrade solutions from operational factors points of view.

5. Updated end to end operational factors analysis framework

The proposed OSP based power analysis framework from [1] can still be used as the end to end framework with the following additional changes –

- *Include ISP operational factors*: The power only analysis conducted previously needs to be extended to include other operational factors such as space and cooling that are relevant for the ISP part of the end to end framework. These factors will offer benefits in ISP and OSP differently. For example, in ISP the space related factor will assist in the facility consolidation, whereas the powering solutions in OSP can assist with the permitting nightmares.

- *Include headroom capability of a solution in architectural measures*: As we are applying this framework in validating different powering solutions, we felt that the expansion headroom created by a powering solution should be clarified in the measure. We recommend such analysis are added to the lifetime of the solution category in the architectural measures.

Next, we apply the updated end to end framework on different scenarios and provide our thoughts on the usefulness of such a framework.

6. Analyzing end to end access solutions using the framework

Using the above framework and sampling the typical access upgrade paths planned by the operators, we have created a set of scenarios as depicted in Figure 1. Here is a brief explanation of the scenarios:

- *ISP considerations*: In the ISP analysis we use the power, the space and the cooling metrics in the end to end framework with the following upgrade considerations:
    o Centralized access architecture (CAA) is used as the first step for the D3.1 upgrade and is used until the DAA architectural components (such as D-RPD) are ready to be used.
    o Distributed access architecture (DAA) is considered as soon as the end to end solution components are available. DAA can be used after mid-split lever in OSP is crossed as shown in Figure 1. Both the CCAP core and virtual CCAP options are used as two options for end evolution of an ISP.
- *OSP considerations*: In the OSP case we use only the power metrics which are part of the end to end framework with the following upgrade path options:
    o Organic levers scenario: Here we use the organic node splits to meet the downstream demand needs, and mid-split and high-split (when full duplex is reached) for upstream driven needs.
    o Extended Spectrum DOCSIS (ESD) levers scenario: Here we use a combination of the spectrum upgrades and node splits opportunistically to meet the growth needs.
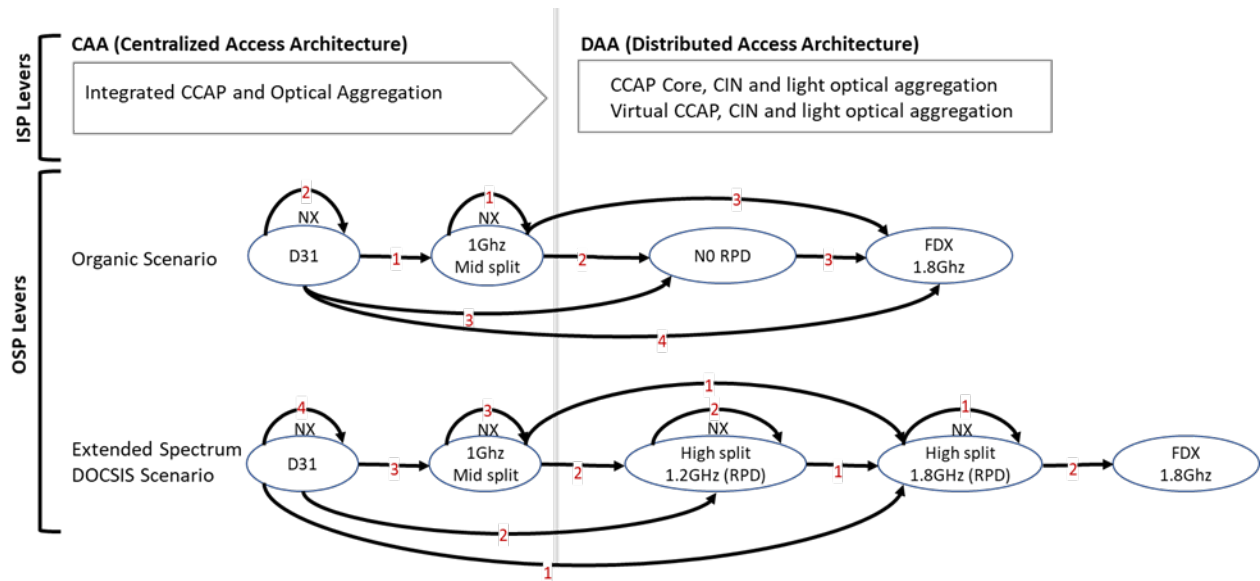
Figure 1 - End to end access architectures evaluated from the operational factors point of view

NOTE: The analysis is conducted with certain assumptions to the best of our knowledge. We want you to pay attention to the framework and the process of the analysis rather than digging deep into the numbers.

6.1. End to end power analysis

As a first step we tried to understand the total end to end power consumption for our sample access network of around 100k homes passed, which we used in our earlier paper (refer to [1], [4], [5]). The results of our analysis are shown in Figure 2.

Here are a few observations we can make from the chart in **Error! Reference source not found.**:
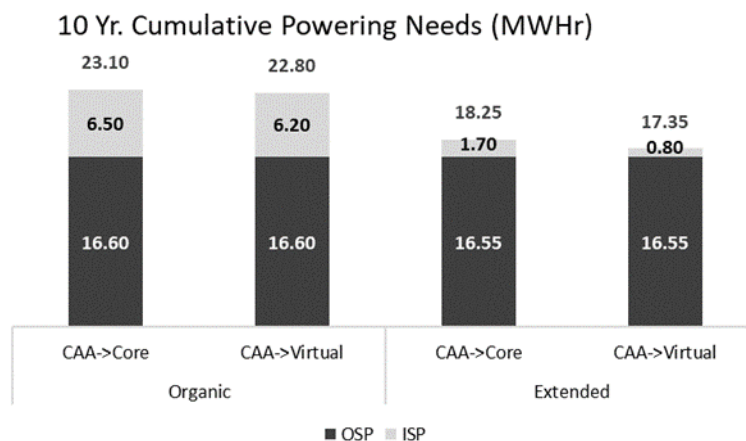
Figure 2 - 10-year end to end cumulative power consuption

The organic upgrade path relies heavily on node splits which lead to higher number of nodes and service groups. This also leads to a much later transition to DAA which drives significantly higher power demand in the long run. The ESD upgrade path on the other hand relies more on spectrum expansion that requires relatively less power. The Virtual CCAP solution shows lower power consumption compared to the CCAP Core solution in the ISP as it shifts some of the CMTS functionality and associated power demand to the upstream regional data centers (cloud) which is outside the scope of this analysis. End to end operational factor analysis
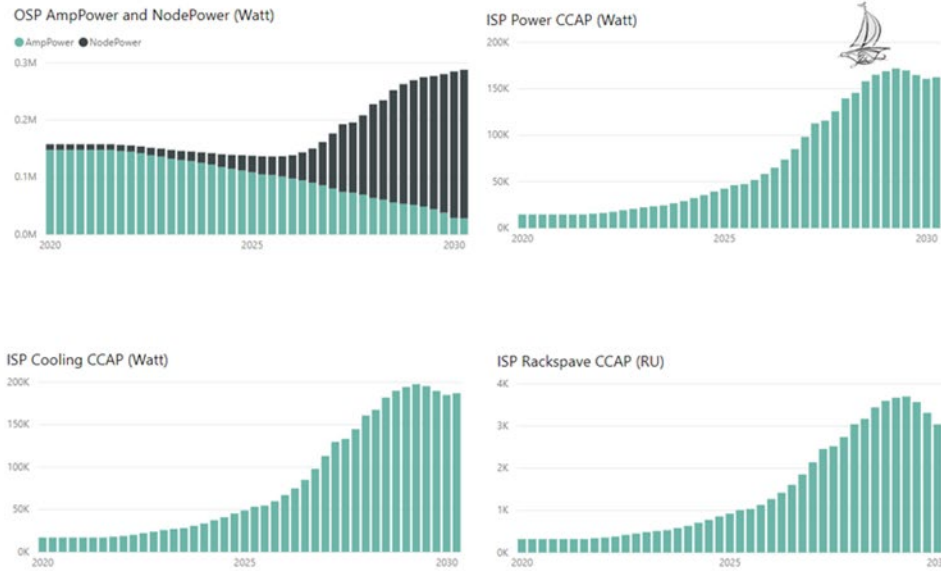
(a) Organic evolution operating metrics for core CCAP
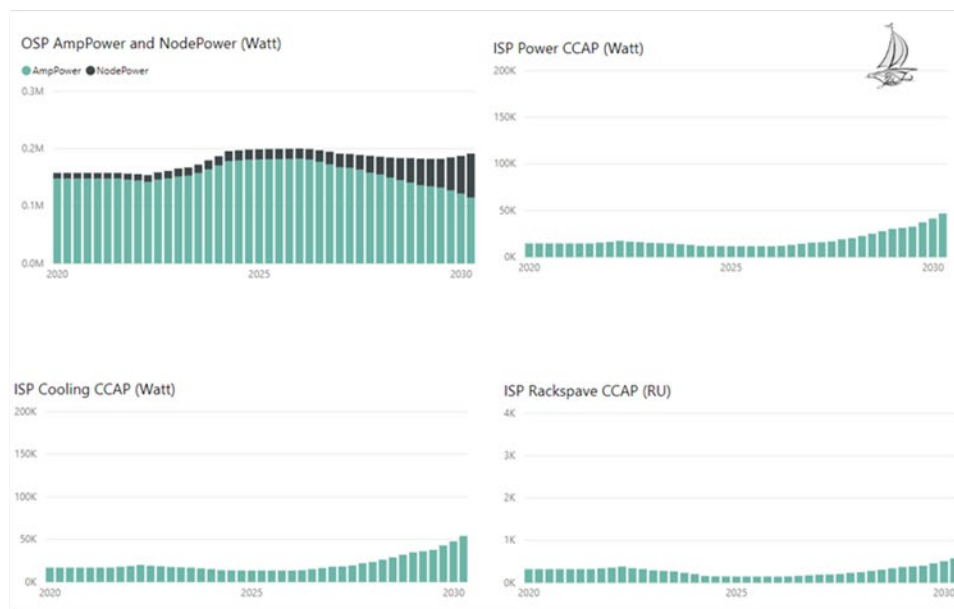
(b) ESD evolution operating metrics for core CCAP

Figure 3 - 10-year quarterly operating factor analysis for organic and ESD evolution to core CCAP

In Figure 3 we provide a detailed analysis of the various operational factors we considered including OSP and ISP power consumption, ISP cooling, and ISP rack space requirement of the organic and ESD

scenarios over a 10-year period on a quarterly basis (refer to [5]). Once again, the exact numbers are not important, but we can make several interesting observations from the trends.

The first observation we can make is that all three factors – power, cooling, and rack-space – are tightly correlated and show the same trend. This is understandable as all three are driven by need for additional equipment to support network growth.

Another observation we can make is that the ESD scenario offers significantly lower power, space and cooling requirements compared to the organic scenario. Organic operating factors spike up in later years mainly due to the increase in number of nodes and service groups.

6.2. End to end power cost analysis

Figure 4 shows the financial analysis of the two scenarios over the 10-year period. In this analysis we have only focused on the cost of the power supplies and the consumed power. The results clearly mirror the trends in the operational factors described earlier.
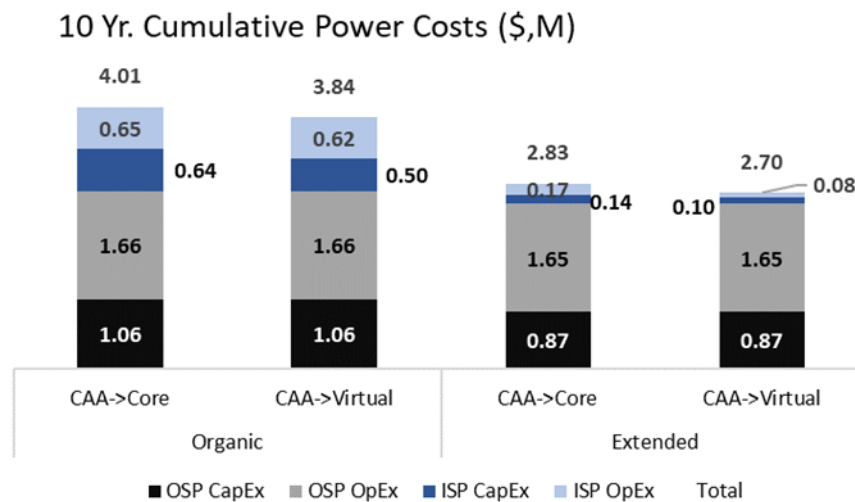
Figure 4 - 10-year total power related cost components

In order to effectively analyze the true financial impacts per our framework the total cost of ownership (including both the CapEx and OpEx) as well as the net present value (NPV) of the costs would need to be determined, which would give the spend timing related insights. Finally, other costs such as maintenance, trouble calls, and truck rolls related costs would need to be factored.

6.3. Other architectural and operational measures analysis

Next, we will compare the two scenarios using the architectural and operational dimensions of our framework.

Looking at the architectural dimension of our framework we need to explore the feasibility, ease of upgrade, and the solution lifetime. From the feasibility and ease of upgrade point of view the organic option has clear advantages due to relative simplicity of node splits vs ESD upgrades. However, in terms of lifetime of the solution, the ESD upgrade comes out ahead.

Looking at the operational dimension of our framework we need to explore the solution reliability, complexity, and failure recovery capability. From a reliability and complexity point of view the organic option would come out in front due to the simplicity and well-established practice of node splits. On the failure recovery front the picture would be a bit mixed. The organic scenario results in many nodes which could increase the failure recovery time. On the other hand, in the ESD case, even though there are fewer nodes, there is greater complexity in dealing with the extended spectrum. That can also impede failure recovery.

7. Recommendations for power architects

World energy consumption has been growing at an unsustainable rate over many years. As a significant energy user, the cable industry launched the SCTE Energy 2020 program [6] to address the end-to-end energy usage. Our framework is put forth to assist in analyzing different powering solutions.

We made following recommendations for power architect in our earlier paper [1] –

- *Align with your company's access strategy*: Powering solutions cannot be an afterthought or a reactive one-time solution. It needs to be aligned with the operator's overall network strategy.
- *Consumption is not the only metric you need to optimize*: While consumption reduction is one of the main goals of the next generation energy strategy, the powering solutions need to be evaluated in the context of the architectural, operational and financial metrics as mentioned.
- *Plan long-term powering solutions before making the short-term next steps*: Understanding the long-term powering needs and their impacts is essential before making short-term decisions.

Based on the end to end access discussion in this paper, we make these additional recommendations –

- *Include end-to-end operational factor analysis*: Conduct your analysis with both the ISP and OSP impacts in mind. One classic example where such a balancing act is clearly visible is fiber deep or extending the spectrum to 1.8 GHz. The former taxes the power and the space in the facility due to service group explosion compared to the latter.
- *Note that the ISP and the OSP incentives can be different*: Optimizing based on OSP or ISP levers alone does not result in an optimal solution.
- *Remember that virtualization does not necessarily mean the costs are eliminated*: Virtualization does not always eliminate costs but often shifts the costs to different locations. For example, V-CCAP reduces the impact of a facility level operating factors, but it keeps the OSP impact the same as before and moves some of the facility costs to the data centers.

As a next step, we are evaluating different operational factor (power, space and cooling) related solutions that are being proposed in the cable industry using the proposed framework. You can reach out to Rajesh Abbi or Sudheer Dharanikota for additional information.

8. Acknowledgements

We thank Thomas Harton of Cox and Luc Absillis of First Principles Innovations for their support.

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Cable's New Gig?

Creating a Standard and an Intellectual Property Pool for Optimizing the Electric Grid with the Internet of Things

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1. Introduction

Once upon a time, decades ago, in a customer experience far, far away from what it is now, the Cable TV industry questioned whether to get into the Internet access business. Then, Big Bang happened, and the Fathers of Cable said, "Let there be Internet" and developed a world-standard cable modem. This group of innovators stepped out ,and boldly created the broadband industry, which now provides billions in revenue.

Over the years, the trials and tribulations in accommodating an increasing number of Internet users and uses led to a better understanding of traffic characteristics, bandwidth expansion, and new network demands such as web services, edge computing, and low-latency communications. Today, in the face of a global shift from fossil fuels to renewable energy sources, uncanny parallels are emerging between traffic management on broadband networks and optimal load shaping (OLS) of energy on the smart electric grid. Indeed, just as networks are optimized to provide better-connected services for the benefit of humans, OLS will optimize the use of renewables to power 100% of today's electric grids while creating revenue-generating opportunities.

2. Optimum Load Shaping

OLS is a recent breakthrough "essential application" for smart cities and regions that reverses the 132-year-old electricity supply-follows-demand relationship to enable a new demand-follows-supply model. By shaping demand to follow the least cost supply, OLS technology slashes billions of dollars in the annual operations and maintenance costs of generating electricity. It is an easy to implement technology that uses the Internet of Things to orchestrate distributed energy storage to accommodate the variable and uncertain production of renewables such as wind and solar power while maximizing the efficiency of traditional fossil-fueled power plants. OLS is a broadcast signal, is the simplest method for optimizing the end-to-end generation-to-load system, can be readily introduced as a world standard, and will reduce Cable's energy bills.

3. The Future Electric Grid

The future grid is managed with bits and bytes—and minimizes all forms of combustion as it electrifies everything in buildings, transportation, and industry. Just as the cable industry pioneered building Internet access back in the day, there are similar opportunities to modernize the grid with communications that manage the infrastructure, energy use, and so-called ancillary services. Moreover, with utilities seeking to enable data services to modernize the grid, there is an increasing awareness, and importantly, money on the table to supply those services.

4. Telecommunications Opportunities

Three telecommunications industries have a first-mover advantage in terms of the infrastructure, global reach, supplier relationships, and purchasing power required to capitalize on grid optimization. While the satellite industry can broadcast OLS signals, in the long term, high

latency will be problematic for fine spatiotemporal grid monitoring and control. The wireless industry is eager to supply privatized broadband networks, as evidenced by recent announcements from AT&T and Verizon addressing this growing market need. However, the cable broadband industry is ideally suited to supply these data communication services given their small node sizes and intimate overlap with the last mile of the grid. Further, Cable's ability to create isolated, private, and secure data streams, while providing the most reliable and lowest latency data services possible, positions them as the industry of choice. With relatively minimal effort, the cable industry can quickly develop a world standard for OLS. Doing so would position Cable to be the dominant provider of load shaping signals that are sent by utilities to inform the residential, commercial, industrial, and transportation sectors of the future availability of low-cost clean electricity.

5. The Standards Landscape

Much work has gone into developing interconnection and interoperability standards to define how to assemble, configure, and connect devices to form a "smart" or "modern" grid. Nonetheless, a major challenge with standards to date is that they are limited to development within specific technology domains, such as vehicle charging or air conditioning control. As such, existing standards lack a complete vision for how distributed energy resources need to interact with generation to deliver end-to-end grid services. While some standards are mature, technically robust, and meet the needs within a specific domain, in aggregate, they do not support optimum load shaping. For reference, an overview of select relevant standards are included as an Appendix.

6. Development of Intellectual Property and an IP Pool

Before leading the development of the DOCSIS® world-standard cable modem[1] at CableLabs and becoming a Cable TV Pioneer, I began researching and developing technology to orchestrate electricity supply and demand in 1980. I have spent the last 3.5 years validating load shaping at the U.S. National Renewable Energy Laboratory and the University of Colorado. I now hold six U.S. load shaping patents, have additional patent applications on file in the U.S and Europe, and am willing to create an intellectual property pool (IP Pool) to speed the global implementation of OLS. The main goal of the IP Pool is to allow utilities and connected device suppliers to license OLS technology on a fair and reasonable basis. Other goals are to provide a covenant not to sue among product suppliers meeting the OLS standard, and to enable the cable industry to reduce energy costs in facilities and fleet management.

7. Conclusion

Just as the world-standard cable modem ushered in new business opportunities, OLS will forge new and unforeseen businesses as the grid increasingly evolves from central station delivery of power to 2-way electricity flows in the last mile that minimizes pollution and increases the

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[1] DOCSIS is a registered trademark of Cable Television Laboratories, Inc., for the Data over Cable Service Interface Specifications.

efficiency of buildings and transportation. The time to strike is now, while the iron (and planet) are hot. In addition to OLS cost savings in power generation and use in facilities and fleet operations, facilitating the transition to 100% renewable energy will reduce heat and greenhouse gas emissions to mitigate global warming. Rapidly implementing an OLS standard is good for the cable industry, good for employees, and good for the world—the higher the penetration and use of OLS, the greater the benefit.

On behalf of Laurie and myself, please enjoy our technical article in this issue of the SCTE•IBSE Journal of Energy Management, *The Value of Optimum Electric Load Shaping*, and reach out to us with your questions at www.gridiot.net. Thank you.

8. Appendix: Relevant Grid Standards

A review of relevant electric grid standards provides a sense of the domain-specific nature of existing standards efforts. By way of example, below is a current list of photovoltaic generation and related standards. In addition, similar sets of standards and efforts exist for electric energy storage, electric vehicles, responsive loads, and grid-connected microgrids. Despite much standards activity, a single end-to-end load-shaping standard that jointly optimizes generation and load is missing.

IEEE 1547, *The Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces*, is mandated by the Energy Policy Act of 2005 and is the main standard for the interconnection of Distributed Energy Resources (DERs) to electrical distribution systems. First published in 2003, reaffirmed in 2008 and 2013, and amended in 2014, a full revision was completed in April 2018 to include features for managing high penetrations of DERs on distribution feeders and to support the grid under normal and abnormal conditions. The standard now recognizes DERs as having interoperability electrical and communications interfaces. IEEE Standard 1547-2018 is now mapped to four communication efforts: IEEE 2030.5, DNP3, SunSpec Modbus, and IEC 61850-7-420. The standard includes various advanced grid support functions such as active/power control, volt-VAR, frequency-watt functions, and voltage/frequency ride-through. More information is available at: https://standards.ieee.org/standard/1547-2018.html and http://sites.ieee.org/sagroups-scc21/standards/1547rev/.

IEEE 1547.1, *Standard Conformance Test Procedures for Equipment Interconnecting Distributed Resources with Electric Power Systems*, was published in 2005, reaffirmed in 2010, amended in 2015, and is the standard for testing compliance of DERs to the IEEE Std 1547 requirements. It is in the process of being revised requiring broad stakeholder engagement with working groups of several hundred people actively participating to reach consensus. The draft standard is fully revised to include testing for new IEEE Std 1547-2018 requirements and is currently under public review and balloting. The revised standard is expected to be published in 2020. More information is available at https://standards.ieee.org/project/1547_1.html.

UL 1741, *Standard for Safety - Inverters, Converters, Controllers, and Interconnection System Equipment for Use With Distributed Energy Resources*, is tightly coupled with IEEE 1547.1 and

contains tests and verifications to confirm two aspects of inverters: safety aspects such as shock and fire prevention, and grid interconnection performance. To verify grid interconnection performance, UL 1741 historically simply referenced the type tests in IEEE 1547.1. With the emergence of high levels of DERs in California and Hawaii, an amendment to UL 1741 was developed and published in 2016, *UL 1741 Supplement A*. More information is available at https://standardscatalog.ul.com/standards/en/standard_1741_2.

IEC TR 61850-90-7, *Communication Networks and Systems for Power Utility Automation-Part 90-7: Object Models for Power Converters in Distributed Energy Resources (DER) Systems*, published in 2013, is a technical report that defines an information model for distributed energy resources to provide grid support services—e.g., volt/VAR, frequency-watt. This technical report was updated in May 2018 and converted to IEC standard 61850-7-420, *Communication Networks and Systems for Power Utility Automation—Part 7-420: Basic Communication Structure—Distributed Energy Resources Logical Nodes*, which includes new functions and DER Grid Codes including California's Rule 21, the IEEE 1547 revision, and the European ENTSO-E Grid Codes of May 2016. Aspects of energy storage systems are included, such as charging aspects. Another revision is expected to be released in mid-2020. More information is available at https://webstore.iec.ch/publication/6027 and https://webstore.iec.ch/publication/6019.

The *SEPA/NAESB Open Field Message Bus*, OpenFMB, is a communications framework and reference architecture designed to enhance interoperability between proprietary devices on the electric grid and is based on existing standards. The OpenFMB Reference Architecture Specifications were ratified in March 2016 by the North American Energy Standards Board (NAESB). An OpenFMB demonstration on use case functionality took place at the 2016 Grid Modernization Summit (November 7–10, 2016). More information is available at: https://www.naesb.org/, and https://openfmb.ucaiug.org/Pages/Overview.aspx?#naesb.

The *SunSpec Alliance* provides a number of information, monitoring, and advanced DER function models—e.g., direct control functions, volt/VAR, frequency-watt, watt-power factor, and others from IEC 61850-7-420 The PV models have been ratified through a consensus process with Alliance members and are undergoing a review for updates. More information is available at: http://sunspec.org.

IEEE 2030.5, *IEEE Adoption of Smart Energy Profile 2.0 Application Protocol Standard*, most recently released in 2018, is a communication protocol that is currently undergoing a revision to include DER advanced inverter functions included in IEC 61850 (information models), California Rule 21 (grid code), Hawaii Rule 14H (grid code), and UL 1741 (certification protocol). More information is available at https://standards.ieee.org/standard/2030_5-2013.html.

Modbus is a serial communication protocol for establishing master-slave/client-server communication among intelligent devices. It is an open standard that is available without royalties and has variants for serial ports (Modbus RTU) and Ethernet (Modbus Transmission Control Protocol/IP). Modbus is used as the base protocol in MESA devices and has been

implemented by hundreds of vendors on thousands of different devices to transfer discrete/analog input/output and register data among control devices. It is widely used by DER equipment manufacturers, for PV inverters, energy storage, on-site generators, and microgrid switchgear equipment. More than 7 million Modbus nodes are located in North America and Europe. More information is available at: http://www.modbus.org/ and http://mesastandards.org/mesa-device, http://sunspec.org/wp-content/uploads/2015/06/SunSpec-Meter-Models-12023.pdf, https://sunspec.org/sunspec-modbus, and http://www.modbus.org/specs.php.

IEEE Std 1547.3, *IEEE Guide for Monitoring, Information Exchange, and Control of Distributed Resources Interconnected with Electric Power Systems*, published in 2007, provides guidance for monitoring, information exchange, and control of DERs. The guide discusses the desire for interoperability, configuration management, communication protocols, and security guidelines. More information is available at https://standards.ieee.org/findstds/standard/1547.3-2007.html.

IEEE Std 1815*, Distributed Network Protocol* (DNP3), initially developed in the early 1990s, has been implemented by U.S. electric utilities. The protocol was developed to meet utilities' need for a standardized option for interoperability between substation computers, remote terminal units, intelligent electronic devices and master stations. DNP3 has also been adopted by entities in related industries such as water/wastewater, transportation, and by the oil and gas industry. In 2010, DNP3 was accepted as IEEE Standard 1815. The latest IEEE revision was in 2012, and in January 2019 a collaborative team published an application note which contains an information model for enabling new DER functional as required in California Rule 21 and specified in IEEE Std 1547-2018. More information is available at: https://www.dnp.org, http://sunspec.org/wp-content/uploads/2015/06/DNP3-AN2013-001-DNP3-Advanced-Photovoltaic-Profile.pdf, and https://standards.ieee.org/standard/1815-2012.html.