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FYPSim: Evaluation Tool for Solar-based Energy Harvesting for WSNs

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Abstract. We introduce a simulation tool for modeling energy harvesting and energy storage technologies with application to wireless sensor networks. Firstly, we provide a concise review of various energy harvesting technologies (solar, wind, thermal, vibrations) that can possibly increase the autonomy of wireless sensor network (WSN) nodes. Secondly, we illustrate the capabilities of the proposed tool by means of outdoor and indoor solar energy harvesting examples. These examples consider four types of WSN nodes (Micaz, Imote2, Dresden-AVR, and TelosB) and two types of storage devices (Li-Ion battery and supercapacitor). The results illustrate how system designers can rapidly assess the feasibility of solar-based energy harvesting for various computational loads on the above WSN nodes. In turn, this could be useful for designing, among others, wearable health monitoring systems making use of e.g. bio-electromagnetic sensors.

Keywords: Wireless Sensor Networks, Energy Harvesting, Indoor and Outdoor Energy Harvesting, Energy Storage, Feasibility Evaluation, Wearable Health Monitoring

1. Introduction

In this paper we describe the first steps of our work that aims at developing an open tool (FYPSim) that can simulate a wide range of energy harvesting (EH) and energy storage (ES) technologies. The proposed simulation tool implements EH and ES analytical models and could be extended to include measurement-based models. Both the models and GUI are implemented in Matlab.

The concept of extracting energy from nature, which can be used to recharge or replace conventional power sources, is called energy harvesting. Energy harvesting is deemed to be a very promising approach for enhancing the life-time of sensor nodes. Energy harvesting is one of the best proposed ideas for recharging or even replacing the power source of WSN nodes, which logically results in increased autonomy. Energy harvesting is also known by other terms such as power harvesting, energy scavenging, and free energy (energy derived from renewable energy) [Little et al., 1998].

WSN nodes typically contain various components such as a power source, a microprocessor, an external memory, one or several sensors, A-to-D converters and an RF transceiver. In WSNs, such nodes are linked together by means of a wireless communication system to serve various applications such as observing the environment, detecting/tracking the movement of objects, monitoring human and structure health, etc. The phenomena measured by the sensors are typically transformed into electrical signals for longer periods of times (possibly ranging from days to years). Generally, WSNs use conventional power or fixed power source (e.g. batteries); because of battery drainage, these need to be recharged or replaced when their energy level becomes too low. This is especially difficult if WSNs are deployed in large numbers and are located around unapproachable environments such as deserts and glaciers. This causes inconvenience when such nodes are fitted on e.g. humans.

Sensor nodes can use rechargeable or non-rechargeable batteries. Typically, a non-rechargeable battery is alkaline- based and handy for micro-sensors with low power consumption, e.g. a few tens of μW, whereas a rechargeable battery is based on lithium-ion and is widely used in sensor nodes that makes used of energy harvesting technologies [Dusit et al., 2007].

Energy harvesting can be a valuable asset in various applications such as wearable health-monitoring, which is really challenging due to some factors like convenience, trust, cost, portability, and reliability. Thus, for such applications, harvesting energy is highly desirable and could possibly exploit e.g. human movements (kinetic energy harvesting), body temperature (Seebeck and Peltier effects) as well as ambient energy such as solar radiation and RF waves.

Table 1 shows various sources and corresponding amounts of power that can be used for energy harvesting purpose [Mathna et al., 2008]-[Wan et al., 2011].

Table 1. *Energy harvesting sources and corresponding performance [Mathna et al., 2008]-[Murugavel et al., 2015].*

Energy Source	*Conditions*	*Performance*
Solar	Outdoors	7500 $\mu W/cm^2$
Solar	Indoors	100 $\mu W/cm^2$
Vibration	$1 m/s^2$	100 $\mu W/cm^2$
RF	Wi-Fi	0.001 $\mu W/cm^2$
RF	GSM	0.1 $\mu W/cm^2$
Thermal	$\Delta T = 5$ ºC	60 $\mu W/cm^2$

2. Energy harvesting technologies

Generally speaking, a generic sensor which uses energy harvesting technologies consists of an energy harvester module, an energy storage unit such as a super capacitor, a microcontroller and a transmitter [Energy.gov], as shown in Fig.1.

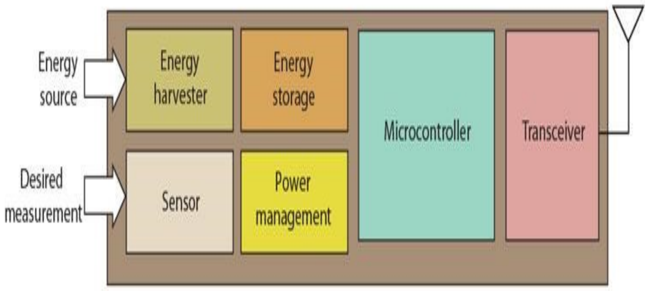

Figure 1. *Generic block diagram of a wireless sensor network node with energy harvesting, energy storage, and power management capabilities [Rfwirelesssensors.com].*

Some of the most common energy sources that can be used for energy harvesting technologies in WSNs are discussed in what follows.

2.1 Solar Energy

Solar energy is often considered as one of the most powerful and best energy harvesting solution for wireless sensor networks, especially in outdoor conditions (see Table 1). Solar electric systems are made up of photovoltaic (PV) semi-conductors which can be coupled with wireless sensor nodes for extracting energy. Idealistically, PV works in a reasonably sunny climate. PV converts the visible light into direct current (DC), which eliminates the need for further current conversion circuits [Photovoltaic, 2014]. Solar cells are typically constructed from crystalline silicon (c-Si). Various forms of silicon such as mono-crystal, multi-crystal, micro-crystal and amorphous are used in the making of Photovoltaic cells [Reddy et al., 2012].

By considering crystalline and thin film amorphous silicon, we calculate how much energy can be harvested as per Table 4 with different parameters but for the same number of PV cells.

Solar EH has a long list of applications; in fact, there is hardly any home or office that does not have at least one solar-powered device. Solar cells are used in consumer and industrial applications, including street lighting controls, portable power supplies and satellites [Lu et al., 2014].

However, solar electric systems have a major limitation in that it is efficient in day light but less in indoor environments, as can be seen in Table 5.

2.2 Wind Energy

Among the various energy sources, nature provides us wind which is considered as non-polluting [Akbari et al., 2014]. The main mechanism in wind-based energy harvesting is that wind turbines convert the kinetic energy of the wind into mechanical power, and generators then convert the mechanical power into electricity [Energy.gov].

A wind turbine turns propellers (that resemble blades) around a rotor. The rotor is connected to the main shaft, which spins the generator to produce electricity [Energy.gov]. A special type of wind turbines, referred to as micro wind turbines, has recently emerged from the research community; however, the practical implementation of such micro wind turbines remains a challenging task because of the required physical size and the need for windy environments (or availability of an air-flow) for energy harvesting to WSNs. Table 2 shows that micro-turbines are more effective when fitted with more blades, but also that more air speed is required.

Specifically, [Rancourt et al., 2007] uses a wind generator consisting of four plastic blades horizontal-axis wind turbine, with diameter of 6.3 cm and length of 7.5 cm. The high number of windings of the brushless generator attached to its shaft allows harvesting significant power even at low wind speeds, which are also the most frequent ones. However, wind cannot be considered a primary energy source because of its irregular behavior.

Table 2. *Comparison of micro-turbines*

Author	*Number of Blades*	*Rotor Tip Diameter (cm)*	*Air Speed (m/s)*	*Maximum Power (mW)*	*Power Density (mW/cm^2)*
[Federspiel et al., 2003]	4	10	2.5	8	0.10
[Priya et al., 2005]	12	10.2	4.4	5	0.06
[Rancourt et al., 2007]	3	4.2	11.8	130	9.38
[Xu F et al., 2010]	4	7.6	4.5	18	0.10

2.3 Radio Frequency Energy

The conversion of radio frequency signals into electricity is known as radio frequency energy harvesting (RFEH). The converted energy could be utilized for increasing the on-time period of WSNs nodes power source (batteries). Usually, the architecture of RFEH-based WSNs has three major components, i.e. information gateways, the RF energy sources and the network nodes/devices. RF energy sources could be either ambient RF sources (e.g., TV towers) or dedicated RF energy transmitters. Usually, the WSNs' nodes can communicate with information gateways wherein information gateways and RF energy sources are supplied by fixed electric sources. WSNs nodes can harvest the energy from RF sources to conduct some monitoring operations in various fields such as e.g. health monitoring system and surveillance [Lu et al., 2014].

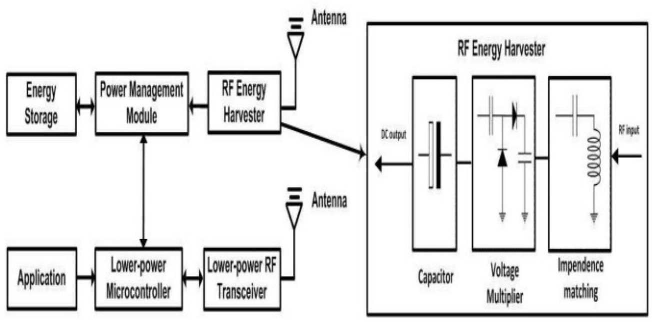

Figure 2. *Architecture of RF energy harvesting* device [Lu et al., 2014].

Fig. 2. shows the block diagram of a RFEH system that consists of the application, a low-power microcontroller (processing data from application), a low-power RF transceiver (information transmission or reception), an energy harvester composed of an RF antenna, a capacitor and a voltage

multiplier (to collect RF signals and convert them into electricity), a power management module and an energy storage device. The applicability of RFEH depends on the efficiency of the antenna along with the impedance accuracy matching of the antenna with a voltage multiplier. RFEH is very flexible and can control the transfer of energy as per the requirement of the WSNs nodes. However, the harvested RF energy is relatively small due to among others, the losses between the source and receiver and the RF-to-DC low energy conversion efficiency [Kishi et al., 1999].

2.4 Thermal Energy

Thermal energy harvesting is based on techniques that exploit the Seebeck and Peltier effects, whereby electricity can be produced from temperature differences. Thermal energy harvesting is increasingly being researched and successful industrial applications that use thermoelectricity (TE) generator have been demonstrated. TE power generation is a good alternative to power source (batteries) due to its heat energy harvesting capabilities [Lu et al., 2010]. A TE generator is developed by heating one face of TE module and cooling the other face, causing an electrical current to be generated by connecting a load to the end points of the TE module.

The Seiko thermic watch is the first application based on thermal energy harvesting in a consumer product. It uses a TE generator to convert body heat into electrical energy that is used to run a wrist watch. Furthermore, this energy not only runs the watch, it also charges a 4.5 mAh lithium-ion battery [Kishi et al., 1999]. Commercially available thermoelectric generators require a temperature difference of 10–200 ºC [Gungor et al., 2013]. However, TE has low efficiency but some research results indicate harvesting efficiency of more than 10% [Minnich et al., 2009].

2.5 Vibrational Energy

Generally speaking, converting vibrations into electricity can be performed by means of three approaches, i.e. piezoelectric, electromagnetic, and electrostatic. Technically, a transducer is an energy to energy converter. The basic advantage of piezoelectricity is that it can provide high voltages [MIDÉ, 2013].

Fig. 3 illustrates how Mid*é's* Volture product can be used to power a wireless sensor node [MIDÉ, 2013].

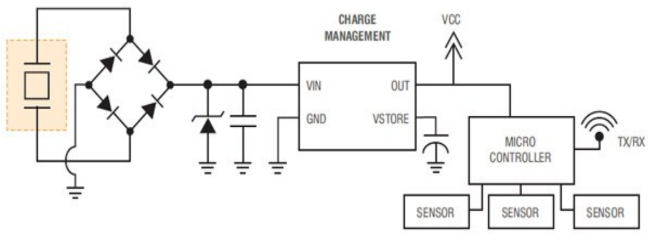

Figure 3. *Midé's Volture powering a wireless sensor node (Courtesy of Midé Technology Corporation) [MIDÉ, 2013].*

Piezoelectricity materials include quartz, soft and hard lead ziconate titane piezoceramics (PZT-5H and PZT5A), barium titanate (BaTiO3) and polyvinylidene fluride (PVDF) [21]. A usable output voltage can be obtained directly from the piezoelectric effect and there is no need for multistage post processing for generating the required voltages [Erturk and Inman, 2011]. Electromagnetic transducers generate electricity through the relative motion of a coil and a magnet. Electrostatic transducers respond to changes due to vibration in the distance between two electrodes of a polarized capacitor. Typically, vibrational energy harvesters can generate a few microwatts to several milliwatts. Midé Technology Corporation produces the Volture line of piezoelectric energy harvesters. The Volture products are developed to extract usable electrical energy from waste mechanical vibrations [MIDÉ, 2013].

The Volture products have numerous application such as industrial health monitoring network sensors, condition based maintenance sensors, and wireless HVAC sensors.

3. Storage Devices

As mentioned above, WSN nodes can use non-chargeable or rechargeable batteries. Table 3 shows the specifications of rechargeable batteries based on lithium-ion and thin films. The coupling or combination of energy harvester device with lithium-ion or thin films rechargeable battery can be implemented for increasing the battery life.

Table 3. *Characteristics of batteries and supercapacitors [Energy.gov].*

	Battery				*Supercapacitor*
	Li - ion	Li – Po	Nickel Cadmium	Thin film	
Operating Voltage (V)	3-3.70	3.7	1.25	3.70	1.25
Energy density (Wh/I)	435	300-450	~110 - 150	<50	6
Specific energy (Wh/kg)	211	150-200	40-60	<1	1.5
Self-discharge rate (%/month)	5-10 at 25°C	1-2 at 25°C	20-30 at 25°C	0.1-1 at 20°C<2%* at 25°C	100
Cycle life (cycles)	2000	>1200	500-2000	>1000	>10.000
Temperature range (C)			-20 to 60	-20/70	-40/65

4. Simulation and Sizing of Energy Storage Devices

Energy storage is playing an important role for the longer life of battery-powered devices, especially those which are expected to operate for e.g. decades without being replaced, like WSN nodes.

Proper operation of the WSN nodes imply that they are powered either from the energy storage devices and/or from the energy harvesting circuit, depending on the conditions.

WSN nodes are typically powered by two kinds of energy storage devices, i.e. batteries and supercapacitors. Specifically, this section discusses the Li-Ion rechargeable batteries that can operate at 3.5 V onwards. Although Li-Ion is more durable, its biggest constraint is that it cannot be recharged more than about 1000 times, whereas supercapacitors have the capability to be charge/discharge millions of times [RFM].

An energy management circuit is often used to check whether a WSN node needs to harvest energy or can continue with its available energy.

Simulation tools described in the literature are usually designed for testing the behavior of energy harvesting technologies but only few of them focus on storage capacity calculation. Our simulation tool has a functionality that provides the solutions for all three major issues related to both Li-Ion and supercapacitors with the help of bar graphs.

The models for energy storage devices take the following parameters into account: WSN node current consumption, total execution time, active, wake/idle, and sleep cycles, storage device type (Li-Ion or supercapacitors), operating voltage, and the number of cloudy days (for the solar energy harvesting case), as shown in Fig. 4 (Li-Ion case).

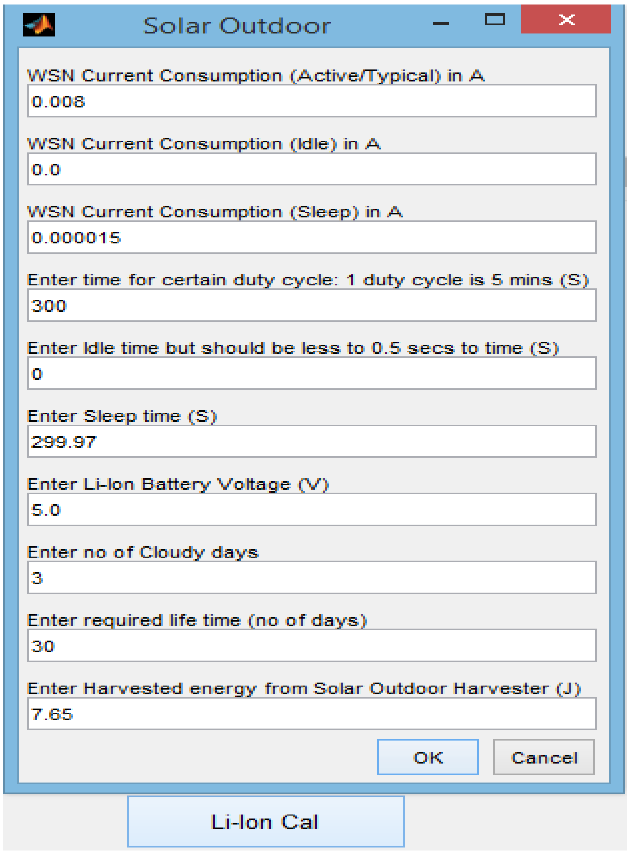

Figure 4. *Screenshot of the tool showing Li-Ion calculation button and inputs box with default values for the energy utilization.*

A screenshot of the simulation results is shown in Fig. 5. The bar graphs illustrate the consumption of the WSN node over a period of 24 hours, the remaining amount of energy, and how much energy is required from the energy harvester.

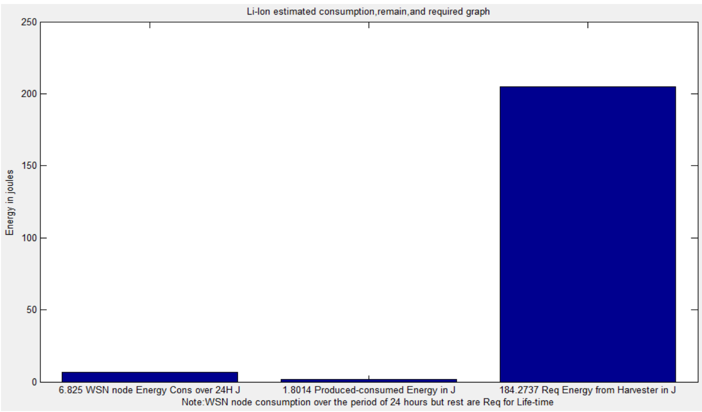

Figure 5. *Screenshot of the tool showing the simulated of Li-Ion with WSN node consumption, remain and required from harvester bar graphs.*

5. Examples of Feasibility Assessment of Solar Energy Harvesting for WSN Nodes

This section illustrates how the proposed approach can be used to rapidly evaluate the feasibility outdoor solar energy to power WSN nodes. For this, we have performed simulations with FYPSim considering real-life MICAZ, IMOTE 2, Dresden-AVR and TelosB-based WSN nodes powered by either crystalline or thin film PV cells, combined with either a Li-Ion battery (5 V) or a supercapacitor (3.5 V), for the energy levels shown in Tables 6 to 9. The behavior of all the WSNs nodes is simulated taking into account three different states (modes), namely idle, active and sleep modes, with corresponding current consumptions indicated in the first column of Tables 6 to 9. Furthermore, several duty cycle cases have been considered, as discussed below. Note that we consider a worst-case scenario whereby the batteries or supercapacitors are initially depleted. All simulations are based on average values for the energy production and consumption, discussed here as Cases I to IV.

5.1 Energy Harvester based on Crystalline PV cells

CASE I: This is the 'best' case from an energy consumption perspective in that the nodes are always in the sleep mode. Although any practical application would require the nodes to be active from time to time, this case is useful for evaluating the behavior of the system during periods of inactivity. As shown in Tables 6 and 7, Case I yields feasible combinations (positive numbers for 'Prod-Cons') for the MICAZ, Dresden-AVR and TelosB-based nodes (which have a lower energy consumption than the IMOTE 2 one).

CASE II: This corresponds to a relatively light load whereby the nodes are active only a small amount of time (1%) as compared to the total time (300s), which can illustrate applications such as slow-variation temperature monitoring. As can be observed in Table 6 and 7, the number of feasible combination is similar to that of Case I (and again for MICAZ, Dresden-AVR and TelosB-based nodes).

CASE III: On the contrary to the above cases, in Case III the nodes are now active for longer periods, corresponding to intensive sensing and signal processing activities. As can be seen in Tables 6 and 7, the nodes require much more energy as compared to cases I and II, and none of the considered combinations is feasible from an energy harvesting perspective.

CASE IV: this can be considered as the 'very worst case' since the nodes are active all the time. Although extreme, this case reflects certain applications where monitoring and/or signal processing is performed continuously on 24/7 basis. The results in Tables 6 and 7 clearly show that energy harvesting is not feasible given this level of activity and the energy consumption level of the selected nodes.

5.2 Energy Harvester based on Thin Film PV cells

CASE I: As shown in Table 8 and 9, TelosB is the only node for which energy harvesting based on thin film PV cells is feasible (whether combined with a Li-Ion battery or a supercapacitor). Since the active time is set to zero in Case I, the results illustrate that this type of technology is not promising for the selected nodes; this is confirmed by the results for Cases II to IV below.

CASE II: Here the active time is slightly higher than in Case I; the results shown in Tables 8 and 9 confirm that TelosB is the only node for which energy harvesting based on thin film PV cells is feasible; however, this time only when combined with a supercapacitor. This further indicates that this technology is not suitable for the selected nodes.

CASE III: In case III, the active time is long as compared to the two previous cases. The results shown in Tables 8 and 9 clearly indicate that energy harvesting based on thin film PV cells is not feasible for the selected nodes, should they sustain such an activity level.

CASE IV: In Case IV, the nodes are active all the time. As for Case III, the results shown in Tables 8 and 9 suggest that energy harvesting based on thin film PV cells is not suitable for the selected nodes should their activity level be continuous.

The above simulation results illustrate how a designer can use FYPSim to evaluate the feasibility of various energy harvesting (here based on crystalline and thin film PVs) and energy storage (here Li-Ion and supercapacitor) technologies for different types of nodes under various activity levels. The proposed framework is flexible enough to accommodate other technologies. For this, the corresponding analytical models simply need to be specified in the Matlab code.

Table 4. *Solar (outdoor) Crystalline and Thin film based harvested energy.*

Size of Solar (Outdoor) PV cell [cm²]	***η of*** *Crystalline*	***η of*** *Thin Film*	*Power [kW]*	*Crystalline based PV Harvested Energy / 24 hours [J]*	*Thin Film based PV Harvested Energy / 24 hours [J]*
1	17%	5%	2500	0.38	0.11
5	17%	5%	2500	1.91	0.56
10	17%	5%	2500	3.82	1.12
15	17%	5%	2500	5.73	1.68
20	17%	5%	2500	7.65	2.25

Table 5. *Solar (Indoor) based harvested energy.*

Size of Solar (Outdoor) PV cell [cm²]	*Absolute Temp [K]*	*Light Irradianc LUX*	*[μA]*	*Solar (indoor) Harvested Energy / 24 hours [J]*
1	290	380	60	0.000018
2	295	425	65	0.000043
3	300	480	74	0.0000735
4	305	640	96	0.00012
5	310	1010	150	0.00024

Table 6. *Solar Crystalline PV EH for MICAZ, IMOTE 2, AVR, and TelosB node powered by Li-Ion Battery (5V).*

	Node Current [A]	*Total time [300s]*	*Case I*	*Case II*	*Case III*	*Case IV*
		Idle [s]	0	0	5	0
		Active [s]	0	0.03	290	300
		Sleep [s]	300	299.97	5	0
Solar (Outdoor) Harvested Energy @20cm² / 24 hours [J] 7.65	*MICAZ*	*Node cons. (24 hours) [J]*	6.48	6.82	3340.9	3456
	I_{active}=8*10^{-3}	*Prod.-Cons. (30 days) [J]*	4.5	1.80	-99997.74	-103450.5
	I_{idle}=0	*Req. Energy (30 days) [J]*	168.48	184.27	100227.24	103680
	I_{sleep}=15*10^{-6}	*No of cloudy days*	4	3	0	0
Solar (Outdoor) Harvested Energy @20cm² / 24 hours [J] 7.65	*IMOTE 2*	*Node cons. (24 hours) [J]*	168.48	170.36	18377.20	19008
	I_{active}=44*10^{-3}	*Prod.-Cons. (30 days) [J]*	-4824.9	-4881.41	-551086.7	-570010
	I_{idle}=0	*Req. Energy (30 days) [J]*	5054.4	5110.91	551316	570240
	I_{sleep}=390*10^{-6}	*No of cloudy days*	0	0	0	0
Solar (Outdoor) Harvested Energy @20cm² / 24 hours [J] 7.65	*Dresden-AVR*	*Node cons. (24 hours) [J]*	4.32	5.18	8424	8640
	I_{active}=20*10^{-3}	*Prod.-Cons. (30 days) [J]*	46.35	20.44	-252492.6	-258970.5
	I_{idle}=10*10^{-3}	*Req. Energy (30 days) [J]*	99.36	119.22	252722.16	259200
	I_{sleep}=10*10^{-6}	*No of cloudy days*	7	7	0	0
Solar (Outdoor) Harvested Energy @20cm² / 24 hours [J] 7.65	*TelosB*	*Node cons. (24 hours) [J]*	2.2032	3.14	9104.10	9417.6
	I_{active}=21.8*10^{-3}	*Prod.-Cons. (30 days) [J]*	109.854	81.60	-272893.7	-282298.8
	I_{idle}=54.5*10^{-6}	*Req. Energy (30 days) [J]*	50.67	72.32	273123.27	282528
	I_{sleep}=5.1*10^{-6}	*No of cloudy days*	7	7	0	0

***Table** 7. Solar Crystalline PV EH for MICAZ, IMOTE 2, AVR, and TelosB node powered by Supercapacitor (3.5V).*

	Node Current [A]	*Total time [300s]*	*Case I*	*Case II*	*Case III*	*Case IV*
		Idle [s]	0	0	5	0
		Active [s]	0	0.03	290	300
		Sleep [s]	300	299.97	5	0
Solar (Outdoor) Harvested Energy @20cm² / 24 hours [J] 7.65	*MICAZ* I_{active}=8*10^{-3} I_{idle}=0 I_{sleep}=15*10^{-6}	*Node cons. (24 hours) [J]*	*4.5*	*4.7*	*2338.63*	*2419.2*
		Prod.-Cons. (30 days) [J]	*39.87*	*32.62*	*-69929.5*	*-72346.5*
		Req. Energy (30 days) [J]	*104.32*	*109.88*	*70159*	*72576*
		No of cloudy days	*7*	*7*	*0*	*0*
Solar (Outdoor) Harvested Energy @20cm² / 24 hours [J] 7.65	*IMOTE 2* I_{active}=44*10^{-3} I_{idle}=0 I_{sleep}=390*10^{-6}	*Node cons. (24 hours) [J]*	*117.9*	*119.25*	*12864*	*13305.6*
		Prod.-Cons. (30 days) [J]	*-3308.5*	*-3348.13*	*-385691.8*	*-398938.5*
		Req. Energy (30 days) [J]	*3538*	*3577.64*	*385921.36*	*399168*
		No of cloudy days	*0*	*0*	*0*	*0*
Solar (Outdoor) Harvested Energy @20cm² / 24 hours [J] 7.65	*Dresden-AVR* I_{active}=20*10^{-3} I_{idle}=10*10^{-3} I_{sleep}=10*10^{-6}	*Node cons. (24 hours) [J]*	*3*	*3.62*	*5896.85*	*6048*
		Prod.-Cons. (30 days) [J]	*85.23*	*67*	*-176676*	*-181210.5*
		Req. Energy (30 days) [J]	*69.55*	*83.45*	*176905.5*	*181440*
		No of cloudy days	*7*	*7*	*0*	*0*
Solar (Outdoor) Harvested Energy @20cm² / 24 hours [J] 7.65	*TelosB* I_{active}=21.8*10^{-3} I_{idle}=54.5*10^{-6} I_{sleep}=5.1*10^{-6}	*Node cons. (24 hours) [J]*	*1.54*	*2.2*	*6372.87*	*6592.32*
		Prod.-Cons. (30 days) [J]	*129.68*	*109.91*	*-190956.79*	*-197540.1*
		Req. Energy (30 days) [J]	*35.47*	*50.63*	*191186.29*	*197769.6*
		No of cloudy days	*7*	*7*	*0*	*0*

***Table 8**. Solar Thin Film PV EH for MICAZ, IMOTE 2, AVR, and TelosB node powered by Li-Ion Battery (5V).*

	Node Current [A]	*Total time [300s]*	*Case I*	*Case II*	*Case III*	*Case IV*
		Idle [s]	0	0	5	0
		Active [s]	0	0.03	290	300
		Sleep [s]	300	299.97	5	0
Solar (Outdoor) Harvested Energy @20cm² / 24 hours [J] 2.25	*MICAZ* I_{active}=8*10^{-3} I_{idle}=0 I_{sleep}=15*10^{-6}	*Node cons. (24 hours) [J]*	6.48	6.82	3340.9	3456
		Prod.-Cons. (30 days) [J]	-135.9	-143.99	-100159.7	-103612.5
		Req. Energy (30 days) [J]	168.48	184.27	100227.24	103680
		No of cloudy days	4	3	0	0
Solar (Outdoor) Harvested Energy @20cm² / 24 hours [J] 2.25	*IMOTE 2* I_{active}=44*10^{-3} I_{idle}=0 I_{sleep}=390*10^{-6}	*Node cons. (24 hours) [J]*	168.48	170.36	18377.20	19008
		Prod.-Cons. (30 days) [J]	-4986.9	-5043.41	-551244.7	-570172.5
		Req. Energy (30 days) [J]	5054.4	5110.91	551316.24	570240
		No of cloudy days	0	0	0	0
Solar (Outdoor) Harvested Energy @20cm² / 24 hours [J] 2.25	*Dresden-AVR* I_{active}=20*10^{-3} I_{idle}=10*10^{-3} I_{sleep}=10*10^{-6}	*Node cons. (24 hours) [J]*	4.32	5.18	8424	8640
		Prod.-Cons. (30 days) [J]	-62.1	-88	-252654.6	-259132.5
		Req. Energy (30 days) [J]	129.6	155.5.22	252722.16	259200
		No of cloudy days	0	0	0	0
Solar (Outdoor) Harvested Energy @20cm² / 24 hours [J] 2.25	*TelosB* I_{active}=21.8*10^{-3} I_{idle}=54.5*10^{-6} I_{sleep}=5.1*10^{-6}	*Node cons. (24 hours) [J]*	2.2032	3.14	9104.10	9417.6
		Prod.-Cons. (30 days) [J]	1.4	-26.84	-273055.7	-282460.5
		Req. Energy (30 days) [J]	66	94.34	273123.27	282528
		No of cloudy days	0	0	0	0

Table 9. *Solar Thin Film PV EH for MICAZ, IMOTE 2, AVR, and TelosB node powered by Supercapacitor (3.5V).*

	Node Current [A]	*Total time [300s]*	*Case I*	*Case II*	*Case III*	*Case IV*
		Idle [s]	0	0	5	0
		Active [s]	0	0.03	290	300
		Sleep [s]	300	299.97	5	0
Solar (Outdoor)	*MICAZ*	*Node cons. (24 hours) [J]*	4.5	4.7	2338.63	2419.2
Harvested Energy	$I_{active}=8*10^{-3}$	*Prod.-Cons. (30 days) [J]*	-84.33	-91.52	-70107.31	-72508.5
@20cm² / 24 hours	$I_{idle}=0$	*Req. Energy (30 days) [J]*	104.32	109.88	53788.61	72576
[J]	$I_{sleep}=15*10^{-6}$	*No of cloudy days*	7	7	0	0
2.25						
Solar (Outdoor)	*IMOTE 2*	*Node cons. (24 hours) [J]*	117.9	119.25	12864	13305.6
Harvested Energy	$I_{active}=44*10^{-3}$	*Prod.-Cons. (30 days) [J]*	-3470.5	-3510.1	-385853.86	-399100.5
@20cm² / 24 hours	$I_{idle}=0$	*Req. Energy (30 days) [J]*	3538	3577.6	385921.36	399168
[J]	$I_{sleep}=390*10^{-6}$	*No of cloudy days*	0	4	0	0
2.25						
Solar (Outdoor)	*Dresden-AVR*	*Node cons. (24 hours) [J]*	3	3.62	5896.85	6048
Harvested Energy	$I_{active}=20*10^{-3}$	*Prod.-Cons. (30 days) [J]*	-23.22	-41.35	-176838.5	-181372.5
@20cm² / 24 hours	$I_{idle}=10*10^{-3}$	*Req. Energy (30 days) [J]*	90.72	108.85	176905.5	181440
[J]	$I_{sleep}=10*10^{-6}$	*No of cloudy days*	0	0	0	0
2.25						
Solar (Outdoor)	*TelosB*	*Node cons. (24 hours) [J]*	1.54	2.2	6372.87	6592.32
Harvested Energy	$I_{active}=21.8*10^{-3}$	*Prod.-Cons. (30 days) [J]*	21.23	1.46	-191118.79	-197702.1
@20cm² / 24 hours	$I_{idle}=54.5*10^{-6}$	*Req. Energy (30 days) [J]*	46.26	66	191186.29	197769.6
[J]	$I_{sleep}=5.1*10^{-6}$	*No of cloudy days*	0	0	0	0
2.25						

6. Energy Harvesting Considerations for Wearable Health-Monitoring Application

In [Le Moullec et al., 2014] we have proposed a wearable health-monitoring system. The concept behind that work is to fit the human body with various vital signs, gesture and gait sensors of which the collected data can be pre-processed either locally or remotely. The system builds upon a multi-hop 6LoWPAN based wireless sensor body area network to collect the data from the various sensors. The early prototype of the sensor node is shown in Figure 6.

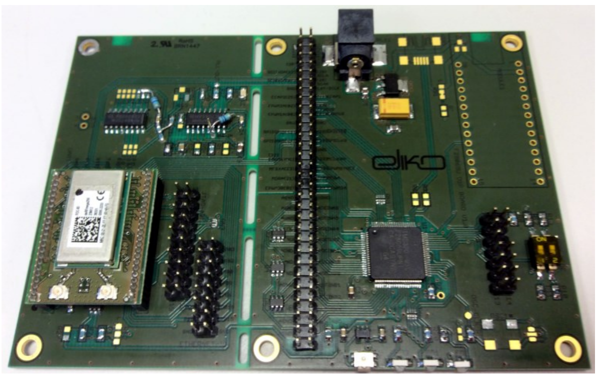

Figure 6. *Early prototype of the wearable health-monitoring sensor node. Left: wireless communication module; right: DSP module*

The data are wirelessly transmitted to a gateway connected to the internet. The targeted usage includes hospitals where multiple patients can be monitored individually or in groups, private and nursing homes, as well as outdoor and urban environments. For such scenarios, energy harvesting is highly desirable since it can minimize the inconvenience that users would face is they were to replace the node batteries too often.

Fitting the human body (either on the WSN nodes or other strategic locations) with miniature solar cells could provide energy to the nodes. However, as humans are rarely static (even if sleeping in a bright environment), the level of harvested energy will greatly vary depending on the body's position. Thus, solar energy harvesting alone may not be sufficient.

RF energy harvesting can also be considered for the health-monitoring application. In many of the scenarios listed above, the user will be located in environments subject to RF waves emitted by mobile phones, Wi-Fi networks, and possibly dedicated RF energy transmitters. Although the energy harvestable from a single RF source may be modest, multiple sources could be exploited by means of a wideband RF energy harvester.

The human body continuously radiates heat; thus placing heat-based energy harvesters on the human body could increase the autonomy of the WSN nodes. A practical difficulty is that the temperature gradient between the human body and its environment is relatively low as human either cover themselves in cold weather or use shadow or cooling devices in warm weather.

Harvesting energy from vibrations and pressure by means of piezoelectric devices may also be suitable for the above applications. Vibrations are present in most human activities; ample movements of the legs and arms (e.g. when running) can provide suitable energy levels whereas smaller movements (e.g. when hand-writing or typing) can provide modest energy-levels. When humans are at rest (e.g. sitting or lying), pressure may be exploited by placing piezoelectric devices between the body and the surface onto which it rests. However, as human tend to move even while sleeping, practical exploitation may be limited.

None of the energy harvesting technology presented above is ideal for the targeted wearable health-monitoring application. Thus, hybrid solutions may be used to exploit various energy sources, either simultaneously or alternatively depending on the conditions set by the environment and human activities.

Such hybrid solutions include the work presented in [Rakotondrabe M et al., 2010] that combines solar and piezoelectric devices together with an energy management circuit. Experimental results show that such hybrid approaches can multiply the level of harvested energy by three as compared to conventional thermal sources [Kheng et al., 2010].

7. Concluding words

In this paper various energy harvesting technologies for WSN applications have been presented. Furthermore, we have shown how our FYPSIM tool can be used for rapidly evaluating the feasibility of outdoor solar energy harvesting for four different types of WSN nodes operating under various activity levels. The results indicate that this type of energy harvesting technology, for the selected nodes, is only feasible when the nodes' activity level is low. Hybrid solutions that combine various energy harvesting technologies appear to be promising. Thus, the next step of our research effort consists in modelling these hybrid technologies for further incorporation in a WSN simulation environment.

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