

Closing the gap towards net zero energy appliances

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Abstract

The concept of net zero energy appliances is less advanced than that of the net zero energy buildings that now form a significant component of many regional, national and local building policies, and have gained the attention of commercial developers. However, there is a range of devices available today that are already net zero energy appliances.

Several small medical devices are self-sustaining and run from the body's motion, and vibration energy is being used to power sensors to measure the condition of some trains in the UK. Lights that are powered by a silk moth cocoon, and mobile phones charged by movement or by sound are just some of the latest developments in the world of energy harvesting to directly power lights and equipment. The 'Internet of Things' will further stimulate a vast growth in the use of various kinds of remote sensors to gather and transmit data, which would benefit from being net zero energy.

However, even though the current research focus of zero-energy equipment is mainly directed towards energy harvesting generators and storage for small mobile or remote devices, the wider application of these technologies and concepts can be envisaged. The convergence of reduced consumption by mainstream appliances with the increasing capacity of net zero enabling technologies means that more and more appliances could reduce their reliance on electricity from the grid. This is a development that policy makers should be aware of and seek to encourage.

This paper defines what is meant by net zero energy appliances. It clarifies their current status and identifies the focus for R&D

efforts within the commercial and academic world. Finally, the paper explores the significance of these developments in terms of policy approaches to mainstream appliances and equipment.

Introduction

The concept of 'zero energy buildings' and its variations has become popular over the last decade and has helped to drive forward innovation in planning and building design. Zero energy buildings can be viewed as a continuous movement in building design initiatives that includes low-energy houses in the 1970s, through passive buildings in the 1980s and then green buildings in the 1990s and 2000s.

Zero energy appliances have received some, although less notice (see Siderius and Brischke, 2011), and are growing in number and commercial application. Like their buildings counterpart, zero energy appliances rely upon a mixture of techniques to be viable, including minimising energy demand and the use of non-grid energy sources. The ability to store energy is also a feature of many zero energy appliances, which is less prevalent in buildings.

Like buildings, the term zero energy appliances is therefore used to indicate that appliance is a stand-alone device that derives its energy from non-grid renewable sources or, if grid-connected, exports an equal amount of energy as it consumes over a given period. As a result, these are more accurately described as Net Zero Energy Appliances, and in this paper such devices will use the acronym 'ZEAP'. A defining characteristic of ZEAPs is that they are either a single physical device or are sold together with a dedicated power source. When batteries or other energy storage systems are used, these must be energised by the energy source.



Figure 1. Example of hand-cranked radio.

In this paper ZEAPs are considered to be:

- Powered by an integral renewable energy source, or one supplied with the product;
- If grid-connected, exports energy equal to the amount consumed over a specified period;
- May include the capacity to store energy.

It should be noted that other terminology is often used in association with Zero Energy Appliances (ZEAPs); 'Self-powered' devices or 'Energy harvesting' technology are both commonly used to describe some ZEAPs.

The following sections of this paper describe the technology commonly used in ZEAPs, and their current commercial applications. We examine the areas where R&D efforts are focussed within the commercial and academic world and provide examples of some of the most interesting and innovative devices. Finally, the paper explores the significance of these developments in terms of policy approaches to mainstream appliances and equipment.

Current applications and markets

Although the current market for ZEAPs is small compared to grid-only-connected devices, it is growing rapidly. IDTechEx estimated the value of the global market in 2012 as \$0.7 billion but forecasts this to exceed \$2.6 billion by 2024.¹ It is estimated that by 2022 there will be 250 million 'self-powered' sensors in use.²

The demand for ZEAPs is driven largely, but not exclusively, by the growth in small electronic devices where connection to the electricity grid is either undesirable, expensive or not feasible, and (single use) battery operation is neither practical nor economical. For example, sensors used to monitor a wide variety of conditions in buildings, the environment, soils & plants, or humans, are a typical application. Required to undertake the quite simple functions of measurement and communication, sensors typically operate on very small quantities of energy, but

may be needed in large numbers and geographically dispersed. Under these circumstances, grid-connection may not be viable and battery operation not economical.

While sensors are currently amongst the most numerous examples of ZEAPs, other applications include:

- Wristwatches.
- Laptops, e-books.
- Mobile phones.
- Other portable consumer electronics: calculators, toys, piezo gas lighters, electronic car keys, electronic apparel, etc.
- Other industrial applications: buildings, machinery, engines, non-meshed wireless sensors and actuators.
- Military and aerospace.
- Healthcare: implants, disposable testers and drug delivery etc.
- Other: research, animals, farming etc.

Not all ZEAPs are small electronic devices. Marine solar-powered navigational aids are well established commercially and supplied by numerous manufacturers.³ In the past decade, many examples of wind-up devices have used the stored kinetic energy generated by hand cranking to power such small equipment as radios, lamps and lanterns and mobile phones (Abdi and Mohajer, 2014). These examples have particular application in remote areas where grid-connected energy supply is not available and where conventional batteries may be either expensive to replace or undesirable.

Increasingly, all ZEAPs benefit from a convergence of several technological advances over recent years. These include:

- Improvements in energy efficiency, to minimise the energy demand;
- Innovations in energy generators, particularly lower cost and smaller solar PV (photovoltaic) technologies;
- Smaller, more efficient and cheaper batteries, or alternative energy storage devices.

Additional innovations, such as the development of flexible solar cells, storage capacity, OLED displays and the ability to produce small and cheap electronics using 3D printing technology, are also opening up new opportunities. The combination of these factors has made a wide range of applications both technologically and economically feasible.

It is expected that the uptake of these technologies will be further increased as a result of the growth and development of the 'Internet of Things' (IoT). The IoT is the network of physical objects that contain embedded technology to communicate and sense or interact with their internal states or the external environment.⁴ By 2020 it is expected that the IoT will include 26 billion units.⁵

1. <http://www.idtechex.com/research/reports/energy-harvesting-and-storage-2014-2024-forecasts-technologies-players-000365.asp>

2. Ibid.

3. <http://www.solartech.com.au/aids-to-navigation/product-types/marine-buoys/show/aqua-buoy-600>; http://www.sealite.com.au/sealite_resources_products.php

4. <http://www.gartner.com/it-glossary/internet-of-things/>

5. Ibid.

Table 1. Energy sources for ZEAP.

Source	Source Power	Estimated Available Power – current technology	Example of ZEAP these could power
Light			
– Indoor	0.1 mW/cm ²	0.01 mW/cm ²	Calculators
– Outdoor	100 mW/cm ²	10 mW/cm ²	Solar lamps
Vibration/Motion			
– Human	0.5 m at 1 Hz		
	1 m/s ² at 50 Hz	0.004 mW/cm ²	Switches, Phone charging
– Machine	1 m at 5 Hz		
	10 m/s ² at 1 kHz	0.1 mW/cm ²	Sensors
Thermal			
– Human	20 mW/cm ²	0.03 mW/cm ²	Pacemakers, Implants
– Machine	100 mW/cm ²	1–10 mW/cm ²	Thermostats
Radio Frequency (RF)			
– GSM BSS	0.3 μ W/cm ²	0.0001 mW/cm ²	Sensors

As shown in Table 1^{6, 7}, solar PV is usually seen as the most viable source of electricity for appliances that require higher quantities of energy. However, for many of smaller ZEAPs, other energy sources include heat, vibration, and radio frequency (RF), whilst harvesting energy from human motion and machines also provide relatively high yields.

Several companies are investing in turning movement into charging devices for mobile phones. In 2010, wireless carrier Orange introduced Power Wellies at the Glastonbury Festival – boots with a thermoelectric panel in the sole for charging mobile phones (Figure 2)⁸. Orange claim that 12 hours of tromping through the mud will provide an hour of battery life. At the 2013 Isle of Wight festival Vodafone went further and produced sleeping bags and short trousers with thermoelectric pockets, providing 24 minutes of talk time for eight hours in the aforementioned sleeping bag.

An example of a combined solar and motion powered ZEAP is the ‘Retriever’, which is a coin sized GPS tracking device powered by an integrated solar panel and motion charger feeding a 3.7 V lithium-ion battery, which can also be charged via micro USB.⁹ Measuring only 28 mm in diameter and 10 mm



Figure 2. Power Wellies.

thick, the GPS ‘ping’ rate can be adjusted from every second through to once per day to reduce energy demand.

Another example of a solar-powered ZEAP is the ‘Sol’, which is a laptop produced by a Canadian firm with built-in foldable solar panels and is designed for use in the military, education and developing countries where electricity is scarce¹⁰ (see Figure 3). The Sol charges in under two hours and once fully charged, the battery is expected to last between eight and ten

6. John Donovan, Mouser Electronics. <http://uk.mouser.com/applications/energy-harvesting-new-applications/>

7. GSM BSS: Base station sub-system for global system for mobile communication.

8. http://content.time.com/time/specials/packages/article/0,28804,2029497_2030623_2029815,00.html

9. <http://www.retriever.com/>

10. <https://store.solaptop.com/>



Figure 3. Solar powered laptop.

hours. The solar panels are detachable and can be used with an extension cord should you wish to work indoors.

Wireless sensors produced by the Japanese company EnOcean are able to transmit a signal 300 meters in the open using just 50 μ W.¹¹ The power requirement is minimised by making the entire process last no more than a thousandth of a second. These sensors are designed to be powered by small solar, thermal or motion generators.

Amongst current applications that use thermal power, the intelligent thermostatic radiator valve produced by Micropelt is one commercial product.¹² The thermogenerator converts the temperature difference between the radiator and the ambient room temperature into electrical energy which drives the valve actuator as well as the wireless communication with the room controller. The actuator includes a gearbox, motor and ultra-low power control electronics, to minimise energy consumption. The unit is also equipped with a rechargeable storage element to store surplus energy for times of lower input power, and is designed to enter sleep mode when the heating is turned off but waken when it is turned back on.

An example of energy generation from motion, are sensors supplied by Perpetuum and used by Southeastern Railways in the UK.¹³ Sensors powered by the train's vibrations are used to measure wheel-bearing degradation and transmit data to enable early forecast of potential failure in wheel bearings. Up to 1.8 million sets of temperature and vibration data are collected each day; whilst automatic email alerts are sent to the technical team when vibration levels move beyond set parameters. The use of vibration energy removes the problems of predicting battery life and the need for costly and logistically challenging replacement of batteries. The sensors are simple to deploy and of robust design for operation in harsh environments, including temperatures between -40 °C and 85 °C.

Finally, during 2014, Philips launched the Hue, a smart lighting package, which has a light switch which requires no batteries but is powered by the depression of the button.¹⁴

To summarise, ZEAPs have been available for some time – from automatic self-winding watches, through to solar hand-held calculators. The recent increase in uptake of ZEAPs is being driven mainly by the growth in applications which currently require relatively small amounts of energy, and a corresponding increase in the range and performance of small energy generators to power them. Most of the growth in ZEAPs is related to sensors, as are these numerous and often located in locations where grid-connection is not viable. Barriers to the wider take-up of ZEAPs include the high capital cost (flowing from small markets and high development costs), niche markets (e.g. navigation aids) and user limitations (e.g. charging devices from solar energy may be limited in indoor locations or cloud cover). However the range of potential applications is growing as devices become more efficient and local energy sources generators become more effective, as discussed in the following section.

Looking into the future

As shown, there are already a large number of small ZEAPs being developed and sold at present, and this trend is expected to continue – especially with the development of more efficient products, through miniaturisation, improved energy generation and storage. This section will outline some areas of research that will continue the drive towards an increased number of ZEAPs.

Medical applications are one area attracting significant research attention, partly due to the opportunity that self-generation provides to minimise the need for the replacement of batteries in medical implants and therefore reduce the risk of infections in patients as a result of surgery. Pacemaker batteries currently last seven years on average, however a Korean research team has developed a self-powered artificial cardiac

11. <http://www.enocean.com/en/energy-harvesting-wireless/>

12. <http://micropelt.com/itrv.php>

13. <http://www.perpetuum.com/rail>

14. <http://www.newscenter.philips.com/main/standard/news/press/2014/20140328-introducing-hue-tap-the-worlds-first-kinetic-powered-web-enabled-light-switch-wpd#:VKMsy4qUdH0>

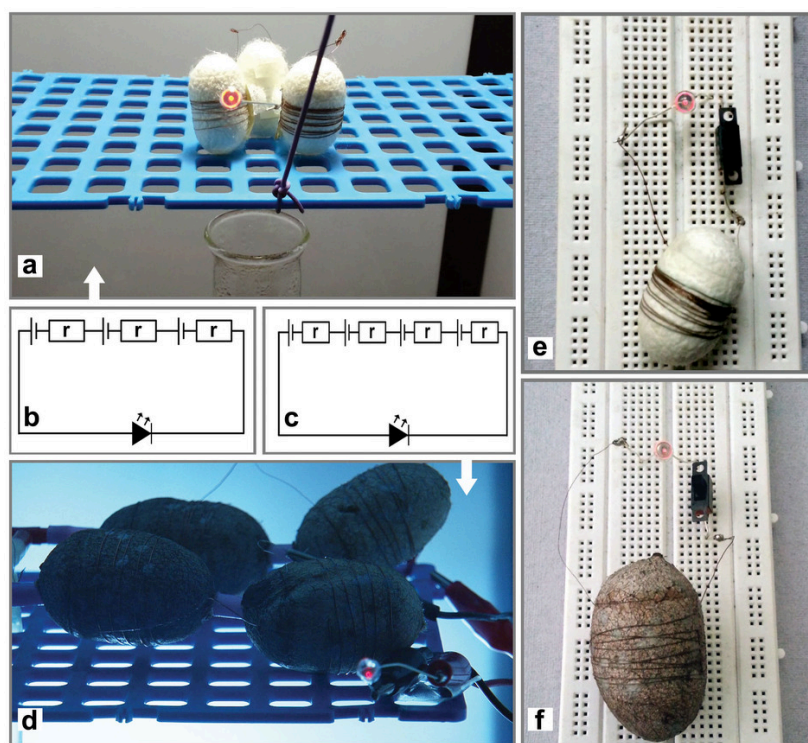


Figure 4. Electricity from the silk moth cocoon.

pacemaker that is operated by a flexible piezoelectric nanogenerator.¹⁵ The nanogenerator has successfully used electrical energy converted from the small body movements of a rat to stimulate the rat's heart. Research teams from the USA and China are working on similar technologies to develop self-powered pacemakers, cochlear implants¹⁶ and implantable defibrillators¹⁷.

To illustrate the range of current research, in one of the more bizarre examples of energy harvesting scientists in India have powered a LED from electricity generated from a silk moth cocoon¹⁸ (see Figure 4). By wetting the cocoon, the trace elements in a silk moth cocoon form mobile charge-carrying ions, producing an electric current across the cocoon membrane. The researchers attached an aluminium electrode to the inner surface of a cocoon and a copper electrode to the outer surface, and exposed the cocoon to water vapour. Three such cocoons were connected in series to light the LED.

The opportunity to extend the battery life of mobile phones, or entirely replace the need for re-charging, through energy harvesting has enormous commercial potential, and this is driving a number of different research activities. For example, researchers at the Massachusetts Institute of Technology have developed a button sized self-charging battery that can scavenge energy from low temperature sources of heat.¹⁹ The device

can charge itself at temperatures between 20 °C and 60 °C, far lower than other heat-harvesting technologies.

ENERGY CAPTURING TECHNOLOGIES

Some new energy capturing technologies are not directly linked to specific end-uses and therefore are not ZEAPs as we have defined in this paper. However, they are relevant as such developments demonstrates the wide and diverse range for potential new energy sources that may be linked to particular applications in the future.

An example of capturing of motion or kinetic energy is the European POWERAMP dynamic speed bump that is able to transfer energy from vehicles passing over it.²⁰ Placed in areas where speed must be controlled, safety must be increased, or where vehicles must come to a stop, such systems leverage the kinetic energy of thousands of kilograms moving at high rates of speed to produce energy. When a vehicle crosses the bump, it forces an arm downward that turns a generator that produces power. The height of the bumps is variable so they can be adjusted for vehicles travelling at different speeds.

Energy generation from plants is an area of considerable research.²¹ When plants create food through photosynthesis, a large portion of the organic matter generated is excreted by the roots into the soil. That organic matter gets fed on by microorganisms living in the soil, releasing electrons as a by-product. By placing an electrode near the roots, this waste energy can be turned into electricity without damaging the plant. A Dutch start-up called Plant-e is marketing and trialling several prod-

15. <http://www.energyharvestingjournal.com/articles/first-demonstration-of-a-self-powered-cardiac-pacemaker-00006653.asp>

16. A cochlear implant is an electronic medical device that replaces the function of the damaged inner ear.

17. <http://www.energyharvestingjournal.com/articles/implant-harvests-heartbeat-power-00006195.asp>

18. <http://inhabitat.com/how-scientists-generate-electricity-from-a-silk-moth-cocoon>

19. <http://www.energyharvestingjournal.com/articles/battery-harvests-energy-from-body-heat-00007133.asp>

20. http://cordis.europa.eu/result/rcn/57394_en.html

21. <http://www.plantpower.eu>



Figure 5. Energy-regenerative speed bump.

ucts to power roadside displays.²² The system works best in watery fields like rice paddies, but it does not matter if the water is brackish or polluted, so areas unsuitable for growing crops could also be re-purposed as a power source, for example in more remote areas.

Such developments in innovative energy capturing will lead to some combination with end-uses, to make new classes of ZEAPs, and new applications possible.

ENERGY STORAGE TECHNOLOGIES

The development of cheaper and smaller energy storage devices is a key element to the wider adoption of ZEAPs. An example of such development is the recent application of low cost paper batteries, which also have lower environmental impact (Ferreira et al., 2010).²³ Energy storage is a separate area of research and not explored further in this paper.

Summarising technology development

From the examination of the current technology and likely future advances based on current research, it appears reasonable to assume that the main developments are going in the following direction:

- diversification of power sources: from the “classical” (PV, motion and heat) to energy harvesting from organic sources;
- increasing the yield of energy sources;
- lowering the energy demand of applications.

It is evident that the demand for small, dispersed devices is driving a wide variety of R&D efforts in improving the efficiency of energy use, storage and supply. While not all of these will reach commercialisation, it is likely that some new technologies and techniques will emerge that have implications for higher energy-consuming conventional energy-using appliances and

equipment. The extent and rate at which this could potentially happen is explored later in this paper.

The limitations of energy supply and storage have created a substantial incentive to reduce energy demand to a minimum, particularly in devices that are designed for use in remote locations. As a result, investigating every potential opportunity for the minimisation of energy consumption is a key design focus in these products and far more attention is paid to this aspect compared to the design priorities for mains-powered equipment. Not only are we seeing the development of more ultra low-power components (motors, etc.) but there have been many significant advances in the ability of devices to manage power consumption automatically, for example to transmit and receive signals only when necessary. The considerable investment in end-use efficiency is leading to innovations that extend the boundaries of what we believe is currently possible and, as these become more widely employed within these niche markets, their cost is coming within the reach of the bigger appliance and lighting markets. This is considered further in the next section.

Solar power continues to be highly attractive as an energy source for ZEAPs, since it can provide more power than other ‘harvested’ energy sources. The improvements in the conversion efficiency of PV cells, coupled with developments in flexible panels and print technologies will only increase the number of applications for solar energy. However, kinetic and thermal sources are also increasing in efficacy and can harvest significant quantities of electricity. Coupled with increasing efficacy of these sources, is the falling costs of manufacturing when production is scaled up. Where they are initially used for niche products, they can become more widely used, creating a feedback – with lower costs generating larger demand, again reducing costs through larger production; and so it continues.

Implications for current appliances and appliances policies

While the latest developments in ZEAPs tend to occur in smaller and remote devices, there are implications for larger and more traditional appliances and equipment. The unit energy consumption of refrigerators, televisions, and other household appliances has reduced considerably over recent years. The application of further energy saving technologies, some of which can be inherited from the innovations in ZEAPs, will continue to drive down energy consumption.

Therefore as energy consumption reduces and the ability of energy harvesting increases, the opportunity to incorporate these technologies within mainstream appliances will increase, powering all or part of the load. This is illustrated in Figure 6. The point at which the energy consumption and the energy harvesting curves cross will be the theoretical point at which it is feasible to have a ZEAP instead of a grid-only appliance.

A good understanding of these developments is useful for those involved in the design of energy efficiency policies for appliances and equipment, since they have implications for the minimum grid-connected energy consumption thresholds for individual appliances. To the extent that such policies are driven by what is technically feasible, these new ZEAP developments can help policy-makers set more ambitious trajectories.

22. <http://plant-e.com>

23. <http://cen.acs.org/articles/92/web/2014/10/Researchers-Design-High-Power-Paper.html>

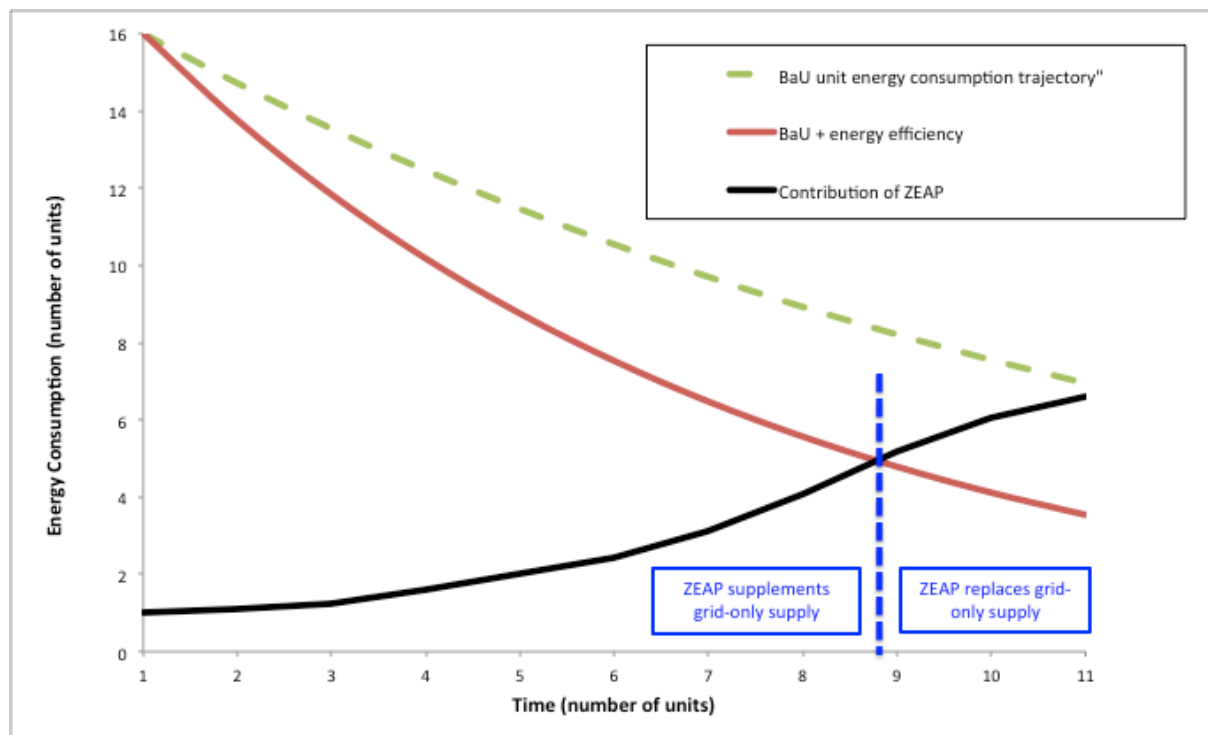


Figure 6. Change in energy demand and harvesting.

The commercial development of ZEAPs across a wide range of applications and the growing R&D in this area have considerable implications for policies designed to encourage energy conservation in appliances and equipment. In principle, these include:

- Almost all low-powered appliances, devices and sensors can be or become ZEAPs in the future, and this should be reflected in policies developed for these products;
- As a transitory step towards ZEAPs for products related to the Internet of Things (IoT), the notion of NZEF (Net Zero Energy-Function) may be useful. For example, it would be possible to designate that network connectivity should be a NZEF, and therefore require no 'external' power to deliver this functionality. Appliance policies would assume that a NZEF will be available/possible for all appliances where that function exists;
- Policies for large appliances should encourage the adoption of efficient technologies developed for ZEAPs and adopt the long-term aspirational goal of becoming a ZEAP.
- The options for applying these principles to energy efficiency policies are varied and might include the following:
- Efficiency policies for appliances will need to include methodologies and protocols for calculating the net energy consumption of appliances and equipment that harvest energy and may export to the grid. In some instances, specific test methods may need to be developed;
- For mandatory comparative labels, the highest rating (or higher rating levels) could be reserved for ZEAP products for relevant categories of products (Note that Siderius and Brischke [2011] proposed that the EU label energy class A should be reserved for ZEAP from 2020);

- There could be a unique label that identified a ZEAP or a product with a NZEF – much like current endorsement labels;
- Although ZEAPs are likely to be considered 'best in class' for most product categories, and therefore unlikely to be driven by Minimum Energy Performance Standards (MEPS), some functional allowances in MEPS thresholds²⁴ may reflect the potential for NZEFs;
- Policies such as awards, e.g. the SEAD (Super-Efficient Equipment and Appliance Deployment) Initiative award, competitions or procurement activities may also be used to drive the development of ZEAPs.

The continued support of R&D in this area by governments will be important to underpin these policy developments, as will be further research, such as a more detailed study on the possibilities for network connectivity to be a designated NZEF.

The potential policy application of these principles to larger appliances is shown in the case of televisions. Figure 7 shows the energy efficiency (EEI) labelling requirement thresholds for televisions being sold in the EU (class F through to A+++) with the average of the products listed on the Top Ten²⁵ website for a couple of years (Siderius, 2013). It can be seen the suggestion of net zero energy TV (NZE TV) being reserved for the top class

24. Some MEPS thresholds are expressed as a base limit (W or kWh) plus a series of additional allowances (W or kWh) for additional product features that consume energy. For example, the European Ecodesign sets an active mode limit of 5 W for simple set-top boxes, but allows up to an additional 6 W where a hard disc is installed, an extra 1 W for a second tuner and 1 W for decoding HD signals.

25. Top Ten is a consumer website which lists the most energy efficient appliances available. <http://www.topten.eu>

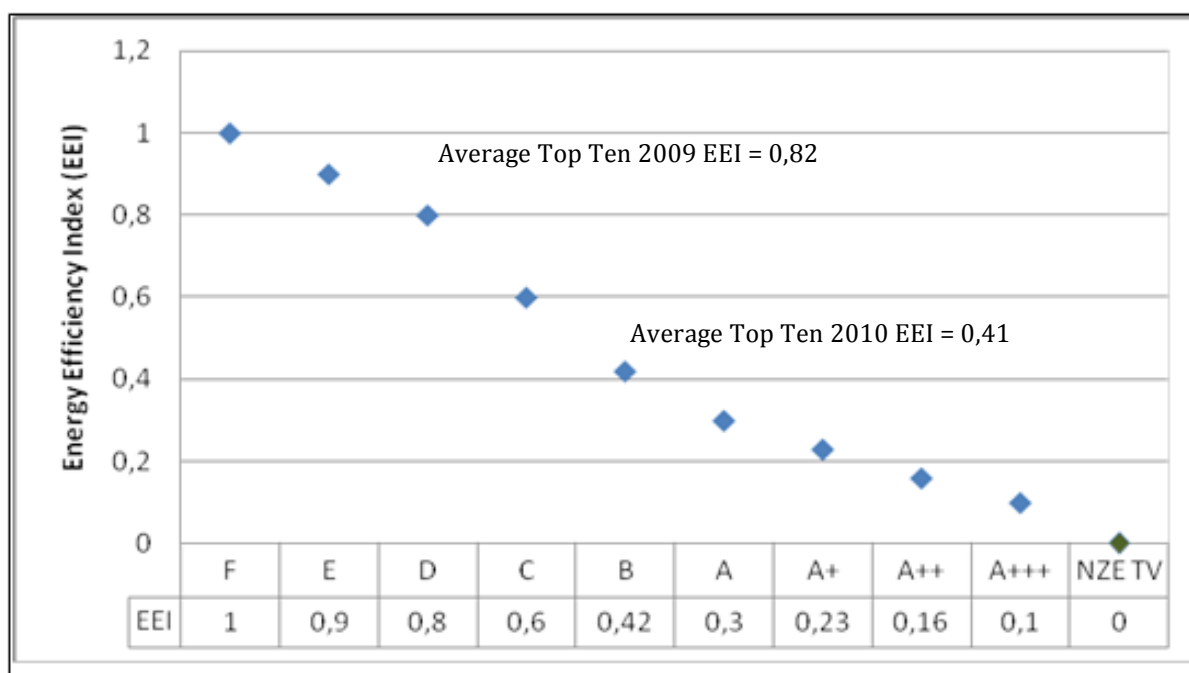


Figure 7. EU efficiency thresholds for TV energy labelling, plus NZE proposal (Siderius, 2011).

in the chart does not represent a large change in EEI from the second highest level – though of course it may be more challenging to achieve for some other larger appliances.

A conservative estimate of the energy implications can be estimated as follows. Many ZEAPs, especially sensors, will replace battery powered devices or will be new devices and therefore will not have an impact on electricity consumption from the grid. For larger devices the qualitative impact is that developments towards ZEAPs could also stimulate the development of more efficient components and devices. An indicative (order of magnitude) quantitative estimate can be provided for networked standby²⁶ as NZEF. According to IEA (2014) the energy consumption of products in networked standby will increase from around 300 TWh/year in 2015 to more than 450 TWh/year in 2025. With best available technology, more efficient components and improved power management, this could be reduced to 170 TWh/year in 2025. If we assume that half of the remaining energy consumption for networked standby could be covered by NZEF, this would amount to 85 TWh/year.

It is likely that some larger appliances may also become ZEAPs (see TV example above).

Conclusions and recommendations

Although ZEAPs are a less developed concept than zero energy buildings, there are already a significant number of examples currently available on the market covering a diverse range of applications. The level of investment in ZEAP R&D suggests that the commercial potential for ZEAPs will continue to grow.

In terms of technology used in ZEAP, the following developments can be observed:

- diversification of power sources: from the “classical” (PV, motion and heat) to energy harvesting from organic sources;
- increasing the yield of energy sources;
- lowering the energy demand of applications.

These developments in energy harvesting and improvements in energy efficiency make ZEAP possible for an increasing number of applications. Besides traditional applications for ZEAP, e.g. sensors and remote devices, also larger appliances can benefit from these developments. As ZEAP technologies are applied to an increasing number of the markets, the scale of production will result in price decreases that open up new potential outside niche markets.

Recommendations for product policy include:

- Undertake more detailed study on possibilities for power sources for NZEF on network connectivity for appliances, and IoT in general;
- Consider the introduction MEPS for NZEF, or at least consider how these could remove the need for ‘allowances’ in some regulations;
- For EU energy labels reserve (from 2020 say) energy class A for ZEAP;
- Explore the feasibility of a special label for ZEAP;
- Organize a SEAD award competition for a product group focussing on ZEAP.

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26. This is the situation where a product is connected to a network and is waiting for a signal through the network to become active, e.g. a network printer waiting for a print job.

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