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TOPICAL REVIEW

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Topical Review

Review of the application of energy harvesting in buildings

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Abstract
This review presents the state of the art of the application of energy harvesting in commercial and residential buildings. Electromagnetic (optical and radio frequency), kinetic, thermal and airflow-based energy sources are identified as potential energy sources within buildings and the available energy is measured in a range of buildings. Suitable energy harvesters are discussed and the available and the potential harvested energy calculated. Calculations based on these measurements, and the technical specifications of state-of-the-art harvesters, show that typical harvested powers are: (1) indoor solar cell (active area of 9 cm^2, volume of 2.88 cm^3): ∼300 μW from a light intensity of 1000 lx; (2) thermoelectric harvester (volume of 1.4 cm^3): 6 mW from a thermal gradient of 25 °C; (3) periodic kinetic energy harvester (volume of 0.15 cm^3): 2 μW from a vibration acceleration of 0.25 m s^{-2} at 45 Hz; (4) electromagnetic wave harvester (13 cm antenna length and conversion efficiency of 0.7): 1 μW with an RF source power of −25 dBm; and (5) airflow harvester (wind turbine blade of 6 cm diameter and generator efficiency of 0.41): 140 mW from an airflow of 8 m s^{-1}. These results highlight the high potential of energy harvesting technology in buildings and the relative attractions of various harvester technologies. The harvested power could either be used to replace batteries or to prolong the life of rechargeable batteries for low-power (∼1 mW) electronic devices.

Keywords: energy harvesting, review of energy sources, buildings

(Some figures may appear in colour only in the online journal)

1. Introduction

Energy harvesting is the conversion of ambient energy present in the environment into electrical energy [1, 2]; some authors use the term ‘energy scavenging’ with the same meaning. Typically energy harvesting relates to the conversion of small amounts of ambient energy for use in powering small, low-power, electronic devices. Ambient energy sources present in a building, and suitable for harvesting, may be: light, heat, vibration, movement, radio waves, electromagnetic (EM) fields and airflow. In most cases the energy that is harvested is wasted energy with no specific use. Energy harvesting has therefore attracted much interest in the research community because of its potential use as a power supply in applications such as low-power wireless sensor networks [3] and electronic systems.

This highlights the need to review the fundamental energy sources in buildings which can potentially be harvested. This review focuses specifically on buildings and presents the state of the art of energy harvesting in this context, discusses available energy sources, and quantifies possible available energy by calculations and measured data collected in typical buildings.

1.1. Limitations of batteries in buildings

The use of autonomous wireless systems in buildings is attractive since it avoids the need to use cabling and the disruption associated with its installation. Such autonomous devices are typically battery-powered but batteries have a number of limitations on their use in autonomous low-power electronics systems.

(1) The life-span of the wireless electronic device is always greater than that of the battery. This means that, at some point, battery replacement will be required. This, not only poses service disruptions during battery replacement, but also leads to maintenance cost, especially when a large number of electronic devices are deployed in a system. Disposing of depleted batteries is an environmental pollutant as batteries contain chemicals which are hazardous both to the environment and to health if not carefully handled.
(2) There are negative consequences of forgetting to change the battery in safety-critical systems such as smoke detectors in a building or in a security system.
(3) Very low-power electronic systems, or systems which are dormant most of the time, can be theoretically expected to remain operative for an extended period of time, ranging to years. Practically, however, batteries self-discharge over time due to internal chemical reactions. Therefore, depletion due to self-discharge becomes the limiting factor, causing a shorter operational life-span than would be suggested by simply considering the average power consumption of the system and the capacity of the battery.
(4) The battery size often exceeds that of the system components in the electronic device [4, 5].

1.2. Attractions of energy harvesting in buildings

There are several reasons why energy harvesting can be considered, to augment, or as an alternative to, a battery.

(1) To remove the maintenance costs and time necessary for battery replacement [6, 7]. In smart buildings, hundreds of electronic devices will be deployed for various functions, and it will be increasingly more expensive and time consuming to replace batteries as the number of these devices increases.
(2) To overcome the problems related to the life-span of the device which is limited by the life-span of battery [8]. For devices in which it is impossible or difficult to replace batteries, device life-spans are limited by the life of the batteries. By using energy harvesting the life-span of these devices can be prolonged.
(3) To reduce the overall size of some electronic devices and reduce the effect of the disposal of used batteries on the environment.
(4) To overcome the problem of self-discharge which is a limiting factor for very low-power systems and systems which remain dormant for extended periods of time.
(5) To capture and use otherwise wasted energy within the building.

1.3. Important applications in buildings

The following are important potential areas in the context of building applications where energy harvesting can be used as an alternative energy source.

- Ambient assisted living (AAL): ambient assisted living is defined as 'the provision of care to people either in their own homes or in supported housing, underpinned by technology' [9]. This involves unobtrusive integration of electronic systems to provide services in a sensitive and responsive way to people and to construct a safe living environment [10], also termed an assistive living environment. The electronic systems in assistive living environments work cooperatively to support the assisted person(s) in carrying out their daily living activities. Although AAL is primarily focused on healthcare applications, the technology can also be used in home automation and entertainment applications. As AAL aims to extend the time people can live independently with no or minimum support, it requires an autonomous system with a minimum of maintenance or user intervention. From a power supply perspective, mains operation is an option but requires significantly more installation effort than battery-powered standalone devices, plus an overhead in terms of transformers. Battery operation facilitates installation but batteries require checking and periodic replacement. An alternative to batteries for standalone devices can be achieved by using energy harvesting technologies to power sensing and communication electronic systems in AAL.
- Smart home: Alderich [11] defined a smart home as 'a residence equipped with computing and information technology which anticipates and responds to the needs of the occupants, working to promote their comfort, convenience, security and entertainment through the management of technology within the home and connections to the world beyond'. Smart home systems are known by several names, including home automation [12, 13], building management systems [14] and intelligent home systems [15]. Generally, smart home systems conveniently control home electronics and appliances such as air conditioners, heating, security systems, lighting, telecommunication systems and home entertainment systems. The interconnection of these units can be done through a conventional computer network and they can be controlled locally, within the home or remotely, via the Internet. This interconnection can be achieved by a part of the Internet of things [16, 17], the technology which enables objects to communicate with one another wirelessly using sensors attached to them. The smart home system can be interconnected to hand-held portable electronic devices such as laptops, tablets and smart phones [18]. As residential and commercial buildings consume around 40% of energy [19], smart home systems can be used as a comprehensive measure to reduce the energy consumption by providing real-time information of energy consumption and actively controlling heating and lighting. Smart home systems

consist of a large number of electronic units used for sensing, controlling and actuating. While many of the controlled units, e.g. central heating system, operate from the mains, sensors (e.g. smoke detector) and wireless communication devices are usually battery operated. Energy harvesting technology has a potential application in this area, either to replace batteries or to prolong the life of rechargeable batteries.

1.4. Scope and structure of this review

Much research work on domestic scale energy harvesting for buildings has already been done with an emphasis on harvesting energy to feed into the existing mains power grid. Domestic scale energy harvesting, which is small-scale reusable power generation, is outside the scope of this review. This review focuses on small-scale energy harvesters for use in powering autonomous electronic systems which are not connected into the building's power infrastructure. These electronic devices require low operating power, <1 mW, and are referred to as low-power electronic devices. An example of such a device would be a solar-powered thermal sensor which wirelessly transmits temperature data to control heating/cooling equipment such as the SR06/07 series devices from Thermokon GmbH [20].

Previous energy harvesting reviews have primarily concentrated on the scientific aspects of harvester design rather than considering any particular application environment. Beeby *et al* [1] focused on vibration energy harvesters providing characteristic equations for inertial-based generators along with the specific damping equations that relate to the piezoelectric, EM and electrostatic transduction mechanisms. Anton *et al* [21] presented a review of advances in energy harvesting using piezoelectric materials including the design of efficient harvesting geometries, improving efficiency through circuitry, implantable and wearable power supplies, harvesting of ambient flows, micro-electro-mechanical devices, self-powered sensors and comparisons of piezoelectric materials to other energy harvesting media. Arnold [22] reviewed compact magnetic power generation systems in the microwatts to tens of watts power range. The review covered both the theoretical and practical implications of miniaturizing magnetic power generators, the design and performance of previously demonstrated devices, and challenges for implementation. Gilbert *et al* [23] reviewed the characteristics and energy requirements of typical sensor nodes and assessed a range of potential ambient energy sources and ambient energy harvesting devices. After comparing data from a number of publications, the author determined a power requirement for a sensor node of around 3 mW and the typical maximum power density from the ambient sources of 1 μW mm^{-3}. Other authors who have also reviewed energy harvesting research areas are: Zhu *et al* [2] who reviewed principles and operating strategies for increasing the operating frequency range of vibration-based micro-generators and two possible solutions, tuning the resonant frequency of a single generator and widening the bandwidth of the generator, were identified. Bogue [24] reviewed the development of energy harvesting techniques and their use with wireless, self-powered sensors and pointed out that energy harvesting devices based on electrodynamics, piezoelectric and thermoelectric effects are attracting strong academic and commercial interest, and anticipated applications of these devices in industrial condition monitoring, structural monitoring and healthcare. Harb [25] presented a review of the state of the art of energy harvesting techniques, power conversion, power management and battery charging, and summarized reported harvesters and their corresponding power levels.

However, a comprehensive review of suitable energy harvesters, potential energy sources and the quantification of the amount of available energy in buildings has not been presented and is the subject of this paper. This review adds to the knowledge in the field of energy harvesting by reviewing energy harvesting technologies and techniques that are applicable in typical buildings and provides typical obtainable energy levels. The paper is organized as follows: section 1 provided an outline of the limitations of batteries, identified the attractions of energy harvesting in buildings and identified some important applications of energy harvesting within buildings. Section 2 describes the main types of energy harvester and the current use of energy harvesting in buildings. Potential energy sources in buildings and estimated energy which can be harvested from them are presented in section 3. To conclude the review, a summary of the measurements and conclusions of this review are presented in sections 3.6 and 4, respectively. Details of the light level and RF energy measurements used to produce the estimated energy levels in section 3 are given in appendices A and B, respectively.

2. Energy harvesters relevant to buildings: state of the art

2.1. Energy harvesting from light sources

Photovoltaic energy harvesting obtains electrical energy from ambient light, either from natural sun light or artificial light, using solar cells also known as photovoltaic cells. Photovoltaic energy harvesting is the most common method of harvesting energy and is now a well-established technology. The amount of power harvested depends on the intensity and spectral content of the light falling on the surface of the solar cell, the incident angle of the light, the size, sensitivity, temperature and type of solar cells used.

An important consideration when using photovoltaic energy harvesting is the source of the light energy that is to be harvested since the spectral composition of light from natural and artificial lighting differs. There are further differences in the spectral composition of artificial light depending on whether the artificial source is incandescent, as shown in figure 1 [26], or fluorescent, as shown in figure 2 [27].

Whilst, at present, the majority of artificial light sources encountered in buildings utilize either incandescent or fluorescent technology the continuing development of high-power white LEDs has led to the introduction of LED-based lighting as a direct replacement for incandescent and fluorescent lamps. These direct replacement lamps are

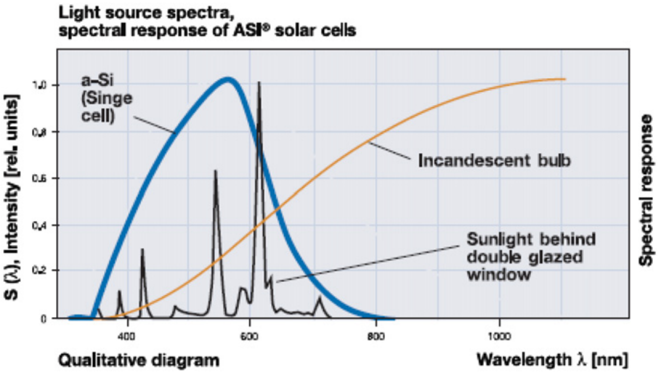

Figure 1. Relative spectra of sunlight and artificial light from incandescent bulbs [26].

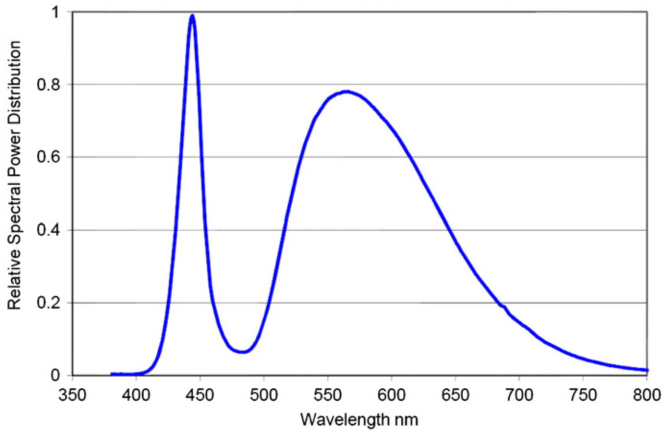

Figure 3. Spectra of LUXEON Rebel LXML-PWN2 [29].

commercially available from a wide range of manufacturers, for example Philips Lighting produces a range of different lamps with standardized bases and supply voltages [28]. For comparison with the spectra shown in figure 1 (incandescent) and figure 2 (fluorescent) an example spectrum is shown in figure 3 [29] for a LUXEON Rebel LXML-PWN2 high-power white LED, a type that can be used in LED-based lighting. The example device has a specified colour temperature of 4100 K, which is described as neutral–white; there are other LEDs available in the range with differing colour temperatures and corresponding spectra. By comparing the spectra of the LED light source with those of the fluorescent and incandescent sources it can be seen that the LED's spectrum is primarily located in the same wavelength range as the fluorescent source, therefore solar modules that have a suitable absorption spectra to work with fluorescent lights should also be suitable for use with the newer LED-based lighting.

To compare the relative performance of indoor and outdoor specification solar cells nominal power densities, provided by the manufacturer, are given in table 1 for a typical indoor specification solar cell (SCHOTT Solar ASI OEM Indoor [26]) and a typical outdoor specification solar cell (SCHOTT Solar ASI OEM Outdoor [30]) under a range of illumination conditions. The 125 000 lx natural sunlight figures are for an incident solar power of 100 mW cm^{-2}, which represents a bright, clear, sunny day; this incident solar power is converted using the following approximation: 1 mW cm^{-2} ≈ 1250 lx [26]. SANYO also produces a range of cells suitable for use under artificial lighting sources, both these cells and the SCHOTT solar devices are fabricated using amorphous silicon which has a greater sensitivity at the lower intensities and wavelengths encountered when using artificial lighting as the energy source.

Table 1. Comparison of nominal power density for SCHOTT solar ASI OEM indoor and outdoor specification solar cells.

Illumination level and source	Indoor specification cell power density	Outdoor specification cell power density
100 lx fluorescent light	2.9 μW cm^{-2}	Not specified
200 lx fluorescent light	6.1 μW cm^{-2}	Not specified
1 000 lx fluorescent light	34 μW cm^{-2}	Not specified
12 500 lx natural sunlight	Not specified	480 μW cm^{-2}
125 000 lx natural sunlight	7.1 mW cm^{-2}	6.38 mW cm^{-2}

Whilst these comparisons suggest that an indoor specification device is the correct choice for use under natural light, it must be noted that indoor modules are specified for continuous use only up to light levels of the order of a few

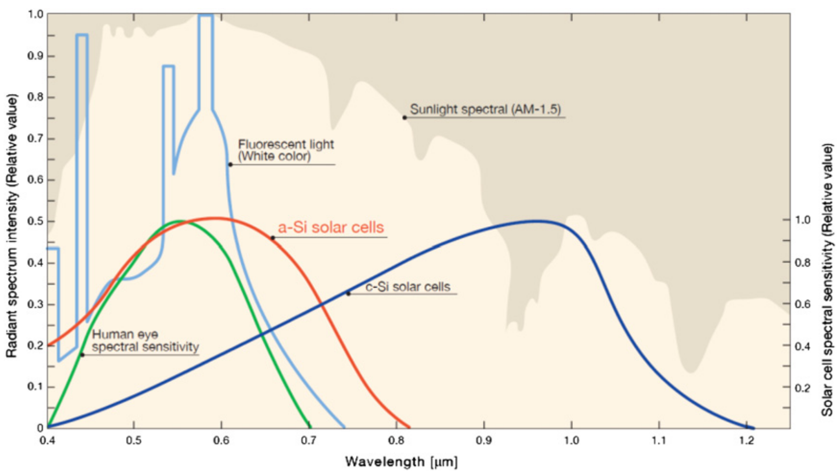

Figure 2. Relative spectra of sunlight and artificial light from fluorescent lamps [27].

Figure 4. Examples of rigid silicon-based solar cell (left) and flexible DSSC (right).

1000 lx. Continued operation at higher illumination levels may cause damage to the modules.

A UK based company, G24 Innovations Limited, is manufacturing and developing third generation, thin film, photovoltaic cells and modules known as dye-sensitized solar cells (DSSCs) on a flexible substrate. This allows installation of solar cells on non-flat surfaces. For applications which do not require the flexibility of the DSSCs it is currently preferable to use rigid-substrate semiconductor devices as these have higher efficiencies. Examples of rigid amorphous silicon (with an active area of 52 mm × 38.9 mm) and flexible DSSCs (with an active area of 50 mm × 48.5 mm) are shown in figure 4.

Electronic consumer products powered by solar power are increasing in the market. Apart from calculators which have been known to be powered from solar power since the 1970s, other products such as computer keyboards [31], radio controlled watches [32] and toys can also be powered by solar cells.

An autonomous wireless sensor network for sensing light, temperature and humidity for environmental management in buildings was reported by Wang *et al* [33]. The network, consisting of 62 wireless sensor nodes, was deployed in an office building. The nodes were powered using indoor solar cells and the measured parameters transmitted to the gateway through a 2.4 GHz ZigBee wireless link.

Standalone solar-powered wireless sensor nodes for wireless sensor networks are commercially available. Some examples are as follows.

- Energy harvesting wireless sensor modules such as the SMT310 from EnOcean. These are specifically designed for building applications such as window contact, temperature and humidity sensors.
- The MSP430 Solar Energy Harvester Development Tool from Texas Instrument consisting of MSP430F2274 microcontroller, CC2500 2.4 GHz wireless transceiver and a solar module.

2.2. Energy harvesting from thermal sources

Thermoelectric energy harvesters, based on the Seebeck effect in semiconductor junctions, are used to convert a temperature gradient into electrical power. By using differing combinations of serial and parallel connection of the junction pairs the output voltage and current of the harvester can be adjusted. Typically a series connection is used to maximize the output voltage, at the expense of current, to permit useable voltage levels to be reached at lower temperature gradients. The basic configuration of a thermoelectric generator (TEG) is illustrated in figure 5.

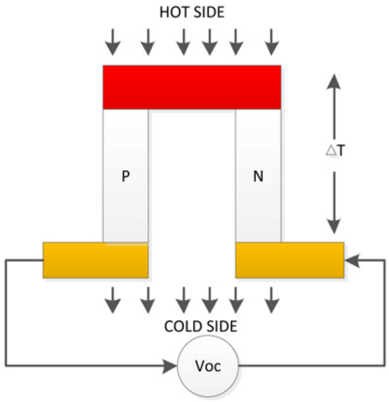

Figure 5. Illustration of the operating principle of a thermoelectric generator.

The voltage (electromotive force) (V_{oc}), which can be generated by this basic TEG depends on the temperature difference between the hot side and the cold side (ΔT), the total number of thermocouples (n) and the Seebeck coefficient (α_{sb}) as shown in the following equation:

$$V_{oc} = n\alpha_{sb}\Delta T. \quad (1)$$

The most common thermoelectric devices are bulk fabricated thermoelectric energy harvesters which are made from individual p- and n-type semiconductors assembled onto ceramic plates to form a number of connected pn junctions. The ceramic plates support the electrical interconnection of the semi-conductor elements and also serve as the device's thermal interface; an example is the TG range of devices produced by Marlow Industries [34] shown in figure 6.

These are unpackaged devices fabricated on ceramic substrates and are rated for use up to 250 °C. To use such a device it is necessary to mount it onto the thermal source and to provide heat sinking to the colder side of the device to maintain the thermal gradient across the harvester.

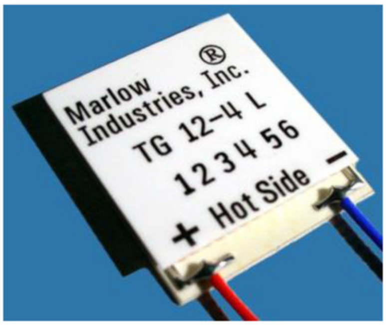

Figure 6. Thermoelectric energy harvester from Marlow Industries Inc. [34].

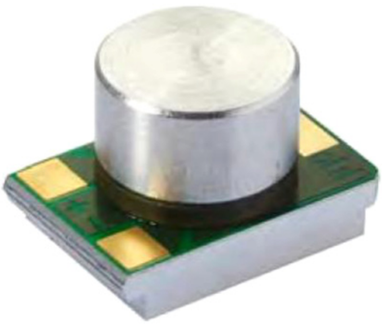

Figure 7. Micro-fabricated TGP 751 thermoelectric device from Micropelt with mounting surface and heatsink (courtesy Micropelt GmbH) [41].

The device shown in the figure is the TG 12-4-01 L and is 30 mm × 34 mm × 3.5 mm in size and can produce 4.05 W of power at it maximum continuous operating temperature of 230 °C.

Similar bulk-fabricated bare devices are also available from the Tellurex Corporation [35] in a range of sizes and output powers. European Thermodynamics also produces thermoelectric energy harvesting devices [36]. Some companies (e.g. Perpetua Power Source Technologies [37] and Custom Thermoelectric [38]) will provide custom designs consisting of either a custom thermoelectric device or a whole energy harvesting system incorporating the device mount, the active device, heat sinking and energy management electronics within a single unit.

An alternative to the bulk-material based thermoelectric devices are the micro-fabricated devices produced by Micropelt [39]. These devices have been micro-fabricated to increase the junction density, permitting operation from lower thermal gradients as a higher number of thermal junctions can be incorporated into a given volume than can be achieved with the bulk-fabrication process. These harvesters are available as just the thermoelectric element, as integrated evaluation units, or as custom designed solutions to fit the end user requirements. The actual energy harvesting element has a hot side area of either approximately 8 or 14 mm^2 depending on the device selected [40]. This provides a size advantage over the bulk-fabricated devices which typically have hot side areas of 400 mm^2 and above. An example of a micro-fabricated device, complete with its mounting surface and heat sink is shown in figure 7; the same device with the harvesting element exposed is shown in figure 8. The TEG has dimensions of 20 mm × 34 mm × 2.2 mm with 127 thermocouple junctions.

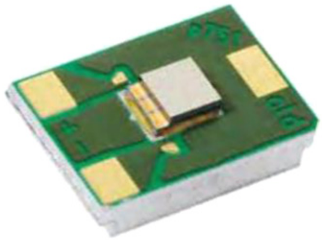

Figure 8. Micro-fabricated TGP 751 thermoelectric device from Micropelt showing harvesting element (at centre of module) (courtesy Micropelt GmbH) [41].

Apart from the advanced development of commercial TEGs, researchers have been working to further develop and test the usability of these TEGs. For example, Lu *et al* [42] reported a TEG prototype wireless sensor node, which could generate up to 150 mW at a temperature gradient of 34 °C; the hot side was at 55 °C and the cold side was at 21 °C. The TEG was used to replace the batteries required to power a ZigBee based automatic radiator valve.

In addition to the Seebeck based thermoelectric devices an alternative is to use pyroelectric materials to convert time varying thermal energy into electrical charge. Pyroelectric materials are dielectrics which show a spontaneous electrical polarization caused by temperature changes. In their operational mode the whole of the active material is at the same temperature, unlike the thermoelectric devices which rely on a thermal gradient for their operation. Materials used for pyroelectric include piezoelectric materials such as PZT (lead zirconate titanate) and PVDF (polyvinylidene fluoride).

To provide a time-changing thermal source experimentally two primary techniques have been reported. The first, as used by Hguyen *et al* [43], uses a piston to move a working fluid back and forth between a heat source and a cold heat exchanger, with the pyroelectric device mounted between these and harvesting from the resulting changing thermal conditions; the second approach is to use a radiant source such as a heat lamp, as used by Mane *et al* [44], or a source of hot air, as used by Cuadras *et al* [45]. The selected source is then either exposed and occluded or simply turned on and off periodically to expose the pyroelectric device to a cyclic thermal profile.

At present there are no known commercially available thermal energy harvesters utilizing pyroelectric materials. Currently research is on-going into the operation and optimization of these materials for energy harvesting with a cyclic heated device described by Mane *et al* [44] reported to have a peak power density of 8.64 μW cm^{-3} for a sample with a surface area of 0.98 cm^2 and with a rate of temperature variation of 8.5 °C s^{-1} and a periodicity of 0.1 Hz.

2.3. Energy harvesting from periodic kinetic sources

Kinetic energy harvesting is the conversion of ambient mechanical energy, typically in the form of vibration, into electrical energy. Within this section we deal with harvesters

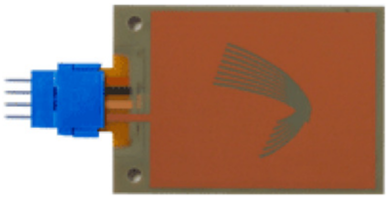

Figure 9. Volture piezoelectric energy harvester element [48].

designed to operate from a periodic source, such as the vibration of a motor. The amount of electrical energy that can be harvested from mechanical vibration depends on the vibration level, the frequency of vibration and the type, and size, of the harvester. If the harvester is modelled as typical inertial, linear, generator the maximum electrical power (P_e) that can be extracted from it can be calculated mathematically as given in the following equation [46]:

$$P_e = \frac{ma^2}{8\omega} \times Q_{\mathrm{OC}}, \tag{2}$$

where m is the mass of the generator in kg, a is the peak acceleration in m s^{-2}, ω ($= 2\pi f$) is the angular frequency in rad s^{-1} and Q_{OC} is the open circuit quality factor. A thorough description and mathematical derivations of this model can be found in [46, 47].

Assuming that the vibrational acceleration is sinusoidal in nature the RMS extractable electrical power (P_{eRMS}) can be found by substituting the peak acceleration level in equation (2) with the RMS acceleration level to give the following equation:

$$P_{eRMS} = \frac{ma^2}{16\omega} \times Q_{\mathrm{OC}}. \tag{3}$$

Most kinetic energy harvesters to date convert vibrations into electrical energy using one of the following transduction mechanisms [1, 2]: electromagnetic (EM), piezoelectric, or electrostatic. EM transduction is based on the principle of induction which arises from the relative motion of a conductor moving through a magnetic flux. Piezoelectric transduction is based on mechanical stress applied to piezoelectric materials. Electrostatic transduction utilizes the relative movement between electrically isolated charged capacitor plates to generate electricity. The source vibrational energy is typically an unwanted side effect which can be usefully damped by energy harvesting.

For periodic vibrations, vibration energy harvesters are commercially available such as the piezoelectric Volture manufactured by Midé [48] and the EM devices manufactured by Perpetuum [49]. The Midé Volture containing a piezoelectric-based harvesting element is shown in figure 9. The dimensions of this device are 50.8 mm × 38.1 mm × 0.76 mm. An example of the EM devices manufactured by Perpetuum is shown in figure 10, with a diameter of 68 mm and a height of 63.3 mm.

These devices are typically designed to harvest vibration energy at a specific frequency and are mechanically tuned to be resonant at this frequency. In the case of mains electricity-powered motors the vibration spectra typically has peaks at multiples of the primary mains frequency (50 or 60 Hz). It is important to note that devices tuned to harvest from a motor supplied by a 50 Hz supply will not work effectively with vibration from a 60 Hz supplied motor and vice versa.

Figure 10. Perpetuum PMG FSH EM energy harvester [49].

Figure 11. Piezoelectric energy harvesting mat from Pisharody [53].

2.4. Energy harvesting from intermittent kinetic sources

When the available kinetic energy results from intermittent human activity, such as opening doors, there are EM-based harvester devices available to exploit these sources. The Kaba PowerLever [50] harvests energy from the action of turning a door handle. This energy is typically used to power security control devices within the lock and the lock mechanism itself. The energy harvester consists of an EM dynamo which is driven through gearing to increase the revolutions of the generator from one operation of the door handle. Another application of energy harvesting from doors is the NRG+ Tourniket revolving door from Boon Edam, which has a generator incorporated into the door mechanism [51]. When the door is rotated, the pivot of the door turns a generator which harvests energy from the rotation. The energy harvesting technology is used for two purposes: firstly it is used to control the rotational speed of the door; secondly the energy harvested is stored in a supercapacitor and then used to illuminate the door with LED lighting.

A number of groups are researching energy harvesting floors for application in buildings. Wu *et al* [52] and Pisharody [53] have reported different approaches to implementing floor mat harvesters based on the use of a piezoelectric material to convert the impact of the foot into electrical energy. The energy generated from the floor mat developed by Wu was used to drive a wireless transmitter module to detect the user's current position in a building. The floor mat developed by Pisharody is shown in figure 11 and its output was used to charge two Ni–Cd batteries which were connected in parallel.

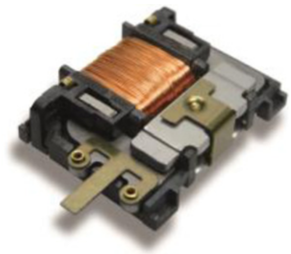

Figure 12. EnOcean ECO-200 energy harvester [58].

Development of commercial products is on-going, with devices currently being offered for commercial evaluation by Pavegen [54] and POWERleap [55]. The Pavegen energy harvesting device was demonstrated at the London 2012 Olympics where 12 harvesters were installed on a temporary footbridge connecting West Ham station to the Olympic park. During the Olympics and Paralympics it was estimated that the devices would receive 12 million footfalls and harvest a total of 72 MJ of energy [56], which is 21 kWh of energy. The energy harvested from the footsteps was used to power 12 LED spotlights. Within buildings, hallways, stairs and entrances are the areas which experience a higher volume of footfalls. If energy harvesters are integrated into floor and door mats and installed in these areas, energy can be collected from these footfalls. A typical stairway in a house has 12 stair steps; ten times use each day provides 120 footsteps per day. An energy harvester, such as the PowerFloor from POWERleap harvests 5 J per step [57], giving 1.2 kJ of energy per person, per day which equates to a continuous average of 14 mW of harvested power per day. This may be sufficient to power a low-power electronic device in a building, depending on the power consumption and duty cycle of the device.

A mechanical energy harvester already widely used in buildings, shown in figure 12, is the ECO-200 from EnOcean. The energy harvester-based wireless technology is in use in over 250 000 buildings worldwide [58].

The operation of a light switch causes an EM bi-stable armature to move from one position to another thus harvesting the mechanical energy. A common application of this harvester is self-powered wireless light switches, such as the PTM250 universal switch insert [59]. The harvested mechanical energy powers a wireless transmitter which sends a control signal to a mains-powered receiver connected to the light to turn it on or off. A similar device is manufactured by Lightning Switch [60], though this device uses piezoelectric transduction to harvest the mechanical energy from the switch operation.

2.5. Energy harvesting from electromagnetic waves

EM energy harvesters convert EM waves available in the environment into electricity. In the literature, EM wave energy harvesters are also known as radio frequency (RF) energy harvesters, as EM waves are colloquially known as radio waves. The EM wave can be the result of emissions from radiation emitting devices such as mobile base stations, Wi-Fi routers, satellite communications, radio and TV transmitters. The amount of energy harvested depends on the RF to dc conversion efficiency and the amount of RF power received by the harvester, which in turn depends on the transmitted power (P_{TX}), the gain of the transmitting antenna (G_{TX}), the gain of the receiving antenna (G_{RX}), and the distance from the RF source to the harvester (R). This relationship is given in equation (4) [61], where η is the RF to dc conversion efficiency, P_{dc} is the harvested power and λ is the wavelength of the transmitting frequency:

$$P_{dc} = \eta P_{TX} G_{TX} G_{RX} \left(\frac{\lambda}{4\pi R}\right)^2. \tag{4}$$

This equation assumes free-space propagation but in a building the amount of received power will be significantly less. Therefore, even if the amount of transmitted power is in the order of more than several kilowatts, the received power will typically be in the order of microwatts to milliwatts [62].

The EM energy source can be already present in the target environment, such as telecommunication transmissions, or a dedicated source specifically provided for harvesting. In the case of a specifically provided energy source, the target device is not harvesting unwanted energy, it is simply being transferred from the source to the target; however in this paper both existing and specifically provided EM sources will be considered. The main EM wave sources in buildings are as follows.

- *Computer networking RF sources*. Wi-Fi routers are commonly used for providing Internet access in many buildings; one or more routers are installed in a building depending on the size of the building. EM waves from these routers and other routers in the neighbourhood can be found in most rooms, with signal strength depending on the distance to the router. In many cases these EM signals can be harvested and converted into usable electrical energy without significantly deteriorating the communication between the router and other devices unless the harvester is placed within a few centimetres of either the router or the receiving device. Similarly, Wi-Fi enabled portable devices such as laptops, tablets and smart-phones transmit EM waves when they are operated. The radiated power from these devices is significant in close proximity, but lower than that from the Wi-Fi routers. Also most laptops, tablets and smart phones have a Bluetooth transmitter and receiver for short range communication. When in operation these devices generate EM waves at 2.4 GHz; however the transmitted power level is usually kept as low as possible. Within Europe the maximum effective isotropic radiated power from these devices is limited to 100 mW [63].
- *Radio and television broadcasting*: These transmitters operate from 88 to 108 MHz for FM radios, 175 to 230 MHz for digital audio broadcasting and 470 to 854 MHz for TV broadcasting. The transmitting antennas of these broadcasting stations radiate a significant amount of power in the form of EM waves. For example, the UK communication regulator (Ofcom) shows a list of all TV broadcasting stations across the UK and their corresponding effective radiated power (ERP). The ERP ranges from 40 W up to 20 kW [64] at the transmitter.

The broadcasting stations are spatially distributed to provide coverage across the country. This means that EM waves are readily available in buildings, and can be converted into electricity by using suitable energy harvesters.

- *Mobile telecommunications.* For mobile communications the Global System for Mobile Communications (GSM) standard has now evolved to the 4G system. The mobile and broadband service providers distribute the base stations in most areas to provide network coverage for their customers. EM waves from these base stations are commonly available at 900 MHz (also known as GSM 900 because of the operating frequency band) and 1800 MHz (GSM 1800) in Africa, Europe, the Middle East and Asia, and at 850 MHz (GSM 800) and 1900 MHz (GSM 1900) in North and South America. Base stations have transmission powers ranging from 20 to 50 W depending on the operating frequency, the power class number and the size of the cell (the area served by one base station). However, the received signal strength within a building is relatively low, in the range of mW, because of the free space path loss, attenuation, absorption and scattering. Calls and text messages made and sent from mobile communication devices result in the generation of EM waves which are transmitted to base stations. These waves and scattered waves can be collected and converted into electricity; however, this may affect the communication channel, particularly in the case of weak or poor connections.

An EM energy harvester consists of a transducer for converting EM waves into an alternating electric current and a rectifier circuit for converting the alternating current into direct current. However, additional circuits such as RF filters, voltage multiplying circuits, and coupling circuits are usually also incorporated.

There are no commercial devices targeted at harvesting EM waves already present in the environment since such devices may impede, or even prevent, the primary function of the EM waves. However, several researchers have reported such ambient EM energy harvesters. Nintanavongsa *et al* [65] reported a two-stage RF energy harvester operating at 915 MHz band, one stage being optimized to work at low input RF power (~ -20 dBm) and the other at high RF input power ($\sim$ 20 dB). The prototype produced 10 μW at -10 dBm and 37 μW at -6 dBm, with efficiencies of 10% and 14.73% respectively. Shao *et al* [66] reported a dual-band RF energy harvester which produced 1.2 V dc for -19 dBm RF input power at 900 MHz with 12% conversion efficiency and 1.05 V for -18 dBm RF input power at 2 GHz with 8% conversion efficiency. Kitazawa *et al* [67] reported a multi-stage RF to dc conversion circuit for harvesting RF power from a mobile base station operating in the 800 MHz band. The conversion efficiency ranged from 0.8% to 19.7%, as a function of the power from the base station. For example, at -5 dBm input RF power, the prototype generated 970 mV at a conversion efficiency of 19.7%. Takhedmit *et al* [68] developed a prototype that could harvest 850 mV and 3 V dc voltage from -15 and -5 dBm input RF power respectively in the 2.5 GHz band. Olgun *et al* [69] reported a planar rectenna for use in the 2.45 GHz band with a conversion efficiency between 8% and 70% depending on the input power level. RF to dc conversion efficiencies ranging from 1% to 20% and from 30% to 60% have also been reported in [70, 71], respectively.

Deliberate transmission of EM waves for harvesting is being used by companies such as WiTricity [72] and PowerCast [73] and is commonly known as wireless electricity. They have developed commercial products which transmit electricity wirelessly to charge electronic devices such as phones. However, like other RF transmissions, the transmitted power decreases rapidly with distance (by a factor of $1/r^2$) and this causes a power loss between the transmitter (power broadcaster) and the harvester. Additional losses occur in the internal circuitry of the harvester during the conversion process. For example, Vullers *et al* [74] reported that a transmitted power of 100 mW reduced to harvested powers of 1.5 mW, 20 cm away from the transmitter and 200 μW, 2 m away.

2.6. Energy harvesting from electromagnetic fields

When an electric current flows through a cable, the EM fields around it emanate into the surrounding environment. Electrical energy can be harvested from these EM fields if the harvester is located within the field; for example energy can be harvested from cables running from wall sockets to appliances. Clearly a limitation with this method is that energy can only be harvested when there is a flow of current through the cable.

Harvesting energy from EM waves emanating from current carrying conductors has been investigated by a number of researchers. Leland *et al* [75] developed and tested devices that could be coupled to magnetic fields surrounding wires carrying ac current. The devices had two functions: harvesting energy for wireless sensor nodes and passive, proximity-based current sensors. In energy harvesting operation, the devices generated 208 μW of power into a 419 kΩ load resister when coupled to a space heater cable carrying 9.4 A, and 345 μW into a 419 kΩ load when coupled to a 13 A current. Taithongchai *et al* [76] reported an adaptive EM energy harvesting circuit which generated 58 mW from a single electric conductor carrying 65 A line current. Bhuiyan *et al* [77] presented a coupling device which could deliver 10 mW of dc power into a 50 Ω load, with a load current of 14.03 mA when coupled electromagnetically to a nearby ac current carrying conductor carrying 13.5 A. Gupta *et al* [78] conducted experiments with various off-the-shelf inductors and current carrying conductors and concluded that up to 1 to 2 mW of power can be harvested from stray EM waves generated from a pair of ac current carrying conductors carrying a current of 8.4 A. The author identifies the limitation that the magnetic field strength decreases exponentially with distance from the current carrying conductor, so the harvester must be located in close proximity to the conductor for effective energy harvesting.

2.7. Energy harvesting from airflow

Many buildings are equipped with air conditioners which cause airflow within the area for the purpose of changing

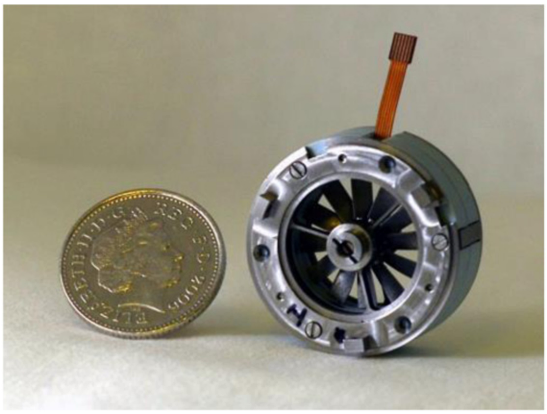

Figure 13. Miniature turbine from Howey *et al* (10 pence coin for scale) [81].

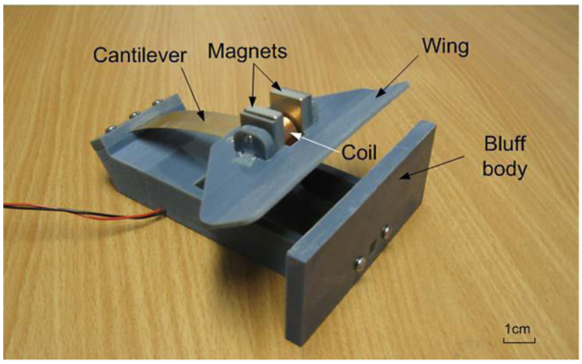

Figure 14. Horizontal airflow energy harvester from Zhu *et al* [85].

the air temperature to a level which is comfortable for the occupants. The airflow can be harvested and there are three main approaches to harvesting energy at small scales from airflow. The first approach, and the most widely used method, is based on wind turbine technology. Small-scale wind turbines consist of a propeller system which is forced to rotate by the airflow. The rotation, via a gearing system, drives a transducer which is usually EM-based. This transducer then converts the mechanical rotations into electricity. Typically, the harvested power depends on the wind speed, air density and the sweep area of the wind turbine blade as given in the following equation [79]:

$$P = \tfrac{1}{2}\rho A v^3, \tag{5}$$

where P is the harvested power in W, ρ is the air density in kg m^{-3}, A is the sweep area of the wind turbine blade in m^2, and v is the wind speed in m s^{-1}.

In 1919, Albert Betz concluded that a wind turbine cannot convert more than 59% of the kinetic energy of the wind [80] into electricity. Including this theoretical limit, C_p, and the efficiency, η_g, of a generator

$$P = \tfrac{1}{2}\rho A v^3 \eta_g C_p, \quad C_p < 0.59. \tag{6}$$

An example of a miniature wind turbine that could be used, for example, in an air conditioning duct within a building is the device described by Howey *et al* [81], shown in figure 13.

The device has a 2 cm diameter rotor blade located within a shroud which serves the dual purpose of guiding the airflow through the turbine and housing the axial flux permanent magnet generator. The device components were fabricated using a range of techniques including rapid prototyping, machining and flexible PCB technology. The miniature turbine was tested in a wind tunnel with wind speeds between 3 and 10 m s^{-1} and the electrical load on the output of the turbine was varied to find the maximum extractable electrical output power at each wind speed. At a wind speed of 3 m s^{-1} the extractable power from the generator was 80 μW, at 7 m s^{-1} the extractable power was 2.5 mW, and at 10 m s^{-1} the extractable power was 4.3 mW. Over the wind speed test range of 3 to 7 m s^{-1} the overall device efficiency varied from 0.61% to 1.52%, with the maximum efficiency at a wind speed of 6 m s^{-1}. However, the authors identify parts of device where the design has not been fully refined and where there is potential to reduce losses and improve the overall device conversion efficiency.

An example of a commercially available miniature turbine is the HYmini hand-held turbine [82] which has a ~6.5 cm diameter turbine combined with a Li–ion polymer battery to store the energy harvested. The whole device, including the storage battery, has dimensions of 134 mm × 87.5 mm × 33.5 mm. The device is specified to operate for wind speeds in the range of 4 to 18 m s^{-1} and it is anticipated that the unit be mounted onto a moving person or a moving object such as a bicycle.

The second approach to harvesting from airflow is based on air-driven vibrating transducer ribbons, which derives from the Aeolian harp, a musical instrument consisting of strings stretched lengthwise across two bridges; wind can blow across the strings to produce sound. The sound is random, depending on the strength of the wind passing over the strings, and can range from a barely audible hum to a loud scream. Energy harvesters using this approach consist of a vibrating ribbon placed in the air stream and excited by the impact of the air. Coupled to the vibrating ribbon is a transducer, which converts the resulting movement into electricity. Potential transducers, to convert the mechanical kinetic energy to electrical energy are based on EM, electrostatic or piezoelectric principles. Humdinger [83] has produced a range of different scale wind belts based on this principle. Their smallest version having a vibrating ribbon with dimensions of 7 mm × 120 mm is reported to produce an ac output power at 70 Hz ranging from 200 μW at a wind speed of 3.5 m s^{-1} to 5 mW at 7.5 m s^{-1} [84]. The technique could be scaled down further, although the levels of harvested energy can be expected to decrease significantly.

The third approach to airflow harvesting, described by Zhu *et al* [85], uses oscillations of a cantilever facing into the direction of airflow. A wing is attached to the free end of the cantilever and to cause the cantilever to oscillate. A bluff body is placed up-wind of it, which leads to the production of vortices within the airflow. By appropriate design and placement of the bluff body, and tuning of the cantilever structure, the system can be made to resonate. An example of this device configured for operation in the horizontal plane is shown in figure 14; the harvester is mounted so that the airflow is perpendicular to the face of the bluff body impacting the bluff body prior to the wing so in the figure the direction of airflow is from bottom right to top left.

The energy harvester has overall dimensions of 14.1 cm × 10 cm × 5.5 cm and is designed to be utilized within horizontal HVAC ductwork. The transduction mechanism, used to convert the mechanical oscillation to electrical energy, is a pair of moving magnets attached to the wing and a fixed coil, as shown in figure 14. In tests in office HVAC ducting typical air flows of 2 to 4 m s^{-1} occurred from which the harvester produced an output power of 90 and 573 μW, respectively.

2.8. Hybrid energy harvesting

Hybrid energy harvesting systems are used to harvest energy from two or more ambient energy sources. Harvesting energy from several sources should increase the total amount of energy available and provide contingency in the case the energy from a single source is not sufficient or available. Tan *et al* [8] reported an optimized hybrid energy harvesting system that harvests energy from indoor ambient light and thermal energy using only one power management system to condition the combined output power from the two energy sources. An average electrical power of 621 μW was reported at an average indoor solar irradiance of 1010 lx and a thermal gradient of 10 K. This result was achieved by harvesting from the two sources simultaneously and also by operating the photovoltaic harvesting efficiently through the use of maximum power point tracking. This high efficiency, combined with the use of shared, highly-efficient, energy management electronics leads to a higher overall energy conversion efficiency, ranging from 80% to 94% over a range of load resistances of 50 to 330 kΩ. A similar hybrid energy harvester which integrates photovoltaic and thermoelectric harvesters was reported by Suzuki *et al* [86]. The combined photovoltaic and thermoelectric module was fabricated using organic material on flexible film; however the efficiency of the hybrid device when operating in photovoltaic mode is very low with values of 4.9×10^{-4}% and 2.1×10^{-2}% quoted by the authors for the percentage of energy converted. Colomer-Farrarons *et al* [87] developed a hybrid harvester which used six solar cells each having dimensions of 22 mm × 7 mm and an efficiency of 17% (indoor environment at 1500 lx), two piezoelectric generators each having dimensions of 50.8 mm × 38.1 mm (operating at 1 m s^{-2} and 80 Hz), and EM induction using planer rectangular antenna of 30 mm × 15 mm (operating with a carrier frequency of 13.56 MHz and located at a distance of 25 mm from an RF source transmitting at 200 mW). The maximum combined power harvested from the three sources was 6.4 mW.

2.9. Current market availability

The different forms of energy harvesting technologies have reached varying degrees of maturity and establishment within the commercial market; choice and availability for the main types of energy harvester are identified in this section.

2.9.1. Photovoltaic. A wide range of rigid solar cells based on amorphous and crystalline silicon are readily available off the shelf from most electronic component suppliers. Devices are available in a wide range of sizes and cell configurations optimized for both indoor and outdoor use. Being a well-established area, there are a large number of manufacturers for traditional rigid solar cells. Flexible solar cells are less widely available but can be obtained directly from the manufacturers.

2.9.2. Thermal. Both bulk material-based and micromachined thermoelectric energy harvesters are available from a number of specialist electronic component distributors and direct from the manufacturers. There are a number of companies producing the bulk material-based devices and several producing the micromachined alternatives.

2.9.3. Periodic kinetic. These devices are commercially available but are not a standard stock part and usually need to be ordered directly from the specialist manufacturer and may need to be made to order to fit the source kinetic energy and/or frequency or if a volume of units is required. There is a limited choice of specialist manufacturer with the choice likely to be guided by the target application and type of harvester required.

2.9.4. EM wave. There are no commercially available harvesters designed to operate from ambient EM wave energy. However 'wireless electricity' modules containing a full EM wave energy harvester designed to operate from deliberately transmitted RF signals and providing a dc output are available as stock items in low volume from specialist electronic component distributors and manufacturers. There are a number of options available at present, although there is currently a limited choice of specialist manufacturers producing the devices.

2.9.5. Airflow. Currently there is limited commercial availability of miniature airflow harvesters, whilst larger devices, designed for operation outside, are readily available. One miniature wind turbine currently on the market is sold as an educational toy although it has found use in a number of group's research.

3. Energy source measurement in buildings

To provide information on the types of energy available and indicative values of ambient energy levels energy, surveys were performed in three European locations (England, Spain and Poland). In the case of light and thermal energy harvesting the available energy is highly affected by climate and geographic location and so the choice of measurement time of year and time of day has been made, as far as possible, to identify these variations. For RF energy the specific country standard will affect energy levels. However we expect the overall conclusions of this survey to be generally applicable.

A summary of the energy sources, measured in different locations and building types, is presented below. Light, thermal, kinetic, EM and airflow energy sources are presented

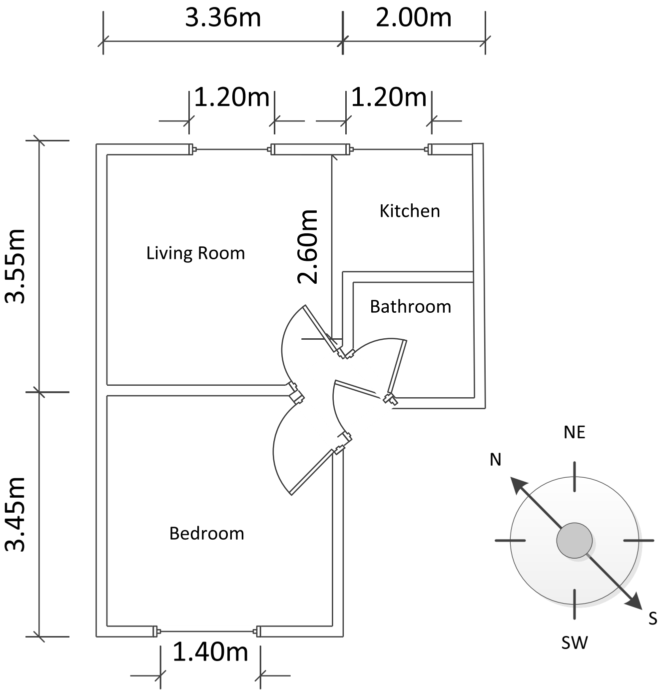

Figure 15. Floor plan of one bedroom apartment in Southampton, England.

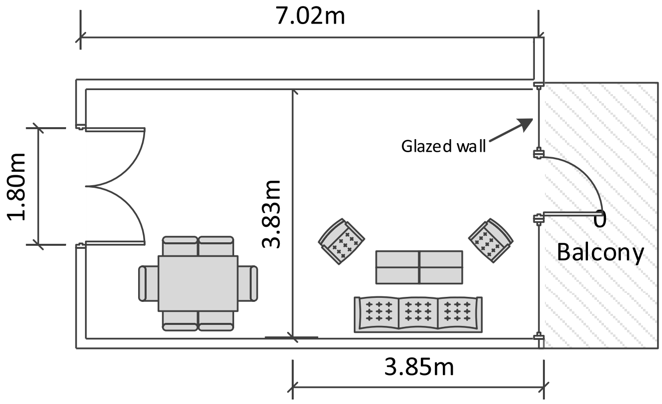

Figure 16. Typical apartment living room configuration in San Sebastian, Spain.

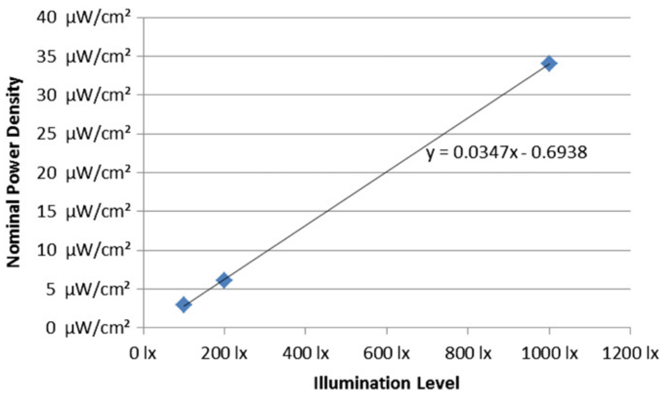

Figure 17. Nominal power density versus illumination level for SCHOTT ASI indoor solar cells.

in sections 3.1, 3.2, 3.3, 3.4 and 3.5 respectively. In each of these sections, the locations and experimental method used is presented first, followed by a summary of measurements and calculated harvested powers from all the locations surveyed. In all cases the availability of all energy sources with the potential for harvesting was assessed, though only those with useable energy levels are reported. Detailed experimental measurements for light and RF energy are presented in appendices A and B, respectively.

3.1. Photovoltaic energy sources

Light level measurements were taken in a one bedroom residential apartment in Southampton, England, the floor plan of which is shown in figure 15, from 1 to 4 June 2012. Measurements were continuously taken, from 8 am, for four consecutive days using a DT-8809A data logging light meter taking readings at 10 s intervals. The weather during the measurement period was sunny with some cloud.

Light levels were also measured in a number of residential apartments in San Sebastian, Spain on 9 November 2010. Light level measurements were made at a range of locations within the living room, with a typical layout of the room as shown in figure 16 to allow for influences such as the presence of natural light from the balcony widows, located to the right of the figure, which provided the main illumination present in the sitting area. Incandescent lighting was used to illuminate the dining area at the opposite end of the space. Five apartments were surveyed during the visit. The measurements were made using an ISO-TECH 1337 light meter. The weather during the measurements was overcast.

Finally, light levels were also measured within commercial office properties, constructed within the last 10 years, in Warsaw, Poland on 24 and 25 January 2011. Spot measurements were at various locations in a range of differently sized offices and communal spaces such as corridors and reception areas. The measurements were made using an ISO-TECH 1337 light meter. The weather during the measurements was a clear sky with light snow falling.

3.1.1. Summary of light energy levels and estimated harvested power.

A summary of the light level measurements is presented in table 2, along with the maximum light level and the calculated dc output power and power density. Detailed measurements are presented in appendix A.

To estimate the harvested output power from a photovoltaic device, a 3 cm × 3 cm SCHOTT Solar ASI OEM Indoor specification solar cell was assumed, and its nominal power density at a range of illumination levels were taken from the manufacturer's datasheet [26] and plotted on a graph, a linear fit was then applied to the data points and the equation of this fit was then used to give the nominal power density at the desired illumination levels. The graph of nominal power density versus illumination level for SCHOTT ASI indoor solar cells is shown in figure 17. This approach includes the efficiency of the photovoltaic device in the calculated figures.

Table 2. Summary of light measurements in all locations.

Building location	Building type	Measurement location	Max light (lx)	Calculated power (μW)	Calculated power density (μW cm^{-3})
Southampton, England	Residential apartment	Living room	370	110	38
Southampton, England	Residential apartment	Kitchen	300	87	30
Southampton, England	Residential apartment	Bedroom	100	25	9
Southampton, England	Residential apartment	Bathroom	110	28	10
San Sebastian, Spain	Residential apartment	Living area (away from windows)	200	56	19
San Sebastian, Spain	Residential apartment	Living area (adjacent to windows)	3700	1149	399
Warsaw, Poland	Commercial office	Single occupancy offices	800	244	85
Warsaw, Poland	Commercial office	Single occupancy offices (adjacent to windows)	2400	743	258
Warsaw, Poland	Commercial office	Large open plan office	900	275	95
Warsaw, Poland	Commercial office	Large open plan office (adjacent to windows)	2200	681	236
Warsaw, Poland	Commercial office	Corridor and reception areas	450	134	47

Table 3. Surface temperature measurements and their estimated output powers.

Building location	Building type	Measurement location	Room location	Temp (°C)	ΔTemp (°C)	Calculated power (mW)	Calculated power density (mW cm^{-3})
Southampton, England	Residential house	Radiator 1	Bedroom, living room	45.38	24.38	6	4.3
Southampton, England	Residential house	Radiator 2	Bedroom, living room	80.50	59.5	>9	>6.4
Southampton, England	Residential house	Cooker surface	Kitchen	38.50	17.5	3	2.1
Southampton, England	Residential house	Water pipes	Kitchen, bathroom, utility room	32.71	11.71	1	0.7
Southampton, England	Residential house	Boiler	Kitchen	36.00	15	2	1.4
San Sebastian, Spain	Residential apartment	Radiator	Living room	34	14	2	1.4
Warsaw, Poland	Commercial office	Radiator	Single occupancy office	32	11	1	0.7
Warsaw, Poland	Commercial office	Radiator	Large open plan office	50	27	7	5.0
Warsaw, Poland	Commercial office	Radiator	Corridor, reception areas	50	31	9	6.4

3.2. Thermal energy sources

Temperature measurements were taken on 2 November 2011 in a typical English student house, the layout of which is shown in figure 18, on the following thermal sources: radiators, pipes, cooker and the boiler. The surface temperature of each source was measured using a contactless infrared thermometer (Calex PYROPEN-E) and the ambient air temperature was measured with a TENMA 72-2065A digital thermometer in conjunction with a K type bead thermocouple located in the room airspace to measure ambient temperature as a reference.

Temperature measurements were also carried out in the residential apartments in San Sebastian, Spain, on 9 November 2010 within the apartment's living space, as shown in figure 16. Thermal energy sources in the surveyed spaces were taken on the HVAC radiators and their associated pipe work. Temperatures were measured using a TENMA 72-2065A digital thermometer in conjunction with a TME KS01-3 fast-response K type surface probe and a K type bead thermocouple, the ambient air temperature was measured 5 to 10 cm from the heat source of interest. This provides information on a different type of residential building in a different location.

Finally thermal energy sources were surveyed within commercial office properties in Warsaw, Poland, on 24 and 25 January 2011 in a range of differently sized offices and communal spaces such as corridors and reception areas; these results provide information on thermal energy sources in commercial buildings.

3.2.1. Summary of temperature levels and estimated harvested power. A summary of the measured temperature levels are presented in table 3, along with the calculated dc output power and power density from the harvester into a matched resistive load.

To estimate the amount of power which can be harvested, a commercially available TEG, TGP-751, from Micropelt was used and its related specification was used with the obtained measurement data. The output power was obtained from the product datasheet graph, shown in figure 19. This approach includes the efficiency of the thermoelectric device in the calculated figures. For the estimation it was assumed that the thermal transfer to and from the device is ideal and that the full temperature difference between the thermal source and the ambient air is present across the TEG element.

This harvested power is only available during the periods when the heating is on and active; in the apartments surveyed

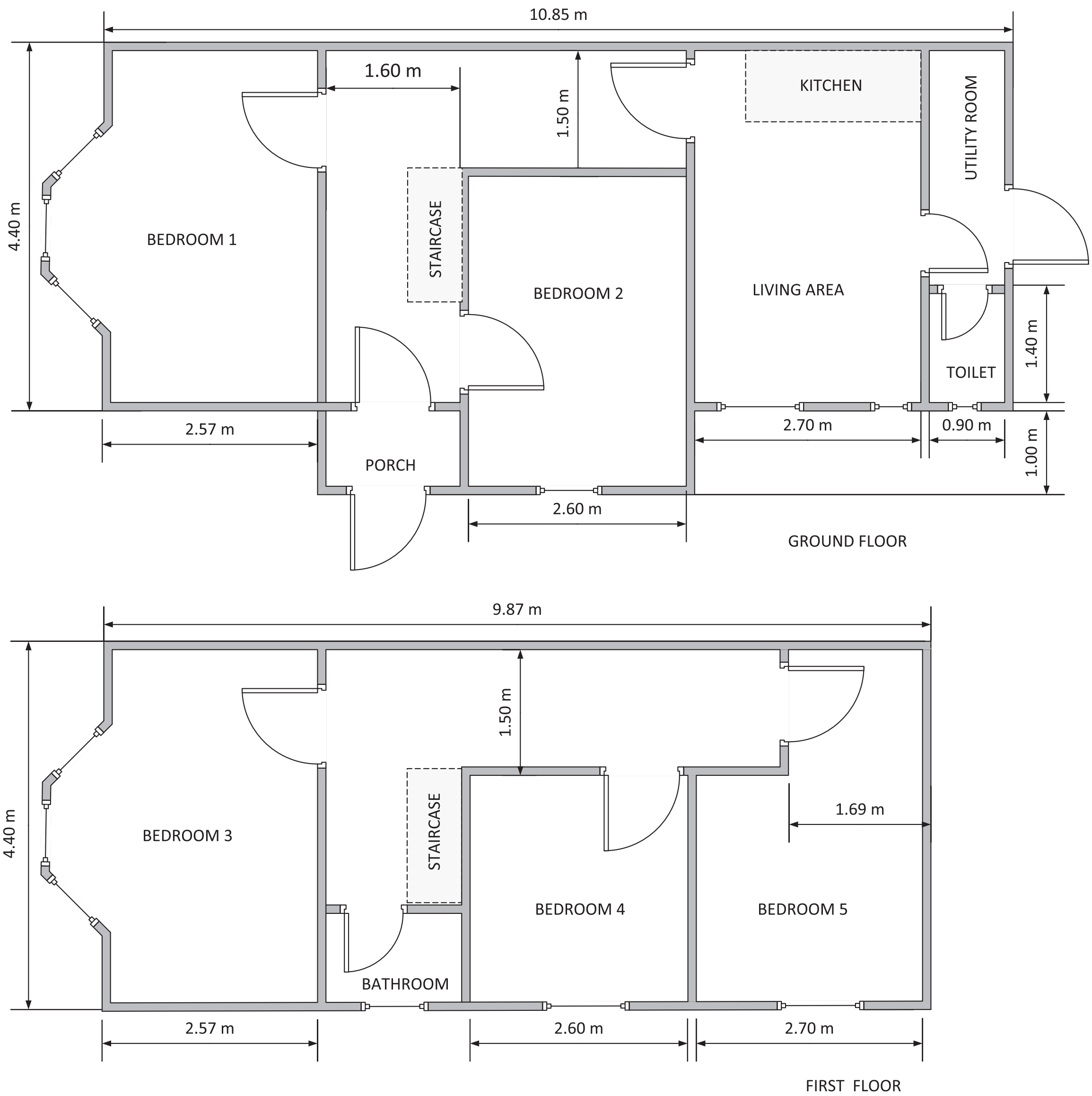

Figure 18. Floor plan of typical student house in Southampton, England.

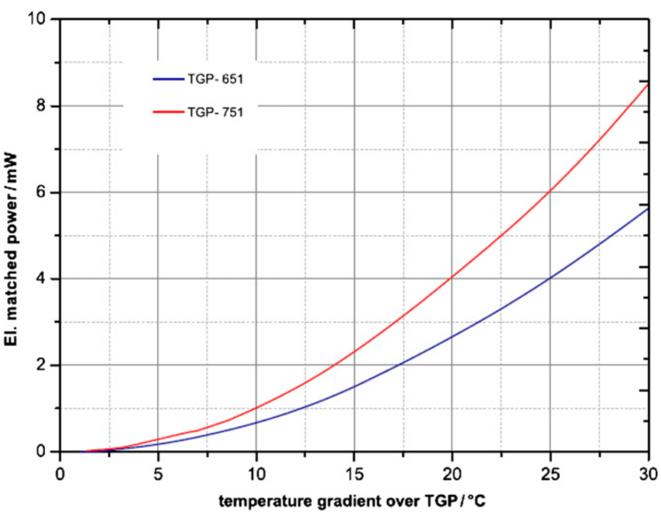

Figure 19. Performance specifications of Micropelt thermal harvesters showing the relationship between thermal gradient and corresponding output power (courtesy Micropelt GmbH) [41].

this would mean that this source is not available for much of the year, and even during the winter period when the heating is available it is only available for part of each day. Within the residential buildings surveyed in San Sebastian the space heating is only available between 12 noon and 10 pm daily between the dates 1 October and 15 May, during the rest of the year it is not operative. Therefore during the period when the space heating is available (from October to mid-May) the thermal source is only available for a maximum of 10 h in each 24 h period.

3.3. Periodic kinetic energy sources

These were measured in a typical English house on 16 November 2011. Periodic kinetic energy sources, within the house infrastructure, are limited to the central heating boiler. However measurements were also made on commonly available consumer products these being: microwave oven, washing machine, tumble dryer, fridge and freezer. The vibration measurement were carried out using

Table 4. Extractable RMS electrical energy from vibrations measured in the kitchen and utility room.

Measurement location	Appliance	Axis	Frequency (Hz)	Acceleration (m s^{-2})	Calculated P_{eRMS} (μW)	Calculated P_{eRMS} density (μW cm^{-3})
Kitchen	Central heating boiler	X	98.1	9.81×10^{-2}	0.13	0.87
		Y	104.6	3.92×10^{-2}	1.93×10^{-2}	0.13
		Z	162.3	4.51×10^{-2}	1.65×10^{-2}	0.11
Kitchen	Microwave	X	100.2	1.43	26.80	178.67
		Y	198	2.82	52.74	351.60
		Z	98.1	2.27	68.97	459.80
Utility room	Washing machine	X	126.3	8.53×10^{-2}	7.56×10^{-2}	0.51
		Y	97.5	2.45×10^{-2}	8.08×10^{-3}	0.05
		Z	100.2	0.119	0.19	1.27
Utility room	Tumble dryer	X	43.1	0.429	5.61	37.40
		Y	73.4	0.155	0.43	2.87
		Z	44.3	0.258	1.97	13.13
Utility room	Freezer	X	136.1	3.73×10^{-2}	1.34×10^{-2}	0.09
		Y	70.4	3.53×10^{-2}	2.32×10^{-2}	0.15
		Z	142.9	3.43×10^{-2}	1.08×10^{-2}	0.07

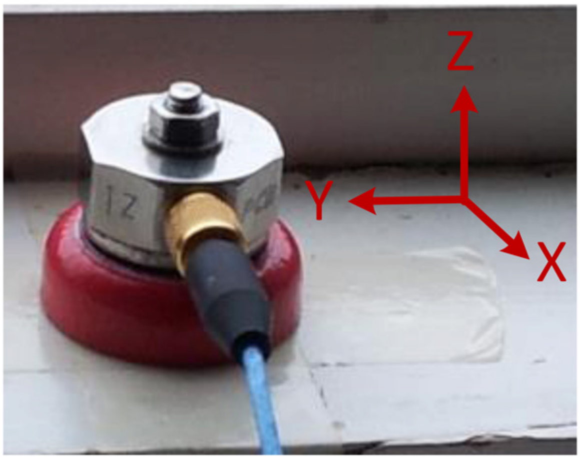

Figure 20. 35C03 Tri-Axis accelerometer mounted on its base illustrating the orientation of the X, Y and Z axis.

a tri-axis accelerometer (model number 354C03 from PCB Piezotronics) with a 3-channel, battery-powered, sensor signal conditioner (PCB Piezotronics model 480B21) connected to a computer using a low gain multifunction data acquisition USB data module (model number KUSB-3102 from Keithley). During the measurement, the accelerometer was fixed to its base and then firmly attached at the location where the vibrations were to be measured. The vibration magnitudes and frequencies along each axis were recorded and stored on the computer at a sampling frequency of 1024 Hz to allow frequencies up to half this to be captured. The accelerometer and its orientation with respect to the XYZ axes is shown in figure 20.

3.3.1. Summary of periodic kinetic energy levels and estimated harvested power. A summary of vibration measurements taken is presented in table 4 along with the calculated extractable RMS harvested electrical power and power density.

The extractable RMS harvested power was calculated, for a typical kinetic energy harvester, using equation (3) using the assumptions that the harvester has an inertial mass made of tungsten alloy with a mass of 6.6×10^{-4} kg and a typical quality factor of 200 [88], as the reported figures for the efficiency of kinetic energy harvesters vary in both definition and value an efficiency of 100% is taken to give a best-achievable value in the calculations.

These results indicate there is the potential to harvest useful energy. However, such powers are only available intermittently when the item is in use and even then cannot always be anticipated to be continuously available. For example, compressors in refrigeration equipment only run whilst the device is cooling to its desired operating temperature; once this is reached they are stopped until the temperature has risen again. In our measurements, the tumble dryer generated more energy than the washing machine and the freezer.

3.4. Electromagnetic energy sources

In order to provide an upper bound on the potential for harvesting energy we selected an environment in which we expected a high level of EM waves. These measurements were taken on 25 June 2012 in an electronics laboratory at the University of Southampton, England with the detector located at a single fixed point.

The measurement of ambient RF EM waves was done using a Rohde & Schwarz FSV Signal and Spectrum Analyser operating from 9.0 kHz to 3.6 GHz frequency range. An overall measurement was taken using a wideband pentaband antenna covering a wide frequency band from 824 to 2170 MHz. A half-wavelength domestic-use dipole ribbon antenna (Pro Signal PSG08012) was used for measuring signals from FM broadcasting stations within the 88 to 108 MHz frequency range. A 13 cm long pentaband antenna (Multicomp IR-GSMPB-02-C5) was used to measure signals from mobile base stations (2G, 3G and 4G) at GSM 900 (880 to 960 MHz), GSM 1800 (1710 to 1880 MHz) and 3G/4G (1900 to 2170 MHz) frequencies. A 2.4 GHz ISM band antenna (Antenova M2M Titanis B4844), capable of receiving signals from Bluetooth,

Table 5. DC power from an RF energy harvester with a conversion efficiency of 70%.

Frequency band	RF power (dBm)	RF power (nW)	Calculated dc power (nW)	Calculated power density (nW cm^{-3})
FM	−66.96	0.20	0.14	8.51×10^{-3}
GSM 900	−28.70	1.34×10^3	944.27	57.37
GSM 1800	−63.50	0.45	0.31	1.88×10^{-2}
3G/4G	−48.40	14.45	10.12	0.62
ISM (2.4 GHz)	−74.00	3.98×10^{-2}	2.78×10^{-2}	1.69×10^{-3}

Wi-Fi and ZigBee, was used to measure frequencies between 2.4 and 2.5 GHz.

3.4.1. Summary of electromagnetic energy levels and estimated harvested power. A summary of the EM energy level measurements is presented in table 5, along with the estimated dc output power and power density from the harvester. Detailed measurements are presented in appendix B.

At the time of writing this review, there are no commercially available ambient RF energy harvesters to estimate the harvestable power from RF energy. We have therefore estimated the harvested RF power from conversion efficiencies presented in the scientific literature. The RF to dc conversion efficiency has been reported from 1% to 70%. If the RF energy harvester is assumed to have a conversion efficiency (η) of 70%, (best case scenario) then the dc power (P_{dc}) that can be obtained from RF power (P_{RF}) can be calculated as shown in the following equation:

$$P_{dc} = \eta P_{RF} = \{\eta = 70\%\} = 0.7 P_{RF}. \quad (7)$$

Substituting the maximum RF power from the measurements into equation (7) gives the corresponding dc output power as shown in table 5.

Although a RF harvester with the highest conversion efficiency is used in the calculations, the obtained dc power is still low. The main reason is the low level of received RF power, which varies significantly depending on the position and distance of the harvester from the RF source. The EM waves from the identified sources are distributed in different frequency bands, and this presents great challenge to the design of efficient harvesters. For instance, if in a particular area the stronger RF signals come from both FM radio transmissions and 3G base stations it is difficult to design an efficient single wideband antenna which can take advantage of harvesting energy from these two frequency bands.

3.5. Airflow

Airflow measurements were taken from air conditioners and computer fans in a computer laboratory and offices in a building at the University of Southampton, England. These measurements were taken on 22 June 2012. The air conditioning units tested were a mobile unit manufactured by Air Force with variable fan speed, an industrial ceiling unit manufactured by Dunham-Bush with variable fan speeds, and three standard ceiling mounted units manufactured by Daikin. The measurements were taken using a vane anemometer, model number 72-6638 manufactured by Tenma. During the measurement, the vane probe was positioned perpendicular to the direction of airflow for maximum airflow reading.

3.5.1. Summary of airflow energy levels and estimated harvested power. The measurements were taken at 0, 5 and 10 cm away from the air source and are summarized in table 6, also shown in the table are the estimated maximum dc electrical output powers achievable from each air source.

The estimated maximum power was estimated by taking the specifications of the micro-scale airflow generator reported in [89] radius of the wind turbine blade, $r = 3$ cm [$A = \pi r^2$], generator efficiency, $\eta_g = 0.41$, and Betz limit, $C_p = 0.39$, and the typical air density at sea level is $\rho = 1.225$ kg m^{-3}. Substituting these constants into equation (5) gives the following equation:

$$P = \tfrac{1}{2}[1.22][\pi(0.03)^2][0.41][0.39]v^3 \approx 0.28v^3[\text{mW}]. \quad (8)$$

Therefore, the estimated electrical dc output power, taking into account the conversation efficiencies, is a function of the airflow speed. Applying the airflow speed measurements presented in table 6 into equation (8), gives the maximum electrical dc output powers shown in the table.

The estimated dc output power from the airflow harvester is dependent on the distance of the harvester from the airflow

Table 6. Airflow measurements recorded from air sources in a university building.

Air source manufacturer (fan speed)	Air speed (m s^{-1}) At 0 cm	At 5 cm	At 10 cm	Calculated maximum output dc power (mW)	Calculated maximum output power density (mW cm^{-3})
Air force (low)	7.9	6.3	2.8	138.1	2.6
Air force (medium)	9.0	7.3	5.4	204.1	3.8
Air force (high)	10.5	8.9	7.2	324.1	6.0
Dunham-Bush 21–240B (low)	4.1	3.6	2.8	19.3	0.4
Dunham-Bush 21–240B (medium)	5.3	4.9	3.2	41.7	0.8
Dunham-Bush 21–240B (high)	6.1	5.1	3.4	63.6	1.2
Daikin—unit 1 (fixed)	3.3	1.8	1.2	10.1	0.2
Daikin—unit 2 (fixed)	3.3	2.1	1.0	10.1	0.2
Daikin—unit 3 (fixed)	3.2	2.1	1.2	9.2	0.2
120 mm PC rear (fixed)	1.5	0.8	0.5	0.9	1.7×10^{-2}
120 mm PC front (fixed)	2.0	0.5	0	2.2	4.0×10^{-2}

Table 7. Summary of energy sources in residential and commercial buildings.

Harvester type	Typical range of ambient energy levels	Estimated electrical dc power	Calculated power density
Photovoltaic	Light intensity: 100 to 3700 lx	25 to 1149 μW	9 to 399 μW cm^{-3}
Thermal	Thermal gradient: 10 to 40 °C	1 to 10 mW	0.7 to 7.1 mW cm^{-3}
Periodic kinetic	Acceleration: 2.45×10^{-2} to 2.82 m s^{-2} Frequency: 43.1 to 162.3 Hz	0.008 to 68.97 μW	0.05 to 459.8 μW cm^{-3}
EM wave	EM wave strength: −74 to −29 dBm	0.028 to 944 nW	1.69×10^{-3} to 57.37 nW cm^{-3}
Airflow	Airflow speed: 1 to 10 m s^{-1}	0.9 to 324 mW	1.7×10^{-2} to 6.0 mW cm^{-3}

source and the speed of the airflow. The harvested power is comparatively high when the harvester is located at 0 cm compared to 10 cm. At 0 cm, for instance, 138, 204 and 324 mW dc power can be harvested from the Air Force air conditioner set to operate at low, medium and high fan speed, respectively. On the other hand, at 10 cm away from the same source, the power is 6, 44 and 104 mW at low, medium and high fan speeds, respectively. This is equivalent to power reduction by 95%, 78% and 68% at low, medium and high fan speeds, respectively. This suggests that the impact of the distance of the harvester from the wind source is more significant at lower airflow speeds than at higher speeds.

3.6. Summary of measurements

A thorough survey performed within residential and commercial buildings and presented in this paper has identified potential energy sources, and the levels of these sources have been used to estimate the amount of electrical power that can be harvested from these sources. A summary of these sources and their corresponding range of typical ambient energy levels, as well as the corresponding estimated output dc powers, are presented in table 7.

3.7. Implementation of energy harvesters in buildings

To successfully deploy energy harvesting technology into buildings a number of key parameters must be considered, these include

- the energy extraction electronics needed to efficiently extract energy from the harvester,
- the method of mounting the harvester so that it is able to harvest its source energy from the environment, and
- the impact of the harvester on the local environment due to its harvesting.

These areas will be discussed in the following sections for the main harvester technologies identified for use in buildings.

3.7.1. Energy extraction electronics and electrical interface. Photovoltaic devices modules used in buildings will typically produce a dc output voltage of a few volts. Whilst this may be sufficient for some low-power and low-voltage electronic circuits, in many cases it may be necessary to use a dc–dc convertor to provide a stable and suitable supply voltage to the functional circuitry. To maximize the efficiency of the photovoltaic device, dc–dc convertors with maximum power point tracking circuitry integrated into the device are commercially available.

Thermoelectric harvesters produce a dc output voltage with the level being a function of the number of thermocouple junctions and the thermal gradient across the device. In locations where the thermal gradient is low, the output voltage may be insufficient to operate the target electronics and will therefore require the use of a dc–dc boost convertor to increase the supply to the required level.

Energy harvesters for use with periodic kinetic energy sources use one of the two main transduction methods to generate an ac output voltage—piezoelectric: in this case a high voltage, low current, output needs to be rectified, smoothed, and then regulated down to the desired level; electromagnetic: in this case the output is typically lower voltage, higher current, requiring rectification and smoothing. As the output can be of the order of a few volts the rectification used needs to be selected carefully to minimize voltage losses.

Electromagnetic wave harvesters require circuitry to efficiently rectify the received RF energy and provide a dc output voltage. To maximize efficiency the receiver circuitry should be tuned to match the frequency range from which it is desired to harvest. RF energy harvesting modules are commercially available that have a tuned RF input and provide a regulated dc output.

Airflow energy harvesters provide an output which is typically an ac voltage with a frequency and amplitude dependant on the rotational speed of the device. In many cases it is sufficient to rectify and smooth this output to give a dc voltage for use with the target electronics, with the addition of voltage regulation if required.

3.7.2. Mechanical mounting and coupling. Mounting of photovoltaic devices within buildings is primarily a matter of affixing the device at a suitable location and angle such that the optimum amount of light is incident upon the active surface bearing in mind both natural and artificial sources of light.

Thermoelectric harvesting devices need to be mounted thermally onto their heat source. In the case of flat, ferrous, surfaces this can be achieved using magnets fitted into a thermally conductive base plate. For mounting onto curved surfaces such as pipework a machined, thermally conductive, clamp can be used to both support and provide a good thermal path. To further improve the thermal conductivity a thermal transfer compound can be used between the device, thermal source and mounting parts. To maintain the thermal

Table 8. Summary of each transduction mechanism.

Transduction mechanism	Calculated maximum power density	Advantages	Disadvantages
Photovoltaic	399 μW cm^{-3}	Well-established and known technology, simple to install	Needs to be installed in a visible location to give incident light
Thermal	7.1 mW cm^{-3}	Capable of harvested powers in the mW range	Needs mounting to a suitable source, many of which are likely to be seasonal in nature (such as heating radiators)
Periodic kinetic	459.8 μW cm^{-3}	Simple installation methods	Requires suitable sources such as plant equipment for the input energy
EM wave	57.37 nW cm^{-3}	Widespread availability of EM wave sources	Very low realizable harvested powers due to propagation losses as a function of distance between RF source and energy harvester
Airflow	6.0 mW cm^{-3}	Well-established and known technology, capable of powers in the mW range	Mounting may be intrusive and affect the distribution of the source airflow

gradient across the device a means of cooling the cold side of the device is needed. A common option is to use a heatsink to dissipate heat to the ambient air. This needs to be selected so as to maintain the temperature at, or as close to, ambient temperature as possible. An alternative approach is to mount the device between two items with defined temperatures, such as hot and cold water pipes.

Periodic kinetic energy harvesters are commonly attached to machinery to provide their input vibrational energy. A common means of achieving this attachment is the use of strong magnets, permitting reliable and ready mounting without the need to drill or cut machinery housings which could introduce mechanical weaknesses.

Electromagnetic harvesters require the RF harvesting antenna to be mounted in a location which will receive as much of the ambient RF energy as possible. Locating the aerial close to metallic objects that may screen it should be avoided.

To mount airflow harvesters the exact mounting technique used will depend on the nature of the source being utilized but it is desirable to orientate the harvester to provide direct air flow onto the device, rather than at an angle, to maximize the harvesting potential. To aid in this it may be desirable to use a shroud or funnel-shaped housing to channel the air flow into the harvester.

3.7.3. Impact on the local environment. The impact of photovoltaic harvesters on the environment local to their deployment is minimal, with their main impact being the space they take up. This can be minimized by using as small as photovoltaic module as practicable.

Thermal harvesters can impact their local environment to a small extent as they will absorb some of the thermal energy from their thermal source, which in many cases is likely to be heating radiators or pipework. If not fitting multiple harvesters in close proximity to each other this should, however, not provide a significant drain on the heating capacity in a given local and not impact significantly on the area's thermal comfort.

As energy harvesters operating from periodic kinetic energy are often deployed on vibrating machinery they may actually benefit their local environment, for example by reducing vibrations in metal covers and thus reducing noise.

Electromagnetic harvesters could impair RF-based communications passing through their locality if they harvest sufficient energy to cause signal degradation and possible loss of the communication channel.

Airflow-powered energy harvesters can affect their local environment by interrupting the flow of air, particularly if they are using air flows intended for ventilation as their source of energy.

4. Conclusions

This paper has reviewed potential energy sources available in buildings in both residential and commercial buildings that are suitable for energy harvesting applications. Table 8 provides a summary of each transduction mechanism's power density and the advantages and disadvantages.

Five main categories of power source have been identified, namely photovoltaic, thermoelectric, kinetic, EM and airflow. The dc power levels summarized in table 7 (up to 1149 μW, 10 mW, 68.97 μW, 944 nW and 324 mW from photovoltaic, thermal, periodic kinetic, EM and airflow, respectively) are sufficient, in some cases (for example: photovoltaic, thermal and airflow), for practical applications, for example, powering low-power electronic systems such as wireless sensor networks. Nevertheless, it is important to point out that the power from many of the surveyed sources is not continuously available, with daily and/or seasonal variations in availability, so careful selection of suitable ambient energy sources for the specific deployment location and target application has to be made when the energy harvesting system is being designed. Estimated daily durations of energy availability and the corresponding overall availability duty cycle are given in table 9.

From these identified energy sources the most practical energy harvesting source identified within the buildings surveyed is light due to its widespread availability. The typical light intensity from the measurements carried out ranges from 100 to more than 3700 lx, this gives, with the assumed size of indoor specification solar cell, a range of approximately 25 to 1150 μW, respectively, of output power.

Table 9. Example estimated energy source duty cycles.

Transduction mechanism	Estimated average daily availability	Energy source duty cycle	Source location and assumptions
Photovoltaic	16 h	67%	Assuming a combination of natural (8 h a day) and artificial lighting (8 h an evening)
Thermal	9 h	38%	Using heating system as source: 16 h per day for 6 months during winter and 2 h per day for 6 months during summer
Periodic kinetic	1.85 h	8%	Using domestic appliances as sources: 6 h washing/drying per week and 1 h per day cooking
EM wave	24 h	100%	Assuming constant transmissions from external sources such as TV stations
Airflow	7 h	29%	Using cooling system as source: 14 h per day for 6 months during summer

However, the light intensity observed varies very much based on the type of the building and the use of the particular area. The intensity can be as low as 0 lx, as was observed in the residential bathroom and in excess of 2000 lx in a well illuminated office in a commercial building. The illumination levels found in the commercial buildings were also over a wider range than those observed in the residential properties, with typical levels away from sources of natural light of the order of 500 lx. This is in part attributable to the Polish building regulations which stipulate that office lighting should be at a minimum level of 500 lx. This is the case in many of the locations surveyed, however in some locations users, particularly computer users, preferred to work in lower light levels so do not use the full installed lighting capacity and also use blinds to reduce the natural light, and therefore the designed level of illumination cannot be assumed to be present in all situations.

Given the range of light intensities observed it would be desirable to use indoor specification solar cells for their increased sensitivity at low light levels and their compatibility with the output spectra of the artificial lighting sources used in the office developments. The light levels observed are also subject to the weather, time of the day, and the type of artificial light used. Generally, it is more likely to harvest a significant amount of power in rooms illuminated using both natural and artificial light than those with only artificial light, as the measurements showed that light intensity in naturally illuminated rooms can be of the order of 15 to 50 times larger than those solely illuminated by artificial light. This suggests that in some indoor locations we can harvest more energy from indoor natural light than from artificial light.

Due to the lower light levels that are found away from exterior windows it may also be necessary to use solar cells designed for use in indoor conditions to provide sufficient sensitivity to harvest useful levels of power. The location of, and therefore the level of incident illumination on, the solar module needs to be taken into consideration when selecting either indoor or outdoor modules, this is as indoor modules are typically specified for use up to illumination levels of the order of a few 1000 lx and degradation of their properties can occur when subjected to higher illumination levels over a period of time [27]. Therefore, paradoxically, it may be necessary to use an outdoor specification solar module indoors to provide a device that will operate at the higher illumination levels that may be encountered in the vicinity of a window permitting the entry of natural light from outside the building.

Some of the locations surveyed had thermal sources available in the form of heating pipework and radiators. Within the domestic locations temperature differences with respect to ambient air temperature (typically 21 °C) ranging from 10 to 40 °C were measured from the surface of the radiators and hot water pipes. These temperature differences can give dc powers in the range of 1 to 10 mW. However, the energy from these sources is only available when the radiators are turned on or when hot water is flowing through the pipes. Some thermal sources were identified in some of the commercial building areas examined; however, due to the preference for using ceiling mounted fan-coil units in office spaces to enable flexible use of the floor space there are limited exposed or readily accessible thermal sources such as HVAC pipe work so mounting of a thermal harvester may prove difficult or impossible.

Periodic kinetic energy sources that are available in residential building are mainly in the form of vibrations from microwave, refrigerator, washing machine, central heating boiler and tumble drier. Commercial buildings are also fitted with central boiler/heating systems and some have microwaves. Most of these units generate vibrations with accelerations in the range of 2.45×10^{-2} to 2.82 m s^{-2} and have vibrational frequencies in the range of 43.1 to 162.3 Hz. The estimated output power was in the range of 8.08×10^{-3} to 68.7 μW. The major disadvantage of harvesting energy from these sources is that the energy availability is dependent on the intermittent usage of the units.

The received signal strength observed during the measurements of EM power was in the range of −72 to −29 dBm which gives a dc output power ranging from 27 pW up to about 1 μW, assuming a conversion efficiency of 70% for the harvester. The main advantage of harvesting power from EM sources is that the power is usually continuously available because most communication base stations and TV and radio transmitters operate continuously. However, the effective power from these transmitters decreases exponentially with distance from the source. This leads to low-power levels which are sufficient for communications purposes, but in many cases unusable for practical energy harvesting applications. Furthermore, the use of existing RF transmissions as the source of the energy entails the interception of communications which has moral and legal implications, so for successful use a dedicated, purpose provided, constant source of EM energy needs to be considered.

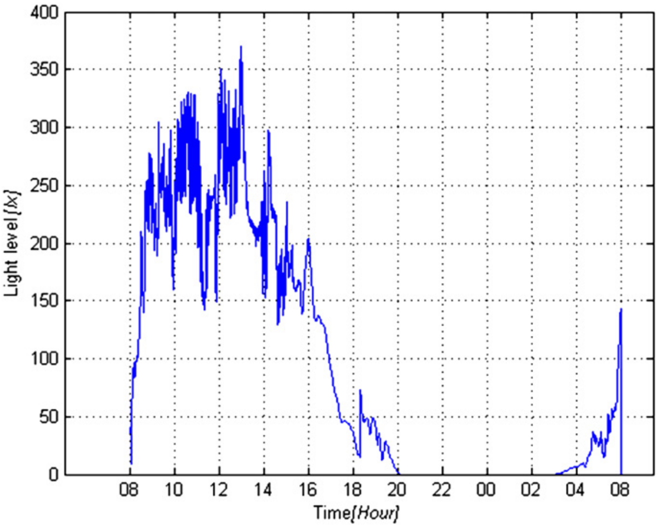

Figure A1. Light level measurements taken in living room on 2 June 2012.

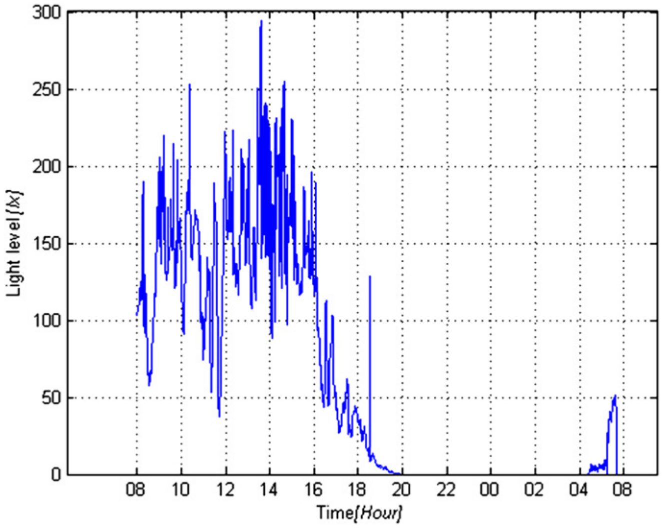

Figure A2. Light level measurements taken in kitchen on 3 June 2012.

Energy can be harvested from airflows where these are available with sufficient velocity, necessitating location of the harvester device in locations such as within HVAC air circulation ducting, where a predictable airflow is available, for comfort reasons many other airflows within occupied building spaces are avoided. From the air speeds measured, it was estimated that (based on numerical calculations) the output power can range from 0.9 to 324 mW at airflow speeds of 1 to 10 m s^{-1}, respectively. Again, however, the power will only be available to harvest from these sources when the air circulation units are in operation.

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Appendix A. Detailed light level measurements

A.1. Residential apartment, Southampton, England—living room

Figure A1 shows the light level measurements taken over a period of 24 h on 2 June 2012.

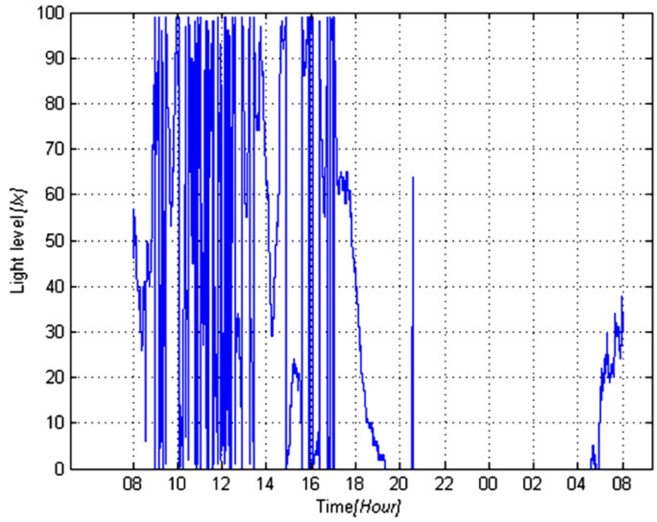

Figure A3. Light level measurements taken in bedroom on 1 June 2012.

The maximum light level was 369.8 lx at about 13:30 and the mean light level over 24 h was 94.35 lx with a standard deviation of 105.88 lx. From 21:00 until 04:30 the light level was 0 lx.

A.2. Residential apartment, Southampton, England—kitchen

Figure A2 shows the light level measurements taken over a period of 24 h on 3 June 2012.

The maximum light level was 294 lx at 15:00 and the mean light level over 24 h was 60 lx with a standard deviation of 71 lx. From 21:00 to about 05:30 the light level was 0 lx.

A.3. Residential apartment, Southampton, England—bedroom

Figure A3 shows the light level measurements taken over a period of 24 h on 1 June 2012.

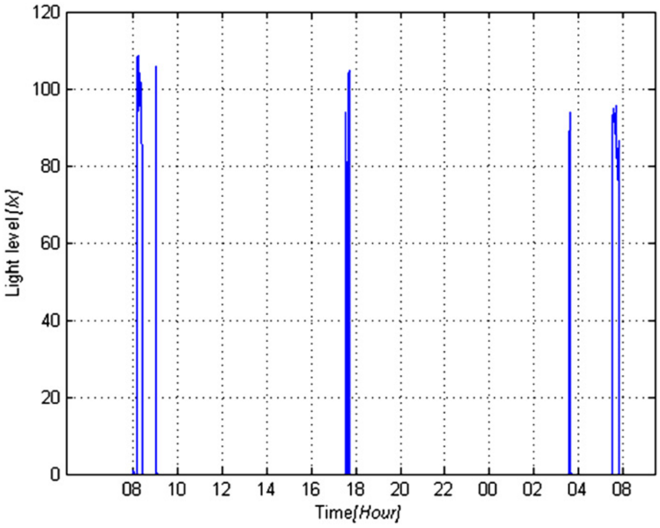

Figure A4. Light level measurements taken in bathroom on 4 June 2012.

The maximum light level was 98 lx and the mean light level was 26.12 lx, with a standard deviation of 32.6 over a 24 h period. The light level was 0 lx from 20:30 to 05:45 with a spike of 60 lx at 21:30.

A.4. Residential apartment, Southampton, England—bathroom

Figure A4 shows the light level measurements taken over a period of 24 h on 4 June 2012.

The bathroom did not have any windows that could allow illumination from natural light. The visible peaks at around 8:00, 18:00, 5:30 and 08:00 are caused by light from the room light which was turned on at these times. The maximum light level from the artificial light was 108 lx and the rest of the time, the bathroom was in total darkness, and the light levels were 0 lx. This mean over the 24 h period was 2.7 lx with a standard deviation of 15.4 lx.

A.5. Residential apartments, San Sebastian, Spain—living areas

Solar energy levels were found to typically range from 70 to 200 lx away from external windows, with higher levels, typically of the order of 1500 lx, adjacent to the windows.

A.6. Commercial offices, Warsaw, Poland—smaller, single occupancy offices

Within the smaller offices, typically occupied by one or two people, light levels away from sources of natural light (exterior windows) were in the range of 200 to 800 lx. Closer to the exterior windows the recorded levels increased to between 1700 and 2400 lx.

A.7. Commercial offices, Warsaw, Poland—larger, open plan offices

In the larger open plan offices, typically occupied by 10 to 15 people, light levels away from sources of natural light were in the range 200 to 900 lx. Where natural light was present from exterior windows the recorded levels increased to between 1300 and 2200 lx.

A.8. Commercial offices, Warsaw, Poland—corridor and reception areas

Within the corridor and reception type areas, in areas which did not have windows providing natural light, the light levels ranged from 150 to 300 lx. In areas which had natural light, for instance the glass atriums found in some buildings, the range of illumination levels increased to between 450 and 7500 lx.

Appendix B. Detailed RF energy measurements

B.1. 9 kHz to 3.6 GHz frequency range

Because of the wideband spectrum of the antenna, the received signal power from each band was lower than that which was obtained when using a suitable antenna for each individual frequency band (as will be presented subsequently). Regardless of this discrepancy, it gives a clear picture of the entire frequency spectrum and the maximum power for each band. In addition, other signals from frequency bands such as DAB radio stations [175 to 230 MHz] and TV stations [420 to 854 MHz], that we did not measure, could be revealed. This is shown in figure B1, and all peaks are marked with their corresponding bands/services.

B.1.1. FM radio (88 to 108 MHz) frequency band. Figure B2 shows the received RF signal power in the FM radio frequency band.

The maximum power received by the antenna during the experiment was −66.96 dBm at 100.3 MHz. The overall mean and standard deviation of the measurements were −88.82 and 5.6 dBm, respectively.

B.1.2. GSM 900, GSM 1800 and 3G/4G frequency bands. Figure B3 shows the received RF signal power in the GSM 900 frequency band, figure B4 shows the same for the GSM 1800 band and figure B5 for the 3G/4G band.

The maximum received RF power and the corresponding frequency were −28.7 dBm at 955.6 MHz for GSM 900, −63.5 dBm at 1821 MHz for GSM 1800 and −48.4 dBm at 2130 MHz for 3G/4G. The mean power of these measurements were −72, −82.6, −81.6 dBm and their corresponding standard deviations were 14.5, 4.1 and 5.6 dBm, respectively. According to the Ofcom frequency allocation scheme [90], the frequencies corresponding to the maximum signals are within the downlink transmission range, that is, the transmission from the base station to the mobile station, this means the strongest signals from each band were not from the mobile terminals, this is to be expected due to the lower powers used by handsets to mitigate any health issues and to extend the device battery life.

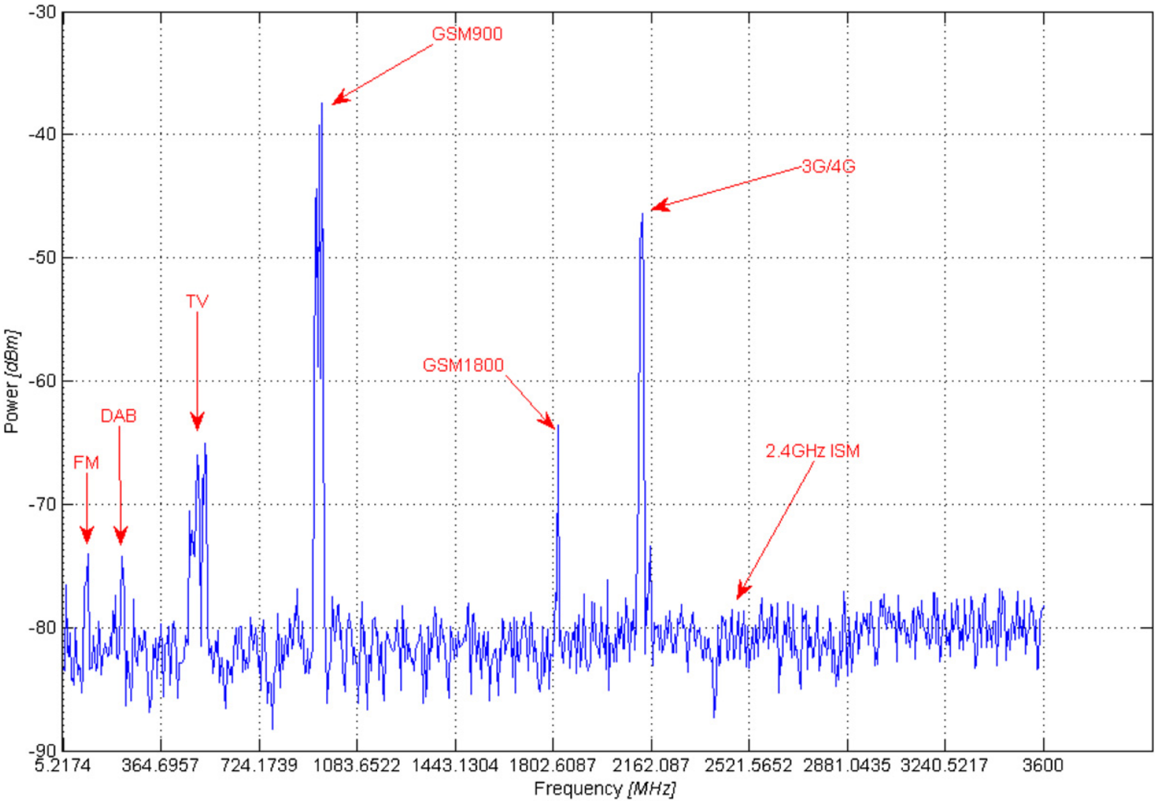

Figure B1. Received signal power over 9 kHz to 3.6 GHz frequency range.

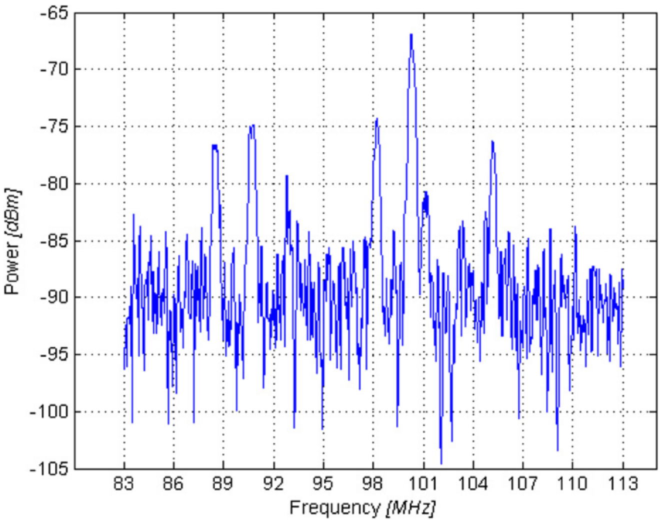

Figure B2. Received RF signal power in the FM radio frequency band.

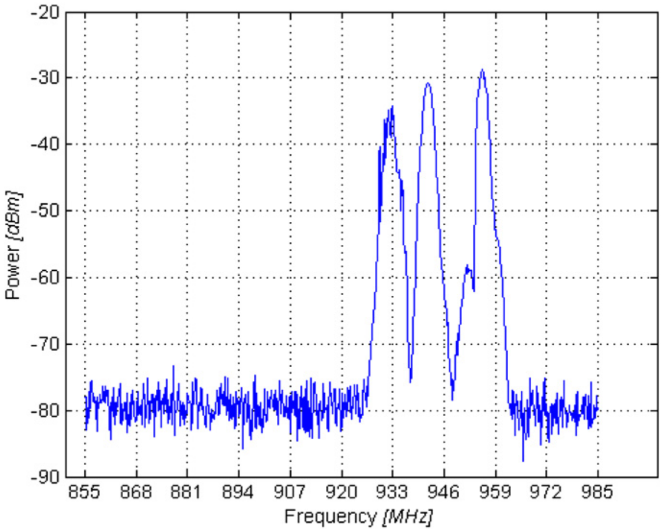

Figure B3. Received RF signal power in the GSM 900 frequency band.

B.1.3. 2.4 GHz ISM frequency band. Figure B6 shows the received RF signal power in the 2.4 GHz ISM radio frequency band.

Despite the presence of multiple Wi-Fi access points in the building the tests were performed in (a university office and laboratory building), the received RF signal power was relatively low in this band. The maximum power was −76.5 dBm at 2467 MHz which corresponds to Wi-Fi channel 12. The mean power was −82.9 dBm with a standard deviation of 2.6 dBm. We further checked the received signal power using a Wifi Analyzer [91] application installed on an android smart phone, which is used to analyse the available access points in the vicinity of the smart phone and their signal strength, and the signal strength reported was −74 dBm.

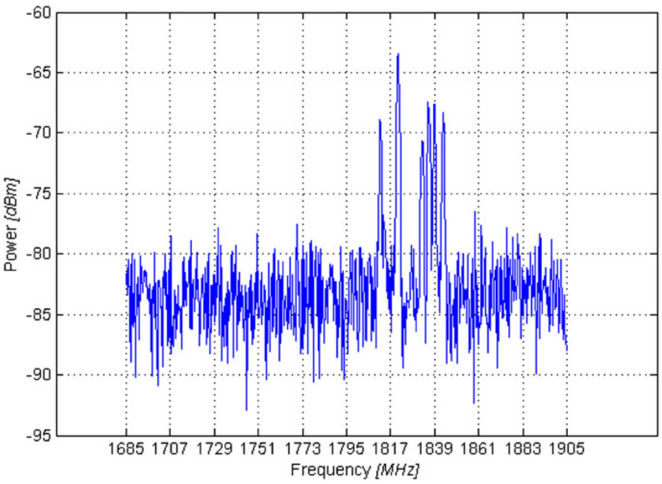

Figure B4. Received RF signal power in the GSM 1800 frequency band.

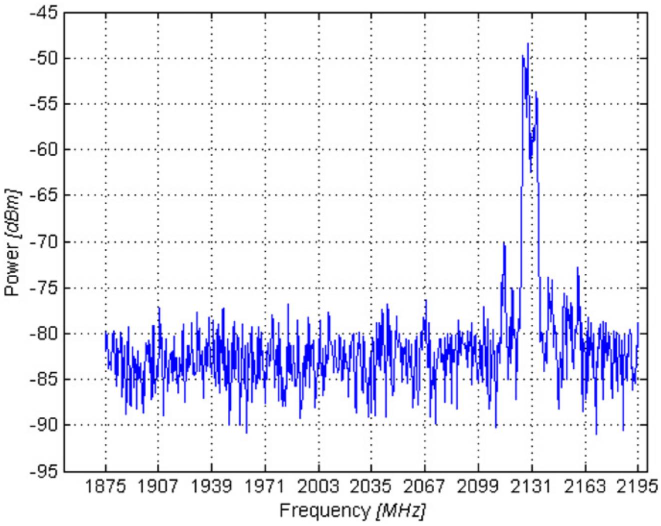

Figure B5. Received RF signal power in the 3G/4G frequency band.

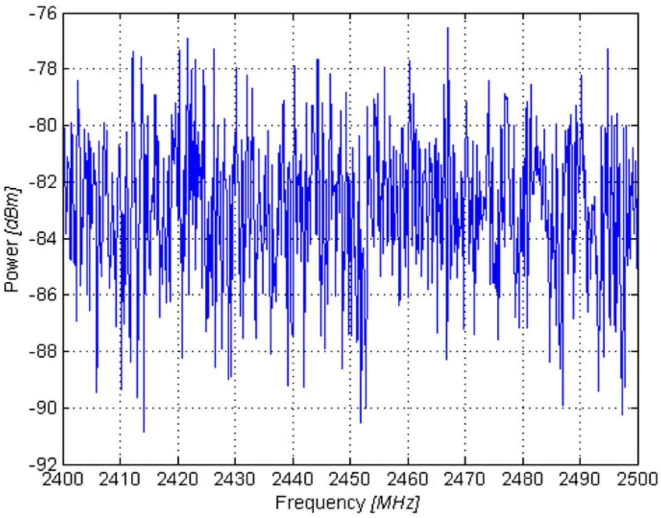

Figure B6. Received RF signal power in the 2.4 GHz ISM frequency band.

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