Operational Practices for Energy Conservation/Sustainability Measures in the Cable Outside Plant

An Operational Practice prepared for SCTE•ISBE by the Access Network Efficiency Working Group in the SCTE•ISBE Standards Energy Management Subcommittee

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Introduction

The cable outside plant consumes the majority of power of the overall network. Power is consumed not only by the active devices (optical nodes, amplifiers, Wi-Fi hot spots, LoRa gateways, micro cells, cell backhaul, 5G, etc.) but also by the process of moving the power through the outside plant to reach these devices and the associated Joule heating (I^2R) losses in the cabling.

Changes underway in the network architecture and increases in the sophistication and functionality of the active devices are predicted to cause an increase in the power required. Remote physical (PHY) and remote media access control (MAC) and PHY are predicted to increase the power dissipation at the locations of conventional optical nodes. Amplifiers with higher gain and higher radio frequency (RF) bandwidth and the resulting linearity demands may also increase the required dissipation at these locations, however this increase may be offset by gallium nitride technology and new energy efficiency measures. Finally, the addition of new active devices such as Wi-Fi hot spots, micro-cells, and LoRa gateway devices will add new powering burdens to the outside plant (OSP).

The present network architecture transports the electrical power for these active devices through existing coaxial cable or cable that is specifically dedicated to transmission of electrical power. The coaxial cable exhibits a significant electrical resistance at the frequencies used for electrical power, typically 60 Hz or 50 Hz. The resistance of the coaxial cable at powering frequencies is virtually identical to the resistance at DC and is therefore typically referred to as the coaxial direct current (DC) loop resistance. The DC loop resistance can result in dissipation of significant amounts of electrical power in the coaxial cable itself as the electrical power is transported through the OSP to active devices.

These sources of power utilization in the OSP will be enumerated in this document. Several expected changes that will affect the power utilization are then reviewed. Finally, energy conservation measures to reduce or minimize the power required to operate the outside plant are explored. The technology trends and recommendations for conservation measures are part of an overall roadmap (see Figure 1) of the SCTE•ISBE Access Network Efficiency (ANE) working group within the Energy Management Subcommittee (EMS) of the SCTE•ISBE Standards program. This roadmap exists to address energy consumption and conservation in the access or "last mile" portion of modern cable networks.

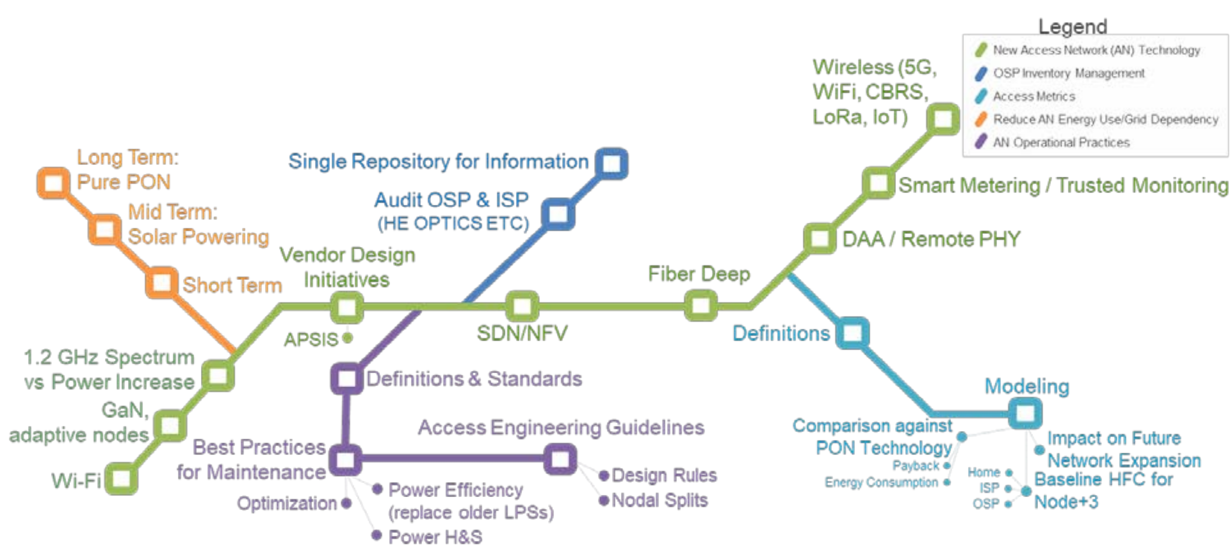


Figure 1 – ANE roadmap of technologies and energy conservation measures

Access Network Energy Consumption, Conservation Measures, and Operational Practices for Improved Efficiency

1. Energy consumption growth with current access network trends

It is well known that the OSP dominates the overall energy bill for a cable operator [ULM]. Figure 2 shows that the access network, as comprised of edge facilities and the OSP represents over 73% of the cable operator's total energy bill, and that the OSP alone can represent over half of the total bill.

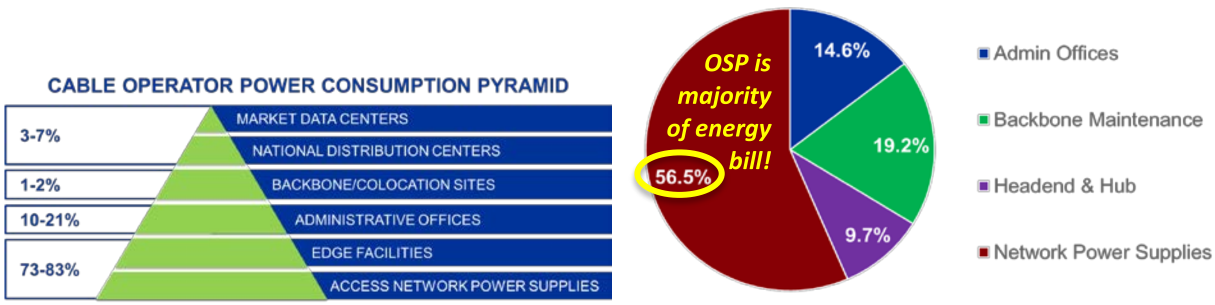


Figure 2 – Breakout of energy bill components for cable operators

1.1. Next generation nodes and distributed access architectures

There are many changes underway in access architecture, such as deployment of fiber deep, distributed access architectures (DAAs), including remote PHY and remote MAC-PHY, expansion of the upper RF spectrum limit to 1.2 GHz, full duplex (FDX) DOCSIS™, and even virtualization of the converged cable access platform (CCAP). Unfortunately, ***each one*** of these are currently predicted to increase the OSP energy consumption. The good news is that DAA, by significantly expanding the capacity of the fiber link from the edge facility to the fiber optic node in the OSP, will significantly improve the energy efficiency of the OSP as measured by the OSP energy efficiency metrics of kilowatt hours per terabyte consumed (kWh/TB). Nonetheless, the total energy bill in the OSP will go up, just not by as much as it would by using conventional hybrid fiber-coax (HFC) architectures to achieve the same capacity increase. A survey of modeling efforts to predict the energy consumption of network architectures is given next.

Ulm [ULM] recently compared several network architectures in terms of energy consumption via the combined edge facility + OSP energy consumption per 100,000 households passed (HP), the results of which are summarized in Figure 3. In this analysis, Ulm neglected the cooling reduction possible in edge facilities from DAAs and pure fiber architectures.

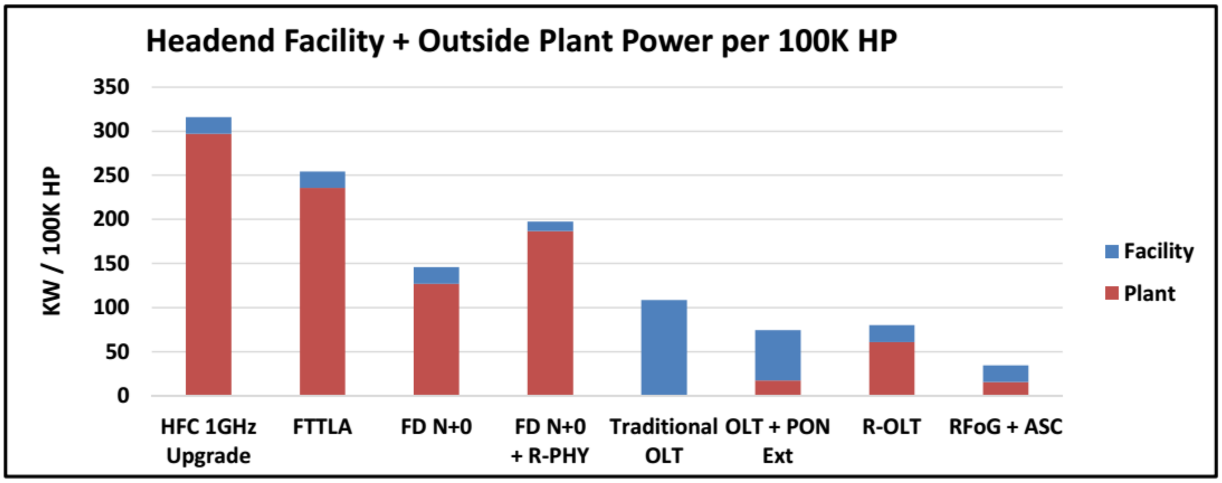


Figure 3 – Power consumed by edge facility and outside plant per 100k HP (from [ULM]

Ulm concluded that for all HFC architectures, the power to drive the outside plant continues to dominate the overall energy consumption of the combined edge facility + OSP, and further that the migration to fiber to the premises (FTTP) will take over a decade. His model predicted a 33% increase in kW/100k HP in adding remote PHY to a fiber deep (FD) architecture. Thus, finding ways to improve the energy efficiency of the OSP to reduce energy consumption will be a critical component to helping cable operators reduce energy costs for the network and the company overall.

Similarly, Loeffelholz [LOE] concluded that the industry migration to FD node plus zero (N+0), shown in Figure 3, makes sense financially in terms of the cost per HP to upgrade the OSP and also in terms of enabling remote PHY/DAA as well as FDX DOCSIS™, and that is indeed the way many cable operators are moving. As will be described below, the desire of many cable operators not to move existing line power supplies (LPSs) so they can avoid permitting costs and delays, is unfortunately resulting in the distributed powering scheme of current OSP to be reverted back into centralized powering schemes, with their concomitant higher Joule heating (I^2R) losses, thereby decreasing energy efficiency.

Holobinko also predicted a 25-30% increase in OSP power consumption and associated energy costs by moving to remote PHY architectures [HOL] (see Figure 4), and he did include the potential reduction in the heating, ventilation, and air-conditioning (HVAC) costs in the edge facilities that are expected from a lower heat load from the telecommunications equipment (Figure 5). Unfortunately, the HVAC energy savings was quite small in comparison to the growth of energy consumption in the OSP, in agreement with Ulm's work. Note that Holobinko used a sample RF design for areas that were selected based on density per mile, node size and aerial/underground ratio, and the sample design consisted of three HFC nodes where the design areas varied in size from ~400 to ~600 HP per fiber node, and the density per mile of coax plant varied from ~95 to 160 HP/mile, while Ulm's work integrated the energy impact across 100k HP. The main point is that a rise in OSP energy consumption of 25-33% is predicted just from moving to remote PHY/DAA by both of these authors.

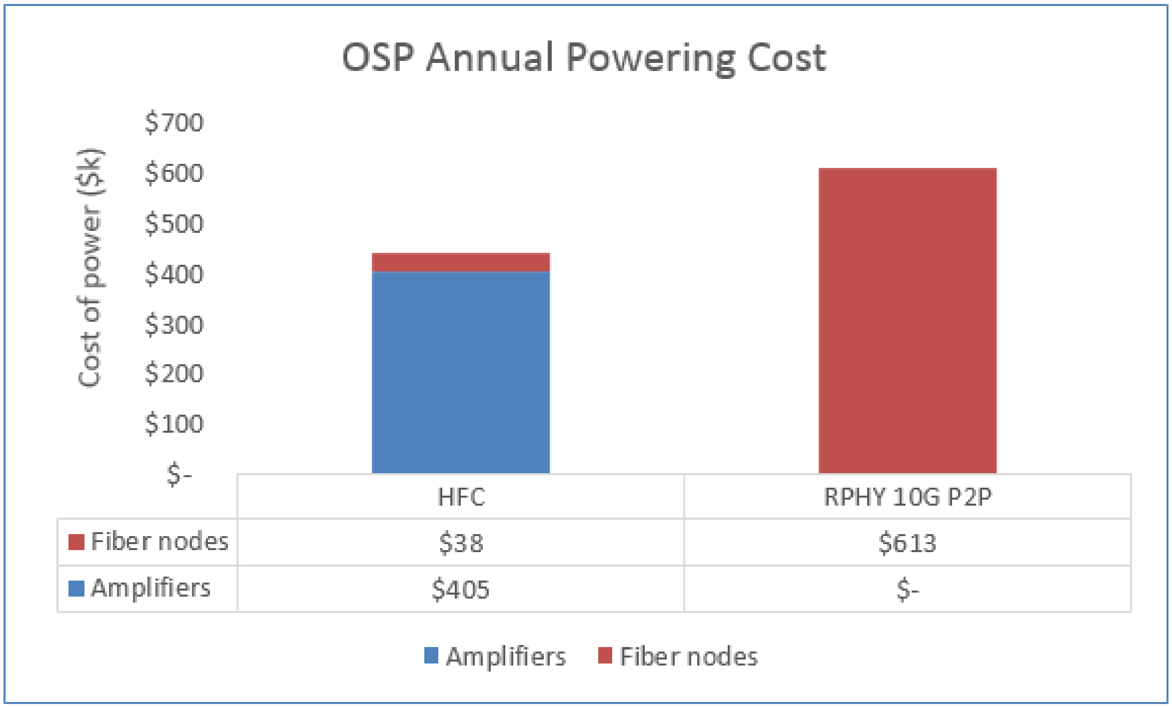
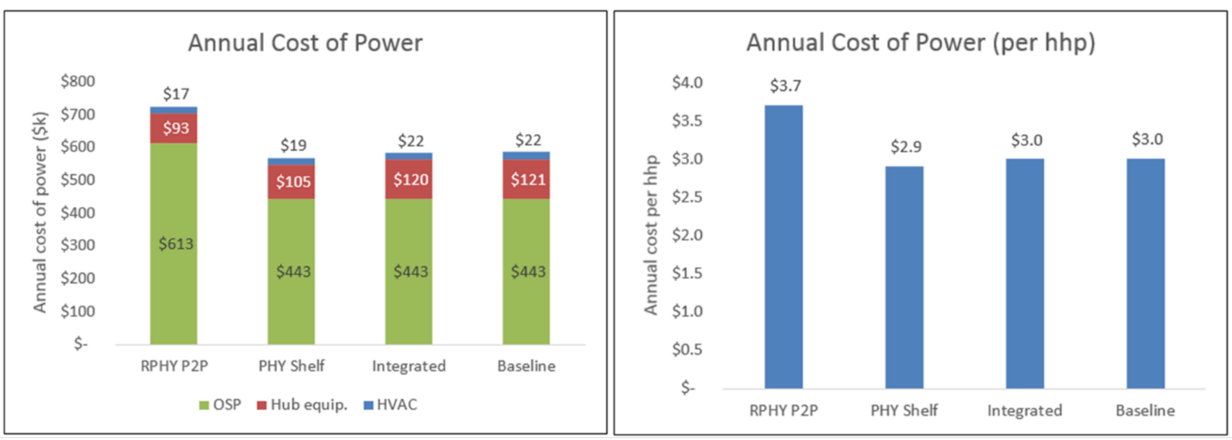


Figure 4 – OSP annual powering cost (from [HOL])



RPHY P2P	PHY Shelf	Integrated	Baseline
$ 17	$ 19	$ 22	$ 22
$ 93	$ 105	$ 120	$ 121
$ 613	$ 443	$ 443	$ 443
$ 723	**$ 568**	**$ 585**	**$ 587**

RPHY P2P	PHY Shelf	Integrated	Baseline
$ 3.7	$ 2.9	$ 3.0	$ 3.0
23%	-3%	0%	0%

Figure 5 – Remote PHY annual powering cost (from HOL)

Finally, a Bell Labs Consulting white paper [BEL] came to similar conclusions about remote architectures causing approximately 25% growth in the OSP energy consumption, while dropping the energy consumption of the edge facilities (see Figure 6). In this case, the point made was the virtualization in the edge facilities and OSP could further and significantly reduce the energy consumption in the edge facilities while only slightly raising the energy consumption in the OSP. However, in light of much smaller energy consumption of edge facilities vs. the OSP (see the pie chart in Figure 2 previously), it is not clear whether the total access network energy consumption (edge facilities plus OSP) will actually decrease from such virtual architectures.

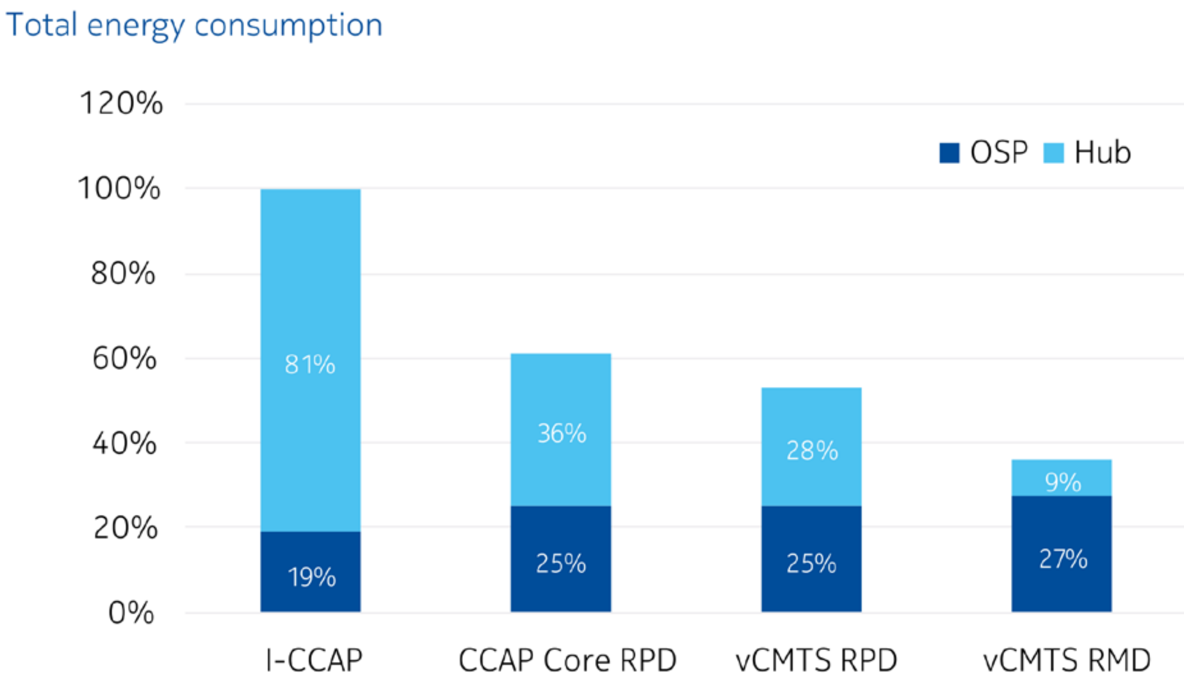


Figure 6 – Total access network energy consumption models for conventional and virtualized architectures (from [BEL])

In important point made by Ulm is that while FD architectures theoretically reduce the total OSP energy consumption by reducing the total number of actives and replacing them with modern, more energy efficient technology, if the LPS units are not moved from the original node locations to the new node locations, the OSP energy consumption per HP could be double what it might otherwise have been if LPSs were moved to the new node locations. Unfortunately, due to permitting costs, the LPS locations are seldom moved. This effect is independent of the OSP energy consumption increase due to remote PHY.

1.2. Impact of wireless access on the OSP energy consumption: small cells/5G, Wi-Fi, IoT, CBRS, LoRa, security and surveillance, and more

In a companion SCTE•ISBE Expo 2018 paper by one author [LOE2] it is shown that the impact of deploying a plethora of wireless devices in the OSP is far from insignificant. A summary of the total energy impact of adding full geographic coverage of a variety of wireless technologies to the OSP on line power supplies (LPSs) is shown in Table 1. If all new wireless devices were deployed maximally, the summation of this additional energy load on the OSP is 820 Watts, or approximately 9.2 amps of additional current draw on existing power supplies, which at a nominal level of 15 amps represents a 61% further increase in OSP energy consumption.

Table 1 – Energy impact of implementing wireless and new revenue generating services

Technology	Watts per Unit*	Units per LPS*	Total Power (W)
CBRS	50	8	400
LoRa (32 Ch)	45	1	45
Wi-Fi	45	5	225
5G LTE	75	2	150

There may be hope to reduce this impact of wireless devices on OSP energy consumption by noting that many of these devices do not operate at full power consumption all of the time, and thus have a lower average power than the peak power usage. In an upcoming SCTE Network Operations Subcommittee (NOS) journal paper tentatively titled "Operational practices for the deployment and maintenance of wireless devices on HFC plant," the Hitachi and Comcast authors note that "understanding real world power consumption by the device and any deviation from the manufacturer's device specifications can help avoid overestimating power requirements and performing unnecessary power supply upgrades." They further note that "Services requiring a two-device solution (a separate radio device and HFC-powered cable modem) can place a substantial load on the network, depending on the required power draw of the radio device supplied over Ethernet from the HFC cable modem," and thus driving to single device solutions could mitigate some of the OSP energy growth shown in Table 1. Finally, they note that "savings can be achieved by understanding the average and peak power draw of the radio device in real world conditions and under normal usage -- rather than conservatively designing to a sustained maximum power over Ethernet (POE) or POE+ output for every device."

1.3. Impact of fiber deep and not moving power supplies

Fiber deep deployment unfortunately is also raising the OSP energy consumption. An example study done by one of the authors (Spee) is shown in Figure 7, where even after eliminating one LPS post-split for fiber deep, total power goes up by 61%. This is a general result when not moving or adding LPSs to be collocated with fiber optic nodes, resulting in a significant increase in OSP energy consumption. The additional power requirements are due to (a) the additional nodes and (b) the losses in transmitting power from power supply to node, including additional power supply efficiency losses.

Pre-Split	Voltage Rating	Current Rating	% Load	Pin	PS Losses (W)	Monthly kWh
LPS 1	60	15	78%	710	82	518
LPS 2	60	15	66%	616	81	450
LPS 3	60	15	29%	307	73	224
				Totals	236	1192
					W/HHP	4.3

Post-Split, Initial	Voltage Rating	Current Rating	% Load	Pin	PS Losses (W)	Monthly kWh
LPS 1	90	22	69%	1400	172	1022
LPS 2	90	18	54%	912	130	666
LPS 3	90	15	29%	460	109	336
				Totals	412	2024
					W/HHP	7.4

Post-Split, Revised	Voltage Rating	Current Rating	% Load	Pin	PS Losses (W)	Monthly kWh
LPS 1	Eliminated					
LPS 2	90	18	77%	1265	147	924
LPS 3	90	24	61%	1371	181	1001
				Totals	328	1924
					W/HHP	7.0

Figure 7 – Energy consumption growth with practical fiber deep deployment

In general, multiple system operators (MSO's) do not want to move power supplies to avoid permitting and cost issues. Likewise the high cost of updating the existing coax to improve direct current (DC) loop performance results in an unattractive return on investment. In some cases, cable replacement also runs into utility pole attachment issues since overlash opportunities are limited.

The results shown in Figure 7 are for going from N+4 to N+0 OSP architecture. The coaxial cable type used was predominantly types 500 and 625. These have loop resistances of 1.7 and 1.1 Ω / kft, respectively, which is typical in many older systems. Many others use type 750 or 875, which drops the loop resistance to 0.76 or 0.56 Ω / kft, and can significantly reduce the additional energy loss from transmitting power to the new, deeper fiber node locations. But optimized coaxial power distribution is still less efficient than a distributed powering architecture where all fiber nodes have their own dedicated and collocated power supplies.

It is possible however to mitigate somewhat the energy inefficiency of not moving LSPs. The initial design increased the projected power requirement by almost 70%, due to both the increased power requirement and also the increased power supply loss. However, the actual power requirement came down a bit in the end: since the LPSs were to be upgraded anyway, this provided an opportunity to increase the power provided by LPS 3 in Figure 7 and eliminate LPS 1. LPS 3 was in a more optimal location for delivering power, so I^2R losses and thus overall powering requirements could be reduced. The savings in fixed monthly utility fee and operational expenditures such as batteries, preventive maintenance (PM), and so on, mitigated the increased energy consumption slightly. Again, this project, along with many current projects, had a strict requirement not to change out any cable in order to avoid utility costs and delays. Essentially, fiber deep projects as practically implemented, revert the distributed OSP powering architecture to a central powering scenario.

1.4. Summary of energy consumption trends for the OSP architecture

It has been shown that nextgen remote PHY/DAA technology will likely increase total access network power consumption by 25-30%. Fiber deep deployment without moving LPSs increases OSP energy consumption by another 61%. And adding a full wireless capability across multiple services can add yet another 61% to the OSP energy consumption. Thus, OSP energy consumption has the potential to more than double from the combination of OSP evolution and new wireless service additions.

2. Energy Efficiency Improvements for OSP Equipment

This section will cover energy efficiency improvements in next generation OSP equipment that can offset the OSP energy consumption growth presented in the previous section.

2.1. New LPS technologies with greater efficiency

Table 2 shows how modern 3rd generation LPS units (GEN 3) are more efficient overall in providing the same amount of power to the OSP active devices than previous generations of LSPs.

Table 2 – Efficiency improvements in power supply technology

PS Model	Load (Watts)	Daily Energy Consumption (kWh)	Annual Energy Consumption (kWh)
GEN 1 PS (90V)	600	18.00	6569.37

PS Model	Load (Watts)	Daily Energy Consumption (kWh)	Annual Energy Consumption (kWh)
1985 - 2000	1000	27.94	10196.64
GEN 2 PS (90V)	600	16.90	6168.48
2000 - 2010	1000	26.88	9812.47
	1350	35.82	13074.30
GEN 3 PS (90V)	600	16.87	6157.42
2011 - Today	1000	26.68	9736.79
	1350	35.45	12939.27

Since this will be explored later as a potential way to conserve energy in the OSP, note that the useful life of modern LSP technology, specifically a typical transformer module, is designed for a 15-year design life at an industry standard design temperature profile. The typical inverter module (IM) is designed for 8-year design life at an industry standard design temperature profile. Past history indicates a 15 to 20+ year life cycle for the power supply transformer modules and more than 8-year life cycle for the power supply inverter modules. Finally note that new LPS units also provide technologies like battery balancing, event recording, and accurate DOCSIS™-based monitoring, in addition to higher efficiency. Newer units also maintain their efficiency down to lower loading conditions, perhaps as low as 30% of max load. But while the energy efficiency improvement may be greater at lower loads, the total energy savings are lower due to the smaller energy consumption at low loading conditions.

Figure 8 shows the utility savings from early retirement of older generation LPS units at @ $0.22 per kWh.

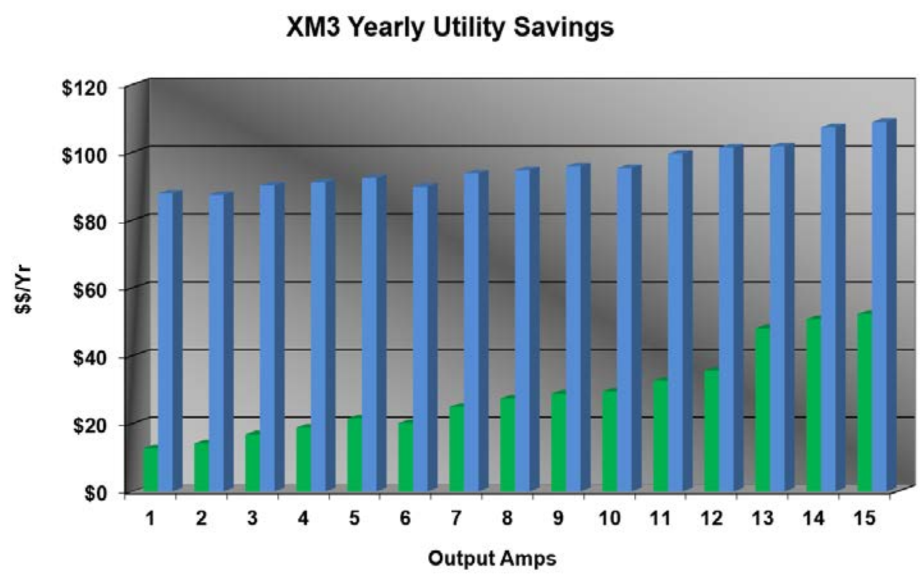


Figure 8 – Utility savings from more efficient LPS technology at $0.22 per kWh

To determine the utility power from LPS efficiency, I^2R losses and network load to utility power consumption, the following equation is used:

$$Utility\ Power\ (kW) = \left(\frac{P_{Network\ Load} + \sum \left(\frac{P_{@Active}}{V_{@Active}} \right)^2 * L_{Ohmic\ loss\ per\ ft\ of\ cable} * D_{ft\ of\ cable}}{Power\ Supply\ Efficiency} \right)$$

where P and V @Active are the power and voltage respectively at the active device, L is the DC loop resistance per unit length of the OSP cable and D is the length of the OSP cable.

2.2. New plant actives with greater efficiency

2.2.1. GaN technology

While remote PHY technology does consume more power overall, it uses GaN technology which is more energy efficient. The energy savings of newer GaN technology for OSP active devices was highlighted in an ANE working group presentation [DAY] where the combination of GaN technology, active linearization, and digital pre-distortion in next generation OSP active devices could have the potential to save up to 50% of power consumption per device.

A brief description of these technologies is below:

- Digital pre-distortion (DPD)
    - Requires digitized signal (Remote PHY)
    - >15 dB composite triple beat (CTB) reduction in back-off
    - ~25% reduction in power (18W drops to 14W, e.g.)
- Envelope tracking: adjust bias depending on envelope of signal (see Figure 9)
    - Cost & overhead of generating envelope
    - Amplifier bias modulation complexity
    - Voltage and current methods
- Beyond Class A : adjust bias depending on RF signal itself
    - Difficult to control broadband amplitude modulation to amplitude modulation (AM-AM) & amplitude modulation to phase modulation (AM-PM) responses
    - High speed devices are increasingly available to soften challenges
    - Can create actively linearized (AL) amplifiers using radio frequency integrated circuit (RFIC) approach (Figure 10)

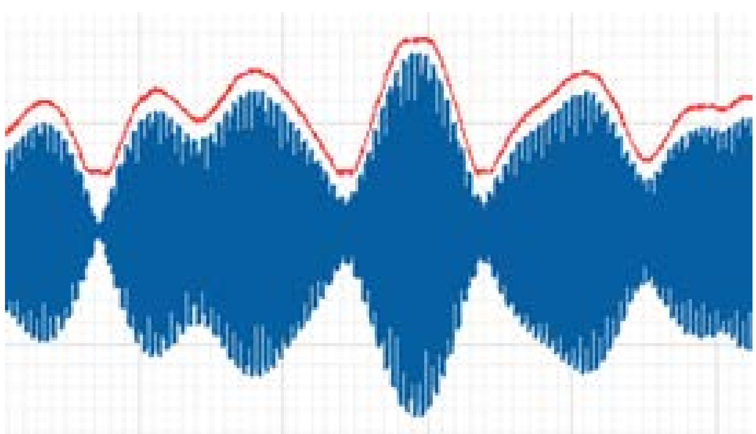


Figure 9 – Envelope Tracking Concept (from [DAY])

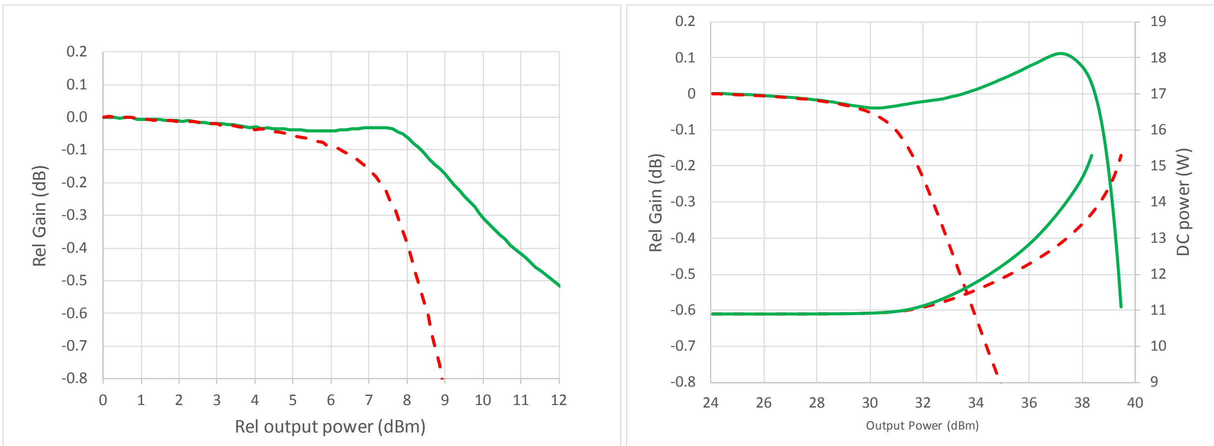


Figure 10 – Active linearization concept (from [DAY])

In the working group's discussion, the OSP equipment vendors noted that while there is some marginal improvement due to DPD, there is also a concomitant cost in processing power. Also, along with the improvements in efficiency in the next generation of GaN technology, there is perhaps another 5-10% improvement on the GaN hybrid itself. Current devices have GaAs driving GaN, so if next gen devices are 100% GaN, further improvements may be seen, however note that optimal GaN performance intimately depends on combining the best of a high speed ultra-linear technology e.g., GaAs p-type high electron mobility transistor) with GaN in a cascode topology. All agreed that the adaptive power systems interface specification (APSIS™) use case (see next section) for active bias control ("smart biasing") would be straightforward to design. The group noted that GaN is a given; without GaN a lot of efficiency improvement would be absent. DPD by itself gives 25% savings. OSP adaptive energy efficiency will mainly come from smart-biasing, but this presumes that DPD is used for all four output ports.

2.2.2. APSIS™ functionality

The other key energy efficiency improvement that may come with new active device technology is APSIS. It's estimated that 15% of power consumption may be saved in active devices using APSIS compliant technology that attenuates the bias current feeding RF amplifiers during off-peak hours [SAN].

APSIS defines a uniform mechanism to collect energy data and issue power state controls to devices in the network [SAN]:

- CMTS/CCAP
- High density edge QAM devices
- Switches/routers
- Fiber transport platforms
- Remote PHY-edge facilities
- Remote PHY-outside plant (OSP)/MDU
- More general fiber nodes
- RF amplifiers
- OSP power supplies

Diurnal adaptation by one vendor at SCTE Cable-Tec Expo 2016 on a CCAP device demonstrated a 40% power consumption reduction during times of off-peak load, which translates to a %15 efficiency gain during the OSP daily cycle. Another vendor has estimated a ~%15 efficiency gain by attenuating bias current feeding RF amplifiers during off-peak times. And in general, the IT equipment demand response applications have yielded up to 30% cost avoidance [GOV].

2.2.3. Example of new MSO node requirements

The following examples of required and suggested new requirements for next generation node technology from a major US cable operator will drive increased energy efficiency in new OSP active devices [HOW]:

- Enable node ports to have their PAs remotely shut off and on, saving significant power consumption when a port is not used (required)
- Consider power factor-corrected DC power packs to optimize efficiency of the AC network power supplies (suggested, especially for FDX DOCSIS)
- Implement digital pre-distortion (DPD) for the PAs to achieve the required modulation error ratio (MER) at lower DC bias levels (required)
- Support envelope tracking technology to reduce the average bias current in conjunction with the variations in the RF waveform (suggested). This is to modulate the power supply voltage with the RF envelope of the input signal to the power amplifier. Envelope tracking to lower average supply voltage to the power amplifier, thereby lowering the DC power consumption of the power amplifier

It is noted that DAA, software defined networking (SDN), and network functions virtualization (NFV) all provide powerful tools for intelligent power management, and orchestration will be a critical component of managing these energy efficiency measures.

2.2.4. Generic access platform (GAP)

Another opportunity for improving efficiency and visibility in OSP active devices exists in the GAP specification currently in development within the Interface Practices Subcommittee (IPS) of the SCTE•ISBE standards program. A possibility exists for integrating energy monitoring, tracking, and control into the platform specification, or as a later module that adhered to the specification.

2.3. Alternate energy for the OSP

In this section, solar generation in OSP is discussed, along with a review of applicable IEEE standards and implications for powering the OSP via distributed solar energy generation, and finally thoughts on utility provider partnering.

2.3.1. Cable operator explorations of solar powering the OSP

In the early days of the SCTE Energy 2020 program, the group explored solar powering of LPSs via photovoltaic panels on the top of the units. Unfortunately, there simply is not enough area on an LSP unit, especially those mounted on utility poles, to provide enough energy to significantly reduce the grid dependence of the OSP. The concept worked for erbium doped fiber amplifiers (EDFAs) for passive optical networks (PONs), but that is only due to the EDFA being used just to extend the reach of radio frequency over glass (RFoG) networks and thus consuming just under a half a watt of power.

Since then, two key industry events have renewed interest in solar power for the OSP. First, back in 2016, Liberty Global International (LGI) held a Spark Innovation initiative and the winning entry was the idea that solar powered cable customer premises might offer their excess energy during the day to power fiber optic nodes [LGI]. By focusing on using customer-provided (and funded) solar energy merely to reduce the need for batteries in the OSP LPSs, they were able to show a payback in 5 years for the small investment required to allow the nearby fiber node to accept power from the customer's premises. Second, Comcast recently announced a partnership with a solar energy installer so they might offer solar power generation to their customers.

Solar energy generation appears to be most prevalent in states with higher utility rates, e.g. CA, HI, and even parts of the northeast US, which is exactly where US cable operators would also like to reduce their energy bills.

But there are challenges for this concept, including:

- Adapting plant taps, to accept customer's solar power:
    - One solution is to power nodes directly, but this only works for FD architectures
    - Another is to use customer solar energy generation to reduce battery backup requirements, similarly to the LGI study
- Not repeating the mistakes of IEEE smart grid standards for frequency accuracy

In the LGI study, the customer as a sustainable energy supplier was promoted for energy savings, and the client gets money for spare capacity through a compensation scheme with two options:

- Purchasing conditions (electricity) LGI to the customer (from 22 cents/kWh to 6 cents/kWh)
- The client could enjoy cable services completely free of charge (or at least at a substantial discount)

The goal was to reduce node energy dependency from "traditional" suppliers by 10% and to also find a way to keep nodes online during power outages for at least 3 hours. Their calculations showed the operation should be profitable within 5 years.

Their plan was to install a separate 230V AC powerline between a fiber node and the residential/business to business (B2B) customer premises as depicted in Figure 11. Then, connect this powerline up to the control unit that is already in place.

The feasibility of the approach is based on the fact that household/business energy generation and consumption vary throughout the day (Figure 12). Excess solar capacity at daytime (orange) loads battery capacity (blue), allowing for energy consumption at night and selling excess capacity to the grid (green), or in this case, to the cable operator.

Strengths of the concept include:

- Direct customer involvement: the cable operator relies on client solar generation, striving to reach a financial win-win situation for both parties, plus they are indirectly "subsidizing" and encouraging sustainable energy production
- Versatile: can be expanded to include fuel cell or wind turbine power sources
- No huge up-front investments
- Compensation scheme discourages early client-side termination of arrangement

Weaknesses include:

- Limited control over hardware: the cable operator takes care of the powerline, the client retains control over their own in-house solar infrastructure; conversely this is also a potential strength

- Varying solar panel density: having all our nodes throughout the cable networks powered 100% through solar generation is far from realistic. Luckily, the target 10% seems possible.

Varying up-front costs they identified include the distance from node to client, as well as local governmental/bureaucratic procedures.

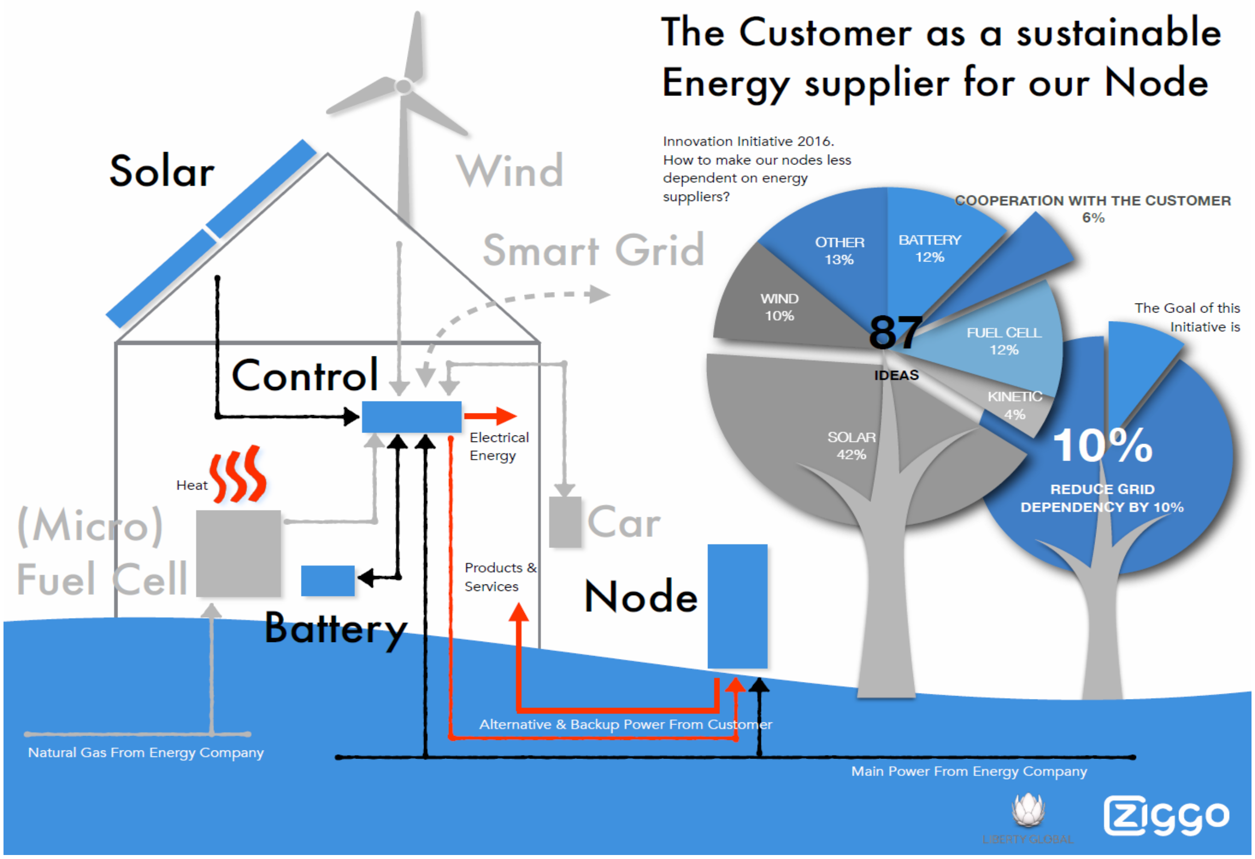


Figure 11 – Customer solar powering of node concept (from [LGI])

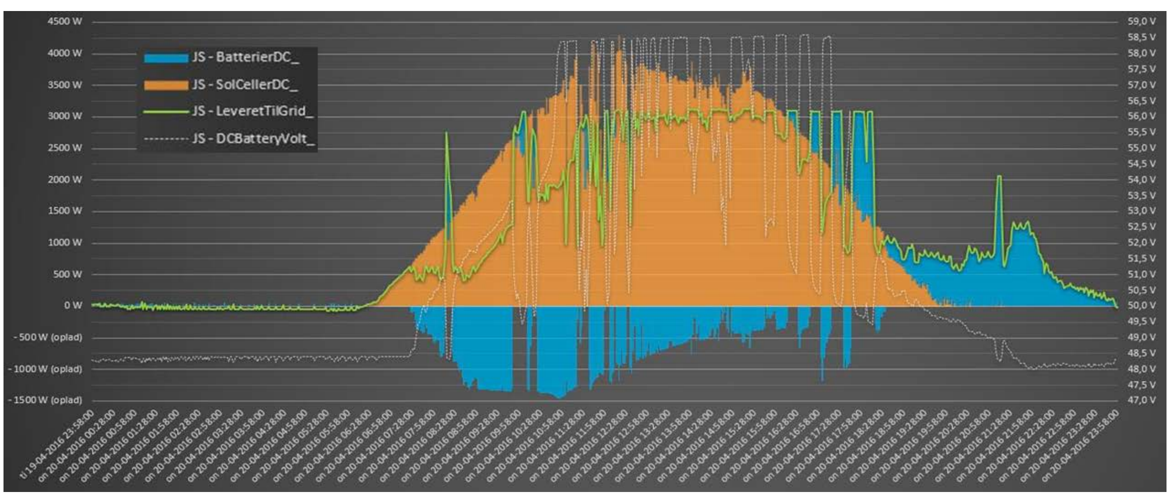


Figure 12 – Feasibility of using customer diurnal excess solar capacity (from [LGI])

2.3.2. Implications of feeding power into the 90 V quasi-square wave OSP power system

Whenever multiple power sources fed power into the same AC power network, each of those sources needs to feed power into the network with an appropriate voltage amplitude and waveform and at the proper frequency and phase. This would be relatively easy if the power network had a master controller that knew the instantaneous available power from each source and then dictated the exact instantaneous voltage waveform (along with exact phase) to be fed from each power source. Unfortunately, such a master controller does not exist today, and the implementation of such a controller is likely to be impractical in the short term.

In the absence of a master controller, each power source needs to inject power into the network while maintaining, as much as possible, the network's present voltage waveform and frequency. This is widely done by frequency inverters used to supply power from photovoltaic (PV) panels into the AC mains power grid and it works quite well as long as the energy from such inverters is not a significant percentage of the total power being provided to the network. Once these independent power sources become a significant percentage of the total power, they can interact with each other, yielding undesirable consequences.

IEEE 1547-2003 was created to standardize how independent power inverters should insert power into the AC mains power grid in a safe manner. The standard was created with the assumption that such power inserters would never be a majority contributor of power to the network. Before system operators attempt to insert power from PV sources directly into the 90 V OSP power network, they should learn from the experiences encountered by the electric utilities.

2.3.3. Lessons to learn from IEEE 1547-2003

IEEE 1547 was designed to assure that PV power was never inserted into a power network that was not running as the correct voltage and frequency. The tolerance was quite strict. This was good because it assured that voltage would NEVER be fed into a network that was not being powered by the utility's generation equipment and, thus, PV power would never be fed into a network that was otherwise offline. This is an important safety consideration, which prevents injury or death to people who come in contact with power utility wires that are presumed to be inactive (primarily after storms).

Units compliant with IEEE 1547-2003 were:

- Designed to be sure that power is never backfed to the network if the network is offline
- Required to adhere to very strict voltage and frequency requirements
- Required to trip offline at <59.3 Hz

This standard worked great until PV generation became a significant contributor to the over-all power in the network. An excellent IEEE article describes the effects of distributed energy resources on system reliability and explains the improvements being made to IEEE 1547 to improve system reliability [IEE]. Figure 13 through Figure 16 are from that article and demonstrate the issues to be mitigated.

Figure 13 shows what happened in an actual network when a generating unit went offline. Since insufficient power was being fed into the network, frequency began to lag. Normal protocol for an electric utility in this situation is to shed loads by cutting off portions of the serving area. Unfortunately, much of the power being generated was coming from PV sources, and all those sources went offline at 59.3 Hz as required by IEEE 1547-2003, exacerbating the problem. When the PV power was needed the most, it was automatically disconnected!

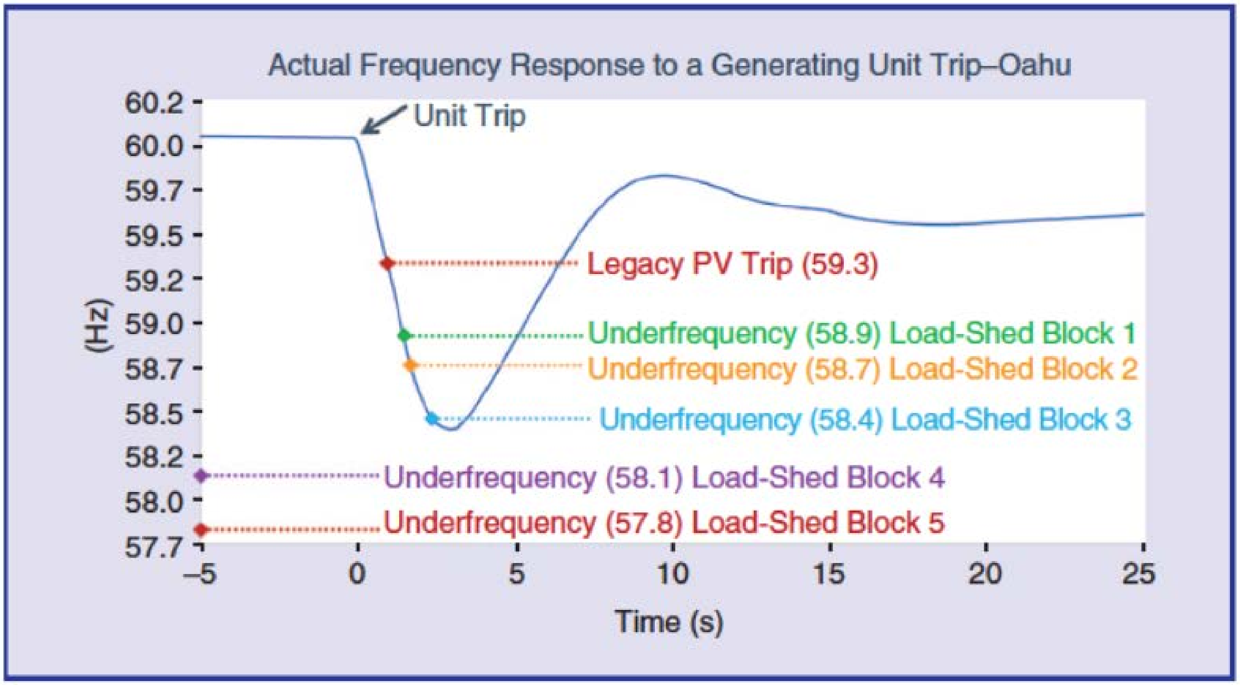


Figure 13 – Actual frequency response to a generating unit trip on Oahu [IEE]

Figure 14 shows that distributed PV (DPV) generation can be a significant percentage of the total power fed into the network during the sunniest part of the day.

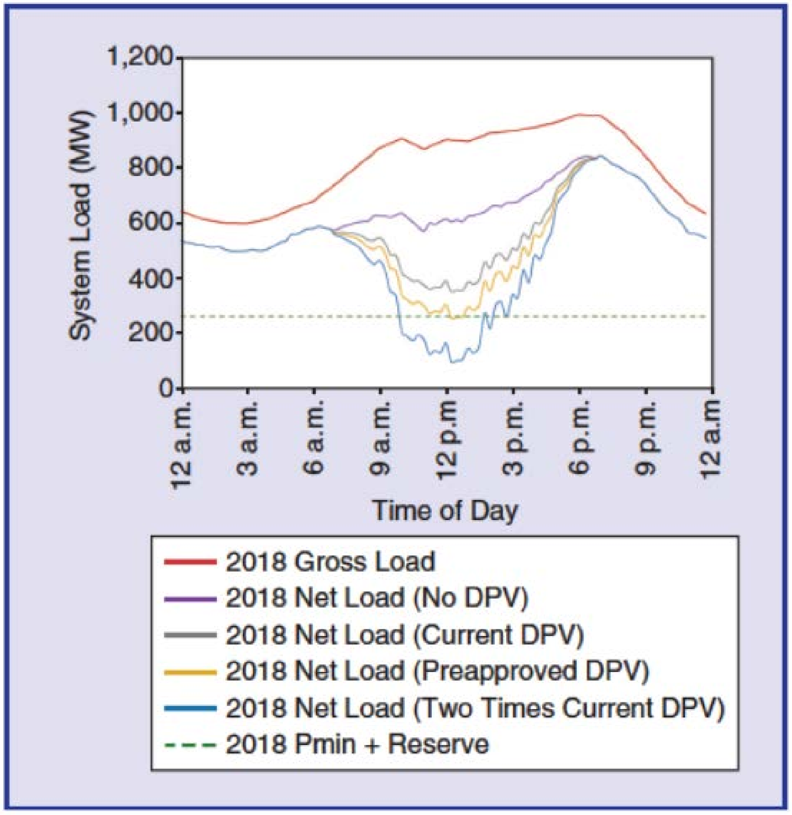


Figure 14 – "Duck curve" showing increased impacts of distributed PV on system load for the worst day of the year [IEE]

Figure 15 and Figure 16 show the proposed frequency and voltage behavior requirements of a proposed update to IEEE 1547. These new requirements are designed to assure that the PV power sources continue to feed power into networks that are experiencing minor fluctuations, while also assuring that the PV power sources disconnect when the power network has a critical fault.

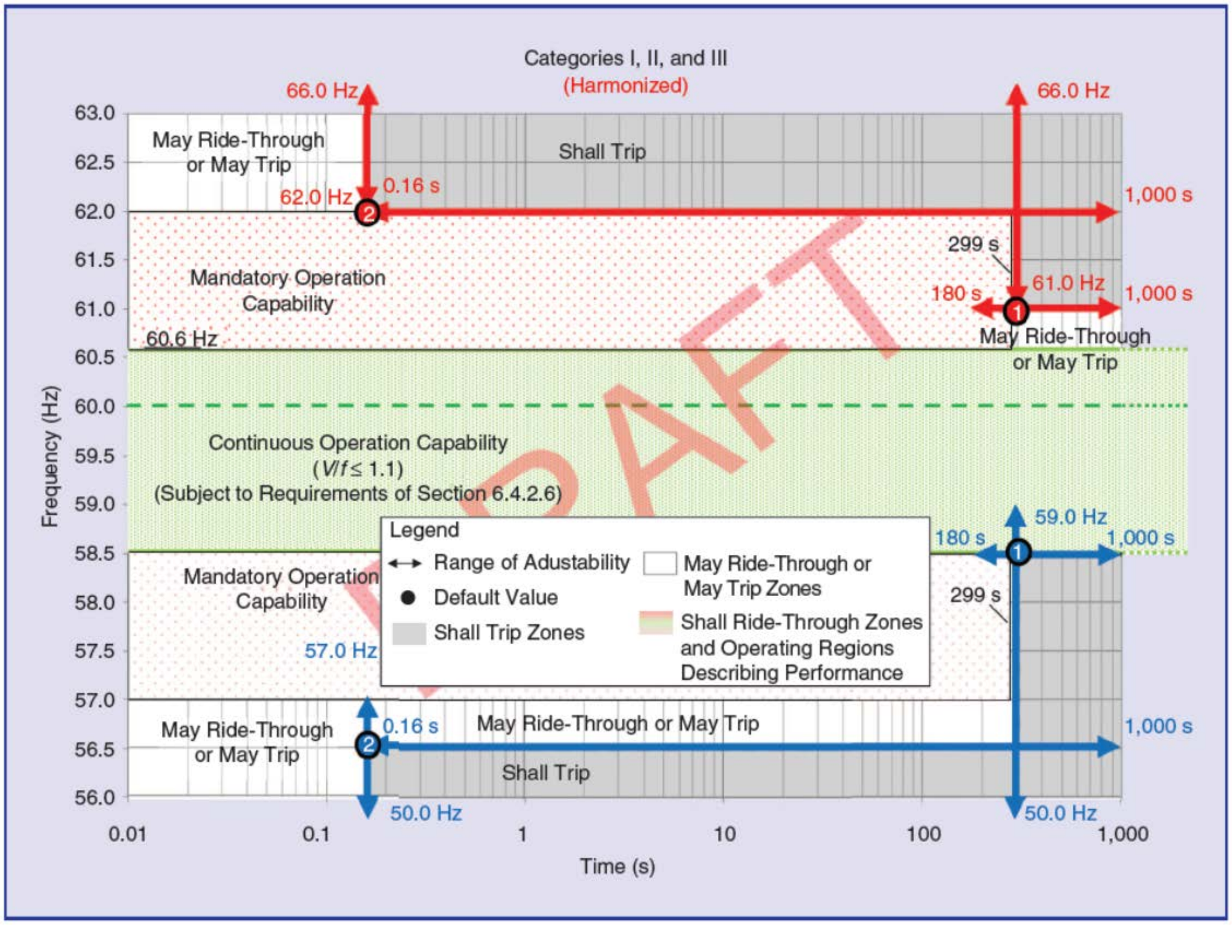


Figure 15 – Proposed frequency behavior requirements of an updated IEEE 1547 [IEE]

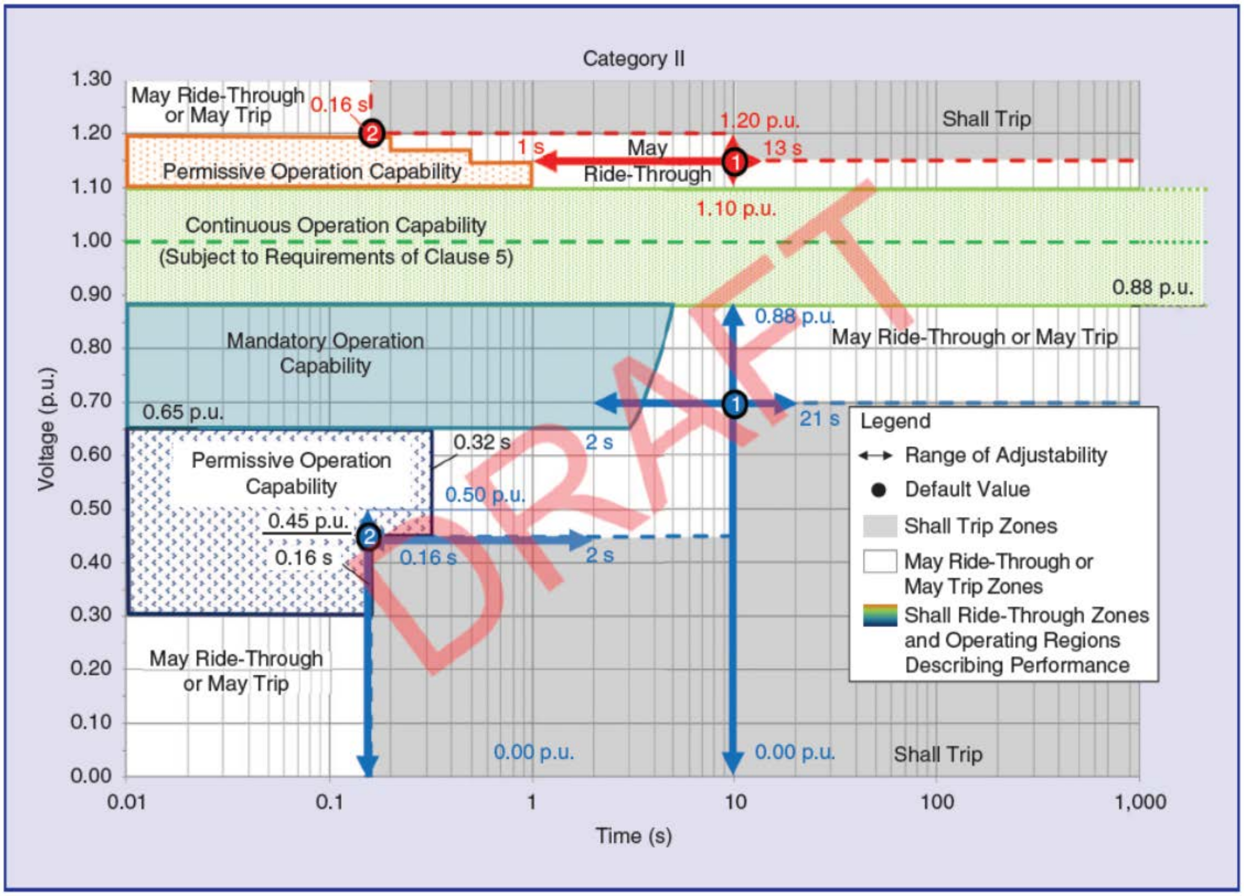


Figure 16 – Proposed voltage behavior requirements of an updated IEEE 1547 [IEE]

2.3.4. What this means to the OSP

In order to feed PV power directly into the 90 V quasi-square wave power system used in the OSP, inverters will need to be designed and built using a methodology similar to IEEE 1547. The inverters will need to match the existing voltage waveform while feeding a current that is proportional to that voltage waveform in order to assure a high power factor. If the PV power is to be used as utility backup, such inverters will also need to be able to create the quasi-square wave voltage waveform when that inverter is the only power system active. Safety factors must also be considered so that PV generated power does not unexpectedly come on and power a damaged network the morning after a storm.

Solving these issues is beyond the scope of this paper. They are mentioned here so that readers are aware of the issues that need to be considered before PV power can be directly fed into the 90 V OSP power system.

2.3.5. Implications for MSO partnerships with utility providers

One of the ANE members is a public utility, and offers the following considerations for cable operators considering using solar energy to power the outside plant and more generally:

- California the only state that has mandated builders by 2020 to require solar installation on new homes and single-story businesses which is in line with Zero Net Energy goals

- Currently solar power provides 16% of the energy used in California
- Solar power is an alternative driver towards energy production
- There are two choices: builders to provide individual homes with solar panels, or build a shared solar-power system serving a group of homes
- By 2030, California state law will require 50% of the state electricity to be from a non-carbon source.

The acceleration of renewable energy generation in the US will likely cause cable operators to:

- Work collectively with builders, solar and utility companies
- Approach solar companies that can utilize smart inverters
  - Note that there are not a lot out there currently
- Partner with battery storage companies
- Partner with utilities that offer IoT programs

3. Payback framework for access network energy conservation measures

Most access network improvements are driven by performance, capacity, and competitive threats. But could they also make sense as energy conservation measures (ECMs) and payoff in a reasonable timeframe? To answer this question for long term investments usually requires net present value (NPV) type analysis, which takes into account the time value of money and all other dynamic growth and depreciation rates to determine if the investment is acceptable.

But for the engineers and technicians who are considering ECMs for their facilities and networks, a simple payback analysis is often sufficient for initial assessment. Simple payback analysis can compare two options, e.g., continuing to use the existing OSP technology compared to adding new OSP devices, LPSs, or technology upgrades. The rule of thumb for ECM payback is that it is usually acceptable if under 3 years.

Simple payback includes initial costs, rebates, installation costs, cost of power, energy costs, maintenance costs, component replacement costs and end of life costs, as well as how these vary over time, and is calculated as follows:

$$Payback\ Period = A + B/C$$

where:

A = The last period with a negative cumulative cash flow.

B = The absolute value of cumulative cash flow at the end of the period A

C = Total cash flow during the period after A.

This will calculate when you ‘break even’ or get your money back. An example is shown in Table 3.

Table 3 – Simple payback period example calculation

	Extra Install	Extra O&M	Savings @ 2% growth	Net Cash Flow	Cum Cash Flow
Yr 1	$1,000	$40	$350	-$690	-$690

Yr 2		$41	$357	$316	-$374
Yr 3		$42	$364	$323	-$51
Yr 4		$42	$371	$329	$278
Yr 5		$43	$379	$336	$613
Cum	$1,000	$208	$1,821	$613	
Simple payback 3+51/329				3.2	years

There are more detailed and well-known financial analysis that can be considered for large projects: NPV, internal rate of return (IRR)and return on investment (ROI). See the SCTE paper on guidelines for facility cooling technology [DOL] for an explanation of these methods of determining more precisely whether an investment makes sense.

It turns out that for such a short, targeted payback period (3 years), and in the absence of all costs and benefits, an even simpler calculation can be made to quickly determine whether an ECM should be pursued. For the purpose of this operational practice document, the term “coarse payback” will be used to refer to the following simple calculation:

$$Coarse\ payback = \frac{extra\ cost\ of\ ECM\ (beyond\ nominal\ costs, cost\ of\ BAU\ or\ alternative)}{estimated\ annual\ savings\ of\ the\ ECM}$$

where BAU refers to “business as usual.” Again, if this calculation gives a result that is in the desired range, i.e., roughly 3 years or less, or even slightly more than 3 years, it warrants considering the ECM, collecting all pertinent financial data and doing a more detailed financial analysis to determine its exact payback period or NPV. One way to rule out non-viable ECMs is to make the calculation in the best-case scenario for energy savings, i.e., at the highest utility rate and under the worst energy efficiency conditions in the OSP, such as oldest LPS technology, highest DC loop resistance legacy cabling, and so on. If this calculation gives a coarse payback that exceeds 4 years, it is extremely unlikely that the ECM will ever payoff reasonably for the cable operator. This is the approach used in the remainder of this document for evaluating potential ECMs for application to the access network and identifying those that have the potential to payoff reasonably under some conditions.

Finally, note that another way to compare technologies, and thus ECMs is to compare the cost per home passed, especially when coupling to a planned deployment of new technology. Like NPV analysis, this is more complex and requires far more data, hence the coarse payback will be used below.

4. Access network energy conservation measures and estimated paybacks

In this section, the coarse paybacks of a suite of ECMs will be calculated. Note that all costs used in this section are merely coarse estimates and used only to show how to calculate and compare payback periods of different ECMs. Each cable operator should determine their actual costs from their vendors and perform the calculations for their situations.

4.1. New plant actives/technology as an ECM

It has been estimated that modern OSP active devices that employ GaN technology are at least 25% more energy efficient, and if active linearization and digital pre-distortion technologies are also used in next generation equipment, up to 50% improvement in energy efficiency is possible [DAY]. This begs the question of whether replacing older plant actives with newer devices could save enough energy to pay for the upgrade over time. However, the upper frequency and RF output power may be extended by the GaN technology and such increases may offset the energy efficiencies, especially if more power is dissipated by the coax itself. Nextgen actives may also include APSIS functionality for further energy savings.

For this ECM, as often happens, cases range from totally infeasible to worth considering, depending on the actual parameters. Here are two examples, with most cases being somewhere in between these:

Case 1: If cost of replacing a plant active (material + installation) is $20,000, and new node saves 150 W or 1314 kWh/yr, at $0.16/kWh, total annual savings is $210 for a coarse payback of 95 yrs.

Case 2: If the cable operator is planning to replace the unit anyway due to maintenance issues/failure or capacity expansion, and newer, more efficient active devices with APSIS functionality only add $2,000 to the material cost (vs. replacing with a non-APSIS unit), and for high energy cost per kWh of $0.25 (e.g., Japan or HI), and finally the energy savings are 40% (400 W, 3500 kWh/yr = $875/yr), then coarse payback would be 2.3 years.

4.2. Early retirement of LPSs: Replacing Gen 1 & 2 power supplies with latest technologies; collocating with nodes

There are energy advantages that result from replacing larger centralized line power supplies with smaller line power supplies that are co-located with each optical node. Such a change reduces the power losses that result from moving power long distances through coaxial cable. The change may also permit the retirement of large, older line power supplies with smaller, newer, more energy efficient line power supplies. However, there is significant initial capital expenditures associated with such a change. There may also be logistical problems such as obtaining access to the commercial power grid. There is also a challenge with properly sizing new line power supplies to support the power requirements of future technologies such as remote PHY, remote MAC PHY, and FDX DOCSIS as was previously described. Finally, if energy incentives are sought for early retirement, as is often done for HVAC systems, the utility provider would require at least one year of useful life left to qualify for an incentive.

Could energy savings from greater efficiency justify replacing older power supplies that are over 15 yrs old? At $0.22/kWh, roughly $13-52/yr savings (2nd gen), and $88-109/yr (1st gen.) units were given in Figure 8. It was seen that the maximum savings are achieved at the highest load even though older generation LPSs are least efficient at lower loads. But even with maximum savings ($109/yr), the coarse payback period would exceed 20 years for just the equipment costs alone.

Can payback for this ECM be improved? Large utility incentives (at least $600) with other planned costs accounted for such as addition of an external transponder ($300) and assuming a near term repair / refurbishment ($450, every 6-7 years) help considerably. At the same high utility rate ($0.22/kWh) the coarse payback for the extra cost to retire a 1st generation LPS early and just prior to upcoming maintenance and upgrade costs would only be 3.2 years. For less than ideal circumstances (e.g. lower utility rates, 2nd generation LPS units and lighter loading, early retirement could only be justified if new service offerings or network analytics need to be implemented.

4.3. Running a lower loss line to power deeper fiber nodes

It was seen that by not moving LPSs when deploying fiber deep, the I^2R losses increase and take the plant from a distributed powering scheme back to a centralized scheme, which is not as energy efficient. The I^2R losses result from the DC loop resistance associated with the coaxial cable. Assume that this DC loop resistance has a value of R ohms. There will be power dissipated in the coaxial cable that is given by

$$Power_{Coax} = I_{LPS}^2 R$$

This power dissipated in the coax is wasted as heat. Note that the power is proportional to the square of the current from the line power supply. Any peaks in the current waveform will result in significant wasted power. Consequently, the peak inrush current that occurs whenever the voltage changes polarity is a significant contributor to the power that is wasted in heating the coax.

One way to reduce I^2R losses is by running a low loss power cable from existing node location to power new node down the line, instead of using the existing coax line surgically to save energy. Table 4 gives example DC loop resistances of various coax types and a relatively new cabling option "PowerFeeder" designed just for power transmission with minimal I^2R losses.

Table 4 – Example DC loop resistances of various coax hardlines and power feeder

Cable Type	DC Loop Resistance
0.75" CommScope P3	0.76 Ω / kft
0.75" CommScope Quantum Reach	1.0 Ω / kft
0.75" CommScope MC2	1.0 Ω / kft
0.5" legacy hardline	1.7 Ω / kft
CommScope PowerFeeder 625 JCAT 3R	0.3 Ω / kft

Consider a best-case ECM for replacing the existing coax with a low loss cable, for example, replacing a 0.5" coax with a PowerFeeder type of 1000 ft. at max current load (18 A). The legacy coax I^2R loss of 550 W drops to 97 W. This would produce $555 annual savings @ $0.14/kWh.

Payback: Install, materials, plus permitting/make-ready costs could easily exceed $2500 for 1000 ft. run, so 4.5 year payback in this case

Therefore, ECM applies only to:

- Legacy hardline with very high DC loop resistance
- High utility cost states/countries
- Minimal permitting/make-ready costs
- Integration with existing deployments (to avoid labor costs associated with the ECM)

Another possible and related ECM would be to minimize the power lost in the coax by controlling the high peak inrush current into the switching regulated power supply in the active devices. This could be done by using power factor correction in each switching power supply in the network. However, this requires modifications at each active device in the network. The feasibility and impact of this ECM is still being investigated by the ANE working group.

4.4. Alternate energy as an ECM for the access network

The LGI study shown earlier gave payback of 5 years when reducing grid dependency by 10%. Would this work in the USA? In some states, the answer is yes, seen in the following:

The cost of industrial electricity in Netherlands (where the LGI study was done) is about $0.09/kWh (similar to USA average) so payback period is similar. But in high cost states (same ones with lots of solar already deployed), payback would be far faster:

- $0.14 / kWh (CA), payback is 3.2 yrs
- $0.25 / kWh (HI, Japan), payback is 1.8 yrs

As a further indication of the viability of this ECM, note that the telcos G.Fast model for next gen digital subscriber loop (DSL) also involves reverse powering. And as it will for cable operators, this DSL reverse powering has to have an orchestration layer that is smart enough to know when power is available, how it's shared, how it depends on the number of homes, etc. Thus, there is some software and management along with the contractual issues to resolve prior to this concept being deployed at scale.

4.5. Machine learning/artificial intelligence as an ECM for the access network

Could we use machine learning (ML) / artificial intelligence (AI) as an ECM? Note first that new technology generally drives the cost of something down [AGR], e.g. semiconductors drove down the cost of arithmetic, the internet drove down the cost of distribution, communication, and search, and so on. Driving down the price of one element often increases demand and expands applicability. AI drives down the cost of prediction, and also decreases the value of substitutes (human prediction), but raises value of complements (data, judgement, etc.).

To evaluate the impact (and ultimately payback) of developing an AI as an OSP ECM, first divide a workflow into tasks as shown in Figure 17, list all the possible places where an AI could be developed, and do an ROI analysis of which tasks would payback well with AI/ML for that task.

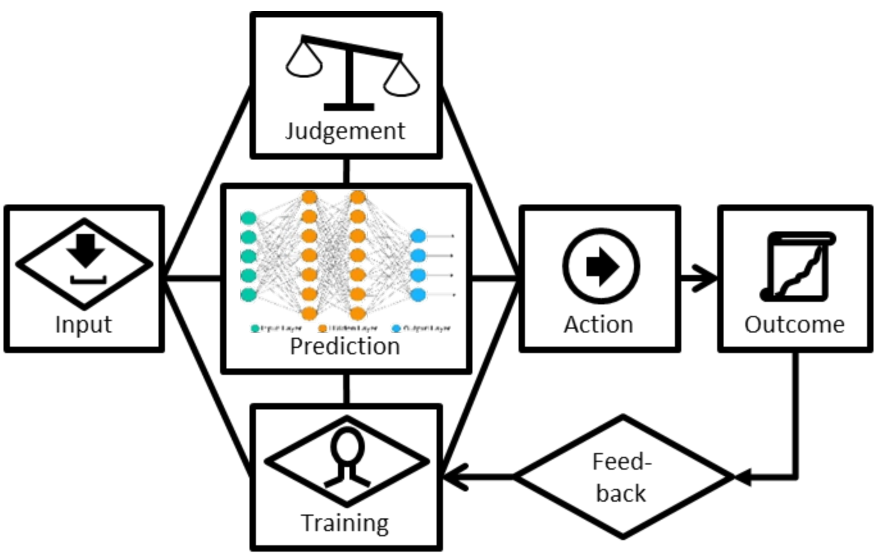


Figure 17 – Task breakout showing potential AI prediction component (after [AGR])

As can be seen from companion papers and presentations in SCTE Cable-Tec Expo 2018, AI is already being applied by MSOs for traffic modeling/ analysis, processing proactive network maintenance (PNM) data, optimal orthogonal frequency division multiplexing (OFDM) profile selection, understanding and predicting network 'behavior,' and much more. Here are some predictions that might be performed by an AI for the OSP as potential ECMs:

- Benefits of upgrading a node vs. various options vs. not upgrading the node at all (since new technology will increase the energy consumption in the OSP)
- Energy costs system by system
- Costs of ECMs over time
- Energy savings from traffic adaption or, more generally, APSIS functionality
- Network design as a function of competition, energy costs, traffic loads, etc.

After listing the potential prediction and associated tasks per Figure 17 that could be performed by an AI for the OSP, the next step is to do the ROI/payback analysis to see if it pays off in the desired timeframe.

It is often said now that data is the new oil, and this is because with AI/ML lowering the cost of prediction, the value of input data goes up. The ROI for developing an AI should thus include the cost of acquiring data (especially any new sensors to be deployed), analytics, and the required orchestration to implement the AI.

5. Access network operational practices to improve energy awareness and efficiency

5.1. Measurement and verification (M&V) to prove energy savings

To realize cost savings from the ECMs, the cable operator must prove the energy reduction to utilities. Typical incentives / measurement and verification (M&V) models require metering to prove energy savings. The cable operator must go through a detailed process to realize the savings and/or garner incentives from the utilities, as shown in Figure 18.

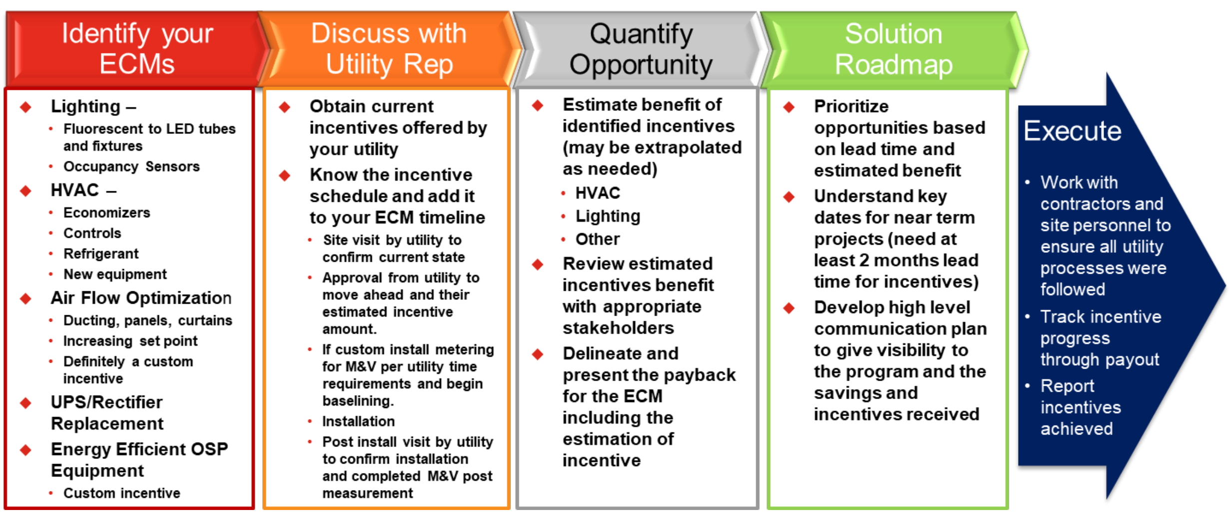


Figure 18 – Detailed energy incentive planning (from [CIF])

The challenge for the OSP in particular is that one must convince each utility on a case-by-case basis. However, if one measures all LPS's in power, there is generally a Gaussian or normal distribution. Then one can approximate the entire population via sampling. Previous efforts of ANE members resulted in agreement with utilities to sample the OSP, measure a subset of LPSs, assume a constant load, and then use utility-approved meters as clamp-on meters to provide data acceptable by the utility companies. Utility personnel usually ride along, measuring a substantial number of LPSs, and then picking a smaller subset of LPSs to come back and check following the energy impacting action taken by the cable operator. While this process is very laborious and done case-by-case, it does work and can be used to reduce OSP energy costs.

5.2. Longer term planning for dynamic power consumption (e.g. APSIS) and renewable energy usage in the OSP

Unfortunately, the sampling method just described would likely not work for dynamic energy consumption such as would occur with APSIS, energy-proportional wireless devices, and solar powering of the OSP as described previously. Real time monitoring would be required using either built-in capabilities of modern LPSs, add on monitoring modules from the original equipment manufacturer (OEM) or a third party, or via add on IoT sensors that use for example LoRa communications. MachineQ and Leverege are two IoT companies that cable operators have partnered with to provide such IoT OSP-based solutions for both new revenue/services, as well as potentially monitoring the access network of the cable operator.

The challenge of metering line power supply actual power consumption to take advantage of efficiency gained from switching to more efficient line electronics (such as GaN) and actual variations between power supplies runs afoul of a power provider’s one size fits all philosophy. It may be possible to qualify some units with a calibrated power metering device that meets power provider standards.

Based on the discussion in the ANE working group and in this document in particular, the time may be approaching for standby power supplies to become more capable and flexible to improve their power consumption footprint. Status monitoring of those devices makes a great deal of sense as a first step. That monitoring can provide a number of benefits for the network and will form the foundation supporting other important functions such as:

- Status monitoring provides the cable operator with a warning if the AC mains power fails. Depending on the charge status of the supplies, batteries, the operator may need provide backup power to that location to support an extended outage.
- With appropriate sensors, status monitoring can inform the operator when the batteries require maintenance. This could reduce the number of regular field inspections saving manpower and vehicle fuel.
- At some point it may be possible to obtain, cost effective, accurate AC line power monitoring modules, with accuracy acceptable to power providers, and incorporate them in the advanced line power supplies. This can provide a means to report the energy consumption for active power supplies which is an idea that is not too far from realization if developers are incentivized. Perhaps the quantities required for outside plant monitoring can drive down cost. For other purposes, power service providers are switching to remotely monitored electric meters. The metering and billing for residential solar systems requires accurate measurement of power flow to and from residences. Many states provide solar renewable energy credits (SRECs) based on residential solar energy generation. Accurately addressing that credit requires power flow measuring and reporting. Those technologies should form the basis of accurate and affordable standby power supply monitoring and reporting devices.
- A first step for operators to become “better partners” on the power grid might be to be able to reduce their power load at times that are critical for power providers. Power companies already offer incentives for actions like disconnecting electric water heaters during critical load periods. The supply status monitoring system can provide the communication control link and assist in the recording of power supply status changes. The cable operator and electric utility will have to negotiate the financial terms of some of these actions. Standby supplies that have disconnected from the power grid will consume some of the standby capacity which will have to be made up by

later charging. Disconnecting the supply in response to a power grid emergency is one possible scenario. Disconnecting during regular daily peak load periods would be another. One interesting opportunity could be to disconnect the supply during periods when "time of day" pricing of electricity is very high. This would require accurate documentation or electric service provider metering of the supply's time of day consumption. The operator would control disconnect times based on the power supply's charge status and weather conditions that might predict a need for the supply's stored energy.

5.3. Measurements to make during normal maintenance

Finally, we can still get visibility into OSP energy consumption for ourselves cost-effectively. The latest generation of LPSs include energy monitoring, but even for the older generation units, it is possible to measure the relatively static energy consumption during general maintenance of LPS and/or deployment of fiber deep, node splits, or DAA. The following measurements might be made without significant additional labor/cost:

- Volt-amperes (VA)
- Volt amperes reactive (VAR)
- True power factor (TPF)
- Displacement power factor (DPF)
- Phase lag angle
- Energy kWh
- Energy cost in $
- Waveform snapshot

In particular when deploying new OSP devices and architectures, it is recommended to use field power analyzers or similar capabilities to do a baseline before, and M&V after an ECM and/or new node architecture or technology is deployed. Again, APSIS and other dynamic energy measures will require dynamic monitoring/data loggers left on site to prove the energy savings.

Conclusion

While challenging and case-specific, there are indeed OSP energy conservation measures with reasonable paybacks in certain situations. Keeping the payback minimal requires careful planning and logistics to minimize cost components like truck rolls, permitting, make-ready, and some material costs. A key to realizing true savings from these measures is having a process and/or new technology to provide energy monitoring that is acceptable to utility companies

For most ECMs, the plant power is stationary following deployment, so existing methods can be refined, combined and scaled via partnership with the utility companies to keep payback periods low. APSIS and any other dynamic energy control technologies will likely require formal metering or a lengthy partnering process with utility companies to demonstrate average (or even minimum) energy reductions to scale for OSP use.

Abbreviations

5G	5th generation long term evolution cell network
AC	alternating current
AI	artificial intelligence
AL	active linearization
AM-AM	amplitude modulation to amplitude modulation distortion
AM-PM	amplitude modulation to phase modulation distortion
ANE	access network efficiency
APSIS	adaptive power systems interface specification
B2B	business to business
BAU	business as usual
BW	bandwidth
CBRS	citizen's band radio service
CCAP	converged cable access platform
CMTS	cable modem termination system
CTB	composite triple beat distortion
DAA	distributed access architecture
DC	direct current
DPD	digital pre-distortion
DPF	displacement power factor
DPV	distributed photovoltaic
DS	downstream
DSL	digital subscriber loop
ECM	energy conservation measure
EDFA	erbium doped fiber amplifier
EMS	energy management subcommittee
FD	fiber deep
FDX	full duplex DOCSIS
FTTP	fiber to the premises
G.Fast	ITU-G recommendation for fast access to subscriber terminals
GaN	gallium nitride
GAP	generic access platform
GEN	generation
H&S	health and safety maintenance services
HFC	hybrid fiber-coax
HP	households passed
HVAC	heating, ventilation and air-conditioning
I^2R	Joule heating losses in conductors, squared-current times resistance
IEEE	Institute of Electrical and Electronics Engineers
IM	inverter module
IoT	internet of things

IRR	internal rate of return
ISBE	International Society of Broadband Experts
ISP	inside plant wiring
IT	information technology
LGI	Liberty Global International
LoRa	long range wireless communications
LPS	line power supplies
LTE	long term evolution cell phone network
M&V	measurement and verification
MAC	media access control layer
MDU	multiple dwelling unit
MER	modulation error ratio
ML	machine learning
MSO	multiple system operator
N+0	fiber node plus zero amplifiers
NFV	network functions virtualization
NOS	network operations subcommittee
NPV	net present value
OEM	original equipment manufacturer
OFDM	orthogonal frequency division multiplexing
OSP	outside plant
PA	power amplifier
PF	power factor
PHY	physical layer of open systems interconnection model
PM	preventive maintenance
PNM	proactive network maintenance
PoE	power over Ethernet
PON	passive optical network
PS	power supply
PV	photovoltaic
QAM	quadrature amplitude modulation
RF	radio frequency
RFIC	radio frequency integrated circuit
RFoG	radio frequency over glass (SCTE FTTP standard)
ROI	return on investment
SCTE	Society of Cable Telecommunications Engineers
SDN	software defined networking
SREC	solar renewable energy credit
TB	terabytes
TPF	true power factor
US	upstream
VA	volt-amperes

VAR	volt-ampere reactive
Wi-Fi	wireless fidelity network

Bibliography & References

[ULM] J. Ulm, Z. Maricevic, "Giving HFC a Green Thumb: A Case Study on Access Network and Headend Energy & Space Considerations for Today & Future Architectures," SCTE Cable-Tec Expo 2016, Philadelphia.

[HOL] J. Holobinko, "Energy Analysis Remote PHY vs. Integrated CCAP," presentation to SCTE ANE working group, 2017.

[LOE] T. Loeffelholz, "Fiber Deep Networks and the Lessons Learned from the Field," SCTE 2017 Fall Technical Forum, Denver CO.

[LOE2] T. Loeffelholz, "What small cell wireless wants (and needs) from us," SCTE Cable-Tec Expo 2018 proceedings, available from www.scte.org.

[BEL] "An economic analysis of distributed access architectures: The next major cable transformation," a white paper available from www.bell-labs.com, Dec 2017.

[DAY] C. Day, "Reducing power in the cable access network," Presentation to the SCTE Access Network Efficiency working group, August 10, 2017.

[LGI] S. Khola and M. Bosman "The customer as a sustainable energy supplier for our node," winning proposal from LGI Spark Innovation Initiative, August 2016 and presented to SCTE•ISBE EMS Plenary/ANE working group breakout, April 2018.

[SAN] F. Sandoval, "APSIS Value Proposition for Service Providers," presentation to IEEE Denver, Feb 2, 2017, available from http://sites.ieee.org/denver-com/files/2017/02/APSIS-Overview.pdf.

[HOW] R. Howald "Energy ramifications of DAA," presented to the SCTE•ISBE Energy Management Subcommittee plenary meeting, April, 2018.

[GOV] US Government web site, "Grid Modernization and Smart Grid: Demand Response," available from https://energy.gov/oe/services/technology-development/smart-grid/demand-response

[HAY] C. Hayes, "Broadband power demands energy efficiency," from Electronic Specifier online, 18 Jul 2015, with material sourced from Alpha Technologies, available from https://www.electronicspecifier.com/power/broadband-power-demands-energy-efficiency

[DOL] J. Dolan, D. Howard, A. Murphy, K. Nickel, and D. Smargon, "Guidelines for Cable Facility Climate Technology Optimization: Cooling Optimization for Edge Facilities," SCTE Cable-Tec Expo 2017 proceedings, available from www.scte.org

[IEE] D. Lew, M. Asano, J. Boemer, C. Ching, U. Focken, R. Hydzik, M. Lange, and A. Motley, "The Power of Small: The Effects of Distributed Energy Resources on System Reliability," IEEE Power and Energy magazine, Volume 15, Number 6, November/December 2017

[AGR] A. Agrawal, J. Gans, and A. Goldfarb, ***Prediction Machines: The Simple Economics of Artificial Intelligence***, Harvard Business Review Press, 2018, p. 75.

[CIF] D. Howard, G. Gosko, and J. VanHeynigan, "HVAC Best Practices and Guidelines Webinar," presented at Comcast Critical Infrastructure Forum, February 2018.

