CABA™ Continental Automated Buildings Association

Driving Energy Efficiency & Occupant Comfort through Printable & Flexible Electronics Applications in the Next Generation Connected Home

A CABA WHITE PAPER

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CABA Connected Home Council

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ABOUT CABA

The Continental Automated Buildings Association (CABA) is an international not-for-profit industry association, founded in 1988, and dedicated to the advancement of intelligent home and intelligent building technologies. The organization is supported by an international membership of over 330 organizations involved in the design, manufacture, installation and retailing of products relating to “Internet of Things, M2M, home automation and intelligent buildings”. Public organizations, including utilities and government are also members. CABA's mandate includes providing its members with networking and market research opportunities. CABA also encourages the development of industry standards and protocols, and leads cross-industry initiatives. CABA's collaborative research scope evolved and expanded into the CABA Research Program, which is directed by the CABA Board of Directors. The CABA Research Program's scope includes white papers and multi-client market research in both the Intelligent Buildings and Connected Home sectors. www.caba.org

ABOUT CABA’S CONNECTED HOME COUNCIL (CHC)

Established in 2004, the CABA Connected Home Council initiates and reviews projects that relate to connected home and multiple dwelling unit technologies and applications. Connected homes intelligently access wide area network services such as television and radio programming, data and voice communications, life safety and energy management/control information and distribute them throughout the home for convenient use by consumers. The Council also examines industry opportunities that can accelerate the adoption of new technologies, consumer electronics and broadband services within the burgeoning connected home market. www.caba.org/connected-home-council

DISCLAIMER

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EXECUTIVE SUMMARY

The advent of printable and flexible electronics (PE) can be hailed as being close to the pinnacle of the digital age, being a fusion of mass production, computer design, innovations in circuit board printing and micro-fabrication. There are many potential applications for PE, from innovating consumer devices, to creating a fully sensored industrial operation. At the same time, the concept of the Connected Home is moving from futuristic concept to reality, in tandem with the rise of the so-called Internet of Things (IoT).

PE is an enabling technology for the connected home and IoT. Both these concepts entail the deployment of networked technologies that deliver anytime access and control of appliances, lighting and heating, window coverings, irrigation, entertainment systems and more.

Adding this kind of intelligence and active functionality to everyday objects, surfaces and structural components of a home poses a number of challenges related to cost, power needs, deployment and integration when using conventional electronics. The cost point of adding this level of intelligence and control to the home can be prohibitively high, especially in a retrofit.

PE changes this paradigm. To quote Stephen Hoover, CEO of PARC, A Xerox Company, speaking at last year's Canadian Printable Electronics Symposium: "PE can turn the Internet of Things into the Internet of Everyday things," due to its advantages, particularly with regard to cost.

According to Peter Kallai, CEO of the Canadian Printable Electronics Industry Association: "Hard-hitting applications based on economics and sustainable development that give people more control to reduce their utility bills and improve the function and efficiency of their homes are likely to drive the adoption of connected home technologies enabled by PE, versus 'nice-to-haves' like refrigerators with TV screens."

In fact, PE is already present in most homes today through the control panels found on many household appliances. These control panels provide simple switching, often integrated with simple lights or touch-based sensor panels, or both. As the technology evolves with many new building blocks, such as printed memories, printed antennas, logic circuits and a variety of sensors for a wide range of applications, more opportunities open up for connecting the home.

Many companies are already active on a number of fronts to advance the state-of-the-art connected home, using PE-related technologies and manufacturing processes, to create new applications, including a new generation of energy-harvesting systems, new sensors for gas, air quality and motion tracking, printed organic LED lighting, printed antennas for over the air reception of television signals, and building structure monitoring systems, just to mention a few.

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In this paper, we examine how this additive manufacturing technology, PE, can play a role to evolve the function and operation of the connected home. We examine:

- How it can create the "net-zero" home, which returns as much energy as it takes from the local power grid
- How the structural and operational health of the home can be monitored with passive PE sensors, to catch problems before they become crises
- How PE is, and could, advance lighting technologies and the benefits of doing so, to reduce energy usage and improve occupant comfort
- The latest advances in PE-enabled switching that provide the functionality homeowners need to control their connected home
- The leading wireless communications protocols already in use for connected home and smart home systems

This paper explores some of the specific applications where PE technologies and applications can provide disruptive and compelling alternatives to some of the conventional technologies used in the connected homes industry, or enable the creation of brand new applications. The focus of this report is the near-term, just-on-the-horizon technology applications that can be developed into fully commercial offerings within the next few years.

INTRODUCTION

What is the connected home?

The connected home is a sum of networked technologies that deliver anytime access and control of appliances, lighting and heating, window coverings, irrigation, entertainment systems and more.

For years, the concept of the connected home has advanced on the premise of providing the typical homeowner with greater comfort and convenience. This is the greatest appeal of the connected home, and driver for the market adoption of related technologies are the cost savings that can be realized.

The need to reduce energy usage

According to the U.S. Department of Energy, commercial and residential buildings each account for about 20 per cent of total energy use. Based on recent data from Natural Resources Canada, Canada is comparable in more densely populated provinces like Ontario.

At a macro level, the need to invest in technologies that substantially scale back building energy usage from carbon sources, be it residential or commercial, has become all the more pressing after almost 200 countries agreed to ambitious new carbon reduction targets during landmark climate talks in Paris in December 2015. By 2070, the world will have had to reduce carbon emissions to practically zero to meet these targets.

How does the connected home figure into this? First, by employing new technologies, and new mechanisms of control, to reduce overall energy usage and to shift electricity loads from peak periods to other times of the day, thereby taking the strain off the local power grid and providing cost savings for the homeowner.

The second is by weaning ourselves off our reliance on power generation from fossil fuels, with energy harvesting technologies that can allow a home to generate some of its own power. The potential is even there to create the "net-zero" home – a building that generates as much power for the local grid as it draws.

And we believe that PE can play a major role on both sides of this equation in energy reduction through, for example, more efficient lighting and/or printed photovoltaic solar cells that can be cost effectively added to large surfaces to generate power with a lower investment than is possible with current solar cell technology.

How could the connected home be a smarter home?

All of this is dependent on having an ecosystem of technologies throughout the home and embedded in everyday appliances and devices.

For example:

1. Renewable energy harvesting and storage systems to generate and store the energy *in-situ*, thus reducing the energy draw from the grid.
2. A wireless network and control system, including a set of smart sensors to monitor security, energy use, and occupant comfort. Algorithms in the control system are programmed to optimize comfort, energy usage and cost savings.
3. Remote access that enables homeowners to access and control their home systems from anywhere with a wireless device such as a smartphone.
4. Dynamic facade components that continuously adjust solar shading to improve daylight utilization and to reduce cooling loads while simultaneously increasing the occupant comfort.
5. Insulation, ventilation systems, including a set of distributed sensors that can control the energy outflow and at the same time maintain a high quality in-door environment.
6. Next-generation OLED lighting technologies based on PE that use significantly less energy, and that can be networked with sensors to direct light where needed and reduce light where less is required, or turn off lights based on occupancy sensors.
7. Wearable systems that monitor the activity levels and health indicators of the occupants and operate as part of the connected home environment. (Not discussed in detail in this white paper.)

Driving the Internet of Things

This is, of course, part and parcel with the so-called Internet of Things, in which everyday objects are embedded with electronics, software, sensors and network connectivity that enables these objects to collect and exchange data. A fully functional connected home is possible today, using conventional technologies that have been around for years. But the cost point of adding this level of intelligence and control to the home can be prohibitively high, especially in a retrofit scenario with existing homes.

But one additive manufacturing technology, PE, can substantially reduce the cost and complexity of adding the functions and the intelligence necessary to create a truly connected home, as well as yield the operational cost savings over the life of the home that have a direct impact on a family's bank account. With PE, electronic components and simple systems are created by printing conductive inks onto a variety of substrates, such as paper, plastic, fabric or glass.

Such hard-hitting applications, based on economics and sustainable development, are the focus of this paper, as opposed to some of the "nice-to-have" applications that have been around for years, such as television displays on refrigerators.

To quote Stephen Hoover, CEO of PARC, A Xerox Company, speaking at last year's Canadian Printable Electronics Symposium: "PE can turn the Internet of Things into the Internet of Everyday things" due to its cost advantages.

Assessing the maturity of the technology

In this paper, we look at products and applications that are, or soon will be, in the market. In many instances, we grade applications in terms of their Technology Readiness Level (TRL), a method of assessing the maturity of a technology.

According to NASA, the TRL Levels are defined as such:

TRL 1	**Basic principles observed and reported:** Transition from scientific research to applied research. Essential characteristics and behaviors of systems and architectures. Descriptive tools are mathematical formulations or algorithms.
TRL 2	**Technology concept and/or application formulated:** Applied research. Theory and scientific principles are focused on specific application area to define the concept. Characteristics of the application are described. Analytical tools are developed for simulation or analysis of the application.
TRL 3	**Analytical and experimental critical function and/or characteristic proof-of concept:** Proof of concept validation. Active Research and Development (R&D) is initiated with analytical and laboratory studies. Demonstration of technical feasibility using breadboard or brassboard implementations that are exercised with representative data.
TRL 4	**Component/subsystem validation in laboratory environment:** Standalone prototyping implementation and test. Integration of technology elements. Experiments with full-scale problems or data sets.

TRL 5	**System/subsystem/component validation in relevant environment:** Thorough testing of prototyping in representative environment. Basic technology elements integrated with reasonably realistic supporting elements. Prototyping implementations conform to target environment and interfaces.
TRL 6	**System/subsystem model or prototyping demonstration in a relevant end-to-end environment (ground or space):** Prototyping implementations on full-scale realistic problems. Partially integrated with existing systems. Limited documentation available. Engineering feasibility fully demonstrated in actual system application.
TRL 7	**System prototyping demonstration in an operational environment (ground or space):** System prototyping demonstration in operational environment. System is at or near scale of the operational system, with most functions available for demonstration and test. Well integrated with collateral and ancillary systems. Limited documentation available.
TRL 8	**Actual system completed and "mission qualified" through test and demonstration in an operational environment (ground or space):** End of system development. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. Verification and Validation (V&V) completed.
TRL 9	**Actual system "mission proven" through successful mission operations (ground or space):** Fully integrated with operational hardware/software systems. Actual system has been thoroughly demonstrated and tested in its operational environment. All documentation completed. Successful operational experience. Sustaining engineering support in place.

(Source: NASA)

PART 1: BUT FIRST, WHAT IS PRINTABLE AND FLEXIBLE ELECTRONICS?

System components and their applications

With PE inks that can conduct electricity – made from materials such as graphite, silver and copper – are printed on a substrate at high enough density to form a complete electronic circuit, but thin enough to have negligible impact on physical footprint. The substrate can be rigid, flexible or even stretchable, such as paper, plastic, fabric or glass.

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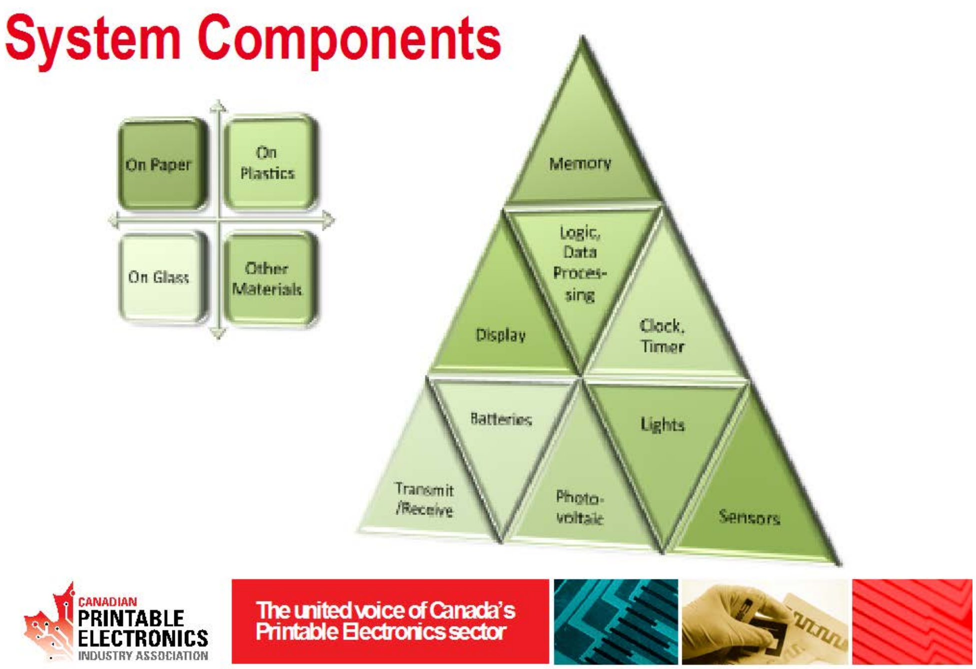
These inks can be applied through traditional printing processes such as flexo, screen, inkjet, gravure and offset, as well as through coatings. This can be done through fast and inexpensive automated processes, such as those used in the commercial printing industry for newspapers and magazines.

These electronic components can also be embedded through additive manufacturing processes, such as 3D printing or in-mould electronics.



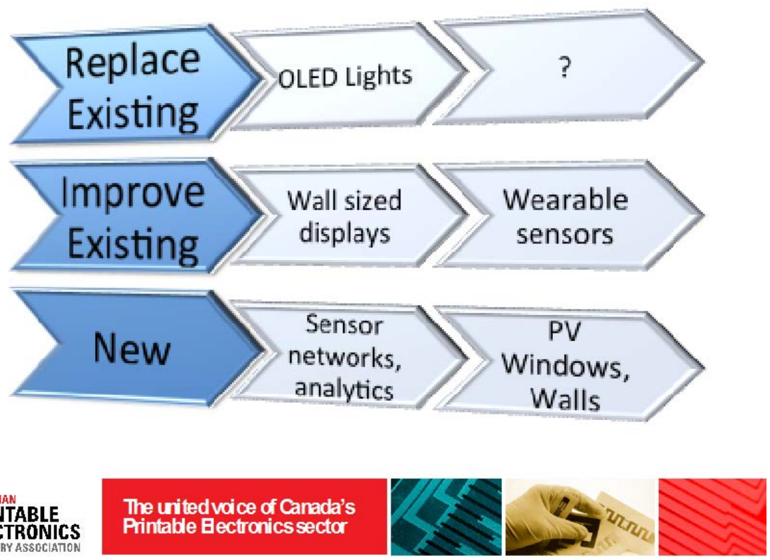
PE can be used to create discreet components such as displays, conductors, transistors, sensors, light emitting diodes, photovoltaic energy capture cells, memory, logic processing, system clocks, antennas, batteries and low-voltage electronic interconnects. These can be integrated into simple systems that, for example, can record, store and then transmit temperature or air quality information. Fully functional electronic systems can be created in this way, or discreet components and sub-systems can be produced to function as part of a hybrid solution with conventional silicon-based integrated circuits or components.

PE can overcome the bottlenecks around the issues of cost, manufacturing complexity, and even environmentally sound disposal and recycling, to:

- Add intelligence to everyday objects, as envisioned by the Internet of Things, by creating functional electronics in the form of labels that can be added to just about anything for sensing, tracking or communication.
- Embed electronic functions within interior design elements and large surface areas within a home, such as wallpapers, blinds and window glazings, reducing, if not eliminating, the need to run traditional cabling.
- Dramatically reduce the form factor of three-dimensional, traditional electronic systems, sub-systems and devices with hybrid solutions by replacing traditional components with two-dimensional printed alternatives.
- Open up a whole new world of large-area flat and flexible displays.
- Be used to create new energy-harvesting systems, such as photovoltaic roofs, sidings, windows/blinds, and/or create low-power systems that can operate as self-powered with harvested energy.

This technology has been under development for 10 to 15 years in various parts of the world. Large volume commercial applications are now hitting the market in the (1) automotive sector through control panels, antennas (2) consumer products such as organic electronic TVs, monochromic book readers, (3) intelligent packaging through labels that measure food freshness, (4) security documents that embed electronic features and (5) home appliances and (6) health and fitness applications where it can measure heat rate, body temperature, embedded into wearable devices.

This technology has a number of applications for connected homes. In the following sections, we explore some of the specific applications where this kind of technology can play a disruptive and compelling role to create the truly connected homes. Our focus is on shorter term tech applications that can be developed into a fully commercial offering within the next few years.



PART 2: ENERGY MANAGEMENT -- ACHIEVING THE NET-ZERO HOME WITH PE

Putting surfaces to use

As we referenced in the Introduction, the home building industry has been working toward achieving the "net-zero" home. This means the total amount of energy used by the building on an annual basis is about equal to the amount of renewable energy created on the site.

Depending on the circumstances, the home may generate surplus energy that can be returned to the local power grid.

Three areas where PE can play a role in creating the net-zero home are the siding, windows and the roof.

Smart glass

Smart glass or switchable glass (also smart windows or switchable windows in those applications) is glass or glazing with light transmission properties that are altered when voltage, light or heat is applied. Generally, the glass changes from translucent to transparent. This allows for some or all wavelengths of light to be blocked from passing through.

Smart glass technologies include electrochromic, photochromic, thermochromic, suspended particle, micro-blind and polymer dispersed liquid crystal devices.

When installed in the envelope of a building, smart glass creates climate adaptive building shells or dynamic envelopes. These can save costs for heating, air-conditioning and lighting, as well as avoid the cost of installing and maintaining motorized light screens or blinds or curtains. Most smart glass blocks ultraviolet light, reducing fabric fading. With suspended particle-type smart glass, this is achieved in conjunction with low emissivity coatings.

Critical considerations for smart glass include material costs, installation costs, electricity costs and durability, as well as functional features such as the speed of control, possibilities for dimming and the degree of transparency.

Coatings, control systems and components based on PE can address issues around material costs and installation factors such as concerns around the bulkiness and higher power needs of conventional electronics. In fact, low-power PE components could obtain all necessary energy from the solar and thermal energy hitting the window itself.

Chromogenic materials for additional insulation

A now common form of smart glass uses chromogenic glazing materials, which selectively control the spectral aspect of radiation. They tint automatically, based on outside temperature and brightness, or as determined by automated building controls.

Infrared radiation transfer is suppressed to provide additional thermal insulation. Modified low-emittance coatings can also reject unwanted heat gain due to solar infrared. Additional energy savings result with dynamic control over the spectral characteristics of the glazing. There are a variety of technologies that can produce the desired effect, such as the transition metal switchable mirror.

In an evaluation in Denver by the U.S. General Services Administration, chromogenic windows significantly reduced heat gain over the baseline low-e window, reducing annual HVAC cooling electricity use by as much as 10 per cent.

Photovoltaics for harvesting energy from sidings, windows, roofs

While glazing technologies such as chromogenics can greatly improve the insulating properties of a window, photovoltaics goes a step further to turn a window into an energy-harvesting device.

And not just a window, but any part of the building exterior, particularly sidings and the roof, with photovoltaic shingles.

PE comes into play with one type of photovoltaic technology, "organic photovoltaics." This encompasses small molecule and polymer photovoltaics, as well as hybrid approaches using both organic and inorganic materials.

According to a market assessment by the market research firm IDTechEx, "An Introduction to Photovoltaics Beyond Conventional Silicon," several research groups are addressing conversion efficiency by employing a combination of nanomaterials and unique nanoscale architectures.

These hybrid organic-inorganic photovoltaics consist of light absorbing polymers in contact with semiconductor nanocrystals, fullerenes or nanostructured metals. The nanomaterials affect electro-optical properties of the conducting polymer, which include assisting in absorption of red and near-infrared photons, a significant portion of the solar spectrum.

Despite its great potential, photovoltaics have experienced mixed results over the years to achieve broad market traction due to issues around form factor, indoor performance, efficiency and cost. But organic photovoltaic cells fabricated using PE's large area coating or continuous printing processes, as opposed to the traditional batch process, could make a profound difference.

"The possibility of using flexible plastic substrates in an easily scalable, high-throughput, high-speed, low-temperature, 'roll-to-roll' printing process may reduce the production costs for organic photovoltaics to a point where they are competitive with inorganic thin-film technologies," IDTechEx concluded in its market assessment.

"Although organic solar cells aren't as efficient as their inorganic counterparts, their other characteristics -- flexibility, weight, ruggedness, cost -- still make them attractive. They can be more readily embedded in other materials, from fabrics to plastics to roofing, and are ideal for small, low-power projects but can also be scaled to much larger areas than conventional solar cells."

In fact, back in 2008, researchers from Konarka Technologies used the inkjet technology of CPEIA-Member company FUJIFLIM Dimatix to produce highly efficient solar cells.

TRL for Energy Management Applications

PE-enabled solution	TRL	Potential Market (e.g. units/building)	Tech readiness - development challenges	Drivers for adoption	End user wants, needs	Next steps for market ready product (time to market)
Smart Glass: Coatings, Control Systems, Components	TRL9	Broad use in residential and commercial buildings	None	Reduce material, installation, electricity costs Improved durability	Occupant comfort Energy cost savings Convenience	In Market
Organic Solar Cells/Photovoltaics	TRL5	Broad use in residential and commercial buildings	Scale up, commercialization, cost reduction through mass production	Flexibility Low weight Ruggedness Lower cost	Reduced energy use Ability to generate own electrical power	4-5 years
Integration of Smart Glass, PV with Lighting, HVAC systems.	TRL4	Broad Use in Residences, Condos, etc.	Integration on large buildings will have to take place first. Smart glass and PV must be installed on more homes first more widely.	Energy optimization and cost reduction	Ease of use, optimization, self managed systems that self optimize.	6-7 years

					Will take place for higher end homes and high end condo buildings as integrations between various home automation systems.	

Integration with artificial lighting

In Part 4, we will discuss PE-enabled lighting systems, including organic light emitting diodes (OLEDs) that consume less power, and the value of sensors that can be used to tune the colour of light for improved occupant comfort and wellness.

In the net-zero home enabled with PE, natural and artificial light can be managed in a holistic fashion.

In one example, a printed colour sensor could be integrated with the OLED that is used to match the colour of the artificial light to that of the natural light. This multi-colour capability could also be used to provide a light colour and intensity specific to the application and time of day.

In another example, a transparent photovoltaic cell could be printed on the substrate to provide power for the daylight harvesting system. While such transparent photovoltaic systems have relatively low efficiency, they may be able to provide enough power for the occupancy or daylight harvesting systems, or for a wireless control node to interface the window to the building control system.

The technological readiness of these examples is summarized in the chart at the end of Part 4.

PART 3: HEALTHY HOME: MONITORING THE HOME THROUGH PRINTED SENSORS

What's behind the wall?

The connected home, by default, is a smart home. In theory, every aspect of its design, operation and maintenance is geared toward ensuring it achieves optimal occupant comfort and efficiency over its lifecycle.

But there is always the possibility of flaws in materials, components and construction. Severe weather events may allow moisture to penetrate the building envelope, where it can work away unnoticed for months or even years, degrading structural materials, or creating health issues such as mould.

But how can we see what's inside the wall without resorting to destructive means of access and investigation, and achieve continuous, low-cost monitoring to spot any issues early?

One option available for years with conventional electronics is battery-powered wireless sensors. These come in different price ranges and can cost up to $50 or more depending on functionality and specifications.

But while the battery life on active wireless sensors has been increasing (>5 years or more), a battery will only last so long. This finite lifespan makes it unsuitable for applications with embedded components intended to last for the lifetime of a home or other built structure.

Enter passive and hybrid sensors

Passive PE sensors, on the other hand, can overcome these power and cost limitations. They can be suitable for *in-situ* long term monitoring of various environmental conditions such as humidity and structural health monitoring, to provide early warning from within the structure and reveal dangers for the stability of the structure or the health and safety of occupants. Passive PE sensors can be either printed on the surface of building components, or embedded in the building assemblies. A change in the environmental condition affects the electrical properties of the passive sensor, for example, an antenna's impedance, which is then transmitted to the scanner on demand.

Mass-produced passive sensor inlays would cost around a dollar, similar to Radio Frequency Identification (RFID) tags, and could be embedded in the construction components/assemblies.

These passive sensors will be very useful where no real-time monitoring is needed and semi-annual or annual inspection with a hand-held scanner is sufficient to detect a problem. On the other hand, it is also possible for these sensors to exploit standard RFID communication protocols and make use of existing RFID technologies that are already mature, for more regular monitoring. Given the current state of the technology, these solutions may begin as hybrid ones that combine conventional and printable components.

Applications

Passive sensors can serve a dual purpose.

The first is during the manufacturing process of a building material or component, as a license plate for identification and sensing. When used as a license plate, the sensor can help in streamlining and monitoring the production and quality control processes.

The second is after installation in the build structure, where it can then be used to monitor performance and integrity.

For some applications it may be possible to design printable sensors with a memory function to record the maximum value of the parameter being monitored. For example, a printed time-temperature sensor can be installed or embedded below the surface on concrete beams and columns. The sensor would record the maximum temperature reached during a fire, which may be valuable information to determine if structural integrity has been compromised.

And because these sensors are low-cost, they can be affordably deployed in clusters to create a redundant mesh network. This ensures the failure of one or even several sensors doesn't compromise the ability to monitor the home's health.

Examples of embeddable printed passive sensors include:

- Pressure sensor to measure ice and snow weight on roofs.
- Sensing moisture in the gypsum board, wall assemblies, or attic. For example, Sensible Solutions Sweden AB has developed a humidity sensing system that uses pairs of standard RFID inlays.
- Detecting very slow water leaks behind the walls.
- Sensing and recording the maximum temperature reached during a fire.
- Sensing moisture in insulated glazing units for windows.
- Sensing displacement in the structural element to monitor the strain or permanent damage.
- Sensing temperature when concrete is curing.
- Sensing critical damage to the infrastructure element such as the foundation and the footing.
- Sensing the onset of corrosion in concrete beams and columns.
- Sensing vacuum failure in Vacuum Insulation Panels (VIP).

Some of the sensor applications listed above are at the early stages of deployment in other sectors but have yet to be deployed in the construction industry. For example, temperature sensors are in the early stages of deployment in the food industry. There is a keen interest from academia and PE manufacturers to develop humidity sensors which are still in the prototyping and testing stage.

Market uptake challenges

Despite their potential cost advantage, the main challenges in the uptake of PE passive sensor technology for smart home applications lies not only in scaling up the solution but also developing a new business model in which companies provide reading and interpretation of sensor data as a part of the home inspection service. As passive sensor technology moves from the current technology readiness to level 9 TRL, it must address the following challenges:

- Recognition of the long term economic value of PE passive sensors by home owners and the construction industry, providing a business case for building component manufacturers and site contractors to embed sensors in host components/assemblies/materials for new construction.
- Developing a low-cost solution to read PE passive sensor data. Though a new generation of smart phones have Near Field Communication (NFC) to read smart tags, the read range of NFC is very small and not suitable for reading embedded sensors. The construction industry will need a consumer grade low-cost PE sensor scanning solution.
- A new business model, under which companies specialize in embedding sensors in home structures, and also provide service to home owners to read data as part of the home inspection process.

PE Passive Sensors TRL

PE-enabled passive sensors	TRL	Potential Market (e.g., units/ building)	Tech readiness - development challenges	Drivers for adoption	End-user wants, needs	Next steps for market ready product (time to market)
Strain sensor	5	Roofing contractors, Home inspection companies/ contractors	Increase life duration Ability of the circuit to remain tuned in proximity to metals Solutions to affix PE sensors on load bearing members of the built structure Low cost scanners or scanning technology that will work with smart phones	Safety Loss Prevention	Warn against the potential failure of roofing truss due to excessive snow loads by monitoring of strain in the structural elements	5+

Humidity / Moisture sensor	7	Building component manufacturers Home inspection companies/ contractors	Accuracy of measurement Ability of the circuit to remain tuned in presence of moisture Increase life duration Ability to print sensors directly on the building components, for example dry walls Low cost scanners or scanning technology that will work with smart phones	Occupant Health Loss Prevention	Early detection of high moisture levels and water leaks in the covered areas to prevent against the mould and mildew problems Prevention of expensive damage to walls and structure caused by persistent elevated humidity levels or slow water leakages	2+
Pressure sensor	4	VIP Manufacturers and installers Home inspection companies/ contractors	Increase life duration Ability to print sensors directly on the building components or solutions to affix sensors on host materials Low cost scanners or scanning technology that will work with smart phones	Energy Efficiency	Detecting loss of vacuum in VIPs for replacement	5+
Corrosion sensor	4	Structural Concrete Contractors	Increase life duration	Loss Prevention	Detecting conditions conducive for corrosion	5+

		Home inspection companies/ contractors	Long term reliability Low cost scanners or scanning technology that will work with smart phones	Preventive Maintenance	Onset of corrosion	
Mildew sensor	4	Home security monitoring companies Home inspection contractors	Increase life duration Low cost scanners or scanning technology that will work with smart phones	Occupant Heath Loss Prevention	Detecting conditions conducive for mildew growth Presence of mildew	5+

PART 4: LIGHTING AND LIGHTING CONTROLS

An overview of lighting in buildings

Great improvements have been made in reducing the energy consumed by lighting. About 25-30% of all generated electricity is used for lighting. Improved lighting efficiency can produce large reductions in energy consumption and reduced generation of greenhouse gases.

The efficiency of producing visible light, a lighting system's "luminous efficacy," is measured in lumens/watt (lm/W). Solid state lighting sources, such as light emitting diodes (LED), have set the new standard for luminous efficacy. But we can do more to reduce energy usage than just increasing the lm/W of these lighting sources. The United States Department of Energy estimates that about 143 trillion btu of energy has been saved by implementing solid state lighting and that ultimate savings could reach almost 5,000 trillion btu of energy.[1]

Standard general service incandescent lamps typically have a luminous efficacy in the range of about 10-20 lm/W.[2] Energy saving mandates in many countries have effectively eliminated many of these lamps by putting minimum luminous efficacy requirements on all lamps, independent of light-emission technology.

Today, LED-based lamps and luminaires are available with luminous efficacies over 100 lm/W. Individual inorganic LEDs are commercially available having efficacies of 180 lm/W and over 300 lm/W in research demonstrations. As can be seen from these numbers, while energy efficiency still matters, LED-based lighting is available that can cut costs by over four times that of incandescent lighting. Even greater energy savings can be enabled with controls that dim or turn off lights when not required.

A very common example of lighting controls is occupancy sensing, to turn off lights when a room or space is not occupied. In some cases, the lights, or a portion of the lights, are dimmed to provide a safe level of ambient lighting.

Additional savings can be achieved by using daylight harvesting – that is combining the use of natural and artificial light, with controls that modify the intensity of the artificial light in response to the available natural light, to achieve a desired light level. Both of these controls are commercially available and are an integral part of energy savings using solid state lighting.

The evolution of lighting

There are two main types of light sources for solid state lighting, inorganic LEDs and organic LEDs (OLEDs). Inorganic LEDs are point sources while OLEDs naturally emit light over large areas.

At this time, inorganic LEDs have higher efficacy, lower cost and longer lifetime. They are the light sources used in almost all commercially available solid state lighting.

[1] United Stated Department of Energy publication DOE Solid State Lighting Program, Modest Investments, Extraordinary Impacts, September 2015.

[2] United States Energy Independence and Security Act of 2007 (EISA 2007)

But OLED performance continues to increase. Its unique ability to produce comfortable, uniform, non-glare light in a large area, in a very thin and potentially flexible form factor, offers unique opportunities for solid state lighting in general and specifically for PE.

A connected home, however, goes beyond straightforward energy savings and solid state lighting. Coupled with the interconnectedness inherent in an intelligent building, there are a number of other attributes that make possible impacts even more significant than energy savings, namely in productivity and wellness.

Productivity and wellness

Solid state lighting has two key attributes that are necessary to address productivity and wellness.

The first is the ability to tune the colour, or spectral power density, of the light much easier than could be done with incandescent lamps. The second is the ability to easily be interfaced to the control system of a connected home.

Colour tuning is important because the colour of the light in which we live can affect our productivity, our mood and our health. There are numerous studies showing the benefit of changing the colour of light throughout the day or for different tasks. Our evolutionary history of living outdoors has conditioned us for relatively cooler white (more blue) in the morning and a relatively warmer white (more red) in the evening.

Such colour shifts are well demonstrated to affect Circadian rhythm. They can be used to boost productivity, reduce fatigue (e.g., in shift workers and people performing critical tasks such as air traffic controllers) and aid in the treatment of various health issues such as attention deficit disorder and dementia. But a means to easily control the colour and intensity of light is necessary to realize these benefits.

Solid state lighting, including both OLEDs and inorganic LEDs, permits control of colour, or spectral power density. In both types of LEDs, the spectral power density of a device can be varied over a relatively wide range at the time of manufacture. In use, colour tuning is typically achieved by varying the intensity of two or more devices, each having a different colour, or spectral power distribution. The fact that LEDs are DC-powered components makes control of the intensity relatively easy.

OLEDs and printed lighting

OLEDs offer a unique opportunity to incorporate lighting and PE in the connected home. These are manufactured using a printing process that is similar to that used to manufacture other PE components and can be fabricated in rigid and flexible forms.

OLEDs are very thin and thus can be easily integrated into walls and ceilings. There is significant cross-over between the processes and materials being develop for PE and OLEDs, including substrate materials, printing technologies, electronic packaging approaches and equipment. This offers the potential for the direct integration of OLED lighting with sensing, communication and control functionality.

For example, a printed light sensor could be integrated into OLED substrate for daylight harvesting. The sensor would measure the incoming level of natural light and add artificial light as necessary to maintain a specific illumination level in the room.

An occupancy sensor could also be integrated into the OLED substrate, which would shut off the light when the room is empty (the most efficient light is one that is switched off). Electronics could also be integrated to perform the control functions. Going even further, photovoltaic cells or other energy-harvesting technologies, as discussed in Part 2, may be incorporated to provide power for the control or communication electronics.

OLEDs can be printed in semi-transparent form, leading to the possibility of intelligent skylights and windows. While electrically dimming glass exists today (for example, using an electrochromic coating), an OLED intelligent window or skylight could provide natural light when available, or artificial light when natural light is not available.

Printing advanced lighting control

The ability to incorporate different functional components in printed fashion on one substrate offers other possible enhancements to an intelligent window or skylight.

First, the OLED could consist of two or more OLEDs having different colours – for example, a warm white and a cool white. These could be individually controlled to provide a specific colour of light in the room.

Lighting is personal - different people have different lighting preferences. Part of a connected home is moving from the one-size-fits-all approach of current lighting systems to personalized lighting. Such systems may offer different modes of control. For example, manual control by occupants from a smart phone, or by using pre-programmed lighting schemes as a function of time and location.

The ability of PE to produce large numbers of low-cost devices and sensors that can be used separately or integrated with other printable electronics components, permits a higher degree of granularity in the control of lighting systems. This produces a more individualized environment that leads to increased comfort and satisfaction.

Longer term, increased granularity of sensors and communications will provide individualized lighting. An important aspect of this is the very thin nature of PE – a large network of sensors and devices can be incorporated into the home easily without increasing the amount of non-occupied space.

The value of printed lighting

Printable electronics can also be used to enhance the operational and maintenance benefits by collecting information such as light or sensor failures, run hours, voltages, amps, ballast health and battery life. Providing additional data from the lighting devices by using low-cost PE devices or accessories can allow homeowners to easily monitor and manage their energy usage, and costs, over the long term.

The following table shows a tabulation of the technical readiness level of some of these printable electronics-based solutions. While there are a number of commercially available OLED-based luminaires, we focus here on a category of large area, high efficacy OLED lighting for general illumination, which is not yet commercially available.

Printable electronics and lighting TRL

PE-enabled solution	TRL	Potential Market (e.g. units/building)	Tech readiness - development challenges	Drivers for adoption	End user wants, needs	Next steps for market ready product (time to market)
Large area, high efficacy OLED lighting for general illumination	3	General illumination in buildings	Improve efficacy Improve yield on large areas Reduce cost Increase lifetime	Provide high quality comfortable light Minimize space and volume taken up by lighting system	Comfortable personalized light	5+ years
Colour tunable OLED	3	General illumination in buildings providing enhanced user experience	Integration and control of multi-colour emission All challenges for OLED in general	Colour tunability	Comfortable personalized light	7+ years
Sensors and Electronics	4	General illumination in buildings providing enhanced user experience	Performance and functionality Reliability Cost	Improved control Increased granularity of control	Personalized lighting experience	1-2 years
PE photovoltaics and energy harvesting	4	General illumination in buildings providing enhanced user experience	Performance and functionality Reliability Cost	Improved control Increased granularity of control	Personalized lighting experience	1-2 years
Fully integrated lighting/sensor/control network based on PE and large area OLED illumination	2	General illumination in buildings providing enhanced user experience	All of the above	Increased information and interaction with customer Improved experience for user Increased granularity of control Improved control	Personalized lighting experience The information that they want in a timely fashion, no extraneous information	10 years

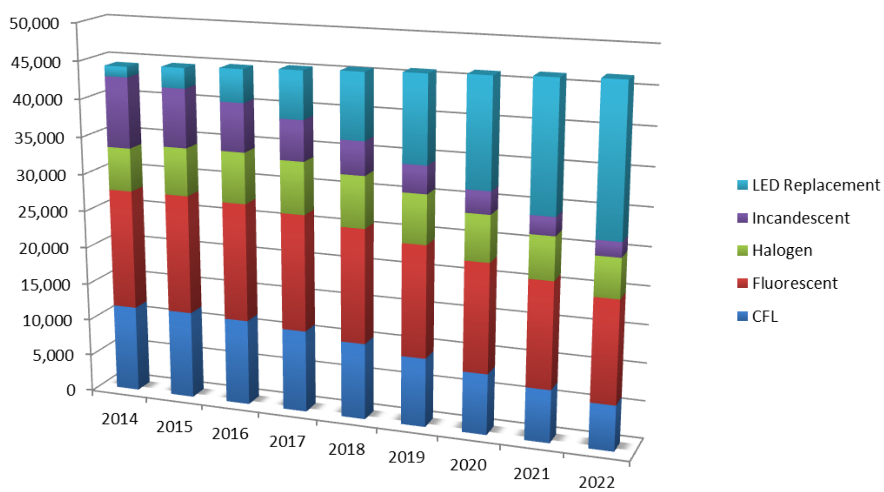
PART 5: PE-ENABLED SWITCHING

Moving on from the traditional mechanical switch

While the concept of the connected home invariably involves some manner of wireless network to control all its systems and devices, the humble wall switch will remain part of the equation.

But the days of the traditional mechanical on/off switch may be numbered, in favour of more functional interfaces intended to take full advantage of the capabilities afforded by solid state lighting (SSL) technologies such as OLEDS, as well as smart windows, as summarized in the previous sections.

Market forecasts see SSL penetration of the global installed base growing rapidly, from less than five percent in 2014 to over 30 percent by 2020[3]:



As a result, additional functionalities will be expected from the switch to address light dimming, colour selection, people recognition, remote controls and comfort enhancement, among others.

Consumer expectations for modes of device interaction and control are also evolving rapidly under the influence of smartphones and video game technology.

Interactive surfaces and control functions TRL

Basic mechanical switch operations can be transferred to tactile surface operations, through capacitive printed components. This technology has already been mastered for mobile device applications and is easily adaptable to switches. The main advantages are device thickness and cost reduction.

But while this tactile technology is at an advanced stage of market readiness (TRL 9), market adoption for switching in the home is a challenge at present because the traditional mechanical switch is so deeply entrenched with consumers.

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[3] Evolution of the Global Installed Lamp Base by Lighting Technology
Source: Philip Smallwood, Strategies in Light Conference, Las Vegas, NV, February 2015

PE-enabled switches can help overcome this adoption challenge by bringing down the cost point of a tactile control interface and also driving the sheer "Wow! Factor" of the user experience that can be created in the home:

- Innovative designs can be achieved through flexible electronics. We are already seeing functional integrations into 3D shapes, thanks to PE. For example, the touch screens under development for in-vehicle infotainment systems in the automotive sector [TRL7-8].
- Remote lighting control with master/slave devices can integrate PE antennas [TRL9].
- Haptic is important for light control in order to enhance user experience on tactile surfaces within connected homes, particularly at night. Pressure sensitive films, using piezoelectric pastes or films, can be adapted [TRL4].
- Disruptive interaction modes with a lighting control panel can be implemented thanks to PE. A matrix of optical photodetectors can enable gestural recognition on large surfaces [TRL5]. Intuitive control through gesture is already being implemented on prototypes for elderly and disabled people as a market entry point.
- Vibration membrane technology that has long been used for microphones can also be adapted for home switching applications [TRL9]. Alternative interaction modes for voice recognition are of interest for niche applications such as medical environments.

Displays & scanners / Connected Homes supervision displays

Integrating PE-based displays [TRL9] within a control panel to interact with a connected home control system is another application area. To reduce cost, energy consumption and footprint, OLED technology is ideal for full-colour displays, while electrophoretic technology is suited for room indicators.

Digital scanners can be integrated into a connected home control system, by replacing conventional silicon electronics with PE optical sensors. But this is only feasible if costs are favourable. Manufacturing at a large scale that will reduce costs sufficiently is expected in Western Europe within the next three years, putting it at TRL7.

Manufacturing

From a manufacturing perspective, organizations active in this market segment are already exhibiting hybrid devices comprised of mechanical parts, PCB silicon electronics and PE foils. The benefits of the PE foil are its large area, for full interaction with the human hand, and its flexibility, which offers disruptive design freedom for a 3D sensing experience.

Some use case examples

Innovative designs are already being promoted that use PE technology and give designers new creative freedom:

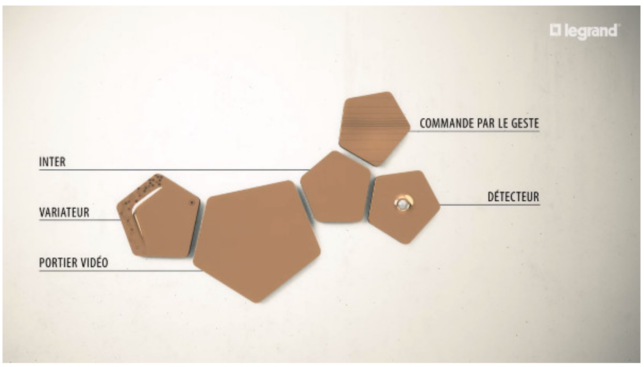
DuPont In-Mould Electronic Technology

Switch shape tuning allows the finger to be directed through the form on the dimmer. Using existing in-mould decorative processes, associated to PE film (such as Canatu CNB), the manufacturing line is very effective with fewer parts and manufacturing steps, for cost reductions of up to 30 percent.

Canatu CNBTM demonstrator

Canatu, a leading manufacturer of zero reflectance and flexible transparent conductive films and touch sensors, launched CNB In-Mold Film at Printed Electronics USA 2014 in Santa Clara, CA. CNB In-Mold Film is a stretchable, formable, conductive film optimized for 3D formed capacitive touch displays and touch surfaces in automobile centre consoles and dashboards, as well as in home appliance control panels.

Flocoon concept car by Legrand



At the 2015 edition of the International Biennial of St-Etienne Design in France, Legrand introduced its Flocoon Pixel concept [TRL4]. Each pixel, a basic pentagon unit, exhibits a particular function (switch, dimmer, optical detector...). Pixels can be combined together by the user to form a raised command. Induction charging is the proposed method of powering this system.

3D gesture recognition interface from Isorg

ISORG has developed prototypes that integrate printed organic photodetectors for hand proximity detection and motion detection [TRL7]. Functionality is based on detection by printed photodetectors that pick up the infrared light reflected by the hand (emitted by low profile LEDs mounted below a plastic surface or a glass surface). This innovative user interface is based on touchless interaction and gesture recognition, which can benefit smart and interactive connected homes systems.

Building on proven technology

It bears noting that switching technologies based on printed components is not new. These examples only demonstrate how a new generation of PE components are enabling more refined and complex sub-systems and devices. The forerunner of these new applications, still common in the market today, is the membrane switch.

The first printed membrane switches made their appearance in consumer devices more than 30 years ago, including various models of home computers. They are common today on many consumer devices and household appliances, such as on the control panels of ovens, microwaves and laundry machines.

Today's technology is taking this proven technology to a new level for greater functionality and versatility, with pressure and temperature sensors and higher resolution displays. Many CPEIA member companies are at the forefront of this evolving market, including Memtronik Innovations, GGI International, and ClickTouch America.

In other words, consumers may not realize they have been using PE in their homes in one form or another for years.

PE-Enabled Switching TRL

PE-enabled solution	TRL	Potential Market (e.g., units/building)	Tech readiness - development challenges	Drivers for adoption	End-user wants, needs	Next steps for market ready product (time to market)
PE based Membrane swiches for Home Appliances	9	Home appliances	Have been in market	Low cost, automated production Integrated in a thin panel with lights, control circuits and touch or click pads	Nice designs, that are simple and easy to understand	Diversify designs for consumer appeal. More integrated functions embedded into plastics. Faster 3D Printed Electronics prototypes.
Tactile Switching with capacitive printed components	9	Broad use in residential and commercial buildings	Commercialization	Reduced device thickness Cost reduction Wow factor of user experience	Convenience Ease of use Functionality Smart-phone-style user experience	Overcoming market dominance of traditional mechanical switches

Remote lighting control with master/slave devices using integrated PE antennas	9	Broad use in residential and commercial buildings	Commercialization, integration, optimization	Low cost sensors Easy to add sensors due to thin 2D profile	Optimization of lighting Energy and cost reduction	Integration, scale up for production
Optical photodetectors to enable gestural recognition on large surfaces	5	Tech savvy home owners Disabled Elderly	Application development, Demonstration of useful applications.	Gesture prototypes already for the elderly, disabled	Ease of use, convenience Safety	4-5 years, need to bring solutions to specific end use markets
PE OLED display within control panel to interact with connected home control system	9	Broad use in B/W and Color control panels	None	Reduce cost, energy use, footprint	Convenience Ease of use Functionality Smart-phone-style user experience	Available today.

PART 6: MESHING IT ALL TOGETHER -- COMMUNICATIONS PROTOCOLS

The need for industry collaboration

The most opportune time to create a truly connected home is of course during the design and construction phases. But the reality is that, in the majority of cases, it will be added to an existing home.

PE's advantages in terms of cost, form factor and suitability to be part of some manner of wireless or mesh network, mean that adding intelligence need not add undue cost or complexity to a homeowner's renovation project.

PE-based components and sub-systems have a role to play with the advancement of any wireless protocols that are, or planned to be, used in the connected home. The challenge is for PE technology companies to work with the home automation industry to develop products that meet the market's need for reliability, security and low power consumption, and can be cost-effectively incorporated as part of either a new build or a renovation.

Here is an overview of wireless protocols for the connected home market, drawn from the "CABA Connected Consumer Roadmap 2015 Report." Note that the connectivity technologies adopted by smart home automation devices will vary by system type and device type.

Wi-Fi

Overall, Wi-Fi is projected to be the most widely shipped connectivity technology in the smart home market because of its inclusion in most standalone smart home gateways and its adoption in other smart devices such as smart thermostats, control panels and some smart plugs. Additionally, its inclusion in smart appliances and smart air conditioners further supports its general adoption in the connected home as these devices become more prevalent.

ZigBee

ZigBee is projected to be the second most commonly shipped technology at a global level. ZigBee is used across most device types, as it is becoming an increasingly common node-level communications technology. ZigBee adoption is projected to be strongest in the Americas and EMEA, with APAC a weaker market.

It is important to note that ZigBee adoption is also heavily influenced by the anticipated in-home display and energy gateway deployments expected to be mandated in the U.K. market. Should this legislative landscape change, this would result in lower total ZigBee shipments.

Z-Wave

Use of Z-Wave is largely concentrated in the Americas, with EMEA and APAC not showing the same level of adoption, although the large size of the American smart home market gives it a strong global standing.

In the Americas, Z-Wave has proved itself as a strong technology for the smart home, with good range and penetration (being a sub-GHz technology) and a wide range of interoperable solutions from multiple vendors. This has helped it to gain traction from service providers such as ADT.

Proprietary sub-GHz wireless has been a relatively widely adopted technology in the fragmented smart home environment because of its prevalence in security devices. Interestingly, smart home systems will often use a combination of proprietary sub-GHz technologies for devices such as motion sensors, and then either ZigBee, Z-Wave or another alternative for other nodes, such as thermostats.

As a result of large unit shipments of window/door contacts and motion sensors, proprietary sub-GHz technology is projected to remain among the top wireless technologies after Wi-Fi, ZigBee and Z-Wave.

Insteon

Insteon is a dual-band technology, using both RF and powerline. Most introductory smart home Insteon kits come with an Insteon hub; this is expected to drive shipments of gateways for Insteon.

Insteon is projected to predominantly find growth with connected lighting systems and, to some extent, smart plugs and smart thermostats. Insteon is the preferred connected lighting technology option, specifically in the Americas, where it is largely concentrated. It is important to note, however, that Insteon technology is proprietary to SmartLabs, Inc., a privately held corporation.

Other protocols

Other wired technologies include a combination of Ethernet, which is used in some standalone gateways to connect to the home network, and specialist wired lighting solutions such as DALI and other wired technologies. DALI's use is projected to increase because of the growth of the gateway and connected lighting categories; however, use in other applications remains relatively low.

The "other wireless" category includes several technologies, such as EchoNET (which is becoming increasingly prominent in certain Asian markets, such as Japan) and the newly announced Thread technology (which is being promoted by Nest along with other prominent vendors like Samsung and Silicon Labs) which uses 802.15.4 as the base PHY layer with 6LOWPAN and IPV6 stacks.

For more on wireless protocols for the connected home, see the "CABA Consumer Roadmap 2015 Report," pages 83 to 91.

CONCLUSION

We've discussed applications for PE in the connected home to help conserve energy, harvest green energy, increase occupant comfort and wellness, and manage a connected home's systems from anywhere, at any time.

Ultimately, the areas we've discussed only begin to address the full scope of what is possible with PE to add the intelligence required to achieve a truly connected home.

With PE, larger building automation systems (BAS), once considered feasible only with large commercial buildings, can be adapted in some form for the residence, be it a single-family home, or a multi-unit dwelling. From HVAC, to security, fire and home health-care applications, PE has an enabling role to play to overcome adoption challenges related to cost, manufacturing complexity, power, deployment and physical footprint.

For more insight into applications for PE in the intelligent building market that can also correspond with the connected homes market, please read our companion paper, "Printable and Flexible Electronics Enabled Intelligent Buildings: New Functions, Improved Performance and Optimized Control."

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