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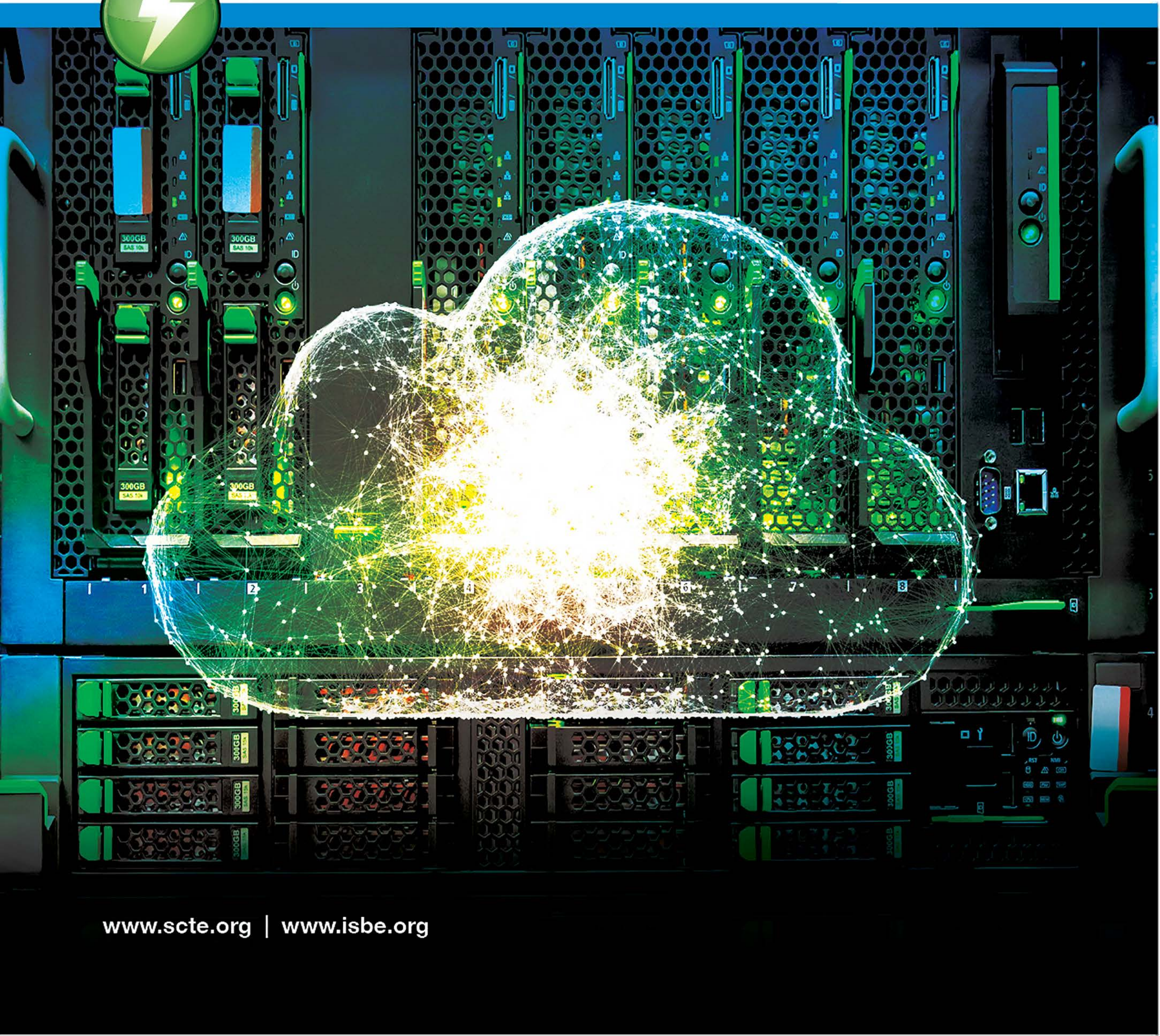

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Society of Cable
Telecommunications
Engineers

International
Society of Broadband
Experts

JOURNAL OF ENERGY MANAGEMENT

VOLUME 1, NUMBER 2
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Society of Cable Telecommunications Engineers, Inc.
International Society of Broadband Experts™
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JOURNAL OF
ENERGY MANAGEMENT

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From the Editors

Welcome to the second issue of the *Journal of Energy Management*, a publication of collected papers by the Society of Cable Telecommunications Engineers (SCTE) and its global arm, the International Society of Broadband Experts (ISBE).

This October 2016 edition of the Journal focuses on cost saving opportunities and various energy saving methodologies, including:

- Financial considerations and risks of off-site alternative energy procurement strategies
- Assessment of changing utility rate structures which could provide financial opportunities for cable operators
- Decoding the IEEE 1366 standard that impacts cable's utility partners
- Measuring HVAC, lighting, energy generation and storage at the critical facility level
- The impact of batteries on the Internet of Things (IoT)
- HFC capacity planning and the impact of evolving architectures on cable plant power
- A deep dive into energy demands of network routers.
- Examination of energy storage with up and coming battery technologies

In support of Energy 2020, the Energy Management Subcommittee has worked diligently this year to expand its team of participants as well as producing 19 standards and operational practices. These journal entries can be further examined by respective working groups ultimately leading to approval by the ANSI accredited SCTE ISBE Standards program.

We would like to thank the individuals who contributed to this issue of *the Journal of Energy Management*, especially the authors, peer reviewers, and the SCTE/ISBE publications and marketing staff. We hope that the selected papers spark innovative ideas to further our collaboration to mature the industry's operational practices, standards and technology solutions to help everyone meet the Energy 2020 goals.

In closing, if there is any editorial information or topics that you would like us to consider for the third issue of SCTE/ISBE Journal of Energy Management, please refer to the "editorial correspondence" and "submissions" sections at the bottom of the table of contents for further instructions.

SCTE/ISBE Journal of Energy Management Senior Editors,

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ENERGY MANAGEMENT

IEEE 2.5 Beta Method Unraveled

A Technical Paper Prepared for SCTE/ISBE by

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1. Introduction

This white paper, written for non-technical audiences, discusses the scope and applicability of the IEEE (Institute of Electrical and Electronics Engineers) 1366 standard methodology. It focuses on solutions available to improve utility indices and MTTX[1] metrics. The purpose is to provide an educational and informational white paper and not overload the audience with statistical formulas and complex details.

1.1. Problem Statement

Internal and external goals are set around reliability performance yet there has been no uniform methodology for removing events that are so far away from normal performance (known as outliers). Without removal of outliers, variation in annual performance is too great to set meaningful targets. Outliers are removed manually today, so they don't skew the stats, but criteria are variable. Normalizing reliability data reduces the variability, thus making trending and goal setting possible.

One of the goals for this white paper is to illustrate the statistical concept and provide awareness. Another goal is to be able to summarize concepts and its applications to facilitate socializing with a wider audience such as Critical Infrastructure, Network Operations Centers (NOCs), and the Energy 2020 Program.

A solution developed by IEEE for power utilities contains the following attributes as detailed within this white paper:

1. A statistics based methodology (referred to as the "Beta Method") for identifying outlying performance (otherwise known as "major event days" or "MEDs").
2. Known as the "2.5 Beta Method" because of its use of the naturally occurring log-normal distribution that best describes reliability performance data.
3. Using this method, we can calculate indices on both a normalized and unadjusted basis.
4. Normalized indices provide metrics that should be used for goal setting.
5. Unadjusted indices, when compared to the normalized indices, provide information about performance during major events (identifies abnormal performance).

2. The Mystery

We know that outages and/or outage durations spike during MEDs, but is there a way to show a true picture of outages without manually removing the MEDs (outliers) that skew Reliability Metrics? That is the piece of the puzzle we set out to find. Metrics drives behavior, but what if the metrics don't show the whole story? This is when you need a good Data Analyst whose curiosity incites him or her to search for and find the answers to such questions. In our case, we need to find out how we can accurately measure outages, but also account for anomalies in a data set.

Having the ability to find truth in the metrics is what makes a brilliant analyst stand apart from the rest. As mentioned in ***Now You See It*** by Stephen Few and explained by George Kuhn, former Director of

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[1] MTTX represents a subset of metrics with the "X" signifying a variable, i.e., MTTR (mean time to restore), MTTA (mean time to acknowledge), etc.

Research Services at research and marketing strategies (RMS), good Data Analysts have 13 traits of which I will mention a few that are relevant to this white paper:

1. Analytical – seems obvious, but it is "being able to take a percentage or a number and 'decompose it' into the sum of the parts that make it up". Applying this trait to this white paper, it is looking at outages and saying "what percent of those outages are on major event days?" and finding the answer.
2. Capable of spotting patterns – "the ability to spot trends or themes in the data. Spotting the data patterns takes a unique eye. Oftentimes, this doesn't materialize until you can see it in graphical format." In our example it is in the realization that outage numbers and/or subscriber counts (in specific markets) increase on major event days.
3. Curious – "the difference here is although you may be interested in a topic, you need to have the curiosity to dig deeper into data. Don't just report the 41% and move on, figure out why 41% is 41%." How can we accurately report outages, but yet separate out abnormal performance that skew the results?
4. Open-minded and flexible – be objective; "although you may have some preconceived notions about how the data will turn out, be open-minded and be able to adjust your findings on the fly." This is evident in identifying the 2.5 Beta Methodology as a viable solution to tracking outages.

3. Discovering the Right Methodology

An IEEE Working Group comprising roughly 130 members developed the "2.5 Beta Methodology" in IEEE Standards 1366-2003. Membership includes representation from utility companies, regulatory staff, manufacturing companies, consultants and academicians. The Working Group evaluated Beta Multiplier values using a number of power companies of different sizes and from different parts of the United States. Though a number of alternative approaches were considered, 2.5 Beta Method came out to be superior. We quickly realized this same methodology could be used in reporting Time Warner Cable (TWC)[2] outages, specifically relevant to MEDs.

3.1. IEEE Working Group 2.5 Beta Methology

- Improves TWC's ability to view day-to-day outage reliability performance without removing the outliers that often distort it.
- Allows for consistent calculation of reliability performance by each TWC Market and/or Power Company.
- Normalizes reliability data and reduces variability, thus making trending and goal setting possible.
- Provides an objective (quantitative basis) for measuring and segmenting major events from normal operations.

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[2] Time Warner Cable (TWC) was acquired by Charter Communications in May 2016.

3.2. Major Event Day Versus Day-To-Day Operations

This pictorial illustrates how Major Event Days are separate, albeit related to Day-to-Day Operations and need to be considered in calculating outages.

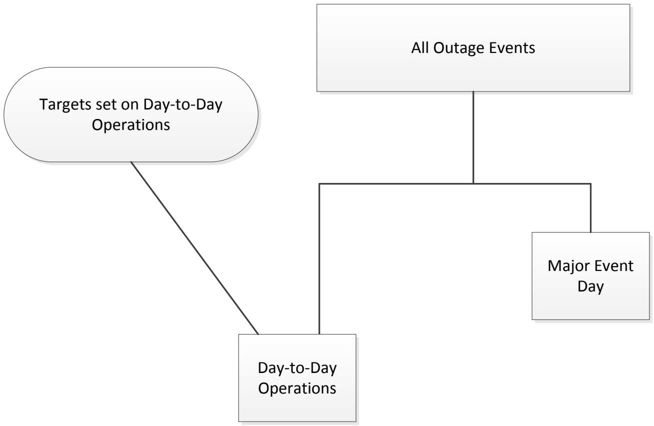

Figure 1 - Major Event Day Versus Day-to-Day Operations

4. Knowing What to Measure and How

Table 1 - Five Indices Used in Outage Reporting Utilizing 2.5 Beta Methodology Along with A Detailed Description Of Each

Metric	Definition	Formula	Description
SAIDI system average interruption duration index	Total duration of interruption (downtime minutes) on an average per customer	Sum of (Max of Outage Duration Minutes) / Total Customer Relationships	SAIDI is the index used to identify Major Event Days (MEDs) and correlates with total cost of unreliability, including utility repair costs and subscriber losses. SAIDI is a quality factor taking into account the duration of interruptions (locating and repairing faults faster). The use of SAIDI approach also accounts for variation in subscriber count, especially in the case of mergers (as in Charter/Time Warner Cable), where the subscriber mix tends to vary. This allows us to set realistic company-wide reliability targets. An important point to note is that SAIDI, excluding MEDs, is controllable.3
CAIDI customer average interruption duration index	Average time to restore service due to a power outage	Sum of (Max of Outage Duration Minutes) / Sum of (Max of Subs impacted)	CAIDI correlates to value per Customer; CAIDI does not reflect the size of power outage events. CAIDI is a more granular index to help in the management of service provider networks and decisions for reliability based capital expenditures. Obtaining the correct number of subs impacted by an outage event is of critical importance for calculating customer based reliability indices such as

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[3] Daily SAIDI values are preferred to daily customer minutes of interruption (CMI) values for MED identification because the SAIDI permits comparison and computation among years with different numbers of customers served.

Metric	Definition	Formula	Description
			CAIDI, since only a fraction of interested customers will call the utility.
SAIFI system average interruption frequency index	Probability of TWC subscribers experiencing a power outage during the time frame under study	SAIDI / CAIDI	SAIFI is another quality factor that takes into account the number of interruptions. SAIFI is a frequency based index and not an indicator of the total cost of the outage. SAIFI has a strong correlation with backup power (prevent faults from occurring).
CIII customers interrupted per interruption index	Average number of subscribers interrupted during a power outage	Sum of (Max of Subs impacted) / Number of outage tickets	CIII allows the ability to drill down to number of subscriber impacts per day and to determine if one outage or multiple outages contributed to the vast majority of the subscribers losing power.
ASAI average service availability index	Ratio of the total number of subscriber hours that service was available during a given time period to the total subscriber hours demanded	[(10,080 minutes – SAIDI)/10,080 minutes] *100, if calculated weekly	ASAI is the availability percentage; major event days must be excluded from the ASAI calculation so it is easy to implement corrective actions on normal day to day occurrences.

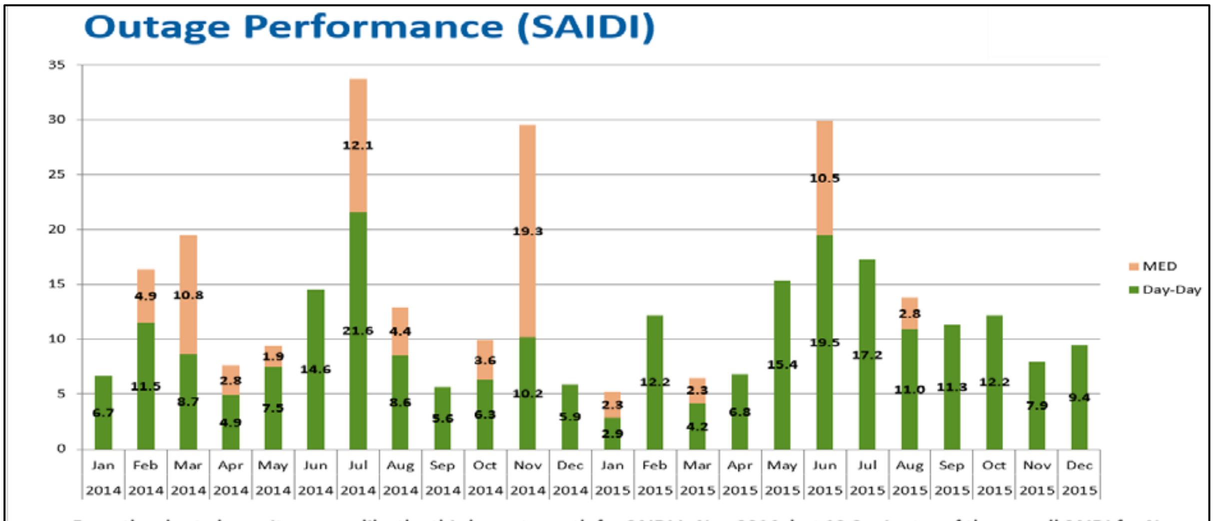
a. Availability can be calculated daily, weekly, monthly, quarterly or yearly.

b. Yearly threshold does not account for seasonality and hence is less valuable.

All of the indices give a baseline for performance and give utilities a method for targeting improvement. The targeting efforts must focus on preventing faults from occurring which impacts SAIFI or locating and repairing faults faster which targets SAIDI.

5. Putting the Pieces Together

Both SAIDI charts below clearly show how MEDs impact outages in the legacy Time Warner Cable world.[4] Time Warner Cable merged with Charter Communications May 2016 and the data analysis is based on pre-merger Time Warner Cable data.



From the chart above, it appears like the third worst month for SAIDI is Nov 2014, but 19.3 minutes of the overall SAIDI for Nov 2014 was due to a major event.

Figure 2 - Outage Performance (SAIDI) – Stacked Bar Chart

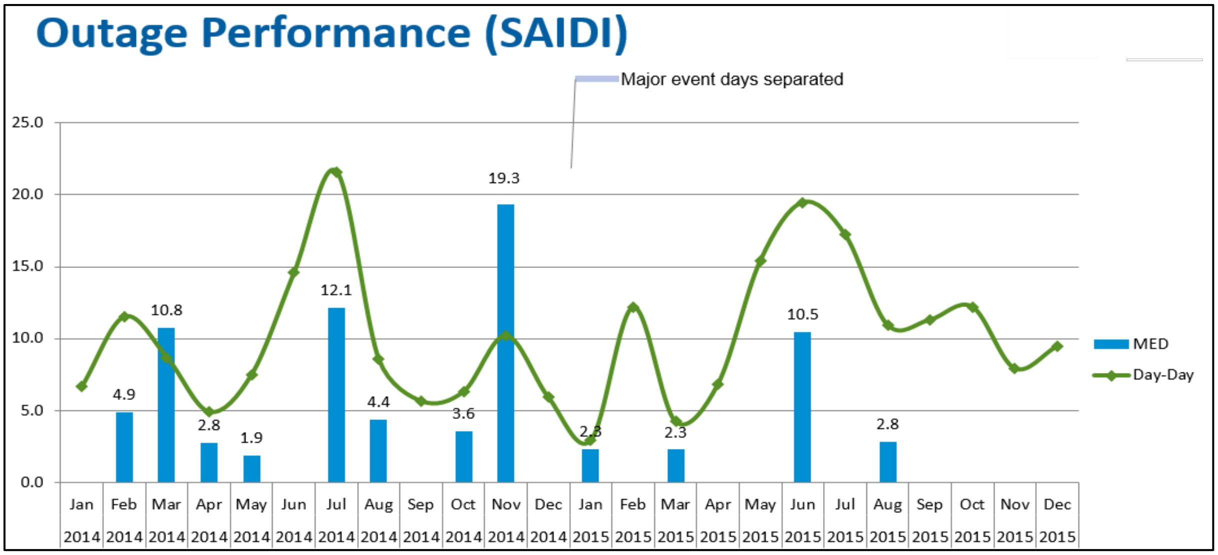


Figure 3 - Outage Performance (SAIDI) – Bar and Line Chart

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[4] The Outage Performance (SAIDI) charts contain sensitive information that is protected and privileged and must not be reproduced without owner's permission.

6. Balancing PUC Requirements

6.1. PUC Mandates

State Public Utility Commissions (PUCs) interest in electricity continues to grow. In some states, PUCs have imposed mandates on Power companies to comply with the reliability indices set forth by the IEEE working group and have attached revenue incentives to performance. Utilities use these indices to determine when an anomaly occurred on the system and to compare their performance against other utilities.

PUCs set performance goals (utility cost per customer) and establish reward and penalty structure. Utilities in turn strive to meet or exceed these goals or miss the goals and either receive financial incentives or pay penalties. Some utilities have implemented flexi-watts that work using the concept of supply and demand. The final outcome boils down to reduced costs to customers, reliable service and increase in customer satisfaction scores.

Both Department of Energy (DOE) and North American Electric Reliability Corp (NERC) require reporting of major electricity system incidents. Reporting to these national bodies is now mandatory, required in real time, and includes incidents that sometimes result in no loss of electric service to customers. The principal purpose of this form of reporting to national bodies is to provide information on major electricity system emergencies that may require immediate responses by industry or government to ensure public health and safety.[5]

California Public Utilities Commission (CPUC) and the National Association of Regulatory Utility Commissioners (NARUC) have petitioned FCC for access to outage information that is filed by Communications providers via the FCC Network Outage Reporting System (NORS). This data can potentially help to enhance homeland security and emergency response functions. Additionally, it helps states to evaluate the causes of the outages and to determine whether they are one time occurrence vs. systematic failures. FCC is working on the best approach to facilitate this information sharing but at the same time investigating options to safeguard sensitive customer data.

FCC released a declarative ruling recently that allows utilities to place robo-calls concerning service outages, service restoration, meter work, tree trimming and other field work, threatened service curtailment, and potential brown-outs due to heavy energy use. Utility callers must still comply with Telephone Consumer Protection Act (TCPA) of 1991, including customer opt-out requirements and ceasing robo-calls to numbers that have been reassigned to new customers.

6.2. Smart Metering

Table 2 - Smart Grid Applications

Smart grid Applications	Primary impacts on outages
Fault detection and automated feeder switching	Reduction in the frequency and duration of outages and the number of affected customers
Diagnostic and equipment health sensors	Reductions in the frequency of outages and the number of affected customers

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[5] According to U.S. Energy Information Administration (EIA) data, 65 million households are served by utilities that offer time varying rates such as Time of Use (TOU) rates where the utility provides a discounted rate outside of peak times.

Smart grid Applications	Primary impacts on outages
Outage detection and notification systems	Reductions in the duration of outages

7. Some Implementation Q&A to Consider

Q1: Do these metrics help us make investment decisions by geography?

A: By enhancing power data with common language code sets (CLLI[6], CLEI[7], and PCN[8]), we can:

- Correlate CLLI codes (location) to where network outages occur
- Map network equipment (CLEI) to a particular CLLI location
- Identify equipment that has a high rate of PCNs
- Display outage hotspot locations and Mean Time to Restore Service (MTRS) via dashboard or heat map
- Predict potential outages and MTRS (with PCN correlation)
- Provide proactive recommendations on preventing potential future outage occurrences

The purpose of CLEI is to act upon Product Change Notification (PCN). Telecommunications equipment is constantly changing and evolving. The changes range from product defect to a product enhancement. The communication of these changes from an equipment supplier to an equipment user is accomplished via a product change notice or PCN.

Q2: Are the SAIDIs controllable?

A: Since we have the ability to exclude major event days (MEDs) from normal operations, normalized SAIDI must be used to control service quality. Events that exceed the MED threshold must be analyzed separately, root cause analysis must be conducted and corrective measures must be taken. [9]

Q3: How can we better enhance the Commercial Power Summary report that will make sense to executives?

A: By identifying Customer Relationships by power company (e.g., anything in the territory for Duke Energy, etc. for each TWC subscriber), taking those addresses and geocoding them we should get a pulse of reliability indices per power company to report on.

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[6] Common language location identifier (CLLI) is a standardized way of describing locations and pieces of hardware in those locations.

[7] Common language equipment identification (CLEI) is a part number of a piece of equipment (usually Central Office equipment).

[8] Product change notice (PCN) is a document issued by a manufacturer to inform customers about a change to a network element.

[9] Research shows that average customer may be dissatisfied if they are without electricity for more than 53 minutes a year. This correlates to the fact that a “four-nine” availability value translates into a SAIDI of 52 minutes per year. The median SAIDI value for North American utilities is approximately 90 minutes. It is imperative therefore for the utilities to maintain that caliber of electric service and make that one of the core facets of the utility’s business model.

8. Applying the 2.5 Beta Method

Key Takeaways:

1. Provide an indication of what percent of the overall downtime minutes (SAIDI), as a result of power outages, are attributed to major events. A preferred MED threshold would be by month/by market to account for seasonality in the data.
2. Triangulate SAIDI (interruption duration), CAIDI (interruption restoration time), and SAIFI (interruption frequency) metrics to enable process improvement efforts.
3. Establish realistic MTTX targets via IEEE normalized CAIDI measurement to enable more accurate NOC to NOC comparisons[10].
4. Apply ASAI index for availability calculation that factors in SAIDI with the ability to exclude major events vs. using the conventional approach [(total circuit minutes in period – circuit downtime minutes)/total circuit minutes)]*100.
5. Use normalized SAIDI to set realistic SAIDI goals and monitor reliability indices by acting on real changes, thus reducing time wasted on chasing variances due to acts of God.
6. Analyze major event day tickets separately from normal operations. Nothing is excluded.
7. Determine Customer Relationships (CRs) by each power company boundary to enhance our ability to compute reliability indices by each utility.
8. Collect findings drawn from publicly available "utility" reliability performance information submitted to respective PUCs to understand evolving requirements by each state and any variation to utility reporting practices with respect to IEEE 1366 standard.
9. Identify correlations (if any) between company specific reliability indices (SAIDI, CAIDI etc.) for each utility vs the reliability indices reported by utilities to their respective State Public Utility Commissions (PUCs).
10. Meet with business partners with the respective power companies to identify improvement areas.

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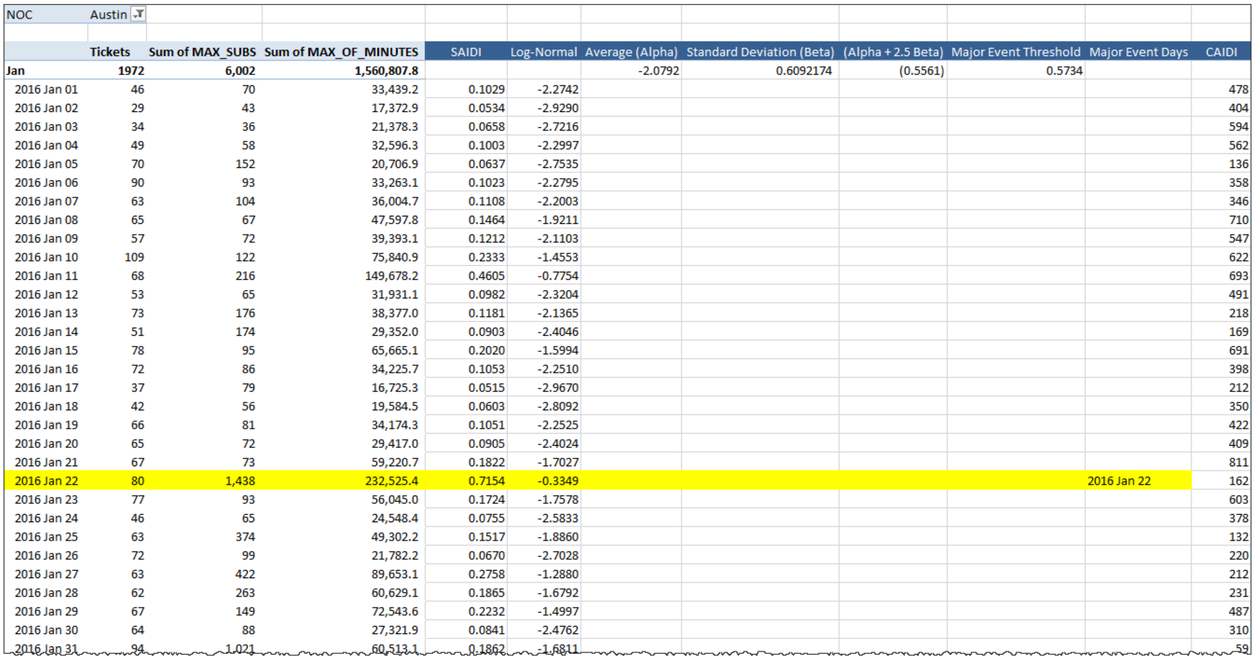
[10] By using unique Customer Relationships specific to each NOC.

9. Supplemental Information

9.1. 2.5 Beta Methodology Example – Applied to NOC Managed Tickets



NOC Austin

	Tickets	Sum of MAX_SUBS	Sum of MAX_OF_MINUTES	SAIDI	Log-Normal	Average (Alpha)	Standard Deviation (Beta)	(Alpha + 2.5 Beta)	Major Event Threshold	Major Event Days	CAIDI
Jan	**1972**	**6,002**	**1,560,807.8**			-2.0792	0.6092174	(0.5561)	0.5734		
2016 Jan 01	46	70	33,439.2	0.1029	-2.2742						478
2016 Jan 02	29	43	17,372.9	0.0534	-2.9290						404
2016 Jan 03	34	36	21,378.3	0.0658	-2.7216						594
2016 Jan 04	49	58	32,596.3	0.1003	-2.2997						562
2016 Jan 05	70	152	20,706.9	0.0637	-2.7535						136
2016 Jan 06	90	93	33,263.1	0.1023	-2.2795						358
2016 Jan 07	63	104	36,004.7	0.1108	-2.2003						346
2016 Jan 08	65	67	47,597.8	0.1464	-1.9211						710
2016 Jan 09	57	72	39,393.1	0.1212	-2.1103						547
2016 Jan 10	109	122	75,840.9	0.2333	-1.4553						622
2016 Jan 11	68	216	149,678.2	0.4605	-0.7754						693
2016 Jan 12	53	65	31,931.1	0.0982	-2.3204						491
2016 Jan 13	73	176	38,377.0	0.1181	-2.1365						218
2016 Jan 14	51	174	29,352.0	0.0903	-2.4046						169
2016 Jan 15	78	95	65,665.1	0.2020	-1.5994						691
2016 Jan 16	72	86	34,225.7	0.1053	-2.2510						398
2016 Jan 17	37	79	16,725.3	0.0515	-2.9670						212
2016 Jan 18	42	56	19,584.5	0.0603	-2.8092						350
2016 Jan 19	66	81	34,174.3	0.1051	-2.2525						422
2016 Jan 20	65	72	29,417.0	0.0905	-2.4024						409
2016 Jan 21	67	73	59,220.7	0.1822	-1.7027						811
2016 Jan 22	80	1,438	232,525.4	0.7154	-0.3349					2016 Jan 22	162
2016 Jan 23	77	93	56,045.0	0.1724	-1.7578						603
2016 Jan 24	46	65	24,548.4	0.0755	-2.5833						378
2016 Jan 25	63	374	49,302.2	0.1517	-1.8860						132
2016 Jan 26	72	99	21,782.2	0.0670	-2.7028						220
2016 Jan 27	63	422	89,653.1	0.2758	-1.2880						212
2016 Jan 28	62	263	60,629.1	0.1865	-1.6792						231
2016 Jan 29	67	149	72,543.6	0.2232	-1.4997						487
2016 Jan 30	64	88	27,321.9	0.0841	-2.4762						310
2016 Jan 31	94	1,021	60,513.1	0.1862	-1.6811						59

Figure 4 - 2.5 Beta Methodology - Applied to NOC Managed Tickets

(The data presented on this report is for legacy Time Warner Cable)[11]

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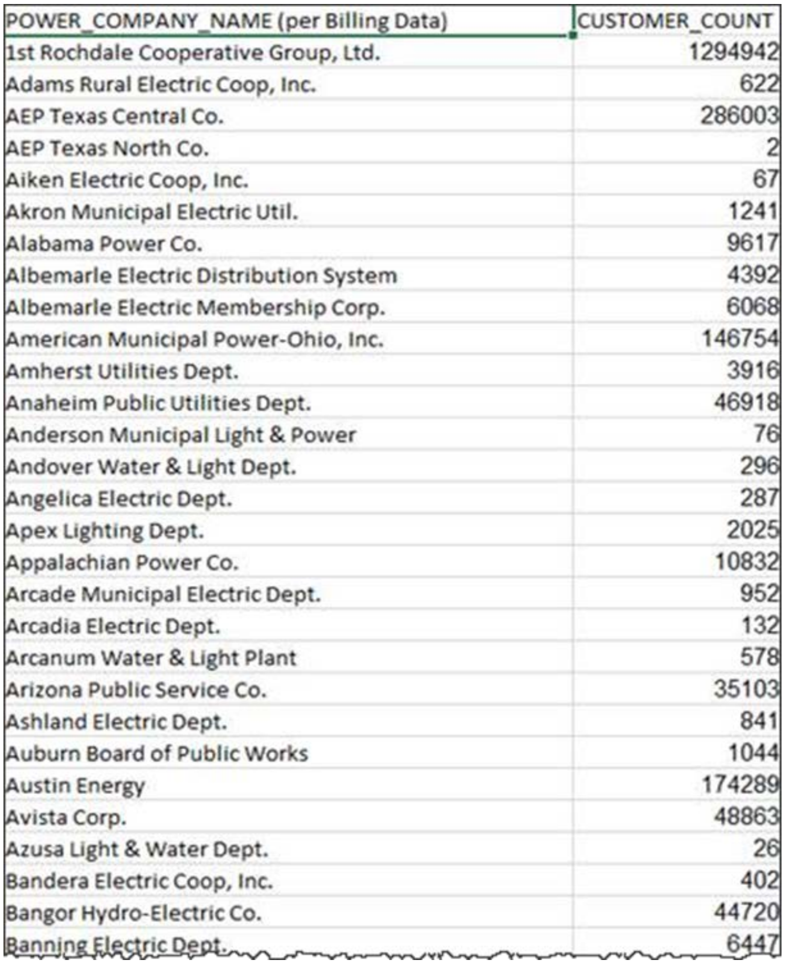
[11] The chart above contains sensitive information that is protected and privileged and must not be reproduced without owner's permission.

9.2. Customer Relationships by Power Company Boundary



POWER_COMPANY_NAME (per Billing Data)	CUSTOMER_COUNT
1st Rochdale Cooperative Group, Ltd.	1294942
Adams Rural Electric Coop, Inc.	622
AEP Texas Central Co.	286003
AEP Texas North Co.	2
Aiken Electric Coop, Inc.	67
Akron Municipal Electric Util.	1241
Alabama Power Co.	9617
Albemarle Electric Distribution System	4392
Albemarle Electric Membership Corp.	6068
American Municipal Power-Ohio, Inc.	146754
Amherst Utilities Dept.	3916
Anaheim Public Utilities Dept.	46918
Anderson Municipal Light & Power	76
Andover Water & Light Dept.	296
Angelica Electric Dept.	287
Apex Lighting Dept.	2025
Appalachian Power Co.	10832
Arcade Municipal Electric Dept.	952
Arcadia Electric Dept.	132
Arcanum Water & Light Plant	578
Arizona Public Service Co.	35103
Ashland Electric Dept.	841
Auburn Board of Public Works	1044
Austin Energy	174289
Avista Corp.	48863
Azusa Light & Water Dept.	26
Bandera Electric Coop, Inc.	402
Bangor Hydro-Electric Co.	44720
Banning Electric Dept.	6447

Figure 5 - Customer Relationship by Power Company Boundary

(The data presented on this report is for legacy Time Warner Cable)[12]

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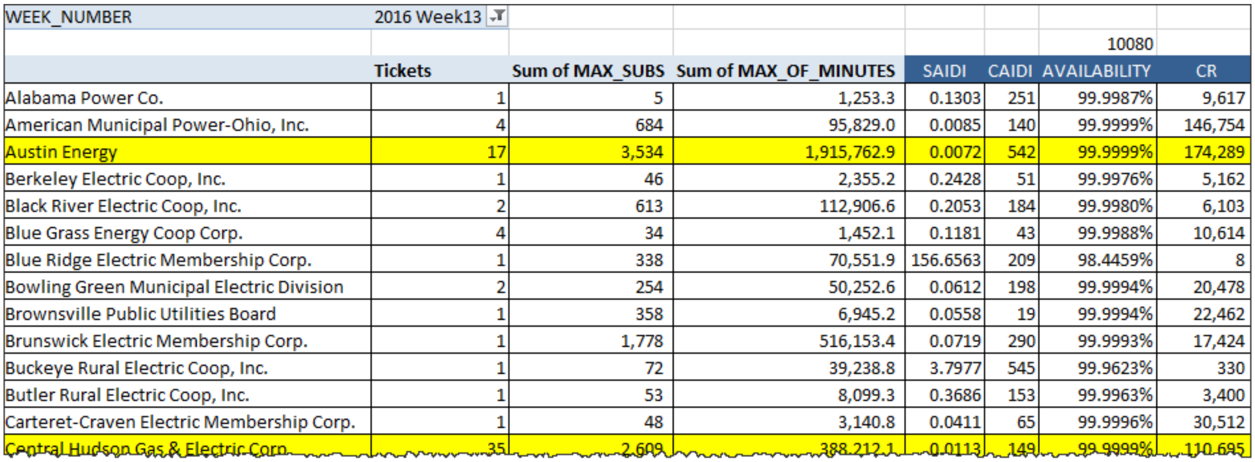
[12] The chart above contains sensitive information that is protected and privileged and must not be reproduced without owner's permission.

9.3. Weekly Reliability Metrics by Power Company



WEEK_NUMBER	2016 Week13						
						10080	
	Tickets	Sum of MAX_SUBS	Sum of MAX_OF_MINUTES	SAIDI	CAIDI	AVAILABILITY	CR
Alabama Power Co.	1	5	1,253.3	0.1303	251	99.9987%	9,617
American Municipal Power-Ohio, Inc.	4	684	95,829.0	0.0085	140	99.9999%	146,754
Austin Energy	17	3,534	1,915,762.9	0.0072	542	99.9999%	174,289
Berkeley Electric Coop, Inc.	1	46	2,355.2	0.2428	51	99.9976%	5,162
Black River Electric Coop, Inc.	2	613	112,906.6	0.2053	184	99.9980%	6,103
Blue Grass Energy Coop Corp.	4	34	1,452.1	0.1181	43	99.9988%	10,614
Blue Ridge Electric Membership Corp.	1	338	70,551.9	156.6563	209	98.4459%	8
Bowling Green Municipal Electric Division	2	254	50,252.6	0.0612	198	99.9994%	20,478
Brownsville Public Utilities Board	1	358	6,945.2	0.0558	19	99.9994%	22,462
Brunswick Electric Membership Corp.	1	1,778	516,153.4	0.0719	290	99.9993%	17,424
Buckeye Rural Electric Coop, Inc.	1	72	39,238.8	3.7977	545	99.9623%	330
Butler Rural Electric Coop, Inc.	1	53	8,099.3	0.3686	153	99.9963%	3,400
Carteret-Craven Electric Membership Corp.	1	48	3,140.8	0.0411	65	99.9996%	30,512
Central Hudson Gas & Electric Corp.	35	2,609	388,212.1	0.0113	149	99.9999%	110,695

Figure 6 - Weekly Reliability Metrics by Power Company

Total Available Weekly Minutes = 10,080 minutes (24*60*7).

CR=Unique Customer Relationships

(The data presented on this report is for legacy Time Warner Cable)[13]

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[13] The chart above contains sensitive information that is protected and privileged and must not be reproduced without owner’s permission.

9.4. Commercial Power Outages – Analysis of Critical Infrastructure Hub Impacting Tickets

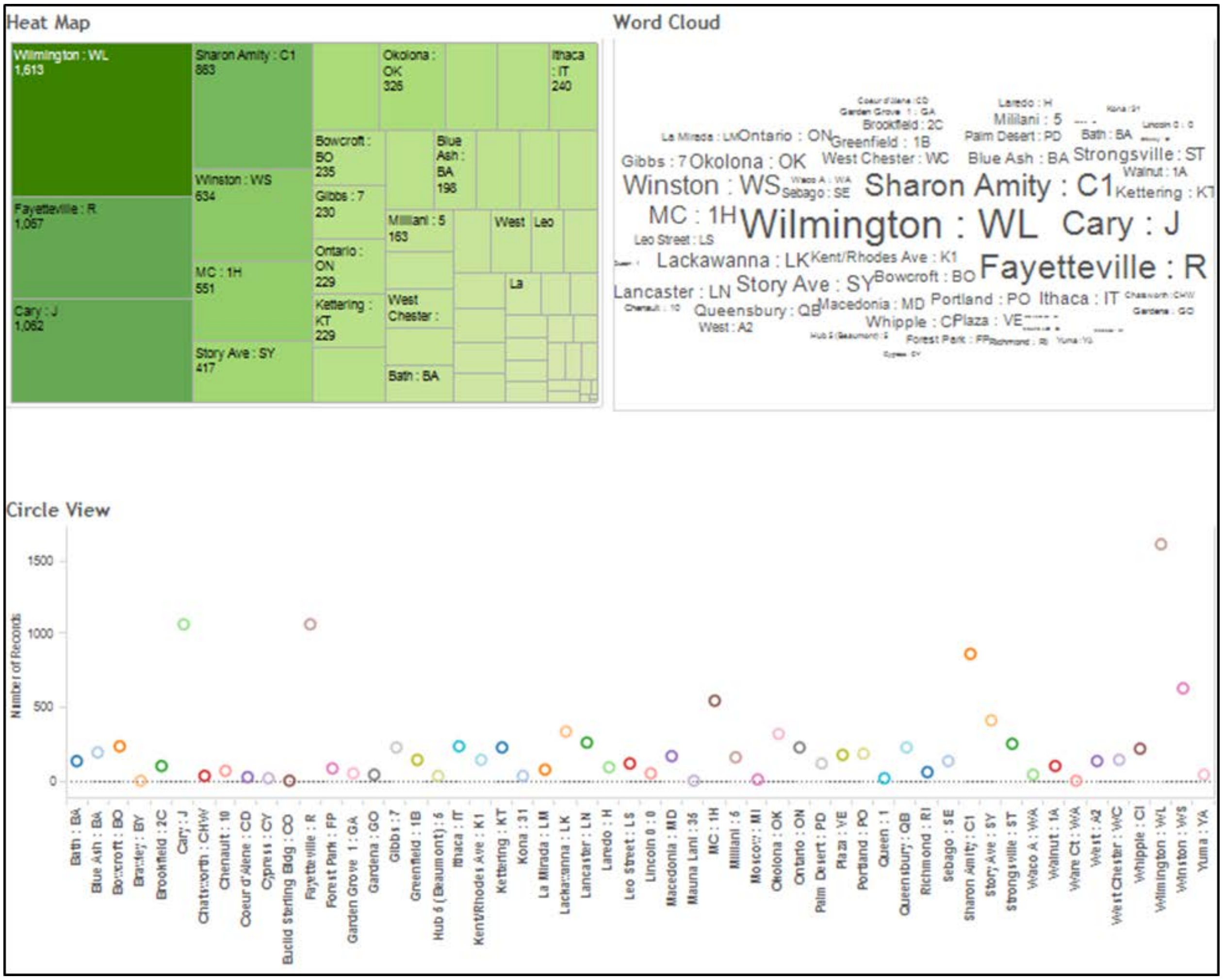

Figure 7 - Commercial Power Outages - Analysis of Critical Infrastructure Hub Impacting Tickets

(The data presented on this report is for legacy Time Warner Cable)[14]

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Now You See It, Stephen Few and explained by George Kuhn, former Director of Research Services at Research & Marketing Strategies, Inc. (RMS); https://rmsbunkerblog.wordpress.com/2012/04/23/13-traits-of-a-good-data-analyst-market-research-careers/

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[14] The charts above contain sensitive information that is protected and privileged and must not be reproduced without owner's permission.

11. Abbreviations

Table 3 – Abbreviation Table

Acronym	Description
ASAI	average service availability index
CAIDI	customer average interruption duration index
CIII	customers interrupted per interruption index
CLEI	common language equipment identifier
CLLI	common language location identifier
CMI	customer minutes of interruption
CPUC	California Public Utility Commission
CR	customer relationship
DOE	Department of Energy
FCC	Federal Communications Commission
IEEE	Institute of Electrical and Electronics Engineers
ISBE	International Society of Broadband Experts
MED(s)	major event day(s)
MTRS	mean time to restore service
MTTX	mean time to x with "X" signifying a variable, i.e., MTTR (Mean Time to Restore), MTTA (Mean Time to Acknowledge), etc.
NARUC	National Association of Regulatory Utility Commissioners
NERC	North American Electric Reliability Corp.
NOC	network operations center
NORS	(FCC) network outage reporting system
PCN	product change notice
PUC	Public Utility Commission
RMS	Research & Marketing Strategies, Inc.
SAIDI	system average interruption duration index
SAIFI	system average interruption frequency index
SCTE	Society of Cable Telecommunications Engineers
TCPA	Telephone Consumer Protection Act
TWC	Time Warner Cable

JOURNAL OF
ENERGY MANAGEMENT

Trading with Utilities

Cable Facility and Customer Opportunities

A Technical Paper prepared for SCTE/ISBE by

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1. Abstract

Electricity grids all over the world are increasingly facing a future for which they were not designed. In the rapidly evolving renewable energy and storage landscape, massive amounts of variable solar, wind and hydroelectric “distributed generation” are being connected to what still is primarily a one-way distribution grid. Just as the Cable TV infrastructure was adapted to provide two-way interactive and Internet services, so too, electricity grids will evolve.

To accommodate and maximize the variable nature of renewable energy sources, new interconnect mechanisms and algorithms will be used pervasively around the world to orchestrate consumer demand minute-by-minute throughout the day in order to meet supply. Real Time Pricing will be broadcast over the Internet[1] to commercial and residential appliances to encourage refrigerators, hot water heaters and electric vehicle chargers to maximize demand when there is an abundance of renewable or conventional generation capacity. Alternatively, during hours of electricity scarcity, appliances will minimize demand by delaying their respective jobs. At the core of this orchestration will be logic that makes or breaks business models for customers to “buy low and sell high” while producing and consuming electric power. Household appliances and even batteries will provide energy elasticity enabling per-building independence, and will play an increasingly important role, e.g., Elon Musk’s “Master Plan Part Deux”.

As electricity grids transition to two-way, there will be many parallels to cable industry developments and deployments over the last 25 years. Examples include fair bandwidth distribution algorithms and other problems solved in the development and refinement of the Data Over Cable Service Interface Specifications a.k.a. DOCSIS®[2].

2. Introduction

In this paper we will discuss first steps on the path to the Cable Industry’s success in having a lucrative piece of the energy pie. Two market forces are opening new realms of possibility: 1) Real Time Pricing, and 2) the reinvention of Net Metering known as Feed-in Tariffs.

Electricity costs money and there’s money to be made. The worth of a watt is rapidly changing. In recent years, energy production, management, sales and use have been steadily metamorphosing. The explosion of connected home energy management systems, private renewable energy production and new energy retail schemes, presents real opportunity for the global cable industry.

Indeed, the global cable industry has an amazing shot at swooping in to take advantage of evolution in energy production and retail sale. This, combined with new technologies in energy efficiency and the connected home will allow cable to really cash-in using pricing schemes through new electrical energy (watt-hour) metering. Cable companies will benefit from this new paradigm resulting in reduced operations costs; cable customers will benefit from energy savings and will be incented to stay on as subscribers, thereby reducing dreaded attrition.

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[1] Internet in the broadest sense, including but not limited to: Smart Meters, Power Line Carrier (PLC) networks, In-home networks, Wi-Fi, LTE, 5G, Data over Cable Service Interface Specifications, etc.
[2] DOCSIS is a trademark of CableLabs

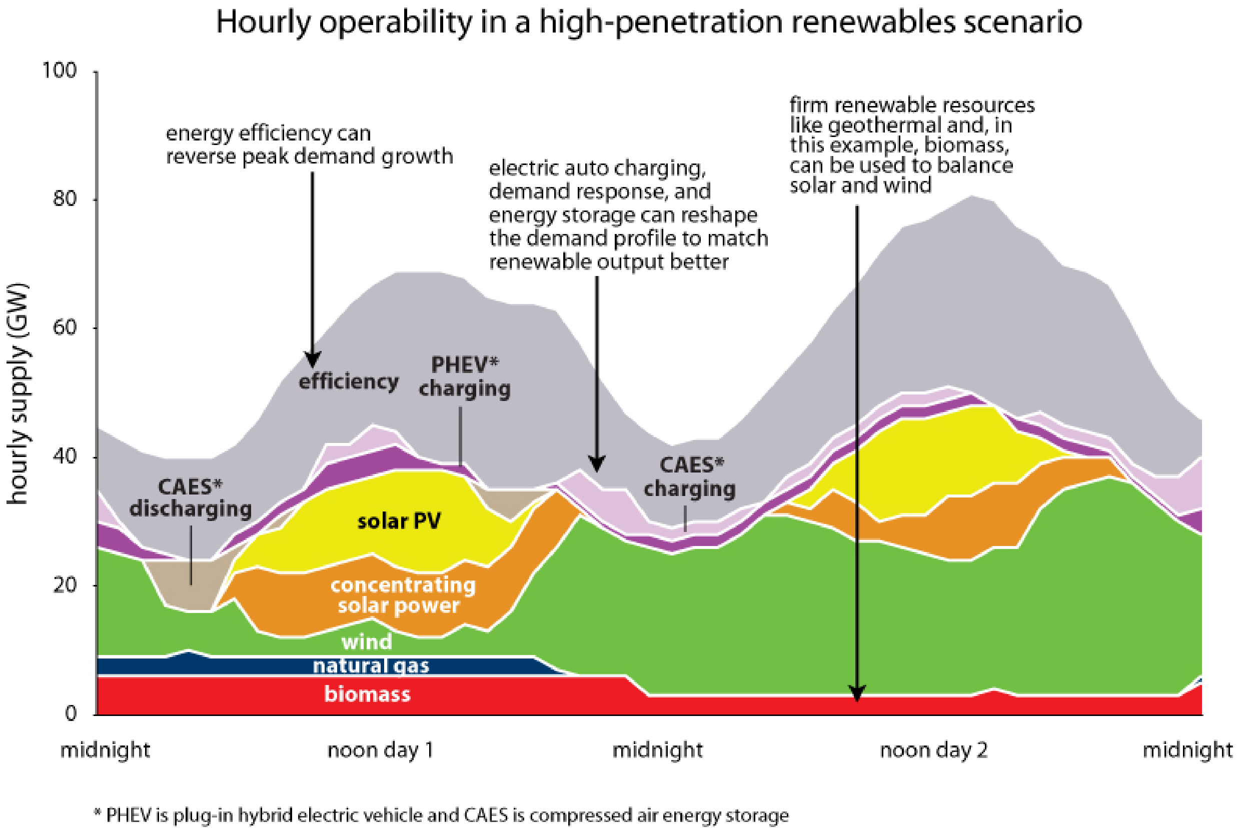
3. Real Time kWh Pricing & The Evolution of Net Metering

It is critical that energy is converted, generated and distributed as efficiently as possible, liberating no more than absolutely necessary while optimizing use of new and conventional power plants, transmission/distribution systems and clean renewable resources. Orchestrating electrical demand to meet supply will help minimize energy generation and "spinning reserve" inefficiencies, maximize use of renewables, and reduce thermal and greenhouse gas pollution.

In homes and businesses, real time kilowatt-hour (kWh) pricing will encourage:

- "off-peak" pre-cooling of buildings, battery charging, and
- "on-peak" load shedding, diesel electric generation[3] and battery discharging.

Pricing schemes will be used in home and business micro grids to sculpt/orchestrate demand to meet supply as shown in Figure 1 and Figure 2 where dramatic efficiency improvements are complimented by renewables and storage over 2-day and 7-day periods[45].



* PHEV is plug-in hybrid electric vehicle and CAES is compressed air energy storage

Figure 1 - Maximizing Use of Renewables over 2-days

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[3] Diesel electric backup power may have a limited future; there is talk of laws to prevent diesel and other polluting generation for this purpose

[4] http://www.rmi.org/RFGraph-hourly_high_penetration_renewables

[5] http://www.rmi.org/RFGraph-hourly_operability_on_microgrid

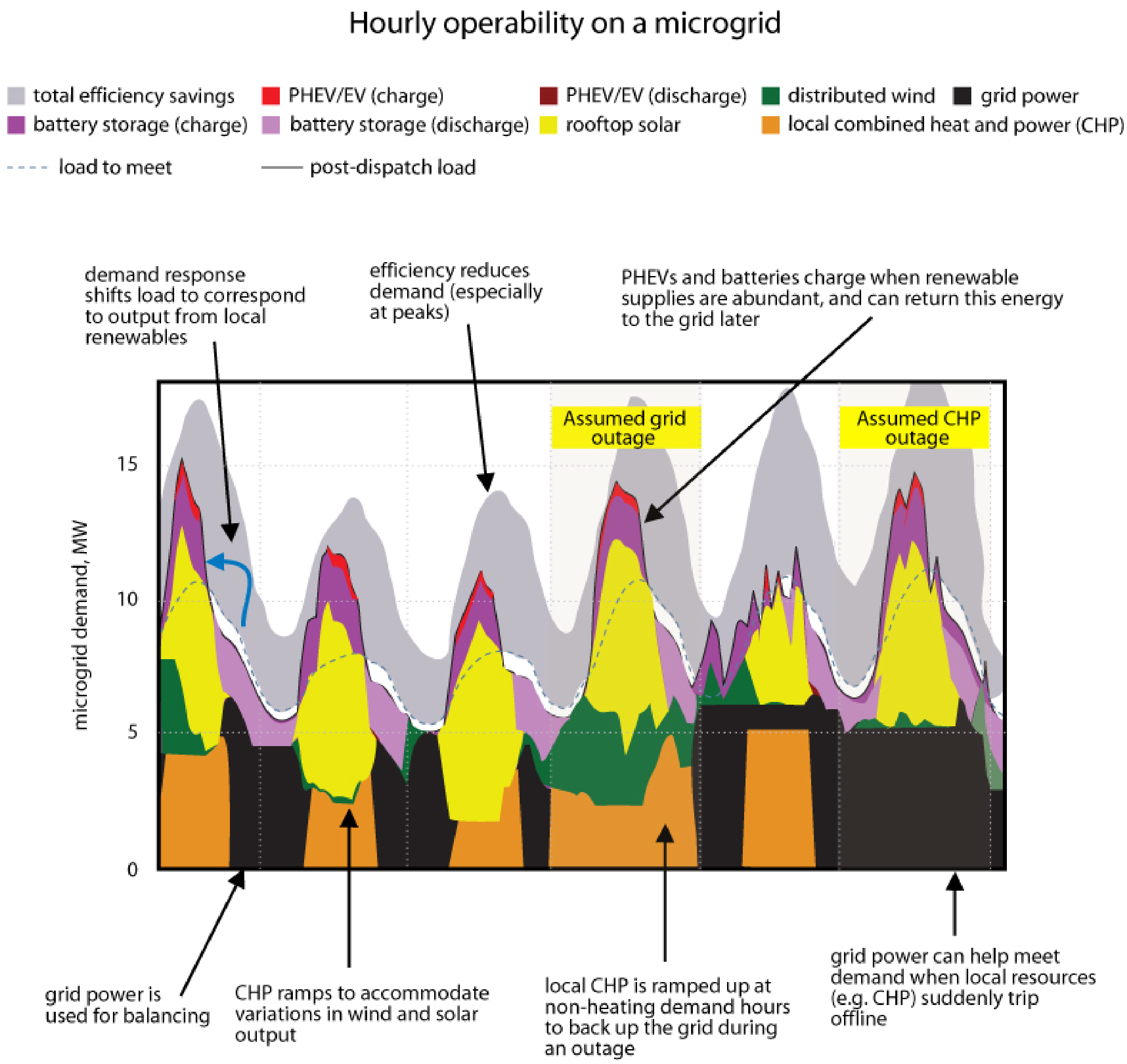

Figure 2 - Pricing Orchestrates Demand and Maximizes Use of Renewables Over 7-days

3.1. “Day Ahead Pricing" and "Real Time Pricing"

Day ahead pricing (DAP) and real time pricing (RTP) are electric supply options in which customers pay electricity rates that vary by hour. In addition to fixed-priced electric supply rates common today, utilities will increasingly offer electricity purchase rate plans that charge time-varying pricing reflective of the costs of electric supply. Unlike utilities' fixed-priced electric supply rates, utilities' charge customers for the electricity they consume each hour based on the corresponding hourly market price of electricity. With DAP programs, hourly prices for the next day are set the night before and can be communicated to customers so they (most likely their automated smart home systems) can determine the best time of day to use major appliances. Figure 3 depicts DAP at a wholesale market level[6].

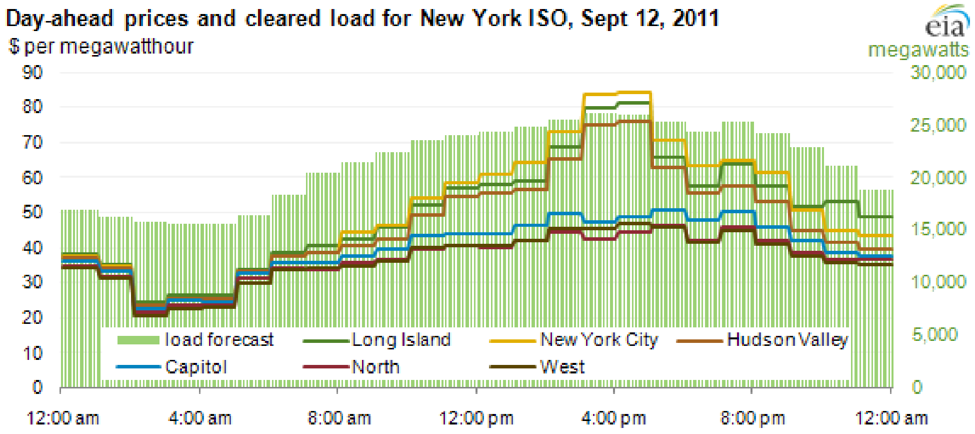

Figure 3 - Wholesale Market Day Ahead Pricing

With RTP programs, prices are based on the actual real-time hourly market price of electricity during the day and customers are notified when real-time prices are high or are expected to be high[7] so they can respond in real-time and shift the use of major appliances to lower priced hours. While savings are not guaranteed, customers can manage electricity costs under RTP by shifting use of electricity from hours when prices are higher to hours when prices are lower. To participate in a residential RTP, customers without a smart meter must have a meter installed that is capable of recording hourly usage. Figure 4 depicts RTP at a wholesale market level[8].

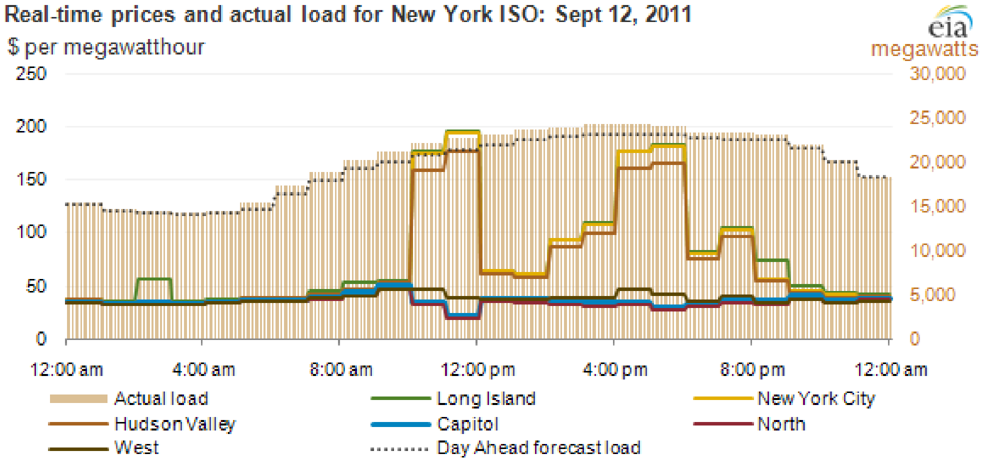

Figure 4 - Wholesale Market Real Time Pricing

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[6] http://www.eia.gov/todayinenergy/images/2011.09.26/FERCday-ahead.png

[7] In some states customers will want to be notified when their demand is setting new monthly high. In Arizona a mandatory component of all solar customers' bills now includes a capacity charge based on maximum demand.

[8] http://www.eia.gov/todayinenergy/images/2011.09.26/FERCreal-time.png

3.2. Net Energy Metering

Today's outdated net energy metering (NEM) allows consumers who generate electricity to use the grid as a storage battery and then later use electricity anytime (instead of just when it is generated). This is particularly important with wind and solar, which are non-dispatchable[9]. Monthly NEM allows consumers to use solar power generated during the day at night, or wind from a windy day later in the month. Annual NEM rolls over a net kilowatt credit to the following month, allowing solar power that was generated in July to be used in December, or wind power from March to be used in August.

NEM policies can vary significantly by country and by state or province: a) if NEM is available, b) if and how long you can keep your banked credits, and c) how much are the credits worth (retail/wholesale). Most NEM laws involve monthly roll over of kWh credits, a small monthly connection fee, require monthly payment of deficits (i.e. normal electric bill), and annual settlement of any residual credit. Unlike a feed-in tariff (FIT), which requires two meters, NEM uses a single, bi-directional meter and can measure current flowing in both directions (to and from the utility). NEM can be implemented solely as an accounting procedure, and requires no special metering, or even any prior arrangement or notification. Figure 5 shows Conventional Net Energy Metering[10].

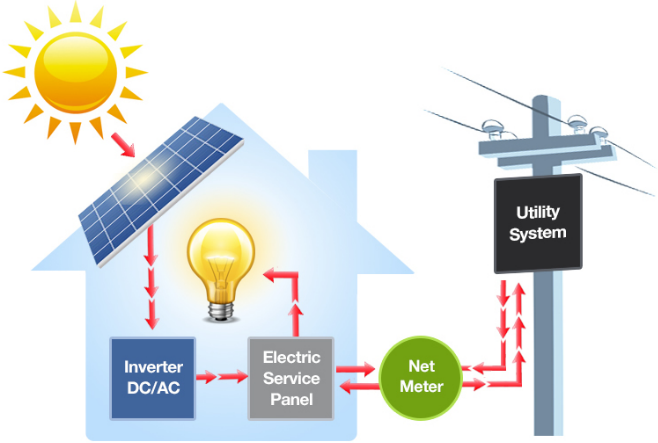

Figure 5 - Conventional Net Energy Metering

3.3. Net Energy Metering Evolving to Feed-In Tarriffs

NEM has been used as an enabling policy designed to foster private investment in, and high penetration of, renewable energy. Successful at first, NEM policy is presently failing because people who are not generating are paying the "freight" for those that are generating electricity. For example, apartment dwellers, those who live in shady areas and those who can't afford a solar system, all end up supporting the shipping costs for those that are generating electricity. For a case in point, in Newsday's recent article "PSEG Raises Power Supply Charge Again", consumers are experiencing a 35% price hike over the last 6 months[11]. This phenomenon occurs as more and more residences and businesses sign-up with subsidized solar panels using NEM interconnection.

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[9] Non-dispatchable means generation that is weather dependent and cannot be controlled.
[10] http://cdn2.hubspot.net/hub/398098/file-1115094088-jpg/blog-files/solar-net-metering.jpg
[11] http://www.newsday.com/long-island/pseg-power-supply-charge-rises-again-1.12017656

The rescinding and decline of NEM tariffs will dramatically change the worth of a watt: electricity will be purchased by consumers, for example, at $0.20/kWh, yet consumers will only be able to sell back the energy they produce at $0.10/kWh.

4. Financial Opportunities created by RTP and Feed-In Tarrifs

The combination of real-time pricing and feed in tariffs create a vast new realm of opportunities in the purchase and sale of electricity. Through the implementation of creative building management algorithms, businesses and consumers will be able to “buy low” and “sell high” hour-to-hour or even minute-to-minute as part of normal daily operations.

While the rescinding of net metering may slow penetration of distributed generation via renewable resources, the arrival of RTP and feed-in tariffs will firmly establish the concept of micro grids on a per-building basis. In addition, the concept of “Islanding”, where a building can survive on its own without the grid, will also be accelerated as control systems are deployed to not only save consumers’ money and improve efficiency of building operations, but to also allow buildings to operate completely independently of the grid when necessary, for example during hurricanes and other outages. Data centers will lead this charge, along with hospitals, military and law enforcement.

Though financial projections and scenarios are beyond the scope of this paper, suffice it to say that in the area of micro grids and building controls, there will be innovation and development for decades to come. There will be countless opportunities for the cable industry to protect the environment and save operations expense while providing energy management services that help customers save money.

5. Cable Facility Opportunities

As stated previously, real time kilowatt-hour (kWh) pricing will encourage Cable TV data center/headend/hub: a) off-peak pre-cooling and battery charging, and b) on-peak load shedding, diesel electric generation and battery discharging.

The first step in Cable facility planning is to task a subject matter expert with identifying and estimating financial savings opportunities created by real-time pricing. The next step is to consider how and when to use feed-in tariffs to sell energy back to the utility.

Many cable facilities have local electricity storage in the form of uninterruptible power supplies that provide battery-backed power during outages. In addition, Cable facilities may have distributed generation such as diesel generators, solar panels, etc.

Weather forecasts will become increasingly important in the prediction of the financial costs and rewards, and the amount of energy that:

- Will be required for heating and cooling of a facility
- Will be produced by solar panels

Throughout the day, it will make sense to buy energy at the lowest prices and to sell energy at highest prices. Updated weather forecasts will allow in-building control systems to fine-tune predictions for when electricity should be bought and sold. During times of extremely high prices (e.g., during grid emergencies, natural disasters and outages), it may make sense to sell diesel electric power or to partially discharge uninterruptible power supply batteries by providing power to the utility grid for short periods of time where it makes financial sense to do so.

6. Cable Customer Opportunities

In support of Industry commitment to energy efficiency, the above scenario can and should be applied to all entities that sell or consume energy. This includes our residential and business customers who will need new cable-provided services and infrastructure that receives pricing signals, weather forecasts, and then advises throughout the day when to “buy and sell” in order to maximize use of renewable energy thus minimizing electricity costs.

During times of disaster, a very important opportunity for cable customers is access to energy. This includes individual homes and humanitarian efforts such as crisis centers and hospitals. Each residence and business micro grid that is able to “Island” itself and even offer energy to neighbors becomes a distributed grid asset.

7. Customer Experience Management & Lifetime Value

As the global cable industry moves forward with this opportunity, communication between customers and industry professionals will be a priceless resource. Globally pooling information and feedback through customer experience management will be essential in beating the competition (FiOS, etc.) in building a successful integrative system that serves both industry and customer interest. Cable’s high penetration of customer relationships gives it a first mover’s advantage in home automation, though competition from incumbent utilities, and the likes of Amazon, Apple, and Google is close behind.

Focusing on the customer experience before this new RTP service is launched will enable the MSO to develop an end-to-end, fully integrated experience for the customer. By utilizing and putting in place from the beginning of the customer journey some of the CEM ‘lessons learned’ like 1) the importance of ‘onboarding’, 2) the criticality of the ‘first 90 days’, 3) ‘one stop’ solutions to customer problems and, 4) being a business that is ‘easy to do business with’, will insure ongoing industry success and lifetime value of a customer. CEM investments are not only the “right thing” to do, but also enhance the bottom line.

8. Summary

There is no doubt that evolution in energy management is necessary for supporting a sustainable world. The cable industry has real opportunity in taking on the challenges discussed in this paper. In doing so the cable industry not only increases opportunity for its own financial gain, it also supports the goals of SCTE 2020 for efficient energy management by the end of the decade and takes action for sustainable energy systems. This may be regarded as a stand for our planet Earth where we all win.

Taking the first step in designing and implementing viable standards in pricing and metering systems for facilities and for consumers will be the flagship into a new paradigm, where the cable industry is no longer the energy glutton but the energy economist. Our best engineers should work hand-in-hand with utilities and public service commissions in designing necessary standards. As we go into this new realm of possibility we support both industry and consumer needs through application of energy management services and continuous customer experience management. In this way both industry professionals and consumers are active partners in reducing the carbon footprint. We all become part of the solution to a very old and dirty problem.

9. Abbreviations and Definitions

9.1. Abbreviations

CHP	combined heat and power
DAP	day ahead pricing
DER	distributed energy resources
DERMS	distributed energy resource management system
DES	distributed energy storage
DG	distributed generation
DOCSIS	Data Over Cable Service Interface Specifications
kWh	kilowatt hour
ISBE	International Society of Broadband Experts
NEM	net energy metering
PV	photovoltaic solar power
RTP	real time pricing
SCTE	Society of Cable Telecommunications Engineers

9.2. Definitions

Day Ahead Pricing	Day Ahead Pricing (DAP) is generally an hourly rate where prices for the next day are set the night before.
Feed-in Tariff	A Feed-in Tariff is an economic policy created to promote active investment in and production of renewable energy sources. Unlike the value equality inherent in NEM, Feed-in Tariffs generally value energy purchased from consumers at a lower value than energy sold to consumers.
Kilowatt hour	The basic billing unit of electricity equivalent to drawing 1000 Watts for one hour.
Micro grid	A micro grid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single, controllable entity with respect to the grid. Micro grids typically can include a mix of conventional and renewable generation resources, as well as energy storage.
Net Energy Metering	Net Metering is system in which solar panels or other renewable energy generators are connected to a public-utility power grid and surplus power is transferred onto the grid, allowing customers to offset the cost of power drawn from the utility wherein the sale and purchase prices are equal. Initially used to stimulate market penetration, NEM has been rescinded in many areas in favor of a lower value feed-in tariff.
Real Time Pricing	Real-time pricing (RTP) is generally an hourly rate which is applied to usage on an hourly basis.

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JOURNAL OF
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How Power Purchase Agreements Impact Your Energy Strategy

Understanding Financial Consideration and Risks of Off-Site Alternative Energy Procurement Strategies

A Technical Paper prepared for SCTE/ISBE by

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1. Introduction

As a key initiative of the Energy 2020 program, the Society of Cable Telecommunications Engineers (SCTE) is committed to developing new standards and operational practices that establish methods to define and continuously analyze what existing and alternate energy sources are best to supply the various components of a cable service network.

This technical paper examines procurement of alternative energy or associated credits from generating assets located off-site, through power purchase agreements, or bilateral contracts with renewable energy asset owners or utilities for the electricity or environmental attributes associated with electricity produced by such generating facilities, and discusses the benefits and the risks associated with such purchases in the context of the buyer's whole portfolio. This paper will consider how power purchase agreements impact several of the objectives of SCTE's Alternative Energy working group, including providing an analysis of financial impacts concerning such investments, and assessing the ability to reduce carbon footprint of cable operations through alternative energy sources and reduced dependency on grid energy.

2. Evaluating Power Purchase Agreements for Alternative Energy

As many organizations, including SCTE members, set goals to reduce carbon intensity and increase the percentage of their operations that are powered by alternative energy sources, procurement and sustainability stakeholders are increasingly turning to off-site alternative energy procurement as a way to make meaningful progress toward achieving their goals. In fact, 80% of respondents indicated that their organization intended to purchase off-site alternative energy in PwC's June 2016 *Corporate Renewable Energy Purchasing Survey Insights*, compared with just 57% who had made such purchases in the past.

Procurement of electricity from off-site alternative generation sources like wind, solar, and geothermal is typically financed by a third party through a power purchase agreement (PPA), wherein the end-use customer agrees to pay for electricity generated by the asset. These payments generate a cash flow that enables counterparty, typically a renewable energy developer, to raise financing from equity investors in order to build the generating asset. While other options for investment and outright ownership of off-site generating assets exist, PwC's survey indicates that the majority of corporations see power purchase agreements as their primary path to securing alternative energy.

Power purchase agreements have several potential benefits to buyers, including the ability to secure electricity generation from alternative sources without contributing capital up-front, the potential to reduce the cost of grid-purchased electricity, and the ability to mitigate exposure to long-term electricity price volatility.

For organizations that need to demonstrate that their investments create additional alternative energy generation on the grid, PPAs can provide a way for sustainability teams to make such claims. By promising a fixed rate of return for new wind and solar projects which would otherwise not get financed and built, as corporate alternative energy procurement pioneers like Google have stated, their position as a counterparty in the PPA enables such projects to receive equity and debt financing to facilitate construction, thus adding to the installed base of renewable energy on the grid.

2.1. Off-Site Power Purchase Agreements

2.1.1. Definition

Power purchase agreements fall under two general structures: physical and synthetic, or virtual. Under a physical PPA, the seller counterparty owns and operates the generating asset, sells the energy generated to one or more customers, and may sell the renewable energy credits (RECs) associated with such generation as well. The seller can be responsible for transmission of the power to a liquid electricity market, but this is not common. This arrangement is feasible only in states where end-use customers are allowed to contract with third-parties other than the utility for the supply of energy, and requires the buyer to take title to the energy as well as the responsibility for scheduling and all market interactions, either directly with the independent system operator (ISO) or through a state-licensed retail energy supplier. Because managing such transactions requires specialized knowledge of electricity market rules, many end-use customers have opted to pursue the second structure, virtual PPAs.

In a virtual power purchase agreement (VPPA), the company developing the renewable project sells the power to the grid when the project is complete. In order to get equity and debt financing for the project, the developer enters into a VPPA with a counterparty buyer who agrees to pay a certain price for electricity generated by the asset, just like in the physical PPA case. In contrast to the previous case, however, the buyer counterparty in a VPPA arrangement does not take title to the electricity generated, and is not responsible for any market transactions to sell the power. Instead, the seller counterparty (typically the developer), takes on this responsibility and agrees to sell the power to an agreed point in the local electricity market, at the floating market price of power, typically settled on an hourly or more frequent basis. Figure 1 below displays a typical structure for a virtual power purchase agreement where the buyer takes possession of the RECs associated with the project.

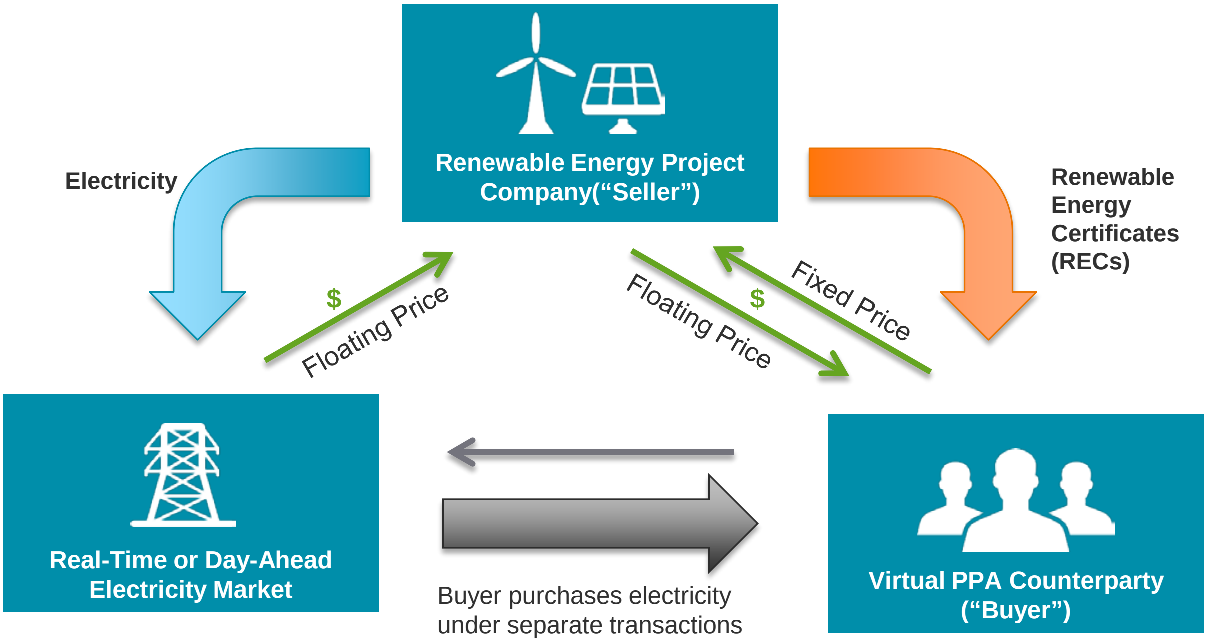


Figure 1 - Virtual Power Purchase Agreement Structure

If the electricity sells on the grid for less than the agreed amount, the buyer of the VPPA will pay the difference to the seller; if the electricity sells to the grid for more than the fixed price, the buyer of the VPPA will collect the difference from the seller. In this arrangement, there are a few benefits for all parties: The developer of the solar array or wind farm has the price security it needs to get financing for the project, and the buyer is able to make the claim (by acquiring the RECs associated with the generation) that their investment has contributed to “additional” alternative energy generation.

In addition, the financial arrangement of a VPPA can provide some protection against fluctuations in wholesale electricity rates, because the structure pays the buyer more if wholesale energy prices rise. Even after entering into a VPPA, a buyer must still purchase energy to physically power facilities, and the prices the buyer pays for retail power will be influenced by the same drivers of wholesale rates. Depending on the methods chosen for purchasing physical power for the facilities, holding a long-term position in a VPPA can improve budget certainty around a historically volatile cost line item. This concept will be further explored in Section 2.1.5 below, along with the associated market risks imposed by a VPPA purchase.

2.1.2. Financial Consideration of a Physical PPA

For a corporation seeking to buy renewable energy, the financial analysis of a physical power purchase agreement typically centers on the price agreed upon by the buyer and seller. Assuming that the buyer will take physical delivery of the power, and thus replace their current electricity supply quantity with that of the PPA, the buyer should consider the PPA price against their best estimates of market prices for the duration of the contract. Because most contracts have durations exceeding 10 years, however, buyers need to evaluate the potential outcomes of technological and regulatory impacts to electricity prices. As shown in Figure 2 below, the US Energy Information Administration projected that retail electricity prices could stay flat from 2013 benchmarks *or* increase by nearly 20% over the lifespan of a theoretical 20-year PPA.

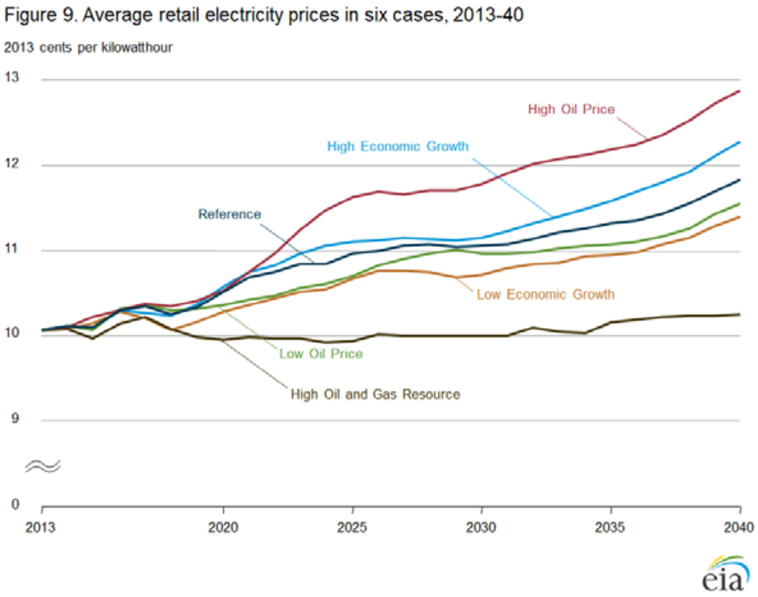


Figure 2 - Retail Electricity Price Projections based on Oil and Gas Price and Resource Availability Assumptions and Varied Economic Growth Assumptions, from US Energy Information Administration, *2015 Annual Energy Outlook*

A buyer should consider different market outcomes to understand the expected minimum and maximum return on investment for a PPA. For example, using scenarios detailed in the US Energy Information Administration's 2015 Annual Energy Outlook along with other forecasts and forward market conditions, coupled with varying assumptions about the average heat rate of natural gas power plants on the grid in Texas's electricity market run by Energy Reliability Council of Texas (ERCOT), EnerNOC estimated that wholesale prices in ERCOT North Hub could vary from $30.84/MWh to $67.6/MWh by 2026, halfway through a 20-year PPA term. Each buyer will have a different attitude toward the risk associated with such changes in market price, and should take care to understand the range of possible outcomes for any large purchase.

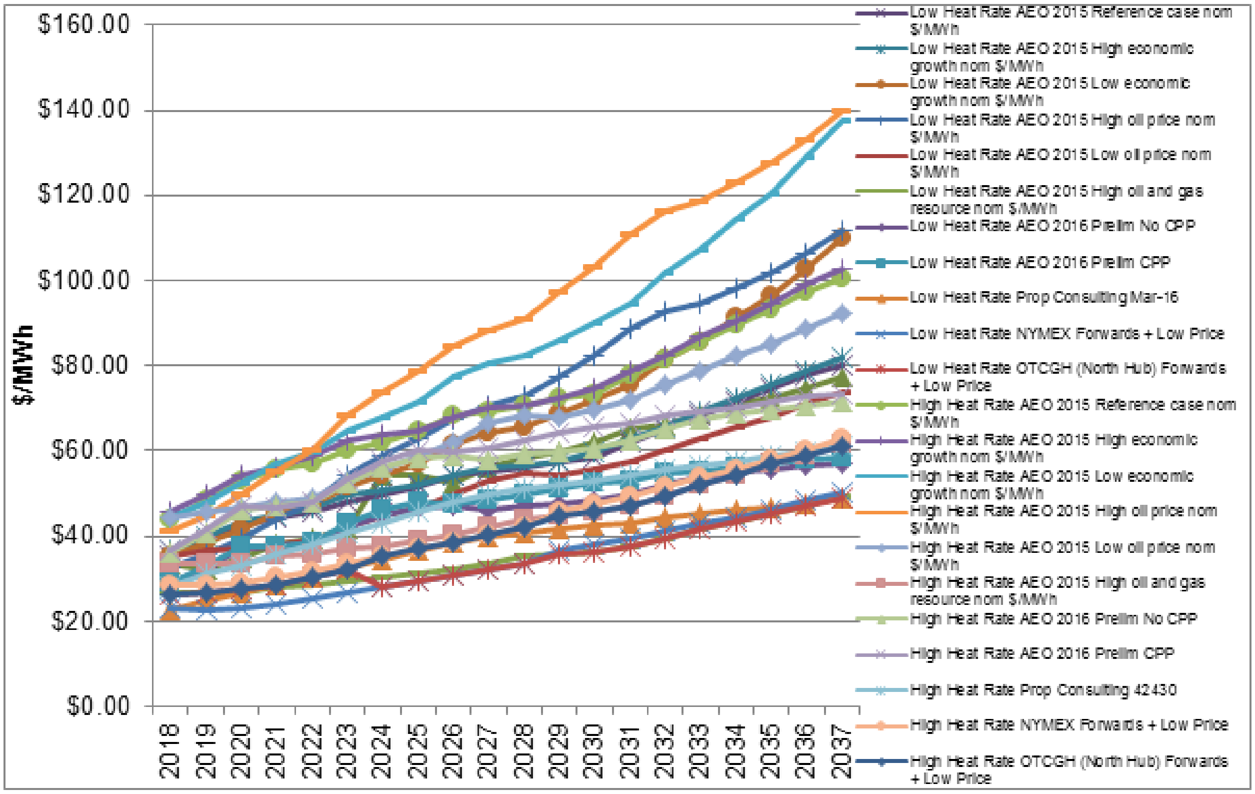


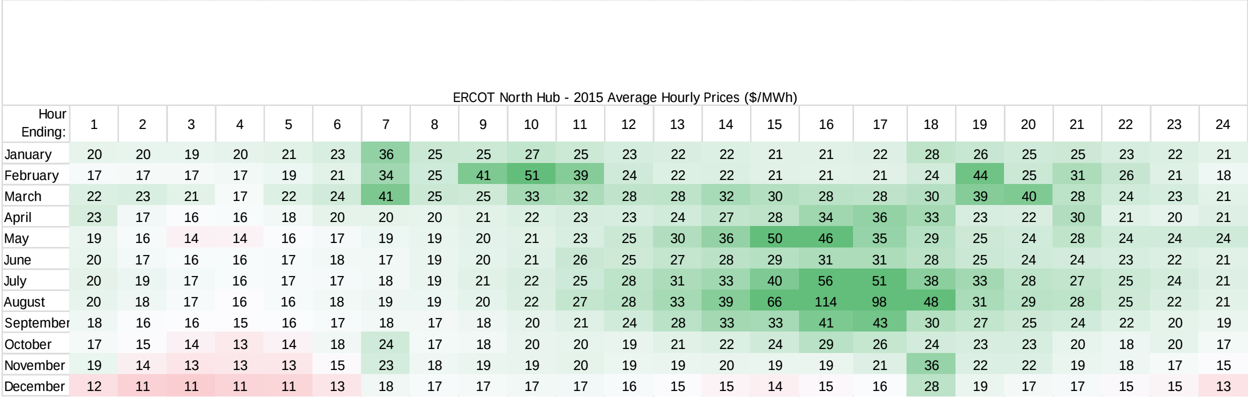
Figure 3 - ERCOT North Hub Wholesale Price Projections based on Varied Heat Rate and Scenarios from Energy Information Administration's 2015 Annual Energy Outlook

2.1.3. Direct Financial Consideration of a Virtual PPA

The financial analysis of a virtual power purchase agreement adds another dimension of complexity on top of future average price scenario analysis, because the VPPA introduces exposure to hourly market prices. In the terms of the agreement, the buyer and seller must first agree to the point at which the seller will deliver the power, which governs the price at which the contract is settled. The counterparties must also agree to the market index (i.e., whether real-time or day-ahead) that will be used to sell the power and settle the contract.

In major competitive electricity markets, like ERCOT and the PJM Interconnection in the Mid-Atlantic, wholesale market participants can buy and sell electricity at different locations in the market. While most transactions are focused around liquid market hubs, such as ERCOT North and PJM West, customer demand for power must be physically met at different geographic points in the system, typically referred to as “nodes.” While the price at the market hub is essentially based on an uncongested delivery system for power, the locational marginal price (LMP) at the node is based on both the market hub price as well as the cost of transmission constraints that require more expensive power to be used due to inability of delivery infrastructure.

In order to understand the financial valuation of a VPPA, the buyer should consider the hours at which power will be generated by the asset, because prices can vary significantly hour-by-hour within the same index market, and hourly pricing profiles adjust season-by-season as well. As Figure 4 below shows, ERCOT North Hub real-time market prices varied dramatically across 2015, with highest pricing during August afternoon hours and lowest pricing during December overnight hours. For a customer considering a VPPA contract with a “strike price” (or agreed fixed price) of $25/MWh, the VPPA would add cost to the buyer’s energy expense whenever the market price is below $25/MWh, and reduce overall purchasing costs when the market price exceeded $25/MWh.



ERCOT North Hub - 2015 Average Hourly Prices ($/MWh)

Hour Ending:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
January	20	20	19	20	21	23	36	25	25	27	25	23	22	22	21	21	22	28	26	25	25	23	22	21
February	17	17	17	17	19	21	34	25	41	51	39	24	22	22	21	21	21	24	44	25	31	26	21	18
March	22	23	21	17	22	24	41	25	25	33	32	28	28	32	30	28	28	30	39	40	28	24	23	21
April	23	17	16	16	18	20	20	20	21	22	23	23	24	27	28	34	36	33	23	22	30	21	20	21
May	19	16	14	14	16	17	19	19	20	21	23	25	30	36	50	46	35	29	25	24	28	24	24	24
June	20	17	16	16	17	18	17	19	20	21	26	25	27	28	29	31	31	28	25	24	24	23	22	21
July	20	19	17	16	17	17	18	19	21	22	25	28	31	33	40	56	51	38	33	28	27	25	24	21
August	20	18	17	16	16	18	19	19	20	22	27	28	33	39	66	114	98	48	31	29	28	25	22	21
September	18	16	16	15	16	17	18	17	18	20	21	24	28	33	33	41	43	30	27	25	24	22	20	19
October	17	15	14	13	14	18	24	17	18	20	20	19	21	22	24	29	26	24	23	23	20	18	20	17
November	19	14	13	13	13	15	23	18	19	19	20	19	19	20	19	19	21	36	22	22	19	18	17	15
December	12	11	11	11	11	13	18	17	17	17	17	16	15	15	14	15	16	28	19	17	17	15	15	13

Figure 4 - ERCOT North Hub Real-Time Market Average Hourly Prices ($/MWh), 2015

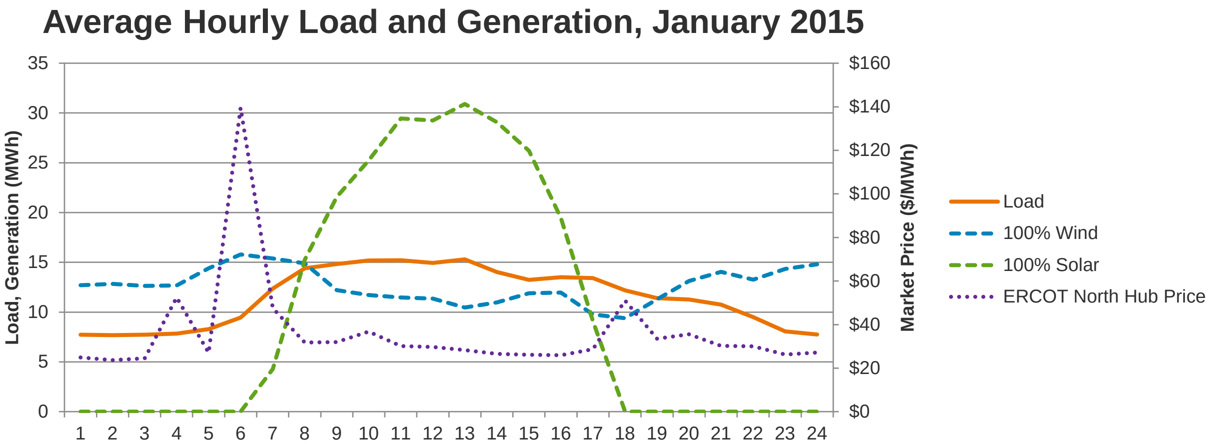
Still, the difference in market prices is only one factor in the economic viability of a VPPA, since the quantity delivered by hour also changes. As Figure 5 shows, the average hourly generation for a wind facility and an equivalent solar facility, each delivering an equal amount of energy on an annual basis, can vary significantly month by month.

These curves, and the subsequent analysis, are based on the following assumptions:

- The customer load profile is based on an anonymized manufacturing location based in North Texas, with annual energy consumption of 4,680,000 kWh
- The wind production profile is based on a proprietary model for an actual facility located in North Texas, scaled linearly to match the annual output of 4,680,000 kWh. The modeled wind facility has a net capacity factor of 45%, and a modeled nameplate capacity of 1.26 MW.
- The solar production profile is based on a simulation run on PVWatts® Calculator, for a solar facility based in Pflugerville, Texas, where 2-axis tracking modules are tilted 30 degrees and face due South. The hourly production output is scaled to match the annual output of 4,680,000. The

modeled solar facility has a capacity factor of 22%, and a modeled nameplate capacity of 2.39 MW.

- Hourly prices are averaged based on 15-minute real-time market prices for ERCOT North Hub



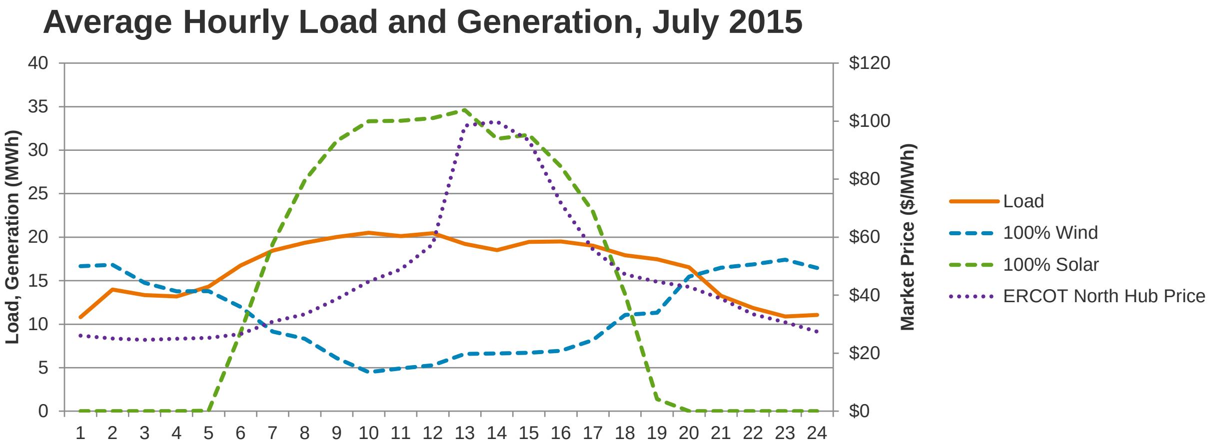
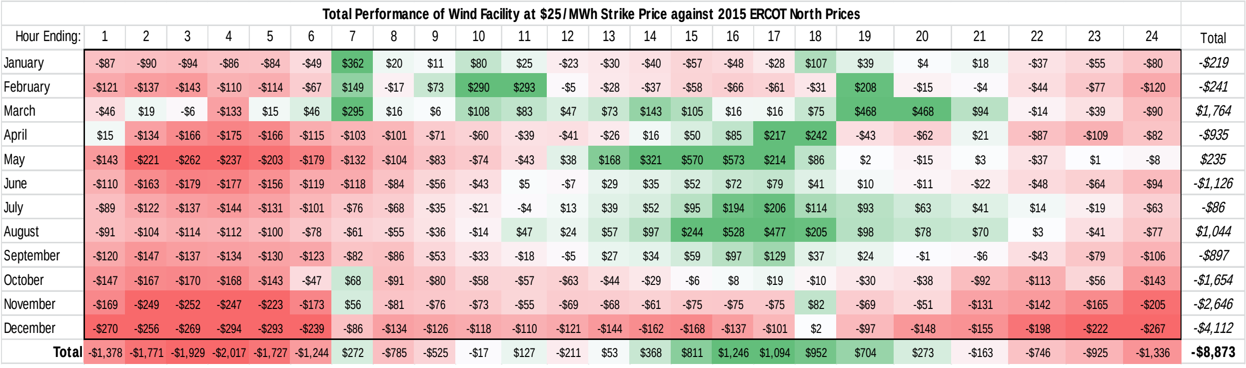


Figure 5 - Average Hourly Profiles in January and June for a representative customer load, wind facility production, solar facility production, and real-time market price.

Based on the modeled output, this wind facility generates less power during summer afternoon hours, when market prices are more favorable to the buyer, and generates more power during the winter evening and overnight hours, when market prices are more favorable to the seller. In order to fully comprehend the financial performance of the VPPA, then, the prospective buyer must consider an hourly analysis of expected production against the hourly average market price. This analysis summarized in Figure 6



Total Performance of Wind Facility at $25/MWh Strike Price against 2015 ERCOT North Prices

Hour Ending:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	Total
January	-$87	-$90	-$94	-$86	-$84	-$49	$362	$20	$11	$80	$25	-$23	-$30	-$40	-$57	-$48	-$28	$107	$39	$4	$18	-$37	-$55	-$80	*-$219*
February	-$121	-$137	-$143	-$110	-$114	-$67	$149	-$17	$73	$290	$293	-$5	-$28	-$37	-$58	-$66	-$61	-$31	$208	-$15	-$4	-$44	-$77	-$120	*-$241*
March	-$46	$19	-$6	-$133	$15	$46	$295	$16	$6	$108	$83	$47	$73	$143	$105	$16	$16	$75	$468	$468	$94	-$14	-$39	-$90	*$1,764*
April	$15	-$134	-$166	-$175	-$166	-$115	-$103	-$101	-$71	-$60	-$39	-$41	-$26	$16	$50	$85	$217	$242	-$43	-$62	$21	-$87	-$109	-$82	*-$935*
May	-$143	-$221	-$262	-$237	-$203	-$179	-$132	-$104	-$83	-$74	-$43	$38	$168	$321	$570	$573	$214	$86	$2	-$15	$3	-$37	$1	-$8	*$235*
June	-$110	-$163	-$179	-$177	-$156	-$119	-$118	-$84	-$56	-$43	$5	-$7	$29	$35	$52	$72	$79	$41	$10	-$11	-$22	-$48	-$64	-$94	*-$1,126*
July	-$89	-$122	-$137	-$144	-$131	-$101	-$76	-$68	-$35	-$21	-$4	$13	$39	$52	$95	$194	$206	$114	$93	$63	$41	$14	-$19	-$63	*-$86*
August	-$91	-$104	-$114	-$112	-$100	-$78	-$61	-$55	-$36	-$14	$47	$24	$57	$97	$244	$528	$477	$205	$98	$78	$70	$3	-$41	-$77	*$1,044*
September	-$120	-$147	-$137	-$134	-$130	-$123	-$82	-$86	-$53	-$33	-$18	-$5	$27	$34	$59	$97	$129	$37	$24	-$1	-$6	-$43	-$79	-$106	*-$897*
October	-$147	-$167	-$170	-$168	-$143	-$47	$68	-$91	-$80	-$58	-$57	-$63	-$44	-$29	-$6	$8	$19	-$10	-$30	-$38	-$92	-$113	-$56	-$143	*-$1,654*
November	-$169	-$249	-$252	-$247	-$223	-$173	$56	-$81	-$76	-$73	-$55	-$69	-$68	-$61	-$75	-$75	-$75	$82	-$69	-$51	-$131	-$142	-$165	-$205	*-$2,646*
December	-$270	-$256	-$269	-$294	-$293	-$239	-$86	-$134	-$126	-$118	-$110	-$121	-$144	-$162	-$168	-$137	-$101	$2	-$97	-$148	-$155	-$198	-$222	-$267	*-$4,112*
Total	-$1,378	-$1,771	-$1,929	-$2,017	-$1,727	-$1,244	$272	-$785	-$525	-$17	$127	-$211	$53	$368	$811	$1,246	$1,094	$952	$704	$273	-$163	-$746	-$925	-$1,336	**-$8,873**

Figure 6 - Output of Hourly Analysis Comparing Modeled Wind Production against ERCOT North Real-Time Market Prices in 2015

While the hourly analysis represented in Figure 6 provides a summary of the financial performance of the VPPA itself against historical market conditions, a prospective buyer must finally consider the method in which their facilities purchase electricity to power their operations, because the VPPA does not provide any physical delivery of the power generated by the asset.

2.1.4. Net Energy Budget Considerations of a VPPA

To understand how different electricity purchasing methods align with the financial performance of a VPPA, a prospective buyer should assess the potential impact to their energy budget of the VPPA combined with a conventional purchasing strategy. Because hourly prices depend on many factors such as availability of generating assets across the grid, input commodity prices, and transmission constraints, it is difficult to forecast hourly prices. Instead, we consider how the combined VPPA and purchasing strategy would have fared in different recent market scenarios, to provide a range of possible outcomes.

In the simplest case, we consider the total budget impact if the facility were buying 100% of its power from the same electricity spot market as used as the floating price in the VPPA against a fixed strike price of $25/MWh. Note that this analysis and all subsequent analyses include only the wholesale energy component of the buyer’s energy budget, and ignores capacity, ancillaries, transmission, and local utility distribution charges.

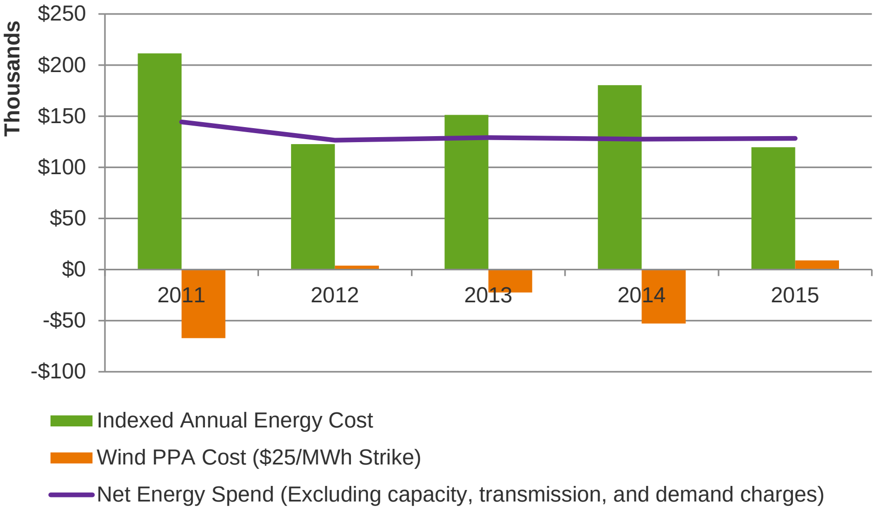
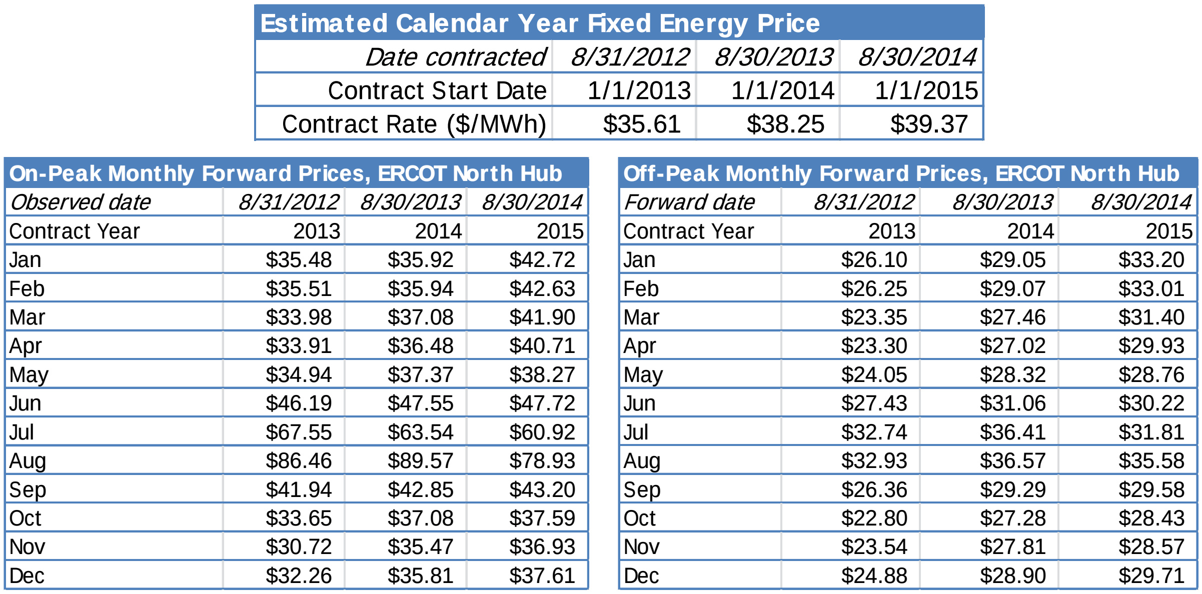


Figure 7 - Budget Impact of VPPA with Indexed Electricity Purchasing

As Figure 7 demonstrates, our model facility would have seen significant volatility in their energy budget if their purchases were fully indexed without a VPPA, capturing the value of low market prices in 2012 and 2015, and exposed to higher prices in 2011 and 2014. The maximum deviation in their budget, prior to the VPPA, would have been $91,818, nearly 77% of their lowest annual expenditure. Adding exposure to the same real-time market prices through the VPPA, however, mitigates such swing in budget, and would reduce the maximum deviation in budget to $17,720. In fact, from 2012 to 2015 there would be no more than $2,400 deviation in year-on-year budget, making it much easier for facility managers and controllers to budget the energy line-item. Note that these totals include only the wholesale component of the utility bill, and do not account for charges based on transmission and distribution, including capacity and local utility peak demand charges.

However, many organizations with facilities in competitive electricity markets have *already* designed purchasing strategies designed to improve budget certainty, such as buying fixed-price power or purchasing blocks of power to reduce their exposure to market price swings. To analyze the impact of layering a VPPA on top of such existing strategies, we assume that the same facility purchased a fixed-price contract for power at a wholesale rate equal to the weighted average of monthly forward prices at the date of purchase, and that the facility signs a calendar-year contract three months prior to the start of each calendar year. Based on a 57% percentage of annual consumption attributed to on-peak hours, we estimate that the contracted rates for calendar year energy supply contracts would be $35.61/MWh, $38.25/MWh and $39.37/MWh for delivery in 2013, 2014, and 2015, respectively.



Estimated Calendar Year Fixed Energy Price			
Date contracted	*8/31/2012*	*8/30/2013*	*8/30/2014*
Contract Start Date	1/1/2013	1/1/2014	1/1/2015
Contract Rate ($/MWh)	$35.61	$38.25	$39.37

On-Peak Monthly Forward Prices, ERCOT North Hub			
Observed date	*8/31/2012*	*8/30/2013*	*8/30/2014*
Contract Year	2013	2014	2015
Jan	$35.48	$35.92	$42.72
Feb	$35.51	$35.94	$42.63
Mar	$33.98	$37.08	$41.90
Apr	$33.91	$36.48	$40.71
May	$34.94	$37.37	$38.27
Jun	$46.19	$47.55	$47.72
Jul	$67.55	$63.54	$60.92
Aug	$86.46	$89.57	$78.93
Sep	$41.94	$42.85	$43.20
Oct	$33.65	$37.08	$37.59
Nov	$30.72	$35.47	$36.93
Dec	$32.26	$35.81	$37.61

Off-Peak Monthly Forward Prices, ERCOT North Hub			
Forward date	*8/31/2012*	*8/30/2013*	*8/30/2014*
Contract Year	2013	2014	2015
Jan	$26.10	$29.05	$33.20
Feb	$26.25	$29.07	$33.01
Mar	$23.35	$27.46	$31.40
Apr	$23.30	$27.02	$29.93
May	$24.05	$28.32	$28.76
Jun	$27.43	$31.06	$30.22
Jul	$32.74	$36.41	$31.81
Aug	$32.93	$36.57	$35.58
Sep	$26.36	$29.29	$29.58
Oct	$22.80	$27.28	$28.43
Nov	$23.54	$27.81	$28.57
Dec	$24.88	$28.90	$29.71

Figure 8 - Summary of Estimated Calendar Year Fixed Energy Supply Contract Rate, based on On-Peak and Off-Peak Monthly Forward Prices Observed Three Months Prior. Source: ICE via Morningstar

Using these estimated fixed contract rates, we can assess the impact of the previously modeled virtual power purchase agreement for wind generation at a $25/MWh strike price. As Figure 9 shows, the ability of a virtual power purchase agreement to provide budget certainty for a given set of facilities or loads is greatly diminished when such facilities or loads are served by fixed-rate electricity contracts. By contrast to the small $2,400 deviation in budget seen when our modeled facility was purchasing power on the spot market index, the same facility purchasing power under fixed rate contracts could see a 51% increase in energy budget after contracting for a virtual power purchase agreement. This is primarily driven by the fixed contracted rate being above market prices, which limits the ability for gains from the virtual power purchase agreement to offset increases in energy spend.

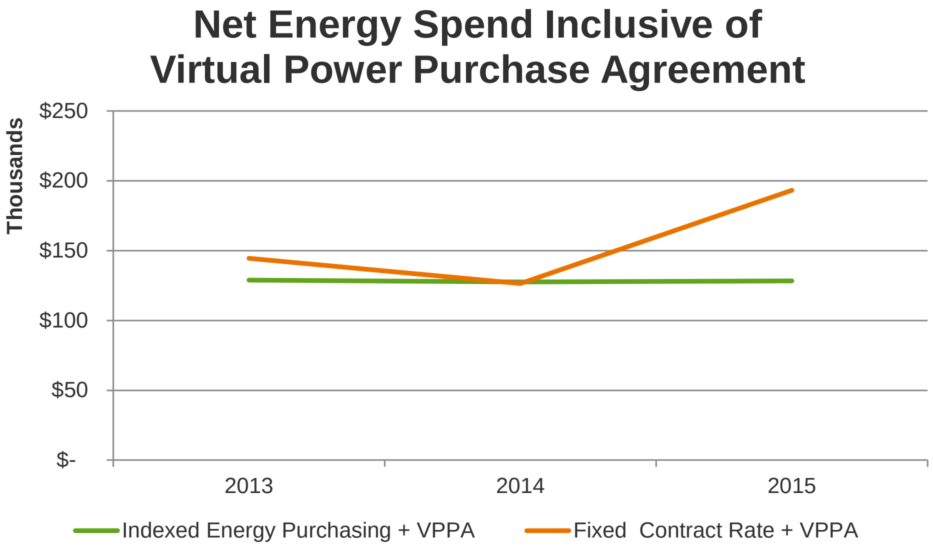


Figure 9 - Net Energy Spend for Different Energy Supply Purchasing Strategies Combined with a Virtual Power Purchase Agreement

In conclusion, we see that the ability of a virtual power purchase agreement to improve budget certainty is contingent on the purchaser having corresponding exposure to the spot market in which the VPPA is settled. In the extreme case where an organization has purchased a VPPA corresponding to 100% of its load in a particular market in order to improve budget certainty, the organization must consider allowing some of the power purchases for its facilities to float the index market price, which would have the effect of off-setting gains or losses from the VPPA.

2.1.5. Consideration of Cross-Market Risk of a VPPA

One primary benefit of a virtual power purchase agreement is that it does not involve the physical delivery of power, allowing corporations to invest in alternative energy projects with the best economics, not necessarily those located closest to their load. An organization could conceivably meet a 100% renewable energy goal with one large virtual PPA in Texas, even if the majority of its load is centered in Ohio, assuming it takes the environmental benefits of such a project.

Despite the seeming attractiveness of this approach to many organizations seeking to meet significant renewable energy goals in a short timeframe, purchasing alternative energy through a VPPA in different grid regions from the underlying electricity load can negate the ability of the VPPA to improve budget certainty.

While underlying fundamentals like the price of natural gas play a role in guiding the prices in most US electricity markets, many other local factors such as transmission and pipeline constraints, large plant retirements, and changes in the supply resources mix have a greater impact on LMPs in particular regions. An organization with demands for electricity in Ohio could see the impact of new transmission lines in Ohio reflected in their energy spend, while the output of a wind asset in north Texas might not see any deviation in price from the same event.

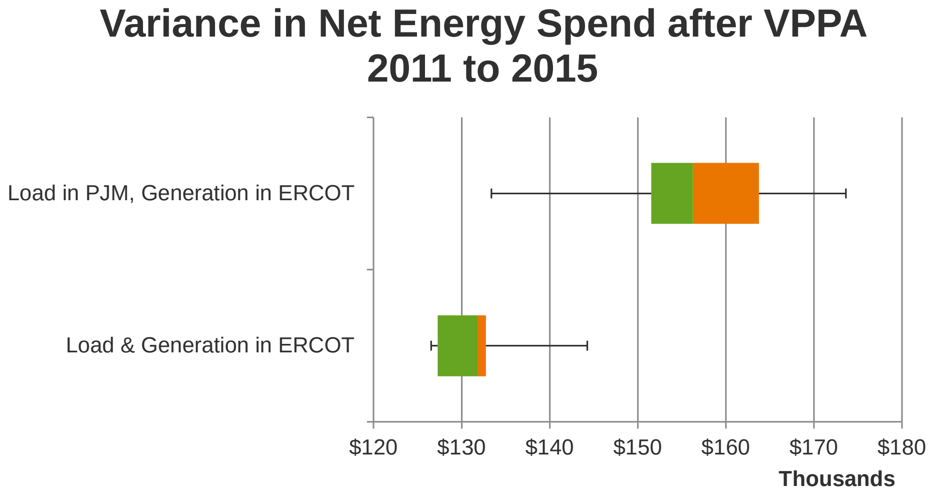


Figure 10 - Net Energy Spend after Adding the Same VPPA Gain/Loss, with Loads Centered in Different Grid Regions

To assess the impact of the imperfect correlation between prices in regional electricity grids, we consider the net energy spend for the previously modeled facility and wind virtual power purchase agreement in ERCOT North, but now assume the facility is purchasing power on the PJM West Hub real-time index market. As Figure 10 shows, the range of potential budget outcomes varies much more significantly when the VPPA is settled in a region outside of the load zone for the buyer's energy demand. Though the average spend for this facility would have been higher simply because PJM West Hub prices exceeded those of ERCOT North Hub for the electricity demanded, the range between the 25% percentile and 75% percentile of energy spend from 2011 to 2015 would also be 122% higher for the facility purchasing at PJM West Hub as well. Thus, an organization seeking budget certainty as a primary benefit of their VPPA should ensure that prices for the market in which their load is located are sufficiently well correlated with the market in which the VPPA is settled.

2.1.6. Consideration of "Shape Risk" and Future Price Changes on a VPPA

As mentioned above, predicting hourly price scenarios for future years is exceedingly difficult and subject to a variety of changing market and regulatory drivers. However, because the net benefit of the VPPA deal to the buyer is a function of both market price and the time of production, any organization considering a virtual power purchase agreement for a long term should consider the possible impacts to hourly prices in the market over the coming years.

For example, wholesale prices in California have changed dramatically over the past five years, largely due to a change in overall demand for power during the middle of the day as more solar generation has been installed on the grid. As Figure 11 shows, the average price on the day-ahead electricity market at the hour ending at 3:00 PM in May declined from over $35/MWh in 2012 to under $20/MWh in 2016. A customer with exposure to such prices through a VPPA will certainly be impacted by such changes, both positively and negatively. For instance, a VPPA with a generating facility producing more of its power in the evening hours could stand to benefit from these changes to California's pricing profile, if prices continued to increase in the time periods immediately following sunset.

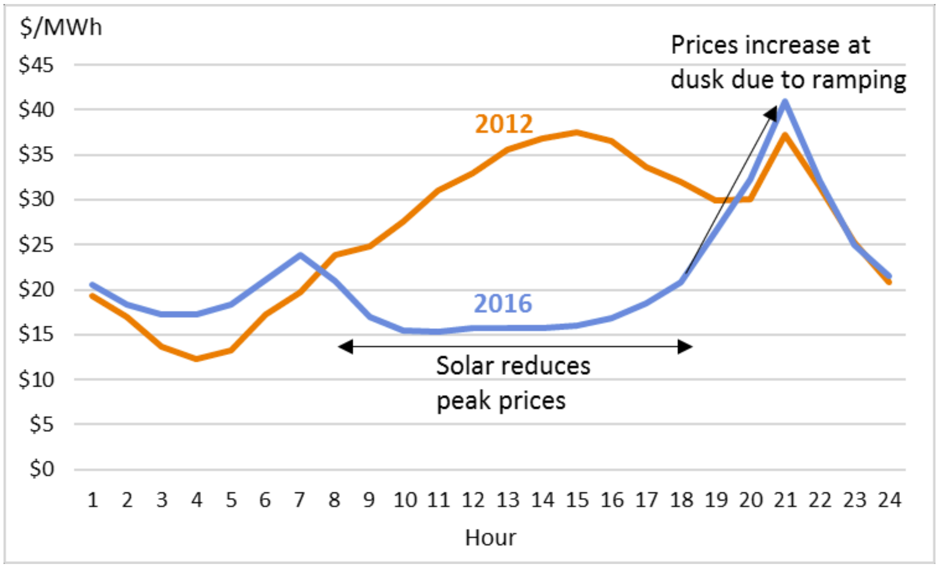


Figure 11 - Day-Ahead Average Hourly Electricity Prices at SP-15 (CAISO), May 2012 and May 2016. Source: SparkLibrary, based on data from CAISO

3. Conclusions

We have demonstrated that consideration of a virtual power purchase agreement should involve not only an analysis of average annual forward prices against the VPPA, but also a review of performance under different hourly market price scenarios and a range of portfolio electricity purchasing strategies. The major drivers of VPPA performance include the expected production profile of the generating asset, the hourly pricing profile of the electricity market at which such a contract settles, the profile of the buyer's corresponding load, the hourly pricing profile of the market at which the buyer purchases electricity, and the strategy with which the buyer continues to purchase power.

Table 1 - Summary of Market Risk Impacts to Virtual Power Purchase Agreement

Risk Factor	Impact on VPPA Gain/Loss	Impact on Net Energy Spend
Correlation of time of generation to hourly pricing	VPPA will have more gains when power produced when market price exceeds strike price, losses when market price below strike price	None, if perfect correlation between generation and load, and load purchased at index price.
Correlation of time of generation to demand for power	None	Less correlation between time of production and demand for power could increase deviation in budget
Correlation of market prices for generation and load	None	Less correlation between market prices at generation and load could increase deviation in budget
Purchasing strategy for corresponding load (indexed or fixed)	None	Less exposure to the market price where VPPA settles could increase deviation in budget

Risk Factor	Impact on VPPA Gain/Loss	Impact on Net Energy Spend
Future shape of pricing curve changes	VPPA will have more gains when power produced when market price exceeds strike price, losses when market price below strike price	None, if perfect correlation between generation and load, and load purchased at index price.

The above Table 1 describes a summary of potential market and budget risks associated with virtual power purchase agreement, as well as their impact on the ability of the VPPA to return positive cash flow to the buyer and its ability to reduce deviation in annual energy budgets. This list is not a comprehensive review of all potential risks facing an investment decision in the virtual power purchase agreement, but should inform a buyer about potential impacts of their investment on their energy management strategy.

The virtual power purchase agreement has emerged as a significant tool at the disposal of energy sourcing departments across the largest organizations in North America in order to meet large alternative energy purchasing goals. While the contract model has significant benefits to the buyer in its ability to remove the complexities of physical delivery of power, buyers should be aware of the market risks entailed by adding a virtual power purchase agreement into their energy portfolio. Used in concert with a calibrated approach to energy sourcing, virtual power purchase agreements have the potential to allow corporations make significant contributions in the deployment of alternative energy while meeting their cost and risk objectives.

4. Abbreviations and Definitions

4.1. Abbreviations

PPA	power purchase agreement
VPPA	virtual power purchase agreement
LMP	locational marginal price
REC	renewable energy credit
MW	megawatt, a unit of electric power
MWh	megawatt-hour, a unit of electric energy
SCTE	Society of Cable Telecommunications Engineers
ISBE	International Society of Broadband Experts
ERCOT	Electricity Reliability Council of Texas
PJM	PJM Interconnection, LLC

4.2. Definitions

Power purchase agreement	A bilateral agreement in which a buyer (utility or end-use customer) agrees to pay for the energy output from an electricity generating facility and, optionally, the environmental attributes from said energy,
Virtual/synthetic power purchase agreement	A type of power purchase agreement in which the buyer agrees to pay a certain price for the output from an electricity generating asset, but does not take title to the energy generated.
Contract for difference	A contract structure, commonly used in a virtual power purchase agreement, whereby two parties agree that the seller will pay the buyer the difference between the current value of an asset and its value at the

	time of contract signature (a "strike price"). If the difference is negative, the buyer pays the seller.
Buyer	The party that agrees to pay a specified price for the generation of power
Seller	The party that agrees to generate power in return for a specified price
Load	The demand for energy from an end-use facility or customer
Forward price	The price today (or on a specific day in the past) for the delivery of a commodity to a specific location on a specified date in the future
Strike price	The benchmark price agreed upon as a reference against which to calculate contracts for difference
Locational marginal price	The price of electricity delivered or produced at a specific node on the electricity grid, inclusive of the cost of transmission congestion

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Evaluating Alternate Broadband Architectures for Energy Consumption

A Video Service Perspective

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1. Introduction

Power consumption is an increasingly important consideration in evaluating alternative broadband system architectures. Currently defined metrics, such as Energy per Consumed Byte (EPCB), are effective for evaluating operations of a common architecture across locations and over time. For architects continuing to evolve these systems however, tools are needed to consider power consumption in the context of video service delivery in addition to key factors such as reliability, manageability, security, availability, cost, and scalability(1). To effectively compare alternatives, architects must ascertain comparable service delivery ensuring the alternate architectures are capable of delivery the same consumer experience.

The television service has been a mainstay of the cable industry since inception. Driven by business and technical forces, the television service has evolved from the simple transmission of broadcast television pictures to expansive catalogue of live and on-demand content. A variety of purchase and consumption models are integrated into a rich user experience to navigate, discover and purchase entertainment. We can expect this definition will continue to evolve with product innovations, however for a core segment of subscribers the expectations are well established.

Like other delivery system designs, broadband television can be evaluated in the context of a consumption model. Viewer measurement and network management methodologies collect key consumption data from which we construct a rating based and measurement based viewership model. The effectiveness of different architectural models is compared using this viewership model. In addition, within a specific architecture, sensitivity analysis clarifies impact of changes of viewership on energy.

2. Discussion

2.1. Consumption Consideration in System Design

Designing a delivery system to meet consumption requirements is not unique to television service. There are many examples of systems designed to satisfy a consumption model. Water supply systems that provide for agriculture, sanitation, washing, industry and waste removal are one of the oldest. The ancient Assyrians created such systems and spread their designs in the 8th century B.C.(2) Technicians have created water systems of massive scale including one supplying the more than 8 million inhabitants of New York City. Water demand requires usage models from varying perspectives(3) including withdrawal, non-withdrawal, per capita (gallons per day per capita) and gross consumption.

The delivery system must consider the usage pattern and service requirements. For a water system, this includes purity, availability, safety, quantity and convenience. The consumer accesses the tap, baths, waters lawns, and washes dishes at various times of the day. Water meters track the total amount of water going into a home and the information is typically recorded on a monthly basis. To better understand usage, researchers work with randomly selected households to collect detailed information including sampling flow rate every 10 seconds.(4)

This detailed data is extrapolated for consideration in design various water supply systems. Systems ranging from municipal reservoirs to aquifers to desalination systems are evaluated for their ability to meet the consumption need. Achieving power optimization in satisfying this need is a critical element in water delivery system design.

We have established the role of consumption models in system design and provided an example of a consumption model being used to compare divergent architectures' power efficiency. We can apply this methodology to the television service. To do so a description of a television service and a viewing consumption model are provided.

2.2. Television Service

For a television service, viewing of television pictures by each individual is defined as usage. Like drinks of water, these events provide utility to each viewer and accumulate across the population. Usage patterns are a function of individual actions and viewing time. In addition to usage patterns, the system must also meet other service requirements such as fidelity, user experience, ease-of-use, and convenience.

Today's modern television experience offers an expansive catalogue of live and on-demand content. With it a variety of low-friction electronic purchase and consumption models are integrated. Many input and display devices offer a feature, graphics, and metadata rich environments to navigate, discover and purchase entertainment. While the experience is well established with the core segment of subscribers, this definition continues to evolve with product, digital media and broadband innovations.

On average, an operator provides 189 broadcast television networks to subscribers.(6) In addition, more than 60% of video users have access to on-demand content using it on an average of 9 hours per month. Many operators boast more than 30,000 on-demand titles(7), far more than can be cost effectively delivered through brick and mortar purchase models. While the full ecosystem enhances user satisfaction, the television pictures are the core of the user experience and the focus of usage measurement.

2.3. Television Service Based Energy Function

For broadband architects to fairly evaluate the energy impact of alternate architectures, the architectures must provide equivalent television services. Consider two architectures that are identical except the system A uses the MPEG-2 CODEC for video streams and system B uses h.265. On average, the h.265 content compresses the video 4 times more efficiently than MPEG-2. Since both systems consume the same amount of energy and deliver the same service, we derive the following EPCB relationship.

$$\mathrm{EPCBsysA} = \frac{\mathrm{Total\ Energy}}{\mathrm{SystemA\ Bytes\ Consumed}}$$

$$\mathrm{EPCBsysB} = \frac{\mathrm{Total\ Energy}}{\mathrm{SystemA\ Bytes\ Consumed}/4}$$

$$EPCBsysB = 4 * EPCBsysA$$

Based on the EPCB metric the system that incorporated the h.265 requires 4 times more energy per byte. The architect may defer proposing this change because of the penalty identified by the EPCB measurement. Alternately, we can consider a service perspective.

Based on the television service definition with emphasis on viewing of television pictures, a service perspective is brought to the architecture comparison. We propose Energy Consumed by Service (ECS) as a function that attempts to account for the data rate flexibility of video that can be elusive if we perform comparisons based solely on bytes consumed.

$$Energy\ Consumed\ by\ Service\ (t, \ldots) = \frac{Energy\ Consumed(t, \ldots)}{Video\ Service\ (t, \ldots)}$$

We derive the functions for the example systems with constant energy consumed.

$$ECSsysA(t, \ldots) = ECSsysB(t, \ldots) = \frac{Energy\ Consumed}{VideoService\ (t, \ldots)}$$

Because the change in CODEC impacts the number of bytes but not the video service, the ECS for each is the same.

A dynamic system adjusts power consumption over time based on service demand. A non-responsive system has fixed power consumption over time. By examining the ratio of per user power consumption at peak to usage at an instance in time, we obtain of measure of system responsiveness during service variation.

As viewership varies, there is an opportunity to reduce energy consumption because of decreased networking and other equipment needed to deliver the service. We define Optimal Dynamic Consumption (ODC) by normalizing to energy consumed per user at peak viewership.

$$Kp = Load/MAX[VideoService\ (t, \ldots)]$$

$$Optimal\ Dyamic\ Consumption(t, \ldots) = Kp * VideoService\ (t, \ldots)$$

An energy-optimized system more closely follows the ODC curve by accessing more energy only as service need requires.

2.4. Ratings Based Usage Modeling

Industry norms of viewership accounting, in the form of ratings or audience measurement, have long been common practice as part of the television advertising business. Measurement began with hand entered viewer logs and over time migrated to increasingly automated measurement mechanisms. Various measures assess the number of times an ad break is viewed within a relevant time period. Measurement has evolved to address viewing of recorded and on-demand video to include 3 or 7 days from original airdate (e.g. C3, C7). Such measurements can be extracted into a ratings based mathematical model.

In 2004, Weber & Gong observed, ‘in a network with a finite number of active viewers at any particular time, some of the more popular programs will be watched by multiple viewers, while some of the less popular programs will not be watched by any viewers.” (8) They proposed a mathematical usage model based on measurement information from Nielsen including expected households watching TV and network ratings. An observation based on the model is many offered channels are not viewed as illustrated in Figure 1. In the figure, ‘Bandwidth Required’ on the vertical access is a representation of viewed channels. Switched Broadcast curves represent the viewing model.

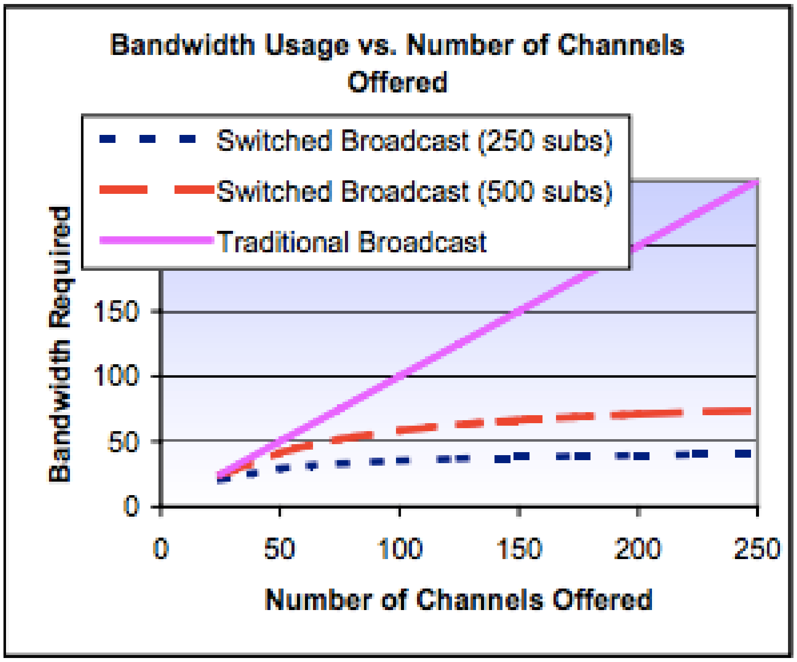

Figure 1 - Viewed Channels vs. Offered Channels (Weber and Gong)

The proposed model assumes a normal popularity distribution for the offered service. The distribution of total households for Nielsen across the top 50 ad based networks in the US is shown in Figure 2 (10). The steepness of the curve diminishes as you move away from the most popular networks and as the slope flatness the fit to the model improves. As seen from the Figure 1, the assumption of a normal distribution is only valid across a subset channels.

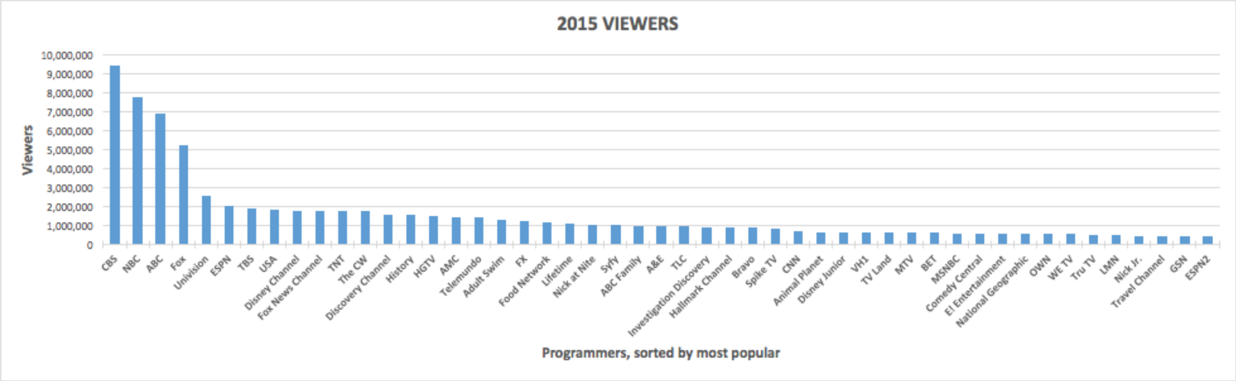

Figure 2 - Histogram of Viewership across networks based on Nielsen data for US Population

Increasingly large sized linear and on-demand television catalogues delivered through digital media distribution results in consumption following a "long-tail" model. (9) However, hit television that does not meet the normal distribution assumption continues to skew viewing patterns.

The Weber and Gong model is a useful tool especially in light of the easy to obtain and readily available ratings data. The model has its shortcomings with respect to finer grain details and time of day variations. Additionally, the model does not explicitly address on-demand viewing.

2.5. Data Collection Description of Television Consumption Behavior

Given the shortcomings of ratings based usage models, we apply expanded data collection techniques. The industry has been investing in network management and analytics collection infrastructure to increase the performance of their systems. This includes state-of-the-art data collection and storage infrastructure. This data offers much finer grained analysis than afford by viewership data derived from ratings information.

Through this collection system, we obtain a comprehensive set of viewing information sampled each second and filtered out durations shorter than 5 minutes. For simplicity, only the linear television consumption model is represented in the following graphs.

Future systems should exploit the variation in video service demand to decrease power consumption especially during periods of peak power cost as illustrated in Figure 3.

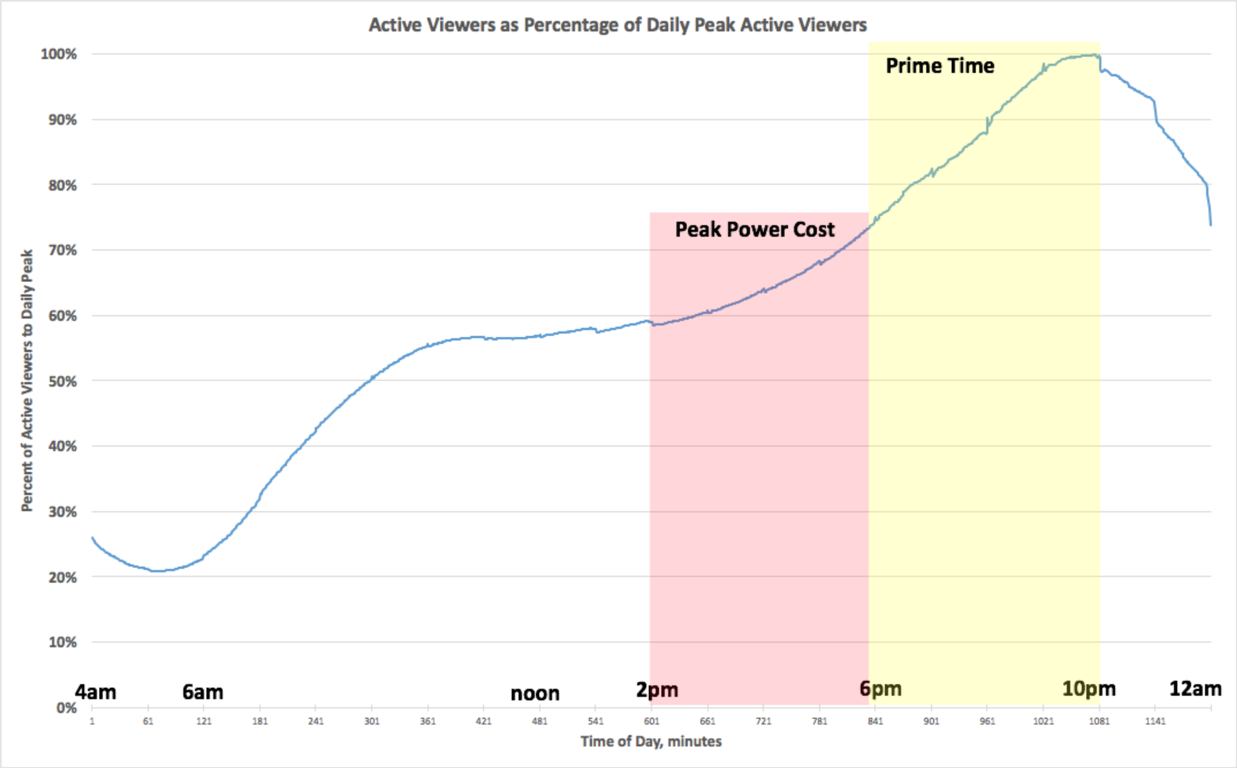

Figure 3 - Peak Power Costs Relative to Prime Time Viewing

Usage data is a rich and complex set of information. Modern data science techniques promise to improve insight into this data including evaluating alternate architectures. Figure 4 and Figure 5 show total viewership across two different geographic regions with different population sizes over 60 days.

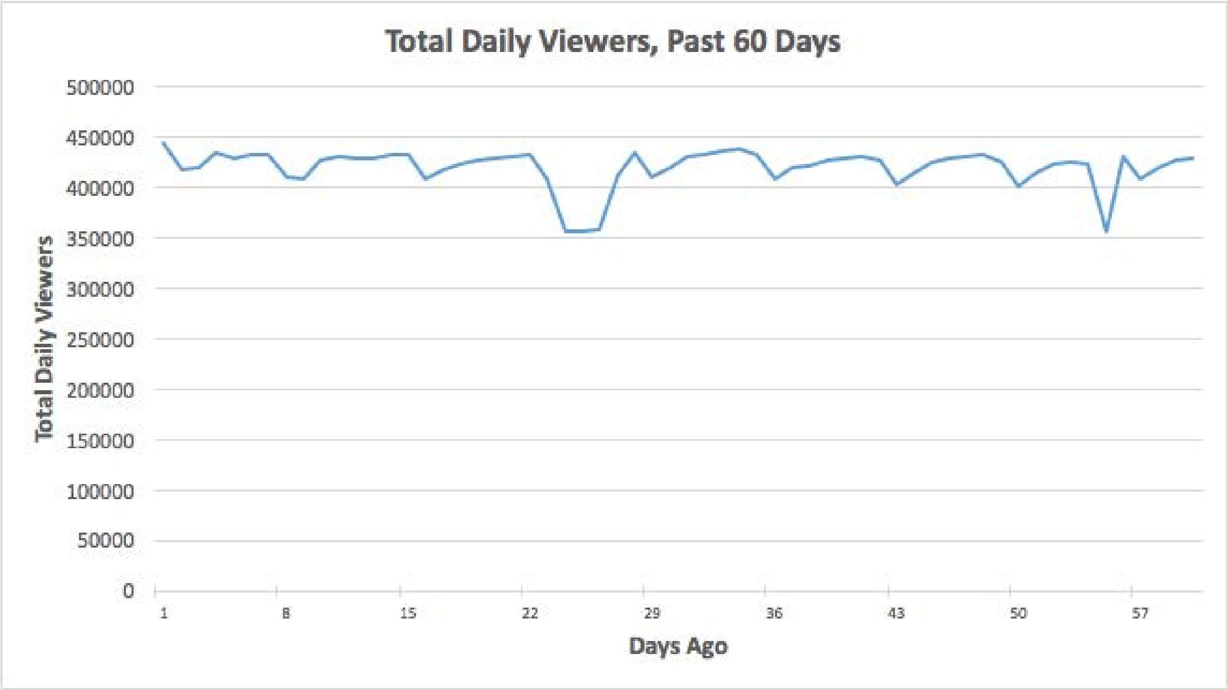

Figure 4 - Viewership across networks for a geography A (Peak 450,000)

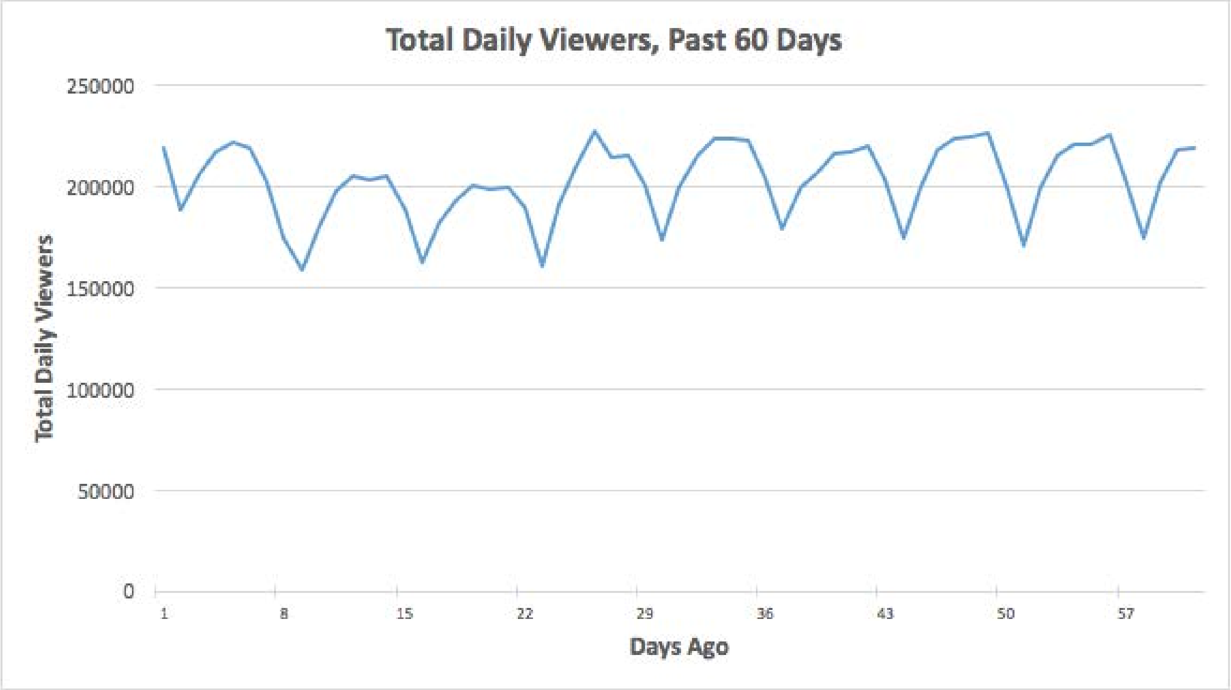

Figure 5 - Viewership across networks for a geography B (Peak 225,000)

At this level of detail, we see weekly patterns in both the large and small system. Variations between each day's peak is on the order of 25% to 50%.

Time of day is an important consideration from both a capacity and energy pricing perspective. Figure 6 shows a large system with variation in the number of viewers by 5 times with the peak being during prime time.

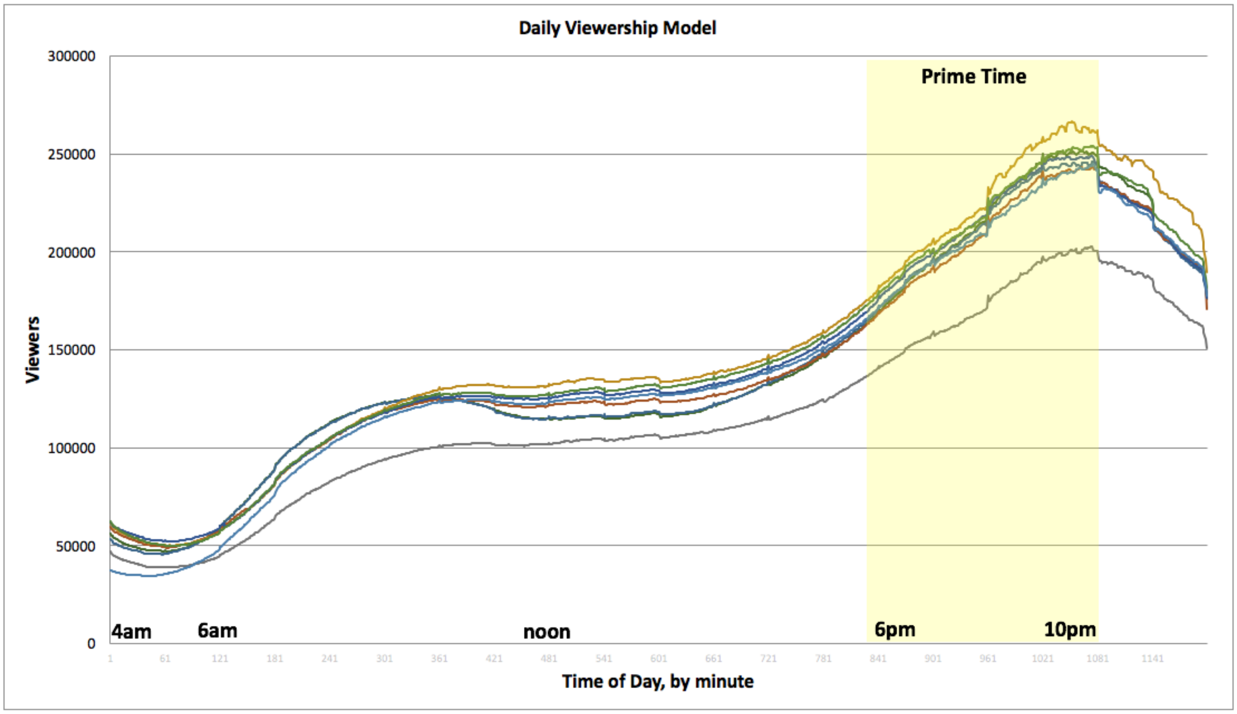

Figure 6 - Daily variation of viewership for across time within a geography A (Tuesday , Peak 450,000)

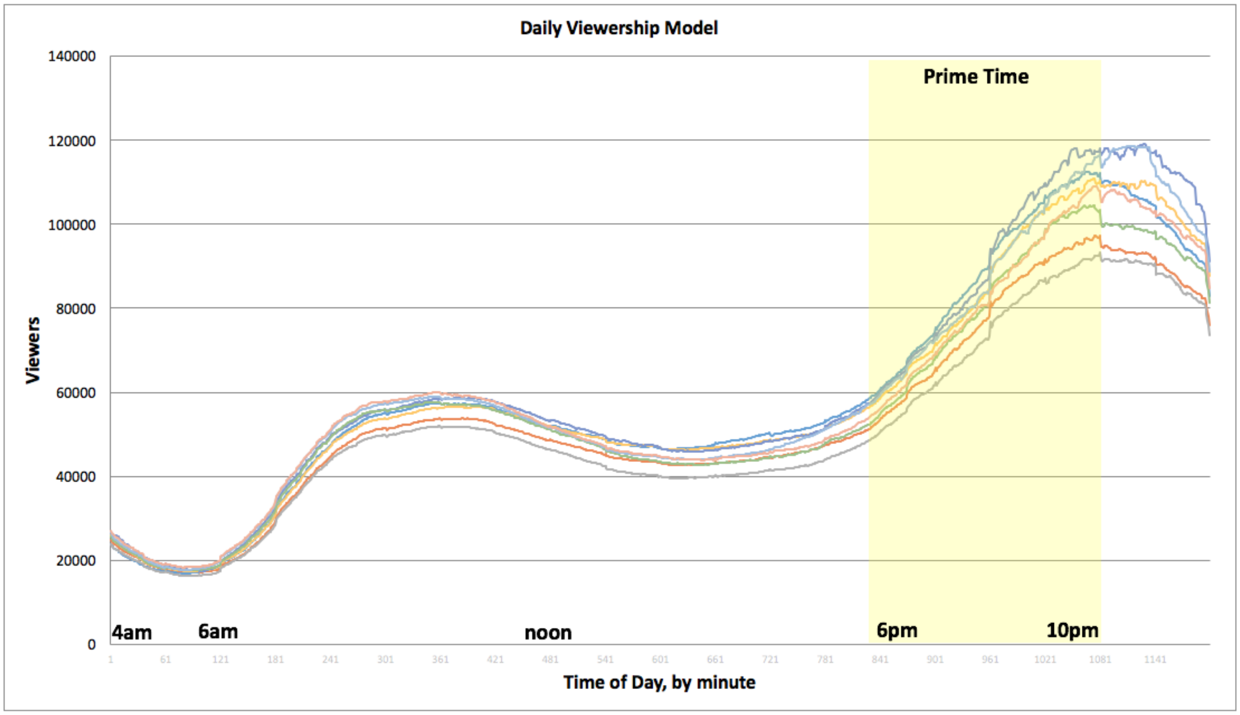

Figure 7 - Daily variation of viewership for across time within geography B (Tuesday , Peak 225,000)

Figure 7 shows a smaller system with variation in the number of viewers by about 6 times with the peak during prime time. This variation results from both television and non-television based activities competing for viewers’ time.

The detailed characteristics of viewing behavior also vary depending on the day of the week. In Figure 8 we show viewing for several consecutive Sundays for the large system. The post noon plateau seen in weekday TV viewership is absent on Sunday as viewership continues to climb through the daytime hours.

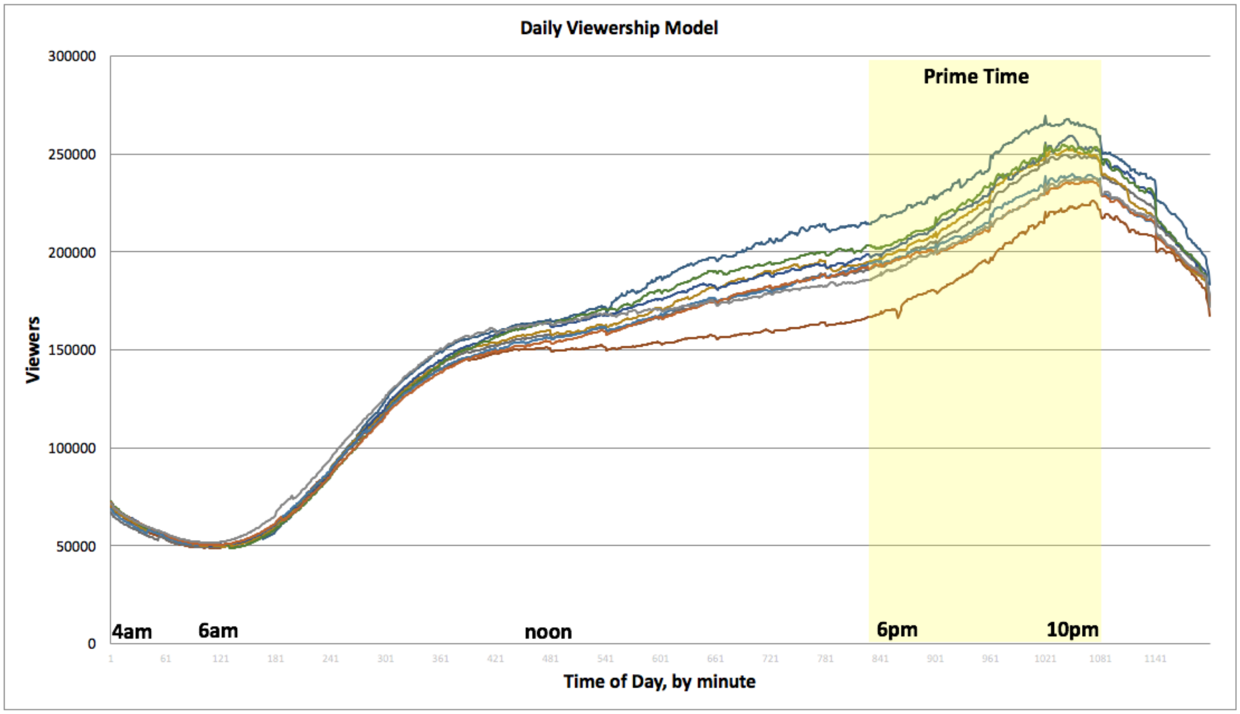

Figure 8 - Daily variation of viewership for across time within geography A (Sunday , Peak 450,000)

Viewing data repositories serve as a real-time snapshot into the evolution of the viewing model. We expect viewership patterns to change over time based on market and societal changes. This evolution represents an additional challenge for the architect who must anticipate the potential changes and incorporate sensitivity analysis into the architectural evaluation. For example, popular programming may continue to cause peak consumption during ‘viral’ events such as live sports. Alternately, as entertainment choices expand, an architect may anticipate a decrease in peak viewership of “hit” programming. The architect applies hypothetical viewing models that capture these projected changes.

2.6. IP Video Architecture

IP video delivery has emerged as a leading mechanism to deliver video entertainment across the Internet. Many operators support delivery to customer provided devices such as tablets and smart-TVs using IP. The IP delivery system is based on the concept of unicast delivery in which the requested video is delivered via a unique stream to the customer premises devices. For the on-demand services, the user may access DVR-like trick-mode operations such as pause, rewind, and fast-forward. Live content service does not offer these control capabilities.

In this example, we apply the simplified IP video architecture to delivery the television service as described above. Figure 9 shows data plane components of an IP video system.

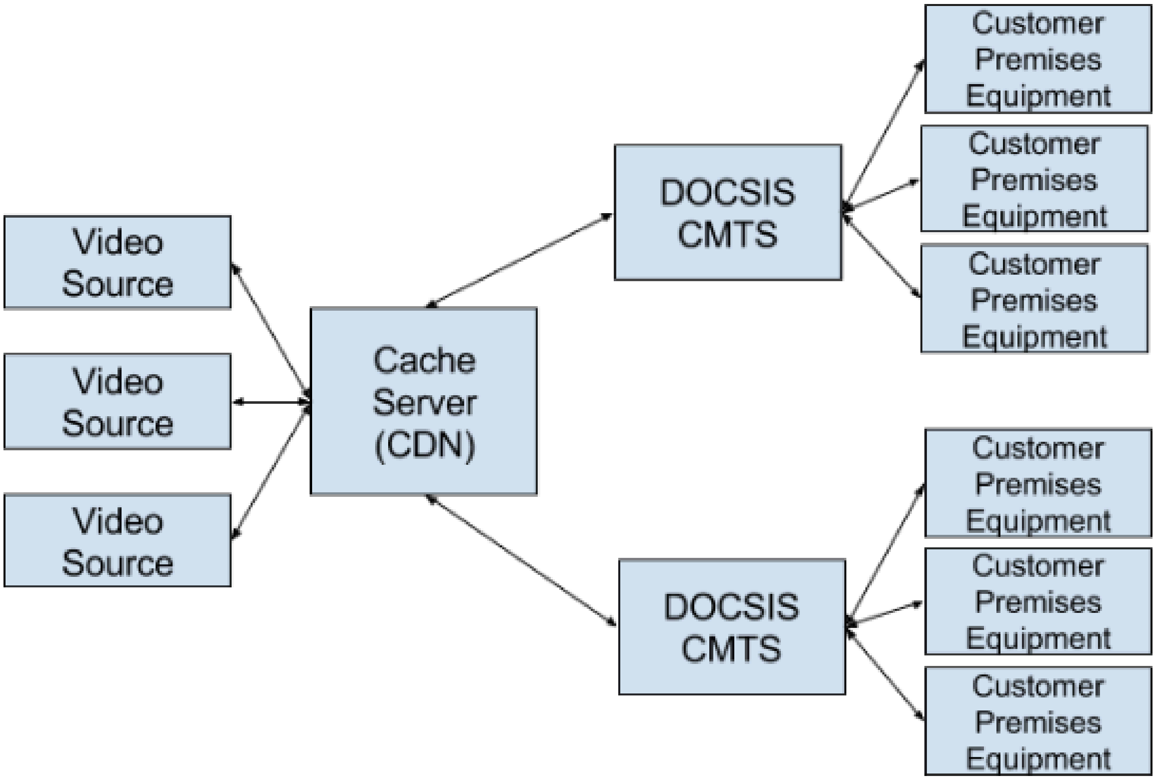

Figure 9 - Representation of IP video architecture

Origin Servers acting as sources constitute live and on-demand video contents that are ingested into a caching server as part of a broader content distribution network (CDN). This content is stored as media files. A manifest file provides playlist of various files pulled by the customer premises equipment using protocols such as HTTP Live Streaming (HLS). The requests for the content, as well as, the video media are transmitted through the Cable Modem Termination System and Cable Modem (not shown).

2.7. Applying Usage Model to an IP Video Architecture

We now apply this viewing model to the IP video delivery architecture. For both live and on-demand content, the system must provide EACH user a dedicated video stream while they are viewing. Consider the linear viewing data for a cable system with 230,000 active viewers for which the video service function is plotted in Figure 6. The system capacity requirement is proportional to the number of viewers present at each instant.

Assume the IP system power architect is a fixed load design with constant power draw of 3 Watts per home passed with 500,000 homes. We estimate over all power consumption is 1.5 MW. Normalizing power consumption against a peak user level of 230,000 viewers (shown as a horizontal line), yields a peak power efficiency of 6.5 Watts / user. As expected power usage per viewer is higher than per home passed because viewing concurrency and penetration are less than 100%. We plot the ODC based on the viewing function in Figure 10.

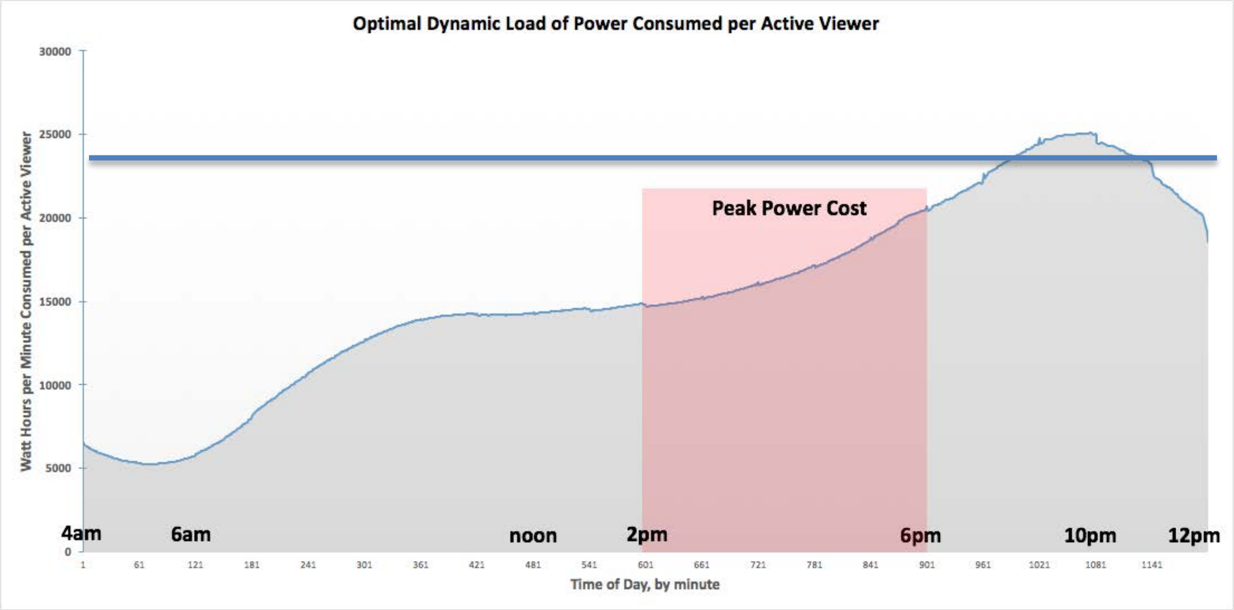

Figure 10 - ECS for Simple IP System (Tuesday, Peak 450,000)

3. Conclusion

A video consumption model aids the architecture analysis of system energy efficiency. Television pictures that are viewed are counted toward usage, while unwatched pictures are disregarded. This method enables comparison of power considerations across candidate architectures through the application of viewing models. While energy consumption per byte is a useful measure within a given architecture over time and across geography, CODEC variations and other factors make ECS more useful tool for cross architecture analysis.

Rating data based mathematical models offer a high level tool that leverages a convenient data source. Data collected via state-of-art data science infrastructure provides finer details and a mechanism to track shifts in viewing patterns. Data collection also allows for tracking trends and changes in viewing patterns that can be extrapolated for future designs. The designs must assure energy flexibility in the face of changing consumption models. Changes in architecture are based on suitable energy analysis using the viewership model.

The ECS function provides a video service based perspective of energy consumption. In the fine grained data collected using advanced data collection techniques, viewership continually varied and peaked by more than 5 times the base in course of the day. ODC illustrates potential energy savings possible from dynamic resource management. Future efforts should consider how system designs could take advantage of the temporal variation in video consumption through dynamic resource management.

4. Abbreviations and Definitions

4.1. Abbreviations

EPCB	energy per byte consumed
ECS	energy per consumed service
HLS	http live streaming

4.2. Definitions

MPEG-2	Moving Picture Experts Group digital video television standard.
H.265	High Efficiency Video Codec compression standard.

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JOURNAL OF
ENERGY MANAGEMENT

Power Efficiency in Modern Routers

Systems and Network Architecture

A Technical Paper prepared for SCTE/ISBE by

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1. Introduction

The power and carbon footprint of Internet networks is not just an environmental concern, it is an economic challenge for large service providers and cable operators. Once thought of as a rounding error or an afterthought in network architecture, the financial impact of power consumption and the resulting impact on facilities, space, cooling and other infrastructure now has a material impact on any network operator's finances. Soon the industry will reach the practical limit of what is achievable to build and scale in a contemporary air cooled system, necessitating the transition to alternative thermal disposal architectures such as liquid cooled systems.

When any router vendor builds a product, there are only so many levers that can be adjusted to improve power and thermal efficiency at the component or system level. Efficiency is not solely the manufacturer's responsibility, to truly make a network power efficient also requires a level of network architecture discipline on the part of the network operator and the consideration of power consumption as a fundamental input to the system as a whole.

This paper explores what a router vendor can and cannot do when building a more efficient system and compares and contrasts some potential component and architectures that are possible. The paper ends with a brief introduction to liquid cooled systems and facilities.

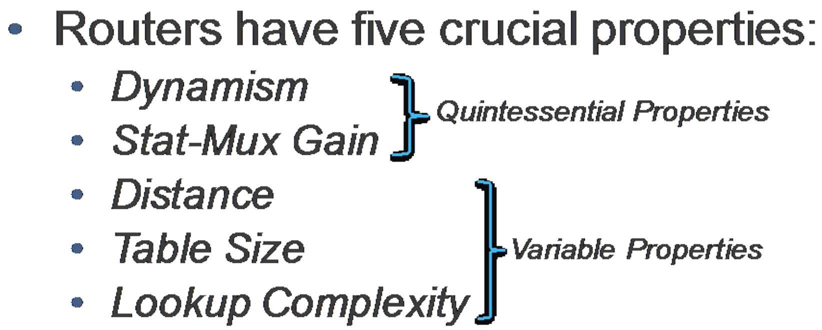
2. The Five Properties of Routers

In router systems architecture, there are five fundamental properties that exist in every routing device. Two of these properties are quintessential across every size and scale of routing device, whether a home WiFi gateway routing a few tens of megabits of per second or a large core router forwarding hundreds of terabits per second. Three of the properties are variable, and these three variable properties when adjusted for a given router's use case can result in a device that is optimized for cost, space and power.

2.1. Quintessential Properties

The two quintessential properties are dynamism and stat-mux gain. Dynamism is the notion of a router self-discovering its placement the network topology, either through a routing protocol or other external configuration such as DHCP or IPv6 SLAAC. A router by itself cannot perform functions if the device does not know where to send packets, and this state information is set in the router dynamically upon startup and periodically updated while operating. Modern core and edge routers will self-discover their location in a topology through the use of an interior routing protocol such as OSPF or IS-IS.

Statistical multiplexing refers to the efficiency benefits inherent in packet switching itself, that is, that because of packet switching more capacity exists in the network than would otherwise be available. Previous data communication systems allocated time slots or frequencies to specific sources and destinations, packet switching by comparison pre-allocates no lower layer resources to any particular path and treats packets asynchronously on a first-come, first-served basis. The result is an improvement of efficiency, and this efficiency is at the heart of economically scaling the Internet to today's global network of networks.



- Routers have five crucial properties:
  - *Dynamism*
  - *Stat-Mux Gain*
  - *Distance*
  - *Table Size*
  - *Lookup Complexity*

Quintessential Properties

Variable Properties

Figure 1 - Five properties of routers

2.2. Variable Properties

The three variable properties of a router are distance, table-size, and lookup complexity. When any of these properties can be reduced in size or scope, a router that is much more efficient in terms of cost and power can be built. While this may seem intuitive, the reality is that reducing the size and scope of a router's three variable properties is quite a challenging thing to do. From a router manufacturer's perspective, optimizing a device's variable properties can result in a much more efficient device, but could limit the amount of total addressable market that product can be sold into. From a network operator's perspective, the simplicity, reliability and efficiency of an optimized routing device is attractive, but requires committing to a disciplined network architecture to reap the full benefits of the optimization. However, if a goal of the network architecture is to reduce the power footprint of the network as a whole, then power must be a fundamental input to the development of the architecture itself. It would be unreasonable to expect any service on any port if one of the goals is efficiency.

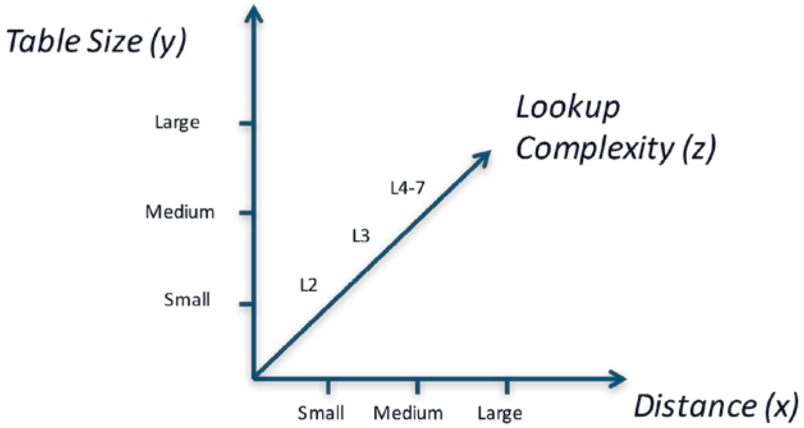


Figure 2 - Variable Properties of Routers

2.2.1. Distance

The first variable property is distance. This refers to the physical distance between two devices, or two devices that are directly connected to each other. When this distance can be relaxed, then the size, power, and thermal production of the interfaces on the router can be correspondingly reduced. If the router requires only 1000 Mb/s or lower interfaces that span only a few meters, then simple twisted-pair copper with standard RJ-45 connectors is sufficient. On the other end of the spectrum, if the requirement is to send packets thousands of kilometers in a colored DWDM wavelength, then a considerable increase in power will be required to support hat interface. There are a wide variety of power saving strategies for interface distance, from twisted pair copper to coaxial / twin-axial cable and multiple types of fiber optic cables – multimode and single mode for various distances of physical interconnections. Convergence of network layers, such as the packet and optical layers by integrating photonic transponders directly into a router, is another way to reduce overall network power demands through the elimination of unnecessary, redundant facilities.

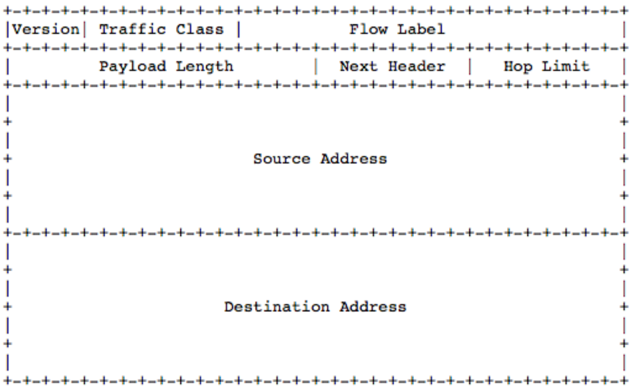
2.2.2. FIB Size and Location

The second variable property is table size, or the size of the route table that must be present in the router’s forwarding information base (FIB). The FIB is a special set of computer memory that is queried by the router, for every packet, to determine where a packet received by the router should egress. The speed, or bandwidth, of which a router can access the FIB is directly related to the packet-per-second (PPS) rate capability of that router, which for a given packet size will determine the ultimate throughput capacity of the router. As the capacity of router interfaces has grown – today’s core interface standard is 100 Gb/s, moving in the near future to 400 Gb/s and 1,000 Gb/s – the size and location of the FIB relative to the packet forwarding engine (PFE) is of critical importance to enable scaling and to enable that scale with power efficiency.

If the FIB is located on the same packaging (chip) as the PFE itself, there is a 3 to 4 order of magnitude increase in the bandwidth capacity of that PFE compared to the FIB being located on off-chip memory. On-chip memory not only improves speed and bandwidth, but dramatically reduces power requirements, reduces latency, and the amount of on-chip resources will only improve with each generation of silicon production process. Locating the FIB in off-chip memory does have an advantage in terms of size, but other than that the improvements in system architecture possible with off-chip memory become challenging without adopting more exotic memory architectures. When designing a router, optimal power efficiency requires finding the right balance between on-chip and off-chip memory use at a given silicon generation.

2.2.3. Lookup Complexity and State

Lookup complexity is a function of how deep in a packet header, and how variable the lookup value is, for a router to determine what the action should be to be performed on a packet. Lookup complexity also becomes a factor if the device must maintain the state of packets, that is, if the action performed on the current packet must be influenced by actions performed on a prior packet.



```
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|Version| Traffic Class |           Flow Label                  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|         Payload Length        |  Next Header  |   Hop Limit   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                                                               +
|                                                               |
+                         Source Address                        +
|                                                               |
+                                                               +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                                                               |
+                                                               +
|                                                               |
+                      Destination Address                      +
|                                                               |
+                                                               +
|                                                               |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 3 - Sample IPv6 Packet Header

If the lookup demand for a router is very simple, the lookup function can be wholly implemented in a simple, compact silicon architecture with a reduced power demand. Consider an Ethernet switch, which forwards Ethernet frames based on a fixed-length, 48-byte MAC address. Such a switch is able to be built wholly in a System on a Chip (SoC) primarily because of the basic nature of Ethernet switching and the fixed length of MAC addresses. MPLS also uses a fixed-length lookup paradigm in the form of the 20-bit label and benefits from efficient silicon switching architectures, and critically adds the notion of a stack of labels (giving context to a packet), TTL, QoS (among other benefits) and in contemporary networks leverages IP only as the control plane for an MPLS-switched data-plane. This reduces the number of IP-routes needed to be stored in a FIB in core environments. Native IP lookups, both IPv4 and IPv6, are also able to be performed in silicon and at line rate on modern routing devices. However, care must be given in native IP environments to ensure the demand on the FIB size does not adversely impact system architecture. The full Internet table of approximately 600,000 routes requires consideration if it is to be installed in the FIB on a router.

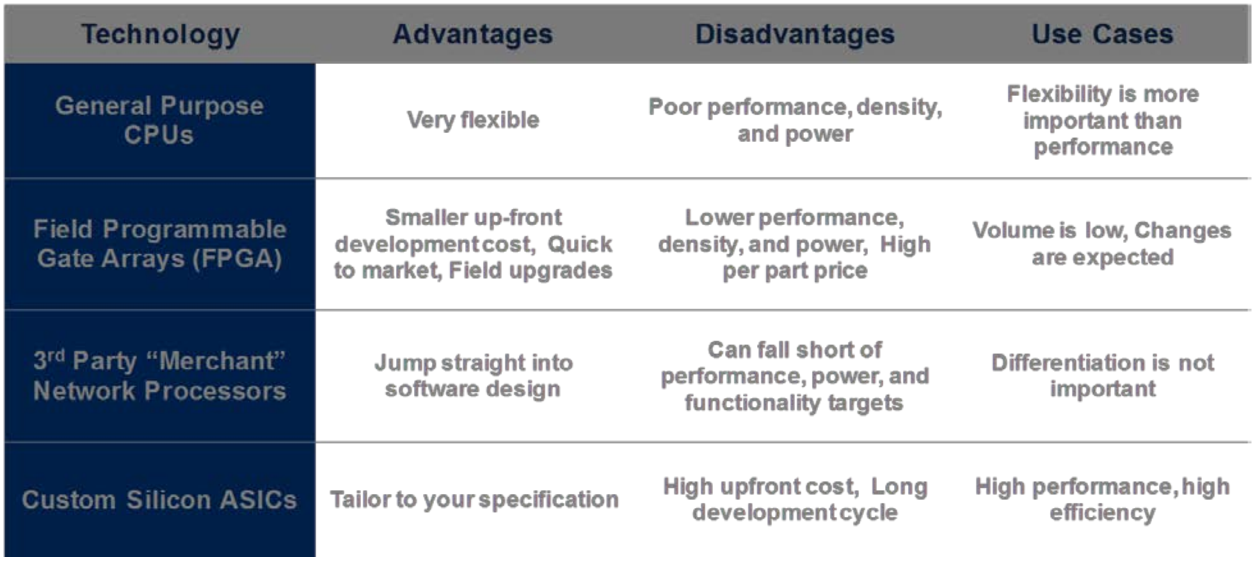
Large routers also contain specialized silicon called Fabric ASICs (FA), which switch packets between line cards and in some architectures between line card chassis. Fabric ASICs in most high end systems perform fixed-length, cell based lookups. This enables the Fabric ASIC to switch cells very quickly and with high efficiency internal to the router itself.

More advanced lookups that look deeper into the packet – at layers 4 through 7 – place a special demand on a lookup engine. Packets that require state to be kept also require a level of computation that typically is better suited to general purpose microprocessors such as Intel’s x86 architecture.

3. Fundamenetals of Packet Forwarding Engines

The use of specialized silicon to switch packets in the data plane constituted a major advance in the performance and efficiency of routers. Pioneered by the Juniper M40 in 1998, separating the control plane to run on standard x86 processors while switching the data plane through specialized silicon resulted in a routing platform with an approximate 20 times increase in total capacity, with a corresponding dramatic drop in the amount of power required to switch a gigabit of traffic. All major router vendors have since designed their high end products to implement a clean separation of control and data plane in similar fashions.

The use of x86 as a platform to build the control plane aligns well with the demands of a modern router, in that control plane is essentially a standard computer running specialized software to compute paths, manage router parameters, interact with management platform and so forth.



Technology	Advantages	Disadvantages	Use Cases
General Purpose CPUs	Very flexible	Poor performance, density, and power	Flexibility is more important than performance
Field Programmable Gate Arrays (FPGA)	Smaller up-front development cost, Quick to market, Field upgrades	Lower performance, density, and power, High per part price	Volume is low, Changes are expected
3rd Party "Merchant" Network Processors	Jump straight into software design	Can fall short of performance, power, and functionality targets	Differentiation is not important
Custom Silicon ASICs	Tailor to your specification	High upfront cost, Long development cycle	High performance, high efficiency

Figure 4 - Comaprison of Silicon Architectures

In the data plane there are typically two major sources of silicon to choose from when designing a routing system. The use of third party, or merchant, silicon is a very viable option when architecting a device which performs simple tasks such as Ethernet switching or basic IP routing at low scale. Custom silicon is selected when very high performance, long-term system viability and very high efficiency is required in a routing platform. Both custom and merchant silicon have discrete roles to play in modern networks and it is important to understand both their strengths and weaknesses when building networks.

The use of general purpose microprocessors is also a very important tool in modern networks and a viable choice for data-plane switching at low scale, or in environments that require keeping the state of packets such as a stateful firewall or CDN (content delivery network) cache. A general purpose microprocessor can, by its flexible nature, perform the role of any other silicon present in a network or even within a large router system. But there is a cost to this flexibility. If it was attempted to replace all network silicon, whether custom or merchant, with general purpose microprocessors, the result would be a very slow, very power hungry system.

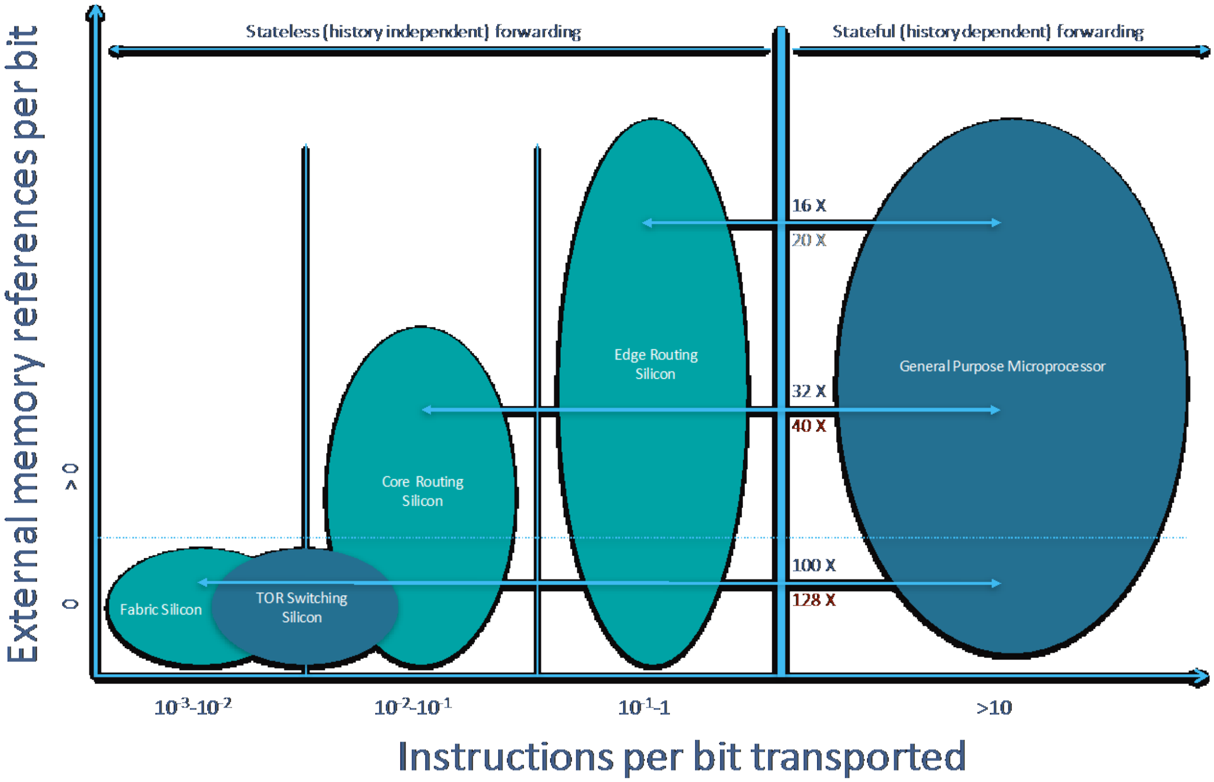


Figure 5 - Silicon Architecture Efficiencies

In the Figure 4, the Y (vertical) axis represents the number of external memory references that are needed to forward a bit of data. When a packet comes into a router, the FIB and other memory areas must be accessed to determine what should happen to that packet. The X (horizontal) access represents the number of executions, or instructions, that are needed to execute to actually perform the needed function on a packet – which could be forwarding, filtering, modifying the packet, encapsulating the packet and so forth.

The large oval on the right represents the relative demand a general purpose microprocessor has to process packets compared to specialized silicon, represented by edge, core, TOR (merchant) and fabric to the left. Theoretically a general purpose microprocessor can perform any of these functions – an x86 processor could function as a Fabric ASIC for example. But the cost to do so would result in a system approximately 100 times slower, and consume 128 times more power, compared to contemporary silicon architecture. Accordingly, using a general purpose microprocessor in place of core routing silicon results in a system that is 32 times slower and consumes 40 times more power, and in place of edge routing silicon, a system that is 16 times slower and consumes 20 times more power.

So at scale, it is completely impractical to build a routing system that needs to be vertically scaled using all general purpose microprocessors. However, at small scale, sub 80 Gb/s or so, or in environments where horizontal scaling is of paramount importance –i.e. running thousands of software routers in a cloud environment - general purpose microprocessors are a very good choice to leverage. GPM's (general purpose microprocessor) primarily bring agility and service velocity to a network environment, and permit the network infrastructure to be much more dynamic and adaptable, enables very specific customization and experimentation, and can allow a network operator to explore new architectures and service models without having to use traditional large router systems. However, GPM's cannot universally replace networking silicon across the entire network architecture. To do so would require an inordinate amount of power and resources.

4. Thermal Architectures

Modern routers are all cooled by passing forced air around and through router components and chassis. This has served the industry well for a long time, but we are reaching a point where in large systems we cannot move air fast enough or with enough precision to efficiently cool the components of a system. The result of this dependence upon forced air cooling is an ever increasing power demand for fans, and an imprecision of cooling resources that can result in lowered component reliability and possibly a limit to how scalable a routing system can be. In some contemporary routers, more than half the power consumed by the device is spent turning fans instead of forwarding packets.

SCTE 186 2016 specifies several parameters for cable facilities to better handle thermal discharge, such as the use of hot aisle / cold aisle and the orientation of equipment in these aisles.

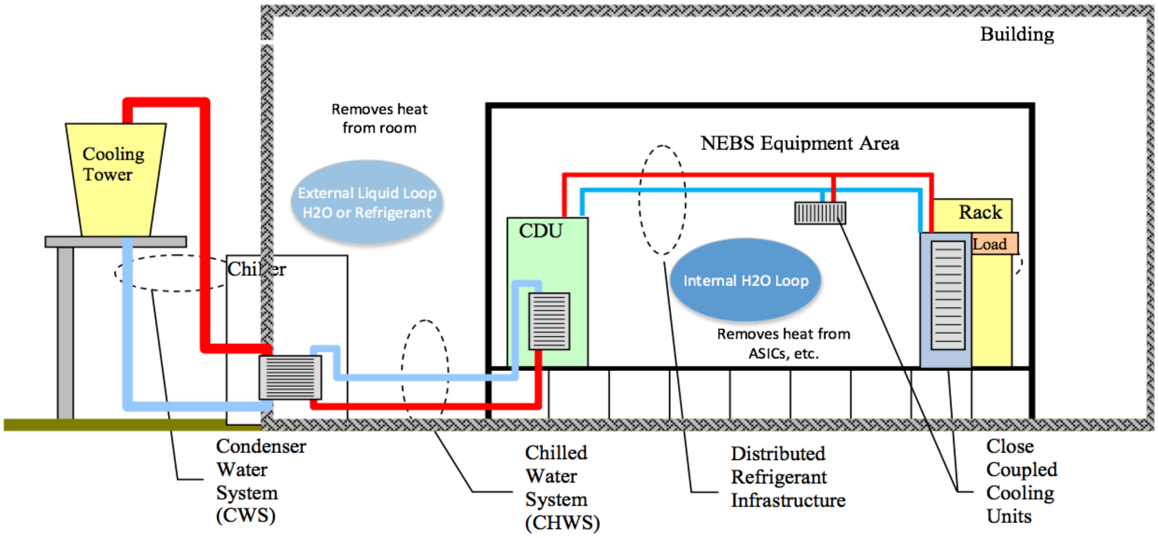
Air can make for a very good thermal insulator, but it is not a good conductor. There is simply too much space in air and not enough molecules to carry heat effectively. The only way to make air a thermal conductor is to constantly move a lot of it. This places a power demand on the system for fans and related infrastructure. The movement of air is highly dependent upon what is around it, and internally to a system the components and the boards will affect how air moves. If a board has to be redesigned for example, the characteristics of airflow must be re-engineered. And finally once air egresses a router, hot air must now be managed by the facility through the form of air conditioning. The demand for air conditioning can in many cases exceed the electrical demand of the router itself. Continuing to accommodate air as the primary thermal disposal method is very, very inefficient.

The thermal cooling power in one cup of water is equivalent to a typical room full of air. While still on the experimental side, in order to build efficient systems, the industry will at some point have to adopt some form of liquid cooling to properly and efficiently dispose of heat from routers.

In a liquid cooled system, early experimentation shows that the total operating expenses for a facility can be reduced at least 30% through reduced air conditioning and more precise use of coolant. Pumping coolant through the heatsink of a router can result in more ASIC's being present on a board and in a device, resulting in a much denser router from a port perspective and consuming less square footage and rack space. Better cooled optical modules can result in much improved performance and tolerate much harsher conditions. And a liquid cooled facility operates much quieter, and every liquid cooled device means those devices which aren't liquid cooled will have a lower inlet temperature of air.

The industry has several working groups exploring liquid cooling and the impact upon facilities. The SCTE Energy 2020 initiative, the Green Grid Alliance, the Alliance for Telecommunications Industry Solutions (ATIS) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE)'s Future Refrigerated Facilities initiative are all researching how to best accommodate future thermal systems in facilities.

Internal and External loops are independent and isolated



With Warm Water, Chiller may not be required

CDU may be integrated into rack as demo shows

Figure 6 - ASHRAE TC9.9 Thermal Guideline Issue 3 (2012)

Liquid cooling remains a key innovation needed to increase efficiency in routing devices. The industry is now building consensus on how best to integrate this technology into facilities and into routing devices themselves.

5. Summary

Building power efficient routers, and a power efficient network, is a collaborative endeavor. Router manufacturers must continue to explore the state of the art in silicon architecture, systems design, thermal design and to understand the specific requirements of operator's networks when producing devices. Network operators must adopt a disciplined network architecture that can take advantage of progress in silicon and system architecture, and be open to operational and facilities changes to support advanced services and thermal architectures.

Only by collaborating together can a true power efficient network be built and economically operated. To keep the Internet growing, usable and economically viable, this is of utmost importance.

6. Abbreviations

ASIC	application specific integrated circuit
CDN	content delivery network
DHCP	Dynamic Host Configuration Protocol
DWDM	dense wavelength division multiplexing
FA	fabric ASIC
FIB	forwarding information base
GPM	general purpose microprocessor

IS-IS	intermediate system to intermediate system
MPLS	multi-protocol label switching
OSPF	open shortest path first
PFE	packet forwarding engine
PPS	packet per second
SLAAC	stateless automatic address configuration
TOR	top of rack

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SCTE ISBE

Giving HFC a Green Thumb

A Case Study on Access Network and Headend Energy & Space Considerations for Today & Future Architectures

A Technical Paper prepared for SCTE/ISBE by

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1. Introduction

With the SCTE Energy 2020 initiative in full swing, the cable industry is seeing vigorous interest in getting a handle on its energy consumption. This paper provides a case study on the combined energy consumption for both the headend facility equipment and the access network plant to understand the total impact of various network access architecture options.

After reviewing the network capacity planning for the next decade, the paper takes a look at a baseline case study of five different actual physical nodes and analyzes several possible HFC upgrade options and their relative power consumption. The upgrade options considered include fiber deep architectures such as Node+0 which includes fiber to the last active (FTTLA).

This is then followed by a space and power analysis of some existing headends with older CMTS and Edge QAMs. The headend facility savings are shown from introducing a CCAP chassis and from including the benefits of integrating all of the narrowcast EQAM into the I-CCAP box.

In addition to this "business as usual" progression, there are several new architectures being considered for the near future. These potential new architectures include:

1. Remote PHY and Remote MACPHY
2. EPON FTTH (centralized OLT with and without PON Extenders; Remote OLT)
3. Distributed Node Architecture solutions

The distributed access technologies can significantly reduce headend energy consumption but push complexity into the plant and have a negative energy impact there. FTTH solutions can offer a completely passive outside plant but could require an increase in energy consumption in the headend and at the consumer premise. It is important to consider both headend and plant energy together to get the total picture on energy consumption.

Our paper takes a look at the space and power impacts of these various architectures and provides the operator with some guidance with regards to total energy consumption in selecting between these options. A companion paper [ULM_2016] takes a look at the economic considerations for several of these architectures.

2. Network Capacity – Planning for the Next Decade

The Internet has been growing at a breakneck speed since its inception. And with it, we have seen a corresponding growth in dedicated network capacity. While Moore's Law is infamous in silicon realms, Nielsen's Law of Internet Bandwidth has become renown in the networking world. It basically states that network connection speeds for high-end home users would increase 50% per year. This law has driven much of the traffic engineering and network capacity planning in the service provider world. It has also led to much research on those topics.

2.1. Nielsen's Law and Cloonan's Curves

In [CLOONAN_2014, EMM_2014], this research was expanded to also include traffic utilization in addition to the network connection speed. In his chart below, known as Cloonan's Curves, Nielsen's Law is represented by the blue line in the middle. Since it is a log scale, the 50% compounded annual growth rate (CAGR) appears as a straight line. An interesting fact is that the graph starts in 1982 with a 300-baud phone modem. We are now in the fourth decade of closely following this trend.

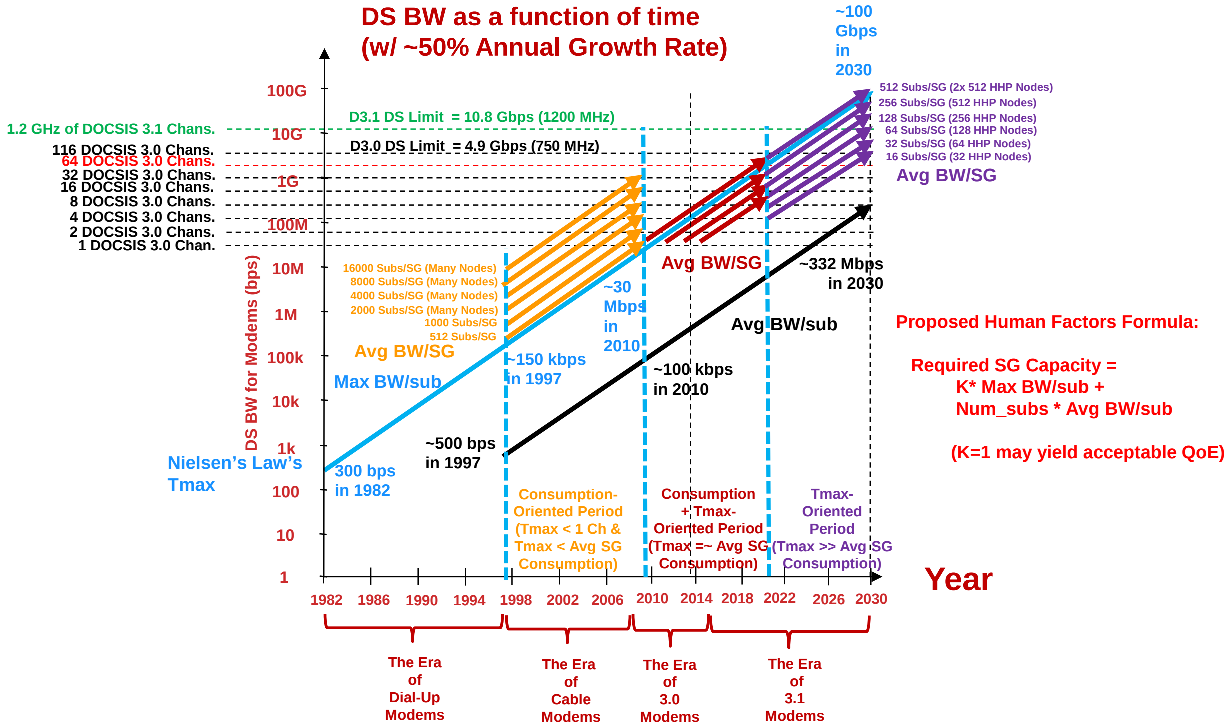

Figure 1 - Cloonan's Curves

Cloonan noted that the primetime average subscriber consumption (a.k.a. Tavg) has also been following this same basic trend as shown in the Figure 1. For service providers, an important metric is the traffic utilization in a Service Group (SG). The SG traffic utilization is a function of the number of subscribers (Nsub) times the average bandwidth per sub (Tavg) and is shown in a series of lines above Nielsen's line.

In the early DOCSIS®[1] days, many nodes were combined together and a SG might consist of thousands of subscribers. At this time, the SG traffic was an order of magnitude higher than the maximum network connection speed (a.k.a. Tmax after the DOCSIS parameter that dictates max network rates). Over time, the SG size has been shrinking and with it the ratio between Nsub*Tavg to Tmax. As shown in the chart above, the SG traffic eventually approaches that of Tmax. As SG sizes dip below 100 subs, then Tmax starts to dominate the traffic engineering.

We have been monitoring subscriber usage for many years now. The chart below shows Tavg, the average subscriber downstream consumption during peak busy hours, for a number of MSOs over the last six years. At the start of 2016, Tavg was approximately 850 Kbps. Over this six-year period, Tavg has grown at ~45% CAGR. We are expecting that Tavg will break the 1 Mbps barrier sometime in 2016. The chart also maps out Tavg growth through the year 2020 assuming a 45% CAGR.

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[1] DOCSIS is a trademark of CableLabs

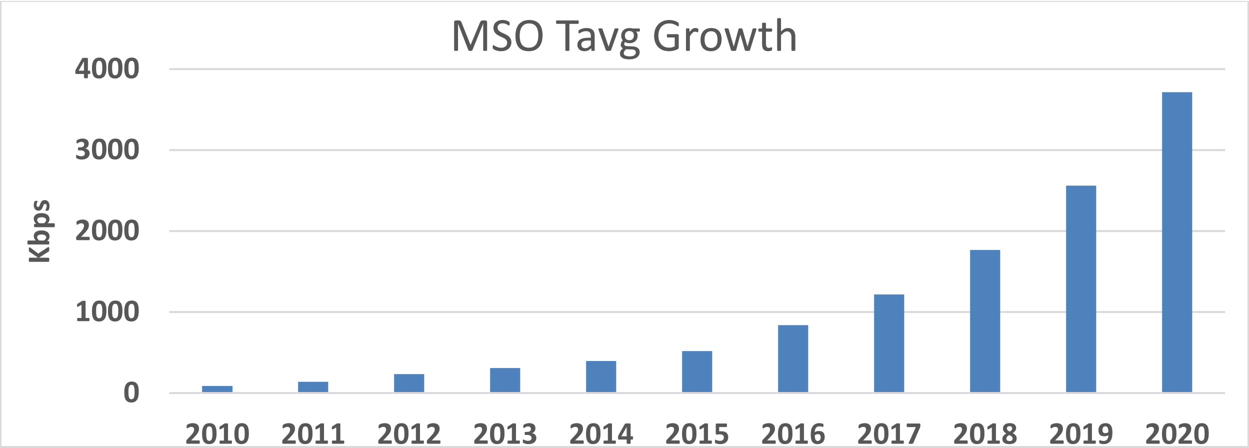

Figure 2 - Tavg, Average Subscriber Consumption

Interestingly, the upstream traffic is growing at a significantly slower rate. During the same six year interval, the upstream Tavg only grew at ~20% CAGR. The industry is seeing more asymmetric traffic with video being the driving application for downstream consumption [see EMM_2014]. At this point, there is about a ten to one ratio in traffic and still expanding.

2.2. Selective Subscriber Migration Strategy

As operators approach capacity planning, they are trying to understand how long the HFC architecture might last before they must migrate to a Fiber to the Premise (FTTP) network. To get an insight into this, the chart below zooms in on the Cloonan's Curve & Nielsen's Law over the next two decades. It predicts that top network speeds will reach 10 Gbps by ~2024 and pass 100 Gbps in the early 2030's. The initial DOCSIS 3.1 (D3.1) goal was 10 Gbps, so that implies that the HFC may hit its ceiling by approximately 2024!

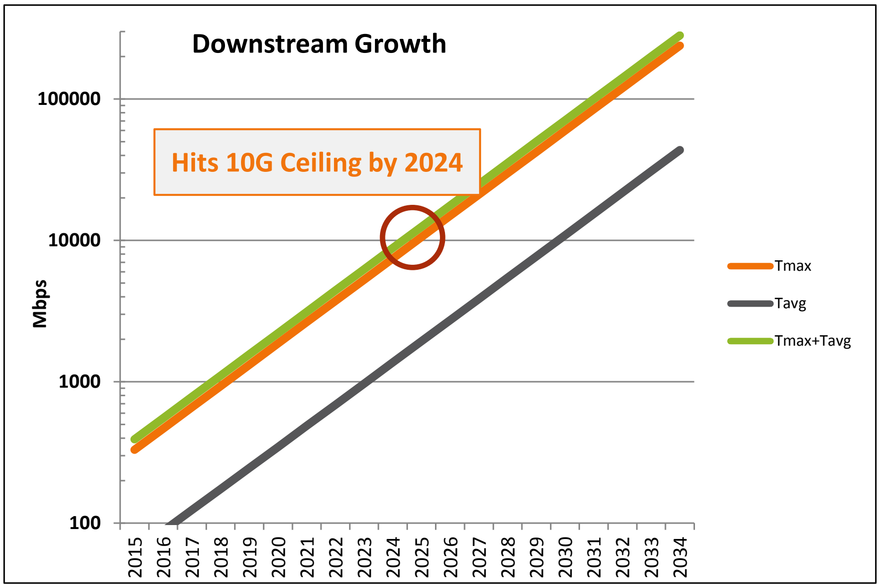

Figure 3 - Downstream Growth over Next Two Decades

At first glance, this is a scary proposition in that HFC networks might be obsolete in 5-7 years while it may take decades to build out an FTTP infrastructure. However, this is not the full story. As was shown in [ULM_2014], Nielsen's Law applies to the top speed tier which is only a very small percentage of the entire subscriber base, perhaps less than 1%. So the key question then becomes, "What happens to the vast majority of subscribers on HFC who are not in the top speed tiers (a.k.a. billboard tiers) and when?"

The [ULM_2014] case study took a look at service tier evolution at a few MSOs. Table 1 lays out results from that study. Perhaps the key finding from this study is that the different service tiers are growing at different rates. While the top billboard tier continues to follow Nielsen's Law 50%, each subsequent lower speed tier is growing at a slower rate. Hence, the lower the service tier rate, the lower its CAGR.

Table 1 - MSO Case Study on Multiple Service Tier Levels

2014 Service Tier Levels on HFC	% of Subs	Tmax (Mbps)	Tmax CAGR
Top Tier – Billboard Rate	1%	300	50%
Performance Tier	14%	75	32%
Basic Tier	65%	25	26%
Economy Tier	20%	5	15%

Figure 4 maps out the various service tier growth over the next two decades. While the 1% of subs in the top billboard tier hit 10 Gbps in ~2024, the 14% of subs in the performance tier don't hit that mark until ~2032. Notice that 85% of subscribers in the flagship basic tier and economy tier stay below this mark for several decades.

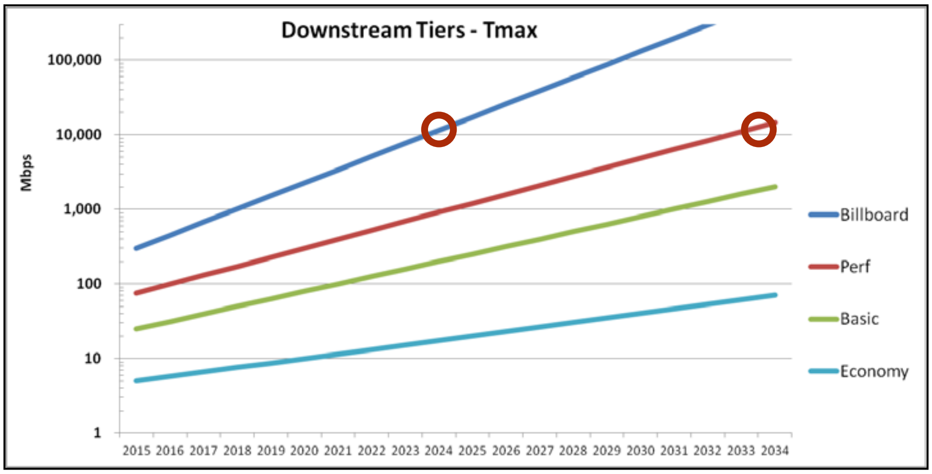

Figure 4 - Downstream Growth with Multiple Service Tiers

Data was input into the ARRIS Network Capacity model to take a closer look at the network traffic growth. Table 2 shows the Tmax migration used for each tier level over the next decade. Note that by 2021, the top billboard tier starts to exceed the capacity of the initial D3.1 modems that are being used today. And by 2026, this tier is forecast to hit 40 Gbps. This will require new technology, which might be a newer generation of DOCSIS (e.g. Extended Spectrum) or possibly a next generation of PON technology (e.g. 100G EPON).

Table 2 - Service Tier Migration for Network Capacity Model

MSO Case Study DS Service Tiers	% of Subs	Tmax CAGR	2014	2016	2021	2026
Top Billboard Tier	<1%	50%	300	675	5G	40G
Performance Tier	14%	32%	75	125	500	2G
Basic Tier	65%	26%	25	40	150	400
Economy Tier	20%	15%	5	10	20	50

It is important to note that 99% of the subscribers are still comfortably using today's DOCSIS technology on HFC a decade from now.

Some results from the ARRIS Network Capacity model are shown in Figure 5. It provides an insight into both Tmax and SG Tavg behavior. During the next 5-7 years, the Tmax component dominates traffic engineering as it is driven by Nielsen's Law. The bandwidth needed by the top billboard tier dominates compared to the SG Tavg.

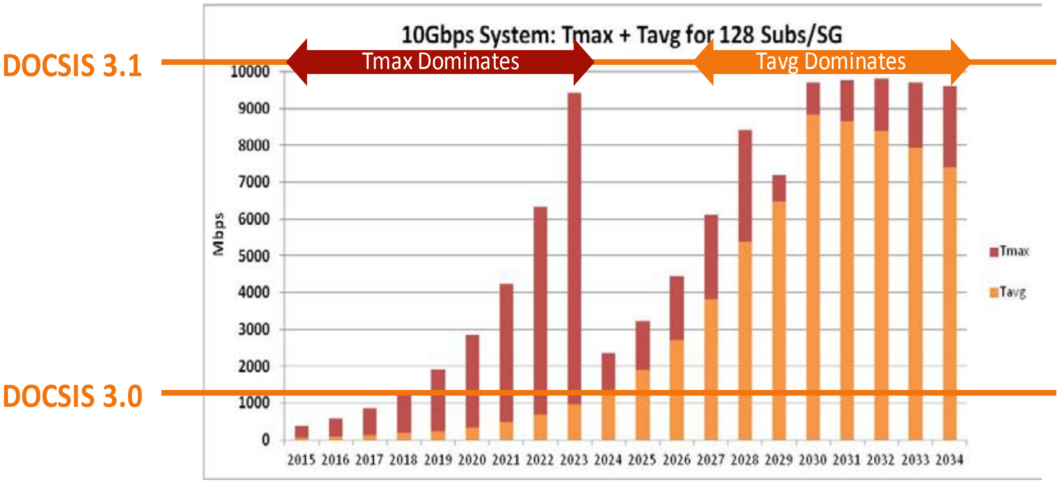

Figure 5 - Network Capacity Model Results

This leads us to a Selective Subscriber Migration strategy that will need to start in the next 5-8 years. By moving the top billboard tier to a Fiber Deep access network that is separate from the general HFC plant, there is a significant reduction in the required DOCSIS capacity. This reduction can be seen in year 2024, in Figure 5, after the top billboard tier is removed from the HFC network. The performance tier is then moved in 2029, in this example, for a smaller drop.

Note that the Fiber Deep access network might be any one of several FTTx options including: FTTP, Fiber to the Curb (FTTC), Fiber to the Tap (FTTT), Fiber to the Last Active (FTTLA), or Node+0 HFC. These options are discussed in detail in the next section.

Eventually, with the top tiers migrated to FTTx, the SG Tavg finally catches up and operators will need to consider reducing SG sizes again. The model in this example predicts that this will be roughly 10-15 years from now.

Another observation from this analysis is that D3.1 is a key technology to extend HFC life for decades to come, especially for the vast majority (e.g. 65-95%) that are in the flagship basic and economy tiers. Any brownfield FTTx transition may take decades, so D3.1 successfully gets operators through that window.

In summary, Selective Subscriber Migration strategy is a sensible approach to the topic of an HFC to FTTx transition. Moving top tiers to FTTx can buy HFC extra decades for 80-95% of subscribers in the flagship basic/economy tiers. Tmax dominates for the next 5-7 years, so it is more important to increase the HFC capacity to at least 1 GHz spectrum rather than split nodes. However, Tavg finally catches up 8-10+ years from now; and SG size reductions come back into vogue. Operators should push Fiber Deep enough to enable Selective FTTx for top tiers on demand and be prepared for the next round of SG splits.

And which FTTx is the best option is another interesting debate. DOCSIS continues to evolve with work on Full Duplex (FDX) and Extended Spectrum DOCSIS. Some of this research was highlighted in [CLOONAN_2016]. These new technologies promise to do for DOCSIS & cable what G.fast is attempting to do for DSL and twisted pair. Figure 6 shows some results from that paper for both FTTC and FTTLA systems. As can be seen, the system capacity can increase significantly as fiber is pushed closer to the premise.

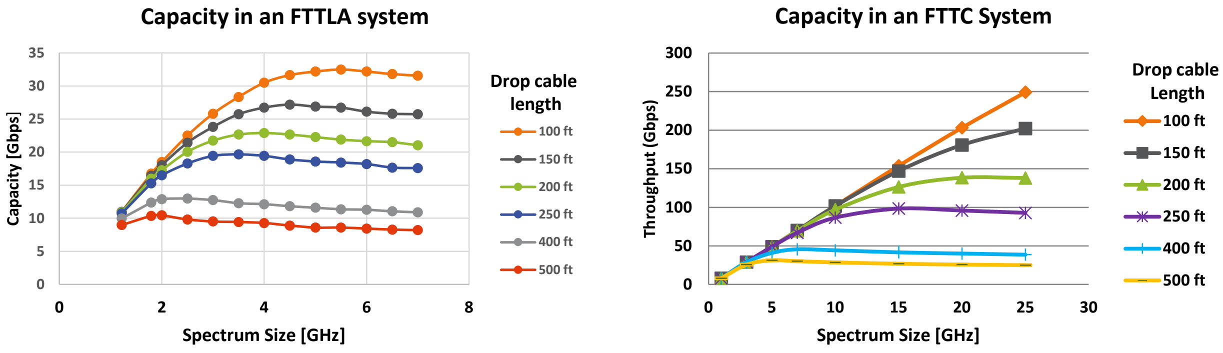

Figure 6 - Network Capacity Model Results

3. Access Network Case Study

The network capacity planning shows that operators will need to evolve their existing Hybrid Fiber Coax (HFC) networks to remain competitive with FTTP service providers such as Google Fiber and Verizon FiOS [VENK_2016, VENK_2015 and ULM_2015]. For cable operators, they can utilize their existing fiber investments as a starting point to get a jump start compared to new entrants that must start their fiber installation from scratch. But the critical question for cable operators is how deep should they pull the fiber? They are presented with a toolbox of architectural choices to consider:

- "Business as usual" (BAU) – a node split where needed, and a refresh of the HFC field actives, with perhaps an upgrade to 5-85 MHz in the return and 104-1002 MHz in the forward
- Fiber deep (FD) Node+0 (N+0) pushes fiber much deeper into the HFC and eliminates all of the active RF elements. There is an array of potential options including:
    - Traditional Fiber Deep Node+0 "FD N+0" which redesigns existing HFC (e.g. N+3 to N+6 with 3-6 actives after the fiber node) into "node as the last active". The typical way to do this is to rewire the coax plant in a way to minimize how many of these standard-size new nodes need to be added. Each new node may ultimately become its own service group, and in addition to the RF and optical modules, it may house Remote PHY Devices (RPDs) and PON OLTs
    - Fiber to the last active (FTTLA) is a variant of the Fiber Deep N+0 architecture. However, in this case the nodes are located precisely at legacy RF amp locations. These nodes then get aggregated into a properly-sized service group. This aggregation can be done by using an "active splitter / combiner", housed in a virtual hub, which is located precisely at the legacy node location to save on optics costs & space in the facility
    - Fiber to the curb (FTTC) or Fiber to the tap (FTTT) where fiber is run down the street but the existing cable drop cables are reused
- Fiber to the Premise (FTTP) – this is what is being deployed today with traditional PON systems as well as RFoG systems

Collectively, these fiber deeper options are referred to as FTTx or Fiber to the "x", where "x" might be Premise, Curb, Tap, Last Active, or Fiber Deep node. For cable operators to build out any of the above architectures in today's brownfields, the new fiber construction begins from an existing fiber node; unlike the new entrants who must build the fiber construction from the central office / headend.

Each MSO will make changes to their own HFC plant to optimize for the attributes that they deem to be the most important. Different MSOs will likely prioritize the many attributes in different ways. For example, some MSOs may choose to optimize their network evolution by moving as rapidly as possible to end-state technologies of the future. These MSOs will likely move rapidly towards (passive optical network) PON or Point-to-Point Ethernet solutions. Other MSOs will choose to optimize their network evolution to reduce headend power and rack-space requirements by moving towards Fiber Deep architectures with Distributed Access Architecture sub-systems that remove functionality from the headend. These MSOs will likely deploy (Remote PHY) RPHY or (Remote MACPHY) RMACPHY sub-systems within their nodes. Other MSOs will want to preserve much of their current architectures while capitalizing on improved technologies.

In order to calibrate our conceptual thinking against reality, a set of five real-life HFC nodes was identified for evaluation, representing a diversity of implementations. These are representative of low, medium, and high densities, as measured by how many homes are passed per mile in each area. The five node areas, labeled A, B, C, D, & E possess other attributes of interest: miles of hardline coax plant, percentage of aerial plant, number of RF actives, number of homes passed per node, and HP/mile, as shown in Table 3.

Figure 7 shows the topology of one of the nodes: Node C. The headend (upper left) is fiber-linked to the node (center-left in pink), which RF-feeds into RF amps (blue triangles) RF splitters (blue circles), and taps (orange diamonds). Two 15A field power supplies provide enough power for the whole node area. Node C contains 3.5 miles of coax plant (excluding drop cables) with 21 actives and 398 Homes Passed (HP). So this might represent ~200 subscribers @ 50% penetration.

Node C will be used as a baseline example to show how the other architectures might be implemented.

Table 3 - Properties of 5 Node Areas Under Study

Node	A	B	C	D	E	Overall	Average
Plant Coax Mileage	4.2	6.2	3.5	2.5	1.9	18.3	3.7
% Aerial	20%	77%	97%	87%	91%	70%	70%
Total Active	21	30	21	19	14	105	21
Actives/Mile	5.0	4.9	5.9	7.6	7.4	5.7	5.7
Cascade Depth	N+3	N+3	N+3	N+3	N+2		N+3
Total Homes Passed	153	352	398	469	520	1892	378
HP/Mile	37	57	112	187	274	104	104

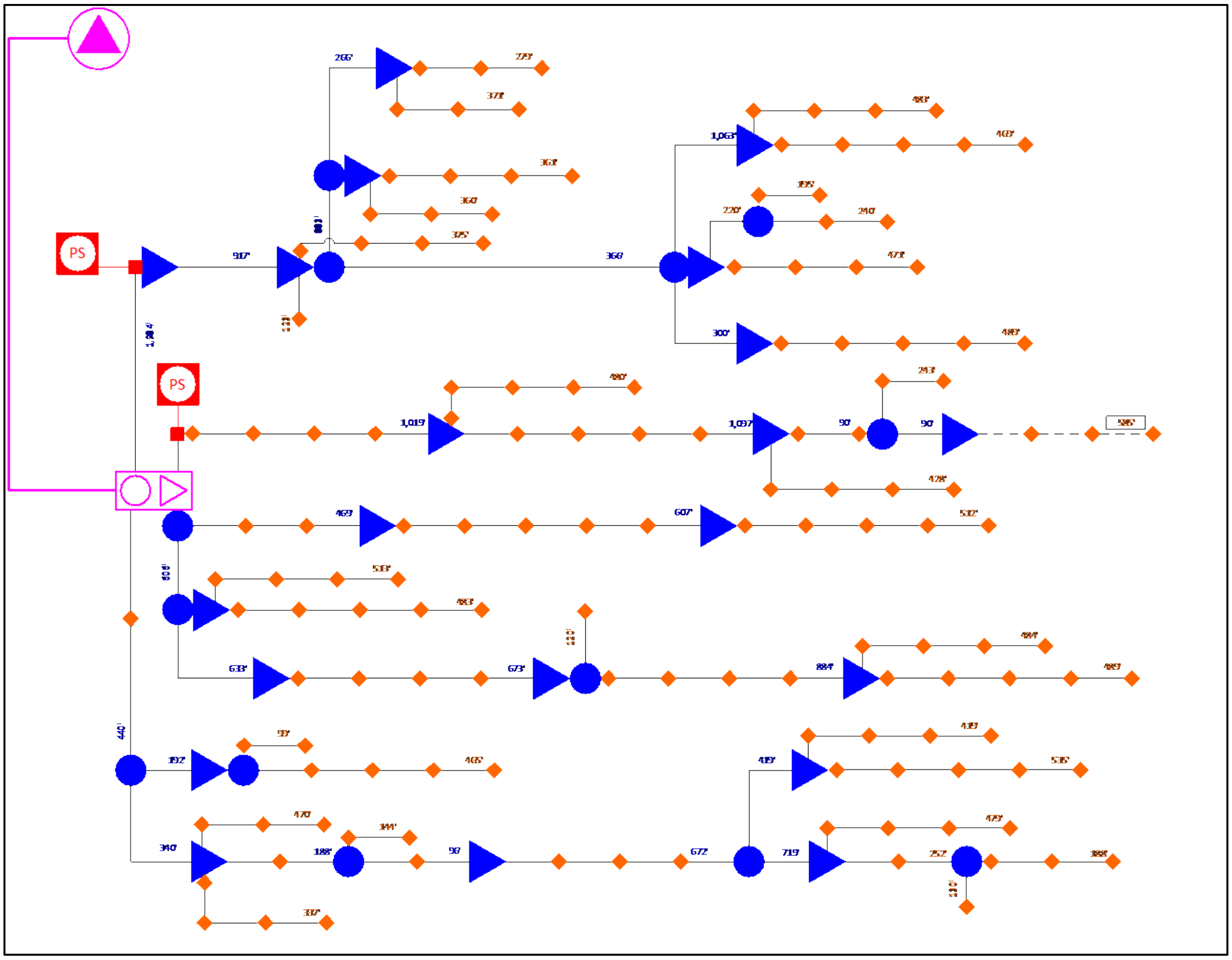

Figure 7 - Topology of the Node C Area

“Business as usual”, as the name implies, applies no topology changes. The idea is to refresh all the actives, typically by replacing the existing RF modules with 5-85 / 103-1003 “e-packs”. Taps are assumed to function to at least 1 GHz. Node segmentation can be done “in place” by converting this 1x1 node up to 4x4 node, with optical transport multiplexed over the same fiber. While the segmentation can drop the average size down to 100 HP (~50 subs), the distribution is often unbalanced between the RF legs.

Fiber deep (FD) N+0 will eliminate all the RF amps and reconfigure the network in a way to deploy the minimum number of new nodes, possibly in a new location. Figure 8 shows one such implementation for Node C, where the total number of new actives is reduced, from the original 1 node and 21 RF amps down to just 6 nodes. Note that the new nodes might need augmented output power, e.g. 64 dBmV, to drive the additional coax to reduce the node count. This is one of many trade-offs to be made in a fiber deep design.

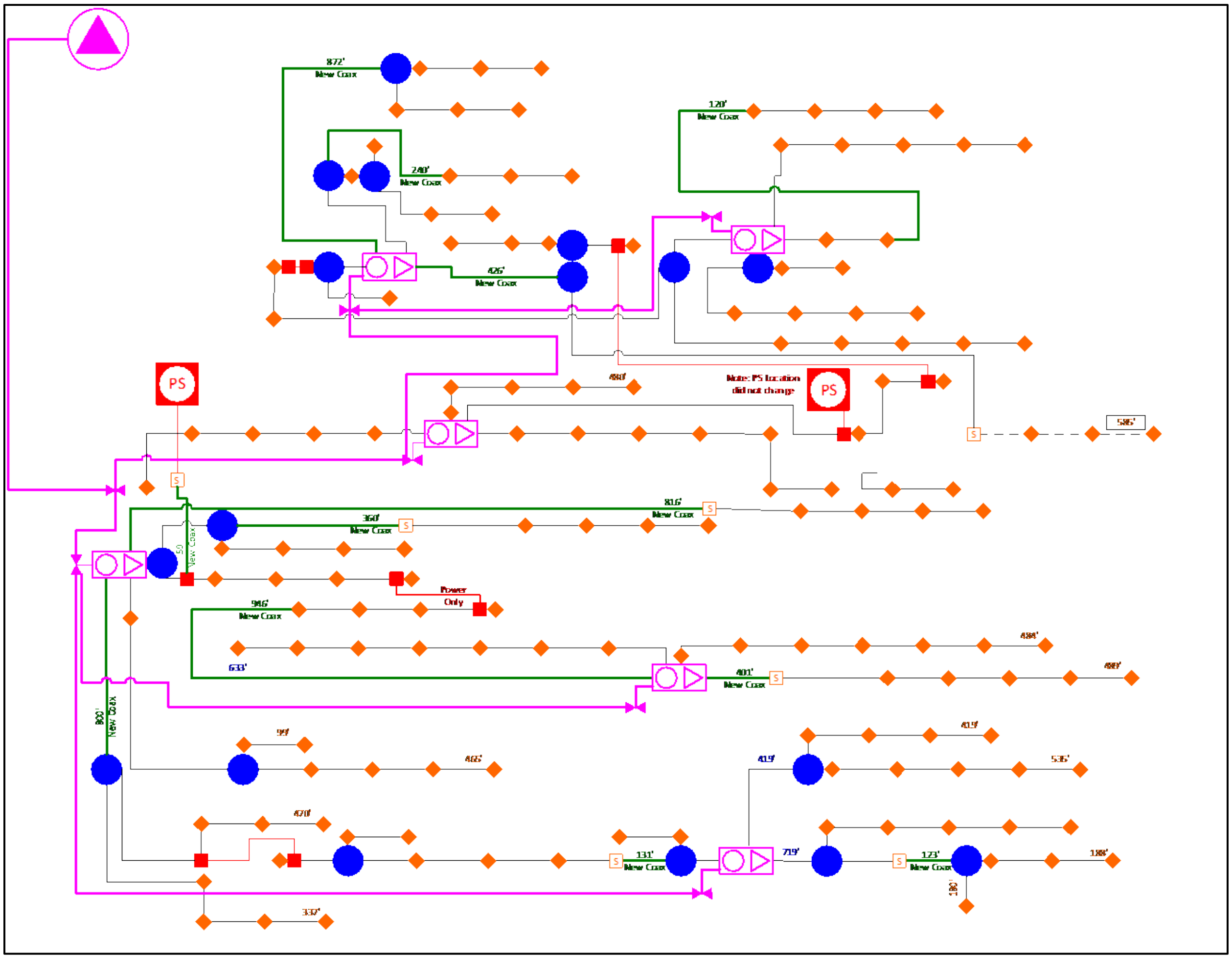

Figure 8 - Node C Area Reconfigured as Fiber Deep N+0

In addition to the new fiber required to feed those nodes, there is a need to add some coax plant, too. The new coax segments are shown in green. A significant redesign of the tap values and orientations is required, too. However, if an operator already plans to upgrade the taps to 1.2 GHz performance, then the argument is the tap rework may not be so onerous of an extra step. The additional new fiber to connect the new nodes is the reason this approach is called "Fiber Deep". For FD N+0 in Node C, this step takes fiber to as close as 195 feet to the last tap, while the furthest tap is at 1,448 feet. On average, taps are 1,007 feet away from the fiber plant. The new nodes are also capable of housing Remote PHY Devices (RPDs) and PON OLTs if and when needed.

Fiber to the last active (FTTLA) is also an N+0 implementation. However, the number of actives is not minimized. Rather, the locations (and even the housings, if warranted) of the existing RF actives are preserved – and reserved for the last-active nodes. Figure 9 shows topology of such a network, if implemented for Node C. This results in 21 nodes for this design replacing the original actives.

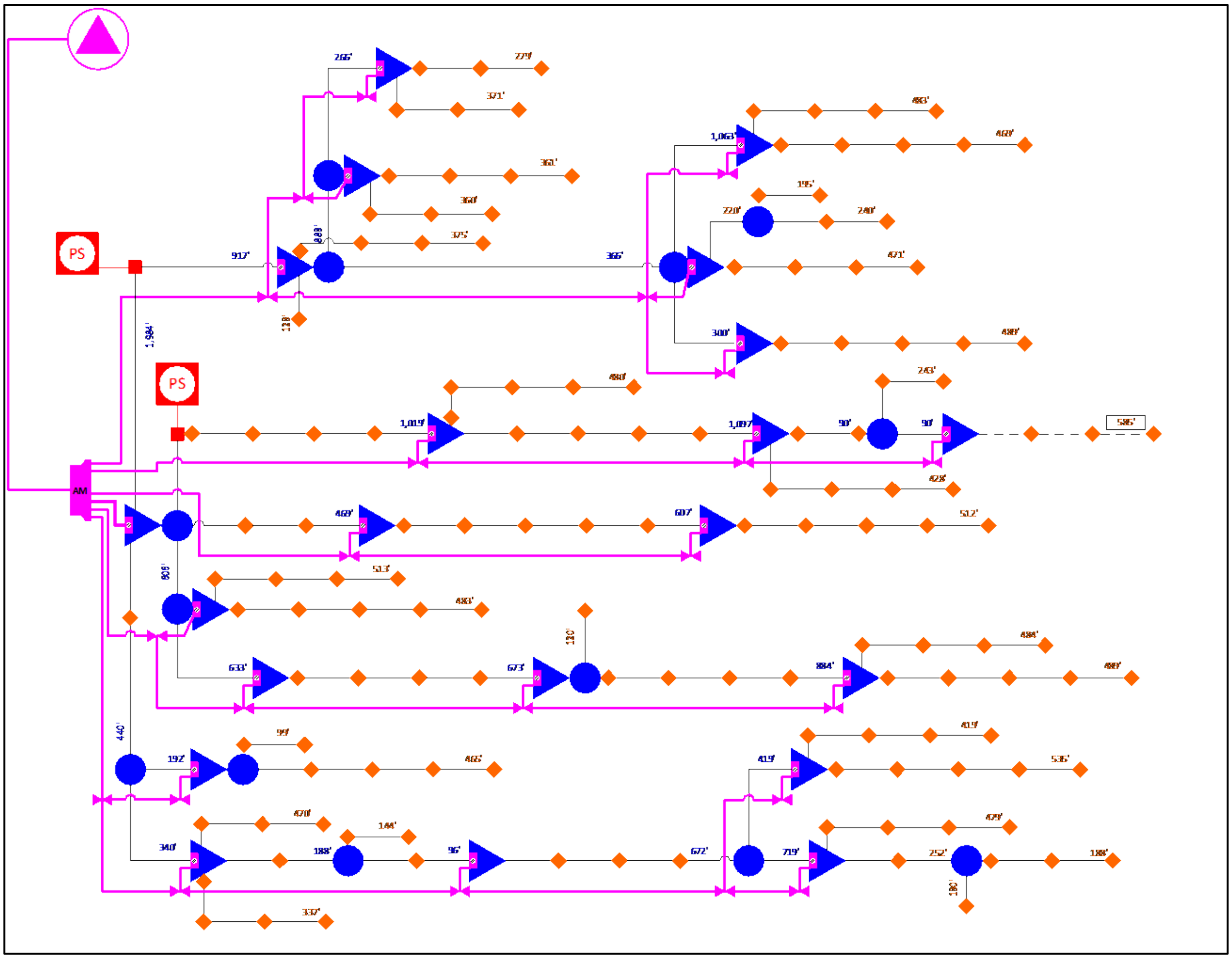

Figure 9 - Node C Area Implemented as an FTTLA in DNA Style

This approach is an even deeper Fiber Deep architecture. In case of FTTLA in node C area, fiber gets as close as 99 feet to the last tap, while the furthest tap is at 585 feet. On average, taps are 408 feet away from the fiber plant. Table 4 shows how much of the new fiber is required for the five areas under study.

For FTTLA, there is no need to touch the coax plant – hardline, taps, even levels for the existing services – so the whole plant upgrade investment is applied to getting fiber deeper, rather than spending part of it on reconfiguring the coax plant. This simplification and getting the fiber even deeper, however, are a trade-off against the number of actives required in the plant. Replacing the taps for 1.2 GHz is an option if an operator wants the additional capacity.

Table 4 - New Fiber Construction Required for FTTLA Implementation for the 5 Nodes

Node	A	B	C	D	E	Overall	Average
New Fiber Mileage	2.1	4.0	2.4	1.4	1.2	11.0	2.2
Aerial	0.6	2.8	2.4	1.4	1.1	8.2	1.6
Underground	1.5	1.2	0	0	0.1	2.8	0.6
New Fiber as % of hardline plant	51%	64%	67%	54%	62%	60%	

FTTLA may be favored by those that don’t want to touch the taps and passives and put more of their investment dollars into pushing fiber much closer to the premise. FD N+0 is more feasible when the taps are being replaced anyways and the operator wishes to minimize the number of active elements in the plant. FD N+0 also has much fewer nodes which reduces overall maintenance costs as well as cable power losses. In reality, there is a spectrum of fiber deep choices between these two extremes that an operator can optimize for any given location.

FTTLA in particular aids the Selective Subscriber Migration strategy in a few ways. In this strategy described earlier, a small number of high performance subscribers are moved onto a separate FTTx network. In the near term, an operator might pull fiber to the last active only for the location associated with the high performance subscriber. In the Node C example with ~200 subscribers, perhaps two subscribers get the top billboard tier. The operator only needs to upgrade two actives to effectively put them on their own separate upgraded SG, leaving the other 19 actives alone. And while pulling fiber to these two actives, it may enable FTTLA for several other actives along the way. Longer term, the operator may want to start migrating the top tiers to FTTC or FTTP. Using the FTTLA as a launching pad gets them much closer to the homes (e.g. 408’ to tap on average for Node C). Selective Subscriber Migration strategy can be implemented with FD N+0 as well. It just requires more work to upgrade the HFC around that node and the fiber is not quite as deep as FTTLA.

DOCSIS full duplex (FDX) may require a fiber deep system with no actives beyond the node. So from an FDX perspective, both FTTLA and FD N+0 will meet these requirements.

The fiber to the curb (FTTC) architecture effectively replaces all of the plant’s hardline coax with a fiber overlay. So the new fiber mileage required would essentially be equal to the plant coax mileage from the first row of Table 3. The fiber to the premise (FTTP) architecture would require all of the FTTC fiber plus the drop cable for each subscriber. No picture is needed as these simply overlay the existing HFC coax with fiber.

4. Access Network Energy Considerations

4.1. HFC Upgrade Options

As a first order of business, the HFC upgrade options for the access network case study in the previous section are considered. Each of the cases was selected to provide a range of scenarios with varying number of homes passed (HP) per mile. This can dramatically impact the HFC design and its potential consumption. Figure 10 shows the power consumption for the various HFC upgrade options discussed in the previous section.

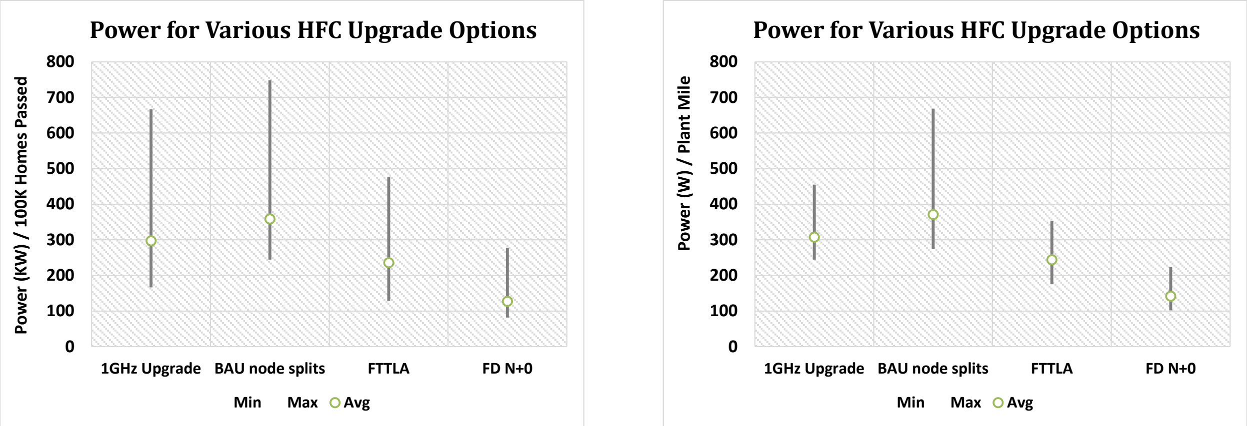

Figure 10 - Power Consumption for Various HFC Upgrade Options

The left hand side of Figure 10 looks at power consumption relative to homes passed (HP), while the right hand side evaluates power per mile of plant. As shown, the five use cases can create a wide variation. The W/HP might vary by a factor of 3X to 4X from use case to use case. The variation in W/mile is less, but is still between 2X to 3X but is the same general overall trend. Note that in all cases the average power consumption is typically much closer to the min value. Note that this analysis does not factor in power losses over the coax distribution. Preliminary estimates indicate that this should be on the order of 5% or less of the total plant power consumption.

The baseline case is a 1 GHz upgrade without changing the number of nodes. Making this a 1.2 GHz upgrade does not substantially change the power analysis. In the business-as-usual (BAU) node split scenario, the number of nodes increased roughly 3-fold on average. The additional new nodes resulted in slightly higher power consumption than the 1 GHz upgrade baseline, on the order of 20% for the average.

The fiber deep approaches, fiber to the last active (FTTLA) and fiber deep node+0 (FD N+0), both eliminate any active components following the fiber node. As such, both of these will accommodate DOCSIS full duplex (FDX) in the future. FTTLA is typically deploying nodes with just one or two outputs while FD N+0 is a more extensive HFC re-design deploying fewer nodes with 3 to 4 high drive outputs. The FTTLA approach provides roughly a 20% power savings on the average compared to the 1 GHz baseline HFC. The FD N+0 with “normal” output power provides more than 50% power savings from the 1 GHz HFC plant. Some operators might consider FD N+0 with high output amplifiers (e.g. 64 dBmV) which consume significant power. The power savings drops to around 35%. This case is not shown in the charts.

While the power consumption per HP and per mile are interesting data points, the power consumption per unit capacity (e.g. KW/Tbps) is also considered. An architecture's total system capacity is a function of the network link capacity and the number of service groups. With DOCSIS 3.1, the network link capacity might vary from architecture to architecture; especially as the length of the cascade is reduced eventually to zero. For this analysis, FTTLA & FD N+0 might have a 5% to 10% advantage over the N+3 1 GHz upgrade (e.g. 4096-QAM instead of 2048-QAM modulation). This is a relatively minor impact.

The most significant impact on total system capacity is the number of unique SGs that the architecture can support. This is shown in Figure 11. It is assumed that the node in the baseline architecture has already been segmented, so there is only one SG for each node. For the BAU node splits scenario, the HP/node is reduced by a factor of three. It is assumed that these could also be 2x2 segmented, so the number of SG increases by a factor of six, compared to the baseline.

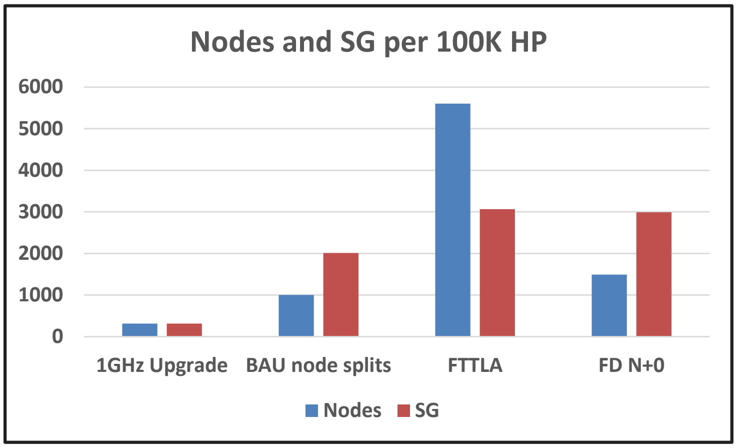

Figure 11 - Nodes and SG per 100K HP

The FTTLA scenario generates extremely small nodes with very few HP/node. Typically, many nodes may be aggregated to form a single SG. For this analysis, it is assumed that the minimum sized useful SG is 32 HP. So while FTTLA may have 18 times as many nodes as the baseline, it roughly has 10 times the number of SGs as the small nodes will be aggregated together.

FD N+0 strives to minimize the number of nodes compared to FTTLA. In this study, FD N+0 has almost 5 times as many nodes as the baseline. This is far less than FTTLA. It is expected that the FD N+0 architecture will support a large node housing with 4 outputs. It is assumed that this node can eventually be segmented up to 4x4. In reality, not every node will support 4 outputs, but this analysis assumes that there will be an equal mix of 3 and 4 output nodes. The net result is that FD N+0 supports a very similar number of SGs as FTTLA!

Given these inputs on SGs per 100K HP along with a network link capacity of 8.6 Gbps for FTTLA and FD N+0, the power consumption per Tbps can be calculated for the serving area. This is shown in Figure 12. The chart on the left shows all four HFC upgrade options. Notice that the baseline 1 GHz upgrade is significantly higher than the other three options. The chart on the right zooms in on the other three options.

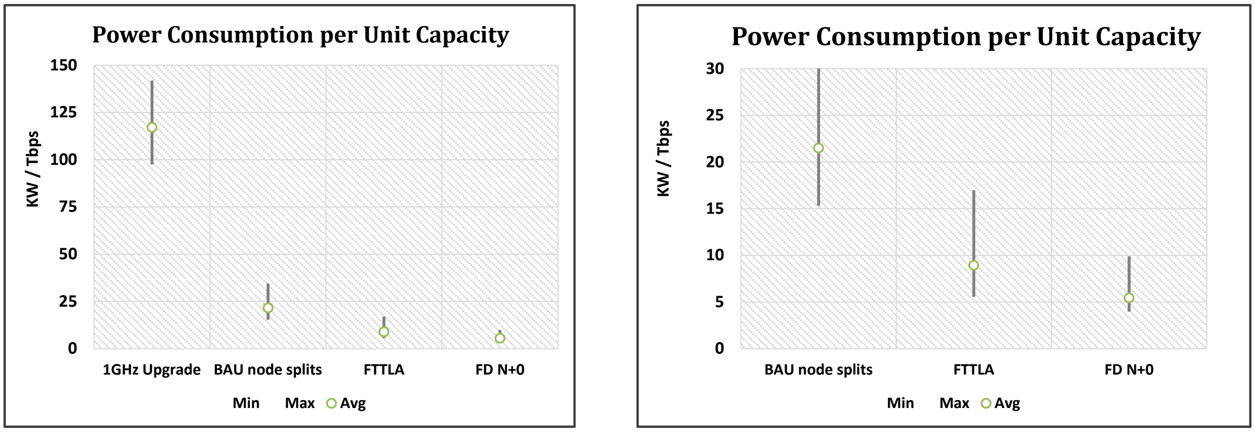

Figure 12 - Power Consumption per Tbps for Various HFC Upgrade Options

The BAU approach achieves about a 5X improvement in this metric. The FTTLA and the FD N+0 are even better. The FTTLA approach achieves about a 13X improvement while the FD N+0 with normal outputs achieves better than 20X improvement.

4.2. Distributed Architectures and PON Options

Distributed architectures are garnering a lot of interest recently. These include DOCSIS options such as remote PHY (R-PHY), remote MACPHY (R-MACPHY), and remote CCAP as well as distributed PON options such as remote OLT (R-OLT). These are relatively new technologies that are still in development. However, enough is known at this point that a preliminary power estimate can be made for some of these solutions.

R-PHY solutions could be applied to any of the HFC upgrade options discussed previously. The focus of this analysis is the relative power impact on fiber deep solutions such as FD N+0 and FTTLA. The R-PHY impact on the other HFC options is relatively insignificant.

For the FD N+0 architecture, it is assumed that every FD node supports a 1x2 R-PHY module. This module is called an R-PHY Device (RPD). In R-PHY solutions, multiple RPDs can then be aggregated in the DOCSIS MAC core in the headend facility to create a single DOCSIS SG. In this case study, there will typically be 5-6 RPDs per SG. Over time, additional MAC core resources can be applied to reduce the number of RPDs per SG. It is also possible that additional RPD capacity can be added to a FD node to virtually segment it into a 2x2 or even 4x4 RPD in the future.

In a conventional FTTLA system, putting an RPD into every node would increase the RPD count by a factor of 3 to 4. This would cause both the power budget and money budget to explode. An alternative approach for FTTLA utilizes the distributed node architecture (DNA). In this architecture, many nodes are aggregated by a splitter element (passive in the downstream and active in the upstream to eliminate optical beat interference – OBI). In a DNA system, the RPD can be located next to the splitter element and shared across many nodes. The RPD must also contain short distance optics that can drive a couple kilometers of fiber. Even with the added power from these optics modules, the sharing of the RPD can reduce the overall R-PHY power impact. Figure 13 shows a logical representation of a DNA system with a shared R-PHY. This distributes the power and the costs of the R-PHY across a larger homes passed population.

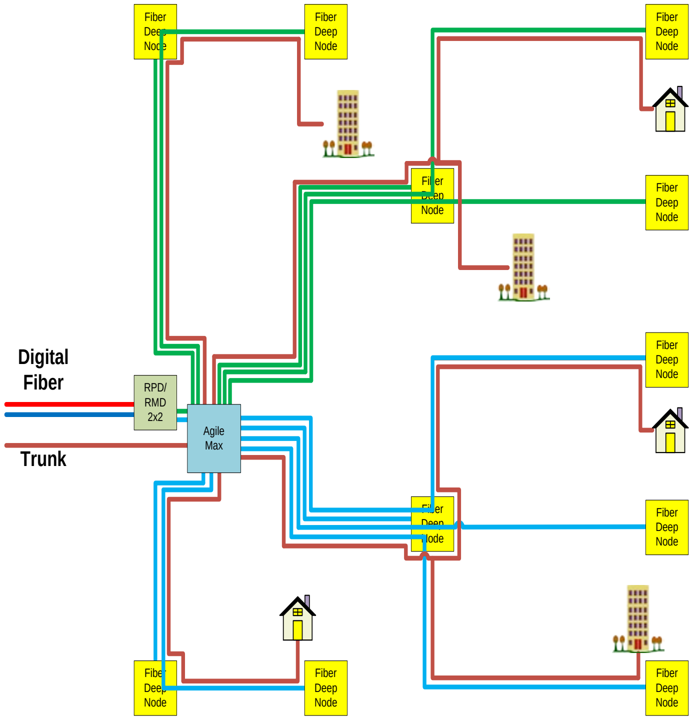

Figure 13 - Distributed Node Architecture (DNA) – FTTLA + Shared R-PHY

Figure 14 shows the power consumption per Tbps for FTTLA and FD N+0 systems, both with and without R-PHY. For FTTLA, adding R-PHY increases power consumption by 7% to 8%, while the FD N+0 plant sees almost 50% increase in power per Tbps. Remember, these are initial estimates and relatively new technologies so there will be improvements over time.

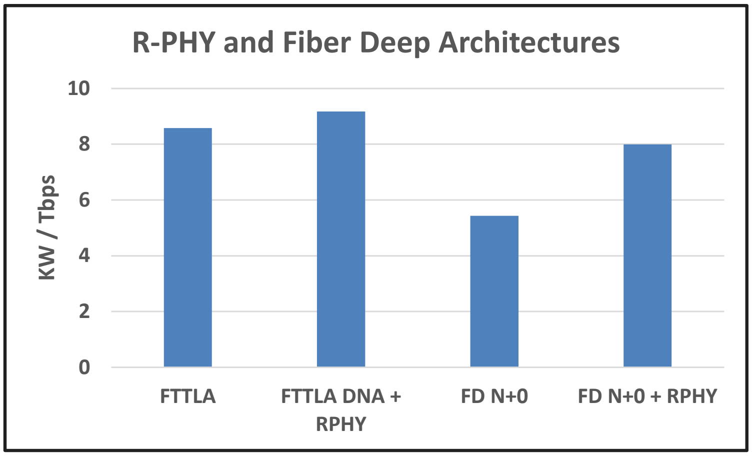

Figure 14 - Power Consumption per Tbps for R-PHY

Adding high power 64 dBmV outputs to the FD N+0 would add additional power as well.

At the time of preparation of this paper, accurate estimates for an R-MACPHY solution were not available. There are many other variables in R-MACPHY system that may affect power consumption depending on which functions are pushed to the node and what stays in the cloud. These options are detailed in the CableLabs technical report [CL_RMACPHY].

Some operators are considering FTTP systems for their future architectures. An FTTP system might be PON or RFoG. The general conception is that a "PON" is completely passive in the plant with no power consumption. This is not necessarily true. Many cable operators must run distances that are greater than 20 km. This long distance trend will increase as operators continue to consolidate hubs and headend facilities. A traditional PON system such as 10G EPON might only support 32 HP at 20 km distances. As distances increase, the fiber optic SNR budget is reduced forcing a reduction in the number of subscribers per OLT port.

There are two basic technologies to get around this problem. One is to move the OLT functionality into the field. This approach is called Remote OLT (R-OLT). The other approach, called PON Extender, is a physical layer repeater where OLT functions stay in the headend facility. This approach supports DWDM connection from the headend facility and converts to the standard PON wavelength in the field. Both solutions have a significantly larger optical budget to the home and can easily support 64 or even 128 HP per port. Also, both of these solutions will require some power in the field.

The power per HP for PON solutions is inversely proportional to the number of homes passed per OLT port. Figure 15 shows the plant power required for R-OLT and PON Extender solutions for several values of HP/port. Since the R-OLT has significantly more functionality, there is a corresponding increase in power. As with the R-PHY solutions, R-OLT technology is in its infancy and its power consumption should improve over time.

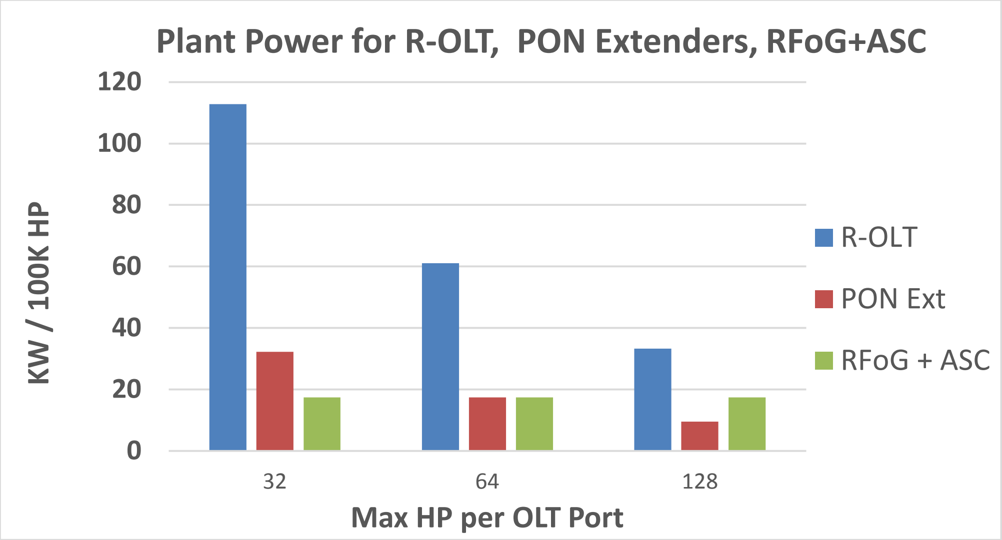

Figure 15 - KW per 100K HP for R-OLT, Pon Extenders, RFoG+ASC

Figure 15 also includes the plant power required for an RFoG system with active splitter combiner (ASC) technology. This has been described in detail in [VENK_2016, VENK_2015 and ULM_2015]. ASC completely eliminates optical beat interference (OBI) which enables RFoG to utilize D3.1 and become a possible end game solution. As Figure 15 shows, its plant power consumption is comparable to the PON Extender with 64 HP per OLT port.

For operators, it is of interest to compare the power requirements of these PON solutions to HFC options. Figure 16 shows power per Tbps for the R-OLT and PON Extender with the HFC fiber deep options shown in Figure 14. Remember that this is only looking at the plant power at this point. The headend facility power will be discussed in the next section. This also does not include the ONU powering required at the premise to terminate the PON system.

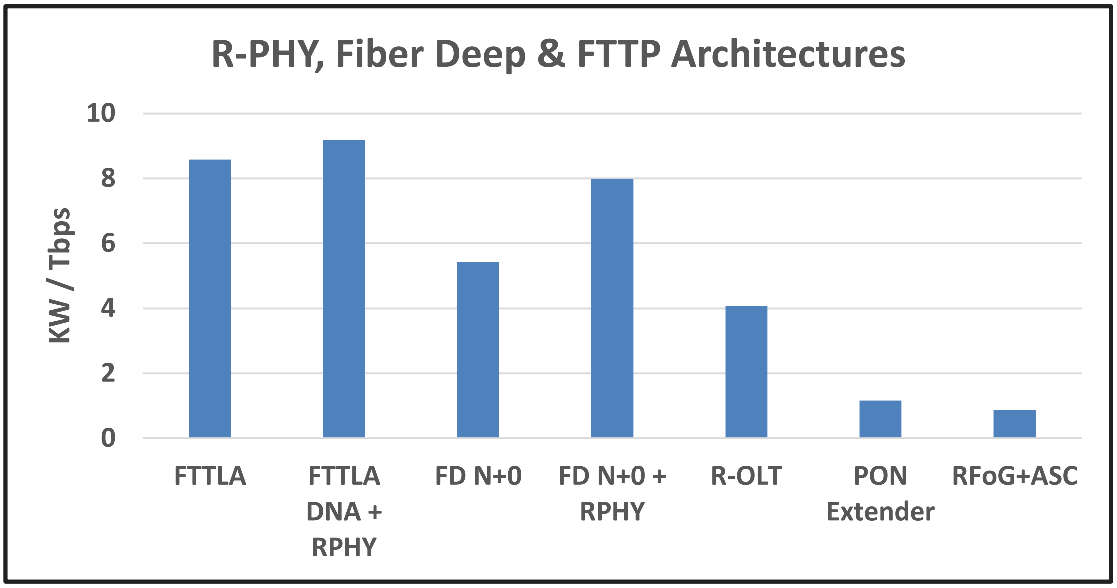

Figure 16 - Power Consumption for R-PHY, Fiber Deep & FTTP Architectures

To put this in perspective, everything shown on Figure 16 is more than 10X better than the baseline 1 GHz HFC plant. The PON extender is the best of these options but will pay a higher power price in the headend facility.

5. Headend Energy & Space Considerations

This study on headend space and energy considerations will only consider the components directly related to the transport of traffic over the access network. This includes the DOCSIS CMTS/CCAP as the major component (or OLT for PON systems), but also considers UEQAM, RF combining/splitting, and TX/RX Optical shelves in our analysis. This analysis does not include any other equipment that might be related to delivery of video services such as Digital Broadcast, VOD, or STB Out of Band (OOB).

5.1. CMTS/CCAP Space & Power – a Historical Perspective

DOCSIS has evolved dramatically over the years and that pace of innovation seems to be accelerating. In recent years, the CMTS transporting DOCSIS high-speed data has given way to a Converged Cable Access Platform (CCAP) that integrates the DOCSIS and digital video EQAM components. For any analysis, it is important to understand the baseline and what is being compared.

A good insight is the space, power, and capacity evolution of the ARRIS product line from the C4 CMTS, to the first generation E6000 CCAP, to newer generation technologies in the E6000. The year 2010 is used as our baseline and three generations of SG density & power are mapped out. This is shown in Figure 17.

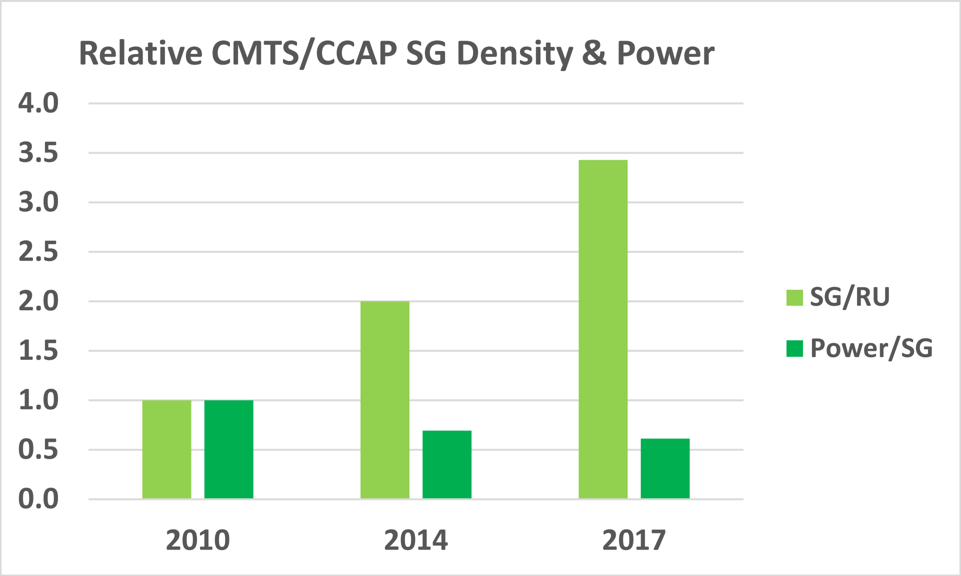

Figure 17 - Relative CMTS/CCAP SG Density & Power

As can be seen, the SG density has increased by almost 3½ times while the power per SG has almost been cut in half. This has helped significantly in allowing operators to keep pace with the broadband traffic growth.

The capacity per SG is another critical element to this picture. With DOCSIS 3.0, the capacity per SG has risen as the CMTS bonded more channels together. Today, D3.1 is available which enhances the capacity per SG even more. Figure 18 shows the resulting increase in capacity per SG along with the increases seen on the CMTS/CCAP Network Side Interfaces (NSI). These data points are all relative to the 2010 starting point. Note that the growth was so significant that this is drawn on a log scale. The capacity per SG will have increased ~60X over an 8 year period.

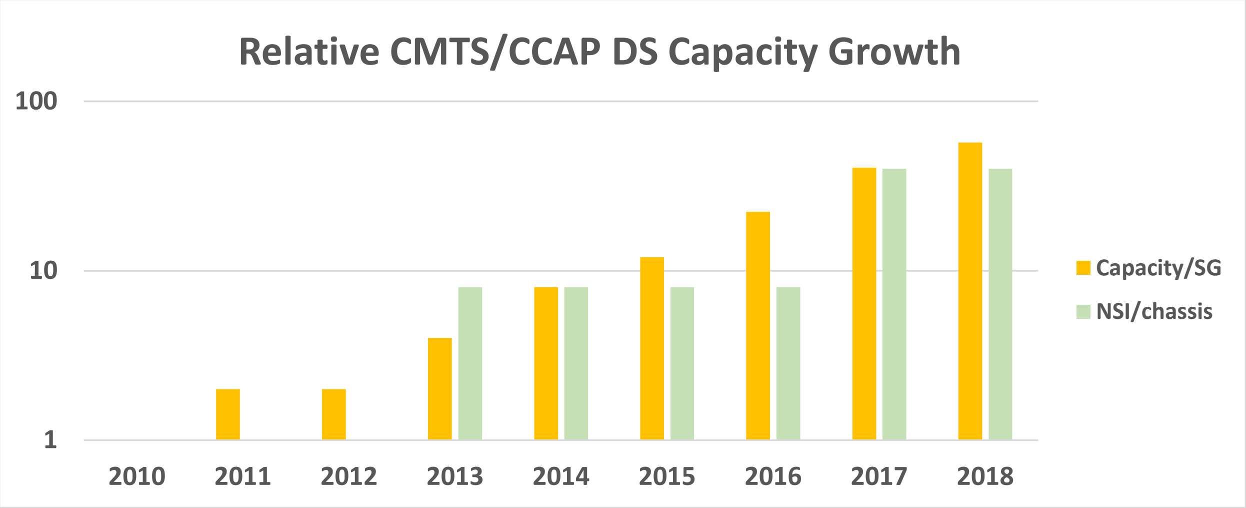

Figure 18 - Relative CMTS/CCAP Downstream Capacity Growth per SG

For our headend space and power analysis, a key metric to measure is the capacity density (e.g. Gbps per RU) as well as the unit capacity/power (e.g. Mbps/W). Figure 19 takes a look at how the CMTS/CCAP products have fared with these metrics since 2010 and compares them to the Tavg traffic growth that was discussed earlier in the paper. Again, note that this is a logarithmic scale.

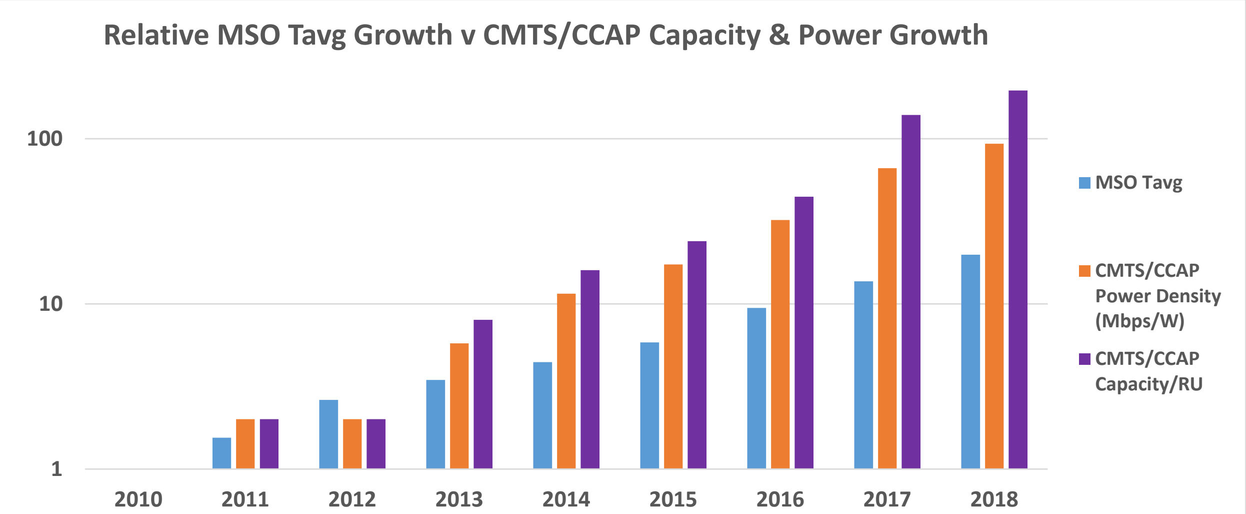

Figure 19 - Relative CMTS/CCAP Capacity & Power Growth vs. Tavg Growth

Over the 8-year window, the 45% Tavg CAGR has resulted in a 20X increase in the broadband data usage. Over that same period, the CMTS/CCAP capacity density has improved by a factor of almost 100X while the capacity/power density (Mbps/W) has increased almost 200-fold. The technological improvements in the CMTS/CCAP have far outstripped the growth in broadband traffic. For operators with older equipment in their headend facility, simply upgrading to the latest CMTS/CCAP products may give them a significant boost in space and energy savings.

5.2. Headend Space Consideration for Future Architectures

The CMTS/CCAP is just one of the access network components in the headend. A case study done by [ULM_2013] showed the possible space savings improvements that were possible with the newer technology. This trend has continued over the last several years as evidenced by Figure 19 above.

This paper extends that original analysis. By 2014, the state of the art technology enabled 112 SG in 4 racks of space for an average of 28 SG per rack. This was a significant increase over older technology that might only obtain 6-10 SG per rack. The 2014 baseline is shown in the first column in Table 5.

Table 5 - Headend I-CCAP Space and Power Case Study

Headend I-CCAP Migration	2014	2015	2015	2016-17	2016-17
SG per Rack	28	32	42	96	128
kW per Rack	4.2 kW	3.0 kW	3.6 kW	-	-

Headend I-CCAP Migration	2014	2015	2015	2016-17	2016-17
W per ‘Chan’ Equiv.	2.66	2.03	1.89	~0.5	~0.5

Recently, the integrated EQAM (IEQ) functionality for integrated CCAP (I-CCAP) has been introduced. This eliminates the external EQAM which results in both a space and power savings. This is shown in the 2nd column. Note the significant reduction in power. An operator can potentially reduce headend access network power by 25% to 30% by upgrading their CCAP with IEQ capabilities and retiring the EQAM equipment. The power savings can actually be higher with retiring older EQAM equipment.

The operator may choose to re-use the IEQ space savings by adding more SG to the racks. This can result in an increased density to 42 SG per rack for a 50% increase in space density. The power per rack increases slightly but the Watts-per-SG metric drops slightly.

With the latest I-CCAP technologies, there will be a significant increase in SG per rack. Part of this is the improvements being seen in I-CCAP densities shown in Figure 19. But there are other factors at play as well. D3.1 capabilities such as proactive network maintenance (PNM) allow the monitoring equipment to be removed. Elimination of the RF combining/splitting is another significant source of space savings. All in all, the SG density jumps to 96 SG per rack in roughly the same power footprint. This means another significant drop in the W per ‘Channel’ equivalent, where a channel is considered to be a 38 Mbps QAM channel.

If space density is a premium, then additional I-CCAP resources may be added to improve the I-CCAP space density to 128 SG per rack. The W per Mbps remains unchanged. So, in a several year span, the operator will have seen a 4.5X improvement in I-CCAP/CMTS space density and roughly 5X improvement in W/Mbps as seen in the last column of Table 5.

Some operators may be considering drastic headend changes such as the consolidation of multiple sites into a single location. This may strain the facilities beyond the I-CCAP improvements just discussed. New distributed access architectures (DAA) have evolved such as remote PHY (R-PHY), remote MACPHY (R-MACPHY), and remote CCAP that can give an operator additional space and power savings in the headend. Some example rack elevations are shown in Figure 20 to give the reader a relative sense of the headend space requirements for each solution.

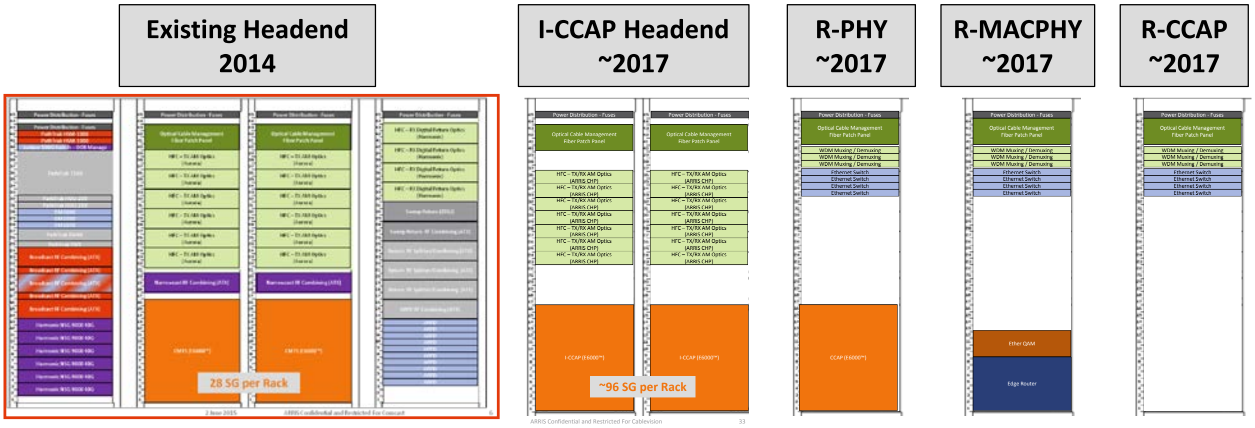

Figure 20 - Sample Rack Elevations for various Centralized and Distributed Architectures

Table 6 below shows the estimated space required to support ~200 SG. The SG Scale uses the 2014 system as a baseline to estimate potential improvements with each architecture. The more functionality that is pushed out into the access network, the more potential space savings in the headend.

Table 6 - Headend Space Density for Various Centralized and Distributed Architectures

Access Architecture (Central-CAA or Distributed-DAA)	Time Frame	Space For ~200 SG	SG per Rack	SG Scale
Older CMTS + Low Density EQAM	Pre-2014	20-50 Racks	4-10 SG	0.2-0.4X
High Density I-CMTS/UEQAM CAA	2014	~7 Racks	~28 SG	1X
I-CCAP CAA	~2016-17	~1½ Rack	~128 SG	4.5X
R-PHY DAA		~⅔ Rack	~250 SG	9X
R-MACPHY DAA		~½ Rack	~384 SG	14X
R-CCAP DAA		~1/5 Rack	~960 SG	34X

How much space an operator needs will be very dependent on what technology is currently deployed in the headend along with the current size of their SGs. Is the current headend utilizing 2012, 2014, or 2016 technologies? This will determine how much potential space savings there might be.

Some operators who already have their CMTS SG sizes under 200 subs, may only need to increase their SG count by a factor of 2 or 3 over the next decade. Other operators who may still have average SG sizes greater than 500 subs may be looking at an 8X increase. Every headend site needs to be individually assessed.

5.3. Headend Power Consideration for Future Architectures

As operators progress to the future, they are faced with a wide array of choices. From a headend perspective, there is business as usual with I-CCAP, there are new distributed architectures such as R-

PHY and then there is the possible FTTP evolution with 10G EPON. Each has a varying impact on headend power consumption.

For I-CCAP/CMTS systems, a key variable in determining the required headend power is the mapping of nodes to DOCSIS SG. In older DOCSIS days, there were often many nodes mapped to a single SG. Over time this has reduced and many operators are now down to a 1:1 mapping of nodes to SG. However, there may be a round of fiber-deep HFC upgrades as suggested in the previous section that may cause the node-to-SG ratio to jump back up. Figure 21 shows the estimated power required for various node-to-SG ratios. The power is normalized to Kilowatts per 100K homes passed (HP).

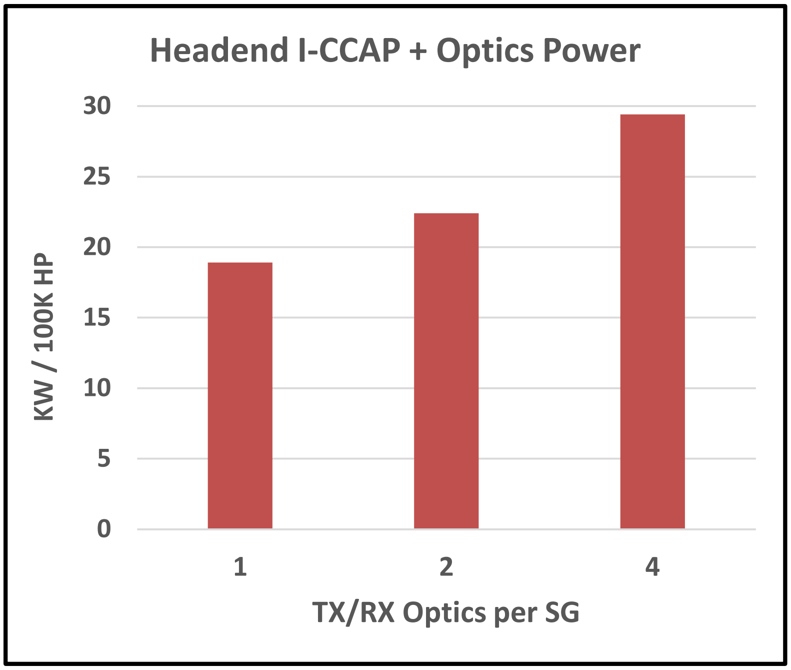

Figure 21 - Headend Power: I-CCAP + TX/RX Optics

As can be seen in Figure 21, the required headend power can vary by 50%.

The next architecture considered is the R-PHY system. This requires a CCAP with the DOCSIS MAC core, but with the DOCSIS PHY removed or disabled. In addition to the CCAP, there may be some Ethernet switches that provide an aggregation function that gathers many 10G Ethernet links and consolidates them into several 100G Ethernet channels.

One of the benefits of the R-PHY MAC core is that an operator can scale their MAC processing as needed. So as utilization increases, additional MAC core resources are added which in turn adds additional power in the headend. Another factor in headend power is the number of remote PHY devices (RPDs) that are connected to each DOCSIS SG. The more RPDs per SG, then the more Ethernet switching that is required. Figure 22 shows the impact of these two factors on headend power for an R-PHY system.

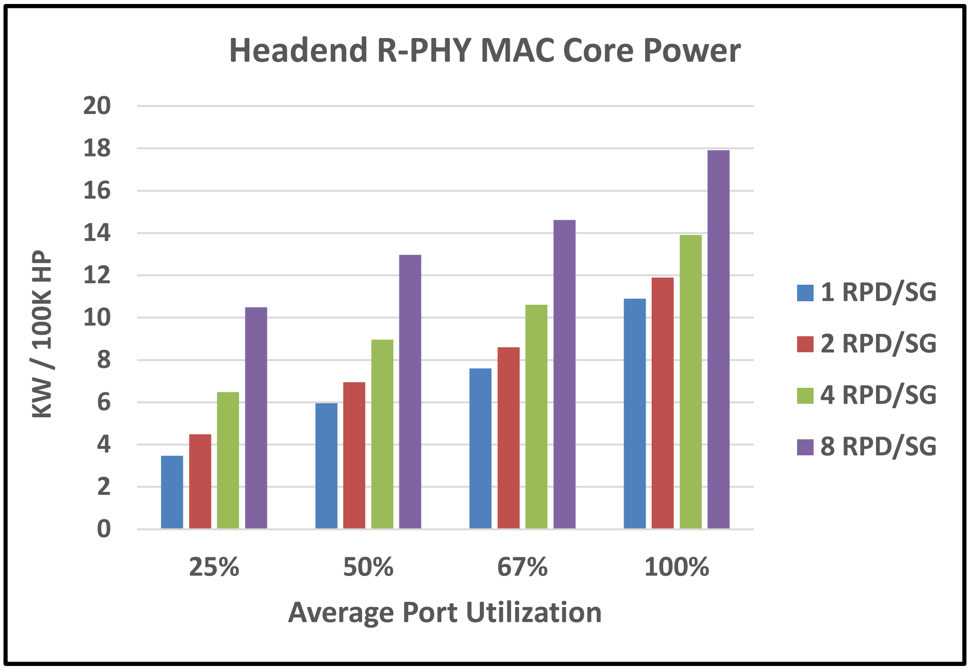

Figure 22 - Headend Power: R-PHY MAC Core + Ethernet Switching

Notice that power consumption can vary by a factor of six. The biggest jump in power occurs when going to 8 RPD per SG. There is also a steady climb in power with utilization.

PON systems can come in three different flavors. In a traditional PON system, there is an OLT in the headend and the access network is completely passive. The major factor in headend power is the number of homes per OLT port. This in turn is driven by the optical SNR budget, which is a function of the distance from the OLT to the homes. For short distances, an operator may configure 128 homes per OLT port. However, for longer distances, the optical SNR budget may limit the operator to just 32 homes per OLT port.

As discussed earlier, there are two ways that an operator can overcome this distance limitation. The first is using PON Extender technology. The OLT remains essentially unchanged except the optics is replaced with DWDM optics. A PON extender in the field then does a wavelength conversion and re-generates the PON wavelength. These PON extenders are typically placed close enough to the subscribers to support the 128 homes per OLT port. The PON Extender is a physical-layer-only conversion.

The other solution to the optic distance problem is to use a distributed architecture with a Remote OLT placed in the access network. Most of the OLT function has been moved out of the headend. However, the headend still needs Ethernet switches to aggregate the R-OLT links. The headend also needs to support controller, DPoE, and routing/switching functionality.

Figure 23 shows the relative headend power required for each of the three PON scenarios.

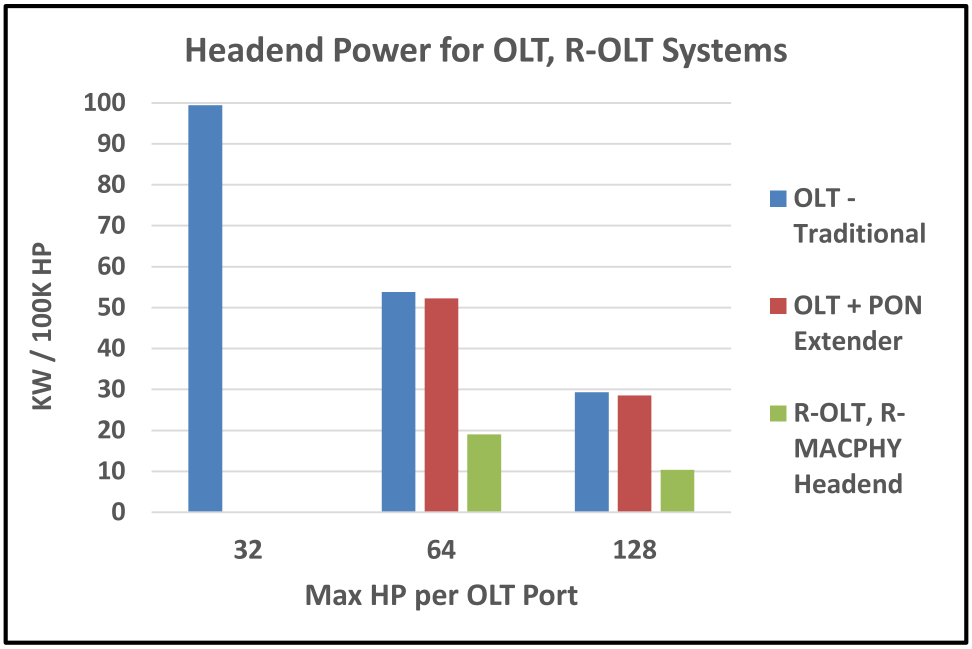

Figure 23 - Headend Power: OLT, OLT + PON Extender, R-OLT

As can be seen in the figure, the traditional OLT system pays a heavy facility power penalty in the headend if it must limit the number of homes per OLT port. If distances are short enough or PON Extender or R-OLT is used for 128 homes per port, then the PON's headend power is in the same ballpark as the I-CCAP and R-PHY MAC Core systems.

6. Total Access Network Energy Considerations

Putting this altogether, Figure 24 gives us an insight into the access network's total system power consumption once the headend facility is combined with the outside plant.

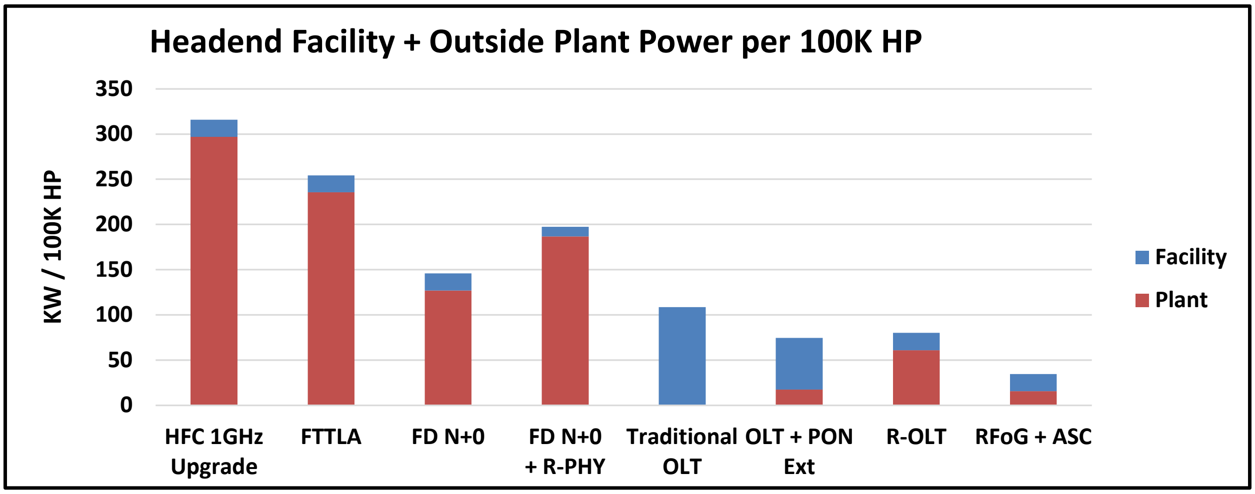

Figure 24 - Headend Facility + Outside Plant Power

For all of the HFC options, the power to drive the coax plant dominates. The Fiber Deep alternatives, FTTLA and FD N+0, reduce overall power consumption from the baseline 1 GHz HFC case. Besides cutting total power consumption by up to 50%, another significant advantage that these two provide is the big jump in total network capacity as was shown previously in Figure 11. The Fiber Deep architectures enable a 10-fold increase in the number of SG for less power. This means a corresponding more than 10-fold increase in total network capacity too.

The power for PON alternatives shown in Figure 24 comes in below the HFC options. But as shown in [ULM_2016], will this be enough to outweigh the economic costs of pulling fiber all the way to the premise? The traditional OLT has the highest headend facility power consumption of all the solutions. As shown in Figure 24, it is assumed to be limited to 32 HP per port due to fiber optic distance / loss budget. If fiber distances are relatively short, then KW/HP could potentially get cut in half. Using a PON extender to remove the distance limitation allows the OLT to support more HP per port. This provides a significant total power savings, especially in the headend facility. The R-OLT option comes in very close to the PON extender option, only with most of its power in the Outside Plant (OSP) rather than the facility.

For comparisons sake, Figure 24 also shows an RFoG solution with active splitter combiner (ASC) technology that eliminates Optical Beat Interference (OBI). RFoG with ASC provides the best of both worlds. It requires minimal plant power that is comparable to the PON extender. Yet, it leverages the DOCSIS headend facilities that handles much larger subscriber counts per SG with the resulting headend facility power savings.

Note that the other piece of the energy consumption that is not addressed in this paper is the consumer premise equipment (CPE).

7. Conclusion

In summary, today’s HFC outside plant power consumption dominates over headend facility power. Migrating to Fiber Deep FTTx technologies can result in a significant power savings for the outside plant. Since migrating to FTTP as an end game will be a multi-decade journey, this paper evaluated various options that might be a stepping stone along the way.

Selective Subscriber Migration strategy is a sensible approach for an HFC to FTTx transition. Moving top tiers to FTTx can buy HFC extra decades for 80-95% of subscribers in the flagship basic/economy tiers. Tmax dominates for the next 5-7 years, so it is more important to increase the HFC capacity to at least 1 GHz spectrum rather than split nodes. However, Tavg finally catches up 8-10+ years from now; and SG size reductions come back into vogue. Operators should push fiber deep enough to enable Selective FTTx for top tiers on demand and be prepared for the next round of SG splits.

To understand what the best option is to enable this migration, the paper analyzed in detail five very unique real nodes that varied from sparse rural node to a very dense urban node. Design work was then done on these five nodes for each of the following scenarios:

- "Business as usual" 1 GHz active drop in upgrade with node split as needed
- Fiber Deep Node+0 – FD N+0 and FTTLA
- FTTP

The results show that there is significant power consumption variations from use case to use case. On average, the FTTLA approach provided a 20% power savings compared to the baseline 1 GHz HFC plant. FTTLA minimizes the amount of re-work required to the existing coax plant while driving fiber closer to the home providing a great stepping stone to FTTP when or as needed. FD N+0 minimizes the number of nodes at the expense of some additional coax re-work but provides about 50% power savings compared to the 1 GHz HFC baseline. The reduced node count will also improve operational savings through reduced maintenance. In addition to the total power savings, these Fiber Deep technologies also increase the number of potential SGs by an order of magnitude, so the KW/Tbps metric increases up to 20-fold!

These Fiber Deep HFC systems are compared to distributed access architectures like R-PHY and FTTP architectures such as PON and RFoG. The R-PHY system effectively pushes functionality and hence power from the headend facility out to the plant with no net power savings. The PON systems have generally lower power consumption than the HFC system but require the largest investment with fiber to the premise. The PON power consumption is very sensitive to the number of homes passed per OLT port. Leveraging R-OLT or PON extenders are useful methods of increasing HP per OLT port and providing more power savings.

Many headend facilities are strapped for space. This may be exasperated as operators continue to consolidate multiple hubs and headends into more centralized locations. As was shown, CMTS/CCAP technologies have made tremendous progress in both space and power densities. Just upgrading from older to newer technology can make a significant space savings. I-CCAP systems will continue to improve and are expected to show a 4-5X space density improvement over 2014 technologies. If this doesn't provide enough space savings for operators, then various distributed architectures can be deployed to provide additional space savings from 9X to 14X over the 2014 baseline.

As operators migrate to a more green, energy efficient world, there are a number of choices available to actually reduce their overall power consumption while keeping pace with the unrelenting growth in consumer data traffic.

8. Acknowledgements

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9. Abbreviations

ABR	adaptive bit rate

ASC	active splitter-combiner
BAU	business as usual
Bcast	broadcast
Bps	bits per second
CAA	centralized access architecture
CAGR	compounded annual growth rate
CAPEX	capital expense
CCAP	converged cable access platform
CM	cable modem
CMTS	cable modem termination system
CPE	consumer premise equipment
D3.1	Data Over Cable Service Interface Specification 3.1
DAA	distributed access architecture
DCA	distributed CCAP architecture
DEPI	downstream external PHY interface
DNA	distributed node architecture
DOCSIS	Data Over Cable Service Interface Specification
DS	Downstream
DWDM	dense wave division multiplexing
E2E	end to end
EPON	Ethernet passive optical network (aka ge-pon)
EQAM	edge quadrature amplitude modulator
FD	fiber deep
FDX	full duplex (i.e. DOCSIS)
FEC	forward error correction
FTTC	fiber to the curb
FTTH	fiber to the home
FTTLA	fiber to the last active
FTTP	fiber to the premise
FTTT	fiber to the tap
FTTx	fiber to the ‘x’ where ‘x’ can be any of the above
Gbps	gigabits per second
GHz	gigahertz
GPON	gigabit-passive optical network
HFC	hybrid fiber-coax
HP	homes passed
HPON	hybrid passive optical network
HSD	high speed data
I-CCAP	integrated converged cable access platform
IEEE	institute of electrical and electronics engineers
IEQ	integrated edge QAM
LDPC	low density parity check FEC code
MAC	media access control interface
MACPHY	DCA instantiation that places both MAC & PHY in the Node
Mbps	mega bits per second
MDU	multiple dwelling unit

MHz	megahertz
MSO	multiple system operator
N+0	node+0 actives
Ncast	narrowcast
NFV	network function virtualization
NPV	net present value
NSI	network side interface
OBI	optical beat interference
ODN	optical distribution network
OFDM	orthogonal frequency division multiplexing
OFDMA	orthogonal frequency division multiplexing access (upstream)
OLT	optical line termination
ONU	optical network unit
OOB	out of band
OPEX	operating expense
OTT	over the top
PHY	physical interface
PNM	proactive network maintenance
PON	passive optical network
QAM	quadrature amplitude modulation
QoE	quality of experience
QoS	quality of service
RF	radio frequency
RFoG	rf over glass
ROI	return on investment
R-OLT	remote OLT
RPD	remote PHY Device
R-MACPHY	remote MAC-PHY
R-PHY	remote PHY
RX	receive
SDN	software defined network
SG	service group
SCTE	Society of Cable Telecommunications Engineers
SNR	signal to noise ratio
TaFDM	time and frequency division multiplexing
Tavg	average bandwidth per subscriber
TCO	total cost of operation
Tmax	maximum sustained traffic rate – DOCSIS Service Flow parameter
TX	transmit
UHD	ultra high definition
US	upstream
WDM	wavelength division multiplexing

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Achieving Energy Savings in Broadband Provider Edge Facilities through a Portfolio-Based Approach

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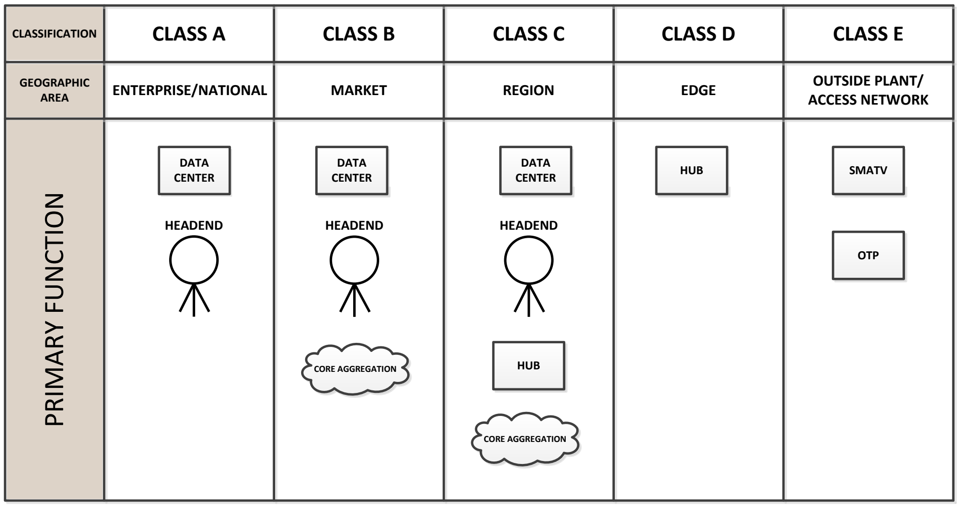
1. Introduction

With energy costs on the rise and increasing pressure to reduce or avoid costs and thereby meet corporate and Energy 2020 goals, companies across the cable industry face the challenges of lowering energy consumption and raising energy productivity. In particular, the largest component of a cable operator's utility bill comes from the numerous edge facilities and outside plant power supplies, which are both key components of the access network. Due to the highly distributed nature of the access network and the fact that portions of it are found in relatively low utility rate states while others are found in very states with very high utility rates, it can be a major challenge to use the same economic model and apply it individually to the entirety of the access network. Further, company size, organizational structure, support from leadership, technology risk and access to capital are also common barriers to achieving energy savings goals across the entire footprint of the cable operator. The good news is these barriers can be reduced with portfolio-based approaches and new ways to finance and manage upgrades. This paper details recommended strategies for employing a staged and macro-level approach to implementing energy management improvements while leveraging unique financing mechanisms in order to meet Energy 2020 goals in particular with accuracy, speed and at scale.

This paper is intended to aid cable operator stakeholders involved in decisions related to reduction of energy consumption and improvement of energy productivity at critical edge facilities, with the intended outcome of increasing energy efficiency, reaching sustainability targets and reducing grid dependency. Stakeholders include, but are not limited to, energy and sustainability teams, design and construction teams, network engineering, critical infrastructure engineering, other engineering units, business management, financial managers, budget coordinators, technical operations and corporate real-estate.

This operational practice provides energy conservation opportunities applicable to critical cable operator facility types. Although they are clearly linked in overall energy efficiency, especially in emerging technologies such as distributed access architectures such as remote PHY, the scope of this document does not include the outside plant. The following figure defines the critical facility classifications applicable to this document (adopted from SCTE 226 2016).



CLASSIFICATION	CLASS A	CLASS B	CLASS C	CLASS D	CLASS E
GEOGRAPHIC AREA	ENTERPRISE/NATIONAL	MARKET	REGION	EDGE	OUTSIDE PLANT/ ACCESS NETWORK
PRIMARY FUNCTION	DATA CENTER HEADEND	DATA CENTER HEADEND CORE AGGREGATION	DATA CENTER HEADEND HUB CORE AGGREGATION	HUB	SMATV OTP

Figure 1 - Critical Facility Classification Quick Reference

(http://www.scte.org/SCTEDocs/Standards/SCTE%20226%202015.pdf)

By building on the energy efficiency measures documented in SCTE-228, Inventory of Energy Efficiency Practices for Broadband Provider Facilities, this paper provides additional detail on energy measures specific to cable edge facilities, including:

- The necessity to prioritize edge facility energy efficiency measures in order meet Energy 2020 goals;
- A list of energy efficiency measures, application options and cost implications specific to head-ends and hubs;
- Development of metrics, KPIs and guidelines pertaining to all edge facility types in the cable industry;
- Strategies for increasing cost savings and return on investment (ROI) for energy efficiency projects; and
- A summary of results from case studies and/or pilots with industry examples and operational practices related to energy management improvements, including energy efficiency, renewable energy, energy resilience, and energy demand reduction opportunities.

In addition, the paper presents novel ways to scale deployments across an entire portfolio such as:

- Modeling strategies for understanding the impact of applicable energy conservation measures (ECMs) across the entire asset base;
- Recommendations for using portfolio modeling to develop a staged plan for achieving high level Energy 2020 goals;
- Organizational change management strategies to support scaled deployments;
- The ability to leverage alternative funding options such as performance based or energy savings as a service (ESaaS) models as a mechanism to achieve sizeable energy savings now across the entire portfolio by avoiding the upfront capital costs;
- Setting organizational goals for driving both speed and impact;
- Identifying the measures that are technologically and financially feasible to implement for selected asset types;
- Performing the portfolio analysis to determine the impact across the cable operator’s footprint of facilities; and
- Prioritize sites by size, age, geography, and criticality to implement those measures that make the most sense.

Finally, typical issues are discussed that can emerge in a portfolio deployment and can restrict the achievable speed and scale, including:

- Deployment man-power;
- Capital constraints; and
- Organizational resistance.

1.1. Benefits

The key benefits of any energy efficiency improvement program aimed at facilities are to: 1. reduce operational expenditure (OpEx) costs, 2. improve robustness and sustainability of facilities, 3. optimize the use of existing and future facilities to avoid future costs when possible, and 4. generally to achieve the

SCTE Energy 2020 and corporate goals. Specific benefits of adopting the tactics in this document include:

- Ability to lower costs in edge facilities where a significant portion of the overall energy bill is found;
- Ability to implement these cost-reducing measures rapidly across the entire footprint by avoiding the upfront capital costs;
- Select projects that provide the best cost savings and ROI for energy efficiency projects;
- Increase HVAC redundancy and thereby operational resilience for critical facilities; and
- Address even the most challenging legacy facilities and even those in regions with lower utility costs via a portfolio-based approach that works for all edge facility types in the cable industry.

The goals of the SCTE Energy 2020 program applied specifically to edge facilities could be implemented as follows:

- Reduce the kilowatt-hours consumed by edge facilities per terabyte of data consumed by these facilities (kWh/TB) by 15% per year. This is achieved in edge facilities primarily via HVAC efficiency improvements that reduce the power usage effectiveness (PUE), coupled with equipment consolidation from deployment of converged cable access platforms (CCAPs), higher density edge-quadrature amplitude modulators (EQAMs), and remote PHY/MAC/CCAP equipment, all of which reduce the number of racks needed in the facility for the same capacity. This creates the opportunity to focus the cooling on a smaller portion of the facility.
- Optimize by 2020 the footprint of edge facilities by 20% via the aforementioned equipment consolidation, consolidation of multiple facilities into newer facilities designed with energy efficient principles, and application of cable technology evolution trends to equipment layouts so that new equipment installations facilitate further energy efficiency improvements.
- Reduce the cost of energy relative to overall OpEx costs by 25% and grid dependence by 10% in edge facilities via deployment of solar and other alternate energy sources using a portfolio-based approach.

Finally, there are more general, corporate-wide goals that can be achieved by the tactics described in this document, including:

- Development of an overall energy playbook for the corporation that includes continuous improvements to edge facility energy efficiency via as-a-service and performance-based business models as well as technician training, new behaviors, and ideas from all players on further improvements possible in such facilities. This playbook can also be aligned with ISO 50001 via SCTE 234 2016, available from www.SCTE.org.
- Positive impacts to corporate energy cost reduction and power consumption targets and carbon footprint reduction goals by increasing awareness of energy efficiency opportunities and facilitating project prioritization and decision-making specifically for cable edge facilities.
- Positive impacts to industry’s grid independence and sustainability goals by providing information on renewable and alternative energies that will help diversify the power source.

2. Need for Portfolio Modeling Approach

Why are portfolios and new ways to finance and manage energy efficiency improvements required? Primarily, it is due to the scale of the problem, the diversity of facility size and layout, and the variability of energy rates across the facilities footprint. It may cost roughly the same to replace a single HVAC system in two similarly-sized sites for example, but if the utility rate in one site is one-third the rate in the other site, it could take three times the time to pay back the investment in the site with the lower rate. Or, even if the rates are identical, one site may be much smaller and have one-third the energy consumption as another site, and again, it could take three times the time to pay back the investment of a single HVAC upgrade.

A portfolio approach makes it possible to absorb higher per site costs, lower per site rates, and lower per site consumption into an integrated portfolio of sites that meets financial requirements even though some of the individual sites would not have met the requirements on their own. The fact that the edge facilities are the most numerous of all cable operator facilities means the scale of this portfolio could easily exceed budget allowances, and thus new ways to finance and manage the upgrades are also needed. Each of these, along with recommendations for making the overall business case and measuring and evaluating the results, are described in this section.

2.1. Portfolio Modeling

Portfolio modeling is a useful strategy for assessing the overall impact of applicable ECMs across an entire asset base under a scaled deployment. A full assessment will allow cable operators to develop a staged deployment plan for achieving Energy 2020 goals. One such strategy is to develop a portfolio assessment workbook to determine the potential impact of energy management measures across the customized makeup of the cable operator’s portfolio. Based on a series of proposed ECMs the workbook calculates a range of projected energy reductions (kWh), projected financial savings ($), and projected reductions in carbon emissions.

In order to perform an assessment, it is important to gather information about the portfolio. A preferred scenario is to collect 12-36 months of historical energy use from utility bills, site level energy consumption by load type (lighting, HVAC, IT, other), utility rate, location, square footage, and asset type. Details of this process are described in ANSI/SCTE 212 2015, and the specific metrics to collect are described in ANSI/SCTE 211 2015 and ANSI 213 2015 for access networks and edge facilities, respectively, all of which are available from www.SCTE.org. Measurement of power usage effectiveness (PUE) as described in ANSI/SCTE 213 for edge facilities is of particular importance in determining which facilities will contribute most significantly in the portfolio to the overall energy savings. This data provides the basis of a complete portfolio analysis, portfolio prioritization, and narrows the degree of uncertainty in projected savings.

Unfortunately, many corporations do not typically have this information aggregated in one central repository. It may be necessary to coordinate between multiple corporate entities such as facilities, accounts payable, and engineering in order to consolidate the data. It is also important to consider assets gained or divested due to acquisitions, consolidations and sell offs. It is also helpful to understand where and what energy management measures have already been deployed as this will reduce the range of projected savings for future implementations.

If getting the granular data needed still proves difficult, it is often possible to gather information for a sample set of sites within a specific asset class in order to determine average values that can be used to estimate across the entire portfolio of assets in the same class. For example, without access to sub-meter data to determine the exact level of energy consumption by load type in every site, it is still possible to establish general profiles based on data that is available, as well as publically available information gleaned from technical case studies issued through the SCTE Energy 2020 or from other government and industry resources which are detailed below.

Typical industry data includes US buildings establishment counts, energy consumption, end-use categories, end-use load breakdown, average square footage per establishment and energy intensity by building type. Additionally, these sources provide average utility rates, emissions factors, interaction factors and energy efficiency potential. Note that average values gleaned from industry data may be necessary to populate a portfolio workbook, but it will increase the threshold of uncertainty in projected savings. However, for those skilled in such approaches, the uncertainty due to lack of granular data from all sites can usually be reduced to an acceptable level.

Asset types are defined by the North American Industry Classification System (NAICS). NAICS provides a standard used by federal statistical agencies in classifying business establishments for the purpose of collecting, analyzing, and publishing statistical data related to the U.S. business economy. At a minimum the cable operator will want to assign values for the following information:

- Asset type;
- # of sites to be included in the portfolio assessment; and
- Location of sites.

Additional inputs, which may be populated with industry data include:

- Total energy consumption per asset type;
- Load breakdown per site by asset type;
- Square footage per asset type; and
- Utility rate per asset type and location.

Utility rates can be collected from current bills to estimate the cost of energy spend across the portfolio. In lieu of a consolidated rate database, it is also possible to pull data from the United States Energy Information Administration. Although no prices are given for commercial consumers, prices for the domestic sector should be fairly close to those for smaller commercial consumers and industrial prices should provide a reasonable proxy for larger sites in the commercial sector.

This data can be accumulated and processed to calculate current energy spend across the portfolio both in kWh and in dollars, projected average energy spend across the portfolio (also in kWh and dollars), projected operations and maintenance savings in dollars, and the breakdown of low and high projected energy savings in dollars from all energy conservation measures.

Energy intensity industry data for average square footage of establishments as well as energy intensity per asset type (kWh per sq ft) is a useful data point. Data for both square footage and energy intensity can be sourced from the commercial buildings energy consumption survey (CBECS), the manufacturing energy consumption survey (MECS), Energy Star, or from case studies and industry references.

Energy efficiency factors are used to provide estimates of projected low and high energy savings a given ECMs will have on a given end use. Energy efficiency factors can be collected from SCTE standards and operational practices, vendor references or practical implementation experience. ECMs should be grouped per end use to avoid double counting the projected energy savings. It is a good practice to include a range of savings in order to account for variability in site conditions and applicability.

The interaction factors are fractions that are applied to a sum of values to account for interactive affect between systems, and energy conservation measures. There is little available research on the subject; however, the Portland Energy Conservation Inc. (PECI) has published a suggested interaction factor of 0.85 in commercial buildings. This appears to be a very conservative estimate and it would be better to incorporate the cable operator's own findings based on practical implementation experience.

Operations and maintenance (O&M) factors can be calculated in order to capture the indirect energy and maintenance cost benefits of the deployment of applicable ECMs in order to bolster the business case. Cable operators are encouraged to develop their own factors based on technology characteristics and maintenance routines and rates for better accuracy. For example, operators should determine the labor cost for re-lamping a site, estimate a cooling savings factor (lighting percentage of the total facility kWh), estimate the disposal fees that can be avoided and calculate financial benefit of the potential maintenance savings.

2.2. Financing Energy Efficiency

Many cable operators are committed to achieving performance targets that address environmental and safety regulations, reduce energy use and associated costs, lower carbon emissions, and support overall sustainability goals. However, these same businesses often struggle to find the internal expertise and financial resources necessary to implement their environmental and energy saving initiatives at scale. Both of these challenges can be met by leveraging third-party energy management consulting services that use both traditional and new financing models to achieve energy efficiency improvements across the entire cable operator's footprint. Such firms provide expertise for large scale deployments, from initial assessments through post-installation support and reporting and to achieve targeted resource-saving goals.

2.2.1. Time and Material Based Fee Structures

For cable operators that have the ability to finance energy-saving projects with internal capital, but are still strapped on human capital to implement them at scale, energy management consulting services can be engaged using time and material (T&M)-based fees to implement their projects. With a T&M-based financing model, energy-saving initiatives are funded entirely through the company's capital or operational budget, and fees are based on the scope of work, materials required and level of effort. Features of the T&M-based fees models include:

- Energy program consulting: Strategic energy portfolio and tactical program management.
- Ownership: Cable operator owns and maintains energy related assets. Asset purchases and installation are funded either through the cable operator's capital or expense budget or as part of the consulting services' expenditures.
- Traditional consulting fees are based on time and materials and the cable operator retains all savings from energy initiatives.

2.2.2. Performance Based Fee Structures

Another option available to cable operators that have the ability to finance energy-saving projects with internal capital is the performance-based fee structure. Performance-based fees are inclusive of the consulting services' fees and are paid over time via the energy savings achieved by the projects. Features of the performance-based fees models include:

- Energy program consulting: Strategic energy portfolio and tactical program management.
- Ownership: Cable operator owns and maintains energy related assets. Asset purchases and installation are funded either through the cable operator's capital or expense budget or as part of the consulting services' expenditures.
- Value-based fee structure: After an analysis phase to understand the cable operator's needs and scope, a portion of, or the entire consulting fee is tied to realization of measured energy savings, which are then shared between the consulting service and the cable operator for a specified time period.

2.2.3. ESaaS Funding Model

For many cable operators, both capital and operational expense constraints are present, especially for a large scale portfolio approach. Cable operators can accelerate results through flexible and innovative financing options – such as Energy Savings as a Service (ESaaS) to upgrade infrastructure without initial capital investments.

The ESaaS funding model enables companies to reduce energy use and expenses with no upfront capital or cash-flow costs. Here's how it works: the energy service provider (ESP) invests and deploys energy-savings technologies at the cable operator's sites and bills the cable operator based on energy savings achieved. Features of an ESaaS model include:

- Variable payments: Monthly payments are neither fixed nor guaranteed, but depend on each month's audited energy savings. Costs are recorded as utility expenses.
- Energy-saving assets are owned by the ESP: The provider thoroughly vets, selects, purchases and installs ideal energy-saving devices at the cable operator's location and includes maintenance and support plus remote monitoring.
- Energy-saving commitment: The ESP defines the total amount of energy savings in the service contract based on expected monthly savings for each site.

In addition to reducing financial and resource constraints that inhibit energy initiatives, both Performance Based and ESaaS approaches enables cable operators to fund sustainability initiatives from their existing energy budget and thus frees capital for other investments.

2.3. Building the Business Case for Energy Measures

It is important for stakeholders looking to implement energy efficiency measures to build a complete business case so they fully understand if a project is worthwhile and both technically and financially feasible. The following considerations will help to bolster understanding of the ROI for proposed measures.

Table 1 - Energy Measure Business Case Considerations

Consideration	Definition
Energy Savings	Energy consumption and demand reduction yield cost savings for cable operators and progress towards goals.
Added Cost Savings	When prioritizing and selecting energy measures for implementation, cable operators should also consider non-energy cost savings the implementation of measures will create. Examples include water consumption savings, maintenance savings, space consolidation, and extended equipment life.
Alternative Energy Efficiency Financing	If funding is unavailable to cover the initial capital cost of energy efficiency measures, cable operators can utilize various alternative financing. Common examples include: • Energy savings performance contracts • Power purchase agreements (PPA) (but not in all states) See Section 2.2 above for more details.
Tax Incentive Programs	Property tax incentives – Most property tax incentives for renewable energy systems exclude the added cost of the system in the overall assessment of the property for taxation purposes. These incentives include exemptions, exclusions, and credits. Sales tax incentives – Sales tax exemptions, typically at the state sales tax level, for the retail sale of energy efficiency technology implementation and renewable energy systems. (Adopted from SCTE 218)
Utility Incentive Programs	State and local governments' pair up with utility providers in order to promote and offer rebates for the installation of renewable energy systems and energy efficient technology (see SCTE 218). To maximize returns for grid connected applications, it is recommended to check local state and utility incentives related to proposed implementation, many of which are compiled in the database of state incentives for renewables and efficiency (DESIREUSA.org).
Sustainability Benefits	Typically, energy efficiency projects also have an inherent greenhouse gas (GHG) reduction benefit. When installing energy efficiency measures, GHG reduction can be calculated and used for internal and external organization reporting. Furthermore, some states and countries (like California) have cap-and-trade markets associated with carbon reduction where organizations can receive a credit for reducing their GHG emissions.
Energy Management Systems	Installing, upgrading and/or commissioning of advanced energy management and control systems can yield significant operational savings and improved facility comfort.
Facility Energy Audits	It is a best practice to have utility or third party analysis of existing facility infrastructure and historical energy consumption and provide recommendations on applicable measures and available incentives for key efficiency upgrades.

Consideration	Definition
Impact on SCTE Energy 2020 Goals	Make impactful decisions on what energy measures to implement and where they are most applicable in order to meet corporate and SCTE Energy 2020 goals.
Standardized Purchasing	Create minimum efficiency standards for common equipment purchases.

2.4. Procedures for Energy Measure Implementation

When using this paper to identify and prioritize energy efficiency measures for facilities, it is recommended to follow these procedures:

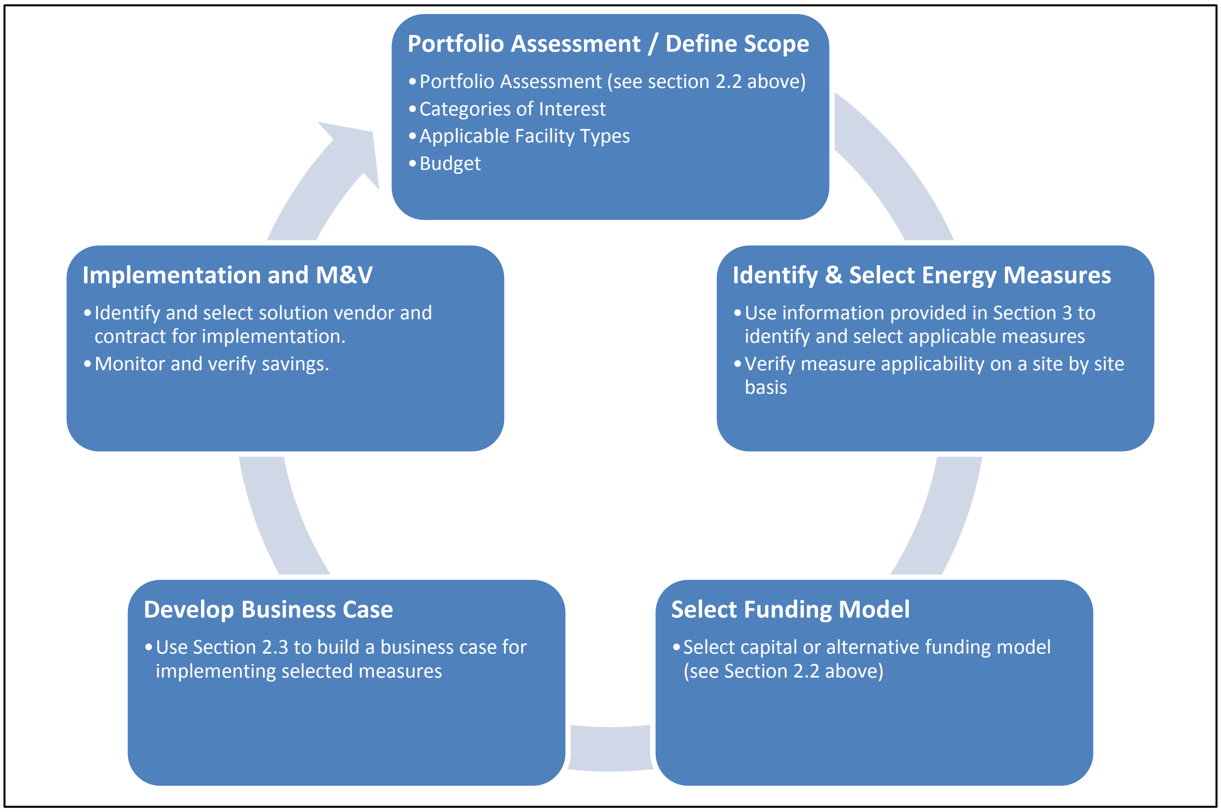


Figure 2 - Procedures for Energy Conservation Measures

1. Portfolio Assessment / Define Scope – Cable operators must first determine the scope of their energy improvements in edge facilities by defining:
    a. What facility types are in their property portfolio?
    b. What categories are applicable and/or of interest for their facilities?
    c. What budget is available for initial energy measure capital costs?
2. Identify & Select Energy Measures – Using the scope of energy improvements defined in step 1, cable operators can group all applicable energy measures using the tables and scatterplots available in Section 3. After a list of applicable energy measures has been developed, cable

operators can then utilize cost and value metrics developed in SCTE-228 and additional case studies to aid in prioritization and eventual selection of energy measures for implementation.

   a. After developing the list of applicable and prioritized measures, cable operators should verify that these measures are relevant on a site by site basis through conversations with property managers, data collection, site audits or other means as necessary.

3. Select Funding Model – Once projects have been selected, cable operators should assess the costs and payback and determine whether to fund projects using their own capital or utilizing a performance contracting mechanism (e.g. ESaaS). See Section 2.2 for more details.
4. Develop Business Case – Once the cable operator has selected one or more energy measures for implementation, they should utilize the guidance in Section 2.3 to building a business case for implementation. The business case should include the projected energy efficiency and cost savings, non-energy benefits (e.g. sustainability benefits, water consumption reduction, maintenance cost reduction, and energy resilience), and opportunities for project financing (e.g. utility incentives, alternative financing).
5. Implementation – If energy measures are approved for implementation, cable operators must then research and select technology vendors who can achieve this work, and contract with them and other necessary parties (finance, installers) to implement the measure on-site. Post implementation, cable operators are encouraged to monitor and verify savings that the energy measures create, and use that for internal and external messaging (e.g. sustainability reporting).

2.5. Key Performance Indicators and Metrics

Whether a single site or a portfolio of sites is being addressed, any project which is intended to apply energy conservation measures to edge facilities should be baselined before, and evaluated and monitored afterwards to ensure that improvements were indeed obtained. The method of measuring the results could vary depending on the funding model. A more sophisticated measurement and verification plan will need to be in place to support performance-based or ESaaS service models, if applicable. And in order to compare these results to industry benchmarks, common metrics and key performance indicators (KPIs) should be used in the evaluation.

The ANSI/SCTE 213 2015 standard titled “Edge and Core Facilities Energy Metrics” is the cable industry’s approved metrics to be used for evaluation of energy consumption, efficiency and productivity in cable edge facilities, and the reader is encouraged to read this standard in entirety prior to embarking on any ECMs in order to understand the data that will need to be gathered for evaluating the effectiveness of the ECMs, as well as the definitions and background behind each metric.

The key metrics from ANSI/SCTE 213 2015 to be used for edge facilities are summarized below:

Total critical facility power P_{TF}, which is measured in kW at any particular instant and in kWh over some period of time, e.g. monthly, from the utility service entrance that feeds the entire facility, and if multiple sources feed a given facility, then P_{TF} is the sum of all such sources.

IT equipment power, P_{IT}, in either kW or kWh, which should include all functional equipment that is used to provide services to customers and is typically the sum of the direct current (dc) power and the uninterruptible power supply/source (UPS).

Power usage effectiveness (PUE) which is the ratio of P_{TF} and P_{IT} and should be measured at least monthly, better if daily and at best every 15 minutes using automated monitoring equipment since this provides the best view of variations each day due to weather and/or environmental factors.

Total energy for the entire facility per consumed byte, $EPCB_{TF}$, measured in kWh per terabyte, which also requires the measurement of the consumed bitrate C_{BR} in b/s for the facility. EPCBTF is an example of the more generalized data center energy productivity (DCeP) metrics used in other industries.

For details on the above metrics, how they can be measured, and the frequency of measurement recommended, the reader is referred to ANSI/SCTE 213 2015, which details for example how to handle non electricity sources such as natural gas and chilled water using source weighting factors in the measurement of P_{TF}. To correctly measure PUE, P_{TF} and P_{IT} must both be in kW, or both be in kWh using conversion equations found in ANSI/SCTE 213 2015. Finally note that from measurement of PUE and $EPCB_{TF}$, other metrics such as the energy productivity of the IT equipment, $EPCB_{IT}$, can be calculated as $EPCB_{TF}$*PUE.

These metrics are not only useful for characterizing energy efficiency in facilities before and after any ECMs, as well as periodically and historically to assess trends, they are also useful in a portfolio-based approach to characterize and prioritize the facilities for staging the ECMs over time. ANSI/SCTE 213 2015 recommends developing a scatter diagram of PUE vs DCeP for all facilities, in the present case for all edge facilities, in order to determine which facilities need ECMs vs those that are already performing well, reproduced in figure 3 below.

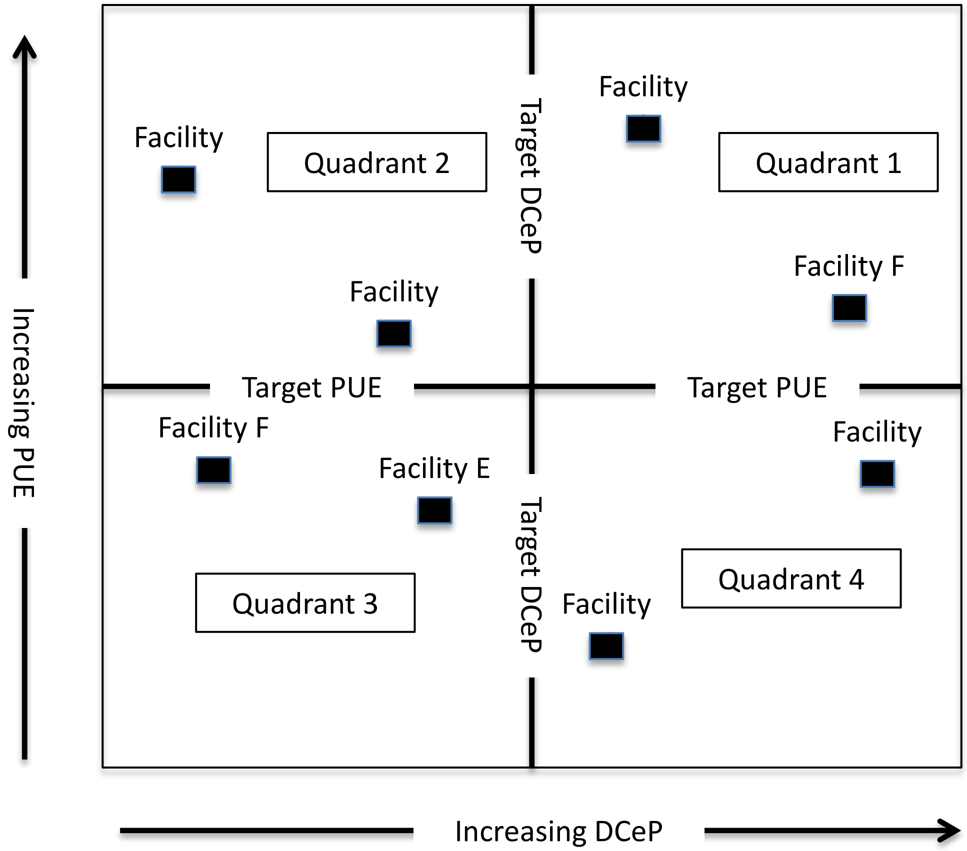


Figure 3 - Scatter diagram (a.k.a. quadrant grid) for facility PUE and DCeP (from ANSI/SCTE 213 2015).

Quadrant 2 above represents the edge facilities that are in most need of ECMs, while those in quadrant 4 represent best practices and benchmarks to strive for (or to consolidate into).

Note that typical PUE values of cable head hubs have already been seen to be greater than the industry average values PUE values for data centers [STILES]. The primary reasons are their age, diversity, and the presence of inefficiently designed HVAC systems. This leads to over cooling, lack of cold and hot aisle containment, poorly designed ducting, inefficient HVAC equipment, lack of economizers, and so on. This section highlights some of the priority HVAC related ECMs for these edge facilities.

While lighting and power distribution losses are also part of the total facility energy consumption, HVAC and IT load are by far the two major energy end uses in an edge facility. These two important parameters along with the total power consumption of the site should to be measured every 15 minutes and at least daily to create an optimum baseline for a site and measure the energy savings after an ECM implementation as well as any performance drift that occurs from predicted improvements.
Two other metrics that The Green Grid proposed recently are the IT thermal resilience and IT thermal conformance. These metrics are important to report especially when HVAC upgrades are made to a site. IT thermal conformance is ratio of the equipment load that operates within the thermal limits under normal operating conditions and the total equipment load. IT thermal conformance is an important metric

to detect performance drift. It helps detect equipment that is experiencing inlet temperature above a pre-defined suitable range and thus indicates need for examining the HVAC systems and control. IT thermal resilience is a ratio of the IT load that can operate under predetermined allowable temperature under worst case cooling failure and the total equivalent load. This metric can be helpful in particular while designing and/or modifying a HVAC system. Failure of different HVAC equipment might lead to alteration of air flow in different ways, and often simulation modeling will be required to model these scenarios and determine the ratio.

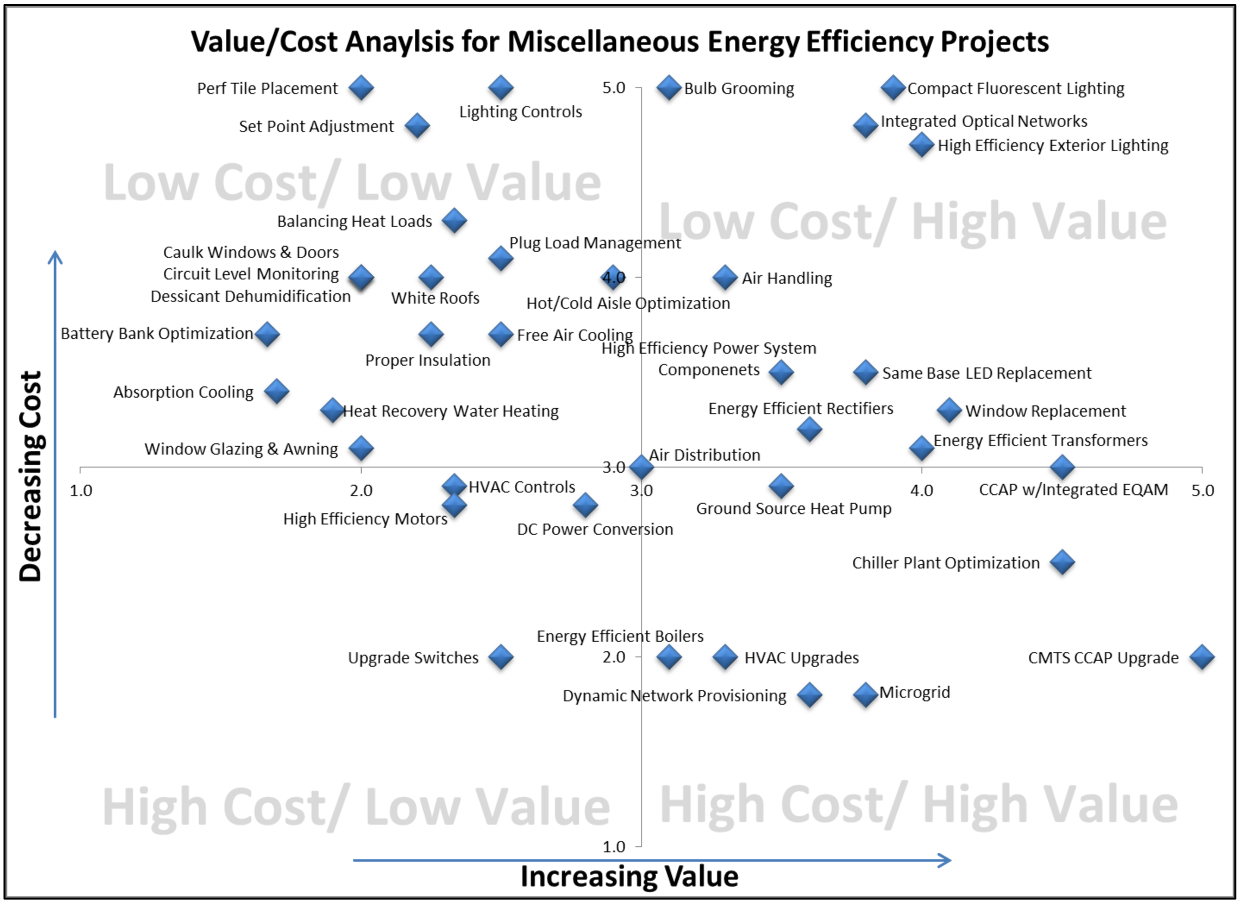
3. Energy Measures – Cable Edge Facilities

Several energy efficiency measures can be considered for edge facilities. The following table shows examples energy conservation measures, such as optimization and system upgrades based on different end uses.

Table 2 - Example Energy Conservation Measures.

	HVAC	Lighting	Energy Generation and Storage	Critical IT Power / Racks
Operational Measures	• Set point temperature monitoring • Humidity control • Optimal HVAC cycling Controllers	• Sensoring at the sites	• Remote Battery and generator testing	• Server Optimization
System Upgrades	• Free air cooling integration • Air flow optimization via ducting, blanking panels, aisle containment, and/or HVAC equipment relocation • Use of more efficient refrigerants • Variable speed fan drives (VFDs) • Complete HVAC replacement or addition of new HVAC units to add redundancy	• Lighting upgrades	• DC power optimization • Demand charge reduction • Fuel cells, solar and wind	• Equipment upgrades that improve energy productivity and reduce the number of racks that must be cooled (e.g. CCAP, high density EQAMs, or remote PHY equipment) • New energy efficient racks with built in monitoring and surgical cooling options • Leveraging smaller form factors of new equipment

Note that redundancy does not improve energy efficiency, but rather is required for robustness of service provision and maximizing customer satisfaction. Ideally, as a result of other ECMs such as airflow optimization, it is possible to reduce the number of HVAC units required for active cooling and use one of the legacy systems for redundancy. HVAC engineers who are skilled at airflow optimization can also recommend which existing units are best to use for redundancy if and when fewer units are required after airflow optimization.



* From SCTE-228

Figure 4 - Cost/Value Analysis of Energy Efficiency Measures for Critical Facilities.

There are recommendations for ECMs designed to improve energy productivity, such as location of new CCAP or high density EQAM equipment in aisles that are already in a hot/cold aisle orientation to improve opportunities for aisle containment, and in which the existing equipment already vents front to back per the product environment requirements in ANSI/SCTE 186 2016 (or has been modified to do so). The greatest impact on energy efficiency in cable edge facilities will generally be from the ECMs described in this section: HVAC upgrades, airflow optimization, lighting upgrades (for larger facilities that have significant human occupancy), energy generation and storage, and critical IT power/rack upgrades.

3.1. Heating, Ventilation and Air Conditioning (HVAC)

There are several HVAC upgrades - operational and system upgrades that a cable edge facility can benefit from. Due to lack of full aisle containment and airflow optimization measure, cable head ends and hubs are generally over cooled and thus optimally controlling the HVAC systems can help save significant amount of energy. Some sites where HVAC equipment is archaic may also benefit from system replacement and/ or integration of free air cooling kits. The air flow optimization techniques described in the subsequent sections can be used to upgrade the sites HVAC systems and/or reduce the HVAC consumption.

Table 3 - Edge Facility Energy Efficiency Measures for HVAC.

Note – Value is on a scale of 1-5, with 5 being a high value. Cost is on a scale of 1-5, with 5 being a low cost.

Value,Cost	Facility Types*	Category	Sub-Category	Energy Measure	Description/Objective
(2.2, 4.8)	Class A-D	HVAC	Cooling	Set Point Adjustment	Align temperature set-point settings with American Society of Heating, Refrigerating, and Air-Conditioning Engineers (ASHRAE) recommendations. Every one degree increase in temperature (in summer months) can deliver up to 4% in energy savings.
(2.5, 3.7)	Class A-D	HVAC	Cooling	Free Air Cooling	Installation of an air-wide economizer to utilizes cool outside air whenever feasible to reduce cooling costs.
(2.3, 4.3)	Class A-D	HVAC	Cooling	Balancing Heat Loads	Minimizes hot spots and provides for equal heat dissipation.
(2.9, 4.0)	Class A-D	HVAC	Cooling	Hot/Cold Aisle Optimization	Provides more efficient cooling and higher HVAC inlet temperatures.
(4.0, 2.0)	Class A-D	HVAC	Cooling	Spot Cooling	Direct cooling service to high-heat generation rack-based equipment reducing overall cooling delivery requirement.
(2.3, 2.9)	Class A-D	HVAC	Controls	HVAC Controls	Utilization of advanced control system to minimize power usage while cooling a space.
(1.7, 3.4)	Class A-C	HVAC	Cooling	Absorption Cooling	Absorption chillers use heat to drive the refrigeration cycle, they produce chilled water while consuming just a small amount of electricity to run the pumps on the unit. Absorption chillers generally use steam or hot water to drive the lithium bromide refrigeration cycle but can also use other heat sources.
(2.0, 4.0)	Class A-D	HVAC	Cooling	Desiccant Dehumidification	Air dehumidification can be achieved by two methods: (I) cooling the air below its dew point and removing moisture by condensation, or (2) sorption by a desiccant material. Desiccants in either solid or liquid forms have a natural affinity for removing moisture.
(3.3, 2.0)	Class A-D	HVAC	Air Flow Management	HVAC Upgrades	Replace current air handling equipment in an HVAC system with more efficient models (e.g. install more energy efficient fans).

Value,Cost	Facility Types*	Category	Sub-Category	Energy Measure	Description/Objective
(3.0, 3.0)	Class A-D	HVAC	Air Flow Management	Air Distribution	Optimized Central heating and cooling systems using an air distribution or duct system to circulate heated and/or cooled air to all the conditioned rooms in a house.
(1.2, 4.5)	Class A-C	HVAC	Air Flow Management	Brush Grommets	Equipment installed in a data center to prevent air leaks from the system, resulting in less energy consumed for data center cooling.
(4.0, 3.7)	Class A-D	HVAC	Air Flow Management	Air Handling	Reduce the amount of air leakage, improve aisle containment.
(1.0, 5.0)	Class A-D	HVAC	Air Flow Management	Air DE-stratification	Process of mixing internal air in a building to achieve temperature equalization and remove stratified layers.
(1.8, 2.9)	Class A-D	HVAC	Heating and Cooling	Wireless Smart Thermostats	Installation of advanced wireless thermostats with improved controls and tracking of temperature and energy savings.
(2.0, 5.0)	Class A-D	HVAC	Air Flow Management	Perforated Tile Placement	Improper placement of perforated tiles is a major culprit behind cooling problems in data centers.

* From SCTE-228

Selection of HVAC upgrades from the above table depends greatly on the site location, IT equipment placement, current HVAC systems, utility rates, and so on. For example, feasibility of implementing free air cooling depends on the climate zone and the kW consumption of the site. ASHRAE Standard 90.1 documents the climate zone economizer map for data centers of different capacities. Other HVAC upgrades related to air flow management may be restricted by certain obstructions at the site or general site layout, although the authors are already discovering a variety of tactics that can be applied to the majority of sites explored thus far. Finally, the choice of up-flow vs. down-flow HVAC units for upgrades is driven by how many legacy systems will remain and what their orientation is, whether they are to be bonded together in a common supply and/or return ducting system for redundancy, and so on. Careful design and considerations are required while selecting and implementing HVAC upgrades.

As has been mentioned, airflow optimization (AFO) is closely tied to HVAC upgrades, although AFO can be applied without any HVAC equipment upgrades. When AFO is applied in conjunction with other HVAC upgrades, the result can be significant. In the Google network point of presence (POP) case study [GOOGLE], they found that cold aisle containment typically reduced the PUE by 0.4, and return collar extensions by another 0.1-0.3. AFO is thus an extremely important component of any HVAC ECM projects planned for cable edge facilities.

AFO refers to the containment and/or redirection of airflow within a technical facility in order to accomplish the following goals:

- Reduce mixing of hot and cold air;
- Reduce or eliminate hot spots/provide consistent cooling of equipment;
- Direct the cold supply air to the input air vents of telecom equipment; and
- Direct the hot air exhausted from the telecom equipment to the return.

The financial benefits of airflow optimization are:

- Reduced cooling costs via:
  - Reduced compressor usage;
  - Higher set point of computer room air conditioning (CRAC) units (for the same input air temperature at equipment);
  - Increased use of free air cooling; and
  - Increased incidence rate of facility viability.
- Maximizing rack population and thus avoiding cost of constructing new facilities; and
- Reduced equipment failures from overheating.

Airflow optimization within a facility may be accomplished via any combination of the following:

- Floor fans;
- Ductwork/collars/turning vanes;
- Blanking panels/shrouds in racks;
- Cable management within racks (brushes);
- Plastic blanking panels or strips for aisle containment; and
- Other air turning/redirection elements within the facility.

Airflow optimization can be done without tools and sensors to guide the airflow optimization, but the benefits can be maximized by combining computational fluid dynamics (CFD) modeling of airflow with temperature sensor placement and monitoring.

As previously mentioned, the challenges in implementing AFO in existing cable edge facilities are the diversity of sizes, layouts, equipment types and associated heat loads, and so on. However, the authors are engaged in several ongoing pilots as of this writing and are already seeing common tactics that can be cost-effectively applied in most cable edge facilities seen thus far. A subsequent case study of these pilots will be presented to the SCTE Energy Management Subcommittee upon completion.

3.2. Lighting

Though many critical edge facilities are unmanned the majority of the time, certain large critical edge facilities are occupied by technicians for a large portion of the day. Replacing the existing lights with LEDs and having occupancy sensor/timers in such facilities can aid the effort to bring down the site's energy consumption. Several lighting measures are tabulated below:

Table 4 - Edge Facility Energy Efficiency Measures for Lighting.

Note – Value is on a scale of 1-5, with 5 being a high value. Cost is on a scale of 1-5, with 5 being a low cost.

Value, Cost	Facility Types*	Category	Sub-Category	Energy Measure	Description/Objective
(3.8, 3.5)	Class A-C	Lighting	Relamp	Replace Incandescent with new same base LED	Replacement of incandescent bulbs with of LED bulbs will save energy as LED requires less power and decreases heat loss.

Value, Cost	Facility Types*	Category	Sub-Category	Energy Measure	Description/Objective
(2.5, 5.0)	Class A-C	Control	Lighting Controls	Install lighting controls	Implementing occupancy sensors and other lighting controls to turn off lights when areas are unoccupied or do not need additional light.
(3.9, 5.0)	Class A-C	Lighting	Efficiency Lighting	Install compact fluorescent lighting	More energy efficient than incandescent.
(4.0, 4.7)	Class A-C	Building	Efficiency Lighting	High Efficiency Exterior Lighting	Use of higher efficiency bulbs and systems for lighting outdoor areas (e.g. LED bulbs).

* From SCTE-228

Most of the lighting measures described above would not be feasible financially due to low lighting loads. However, larger facilities like head ends and some critical hub facilities are occupied by technicians for a large portion of the day. Replacing the existing lights with LEDs and installing occupancy sensors/timers in such facilities can aid in bringing down the site's energy consumption.

3.3. Energy Generation & Storage

Majority of cable hubs are located in remote areas which may be affected by an unreliable grid. Critical edge facilities are backed with a conventional generator but truck rolls to top the fuel for the generators at remote sites can be costly. Such sites make perfect candidates for on-site generation. Based on the climatic conditions, solar, vertical axis wind turbine, fuel cells or suitable hybrid generators can prove to be cost-effective at selected sites.

Table 5 - Edge Facility Energy Efficiency Measures for Energy Generation & Storage.

Note – Value is on a scale of 1-5, with 5 being a high value. Cost is on a scale of 1-5, with 5 being a low cost.

Value, Cost	Facility Types*	Category	Sub-Category	Energy Measure	Description/Objective
(3.8,1.8)	Class A-D	Power	Energy Generation	Micro-grid	Installation and use of an on-site microgrid (localized grouping of electricity sources and loads) to generate DC power for a facility or facilities, or for portions of that facility. Microgrids are individually applicable to only the largest edge facilities, however in a portfolio, it is possible to make smaller sites viable.

Value, Cost	Facility Types*	Category	Sub-Category	Energy Measure	Description/Objective
(2.0,4.0)	Class A-E	Power	Energy Distribution	Circuit Level Monitoring	Software and hardware for distributed network monitoring and management. DC equipment monitoring at circuit-level, optimizing the network and equipment protection. Cable operators are increasingly monitoring the total edge site power, the total IT load power (via the DC plant, including the UPS), and even the individual HVAC systems, thereby enabling PUE measurement.
(1.7,3.7)	Class A-E	Power	Energy Distribution	Battery Bank Optimization	Utilize control strategies for increased system performance in back up DC power supplies. Accurate monitoring of battery state/health for both edge facilities and the outside plant will increasingly be used, and batteries for intermittent energy sources such as wind and solar will also require advanced controls and monitoring.
(2.5,4.1)	Class A-E	Power	Energy Distribution	Plug Load Management	Optimizing electrical plug loads by assessing current plug loads and implementing changes to reduce load and energy consumption, especially at peak demand periods.
(2.8,2.8)	Class A-D	Power	Energy Distribution	Eliminate conversion Steps – transition to DC	Transitioning to DC power will reduce the number of conversions power must go through before reaching the equipment. The outside plant (Class E) will remain non-DC for the foreseeable future given the transmission distances and number of legacy systems.
(3.6,3.2)	Class A-E	Power	Energy Distribution	Power Supply Rectifiers	Ensure purchasing most energy efficient units when doing replacements and new deployments for increased energy efficiency.
(4.0,3.1)	Class A-E	Power	Energy Distribution / Supply Chain	Energy Efficient Transformers	Where transformers must be used, energy efficient transformers can reduce the losses from energy conversion.

* From SCTE-228

Microgrids can be considered for smaller edge facilities that would normally not be economically viable, a portfolio-based approach for microgrid deployment makes it possible to address these smaller sites by aggregating them with larger, more viable sites.

Note also that many cable operators are already implementing detailed automated monitoring systems in their edge facilities, hence many of the metrics, KPIs, and general energy consumption monitoring apsects discussed in this paper are already available for use in ECM prioritization, planning, deployment and monitoring.

3.4. Critical IT Power/ Racks

One of the best ways to improve energy productivity and achieve the first Energy 2020 goal is to upgrade cable telecommunications equipment to higher density platforms that reduce the total number of racks required and inherently provide greater productivity. The converged cable access platform (CCAP), high density edge quadrature amplitude modulators (EQAM) have already been shown in several SCTE Energy Management Subcommittee plenary presentations and SCTE Cable-Tec Expo papers to provide considerable improvements in energy productivity and even reductions in total energy consumption if legacy equipment such as switched digital video equipment is also eliminated via deployment of CCAP equipment. Additional metrics such as watts per QAM or watts per subscriber have been shown in these presentations to be significantly improved when newer, more-dense IT equipment is deployed, and now SCTE 232 2016 defines these CCAP/CMTS metrics in a standard way for the industry.

Table 6 - Edge Facility Energy Efficiency Measures for Critical IT Power/ Racks.

Note – Value is on a scale of 1-5, with 5 being a high value. Cost is on a scale of 1-5, with 5 being a low cost.

Value ,Cost	Facility Types*	Category	Sub-Category	Energy Measure	Description/Objective
(3.5, 3.5)	Class A-E	Power	Equipment	High Efficiency Power System Components	Efficiency gains in Information and Communications Technology (ICT) equipment and software drive savings in all areas by reducing loads.
(2.5, 2.0)	Class A-D	HVAC	Equipment	Upgrade Switches	Install better switches in an HVAC system to improve controls and protect equipment.
(2.3, 2.8)	Class A-D	Mechanical Plant	Equipment	High Efficiency Motors	Energy-efficient motors are typically 2 to 8% more efficient than standard motors. Motors may qualify for various incentives if they meet or exceed standard efficiency levels.
(3.6, 1.8)	Class A-E	Equipment	Software	Dynamic Network Provisioning	Sequencing equipment and radio cycling to obtain highest efficiency.
(3.8, 4.8)	Class A-E	Equipment	Software	Integrated Optical Networks, Software Defined Networking (SDN) and Network	All optical and increasingly software-defined/virtualized networks are very often considered to be the main candidate for constituting the backbone that will carry global data whose volume has been growing exponentially and new

Value ,Cost	Facility Types*	Category	Sub-Category	Energy Measure	Description/Objective
				Functions Virtualization (NFV)	services must be added at accelerated rates ("service velocity").
(5.0, 2.0)	Class A-E	Equipment	Upgrade	(CMTS) Converged Cable Access Platform (CCAP) and EQAM Upgrades	Significant operational savings can be achieved through the CMTS/EQAM/CCAP upgrades, especially if replacing older equipment that is less dense and less energy efficient. Business case may be justified by the need for more bandwidth capacity, but benefits include reducing the footprint of rackspace needed and thereby enabling better airflow optimization, spot and close-coupled cooling solutions in edge facilities. (see Appendix B of SCTE-228)
(4.5, 3.0)	Class A-E	Equipment	Software	Converged Cable Access Platform (CCAP) with integrated EQAM	Additional operational savings can be achieved by integrating EQAM inside CCAP. Assumes that newer equipment is already installed. (see Appendix B of SCTE-228)

* From SCTE-228

Most cable operators will upgrade these systems as a natural consequence of increasing the network capacity to keep up with customer demand for higher Internet speeds, but it should be noted that different manufacturers have different energy consumption/productivity metrics, and thus all other things being equal, the cable operator should deploy new technology that adheres to SCTE environmental standards as well as providing the best energy productivity metrics for that type of equipment. Placement of the new equipment in the existing facility should also be done with an eye towards future cold aisle containment or other ECMs that would leverage the increased productivity and density via reducing the total volume to be cooled, for example. Finally, there are emerging standards in the SCTE Energy Management Subcommittee such as the Adaptive Power System Interface Specification (APSIS^{TM}) that will permit coordination of reduced IT heat loads based on for example lower data traffic levels, with HVAC system controls so that the cooling provided is also reduced in like manner.

4. Conclusions

Selecting the energy measures that are most applicable to cable edge facilities is of vital importance for an effective energy efficiency upgrade project. However, it is of equal importance to design a deployment strategy that achieves stated energy savings goals at scale across the cable operators' entire portfolio of assets.

Portfolio-based modeling is an important tool for understanding the impact of applicable ECMs across the entire asset base. A portfolio-based approach can be taken with greater speed by utilizing new ways to finance and manage upgrades offered by third-party energy service providers.

The output of a portfolio assessment forms the basis for a program-wide business case and deployment strategy that addresses major issues such as deployment man-power, capital constraints and organizational resistance to new technology. Adoption of these tools and strategies will lead to achieving substantial energy savings in broadband provider edge facilities and ultimately contribute to successfully meeting Energy2020 goals.

5. Abbreviations and Definitions

Abbreviation	Term	Definition*
AC	alternating current (electricity)	In alternating current, the flow of electric charge periodically reverses direction, whereas in direct current circuits, the flow of electric charge is only in one direction. The abbreviations AC and DC are often used to mean simply alternating and direct, as when they modify current or voltage. AC is the form in which electric power is delivered to businesses and residences. The usual waveform of an AC power circuit is a sine wave.
APSIS	Adaptive Power System Interface Specification	SCTE standard for adding transaction-based and energy proportional functionality to cable equipment, detailed in ANSI/SCTE 216 2015 and available from www.SCTE.org
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers	Global society, founded in 1894, focused on advancing sustainable technology and energy efficiency in building systems.
CCAP	converged cable access platform	Technology that integrates the functions of a CMTS and EQAM into a single platform. See Appendix B for more information.
CHP and CCHP	combined heat and power and combined cooling, heat and power	CHP is the use of a heat engine or power station to generate electricity and useful heat at the same time. Trigeneration or CCHP refers to the simultaneous generation of electricity and useful heating and cooling from the combustion of a fuel or a solar heat collector. Cogeneration is a thermodynamically efficient use of fuel. In separate production of electricity, some energy must be discarded as waste heat, but in cogeneration this thermal energy is

Abbreviation	Term	Definition*
		put to use. All thermal power plants emit heat during electricity generation, which can be released into the natural environment through cooling towers, flue gas, or by other means. In contrast, CHP captures some or all of the by-product for heating, either very close to the plant.
CMTS	Cable Modem Termination System	A headend component that provides the operator network side termination. A CMTS communicates with a number of cable modems to provide data services. See SCTE 137-7 for more details.
DC	direct current (electricity)	Direct current is the unidirectional flow of electric charge. Direct current is produced by sources such as batteries, solar cells, thermocouples, and commutator-type electric machines of the dynamo type. Direct current may flow in a conductor such as a wire, but can also flow through semiconductors, insulators, or even through a vacuum as in electron or ion beams. The electric current flows in a constant direction, distinguishing it from alternating current.
ECM	energy conservation measure	The technology which allows for energy to be saved compared to previous operational baselines.
EPCB	energy per consumed bit	A measure of data center energy productivity (DCeP) that is specified for use in cable edge and core facilities.
ESP	energy service provider	A third-party business entity with specialized experience in designing and deploying energy efficiency improvements a client sites.
ESaaS	energy savings as a service	A financing option for energy efficiency deployments which utilizes a payment structure based on saved energy via the technology deployed.
EQAM	edge quadrature amplitude modulator	A head-end or hub device that receives packets of digital video or

Abbreviation	Term	Definition*
		data from the operator network. See SCTE 137-7 for more details.
HVAC	heating, ventilation and air conditioning	HVAC is important in the design of industrial and office buildings where safe and healthy building conditions are regulated with respect to temperature and humidity, using fresh air from outdoors. The three central functions of heating, ventilation, and air-conditioning are interrelated, especially with the need to provide thermal comfort and acceptable indoor air quality within reasonable installation, operation, and maintenance costs. HVAC systems can provide ventilation, reduce air infiltration, and maintain pressure relationships between spaces.
ICT or IT	information and communications technology	Application of telecommunications equipment and technologies to manage information/data (hardware, software, electronics, etc.).
kVA	kilovolt-amps	One thousand volt amps – metric for measuring the apparent power in an electrical circuit.
kW	kilowatt	One thousand watts – metric for measuring the electricity flow through a customer meter
kWh	kilowatt hour	The amount of kilowatts used in one hour. If a customer uses 100 kW an hour for two hours the total kilowatt hours for the two hour period would be 200 kWh.
LED	light-emitting diode	A two-lead semiconductor light source that can be used in lamps or light bulbs. LED lamps are more energy efficient and have a lifespan longer than most other lamp types.
MSO	multiple-system operator	A corporate entity that owns and/or operates more than one cable system.
OTP	optical transition point	A critical facility for transport aggregation or extension to support the edge facility's service delivery and typically contains amplifiers for optical links or transmitters and receivers feeding optical nodes.

Abbreviation	Term	Definition*
PUE	power usage effectiveness	Ratio of total amount of energy used by a computer data center facility to the energy delivered to computing equipment
ROI	return on investment	Performance measurement used to evaluate the efficiency of an investment or to compare the efficiency of a number of different investments. In economic terms, it is one way of considering profits in relation to capital invested or how quickly an investment will repay itself.
SCTE	Society of Cable Telecommunications Engineers	SCTE is a membership organization, founded in 1969, that provides technical and applied science resources and programs for the cable telecommunications industry.
SMEs	subject matter experts	A person or persons that have an in-depth understanding or knowledge on a specific subject.
SMATV	satellite master antenna television system	A legacy critical facility for receiving video signals for processing and distribution directly to the customer, where no connection to an Operator's Core Network exists.

**Some definitions taken from SCTE 218, SCTE 137-7 and SCTE EMS 025.*

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Overview of Current Battery and Energy Storage Technologies

A Technical Review of Performance

A Technical Paper Prepared for SCTE/ISBE by

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1. Abstract

Telecommunication networks and data centers consume an immense amount of energy for their operations. Due to the expected growth in energy demand and the gravity of current consumption, industry leaders are looking for ways to maximize efficiency within their businesses. Energy storage systems have the potential to increase energy efficient operations in various industries and are critical for increasing the utilization of renewables. These technologies can also help meet future energy demand and reduce greenhouse gas emissions if they are strategically deployed. With these technologies in place, unused electricity can be stored in various systems and supplied back into the grid when needed, though growing consumption could eventually strain this novel upgrade in technology. This paper will focus on the different battery and energy storage technologies that are both under research and commercially available. Nevertheless, without favorable legislation, the telecommunications industry will be less likely to invest in both energy storage systems and renewable energy. Furthermore, the use of storage systems for telecommunication will most likely be limited to backup power.

2. Introduction

Energy storage systems are key factors for increasing the utilization of renewable energy sources and augmenting the efficiency and operating capabilities of nonrenewable sources [1]. These technologies can help meet future energy demand and reduce greenhouse gas emissions if they are strategically deployed. This paper will focus on the different battery and energy storage technologies that are both under research and commercially available. Since electricity is a secondary form of energy that cannot be stored directly, it must be either consumed upon production or converted to other forms of energy for storage. Energy storage technologies are classified by the conversion process involved in their storage, and their useful applications depend on their various performance capabilities. Furthermore, the best system for a preferred application will in some cases be a combination of different technologies.

Three main classifications are included in electricity energy storage (EES), the list is as follows: mechanical energy storage; electro-chemical energy storage, and electrical energy storage [2]. Each of these types of technologies will be discussed in this paper. Pumped hydro storage (PHS) and flywheel technologies are examples of mechanical energy storage technologies that will be reviewed. The electrochemical energy storage technologies to be discussed are lithium-ion batteries and lithium-air batteries. Last but not least the electrical energy storage technologies to be reviewed are supercapacitors and superconducting magnetic energy storage (SMES) systems. The other types of energy storage technologies that will not be discussed are thermochemical, chemical, and thermal EES technologies. All these technologies have the potential to revolutionize the means by which industry supplies and attains energy. However, even with the maturity of energy storage systems and optimal implementation of renewables in commercial, residential, and industrial settings; advancements in technology will be inadequate to satisfy a parallel growth in energy demand. If increased energy efficiency in the telecommunications industry is coupled with increased demand, then the business model of respective companies within this industry will be no more sustainable than beforehand.

About three-quarters of the electricity consumed by communication networks is due to operator networks [3]. A graphical depiction of the electricity consumption breakdown within communication networks can be found in reference [3]. Office networks and customer premise equipment comprise the smaller fraction of electricity consumption within networks. Between the years 2007 and 2012, the overall global electricity consumption within this sector has increased from 219 TWh per year to 354 TWh per year [3]. Table 1 below shows this breakdown in consumption just for customer premise equipment.

Table 1 - "Customer premise equipment: average power consumption per user, numbers of users and worldwide annual electricity use" [3].

	Power per user (W)	Subscribers, 2007 (million)	Electricity use, 2007 (TWh)	Subscribers, 2012 (million)	Electricity use, 2012 (TWh)
Cable	9.5	74	6.2	123	20.2
DSL	7.1	228	14.2	388	24.1
FTTH	13.0	38	4.3	115	13.1
Other Broadband	8.3	6	0.4	24	1.8
Narrowband (dial-up)	2.5	283	6.3	142	3.1
Total		629	31.4	792	52.4

The number of subscribers and consequently the electricity used for customer premise equipment has increased between 2007 and 2012. This does not even include the full consumption from communication networks, yet alone data centers. The prefix "tera" for terawatt hours represents a magnitude of 10^{12} watt hours. This is a very large unit of measurement. Considering the fact that the combined energy consumption within communication networks and datacenters keeps on increasing, there is a reason to be alarmed as both a consumer and provider in this industry.

The reason for reducing energy consumption and increasing energy efficiency is beyond financial. The greatest sources of electricity in the U.S. come from coal and natural gas fired plants. Although fossil fuels provide a constant and reliable source of power, they tend to have huge price fluctuations and high greenhouse gas (GHG) emissions. In 2014 the price of oil fell from $100 a barrel in the beginning of the year to below $50 a barrel by mid-year which is just one example of the price volatility of this commodity [4]. Wind and solar energy are cleaner sources of energy but they are less reliable. If the energy generated from renewables could be stored, then industry would not have to rely on fossil fuels quite as much. Due to the magnitude of our energy consumption, it is only logical for us to invest in technologies that reduce pollution and change our energy consumption habits. Mature energy storage technologies can help address this massive challenge. Combining commitments to reduce energy consumption with investments in energy efficient technologies will help the communication networks become more sustainable and consequently more resilient.

3. Energy Storage Technologies

Primary energy storage is the most common and stable form of energy storage [5]. Some common forms of primary energy are crude oil, coal, and liquefied natural gas, all of which can be stored. Other primary forms of energy that cannot be stored directly are wind, solar, and tidal wave energy. Secondary forms of energy include gasoline, diesel, biofuels, and hydrogen. These forms of energy are usually stored in high pressure containment vessels or tanks of different sizes and shapes [5]. Secondary forms of energy that cannot be stored include: electricity, work, and heat. Notice that fossil fuel based energy can be stored in both primary and secondary forms but the renewable energy types are not conventionally stored. Without gasoline for cars, and electricity to light offices, power electronic devices, and machinery, our quality of life would be drastically diminished. Since fossil fuels are nonrenewable resources and are rapidly being consumed, renewable energy must be considered to meet future energy demand. However, renewable energy is an intermittent resource and cannot be fully utilized without some form of energy storage. Furthermore, secondary forms of energy have been directly used by people and corporations since the

Industrial Revolution. Secondary energy storage is based on the concept of capturing energy produced at one time and using it at a later time. Charging is the process used to capture energy while discharging is the process of releasing that energy. This paper will only focus on secondary energy storage which occur in the form of electricity. An economic means of secondary energy storage would not only be useful for the telecommunications industry, but could help meet future energy demand as well.

3.1. Pumped Hydroelectric Storage

Pumped hydroelectric storage is a type of mechanical energy storage technology which has over 178 GW of installed capacity and is the most mature and widely used large-scale electricity energy storage system in the world [2]. In 2012, pumped hydroelectric storage had an installed capacity of 127-129 GW, which is over 99% of worldwide bulk storage capacity [6]. In this system, two water reservoirs of different elevations are connected by pipes and turbomachinery [2]. To store energy, water is pumped from the lower to the upper reservoir; to reverse this process, a turbine is used to restore energy with water traveling from the upper to the lower reservoir. The height difference between the lower and the upper reservoirs determines the energy storage capacity of PHS. The two classifications for conventional PHS are Pure/Off-stream and Hybrid/Pump-back. If the upper reservoir is not physically connected to natural watercourses, then it is a Pure or Off-stream system. If the lower and upper reservoirs are both incorporated into watercourses, then it is a Hybrid or Pump-back system.

Pumped hydro storage typically has a low energy density, a large storage capacity, a moderate to high efficiency, and a long lifetime. Various PHS plants have approximately 70-85% cycle efficiency and over 40 years in their lifetime. Some significant drawbacks to PHS systems are the high capital investment and long construction times needed to build this technology. Many restrictions are placed on suitable geographic sites because of the detrimental impacts that PHS can have on the environment [6, 2]. Other significant drawbacks are high cost and long lead-time. Nonetheless, the potential to adopt renewable energy in distributed networks is increasing due to the development of wind or solar power generation coupled with pumped hydroelectric storage. Furthermore, the types of PHS plants that have been planned or that currently exists have expanded from previous years due to advancements in technology, these include: underground caves and oceans as reservoirs and flooded mine shafts used in the plant. The table below show leading PHS facilities and their power capabilities.

Table 2 - Pumped Hydroelectric Storage Plants [6]

Plant name	Country	Power rating	Features
Ricky river PHS plant	U.S.	32 MW	The world’s first large-scale commercial PHS plant
Bath County PHS plant	U.S.	3003 MW	The world’s largest power rated PHS plant
Okinawa Yanbaru PHS	Japan	~30 MW	Only commercial seawater PHS plant
Hawaiian Elec. Co. PHS	U.S.	-	Claimed 87% relatively high cycle efficiency
PHS of Ikaria Island	Greece	2.655 MW	One of the first wind-PHS plants (under construction)

Among the PHS plants listed in Table 2. above, the facility with the largest power rating is the Bath County PHS plant which is located in the U.S. This plant has a power rating of 3003 MW which is much greater than all the other plants on this list. The PHS plant in Ikaria Island, Greece, which is still under construction will utilize wind in its technology. The power rating of this site is expected to be about 2.6 MW which is much smaller than the other plants on this list. There are many more innovative PHS plants both under construction and commercially available; the list above just shows a few examples of prominent capabilities within this technology.

3.2. Flywheel

Flywheel energy storage is a type of mechanical energy storage technology that converts energy from the grid into a spinning disc [1]. Flywheel technology was first used during the Industrial Revolution for high impulsive forces in punch presses and forges and to stabilize the power from steam engines [7]. In this system, two magnetic bearings are placed in a vacuum and the disc is connected to a central shaft which rotates on the bearings [1]. More energy is absorbed from the grid and stored when the flywheel spins faster and the system can be slowed down to utilize the energy. Flywheels have low energy densities relative to other technologies but high power densities. A limitation of this technology is the strength of the disc material to endure the stresses due to rotation [1]. Prior to the modern development of fibers and resins for the plastics industry, steel presented a limitation to the advancement of flywheel technology because of the speed/weight ratio and safety [7]. Strong, lightweight materials have enabled new designs of flywheel technology to outperform the previous ones. In regards to grid applications, flywheels are most suitable for short-time power quality services and frequency regulation [1]. Nevertheless, they can be utilized as a hybrid with battery or fuel cells which are high energy storage devices.

There are two main types of flywheel energy storage (FES) systems: low speed and high speed [6]. Low speed flywheels are made from steel and rotate below $6x10^3$ rpm. Advanced composites such as carbon fiber are used for high speed flywheels which can rotate up to about 10^5 rpm. The inertia and the rotating speed of the flywheel determine the amount of energy stored in the system. High speed flywheels tend to cost much more than low speed flywheels. Table 3 below shows different flywheel systems and their useful applications based on their performance characteristics. The Beacon Power Company built a 20 MW modular plant in New York in June 2011, which is listed in the table below [6]. This facility is under commercial use and employs 200 high speed flywheel systems. This plant provides about 10% of N.Y.'s frequency regulation demand and fast response frequency regulation to the grid. Table 3 shows other useful areas for flywheels such as a high power supply for nuclear fusion furnace in the Japan Atomic Energy Center and applications in Aerospace research. Focus areas for emerging research in this field include: materials for increasing the rotation speed and power densities, high carrying capacity for bearings, and high speed electrical machines.

Table 3 - Flywheel Energy Storage Facilities [6]

Firms/Institutes	Characteristics	Application Area
Active Power Company	Clean Source series 100-2000 kW	Backup power supply, UPS systems
Beacon Power Company	100/150 kW a unit, 20 MW/5 MW h plant	Freq. regulation, power quality, voltage support
Boeing Phantom Works	100 kW/5 kW h, HT magnetic bearings	Power quality and peak shaving
Japan Atomic Energy Center	235 MVA, steel flywheel	High power supply to Nuclear fusion furnace
Piller power systems Ltd.	3600-1500 rpm, 2.4 MW for 8 s	Ride-through power and sources of backup power
NASA Glenn research center	$2x10^4 – 6x10^4$ rpm, 3.6 MW h	Supply on aerospace aviation & other transports

3.3. Battery Performance

The cost, performance, and lifetime of batteries are all impacted by the conditions and manner in which they are used. The depth of discharge (DoD), is the capacity of a battery that has been used [8]. The DoD significantly impacts the operational life which is measured in charge cycles. The amount of charge and discharge cycles completed by a battery before it considerably loses its performance is called the cycle life of a battery. Furthermore, if a battery is only capable of delivering 60-80% of its original capacity when it is fully charged, then it could be considered at the end of its cycle life [8]. Charging profiles, discharging profiles, and power requirements all vary for different electric system services. For example, load shifting to store excess renewable energy to be used at a later time tends to require longer charging profiles. These factors, along with other benefits and disadvantages should be considered in selecting battery and other forms of energy storage technologies.

3.4. Lithium-Ion Batteries

Fifty percent of the small portable application market is dominated by lithium-ion batteries [1]. This is primarily because lithium ion batteries are very efficient, have a quick response time, and possess both a high energy density and a long cycle life. These batteries do not emit hydrogen gas and have a higher energy density (both in terms of volume and weight) than lead acid batteries [9]. Among available secondary batteries, lithium-ion batteries have the highest energy density because lithium is the lightest metal on earth. The telecommunications industry can use lithium ion batteries for its applications since large form factor batteries are commercially available [9].

For back-up applications in the telecommunications industry, the lithium-ion battery is assimilated into a power plant. Protection features are integrated inside the battery pack of lithium-ion batteries to ensure safe operation. The internal overcharge protection circuits and special packaging required for large scale utilization of lithium-ion batteries make them very costly [1]. However, lithium-ion energy storage ranges from a few kilowatt hours to multi-megawatt hours. Grid ancillary services such as spinning reserve and frequency regulation are examples of the larger scale storage use, while residential applications such as solar panels on rooftops are representative of one of the smaller scale uses.

In lithium-ion batteries, graphitic carbon is used for the anode and lithiated metal oxides (compounds with lithium, an appropriate metal, and oxygen) are used for the cathode [1]. Lithium ions at the cathode move through the electrolyte toward the anode during battery charging and the electrons move in the opposite direction during discharging. Intercalation is a process in which ions fit between the atomic layers of the electrode [10]. The mass of the electrode hence determines the capacity of a lithium-ion battery. The other components of this battery include distribution panels, rectifiers, a controller, and different sizes of cables [9]. Smooth integration of the lithium-ion battery into the power plant is crucial for safe operation. The viability of lithium-ion batteries is constrained due to a limited number of sources to derive lithium and the high costs associated with the special packaging for large-scale use [1]. Lead acid batteries do not need the electronic control circuitry that lithium-ion batteries require for optimal safety. Furthermore, system testing is the only means by which telecommunication systems can successfully utilize lithium-ion batteries and ensure safe operation [9].

3.5. Lithium-Air Batteries

Lithium –air batteries take oxygen from the air outside and use it for a chemical reaction [11]. Chemical energy is converted to electrical energy via the sharing of a common carrier electron in electrochemical storage [10]. During discharge, these batteries release lithium ions at the metallic lithium anode [10]. The ions travel through the electrolyte and combine with oxygen at the cathode to form lithium peroxide (Li_2O_2). This product accumulates at the porous carbon cathode where the reaction takes place. In order to recharge this battery, an external voltage is applied to break up the lithium peroxide. The oxygen is released back into the environment and the metal ion moves back towards the anode.

These batteries have a high energy output in proportion to their weight, and thus are considered promising for portable electronic devices and electric cars [11]. The reason Li-air batteries have high energy densities is because the surface area of the cathode primarily affects the accumulation of lithium peroxide during the chemical reaction, not the mass or volume of the cathode [10]. The theoretical energy density of Li-air batteries can be compared to that of a gasoline engine (13,000 Wh kg^{-1}, the practical energy density is 1,700 Wh kg^{-1}) [12]. However, this comparison is incomprehensive since it does not take into account all the components of the battery that would significantly reduce that energy density figure. One of the major drawbacks to this technology is that a lot of energy is wasted as heat [11]. Lithium-ion batteries cannot handle moisture or carbon dioxide, hence they degrade relatively quickly. Side reactions can also occur which hinders the performance of the battery [10]. Furthermore, the challenges posed by Li-air batteries are their unstable cathode in moist atmospheres, incomplete discharge, formation of alkyl carbonates, and a lack of understanding of the catalytic effect [12]. A lot more research must be done before these batteries become commercially available.

3.6. Supercapacitors

Supercapacitors, also referred to as electrochemical capacitors, store electrical charge at a surface-electrolyte of high-surface area carbon electrodes [13]. If the supercapacitor has its two electrodes connected to an external current path, current will flow until there is complete charge balance. Voltage must be applied to return the capacitor to its charged state. This process occurs very quickly and is easily reversed because the charge is stored physically and there are no chemical phase changes taking place. There are virtually no limits to the discharge-charge cycle which means that this process can be repeated over and over again [13].

In supercapacitors, the energy is stored across the double layer located at the interface between an electrolyte and an electrically conductive carbon [1]. High surface-area materials such as activated carbon are used in supercapacitors in order to increase their energy density. Furthermore, two types of electrolytes are used for supercapacitors: organic and aqueous. These types of electrolytes differ in the cell voltages at which they are stable. Organic electrolytes are stable at 2.7 V, while aqueous electrolytes are stable at 0.9 V [1]. Consequently, a much greater energy density can be achieved with organic electrolytes versus aqueous electrolytes. Supercapacitors also have two different types of designs: symmetric and asymmetric [13]. The same high surface-area carbon is used to make both the positive and negative electrodes in a symmetric design. On the other hand, different materials are used for the two electrodes in an asymmetric design. One material is a high-surface area carbon and the other is a battery-like electrode with a higher capacity. Supercapacitors have high power, good reliability, and long life cycles [15]. The drawback to supercapacitors, however, are their very low energy densities [1].

3.7. Super Magnetic Energy Storage

In a super magnetic energy storage (SMES) system, energy is stored in the form of a direct current (DC) magnetic field after current passes through a superconductor [14]. The superconductor carries current with nearly no resistive losses as it produces a magnetic field because it operates at cryogenic (very low) temperatures. Therefore, energy can be stored persistently until it is needed. Stored electrical energy is released in the alternating current (AC) system during the discharge phase [6]. An SMES system is generally comprised of four parts: the power conditions system, the superconducting coil with the magnet, the cryogenic system, and the control unit [14]. SMES systems have exceptional performance capabilities for use in power systems largely due to advances in power electronics and superconducting technologies. Hence, electrical energy storage by SMES is expected to be the next generation technology.

The advantageous properties of SMES technologies are: long cyclic life, high power density, and quick response times. The SMES system response, however, would depend on the power conditioning system and the superconducting coil [1]. The two groups in which superconducting coils are classified are Low Temperature Superconducting coils (LTS) and High Temperature Superconducting (HTS). The LTS coils work at approximately 5 K while the HTS coils work at approximately 70 K [6]. Liquid hydrogen is used to operate a low temperature SMES, which increases operation cost due to cooling [14]. A high temperature superconducting coil, which is now available, uses only liquid nitrogen. Liquid nitrogen is readily available and much cheaper than liquid hydrogen. Higher temperatures, which are only suitable with HTS coils, increase the reliability of the system and reduce costs for refrigeration.

Power system and pulse power are two types of applications for SMES systems. The concept of applying a SMES system to a power system requires the superconducting magnet to be charged during off-peak time with excess generation of the basic load units. During peak time, the surplus is discharged to the AC power system. Pulse power applications involve smoothing out voltage and mitigating flicker by using the pulse magnets of the SMES. The 500 kV Pacific Intertie, the electric power transmission line which transmits electricity from the Pacific Northwest to California, was the first SMES to receive full commercial status for superconducting power grid-application in 1981 [14]. A lot of research has been conducted since then for SMES applications to power systems. However, the stability of power systems has been compromised in recent years because of environment and energy costs. Stabilizing devices are thus needed in modern power systems for reliable operation.

4. Discussion and Conclusion

4.1. Discussion

Data centers and communication networks are amongst the largest power consumers and emitters of greenhouse gases (GHGs) and consequently have a lot to benefit from smart-grid driven practices such as real-time pricing and distributed generation [15]. Datacenters and telecommunication networks have a combined electricity demand equivalent to that of the fifth largest country [15, 16]. Large direct current (“DC”) power supplies and uninterruptible power supply (“UPS”) plants are used in conjunction with extensive battery banks for central offices in Telecommunications Companies (“Operators”) [17]. This is in order to maintain connectivity of equipment during power outages and ensure reliability. It is hence no surprise that both datacenters and telecommunication networks are impacted by carbon costs and high electricity prices. Furthermore, reducing carbon emissions and promoting energy efficiency have become prominent focus areas in these fields.

Evidently, a top priority within this sector is to maintain continual and reliable service. As will be discussed shortly, redundancy is built into datacenters and many other systems to ensure reliability. If this industry could tap into an unlimited supply of energy for operations, then the magnitude of energy consumed by datacenters and telecommunication networks would be no cause for alarm. However, the gravity of this energy demand poses a threat to the long-term sustainability of the industry even with the increased utilization of renewables and energy storage technologies. The analysis to follow will include: a review of the aforementioned storage technologies; a brief examination of datacenter operation and costs; a note on a diesel-photovoltaic hybrid system; and an analysis on the state and outlook of federal tax incentives for renewable energy deployment. The considerations within this paper are not fully comprehensive but provide a brief insight into the state of energy storage and potential challenges and opportunities for the telecommunications industry.

Technology Review

Six types of electrical energy storage technologies have been reviewed in this paper. Table 4 and Table 5 below show a costs and performance analysis of five of those technologies. There are many technical and commercial aspects to review prior to selecting the most appropriate energy storage system. Some of these technical terms have been used earlier in this paper but will be further defined now for clarification. The response time is the speed in which energy is released or absorbed. The energy density is the stored energy per volume while the power density is the rated output power per volume. Power is the amount of energy used per time. The storage capacity is the amount of energy available in a storage system after charging. Self-discharge is the amount of stored energy that has dissipated during a period of time when the system was not used. The efficiency is related to the amount of inherent energy losses in the storage principle. Many internal components of energy storage technologies have a constant power demand and can consume energy outside the intended use of those systems. The more energy lost in relation to the energy content stored, the less efficient the system. The efficiency, storage capacity, energy density, and response time are the technical characteristics included in Table 4 and Table 5 below.

The technologies listed in Table 4 and Table 5 are supercapacitors, SMES, flywheel, PHS and lithium-ion batteries. A similar analysis of the technical characteristics of lithium-air batteries has yet to be conducted since the state of this technology is still in the early phases of research and design.

Table 4 - Technical characteristics of energy storage systems [18]

Storage technology	Efficiency (%)	Capacity (MW)	Energy density (Wh/kg)	Capital ($/kW)
Supercapacitor	90-95	0.3	2.5-15	300
SMES	95-98	0.1-10	0.5-5	300
Flywheel	93-95	0.25	10-30	350
PHS	75-86	100-5,000	0.5-1.5	600-2,000
Li-ion battery	85-90	0.1	75-200	4,000

Table 5 - Technical characteristics of energy storage systems [18]

Storage technology	Capital ($/kWh)	Response Time	Lifetime	Environmental impact
Supercapacitor	2000	Very fast	20+	Small
SMES	10,000	Very fast	20+	Benign
Flywheel	5,000	Very fast (<ms)	~15	Almost
PHS	5-100	Fast (ms)	40-60	Negative
Li-ion battery	2,500	Fast	5-15	Negative

In Table 4, most of the technologies can reach up to 90% efficiency with the exception of PHS. However, the capacity of PHS systems is more than 10 fold that of the others. Pumped hydro storage is the most mature energy storage system amongst those listed and it has the longest lifetime. The drawback to PHS is its negative impact on the environment. The only technology with a benign environmental impact is the SMES system. However, it has a capital cost of $10,000/kWh which is the largest amongst the list in Table 5. If capital cost is measured in dollars per kilowatt ($/kW), then the cost of pumped hydro storage and lithium-ion batteries far exceed that of SMES systems. All the technologies have either a fast or a very fast response time. Even with these similarities, a further review of response times would be crucial to choosing the most appropriate system. Furthermore, a comprehensive technical review and cost benefit analysis must be considered prior to determining the most appropriate technology.

Datacenter Operation and Cost

The primary source of power for a datacenter is the utility substation by which power enters. Diesel generators (DGs) are used as secondary backup power [19]. To switch between these two power sources, an automatic transfer switch (ATS) is used. About 10-20 seconds is required to switch to the DG power source if there is a utility failure and UPS systems are used to bridge that gap. Power distribution units (PDUs) receive power from the UPS and route that power to racks which host IT equipment [21]. Dual power supplies are used for IT equipment for redundancy and they both draw power from one of the UPS units. The peak power requirement of a data center directly impacts the one-time capital cost known as the capital expenditure (“Cap-ex”), which is the cost of designing and constructing the datacenter [19]. The power infrastructure of a datacenter includes: diesel generators, utility substations, and an uninterruptible power supply (UPS). The provisioned capacity of a datacenter’s power infrastructure is determined by the peak power. The average growth of Cap-ex along with provisioned peak capacity is estimated to be $15-20/W [21]. At this rate, a datacenter with a provisioned peak capacity of 1 MW would result in a Cap-ex value of $15 million.

The operational expenditure (“Op-ex”) is the cost associated with electricity bills of the datacenter and it is also related to peak power. Datacenter operators have a vested interest in reducing their energy consumption and improving their energy efficiency. However, utility billing at datacenters is somewhat complex and there are two important points worth noting. First off, utilities charge datacenters separately for the energy consumed and the peak power they draw over a month [19]. Secondly, energy tariffs vary for on-peak and off-peak time periods. Tariffs for major U.S. utilities are listed in the table below.

Table 6 - Commercial Tariffs (2011 data) [19].

Utility	Energy Cost (c/kWh)	Peak Cost ($/kW)
Duke	4.7	12
Ohio AEP	4.9	9.86
PG&E	10.8	12
Georgia Power	10.7	12.93
PEPCO	4.3	7.36

The peak cost shown above is different from the provisioned peak capacity. Peak power is typically tracked over finer time scales than the energy component. Table 6 above was replicated from a study about stored energy in data centers in order to show two important contributions of the utility bill for datacenters [19]. Note that the rates listed in Table 6 are 2011 values and have most likely changed since then. For some utility providers such as Georgia Power and PG&E the rates are comparable for energy costs and peak costs. The peak cost for each utility listed in Table 6 is greater than the energy cost in every case. The peak demand periods are the times during the day when energy consumption is the highest. Utilities must plan their operations more strenuously during these times and thus charge their customers more for on-peak time periods as opposed to off-peak time periods. Consequently, companies and data centers can reap immense savings by reducing their on-peak consumption.

Emerging and disruptive technologies that improve energy efficiency may not necessarily mitigate the challenges of growing demand for the telecommunications industry. Furthermore, telecommunications companies must factor in the rising rate of electricity prices and peak demand surcharges into their operational expenses [17]. Central offices in the telecommunications industry as well as smart devices are rapidly growing in their demand for electricity. Higher demand results in greater power requirements for the associated equipment [17]. Telecom companies have managed some of these costs with demand side management programs by utilizing existing assets such as backup power systems. These strategies can be expanded upon for future environmental and financial benefits but maintaining reliability in telecommunication networks and data center will depend on sustainable energy consumption. Since peak demand periods strain utility providers, they also pose a risk for their customers as well. Newer technologies may be more equipped to handle more demand; nevertheless, operating any system to full capacity creates insecurity within a business. Just as back-up power system ensures reliability within datacenters, lower consumption creates a threshold which makes operation more sustainable and justifiable from business financial management perspectives.

Diesel-Photovoltaic Hybrid System

Hybrid systems are increasingly becoming the best option for supplying telecommunications equipment for remote locations [20]. With these types of systems, reliable power is ensured through a combination of different technologies that generate and store energy. Design and operation considerations for these technologies include: availability of local resources, load requirements, maintenance, environment issues, efficiency, and economic aspects. The hybrid system that will be briefly discussed here is a diesel-photovoltaic power system which includes batteries and supercapacitors [20]. The diesel generator was included in this system to balance the intermittent nature of photovoltaic generators. Diesel generators, however, operate dynamically and do not instantaneously produce the required energy. Hence, supercapacitors and batteries were also included to compensate for the short periods of time when the PV and diesel generators lack energy and to utilize the surplus production of the PV generator.

One objective within this system is to minimize the fuel consumption of the diesel generator and maximize the production of the photovoltaic generator [20]. Control systems are essential to optimize all the components of such a complex system. The configuration of these technologies will not be discussed but can be viewed in reference [20]. The purpose of the battery is to supply the average power to the load and absorb surplus energy from the PV array. The batteries are complemented by supercapacitors which are controlled in order to smooth power bursts from either the PV generator or the load. The most suitable conditions for this standalone power system are in areas that are primarily sunny throughout most of the year. Although it is challenging to identify the appropriate number and type of generators and backup power, standalone power systems are a self-sufficient alternative supply of energy to the grid. Diesel generators do not have to be used for these systems and have often been avoided due to their fuel dependence and polluting features. Nonetheless, this hybrid relies on PV generation and the energy storage of supercapacitors which enable the standalone power system to supply telecommunications equipment in remote locations.

Federal Tax Incentives for Renewable Energy

Over the last two decades, one of the primary incentives for renewable energy deployment in the U.S. has been federal tax credits [21]. The Energy Policy Act of 1992 enacted the production tax credit (PTC) which has notably supported wind energy over the years. The Energy Policy Act of 2005 established an investment tax credit (ITC) of 30% for solar projects which further incentivized the deployment of renewables. Federal renewable tax credits have been modified, extended, expired, and renewed a few times since their establishment. The Consolidated Appropriations Act of 2016 was passed in December 2015 and has granted a five year extension of both the ITC and the PTC. Prior to this, the PTC had already expired and the ITC was set to expire by the end of 2016. The wind PTC terminated on December 31, 2014 and had a value of 2.3c/kWh for electricity production for the plant's output during the first 10 years of its operation. The PTC expiration was very nuanced in that projects that had "commenced construction" with commercial operation dates after 2014 were still eligible for the tax credit. The Consolidated Appropriations Act of 2016 specifically extended the provision to the ITC for commercial and utility-scale solar and it retained the provision for the "commenced-construction" for the wind PTC [21]. Table 7 below shows the breakdown on the new policy in comparison to the lack thereof.

Table 7 - Schedule of Wind and Solar Tax Credits Prior to and After the Consolidated Appropriations Act of 2016 [21].

	New Policy	2015	2016	2017	2018	2019	2020	2021	Future
Wind PTC		Full	Full	80%	60%	40%	0%	0%	0%
Solar ITC	Utility	30%	30%	30%	30%	30%	26%	22%	10%
	Commercial/Third-Party-Owned	30%	30%	30%	30%	30%	26%	22%	10%
	Residential Host-Owned	30%	30%	30%	30%	30%	26%	22%	0%
	Prior Policy	2015	2016	2017	2018	2019	2020	2021	Future
Wind PTC		0%	0%	0%	0%	0%	0%	0%	0%
Solar ITC	Utility	30%	30%	10%	10%	10%	10%	10%	10%
	Commercial/Third-Party-Owned	30%	30%	10%	10%	10%	10%	10%	10%

As evident in Table 7. above, the Consolidated Appropriations Act of 2016 starts phasing out in 2020 for solar and is completely phase out for wind by 2020. A study by Bloomberg New Energy Finance shows a dwindling gap in the global average levelised cost of electricity (LCOE) for renewable energy as opposed to gas and coal [22]. The research conducted in 2015 indicates that the LCOE for solar PV fell from $129 per megawatt-hour in the first half of the year to $122 per mega-watt-hour in the second half. Similarly, the cost for onshore wind fell from $85 to $83 per mega-watt hour between the first and second half of the year. These may seem like small changes but in that same time frame, coal-fired generation had an increased LCOE from $66 to $75 per MWh in the Americas. In Europe, that increase was from $82 to $105 per MWh and in Asia-Pacific the increase was from $68 to $73 per MWh. Levelised costs account for capital expenditures, the cost of equity and debt finance, and operation and maintenance fees. Offshore wind still remains substantially more expensive than wind, solar PV, coal or gas. Nonetheless, the LCOE for offshore wind has reduced from $176 to $174 per MWh in 2015.

With the trend of lower electricity costs for renewable energy sources and the passage of the Consolidated Appropriations Act of 2016, the outlook for renewables seems to be quite favorable. Both legislative and market forces affect the return on investment that investors will receive from purchasing renewables and the current state of both factors are encouraging. Even with increased investment in renewables, the telecommunications industry will still rely on back-up power systems in addition to energy storage systems until storage technologies increase in their level of maturity. All these measures help promote energy efficiency and meet the energy demand in their networks. However, it is worth noting that consumers all over the world are becoming increasingly accustomed to instant data and internet access. As more people plug into telecommunications networks, more energy will be required from the networks themselves. Thus, incentivizing lower consumption from customers will help promote long-term network stability and efficiency.

4.2. Conclusion

No system is 100% thermodynamically efficient; therefore, energy storage is an essential link in the energy supply chain [5]. Typically, energy is lost as heat to the external environment in most systems. If the waste heat from different systems was captured and stored, then it could be used as an energy feedstock for other processes. The change in global resource consumption to thrive off a low carbon economy requires more energy storage as more energy is predicted to come from renewable resources. Since renewables such as wind and solar are intermittent resources, they are unreliable as stand-alone systems. Energy storage drastically increases the reliability of these resources. The subject of energy storage is a wide and growing topic. There is still a lot more to learn about this subject; be that as it may, this review paper briefly surveyed a portion of current technologies.

In order to determine energy storage capacity within an industry, electrical network constraints must be considered for an accurate forecasting of the required investments and the future energy balance [23]. Energy storage systems are essential for the optimal utilization of renewable energy sources and for increasing the efficiency and operating capabilities of nonrenewable sources [1]. The deployment of these technologies helps reduce greenhouse gas emissions and meet future energy demands. Unused electricity can be stored in various systems and supplied back into the grid when needed, though growing consumption could eventually strain this novel technology as well. As for deployment of these technologies, two important considerations must be addressed. The first consideration is that these technologies must be cost competitive to conventional ones in order to increase their deployment. Without favorable legislation, the telecommunications industry will be less likely to invest in renewable energy and storage technologies and their use will be limited to backup power. The second consideration is the growing demand for energy and other resources which may render new technologies insufficient to satisfy global consumption. This latter point is more challenging to resolve because businesses and individuals must begin to understand that they cannot attain linear growth from finite resources. Ultimately, a combination of energy efficient upgrades, renewable energy deployment, energy storage systems, and most importantly, a commitment to reduced energy consumption is needed to ensure the long-term stability and success of the telecommunications industry.

5. Abbreviations and Definitions

5.1. Abbreviations

AC	alternating current
ATS	automatic transfer units

DC	direct current
DoD	depth of discharge
DOE	Department of Energy
EES	electricity energy storage
GHGs	greenhouse gases
GW	giga-watt
HTS	high temperature superconducting
Kg	Kilogram
kWh	kilo-watt hour
Li	Lithium
LCOE	levelised cost of electricity
LTS	low temperature superconducting
ms	milli-seconds
MW	mega-watt
PDUs	power distribution units
PHS	pumped hydro storage/pumped hydroelectric storage (interchangeable)
PV	photovoltaic
TWh	tera-watt hour
UPS	uninterruptible power supply
U.S.	United States
Wh	watt hour
V	volts
SMES	superconducting magnetic energy storage
SCTE	Society of Cable Telecommunications Engineers

5.2. Definitions

Alternating Current	AC occurs when electrons in a conductor reverse their direction of movement[2]
Aqueous	A chemical or compound that is soluble in water
Direct Current	The unidirectional flow of electrons
Electrolytes	A chemical compound that conducts electricity
Lead-time	The amount of time that passes between when a process starts and ends
Organic	A chemical or compound that contains carbon atoms
resins	Natural or synthetic organic compounds[3]

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[3] https://www.britannica.com/science/resin

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Methods to Maximize IoT Battery Life

A Technical Paper prepared for SCTE/ISBE by

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1. Introduction

Addressing Internet of Things (IoT) energy consumption has a number of potential benefits, from the obvious environmental value of reducing the disposal of batteries, to the customer experience benefits and resource savings that could be associated with fewer service calls. The concurrent migration to smaller devices requires action to extend the sensor battery life; chief among these is to improve battery selection techniques.

On the surface, choosing a battery for an IoT sensor may seem like a simple task, but in reality it involves a complex process of discovery, selection, and testing as outlined in this paper. Typically, replaceable Lithium Coin Cell, Cylindrical Alkaline, and Lithium batteries are utilized, as are other flat battery designs. While some IoT sensors use special high-cost chemical or rechargeable batteries, this paper is focused on extending battery life for low-cost wireless IoT sensors with replaceable batteries, deployed by the cable industry.

Simulated implementation for both performance and economic aspects are evaluated. Among important factors are assessing subscriber and system operator experiences from time, cost savings, safety, and disposal perspectives. Recommendations are proposed to identify product design and deployment opportunities for Multiple System Operators (MSOs).

2. Battery Procurement

The objective for choosing a battery for an IoT sensor design is to find either the lowest-cost battery or, in some instances, to find a name-brand battery that meets your requirements. Battery manufacturers consistently advertise that their battery is superior and longer lasting, but the reality may be that only a marginal improvement of one over another battery exists. Also, often what is advertised differs drastically from what is delivered.

There are four false assumptions about procuring batteries: (1) major manufacturers have the highest-quality batteries; (2) lithium batteries are more powerful than alkaline batteries; (3) brand-name batteries cost more than no-name batteries; and (4) buying batteries from major vendor websites or distributors is good enough.

2.1. Origin of Manufacture

Major battery manufacturers may procure their batteries from their own factories or from third-party factories. From either source, the case and look of the battery can be identical. There are two methods to determine the quality of the battery. The first is to contact the battery vendor directly, which is usually performed under NDA, and ask in what factory (or factories) the battery in question is manufactured and which factory carries out quality control; then confirm the country of manufacture on the battery label. If the battery manufacturer has multiple factories in China, for example, modify the procurement agreement to state that only batteries of this type are acceptable from this factory, unless notified and agreed to otherwise.

2.2. Pricing

Typically, information on battery pricing is found on bulk battery or distributors' websites, but this pricing does not reflect the discounts that a large company would be provided for volume discounting for a new IoT device and other products for which the company is currently procuring. Public website pricing is typically higher than what can be negotiated by a bulk customer, so it is suggested that pricing should become an exercise of discussions between major battery manufacturers and, in some cases, lower-cost manufacturers for cost comparison. Major manufacturers may sometimes charge the same price or a price within a couple of cents per unit as a lower-cost manufacturer, so that value becomes a less important factor than other considerations when deciding on which battery to use.

2.3. Storage

Vendors must be able to provide documentation that their batteries are stored at a temperature close to 70 °F in a humidity-controlled environment, and that batteries provided are fresh and are not from dated warehouse stock. For manufacturer devices shipped, it is strongly suggested to require batteries be dated no more than 3 months from the date of manufacture as battery capacity generally degrades about 10% per year. Recently, battery manufacturers have been marking batteries with an expiration date rather than a date of manufacture. For example, in 2016, a battery with a 2022 expiration date and a 10-year shelf life is likely to be 4 years old, and thus have an estimated 40% reduction in capacity. Battery manufacturers that have fully automated factories usually have less contamination as a result non-manual production and a better level of quality therefore exists. Battery contamination during manufacture, such as a dielectric marred by micro-pinholes, will result in a shorter battery lifespan than rated.

3. Battery Internal Resistance

All batteries will have some amount of internal resistance (see battery schematic in the figure below). For example, a CR2450 cell will have an IR of 20 Ω or less. IR can be measured by calculation or using a test meter.

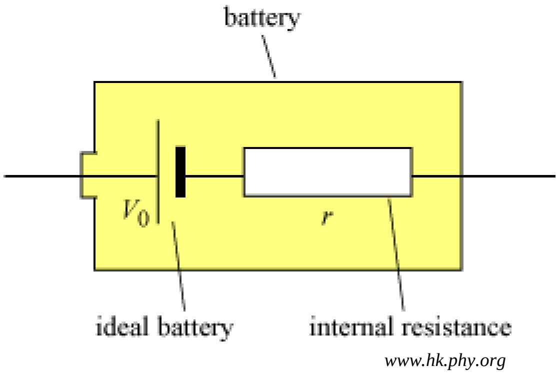
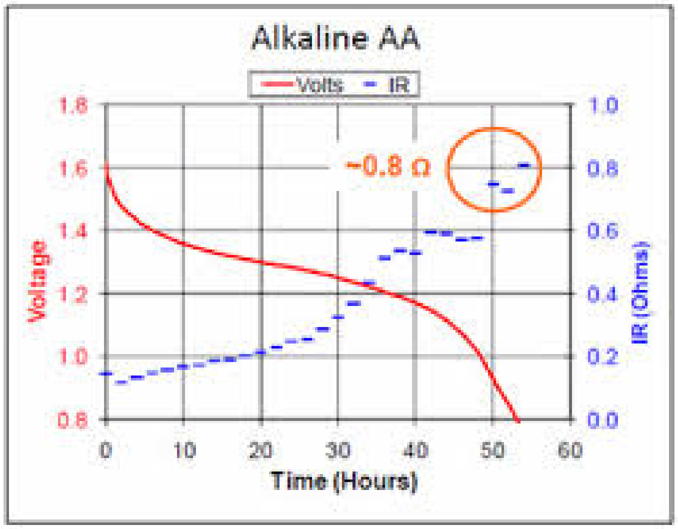


Figure 1 - Battery Schematic Illustrating Internal Resistance

Internal resistance generally varies as the inverse of the battery voltage drop over the life of the battery, as shown in the below diagram. Battery charts such as those shown below typically show “light loading” over time, while IoT devices on transmission, for example, exhibit a high level of instantaneous current draw which results in a lower voltage provided by the battery, depending on the battery maximum current draw specification and the internal resistance of the battery. Hence, there is a need to select device circuits with the lowest current draw for a max-loading operation such as wireless transmissions. For example, for a 50 mA instantaneous draw, a 3 V lithium coin cell may drop 400 mV, while two 1.5 V AA alkaline batteries in series (i.e., 3 V) may only drop 100 mV, mostly due to the much lower internal resistance of the alkaline battery.

In some cases, depending on current drawn, alkaline batteries can outperform lithium coin cell batteries. Performing a load test with both lithium and alkaline batteries is an improved method to determine the best battery for a particular application.



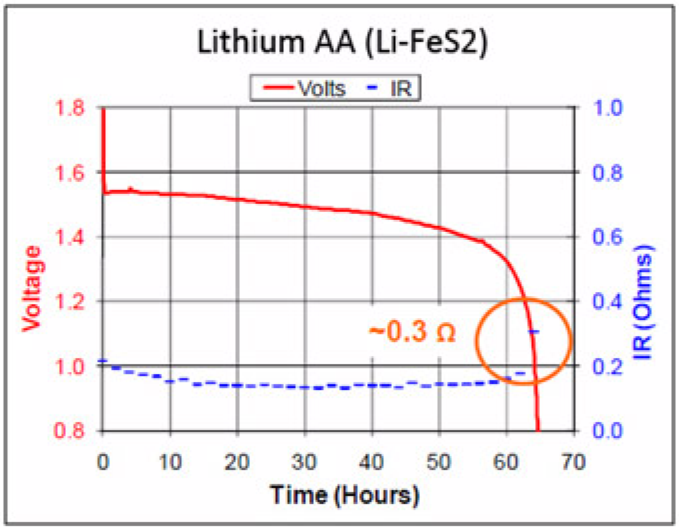


Figure 2 - Variation of Voltage and IR over Time for Alkaline (top) and Lithium (bottom) Batteries

4. Advanced Battery Designs

New battery chemistries bring more resistance to degradation over time, particularly in a high-heat environment. However, these batteries have the trade-offs of smaller capacity and slightly higher cost. Modern smoke alarms are using such batteries for a sealed 10-year life span. (Note: While the battery life of these devices is longer than that of standard batteries, the 10-year life span assumes a life spent in standby. Battery life is shortened when alarms occur.) Taking into account customer satisfaction, truck-roll costs, and disposal related to battery replacement, utilizing the new chemistry, longer-life batteries is well worth the small increase in cost.

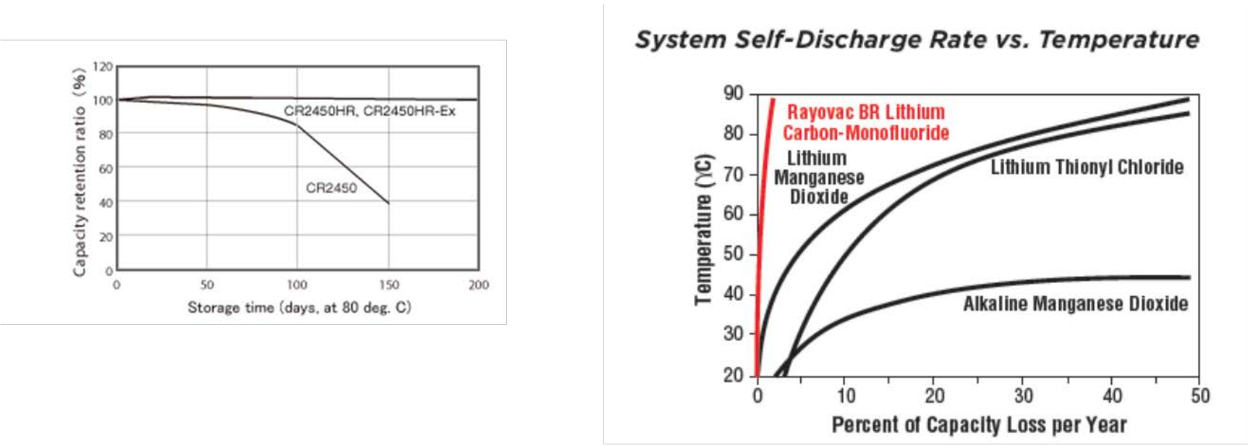


Figure 3 - Analysis of Battery Capacity over Time for Different Manufacturers/Products

5. Storage and Disposal

It is suggested that only a limited number of batteries and devices with batteries be carried in trucks and that stock be regularly turned over, as trucks exposed to the extreme summer heat will reduce battery life. (Extreme heat degrades batteries; cold preserves batteries as long as the temperature is not at or below the manufacturer's extreme cold battery rating.)

Batteries removed from IoT sensors should be wrapped/stored as recommended by the battery manufacturer and returned for recycling or proper disposal as advised by the battery manufacturer. One benefit of battery recycling is that some new batteries are composed of a small amount of recycled battery material, and are marked as such. Thus, battery recycling is encouraged to promote a "greener" environment for battery usage.

6. Safety

Accidental shorting of batteries must always be a consideration. Some battery types, but not all manufacturers within that type, incorporate a built-in PTC circuit for additional protection. Other recommended protective measures include: the addition of battery protection circuits in the device design, mechanical reverse battery protection, and wrapping the batteries individually in plastic by the manufacturer. It is strongly suggested to contact the battery manufacturer for their complete list of battery safety recommendations.

7. Summary

To maximize IoT battery life the following steps are required:

1. Select device designs with the lowest battery cut-off voltage, lowest sleep current, lowest max-load draw, and adequate (low ESR) capacitance across the battery circuit.
2. Review the battery candidate's data sheets and select advanced battery chemistries with the lowest internal resistance, widest operating temperature range, largest capacity, and lowest capacity loss over storage time.
3. Pre-screen a large sample of batteries to find the product with the most consistent and lowest internal resistance.
4. Test and compare candidate batteries over a temperature range, loading down to the cut-off voltage of the device.
5. Follow the procurement procedures in this paper for the final battery vendor selection criteria.

When the steps above are taken for the IoT design and battery selection, the result will be maximal battery life (reduced overall battery change-out cost), fewer service calls (reduced operator cost), and increased customer satisfaction (customer retention benefit).

To truly maximize IoT device battery life beyond this paper's recommendations, device designers must employ smart software to conserve battery life: sleep the device for the maximum time the application will allow and ensure device functions take as little time as possible.

8. Abbreviations and Definitions

8.1. Abbreviations

ESR	equivalent series resistance
IoT	Internet of Things
IR	internal resistance
MSO	Multiple System Operators
PTC	positive temperature coefficient

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IoT Device Energy Harvesting Technologies and Implementations

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1. Introduction

The proliferation of wireless home security and automation sensors and devices: the so-called Internet of Things (IoT), has advanced the need for improvements to battery life. The cable industry has deployed IoT sensor solutions for many years, but needs to reduce costly service calls for replacing batteries and to work towards addressing global environmental concerns regarding the disposal of spent batteries.

Increasing inexpensive chemical battery capacities is reaching its physical limits, and the concurrent migration to smaller devices calls for further innovations to extend battery-powered sensor life. Chief among these is energy harvesting. This paper focuses on describing promising energy harvesting methods and solutions that may be applied to IoT devices. Business and consumer drivers for improved efficiency sensor-powering solutions are discussed.

Sample test results from both performance and economic aspects are evaluated. Of particular importance are assessing user and system operator experiences from time and cost savings perspectives. Recommendations are proposed that identify implementation opportunities for Multiple System Operators (MSOs).

2. Sources of Power

A variety of energy harvesting sources such as, but not limited to: wind, rain, heat, cold, vibration, water flow in pipes, ocean currents, induction (temperature/electrical), motion, sunlight, and artificial light, will be discussed in this paper. Some of these energy sources can provide a direct power input while others, depending on the application, can be utilized for target implementations. For example, solar energy can be converted directly into power to be used for long-term functions such as a solar light or to top off batteries such as a solar calculator. Separately, the water flow in home plumbing pipes can be used to power a sensor (to send a status message) to indicate water flow is present.

3. Transferring Environmental Energy to Power IoT Devices

There are three modes of providing harvested energy to a device:

- Hybrid Mode
- Assist Mode
- Standalone Mode

These modes are described more fully in the subsections that follow.

3.1. Hybrid Mode (Ability to charge a battery)

Hybrid mode extends battery life and, in some cases, allows for a battery of a smaller form factor for the same design functionality and expected battery life. The device operates either on energy harvested in real time or on harvested energy stored, depending on the amount of energy available for harvesting.

Using harvested energy for charging a battery has some drawbacks. There is a loss in energy to implement a step-up or step-down circuit; the device requires the addition of a rechargeable battery and a charging circuit (for example, as shown in Figure 1, below), and power for the device is dependent upon favorable environmental conditions (e.g., solar cells typically yield the most energy in sunny climates).

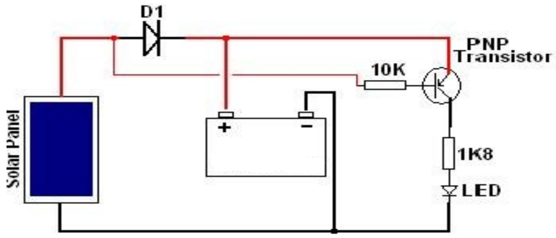

Figure 1 - Charging Circuit and Battery for Storing Energy from a Solar Panel

3.2. Assist Mode (Ability to store limited energy)

Assist mode is an efficient method where a smart circuit utilizes environmental energy, which may be very low power or have infrequent availability, as in a solar cell utilized indoors, to either assist in a function or "store" energy for future use in a capacitor or a supercapacitor: a capacitor with extremely high capacity and low leakage loss over time. It is challenging to use coin cell batteries in an assist mode configuration since they have a high internal resistance which causes a voltage drop during high-current demand, such as transmissions in IoT devices. IoT SoCs (Systems on a Chip) are rated for a "cutoff voltage": the voltage at which the device will cease to operate. The addition of a supercapacitor significantly reduces the voltage drop at high-demand periods, consequently raising the cutoff voltage of the device and thereby extending the battery life.

Assist mode can also be implemented with the addition of a small solar cell utilized to "top off" a battery for extremely low cost, for example, in basic handheld calculators or wearable devices where motion is converted to supplemental power for a device.

Figure 2 - Example of a Supercapacitor

3.3. Standalone Mode (Operated by harvested energy only)

In standalone mode, only the harvested external energy powers the device. Examples of using this method are in IoT devices without internal energy storage such as low-cost ZigBee light switches (mechanical-to-piezoelectric) and solar-only powered IoT devices. In Figure 3, below, is a solar-only powered calculator which works well in bright light, but is challenged by low-light conditions.

Figure 3 - Solar-powered Calculator

4. Device/Sensor Design Considerations

Circuits, including SoCs with wireless capability in IoT designs, are utilizing less power over time for increased functionality. Sleep currents in SoCs and MCUs are now in the Nano amps range and operational voltage required is decreasing over time: as low as around 1.7 V currently for SoCs. By reaching below 1.5 V if accomplished in the future, SoC operational voltage requirements would line up with commonly available 1.5 V batteries. Utilizing 1.5v battery(s) would generally not require boost circuits or batteries in series to support the SoC's operational voltage requirements. Efficiency of energy harvesting technologies is increasing while the wattage required for the electronics is decreasing.

Energy Harvesting Technologies Wattage

Electronic Circuit Wattage

The third leg of the stool for the above diagram is the most challenging for designers to implement: crafting software that goes beyond basic functionality to achieve a highly energy-efficient device. For example, turning off circuits when they're not in use and decreasing the CPU cycles for targeted functions, if supported by the SoC, decreases energy use and hence extends battery life.

5. Device/Sensor Examples

Device/sensor energy harvesting can be one of three types: conductive, mechanical, or radiant/electromagnetic energy. Conductive energy harvesting can be achieved through a temperature differential between two surfaces. Mechanical energy harvesting is achieved through motion/vibration. Radiant energy can come from the sun as solar energy and from the Earth's natural electromagnetic field as Schumann resonances. Unfortunately, the energy harvested via Schumann resonances is impracticable for sensors since the amount of energy collected would be very small and would require a very large antenna to collect it.

A push-button ZigBee wall switch (Figure 3) utilizes mechanical energy, through the motion of pushing a switch, to generate enough energy to send out a ZigBee message. This technology is excellent for sending a simple one-way message. However, without having the power to receive an acknowledgement or retry message without another mechanical action limits the use of this type of harvesting method.

Figure 4 - ZigBee Wall Switch

6. Mechanical Energy Harvesting

Mechanical energy can be harvested from motion or vibration and converted into electrical energy for devices/sensors. Utilizing Peltier technology, applied vibration provides electrical power such as a Peltier device mounted to a vibrating motor. Door sensors can utilize the mechanical motion of the door opening and closing to power them. In the shake flashlight (Figure 4), magnets and wire coils are combined with mechanical motion to induce a current that generates power to light an LED.

Figure 5 - Example of a Shake Flashlight

7. Solar Cell Energy Harvesting

Solar cell devices are ideal for outdoor areas where sunlight is prevalent for approximately 12 hours a day, though solar cells can be utilized indoors providing supplemental power to a device. Obviously, there are limitations for indoor use (indoor power is generally 1/1000 of outdoor), and efficiency is highly dependent on application and placement.

For IoT devices two-way and one-way communications may be utilized for applications. For simple one-way communicating devices with short messages, energy harvesting is ideal in standalone mode where it is the sole source of power such as with the ZigBee light switch. For two-way communications, especially for security systems where there is a high frequency of messaging, energy harvesting is more applicable as a supplemental energy source.

Most IoT devices tend to be black, dark gray, white, or off-white in color. Adding an energy harvesting solution such as a solar cell may change the aesthetics of the device, as solar cells are usually copper or black in tone with an overlaying metal grid. IoT device manufacturers strive to integrate the energy harvesting technology into the device with the best aesthetics possible. The remote control with a solar cell (Figure 5) uses the ambient light in the home, when available, to provide supplemental power and charge the battery. With this, either the life of the remote control primary batteries can be extended or the number of primary batteries in a remote control can be reduced. The addition of a non-replaceable rechargeable battery or a supercapacitor storage mechanism is typically utilized to accomplish the aforementioned applications. The customer experience would thereby be enhanced by the extension of the battery replacement period and/or the overall reduced cost of primary cell replacement.

Figure 6 - Remote Control with Solar Cell

8. Temperature Transfer Energy Harvesting

The concept of harvesting heat energy is used by a flashlight that uses Peltier tiles to convert the heat from the hand holding the flashlight to electricity to power the light. Peltier tiles generate electricity when the temperature differential of its top and bottom layers is approximately 5° C.

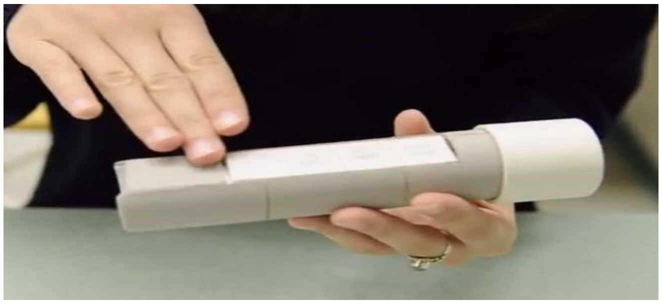

Figure 7 - Flashlight with Peltier Tiles

9. RF Energy Harvesting

Harvesting RF-transmitted energy depends on the level of transmissions and the conversion of RF energy to actual utilized power, such as paralleling the antenna and energy harvesting from the RF power provided by the antenna on transmission. Directing such power to a capacitor to be utilized for future transmission or other device is one harvesting method.

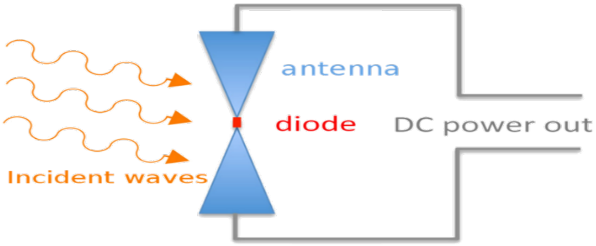

Figure 8 - Harvesting RF Energy to Generate DC Power

9.1. Advanced Energy Harvesting

Advanced energy harvesting technologies may be cost- and implementation-challenged, but they are noted here for their promising potential.

9.2. MEMS Pyroelectric Capacitor

A MEMS pyroelectric capacitor is technology for harvesting residual heat to power devices/peripherals such as a USB port or HVAC system vent position.

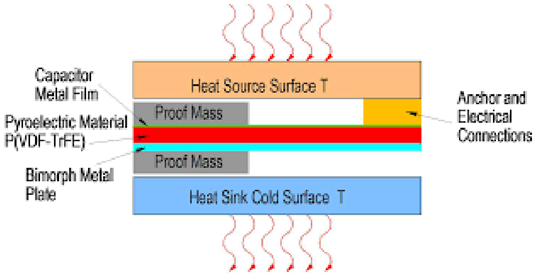

Figure 9 - MEMS Pyroelectric Capacitor Concept

9.3. Nano-Antennas (Nantennas) for Solar Energy Harvesting

Nano-antennas achieve close to 90% efficiency compared to 10-20% for silicone-based solar cell energy harvesting. Utilizing silver in nantennas produces higher efficiency in conjunction with fine-tuning the dipole dimensions. Below are two examples of nantennas (Figure 4).

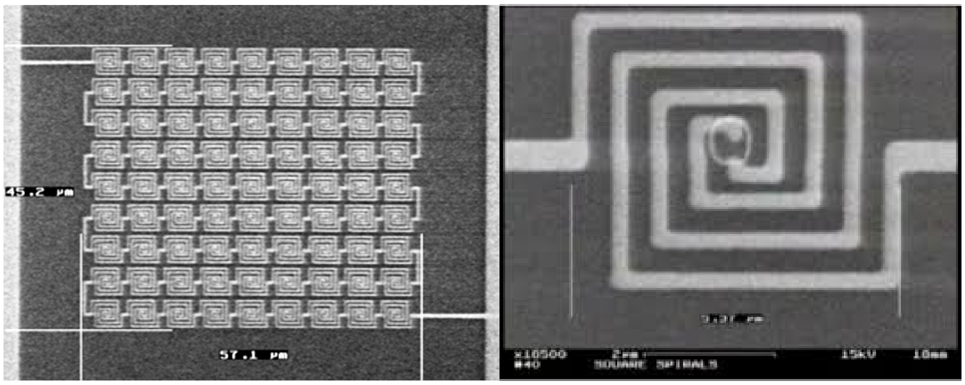

Figure 10 - Two Examples of Nano-Antennas

10. Summary

Battery technology capacities per form factor for IoT devices have somewhat stabilized lately. The IoT battery-life design challenge is a “coordinated multi-pronged approach” matching the environmental energy available for harvesting to the design choice, choosing low-energy electronics/designs, and most importantly, crafting smart software for energy conversation wherever possible.

Improving IoT battery life reduces overall battery change-out costs, provides for fewer service calls (reduced operator cost), and increases customer satisfaction (customer retention benefit). Additionally, the extension of primary cell battery life or the reduction in the number of primary cells utilizing energy harvesting opens up extensive opportunities for a “green initiative” for the cable industry.

11. Abbreviations and Definitions

11.1. Abbreviations

IoT	Internet of Things
SoC	system on a chip
RF	radio frequency
HVAC	heating, ventilation and air conditioning
LED	light emitting diode
USB	universal serial bus
MEMS	micro-electro-mechanical systems

11.2. Definitions

Downstream	Information flowing from the hub to the user
Upstream	Information flowing from the user to the hub
MEMS	Miniature devices composed of integrated mechanical and electrical components which work in conjunction with each other for sensing and reporting.

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