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Energy Storage in Communications & Data Centre Infrastructures

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Abstract: *As communications technology is ubiquitous, and energy savings are ever more crucial in communications and data storage infrastructures, it is timely to revisit the technologies used for energy storagein that field. Thismultidisciplinary paper especially focusses on the specific requirements onto energy storage for communications and data storage,derived from traffic, climate, high availability, and resilience, irrespective from energy sources used. It also addresses techno-economic, environmental &emissions tradeoffs offered by a model, and concludes with discussing future energy storage technologies for communications.*

Keywords: *Energy storage, Communications networks, Data centers, Batteries, Battery power loss, AD-DC power conversion, Life-cycle costs, Environmental life-cycle cost, Emissions life-cycle cost*

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PLAN

I. Introduction: Specific Requirements

Energy storage for communications networks and data centers have highly unpredictable demands(due to the nature of the traffic requests and services rendered), much higher than in electricity grids [17].And the energy storage does not serve, as in the electrical grid or with renewable energy sources, to level the load except in case of power failure...

The second distinguishing characteristic is thatfor the end user in modern societies, availabilityand resilience of communications networks and data centers must be extremely high, higher than the availability of electricity grids which serve as their main energy source.

The third characteristic is that energy storage for communications and data infrastructure is normally placed on the same premises as communications nodes, to reduce the risks due to electrical power transmission failures. Energy storage also often needs to be autonomous for some rather long durations, as these node premises may be on inaccessible sites where they cannot be resupplied easily.

Therefore, energy storage for communications networks and data centers carries out ancillary services:

-provides operating reserve power;

-ensures power quality for devices such as voltage regulators, rectifiers and uninterrupted power systems (UPS);

-providesback-up or black start energy services to compensate for partial or full electrical grid blackouts, as well as to keep on “hot stand-by” some equipmentused as active spares.

As a result, the power injection request from communications nodes can be instantaneous, while the typical discharge time from energy storage onto communications and data centers, is in hours or a few days at most, and the power ratings should keep operational the core network or data center infrastructure. The charging times can be longer, corresponding to the periods where the electrical grid is up with at least full needed capacity. These criteria largely eliminate, by their underlying physical or chemical characteristics, some groups of electricity storage technologies, namely: mechanical storage, thermal storage and chemical storage.

The extent of the above requirements is furthermore driven by at least four fundamental trends. First, wireless 5G infrastructures operating in new spectral bands will rely on a significantly increased number of distributed and central nodes. Secondly, data centers proliferate and must often be localized at sites where cooling and renewable energy sources are available, thus further away from peak traffic locations. Third and importantly, energy savings and efficiency [5,11,23] must be enforced everywhere in energy storage by system architectures & design [3], operating procedures , and technologies, which at first sight would reduce the energy storage capacities, but in fact increase it due to the above mentioned more frequent on/off cycles. Last, while the power grid and content clouds have intrinsic actively managed distributed redundancies, the individual energy storage nodes must be able to operate autonomously for a while if grid or cloud have disruptions.

Table 1 surveys existing energy storage technologies used in communications and data center infrastructures, summarizing technical and operational advantages/ disadvantages, and assessing qualitatively the impact on climate and environment (taking an energy storage system life-cycle emissions and environmental perspective from manufacturing to operations and recycling).

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	ADVANTAGES	DISADVANTAGES	CLIMATE and ENVIRONMENTAL LIFE-CYCLE
Mechanical: Flywheels	Power density, efficiency, scalability	High cost, low energy density, bearing replacements	Favorable
Electrochemical: Conventionaland Flow batteries	Independent energy and power sizing, scalability	Cost, balance of system, chemical hazards, lower life-time at high temperatures	Bad
Electrochemical: Li-Ion	Efficient, density (energy and power), mobility	Cost, safety	Bad
Electrical: Supercapacitors	High power density, efficient and fast time response	Low energy density, cost (Eur/kWh), voltage changes	Favorable
Electrical: Li-ion-polymer	High power density, efficient, cost	Availability	Bad

Table1: Established Energy storage Technologies pro's and con's

II. Redundancies in Telecommunications Flows Affecting Power Requirements And Consumption

The high dependability of telecommunications services is mandatory and enshrined in a number of standards, dealing with hardware (originating in so-called "Bellcore" standards) as well as software (a wide diversity of ITU, ETSI, 3GPP, IETF, CEN-CENELEC standards).But what is furthermore very specific is the very high degree of redundancy triggered by this resilience in the overall handling of communications traffic at all levels: data structures (e.g. ATM cells and IP packets) , channels (e.g. transmission links, radio channels, wavelengths), coding and multiplexing (e.g. checks on all data structures, acknowledgment/resending features), node redundancies (e.g. multiple simultaneous links to the same user equipment from different radio base stations), and hardware design itself (e.g. backplanes, switches, redundant blades, redundant signal processing paths in ASIC's, etc...).This redundancy implies overall a higher level of energy consumption than needed for a simple protocol execution. In turn this higher consumption is only alleviated by temporal and logical energy savings schemes (e.g. dynamic sleep state modes with low traffic, energy efficient routing, etc...). Circuit performances are not energy neutral, and essential are e.g. such parameters as Peak-to-Average-Power-Ratio (PAPR), robustness against RF impairments and Doppler,compatibility with multi-antenna technologies, etc..

One element of the overall redundancy has to do with power management of most critical communications nodes (such as evolved Node-B's (e-Node-B) , radio access networks (RAN's), analytics platforms, switches, routers in packet core, multi-nodes, transmission links [9], authentication servers, application specific servers, etc.)[3], all in response to different failure modes. The node specific power management schemes in general all rely on the following hierarchy:

-"Cold spare" nodes or subsystems, which are functional tested nodes or subsystems, which are not powered at a given time, but which are connected to the operational system;

-"Hot standby" nodes or subsystems, which are functional tested nodes or subsystems, which are powered at a given time but do not handle real traffic load at that time, and which have undergone prior configuration and boot phases; the nodes or subsystems in general do not have hardware redundancy, although this happens; "hot standby" nodes usually have their own power supplies, independent from the operational power supplies; "hot standby" power systems have often dual redundancy with, on one hand access to a power grid, and on the other to a back-up battery system;

-"Operational" nodes or subsystems, which are functional tested nodes or subsystems, which are powered and handle real traffic load at a given time (including all redundancies in traffic); such systems are always at least double or triple redundant; "operational" nodes always have their own power supplies, with double or triple redundancy: power grid access, local energy sources, and redundant local back-up power systems.

As a result of this default power management hierarchy, which can be declined in a dynamic mode, one functional capacity at one given node, in effect has eight -fold power supply redundancy, namely two-fold at “hot standby” nodes or subsystems, and six-fold redundancy at “operational” nodes or subsystems. Of this factor eight, a factor three in average applies to power storage units, and in effect a factor five if one assumes that local energy sources themselves must have power storage.

III. Energy Storage Techno Economic Tradeoffs

For communications operators and all infrastructure providers, as well as for equipment and terminals suppliers, energy storage technology choices cannot just be on the basis of manufacturing costs, as each time their customer’s interests have to be evaluated. Likewise, for end users of services, and terminals or infrastructure nodes, energy costs to operate these accrue to operating costs and equipment depreciation. Therefore, a key approach to assess techno-economic tradeoffs is the “energy life cycle cost” EnergyLifeCycleCost which expresses the actualized energy costs of an energy storage device(S), from its manufacturing, to its operations, and finally to its dismantling. The actualization by the net present value in turn depends on the economic time preference by the user, a notion which is actually decoupled from the technical operational life time of the energy storage device.The energy life cycle costof a given device (S)depends crucially upon:

-the energy storage device S’s operational lifetime T;

-the vector EnergyCapacity(StorageTechnology(i,t)) giving the contribution to the device S‘s total energy capacity at time t from each constituent StorageTechnology(i), i=1,…,NTechnologies;

-the total manufacturing, assembly and installationcosts of the energy storage device S, which is a function ManufacturingCost (EnergyCapacity(i,0));

-the preventive maintenance, test and safety certification costs MaintenanceCost(t);

-the externally supplied energy recharging, materials resupply and recalibration costs which are specific to each storage technology ResupplyCost(t)= ∑ ResupplyCostTechnology(i,t), i=1,…,NTechnologies;

-the total net dismantling cost DismantlingCost(EnergyCapacity(i,T), at terminal time T, net of possible materials recycling.

and of course of the exogenous dynamic energy load EnergyLoad(i,t) met by the device S ‘s energy supply function EnergyCapacity (StorageTechnology(i,t)), both being vectors assumed to be at a static equilibrium:

$\text{EnergyLoad}(.,t)= K\ \text{EnergyCapacity}(.,t)$ (Eq.1)

where K is a fixed matrix representing different power distribution schemes inside S (after internal losses).

It is now possible to define the EnergyLifeCycleCost of the device (S)as :

$\text{EnergyLifeCycleCost}=\sum\big(\text{ManufacturingCostEnergyCapacity}(i,0)+\text{DismantlingCost}(\text{EnergyCapacity}(i,T))\big)*\text{NPV}(T)\ ;\ i=1,..,\text{NTechnologies}\ +\int \text{NPV}(t)*[\text{ResupplyCost}(t)+\text{MaintenanceCost}(t)]dt\ \ (t=0,\dots,T)$ (Eq. 2)

, subject to the constraint (Eq. 1), where $\text{NPV}(t,r)= 1/[(1+r)**t]$ is the discounting factor at time t and r is the discounting rate set by the storage system user.

It can be seen that the energy life cycle cost is a complex relation to technologies, as well as to the energy load, reloads and to the maintenance.

EXAMPLE (for illustration):

Taking for (S)a simplerechargeable lead battery of 1,45 Volts, with initial capacity 1000 A.h, and a life time T=500 hours, a typical case has as characteristics:

$\text{EnergyCapacity}(\text{Lead},t)= 1000.\ \exp(-0.02*t)$

$K=1$

ManufacturingCost(Lead,0)= 0,50 Euro

DismantlingCost(Lead,500)= 0,02 Euro

$\text{ResupplyCost}(t) = \text{kWhCost}(t)*1000(1-\exp(-0.02*t)$

$\text{MaintenanceCost}=0$

, where kWhCost(t) is the cost per externally resupplied kWh, we get as energy life cycle cost:

$\text{EnergyLifeCycleCost}= 0{,}50+0{,}02*\text{NPV}(500,r)+1000*\int \text{kWhCost}*[\text{NPV}(t,r)*(1-\exp(-0{,}02*t))].dt\ (t=0,\dots,500)$

This explicit result demonstrates that the energy life cycle cost depends on the overall energy grid costs over time, and of the time preference set by the user.

The DOE manual [4] provides, for many electrical storage technologies, qualitative and quantitative cost-benefit analyses, but not life cycle costs, with however an emphasis on the needs of electrical power utilities rather than network providers.

IV. Energy Storage Environmental And Emissions Tradeoffs

Additional benefits of the formalism in Section 3., are that it can very easily be adapted to address respectively environmental life cycle effects, and emissions effects. The functions ManufacturingCost, DismantlingCost, ResupplyCost must be replaced by new units and new functions measuring the environmental costs and emissions effects respectively. It is noted that older models do not offer this capability [28,30].

For lack of space, the Example of Section 3., has been expanded to determine explicitly the monetary environmental cost, and the CO2 emissions in kg, of the same battery. But a full e-Node-B has also been modelled for its environmental and climate performances.

V. Communications Network Infrastructure as A Distributed Energy Storage Grid

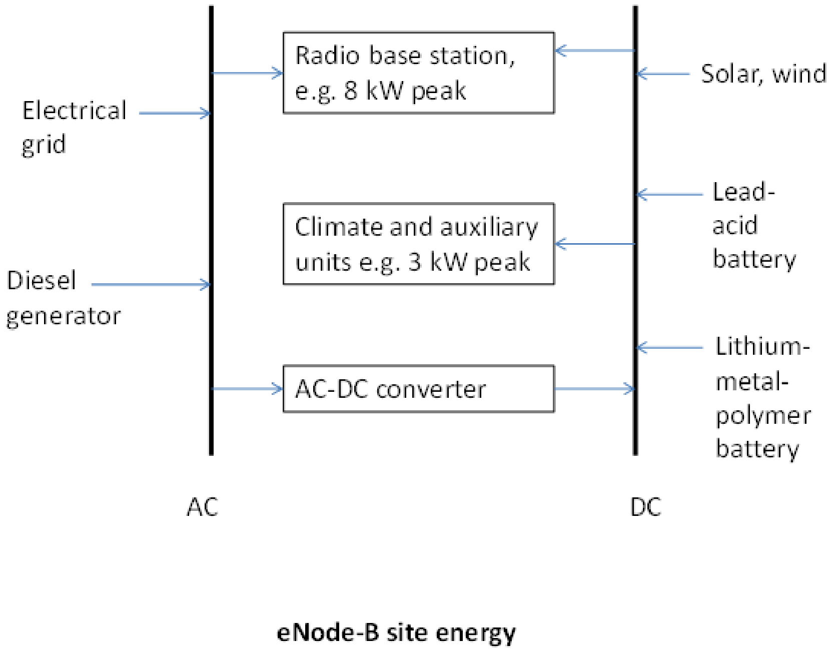


Figure 1: Overall energy distribution architecture of a 4G wireless network e-Node-B base station; the connection to the direct power grid, and localized diesel generatorare shown on the left, and localized possible renewable energy sources are shown on the right.

Converged communications networks serve users with a range of communications services which generate traffic carried through communications nodes, links, servers and data centers, each of which needs energy to operate and to carry this traffic further in the network. A few studies and models have characterized the relation between service mix, service demands, energy consumed in the networks, and CO2 emissions [15].

Most requirements fall in the range of module level system power ratings of 100-1000 kW, for long lasting operations. According to the DOE categorization by capacity and usage duration, the relevant existing energy storage technologies are therefore: flow batteries (Zn-Cl, Zn-Air, Zn-Br), advanced lead-acid VRLA batteries (valve regulated lead acid) [14], with new technologies underway also. Ni-Cd batteries offer replacements to the previous ones when limited space is available, or when over 35-degreeCelsius temperature environments apply. However, as discussed, high dependability telecommunications service requirements put specific constraints. .Lead-acid batteries are used for this purpose today, but they are toxic and require air-conditioning to avoid deterioration in some climates, raising costs.

Many zinc-bromine flow batteries must be dismissed due to the extremely corrosive nature of the elemental bromine electrolyte; life time is therefore only dependent on the number of times the system has been operational, and not on load. Zinc-air batteries cannot be recharged many times due to the cessation of the oxidation reaction; the technology however still holds potential because of its low capital cost.

Fuel cells for distributed generation/cogeneration running on natural gas have been considered, but their low efficiency (about 35-40 %), moderate capacity per cell (1-5 kW), and high costs, have disqualified them until now for telecommunications use. One experiment is reported by Verizon in Garden City, NY for a central switch [18].

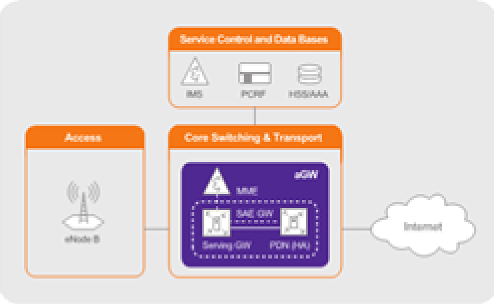
The dominant energy sources for communications network infrastructure, are therefore:
-electrical grid, with a local backup source for whenever the grid is not available;

-diesel fuel generators (which can operate 2-3 hours a day); their operation, resupply and maintenance [13] is costly, and accounts typically for 35 % of the total cost of ownership of a base station [3]; such generators are to be phased out due to climate regulations, but the fact is that there are a big help;
-intermittent localized renewable energy sources (mostly solar, wind);
-energy storage batteries, which are in general scaled so that the communications network site can be operated on batteries 75 % of the time.
As a consequence of the communications or content distribution service dynamics, the traffic load is dynamic, so the energy needs of each node are the sum of three components:
-the static traffic load independent node operating energy (including boot time energy);
-the dynamic traffic load dependent node operating energy, with its time constants sometimes due to communications buffering and delays;
-the more slowly changing backup energy needs required by “hot” activated stand-by subsystems,spares and data storage.

Whenever it is initially not possible by design to separate these three types of energy demand patterns, one should aim for sucha decomposition by locating correspondingly power meters or other energy consumption measurements. Such an analysis would reveal that typically 50 % of all4G network sites carry only 15 % of the total traffic, while 5 % of the sites carry 20 % of the traffic. See also comparable data in [10]. It would also show that a 5G central base station , and before that a 4G macro base station, consume about twice as much power at full load compared with the load when no user data are being transmitted (Project EARTH).Although industry, driven in the past by circuit switching concepts, tended to design energy storage systems based on peak traffic loads, with 5G , cloud services and Internet, energy consumption is in fact dictated by how well an eNode-B performs at low traffic load.
EXAMPLE
Whereas the complexity of 4 th and 5 th generation public wireless networks has rendered very tight the integration into so-called eNode-B’s (or enhanced eNode-Bs)(Figure 2) , of the different functionalities of what used in 3G to be called a “base station” (Figure 3), we will illustrate the above point by a simplified illustration. A typical eNode-B (macrocell) consumes 5-14 kWh of electricity, with typically 65 % due to the electronics and 35 % to climate & auxiliary equipment.

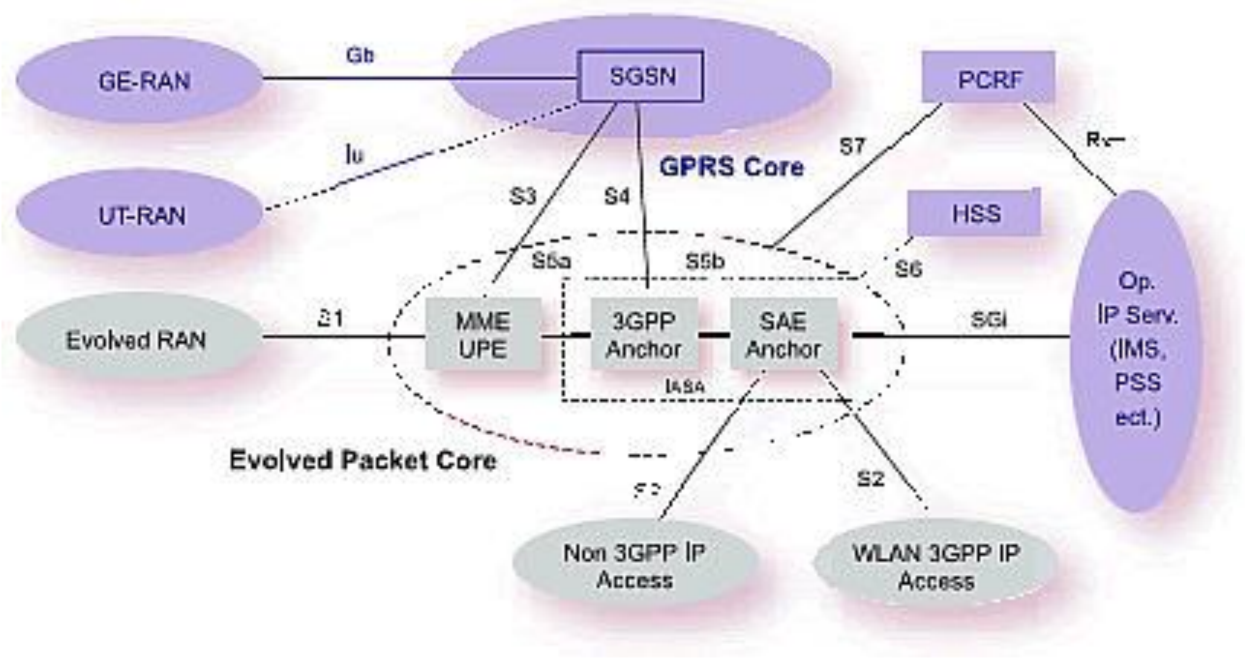
The three energy supply or storage technologies considered are:
-lead batteries, placed on eNode-B premises, associated sometimes to a diesel fuel powered generator;
-electrical grid, supplying the eNode-B;
-a localizedrenewable energy source (solar, wind);
, in that the last two are equipped with inverters or transformers to resupply the first.
The following modules have by and large a mostly static traffic load independent operating energy demand: the MIMO transceivers and the radio frontends with their power amplifiers, the radio management, as well as the backend interface to the transmission network.
The following modules have by and large a mostly highly dynamic traffic load dependent operating energy demand: evolved packet system (EPC), IP header compression/decompression, mobile management entity selection of attach of the user equipment, inter eNode-B interface, user data routing, etc…
Require backup energy“hot” standby items such as: switches, router blades, and transmission gateways, as well as clocks and remote operations & maintenance subsystems.
DC power and storage systems can lower the total cost of ownership of 4G/5G networks.

SIMPLIFIED LTE ARCHITECTURE



eNodeB: Evolved node-B
AGE: Access gateway entity
EPC: Enhanced packet core
IMS: IP Multimedia system
PCRF: Policy and charging function
HSS: Home subscriber server
MME: Mobile management entity
SAE: System architecture evolution

Figure 2: Simplified 4G wireless network infrastructure, with corresponding node acronyms



RAN (Radio access network)
SGSN (Serving GPRS Support Node)
PCRF (Policy and charging function)
HSS (Home Subscriber Server)
MME (Mobility Management Entity)
SAE (System Architecture Evolution)

Figure 3: Expanded 3 G wireless network infrastructure, with corresponding node acronyms

VI. Characteristics Of Energy Storage Technologies For Communications Nodes

Communications carriers spentin 2017 an estimated $36 billion globally on energy expense to keep wirelessbase stations online. That includes $21.9 billion in grid power, according to ABIResearch, and another $14.6 million in gasoline and diesel for gen-sets according to theGSMA. These costs have grown rapidly recently, as, on one hand, energy prices have climbed, and, next, because of the proliferation of wireless base stations, DSLAM units and routers. In addition, it is unknown how much OTT operators also spent on their networks and data centers.

Energy storage systems for communications networks almost always include enclosures &cabinets compliant with that industry’s environmental and interconnect standards. The power output levels range from 2kW to sometimes above 60 kW. The typical DC voltage is 48V, but with instances at 12 V, 24 V, 60 V, 110 V, 125 V and 220 V. Next to energy storage, typical components are rectifiers, converters, chargers, inverters, power distribution bays, and monitoring. Typical design standards are IEC 60950-1, UL 60950-1, ETS EN 300 019-2-1 Class 1.2, ETS EN 300 019-2-2 Class 2.3 ETS, EN 300 019-2-3 Class 3.2., IEC 60623, Telcordia GR-3020, and NF C 15-100. Regarding safety of the power storage some of the applicable standards are: EN 50272-2/ IEC 62485-2, UL 94 VO, UL 189, Telcordia GR 63 NEBS Level 3. For electromagnetic compatibility some of the standards are: EN 61000-6-1, EN 61000-6-2, EN 61000-6-3, EN 61000-6-4, ETSI EN 300 386 V.1.3.1 (telecommunication network), Telcordia GR 1089 NEBS Level 3. All these standards aim at maximizing dependability, reducing fires, and covering the large environmental deployment conditions.

TYPICAL	LEAD ACID BATTERY STORAGE	Ni-Cd batteries	Lithium Metal Polymer (LMP) BATTERY	Flywheels	Diesel power generators 20 kVA (*)	Solar Inverters (*)
Input nominal AC voltage range	185-250 V single phase	1,38-1,42 V / cell (float voltage)				900 V
Frequency	45-66 Hz					
Max AC input current	20 A					20 A
Output nominal DC power	2500 W			With frequency regulation		6000 W
Output DC voltage range (cabinet)	48 (or 24) V (DC)	48 (or 24) V; 1,20 V /cell	410 V			
Max DC output current	8,7 A					8,7 A
Efficiency	70-96 %	85 %		70-95 %		98 %
No load consumption	< 20 W					N/A
Standby consumption	< 2 W					< 2 W
Energy capacity (cabinet)	2,4-18 kWh		30 kWh (peak 45 kWh for 45 seconds)	0,1 MW or 0,001 MW	1500-15 000 W	16 900 Wh
Nominal rated capacity	Up to 200 Ah by battery and 1200 Ah by cabinet	75-185 Ah				
Lifetime	5000 cycles, or 3-10 years	20 years at 25 degrees C; discharge time about 24 h (optimal: 8 h)	10 years	20 years; 100 000 full charge/discharge cycles		
Dimensions	600 x 600 x up to 1800 mm		30000 cm3			600 x 500 x 300 mm
Weight	40 kg	25 kg	300 kg			40 kg
Specific Energy density	30-50 Wh/l	95 Wh/l	110 Wh/l	20-80 Wh/l		
Power density	75-300 W/kg					
Operating temperature	-25 to +50 degrees C	-20 to +65 degrees C	-20 to + 160 degree C (but internals at 60-80 degree C)			-20 to + 60 degree C

Memory effect	Small		None			None
Load cycle duration		24 h at 1,42-1,47 V	8 hours (16 A load current), or 4 hours (32 A load current)			
Self discharge	0,03-0,3 % energy/day			Min 1,3 % energy/day		
Estimated energy supply cost			1400 USD/kWh; compared to 1000 USD/kWh for Li-Ion			

Table 2: Typical characteristics in 2017 of different energy storage technologies used in communications network nodes ; these data have been collected from datasheets of about 15 different vendors, and represent only state-of-the art ranges for commercial products; the last two columns (*) provide data on on-site energy sources used in same cases (diesel power generators, and solar inverters).See also [29].

Hybrid systems are very rarely used in communications, because of liability and environmental testing issues [8]. Also,themaintenance of hybrid systems, esp. often remote diagnostics, raises organizational responsibility issues.

Most communications battery sizing calculations are based on an estimated Ah requirement, taking the ratio of the stand-by time required in hours, by the Ah capacity per cell/string. Dependent on the battery design, more complex calculations are possible. These advanced methods increase the number of cells/ strings required taking an aging factor into account (e.g. 1,25), and adjustment of the load current in A from the nominal value. Examples of on-line battery sizing programs are provided by EnerSys[21] and Total / SAFT [22].

The storage and energy source systems must be designed for reliability and environmental risks, associated with packaging technology and suitable enclosures. Most systems powering communications infrastructure nodes must achieve MTBF greater than 300 000 hours (or a 87 % probability of operating for 5 years without a failure). This can only be achieved by (N+1) parallel redundancy (as discussed above) and stand-by units, including for energy storage., and by modular designs of thereof. The telecommunications environmental operating ranges as set forth e.g. in the so-called NEBS Telcordia standards (IEC-68-2-XX, ETSI-300132-2, IEC-61204-7), usually also require air conditioning solutions; as the energy systems are mostly DC powered, during generator or renewable source drop out, the batteries continue to supply also the cooling inside the cabinets which assist in maintaining the storage life, thus reducing overall replacement and maintenance costs.

VII. Efficiency in AC-DC Power Rectifier Conversion

The efficiency of AC-DC power rectifiers is defined as the ratio of the DC output in Watts to the load, divided by the AC input in Watts. The loss is mostly converted to heat. The loss of efficiency also converts into costs; e.g. a 10 % conversion inefficiency on a 1 kW AC input converts into approx.100 Euros (2017) assuming a 0,10 Euro/kWh energy cost. In a typical communication node, energy losses from a battery system are 3000 kWh/year, while rectifier conversion inefficiencies can reach 18 000 kWh/year.

This loss exists, whether the power storage is in batteries, or the energy supply comes from renewable intermittent energy sources (solar, wind), as these hybrid sources always integrate backup storage, and switching control systems between energy sources, some of which are AC while other are DC.

By letting a controller optimize both over time and energy loads, the total energy costs, while taking AC-DC conversion efficiencies into account, allows an operator to make significant operating expense savings without affecting network dependability.

As communications nodes themselves are distributed systems, DC-DC converters are needed also to provide on-board solutions in distributed power architectures for internetworking (typically between 36 and 75 V DC, with outputs up to 80 A / 128 W) [6].

Power excursion must be minimized in all communications systems for different reasons. One reason is the fact that the electronic, radio, and computing components in the communications nodes require stable voltage and supply; this is not easy to implement across all the environmental operational envelope, leading in rare instances to the use of hybrid solutions, and, in the future, to reliance on power storage using graphene or carbon nanotubes.

VIII. Monitoring Of Battery Capacity Loss

Second-usage batteries can be used in boot and buffering mode for “hot standby” nodes and subsystems. But because extreme dependability is expected from communications networks, special measures must be implemented on first and second-usage batteries to monitor capacity loss, in addition to other traffic related monitoring taking place (see Section 2).

Regarding the typical lead-acid batteries, there is no certain method to predict their capacity [1]; therefore, capacity tests must be carried out using the manufacturers discharge tables. A capacity test implies that the battery needs to be disconnected from the load, and a back-up unit connected. However, tools exist to identify failing cells while the battery is online:

-measurement of a large deviation >25 % in the battery impedance, conductance or DC resistance, from the initial value; it is noted that within a batch of batteries, these values may deviate +/- 10 % under normal conditions;

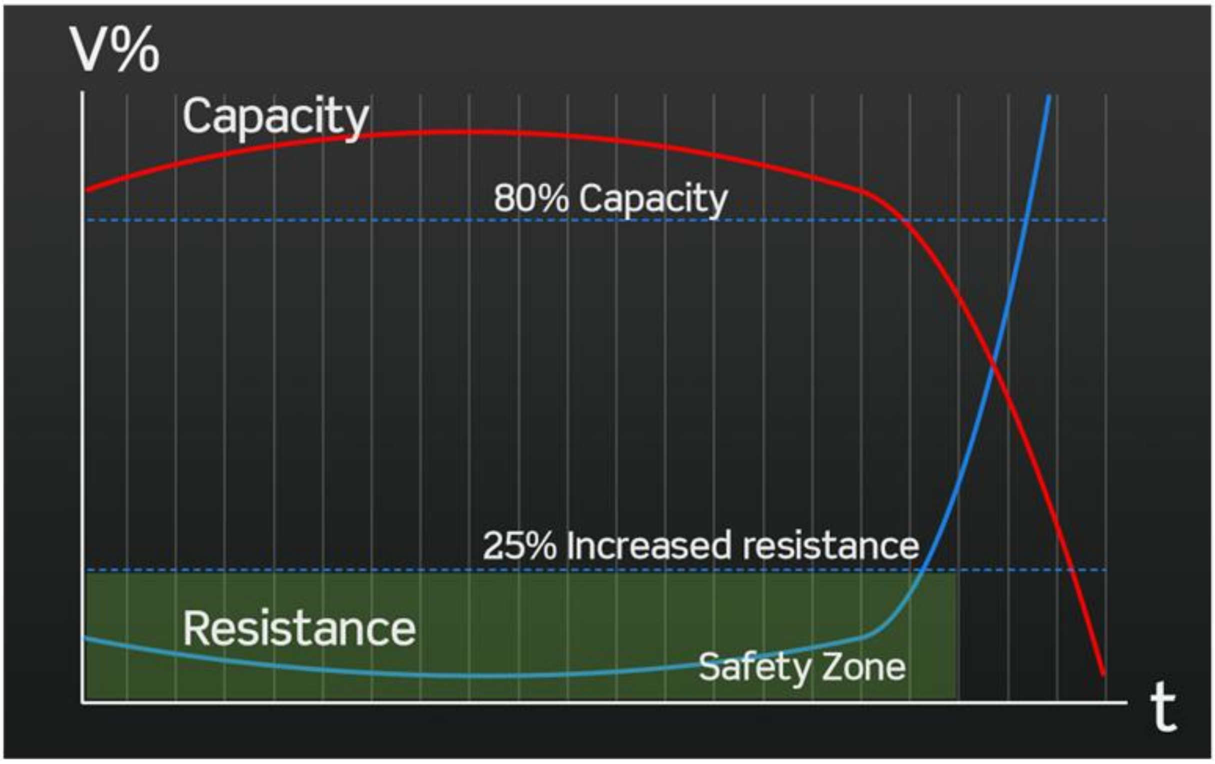


Figure 4: Battery discharge profile with time for capacity and resistance

-partial discharge test, by lowering the rectifier float voltage below the open circuit voltage, and discharging the battery with the connected load current;
-battery intercell cell temperature recording: the higher the temperature, the faster the chemical reaction in the cells, and thus also corrosion; the rule of thumb is that for every 10-degreeCelsius rise in temperature, the operational life of the battery is reduced by half. A 3-degreeCelsius temperature difference between cells indicates a possible cell failure;
-battery voltage comparison to midpoint voltage.

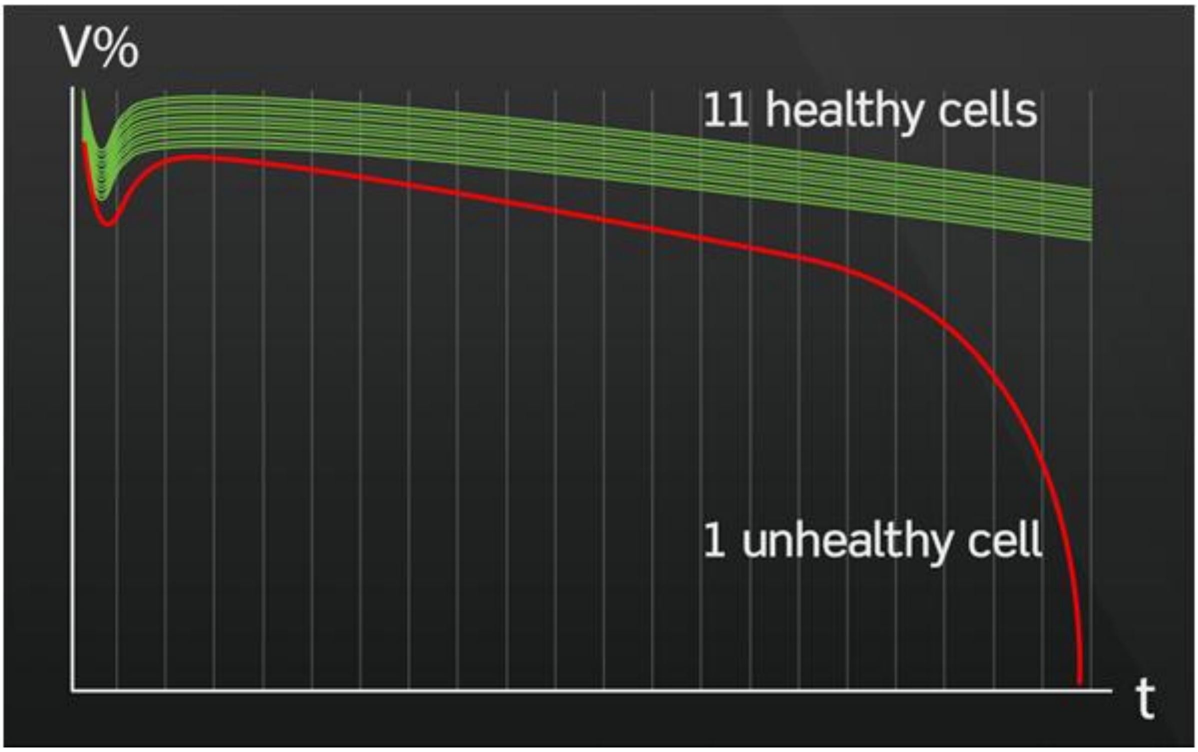


Figure 5: Battery cabinet discharge profile in view of a failed cell

IX. Energy Storage In Computing Clouds

Data centers serving computing, media distribution, as well as cloud storage needs, have very high energy consumptions to operate computers, local area networks, disk storage units, communications network interfaces, as well as cooling equipment [2,16]. To a very large extent, data centers operate on the electrical power grid, with instances of own renewable or non-renewable power plants. Uninterruptible power supplies (UPS) and transformers are also widely used. The largest energy savings come from new computing and storage devices & architectures, virtualization, power-down schemes, and from more efficient building & cooling solutions [18].

The computer industry uses other definitions than electro technical engineering to characterize energy density [19]:

-Power density: Power of a given set of equipment divided by a given area of floor space. Confusion often arises when discussing power use in data centers if these terms are not accurately defined.

-Computer power density: Power drawn by the computer equipment divided by the computer room floor area.

-Building power density: Total power drawn by the building divided by the total floor area of the building.

-Total computer room power density: Power drawn by the computer equipment and all supporting equipment such as PDU's, UPS's, HVAC, and lighting divided by the computer room floor area.

-Power usage effectiveness: Defined as the ratio of total data center energy use, to total IT equipment energy use; considering only critical IT equipment use from servers, a total power/critical load ratio can be further defined (with typical best practice values around 1,8).

Back-up energy storage, also called emergency backup power, is limited to battery storage and in rare cases to diesel generators. Some experiments have also been made using fuel cell banks of 200 kW running on natural gas [18].

In data centers, and in proportion to IT equipment energy use (scaled at 1), UPS losses represent 0,2, transformer losses represent 0,05, and chillers/air cons represent 0,3 [18].

X. Futureenergy Storage Technologies For Communications Networks And Data Centers

This Section reviews promising energy storage technologies which may meet the specific requirements of communications networks and data centers.

10.1. DC picogrids

An increasing number of network nodes operate on DC and providing uninterrupted power supply (UPS) to them through outages requires two conversions: first from the main energy storage (DC battery) to AC, and then from AC to the DC inputs required bythe specific node subsystems. Adding energy storage locally to each subsystem and managing it as an intelligent picogrid can lead to higher efficiency and lower costs [7]. The picogrid should not draw power from the UPS’s battery but should charge from the electricity grid when available. This can be carried out as the AC distribution from the electrical grid is sufficiently different compared to an AC UPS or a diesel generator, that a hidden Markov model for state estimation can discriminate between those two using line voltage and frequency measurements.

The dominant energy storage components in picogrids are 200-2000 kW lithium-ion batteries in modular cells, or zinc bromide flow batteries, or nickel-manganese-cobalt batteries, because of the need to provide frequency regulation and capacity services in view of grid stabilization[17].

Microgrid use	Lead-acid	Lithium-Ion	Li-Ion capacitor
Energy density (energy capacity)	20 Wh/kg	60-400 Wh/kg	8 Wh/kg
Power density (instantaneous power)	40 W/kg	2000-8000 W/kg	2200 W/kg
Nominal voltage	12 V	22 V cabinet (2,7-4,2 V /cell)	3,8 V
Nominal capacity	12000 Wh	1700 Wh	2,7 Wh
Max current discharge	600 A	300 A	450 A (continuous 150 A)
Maximum current charge	300 A	225 A	
Operating temperature	0-40 degrees C	-20 to +50 degrees C	-15 to 80 degree C
Storage duration		1 min-8 h	
Efficiency	70-96 %	85-98 %	
Self-discharge	0,03-0,3 % energy/day	0,1-0,3 % energy/day	

Table 3: Energy storage technologies for picogrids

10.2. New flow batteries

Iron-chromium flow stacked cell batteries (250 kW), with two electrolyte solutions, areenvisaged thanks to their expandability, and lower cost than lithium-ion batteries, andbecause they do not have the risks of zinc-bromide. The costs are claimed to be around 180 Eur/kWh (EnerVault), but membrane lifetime is uncertain.

10.3. Liquid metal batteries

These are large units of 2 MWh,with molten electrodes, with long lifetime and high lasting efficiency (98 % after 10 000 charge/discharge cycles), and small volumes. Tests are carried out by Ambri.

10.4. Carbon nanotubes

Hydrous ruthenium oxide (RuO2) nanoparticles, modified by carbon nanotubes (CNT) and graphene foam as the electrode material for the supercapacitor [27], offer longer term potential [20]. They use electrodes in an aqueous electrolyte. The combination operates safely, but also provides a higher power density (40Wh/kg) than what today’s commercially available supercapacitors can give. This design merges the supercapacitor’s high conductivity and pseudo-capacitor’s high specific capacitance.

10.5. Use of graphene electrodes

Co(OH)2/ GNS-K3Fe(CN)6-KOHultracapacitive graphene electrodes combined with suitable electrolyte, with an announced 7514 Fg(-1) specific capacitance, over 100% coulombic efficiency , and long term cycling stability(capacity retention of 75 % after 20 000 continuous charge-discharge cycles) [24] , pave the way for use in high environmental envelope super capacitor storage systems used in communications systems. Such super capacitors with graphene electrodes are claimed to have aspecific energy of 5-10 Wh/kg (comparable to LiB), with layered assembly techniques [25]. They will fit, with their redundant power storage units, into the low volumes of wireless bases stations.

10.6. Hydrogen fuel cells

Fuel cells have been considered for a long time for a possible use in communications networks but were often dismissed due to very high costs and insufficient environmental operating envelope. However, research in the automotive sector may change this perspective. Recently, some start-up’s have been producing ultra-light compact hydrogen fuel cells for IT use [26].

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