White Paper:

Pervasive Power: Integrated Energy Storage for POL Delivery

Pervasive Power Overview

This paper introduces several new concepts for micro-power electronic system design. These concepts are based on the fundamental power distribution and energy storage techniques deployed in advanced power grid architectures. With the introduction of small solid state energy storage ICs, new Pervasive Power solutions can now be created by placing micro energy storage devices directly at the point of load (POL) where the energy is used. Point of load architectures have been deployed in various power architectures down to the circuit board level. Recently introduced breakthroughs in solid state energy device technology enable circuit designers to place energy storage directly inside a chip for true point of load powering.

In order to provide a foundation for understanding Pervasive Power and the advantages of Point of Load energy delivery, the following areas are discussed:

- Defining Pervasive Power
- The interconnected power grid hierarchy
- Power distribution and energy storage techniques in the various grids
- Micropower and nanopower trends with enabling technologies
- Solid state energy storage devices and Embedded Energy
- New point of load and Pervasive Power applications.

What is Pervasive Power?

Pervasive Power is a recently introduced power distribution architecture that utilizes energy storage devices at the actual point of energy usage (point of load). This is accomplished by placing micro energy storage devices inside a complex device requiring power. Examples include microcontrollers, real-time clocks, SRAM memory, sensors, and multi-chip modules. The introduction of new solid state energy storage devices utilizing a silicon substrate is the enabling technology for this “Power on Chip” configuration. Co-packaged modules using a solid state energy storage device with other ICs are now commercially available.

A Pervasive Power architecture is created when Power on Chip enabled devices are placed together on an electronic assembly. This new distributed energy storage configuration provides many advantages.

Advantages of Pervasive Power

A Pervasive Power architecture is realized when most of the major functional semiconductor chips on a circuit board have Embedded Energy capabilities. There are many advantages that are realized with a Pervasive Power architecture:

- With Power on Chip for all major chips, overall system power is reduced
- Power saving techniques for “trickle charging” circuit boards can be used
- Damaging in-rush currents are reduced with Power on Chip
- Minimizes induction in the Power train

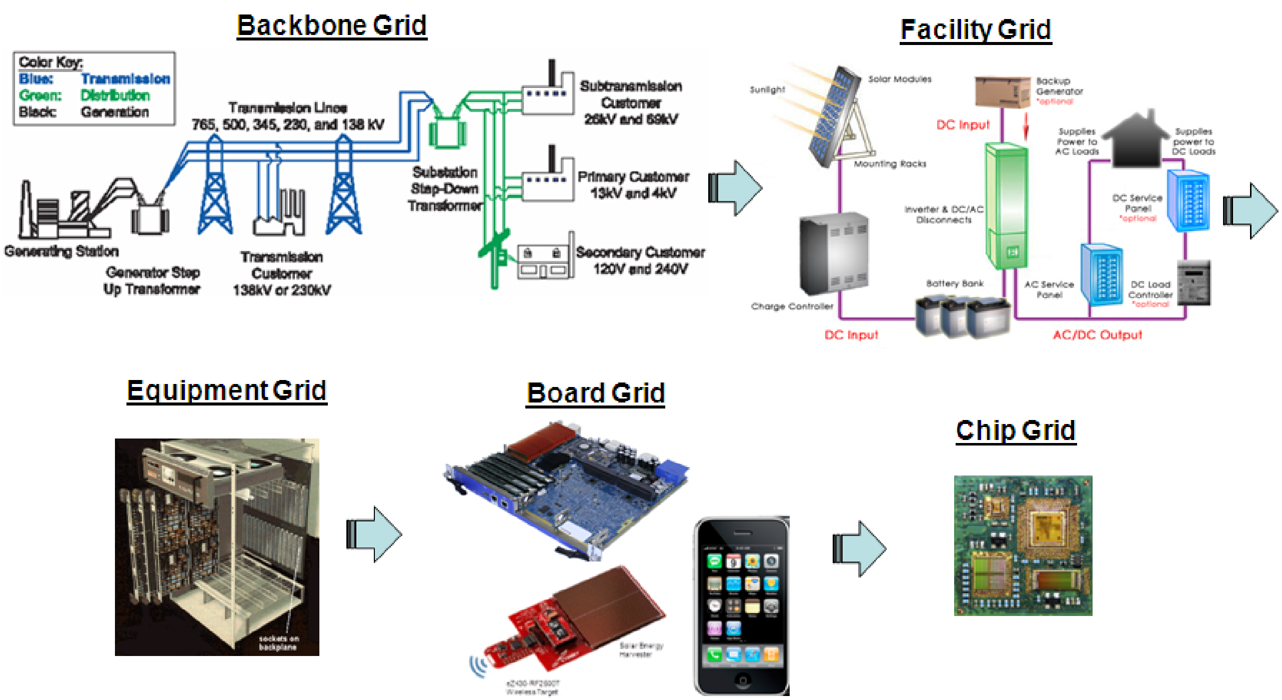
- Reduces current draw variability
- Reduces heat
- Peak energy shaving and energy shifting techniques can be utilized
- Lower power budget is realized through efficiencies
- Fewer voltage conversion interfaces
- “Dirty” power into chips is corrected, with “pure power” delivered
- Reduces bypass capacitors surrounding ICs.
- Lowers I/O switching noise
- Scalable – energy storage on the System increases with each added device

Pervasive Power and Power Grid Techniques

In order to have a better feel for the benefits of Pervasive Power, it is instructive to look at Power Grid techniques and how Power Grids are interconnected. It turns out that almost every technique for: power distribution, voltage conversion, energy storage, noise reduction and energy loss avoidance can be utilized in each grid topology.

Power Grid Hierarchy and Power Distribution Techniques

When people think of power grids, they often think of the main Backbone Grid providing power from a Power Utility to a business or home. Recently, there has also been a great deal of news coverage on the “Micro-Grid” in either green buildings or home-based solar energy deployments. But if you look at power distribution from the point of energy creation to the actual point of load, there are actually 5 interconnected grids as shown in the following diagram.



The 5 interconnected grids are:

1. **Backbone Grid** - Power is generated at a power plant and distributed to facilities (business or homes) using high voltage AC power transmission lines that is stepped down to AC Power delivery at the facility. The Backbone Grid utilizes AC current and typically do not have large power storage elements due to the losses associated with AC to DC to AC power conversions. However, many new techniques for Backbone Grid power storage are now being explored.

2. **Facility Grid** – Once AC power enters a facility (typically a business or residence), the power is distributed within the facility. The facility itself may have the ability to provide standalone power in the event the Backbone Grid power feed fails using local generators. The Facility Grid might be equipped with local power generators that could supply power back into the Backbone Grid – recent examples are home solar cells that create more energy than is used in the facility. There may be local energy storage in the Facility Grid, and new energy storage technologies and devices are being introduced.

3. **Equipment Grid** – this grid is most often seen in commercial facilities for data centers or manufacturing machinery. In most cases, this demarcation occurs at the point where input power from the Facility Grid is converted from AC to DC to run electronics. Often times, the power distribution in the Equipment Grid is a DC. Voltage (380V, 48V, 12V) Using DC power also enables more cost effective energy storage solutions (e.g. Uninterruptible Power Supplies) to be used to back the Rack Grid in the event of Facility Grid power failure.

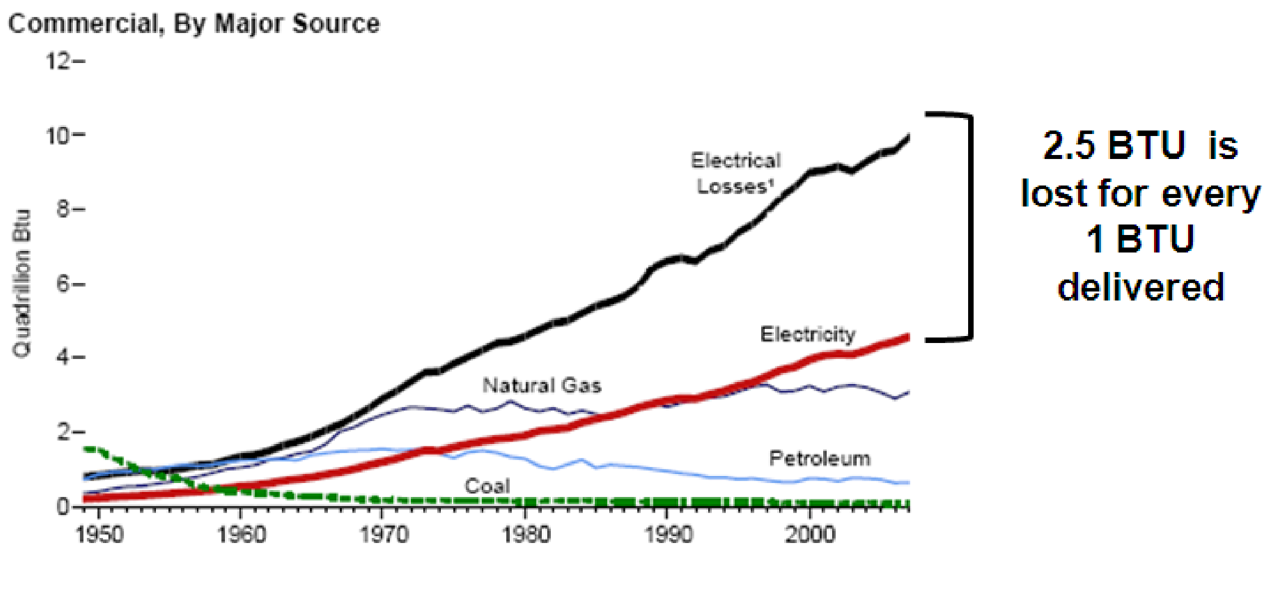
4. **Board Grid** – this the power grid used on a circuit board or electronic assembly. The electronic assembly might be autonomous like a portable hand held device that was powered from an AC/DC converter on the Facility Grid. Board Grids are almost always use DC power distribution (12V, 5V) and step down the DC voltage from the Board Grid input source to the electronic devices on the board.

5. **Chip Grid**- this is the power grid that is inside a semiconductor-based device. Initially power distribution in semiconductor devices was a fairly simple architecture. But with the advent of highly integrated large-scale devices and multi-chip module implementations, the Chip Grid power architectures have become very complex. Many of the power distribution and energy storage techniques used in the other grids now are being used in the Chip Grid.

Demarcations between each power grid are defined by:

1. A physical hand-off from a one entity to another (e.g. power company to a consumer or a factory power center to a process machine)
2. A standardized physical power connection interface (e.g. wall outlet to electrical device or a electronics rack backplane to a circuit card)
3. A current conversion from AC to DC
4. A DC-DC voltage step down.

Reducing Grid Energy Losses
There is currently a great deal of focus on the "Smart Grid" where many new solutions are being brought to bear to improve the performance of the Backbone Grid. The following chart of power uses by commercial enterprises is sourced from the DOE's Energy Information Administration. Note how important it is to lower the Electrical Losses (wasted energy) on the Backbone Grid. Of course, lowering the amount of Electricity used in commercial enterprises will lower the corresponding amount of energy



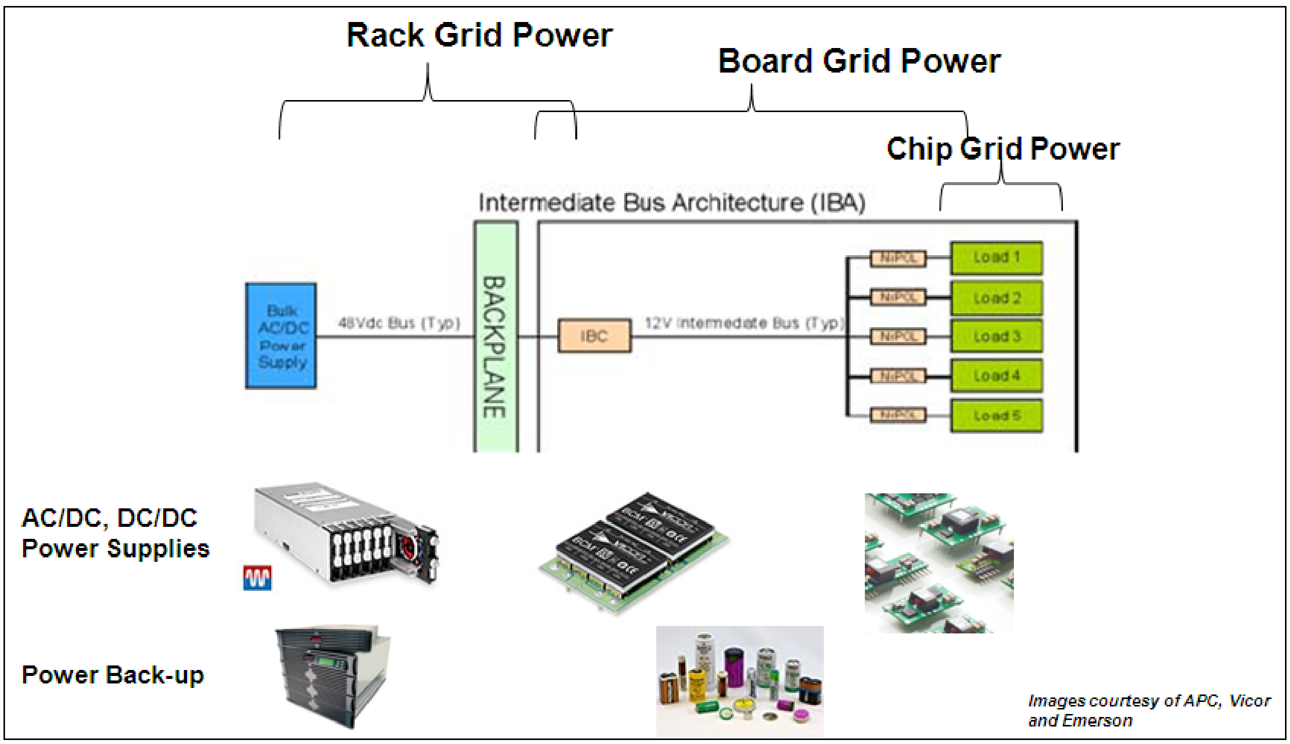
(1) Energy Information Administration / Annual Energy Review 2007

In order to reduce Backbone Grid losses, new techniques such as: active status monitoring, energy storage, more efficient energy conversion electronics, dynamic demand algorithms, and point of load energy delivery are being deployed.

Cross-grid Similarities and Point of Load Power Management
Just like the Backbone Grid, the need to effectively manage power and reduce energy losses are just as important in the other 4 interconnected grids. Many of the same techniques and technologies implemented in the Backbone grid apply even down to

the Chip Grid. The following figure shows the relationship between the Equipment, Board and Chip grids. System level designs need to view these grids holistically in order to manage the energy used by the system effectively. One of the key methods of effectively managing power is to use Point of Load technologies. Point of Load management involves the following:

- Measuring the power being used at the actual point of use
- Characterizing all the points in the power delivery chain
- Actively managing the power to the point of use through a closed loop control system
- Implementing dynamic power demand algorithms to optimize the efficiency of the power used.
- Providing energy storage at the point of load to enable optimal energy saving profiles independent of the power input.



Point of Load Power-On-Chip Benefits
Placing rechargeable energy storage at the point of load in the Chip Grid has many advantages. These include:

- Minimize I^2R losses – because devices with Power on Chip can be trickled charged, less power needs to be presented to the electrics from the power supply
- Power Sources can be isolated – with Power on Chip devices can be “lifted” off the grid and run on the pure power in the rechargeable energy storage device. When isolation is no longer required, the device can be “placed” back on the grid.
- Reduced I/O switching noise when using on chip power
- Power where ever it is needed – Power on Chip can be placed in any type of device
- Power Bridging – In the event of power brownout/blackout, the on chip energy storage takes over and powers the device.
- Power Boosting – there may be times when a device needs additional power and can draw upon the on chip energy storage vs. placing an additional demand on the main power supply.
- Effective in ultra low power applications which are typically also miniaturized.
- Warm start energy can be used for devices in deep sleep or standby.
- Bridging “error” or early termination conditions – There may be times when a power interruption would create device operation errors or even device failure. Having Power on Chip provides power to complete operations in an orderly fashion.

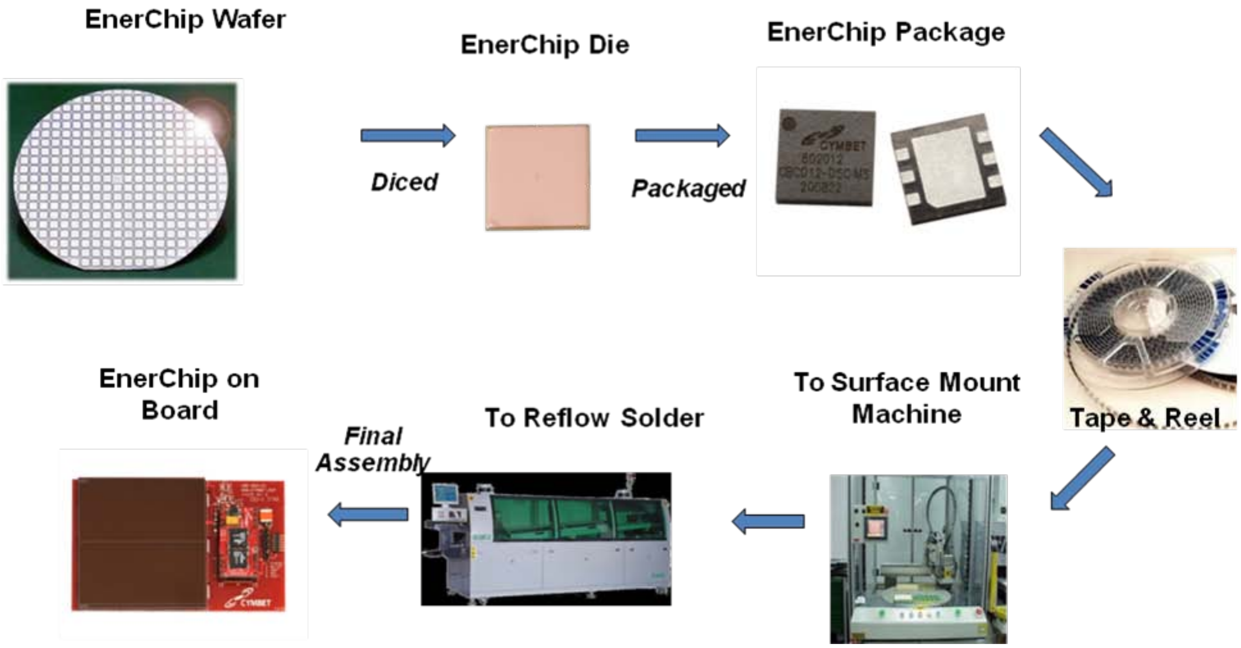
Chip Grid Trends
The key trends that are occurring at the Chip Grid level include:

- Lower power devices using lower voltages
- Denser Devices
- Multi-chip modules
- System on Chip
- Lab on Chip
- Advanced power management techniques
- Same digital power control techniques as Board Grids and Rack Grids

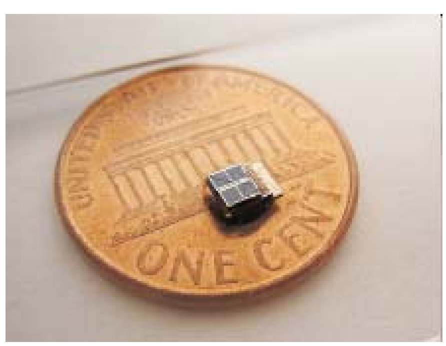
All of these trends are pointing toward integration and miniaturization. Many technologies have progressed down this curve, but batteries have not kept pace. So what are the implications to the Chip Grid? One key implication is that we need to integrate intelligent rechargeable energy storage into the Chip Grid. In order to achieve this requirement, a new product technology has been introduced: solid state rechargeable energy storage devices.

Solid State Rechargeable Energy Storage Devices

Cymbet has introduced a solid state rechargeable energy storage device based on a silicon substrate called the EnerChip™. The following photo diagram shows how the EnerChip is created on a silicon wafer. The EnerChips are diced and then can be used as bare die or packaged in standard semiconductor package. Mounted on tape and reel, the EnerChips are placed on circuit boards using Surface Mount Technology and then can be reflow soldered to the board. The EnerChips are treated like the other IC packages on the final board.



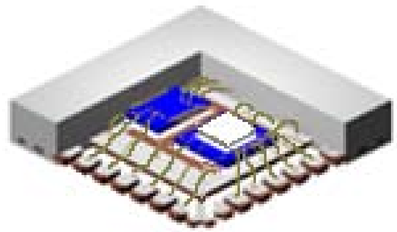
Using the EnerChip bare die has unique advantages for Point of Load energy storage from a packaging perspective as they are small and can be co-packaged in many ways with other ICs or micro devices. The photo below is a millimeter-sized Solar Energy Harvesting sensor. The solar cell sits on an ultra low power microcontroller that sits on a solid state rechargeable energy storage device (EnerChip CBC012). The devices are wire bonded to each other.



Integrated Energy Storage for Point of Load Power Delivery
With the introduction of solid state rechargeable energy storage devices it is now possible to co-package energy storage directly with other Integrated circuits.

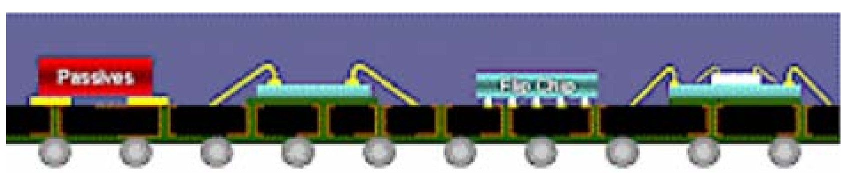
Examples are shown in the following diagrams:

Rechargeable Solid State Energy bare die Co-packaged side-by side with an IC:

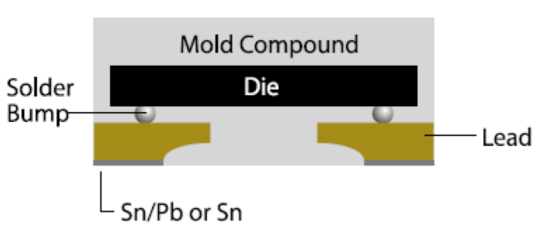


Rechargeable Solid State Energy bare die Co-packaged in "wedding cake" die stack:

Rechargeable Solid State Energy bare die in System on Chip module:



An important attribute of Solid State Energy Storage built on silicon wafer is that they can be solder attached to the circuit board surface using a "flip chip" technique. The flip chip attach mechanism opens up many new miniature packaging options.



Conclusions

This paper introduced several key concepts which are summarized as follows:

1 – Pervasive Power is a new power distribution architecture that provides enhanced use of power at the point of load that increases overall system energy efficiency.

2 – There are 5 levels of interconnected Grids terminating in the Chip Grid. Each grid type shares the same principles of power generation, power distribution, energy storage and energy management using dynamic demand algorithms.

3 – The interconnected Grids can utilize digital power control techniques to optimize the end to end use of power and improve energy efficiencies.

4 - In order to enable the Chip Grid, a new energy storage device that can be integrated into the Chip must be used. Rechargeable solid state energy devices ideally meet this need.

5 – These rechargeable energy storage devices can be co-packaged with other ICs in the Chip Grid to create a miniature highly integrated package.

6 – Once boards are populated with Chips with on-chip energy storage Pervasive Power architecture is created.

For additional information on Pervasive Power for Integrated Energy Storage for Point of Load Delivery, the www.cymbet.com website has application notes, datasheets, videos and contact forms.