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Energy Scavenging for Long-Term Deployable Wireless Sensor Networks

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Abstract

The coming decade will see the rapid emergence of low cost, intelligent, wireless sensors and their widespread deployment throughout our environment. While wearable systems will operate over communications ranges of less than a meter, building management systems will operate with inter-node communications ranges of the order of meters to tens of meters while remote environmental monitoring systems will require communications systems and associated energy systems that will allow reliable operation over kilometers. Autonomous power should allow wireless sensor nodes to operate in a "deploy and forget" mode. The use of rechargeable battery technology is problematic due to battery lifetime issues related to node power budget, battery self discharge, number of recharge cycles and long-term environmental impact. Duty cycling of wireless sensor nodes with long "SLEEP" times minimises energy usage. A case study of a multi-sensor, wireless, building management system operating using the Zigbee protocol demonstrates that, even with a 1 minute cycle time for an 864 milli-second "ACTIVE" mode, the sensor module is already in SLEEP mode for almost 99% of the time. For a 20 minute cycle time, the energy utilisation in SLEEP mode exceeds the ACTIVE mode energy by almost a factor of three and thus dominates the module energy utilisation thereby providing the ultimate limit to the power system lifetime. Energy harvesting techniques can deliver energy densities of 7.5 mW/cm^2 from outdoor solar, 100 μW/cm^2 from indoor lighting, 100 μW/cm^3 from vibrational energy and 60 μW/cm^2 from thermal energy typically found in a building environment. A truly autonomous, "deploy and forget" battery-less system can be achieved by scaling the energy harvesting system to provide all the system energy needs. In the building management case study discussed, for duty cycles of less than 0.07 % (i.e. in ACTIVE mode for 0.864 seconds every 20 minutes), energy harvester device dimensions of approximately 2 cm on a side would be sufficient to supply the complete wireless sensor node energy. Key research challenges to be addressed to deliver future, remote, wireless, chemo-bio sensing systems include the development of low cost, low power sensors, miniaturized fluidic transport systems, anti-

bio-fouling sensor surfaces, sensor calibration, reliable and robust system packaging as well as associated energy delivery systems and energy budget management.

Keywords: wireless sensors, energy harvesting/scavenging, building management systems, remote environmental monitoring.

1. Introduction

The coming decade will see the rapid emergence of low cost, intelligent, wireless sensors and their widespread deployment throughout our environment. This sensor-rich world, referred to as “Ambient Intelligence” or “Smart Environments”, will be based on smart electronic systems or wireless sensor network technologies. It will have millions of sensors embedded throughout our environment and it will dramatically improve the quality of peoples’ lives in terms of our environment, health and well-being, security, comfort, education and entertainment

Chemo-biosensing using wireless sensor systems is being investigated across a broad range of applications including environmental monitoring of the external environment (i.e. remote environmental monitoring of the quality of air, water and ground soil including precision agriculture) [1], [2], [3] the built environment (building energy management and occupant comfort, safety and security) [4], automotive (i.e. for safe and efficient motoring), aeronautical/aerospace (i.e. for safety and security) [5] and in both wearable (i.e. physiological monitoring and fitness) [6] and in-vivo (i.e. smart pills, catheters and implants) applications.

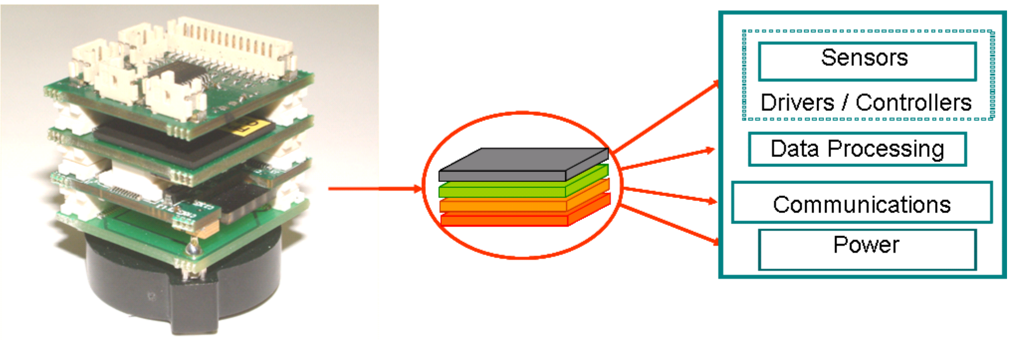

Figure 1: Photograph and schematic of Tyndall 25mm wireless sensor module.

A typical wireless sensor module consists of a number of functional blocks which include sensors, data acquisition, microcontroller for control and signal processing, an RF transceiver for wireless communications and a power source. In some cases, where local signal processing is required, a DSP chip (digital signal processing) or FPGA (field programmable gate array) may also be used. Most existing systems contain a power source which consists of a standard primary battery or a rechargeable battery. In the case of wireless chemo-bio sensing systems, extra operational and functional issues arise due to the need for many sensor types to be in direct contact with the fluid being monitored, introducing issues of fluidic transport, sensor fouling, drift and calibration.

Remote monitoring applications require reliable and extended lifetime deployments of potentially a very large number of wireless sensor nodes. As hardware becomes cheaper and smaller, more of these applications are likely to appear, particularly as these miniaturised nodes offer the opportunity for the electronics to be embedded unobtrusively into everyday objects. A key issue for these wireless node designs is that they achieve high degrees of power-efficiency for autonomous, maintenance-free operation, where it is likely that nodes will require deployment for periods of years since the cost of battery replacement will be prohibitive and impractical. This can effectively be described as a “deploy and forget” scenario.

At first glance, batteries appear to offer the optimum source of energy for wireless sensor systems with commercial battery technologies offering significant energy capacities in relatively small form-factors. The principle trend in battery technology is towards higher energy densities, which has obvious advantages for portable equipment where increasing time between charges and miniaturisation of system size are important drivers. However, energy density is not necessarily the critical factor for the choice of battery technology for a wireless sensor node in a “deploy and forget” application. In such a case, battery characteristics such as lifetime, self discharge rate and, if charging from a renewable energy source such as solar, the number of allowable charge cycles, are perhaps more important then energy density or capacity.

For example, self discharge rates for batteries vary from, 30 % per month for Nickel Metal Hydride (Ni-MH) to 2 – 3 % per month for Lithium batteries. Therefore, for a typical wireless sensor node with low energy consumption and long duty cycle operation, the self discharge rate of the battery could exceed the discharge due to the system consumption. For rechargeable batteries, the battery lifetime, measured in charge cycles, varies from approximately 500 cycles for NiCd, NiMH, and Li-ion to approximately 300 for Li polymer. Thus, for example, if battery re-charging from a solar cell is used, and a charge cycle is completed in a day, the lifetime may be limited to 500 days or less than 18 months. Furthermore, another issue that is not well characterised is the impact on battery lifetime of temperature variations and other environmental conditions in the end-use application, which can significantly undermine the long-term reliability of the battery technology. Considering these factors it may be seen that, in a "deploy and forget" scenario, regardless of whether some form of battery recharging can be implemented, the battery performance and reliability is still likely to limit the lifetime of the wireless sensor node**.**

This "deploy and forget" nature of wireless sensor systems effectively results in the energy available to the system being constrained by the initial energy capacity of the battery and the unpredictable lifetime performance of the battery. This has driven the development of approaches to maximise wireless sensor system lifetime through minimising energy usage by employing ultra-low power sensors, electronics and wireless communications and through the use of duty cycling based on long sleep times (i.e. the wireless system remains in a low power SLEEP mode for greater than 99% of the time). Thus the sensor node components will be active only for the time required to perform the operations of sensor sampling, data processing and wireless data transmission or communication. In this duty-cycle mode of operation, it is appropriate to refer to energy utilisation in joules and not power consumption in watts as we are concerned with the lifetime of the power system delivering energy (i.e. the product of the component operating mode power and the time the component spends in that mode) and the energy utilisation, or energy budget, of the various components of the wireless system.

Given the above limitations of battery technology and the resulting potential incompatibilities of conventional batteries with wireless sensor systems, significant research is ongoing to deliver power from the environment using energy scavenging or harvesting techniques such as vibration/motion, thermal gradients and solar energy which can deliver energy directly to the wireless sensor load or to a storage element such as a rechargeable battery or capacitor.

This paper addresses some of the key issues relating to the delivery of autonomous power for wireless sensor systems. Section 2 initially provides a summary review of research and development into wireless sensor nodes and then presents a summary review of the major energy scavenging techniques and the levels of available energy which can be harvested from the environment. In section 3, we present a case study for a wireless sensor deployment in a building management application in order to illustrate the energy budget requirements of a typical wireless node operating using the Zigbee protocol. We then discuss the potential lifetime of the wireless sensor system by undertaking a comparison of a battery-driven scenario with systems supported by a range of energy-harvesting techniques. In Section 4, a case study is presented of the energy requirements for a wireless sensor module in a remote environmental monitoring scenario. Finally, in Section 5, we look to the future and consider the opportunities and challenges for remote wireless, chemo-biosensing systems.

2. State-of-the-Art

2.1 Wireless Sensor Modules:

Wireless sensor nodes (typically called motes) have recently become available commercially from a number of start-up companies, mainly US-based. These include Crossbow [7], Moteiv [8], Dust [9], Phidgets [10], Meshnetics [11], Sensicast [12], AccSense [13], Millennial Net [14] and Ember [15]. These first generation products have been used in developmental test-beds, however, the demonstrated deployments have typically low numbers of nodes and do not address real-world issues of scalability, network robustness and quality of service [16].

A number of research groups are developing motes to address specific research challenges in sensor networks such as algorithm testing, power management, antenna miniaturisation and wireless range improvements. Increasingly, the motes are also being designed for specific applications, including environmental monitoring, building energy monitoring, e-health and animal tracking. Active research groups include Tyndall National Institute [17], Fraunhofer-IZM [18], IMEC [19], Harvard [20], Imperial

College London [21], the Centre for Embedded Networked Sensing at UCLA [22], UC Berkeley [23], Lancaster University [24], ETH Zurich [25], MIT [26], Sandia National Laboratories [27], Yale [28], EPFL [29] and companies such as Intel [30] and Philips [31].

Advanced mote research into miniaturised and robust hardware configurations and 3D packaging of motes, using stacked PCBs or silicon, is being carried out at Tyndall National Institute [17], Fraunhofer-IZM [18] and IMEC [19].

2.2 Harvesting of energy from the environment

In order to provide an autonomous source of energy for the wireless sensor system, one can consider extracting energy from the environment in order to augment the battery energy storage or indeed replace it. A comprehensive review of the many possible sources of energy which could potentially be harnessed is given in [32], [33]. Among the more feasible, for which promising results have already been achieved, is the extraction of power from solar energy, from thermal gradients and from vibrations and movement. In the review which follows, the energy harvesting techniques are not exhaustively reviewed as such detailed reviews are available elsewhere. The objective of this review is to determine typical values for the energy levels which can be harvested from the various techniques, so that these values can be used in Section 3 to assess the feasibility of using energy harvesting to power a typical wireless sensor node.

2.2.1 Solar Power

The use of ambient light to generate power is well established, with solar powered calculators and wristwatches being popular for several decades. The power available from solar cells varies widely depending on the illumination level (e.g. indoors or outdoors) and on the solar cell technology. The efficiencies of various solar cell technologies at different illumination levels have been reported in [53]. For a typical outdoor illumination level of 500 W/m^2 (bright, sunny day in Ireland) efficiencies vary from approximately 15 % (for polycrystalline silicon and Gallium Indium Phosphide) to 2 – 5 % for amorphous Silicon cells. For typical indoor illumination levels of 10 W/m^2, efficiencies vary from approximately 10% for crystalline silicon and Gallium Indium Phosphide, to approximately 2% for amorphous Silicon. Therefore, in order to assess the feasibility of solar energy harvesting for powering wireless sensor nodes, we will assume a typical power density of 75 μW/mm^2 for outdoor solar cell operation and a typical power density of 1 μW/mm^2 for indoor operation.

2.2.2 Thermal Energy Harvesting

Harvesting of energy from heat sources (such as the human body) can be achieved by the conversion of thermal gradients to electrical energy using the Seebeck effect. Many such large scale devices exist, for example, for the generation of electricity from hot exhausts on vehicles. At a smaller scale, the main interest has been in the generation of power from body heat, as a means to power wearable devices. For example, Seiko have produced a wrist watch powered by body heat [54]. Reported results for power densities achieved from micro-fabricated devices are 0.14 μW/mm^2 for a 700 mm^2 device [55], 0.37 μW/mm^2 for a 68 mm^2 device [56] and 0.60 μW/mm^2 for a 1.12 mm^2 device [56] All these results relate to a temperature gradient/difference of 5K, which is typically achievable for wearable applications. Higher temperature differences may be achievable in other environments, e.g. heaters in a building, and in that case the assumed power density can in principle be scaled by the square of the temperature difference.

2.2.3 Energy from vibration and movement

Ambient vibrations are present in many environments, such as automotive, buildings, structures (bridges, railways), industrial machines, household appliances, etc. The energy present in the vibrations can be extracted using a suitable mechanical-to-electrical energy converter or generator. Generators proposed to-date use electromagnetic, electrostatic or piezoelectric principles.

The majority of electromagnetic generators make use of Faraday's law of electromagnetic induction. The energy in the environmental vibration is used to make a magnetic mass move relative to a coil, thus inducing a voltage and causing a current to flow in the attached electrical load. Piezoelectric generators make use of the piezoelectric properties of some materials which develop a voltage when stressed. The vibration is used to stress the piezoelectric element, thus developing a voltage which can be extracted as electrical energy. Electrostatic generators generally make use of the vibrational energy to pull apart the plates of a charged capacitor, against the force of electrostatic attraction, thus converting the vibrational energy to energy stored in the capacitor’s electric field.

Detailed reviews of recent work in the area of vibrational energy harvesting have been conducted elsewhere [34],[35], and the reader is referred to these works for a thorough discussion of the different types of generator which have been developed. Here we restrict ourselves to summarising the important results from the work to-date.

From the theory of the resonant vibrational generator, where a spring mounted mass, m, is made to vibrate at its mechanical resonant frequency, the maximum power generated, P, can be expressed as;

$$P = \omega^3 m Y^2 / 4\xi \qquad (1)$$

Where ω is the angular frequency of vibration and is assumed equal to the mechanical resonant frequency of the system, m is the moving mass, Y is the amplitude of the vibrating source, and ξ is the damping ratio which consists of useful damping due to the extraction of electrical power and parasitic damping due to mechanical damping in the structure. Making use of the fact that for a sinusoidal source vibration, the amplitude of the acceleration, a, can be written as $\omega^2 Y$, then the above equation can also be re-written as:

$$P = m a^2 / 4\xi\omega \qquad (2)$$

This highlights the fact that the generated power is proportional to the moving mass and the square of the acceleration. The graph in Figure 2(a) summarises the levels of power generation which have been reported in the literature to-date [36]-[48]. Note that the results from the various different generation techniques can only be validly compared if the reported generated power is normalised by the square of the input acceleration. Therefore the graphs in figure 2(a) and 2(b) plot the reported power generated, normalised to an acceleration of 1m/s^2.

We can see from the graph that generated power levels generally increase with device volume, indicating that power levels are directly proportional to the volume of the device. In large devices of approximately 100cm^3 volume, power levels of 10mW have been achieved (normalised to 1 m/s^2 acceleration) and for small devices with a volume of less than 0.01 cm^3, power levels are less than 10nW (again normalised to 1 m/s^2 acceleration). Such smaller devices could be batch fabricated using micro-fabrication techniques, and this is a desirable goal from the point of view of cost reduction.

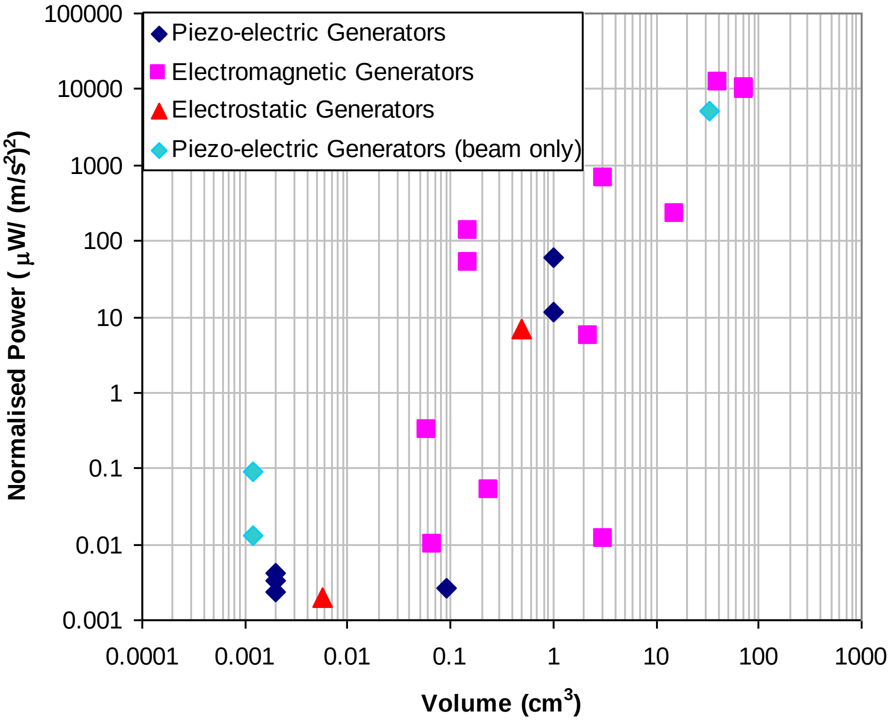

Figure 2(a): Power density of reported vibrational generators normalised to (1 m/s^2)^2 .

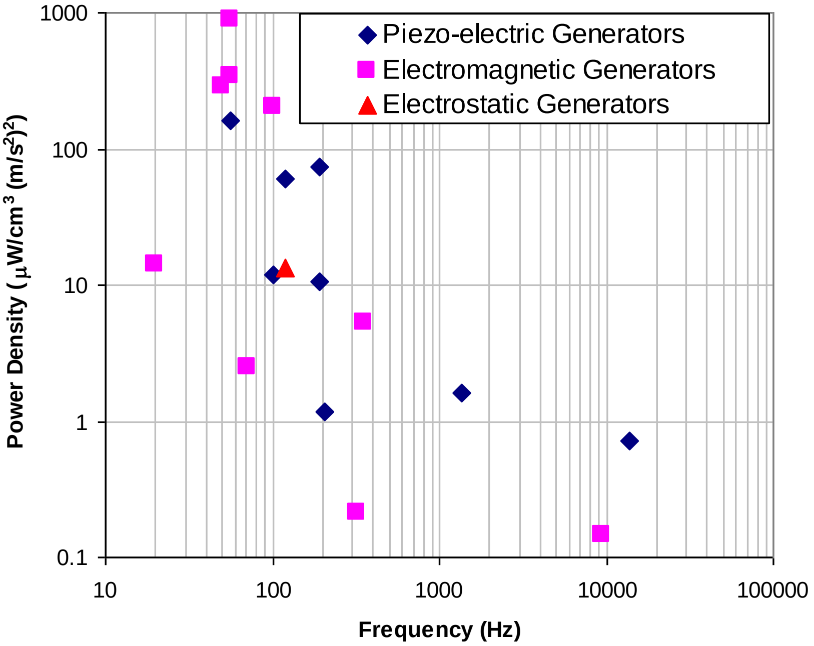

Figure 2 (b): Power density of reported vibrational generators vs. the frequency of operation. Note the decrease in power density with frequency.

However it is also worth noting that very few of the reported devices have been fully micro-fabricated. In general micro-fabrication is more suitable for electrostatic devices and piezoelectric devices than for electromagnetic devices as it can be shown that the scaling laws dictate that microfabricated electromagnetic devices are difficult to operate at optimum conditions [49].

The devices for which the results are summarised in 3(a) have mostly been designed to operate at a very specific frequency. Although equation (1) indicates that the power generated is proportional to the cube of the frequency, this does not account for the fact that, in practical situations, displacements are much smaller at higher frequencies. Thus a more practical analysis is suggested by (2) which indicates that for a fixed acceleration level, the generated power is inversely related to frequency. In fact this is borne out by an analysis of the results reported to date, which show a decrease in generated power with frequency as shown in figure 2 (b).

It should also be noted that the majority of the piezoelectric and electromagnetic generators reported to-date are resonant devices, i.e. the natural resonant frequency of the generator is matched to the vibration frequency, so that the displacement of the generator mass can be maximised. At resonance the displacement of the mass is limited only by the damping, which is composed of useful and parasitic damping. This leads to the situation where maximum energy can be extracted where the parasitic damping is a minimum. However such a device with very low parasitic damping will have a very narrow frequency band and very sharp resonance. In practice, this means that if the resonant frequency of the generator should shift or the frequency of the vibration change, then the generated power decreases drastically. In practice, a generator which has a more broadband response would be of greater practical use. However there are, to-date, very few reports of such devices in the literature.

To the best of the authors' knowledge, the highest, normalized power density which has been achieved, is approximately 880 μW/cm^3, reported in [48]. This device, shown in Figure 3, had a volume of 150 mm^3 and achieved a power level of 45 μW, for a 0.6 m/s^2 acceleration at 50 Hz.

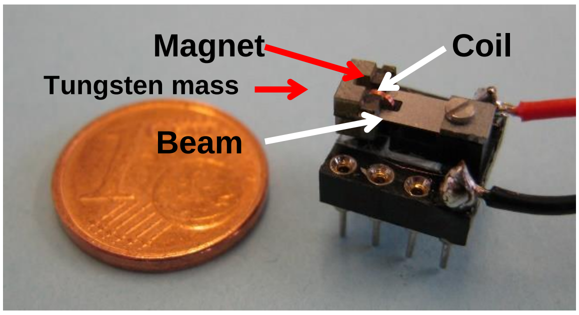

Figure 3: An electromagnetic-based vibration generator which has delivered approximately 880μW/cm^3, the highest energy density reported for a vibrational energy harvesting device [48]. This device, with a volume of 150mm^3, achieved a power level of 45μW, for a 0.6m/s^2 acceleration at 50Hz.

Optimistically, and considering that improvements are possible, a power density of 1 mW/cm^3 @ 1 m/s^2 may be achievable for vibration-based generators. Taking into account the fact that real world generators will probably require a more-broadband operation than the majority of devices reported to-date, and that this broadband response is achieved at the expense of power density, a more conservative estimate of the achievable power density might be 0.1 mW/cm^3 @ 1 m/s^2. Considering this, a quick assessment of the feasibility of vibrational energy harvesting for any particular application can be made if the vibration acceleration levels, and the allowable size of the final solution, are known. Some applications such as powering of tyre pressure sensors are entirely feasible based on this, as the acceleration levels present in such an application can be very high (tens of g). Applications with very low acceleration levels, for example industrial machine monitoring (0.6 m/s^2) are feasible if the volume of the device can be sufficiently large, e.g. > 1000 mm^3 in order to supply several hundred μW. The key challenges to be addressed are widening of the bandwidth of the device and a greater understanding of the parasitic damping issues so that the overall power densities can be improved.

2.2.4 Power from Human movement

Although not directly relevant to remote sensing, we include short review of human-powered energy harvesting systems which have relevance to on-the-body environmental monitoring in the form of wearable physiological monitoring systems. Compared to vibrations, human movements are generally characterised by large amplitude and high acceleration levels but very low frequency or, more generally, non-periodic. For example, acceleration levels of up to 100 m/s^2 at frequencies of 2 Hz have been measured for positions on the foot while jogging. The extraction of energy from human movement is far from new. Perhaps the most successful examples of such energy extraction are the self-powered watches of which the Seiko Kinetic and the ETA Autoquartz [32] are the best modern examples. Apart from these wrist watches, the most researched area is the extraction of energy from walking. For example, it has been calculated that up to 7 W of power is available per foot for the average human walking. Several examples of generators which convert walking motion have been reported. These range from approaches which use shoe-mounted, conventional rotary generators [50] and linear generators [51], hydraulics coupled to piezoelectrics [52] and electroactive polymers [32] and piezoelectric sole inserts [50]. The highest power actually achieved to date from any of these approaches has been in the range of 0.2 – 0.8 W, so that there is still significant room for improvement.

	Conditions	**Power density**	**Area or volume**	**Energy/day**
Vibration	1 m/s^2	100 μW/cm^3	1 cm^3	8.64 J
Solar	Outdoors	7,500 μW/cm^2	1 cm^2	324 J (assuming light is available for 50% of the time)
Solar	Indoors	100 μW/cm^2	1 cm^2	4.32 J (assuming light is available for 50% of the time)
Thermal	Δ T = 5^{0}C	60 μW/cm^2	1 cm^2	2.59 J (assuming heat is available for 50% of the time)

Table 1: Typical data for various energy harvesting techniques that can be used for remote wireless environmental sensing.

We conclude this review by summarising, in Table 1, the typical power density levels which are achievable from the various energy harvesting techniques that can be used for remote wireless environmental sensing. These power densities are used to calculate energy levels available over the course of a single day assuming, in the case of solar and thermal energy, that the light or heat source is only available 50 % of the time. In the later sections, these values are used to illustrate the potential impact that energy harvesting techniques can have on wireless sensor node lifetimes.

3. Wireless Sensor Deployment Case Study in Building Management

In order to illustrate the energy requirements for wireless sensor systems, we present, in case study form, the analysis of a wireless sensor operating using the Zigbee protocol in a wirless building management application [59]. The ZigBee standard is a low-power, wireless communications standard defined by the ZigBee Alliance. The intended applications of the ZigBee standard are home and building management, industrial controls, and general sensing applications. In this case study, since there is lots of possibilities of network topologies and networking management strategies, we limit ourselves to estimate the energy consumption for the ZigBee end device to sample data from different commercial-off-the-shelf (COTS) sensors and transmit the data back to the base station.

The ZigBee platform employed is based around the ZigBee compliant EM2024 transceiver and the low power, 8-bit, Atmega128L microcontroller. In this case, the sensor node is required to sense five different parameters: temperature, light level, humidity, vibration levels and barometric pressure. Thus a complete cycle for the sensor node involves sampling from the five sensors, processing the data and transmitting the sampled data. Table 2 details the specifications of the sensors used. In particular, the energy per sensor sample shows that the temperature sensor has the lowest energy utilisation while the light and temperature sensors require the shortest sampling time of 0.2 milli-seconds.

The key sources of energy utilisation to be considered in defining the wireless sensor module energy budget are as follows:

- Sensor Sampling: this includes the wake-up/stabilisation time associated with the sensor and the data acquisition time. At all other times, the sensors are completely off and consume no power.
- Processor: The microcontroller controls the wireless module operation and undertakes any required processing of the sensor data. When not processing data or controlling the system operation, the processor is in a low power SLEEP mode.
- Transceiver: The RF transceiver enables the wireless module to communicate and transmit the processed sensor data. Again, when not transmitting or receiving, the transceiver is in a low power SLEEP mode.

Table 3 provides detailed data of the calculated energy utilisation for the wireless sensor in both ACTIVE and SLEEP mode. The wireless system undertakes a full operation of sampling, processing and transmission in 864 milli-seconds. It is interesting to note that, although the transceiver has by far the largest power consumption, in this application, and contrary to the general opinion, some of the sensors dissipate significantly more energy than the transceiver. In particular the humidity sensor requires a long sampling time, during which time the processor is also active, thus giving rise to energy usage which is

60 times higher than the transceiver energy utilisation. This issue of power-hungry sensors is going to present a major R&D challenge in the wireless, chemo-bio sensor space.

Sensor	**Voltage (V)**	**Current (mA)**	**Power (mW)**	**Sampling Time (s)**	**Energy/sample (μJ)**
Temperature	3.3	0.008	0.026	0.0002	0.00528
Light	3.3	0.03	0.099	0.0002	0.0198
Humidity	3.3	0.3	0.99	0.8	792
Vibration	3.3	0.6	1.98	0.02	39.6
Barometric Pressure	5.0	7.0	35.0	0.02	0.7

Table 2: Sensor specifications for wireless module in building management system.

Operation Mode	***Time (s)***	***Sensors Power (mW)***	***Processor Power (mW)***	***Transceiver Power (mW)***	***Total Power (mW)***	***Total Energy (mJ)***
Transmitting	**0.003908**	0.000	19.965	63.162	**83.127**	**0.325**
Receiving	0.000452	0.000	19.965	71.511	91.476	0.041
Processing	**0.02**	0.000	19.965	0.018	**19.983**	**0.400**
Sampling 1 (Temperature)	0.0002	0.029	21.054	0.018	21.101	0.004
Sampling 2 (Light)	0.0002	0.109	21.054	0.018	21.181	0.004
Sampling 3 (Humidity)	0.8	1.089	21.054	0.018	22.161	17.729
Sampling 4 (Vibration)	0.02	2.178	21.054	0.018	23.250	0.465
Sampling 5 (Pressure)	0.02	38.500	21.054	0.018	59.572	1.191
Total Active	**0.86476**					**20.160**
Sleep		0	0.0363	0.018	0.054	

Table 3: Detailed data for the calculated energy budget for the wireless sensor system in operation and sleep mode.

Note that in Table 3, even in SLEEP mode, the module is dissipating 54 μW of power due to the stand-by power of the transceiver and the microcontroller. Table 4 below presents data for a range of cycle times from 1 second to 24 hours in order to illustrate the impact of the duty-cycle driven operation. Here the duty cycle is defined as $t_{on}/(t_{cycle})$, where t_{on} is the time for which the system is active (sampling, processing and transmitting or receiving data), and t_{cycle} is the time between measurements. It is clear from the table that, even with a 1 minute cycle time for an 864 milli-second ACTIVE time, the sensor module is already in SLEEP mode for almost 99% of the time. It is also clear that for a 20 minute cycle time, the energy utilisation in SLEEP mode exceeds the ACTIVE mode energy by almost a factor of three and thus dominates the module energy utilisation, thereby providing the ultimate limit to the power system lifetime. Table 4 also shows the dramatic reduction in total energy utilisation over the period of one day, as the module cycle time is extended from 1 second to 24 hours.

Sleep time	**Sleep time (s)**	**Duty Cycle On-Time (%)**	**Duty Cycle Off-time (%)**	**Energy in Sleep Mode (mJ)**	**Energy in Operation Mode (mJ)**	**Total Energy per Cycle (mJ)**	**Total Energy/day (J)**
1 s	1	90.48	9.52	0.05	21.53	21.59	1864.95
2 s	2	45.24	54.76	0.11	21.53	21.64	934.83
30 s	30	3.02	96.98	1.63	21.53	23.16	66.71
1 min	60	1.51	98.49	3.27	21.53	24.80	35.71
2 min	120	0.75	99.25	6.53	21.53	28.06	20.21
20 min	1200	0.08	99.92	65.34	21.53	86.87	6.25
1 hour	3600	0.025	99.975	196.02	21.53	217.55	5.22
12 hours	43200	0.002	99.998	2352.24	21.53	2373.77	4.75
24 hour	86400	0.0010	99.9990	4704.48	21.53	4726.01	4.73

Table 4: Energy budget for a range of wireless sensor system cycle times from 1 second to 24 hours.

This energy must be supplied to the system and, in the most common case, is simply stored in a battery. Clearly therefore, the lifetime of the sensor node depends on the storage capacity of the battery and the total energy consumption of the system. However, if the energy harvesting techniques discussed above are used to augment the battery power, then the energy storage requirement is reduced by the amount of energy harvested from the environment. An estimate of the energy harvesting capabilities of various techniques has been given in Table 1 above. For reference, Table 5 provides the energy capacity of typical commercially available battery form factors.

In Figure 4, the impact of the various energy harvesting techniques on the stored energy requirements, E_s, is presented by plotting the system energy, E_{sys}, minus the harvested energy, E_h , i.e. $E_s = E_{sys} – E_h$, for a 24 hour period**,** as a function of the on-duty cycle for the sensor node. For the sake of comparison,

Battery Type	**Voltage (V)**	**Capacity (mAhr)**	**Energy (J)**
12V Car Battery	12	32,000	216,000
AA 1.5Vx2	3	2,900	31,320
Mobile/Cell Phone	3.7	900	11,988
Coin Cell CR2450	3	600	6,480
Coin Cell CR2032	3	250	2,700
Coin Cell LR44	3	105	1,134
Li Polymer Film	3	25	270

Table 5: Energy capacities of typical battery form-factors. Move to later in text to show energy capacity of batteries.

we have arbitrarily chosen the size of the energy harvesting device to be 1 cm^2 for the solar and thermal scavenger and 1 cm^3 for the vibration harvester. With no energy harvesting, the energy storage requirement varies from a constant sleep energy of approximately 5 Joules for duty cycles less than 0.02% to a maximum of 1746 Joules for a duty cycle of approximately 86 %. Considering the energy available from harvesting techniques in Table 1, the sleep energy of the system could be provided by the outdoor solar and vibration harvesting techniques. For these energy harvesting techniques, there is, in principle, a maximum duty cycle, below which all of the system energy could be provided by the energy harvesting system. For outdoor solar, this maximum duty cycle is approximately 20 %, and for vibration harvesting it is approximately 0.4 %. At duty cycles less than these, the system could essentially be battery-less. At duty cycles greater than these, the various energy harvesting techniques can only provide part of the system energy and therefore energy storage, in the form of a battery, is required with the battery lifetime implications discussed above.

To have a truly autonomous, battery-less system one could consider scaling the energy harvester so as to provide all of the system energy needs. In such a case, energy storage would still be required in order to supply the system peak power requirements, however this could be provided by a capacitor, the lifetime of which, in terms of charge cycles is orders of magnitude greater than a typical battery. In order to consider realistic scaling of the thermal and vibration harvesting devices, it would be vital that specific information relating to the available temperature difference and vibration acceleration levels be known. We assume that, in a building management application, temperature differences of 5 °C would be available by placing the thermal energy harvesting device on a heater. In a building situation, vibrations are present in air-conditioning units, windows, floors and most equipment which use electric machines (e.g. pumps and motors). Roundy et al. [37] measured vibrations in HVAC vents in the range of 0.2 – 1.5 m/s^2 at 60 Hz and in office windows in the range of 0.7 m/s^2 at 100 Hz. Torah et al. designed their generator to operate from vibrations in an air compressor unit, which they found to be in the range of 0.5 m/s^2 at 50 Hz. We can therefore assume that vibration with acceleration levels of 0.5 m/s^2 are available in a building environment.

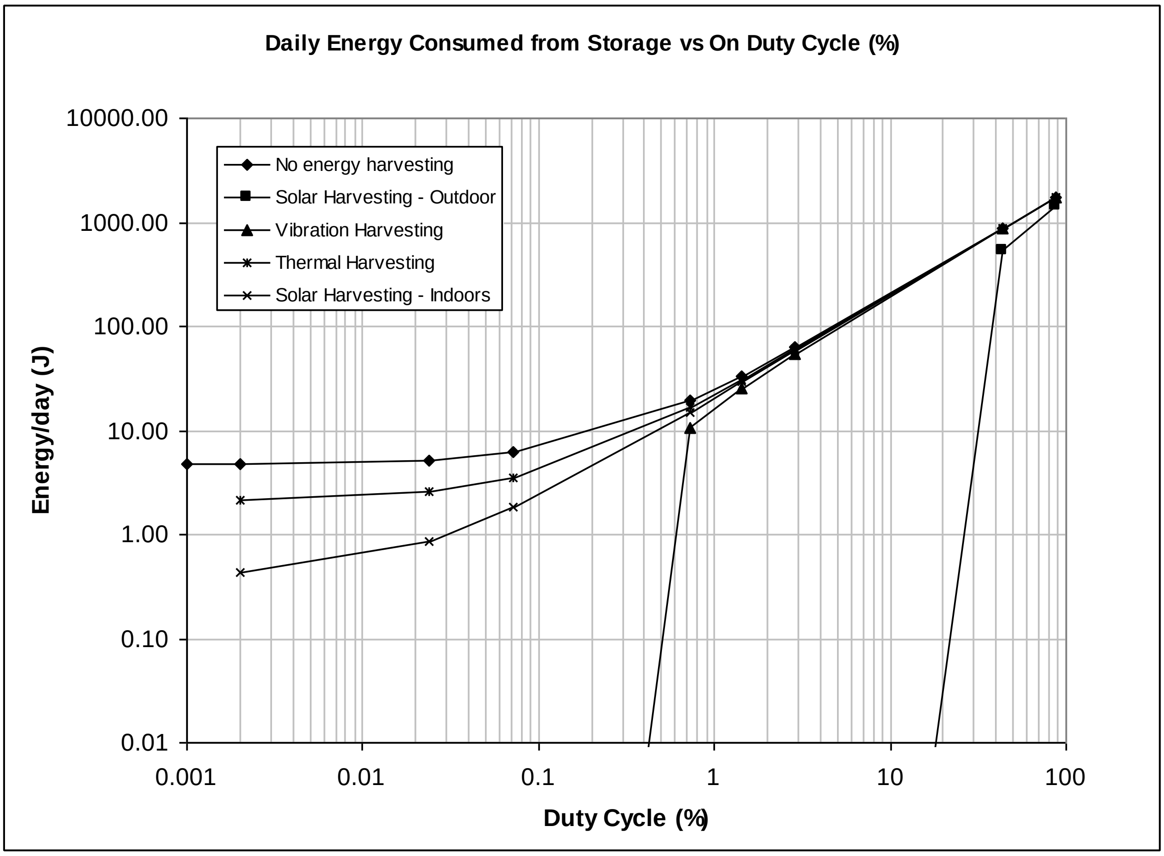

Figure 4: Daily energy consumed by wireless sensor node in Zigbee application within bulding management system. Graph also includes the contribution that can be made to the wireless sensor system energy budget by the various energy harvesting approaches under consideration. Note that the size of the energy harvesting devices used in the analysis are 1 cm^2 for the solar and thermal scavenger and 1 cm^3 for the vibration harvester

In the graph in figure 5, the dimension of the energy harvester required to supply the system energy is plotted against sensor node duty cycle. The dimension is taken as the square root of the required area for the thermal and solar energy harvesters, and the cube root of the required volume for the vibration harvester. The plot indicates that for low duty cycles of less than 0.07 % (a reading every 20 minutes), an energy harvester device with linear dimensions of approximately 2 cm on a side would be sufficient to supply the energy. For high duty cycles, dimensions of up to 25 cm for thermal, 20 cm for indoor solar and 10 cm for vibration are required.

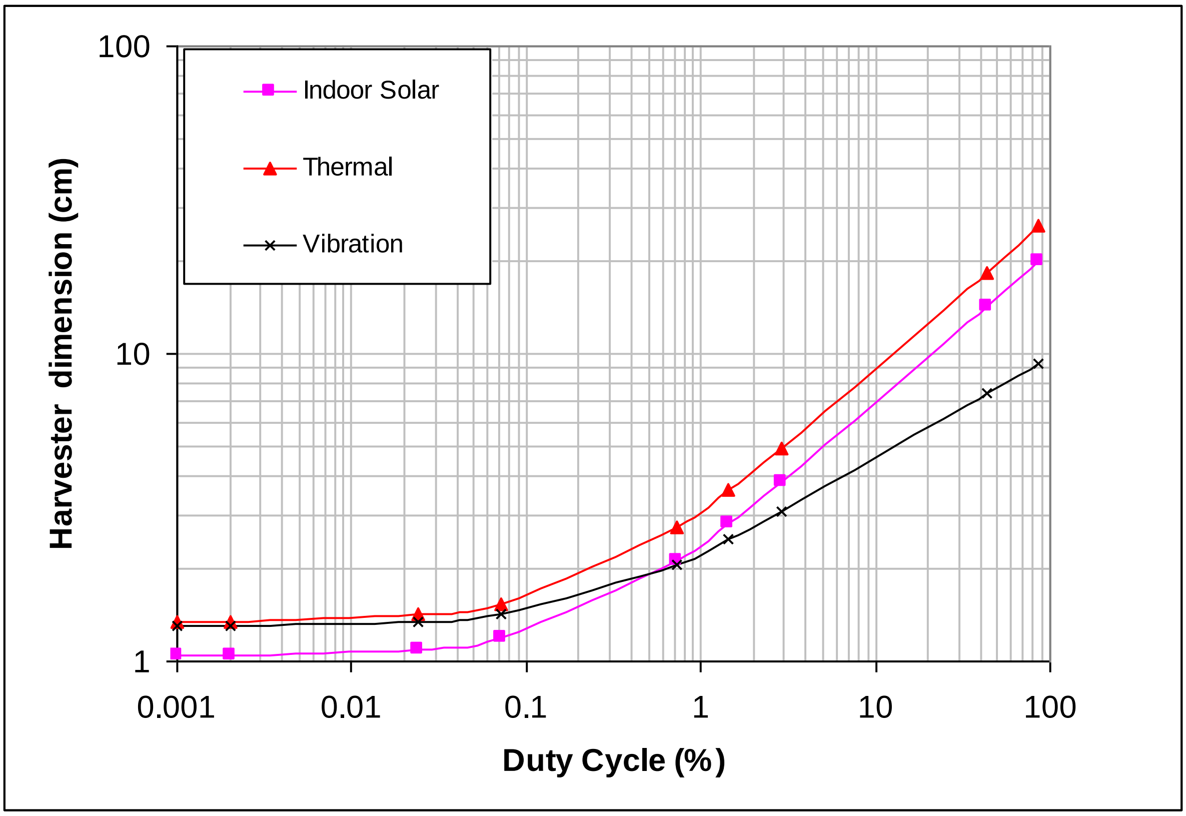

Figure 5: For the building management case study under discussion, this graph plots the dimension of energy harvester required to supply the sensor node daily energy needs as a function of sensor node duty cycle. A temperature difference of 5 degrees is assumed for the thermal and vibrations of 0.5 m/s^2 are assumed for the vibration harvesters.

4. Wireless Sensor Deployment Case Study in Remote Environmental Monitoring

The promise of wireless sensor systems is that they can deliver remote environmental monitoring technology whereby autonomous wireless sensor modules can be deployed in large numbers for long periods of time; of the order of years. This requirement is not in line with the utilisation of batteries as the principle energy source as it precludes the possibility of regularly replacing batteries. Even if one could afford the manpower resource to replace batteries, this would assume that one could reliably and quickly locate all the wireless devices. This is the driver for identifying suitable, truly-autonomous sources of power for wireless sensors – that is to facilitate the long term, large-scale deployment of millions of sensors which do not need replenishing of the energy source during the lifetime of the monitoring programme – that is “deploy and forget”.

Sensing Parameter	Voltage (V)	Current (mA)	Power (mW)	Warm-up Time (s)	Energy per Sample (mJ)
temperature	10	12	120	5	600
ph	10	17.5	175	3	525
Conductivity	12	12.8	153.6	3	460.8
Dissolved Oxygen	10	27.5	275	10	2750
Turbidity	10	43	430	10	4300
Water level	10	12	120	0.01	1.2

Table 6: Sensor specifications for a prototype, remote, wireless, water-quality, monitoring system

Table 6 presents data for a prototype remote environmental monitoring system which is being investigated for assessment of wireless sensors to address the EU Water Framework Directive. The directive requires that, by 2015, all European bodies of water will be required to achieve pre-defined quality levels [60]. From Table 6, the power requirements and sampling time for the developmental sensors result in over 8.5 Joules of energy per measurement cycle. This figure contrasts with the very low figure, in Table 3, of 20.16mJoules for a full operation cycle of sensor sampling, data processing and data transmission in the building management case study.

Table 7 provides a first order estimate of the anticipated energy budget associated with a fully operational remote environmental monitoring unit. A system operating cycle of once every 20 minutes

Operation	**Energy per Operation Cycle Joules**	**Energy Per Day Joules**
Sensor Measurement	8.5	612
Data Processing	0.85	61.2
Data Transmission	0.1	7.2
Fluidic Transport, Sensor Calibration, System Cleaning	72	5184
Sleep Mode	6	432
TOTAL SYSTEM ENERGY BUDGET	87.45	6296.4

Table 7: Estimated energy budget for remote environmental monitoring system.

is assumed. As well as the energy budget for the sensor measurement cycle, the table includes estimates for the other system functions with significant energy usage. These include data processing (assumed as 10% of sensor measurement energy budget), long range data transmission, liquid pumping required for fluid transport and control during sensing, sensor calibration and cleaning operations. For data transmission, a long range transceiver, operating at 433MHz, is assumed which will transmit data over a distance of 6km, line of sight, while dissipating 100mWatts over a time interval of one second (worst case), thereby dissipating 100mJoules per operation cycle. For the fluid transport system, a worst-case estimation is also assumed, that the system requires a 240mW pump (i.e. 20mAmps at 12Volts) operating for 5 minutes after every measurement cycle, thereby requiring 72 Joules of energy per measurement. One also needs to take into account the “SLEEP” mode energy usage of the system. An estimate for this figure is taken from the building management case study which was less than 6 Joules per day for measurement cycles over 20 minutes. From Table 7, it can be seen that the fluid transport system energy budget is almost an order of magnitude higher than the sum of the next highest energy figures, that is the sensor measurements and the sleep mode energy. It is also noteworthy that the energy used in the data processing and data transmission operations are negligible in comparison.

Currently, this first prototype system is housed in a 125litre water tight, plastic container, mainly to accommodate the fluidic system associated with the sensor measurement, cleaning and calibration. A car battery is used as the power source which has a capacity of the approximately 30Ahr equivalent to 1.3 million Joules of energy. Furthermore, the lifetime of a car battery is typically 4 years in a harsh automotive environment, giving the option of a relatively long term, large capacity, energy storage unit.

To deliver a "deploy and forget" solution, the battery would also require an energy source for daily re-charging. If we assume an outdoor solar cell providing the energy to the system, at a harvesting level of 324 Joules per day per cm^2 (as presented in Table 1 for 12 hours of light on a cloudy, overcast day), the daily energy budget for the system of 6,296.4 Joules could be delivered by a solar cell panel of approximately $20cm^2$ in area. Therefore, even assuming significantly lower daylight hours, standard, commercial, solar panels, available in low cost, robust formats, can more than adequately supply the energy requirements for the proposed remote environmental monitoring system. These solar panels come in water-proof, corrosion-proof solar cell arrays with adjustable mounting stands, UV-proof polycarbonate plastic case and built-in blocking diode to prevent discharge at night.

5. Conclusions and Future Perspectives:

Wireless sensor systems are emerging as a key technology for future remote environmental monitoring in both our built and external environments. A case study presented for a multi-sensor, building management system, operating using the Zigbee protocol shows that, even with a 1 minute cycle time for an 864 milli-second ACTIVE time, the sensor module is already in SLEEP mode for almost 99% of the time. It is also clear that for a 20 minute cycle time, the energy utilisation in SLEEP mode exceeds the ACTIVE mode energy by almost a factor of three and thus dominates the module energy utilisation thereby providing the ultimate limit to the lifetime of the energy source.

A key issue for these wireless node designs is that they must achieve high degrees of power-efficiency for truly autonomous, maintenance-free operation, where it is likely that nodes will require deployment for periods of years and the cost of battery replacement will be prohibitive and impractical. From a review of energy harvesting technologies, including outdoor and indoor solar energy and energy from thermal gradients and vibrations, there is, in principle, a maximum duty cycle of operation for a wireless sensor node, below which all of the system energy could be provided by the energy harvesting system in conjunction with a rechargeable battery to store energy for peak power requirements and for periods when the energy harvester is not operating (i.e. at night for solar cells). Alternatively, a capacitor could be utilized to store the energy, the lifetime of which, in terms of charge cycles is orders of magnitude greater than a typical battery.

Clearly, large scale deployment of bulky, remote water quality monitoring systems will not be economically viable, even with the predicted volumes required on a European-wide, or even a global scale. Therefore, a key issue for the future emergence of a viable market in this area will be the development of miniaturised systems which will ultimately be enabled by "lab-on-a-chip" technologies. In this case, microelectronics and microsystems will be required to deliver robust, miniaturised, low power and low cost chemo-bio sensors and associated microfluidic/micropumping systems which can be interfaced to the already miniaturised electronics. Reliable sensors will require anti-fouling coatings on sensor surfaces and, most likely, utilising non-contact measurement protocols. The microfluidic transport systems will be required to be low power, ideally zero power, with high reliability over the full lifetime of the system. These "lab-on-a-chip" systems also raise the challenge of providing adequate supply of reagents to enable proper cleaning and calibration over the entire lifetime of the system. Again, ideally, a sensor system that does not require cleaning or calibration would solve many of these challenges. These miniaturised systems can also be expected to deliver significant reductions in system energy budgets and therefore the size of the required power supply system (i.e. the energy harvester and the energy storage element) thereby dramatically increasing the lifetime of the system in the field. Further study is required to evaluate the long term performance and reliability of conventional rechargeable battery technologies. The remote and large scale nature of future environmental deployments may restrict their application due to their inherent lifetime characteristics of self discharge, number of charge cycles, impact of environmental conditions and potential environmental impact of the batteries.

As a closing remark, serious consideration should be given to the ultimate water-based chemo-biosensor, the fish. Fish, and shell fish, have been used to monitor water quality for centuries. The interfacing of electronics to a mussel "biosensor" has been demonstrated in a water quality monitoring system using electrodes to monitor impedance changes in the shell fish [61], [62] and deserves further attention in the context of future large scale, autonomous environmental monitoring.

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