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ENERGY HARVESTING SYSTEMS IN LOGISTICS

SÁNDOR NAGY[1] – PÉTER TAMÁS [2]

Abstract: *Energy efficiency is also playing an increasing role in logistics systems. But to join the global trend, knowledge of existing technologies is essential. Today, it is no longer enough for an asset to be low-consumption; it is also necessary to use the energy that is lost. To choose the right solution in a given area, it is essential to know the technological background, its advantages, disadvantages and conditions of applicability. In this publication we describe the most common energy harvesting systems and their applications. We examine the solutions used in logistics systems and the areas where energy harvesting systems can be introduced and applied. We will examine future application possibilities that contribute to a more efficient use of energy.*
Keywords: *Energy harvesting, tracking systems, logistics, IoT, Industry 4.0*

1. INTRODUCTION

Nowadays, the fight against energy waste and global warming is becoming more and more important in all aspects of life. It is also important for logistics tracking solutions to minimize the energy consumption of the systems used. This means not only using low-power, environmentally friendly solutions, but also reducing energy losses. Today, it is no longer enough to replace internal combustion engines with electric ones, or to use solar panels or wind turbines to generate electricity; it is also important to collect and recover energy that would otherwise not be used. Energy harvesting is the umbrella term for many different technologies. The most common definition is that energy losses from the operation of systems are recovered and converted into electrical energy instead of being released into the environment [1].

Today, large wired systems are increasingly being replaced by portable, wearable devices, which are increasingly powered by energy harvesting technologies. The main applications may be where wired power supply is not feasible or where sensors are installed in difficult to reach locations. Energy harvesting systems are partly a solution to this problem by collecting and storing energy to achieve longer operation and lower energy consumption. Industry 4.0 solutions, which are also becoming more prevalent in logistics, require the most accurate and up-to-date information to be collected throughout the logistics process. This in turn requires the use of IoT systems, which are low-power devices, but their stable, reliable and long-term operation is essential for efficient information collection. In this publication, we would like to describe the energy harvesting solutions currently used in the field of logistics. We will analyze and compare the different solutions, highlighting their advantages and disadvantages, and provide insight into future development opportunities.

[1]PhD student, University of Miskolc, Institute of Logistics, Miskolc, Hungary
sandor.nagy5@student.uni-miskolc.hu
[2]University prof., University of Miskolc, Institute of Logistics, Miskolc, Hungary
peter.tamas@uni-miskolc.hu

2. LITERATURE RESEARCH

2.1. General literature research

To investigate the application of energy harvesting systems in logistics, a systematic literature search was carried out using the Scopus database. For the search, we generally searched for publications published since 2010. The search for "energy AND harvesting AND logistics" returned 331 results. However, the majority of the results for the search term "harvesting" were mostly publications on agricultural harvesting. For more precise results, Scopus returned only 68 hits for the keyword "logistics", but again, agriculture is the predominant topic. After a detailed review of the articles found, only two articles met our research requirements. The first article describes the use of regenerative braking systems in automated material handling systems in high-bay warehouses [2], while the second article investigates the use of energy harvesting systems for machine monitoring and logistics processes [3]. Since the general search found few relevant publications within the field of logistics, we approached the search from the side of the more common energy harvesting solutions. In the following, we present the results of the literature search related to these types.

2.2. Literature review of energy harvesting systems

First, we had to determine which systems we were looking at. Of the common solutions, only those that are relevant to logistics were considered, so the areas were defined as follows:

- Motion, vibration and other kinetic
- Electromagnetic (RF)
- Temperature difference
- Natural resources (solar, wind, geothermal) [4, 5]

Energy harvesting systems also include the harvesting of solar, wind, hydro and geothermal energy [5]. These resources are not considered to be energy harvesting systems in the narrower sense and so were not examined in the literature search, but their use is described later. For applications of mechanical motion, using the search term "energy AND harvesting AND motion AND logistic", only 6 publications were found in the Scopus database, but here again, the keyword "harvesting" also resulted in irrelevant results, so a narrowed search using the keyword "energy harvesting" only yielded relevant publications. The same method was used to search the other areas by entering the relevant search term in place of "motion". The results are described and evaluated in the next chapter. The results include a solution for harvesting energy from human motion during work [7] and energy harvesting systems for smart factories that can be integrated into wireless sensors [8].

3. THE APPLICATION OF ENERGY HARVESTING SOLUTIONS IN LOGISTICS

In both everyday and industrial systems, considerable amounts of energy are wasted, which can be used as useful energy, in whole or in part, with energy harvesting systems. Energy recovery systems, such as the energy recovered during braking in electric drives, can also be partly classified under this heading [5]. Energy efficiency is becoming increasingly important in logistics today. To this end, logistics systems and supply chains are also using energy harvesting systems and environmentally friendly solutions. In the field of transport, the use of biodiesel and electric transport vehicles, as well as regenerative braking systems [2, 5], are common. Of course, these solutions cannot be considered as energy harvesting, as they only reduce the negative impact on the environment. Similarly, in the field of warehouses and production units, solar panels and wind turbines installed on the roof or nearby can help reduce or completely replace external energy consumption. Sufficient energy can be generated to power and charge material handling equipment, although the performance of these systems is highly dependent on the weather, the time of day and the variation in sunlight intensity throughout the year, so they are not a reliable, constant source of power. This power fluctuation can be overcome by battery packs that can store the energy generated during the day for later use. However, these solutions cannot be considered as concrete energy harvesting systems.

3.1. Use of motion, vibration and other kinetic energies

A number of solutions for harvesting energy from mechanical movements are widely used. Energy can also be harvested from the human movement during work, which assists the worker in lifting [6]. Fig. 1. shows the design of a prototype HMAS. An energy harvesting device attached to the worker's knee assists movement when standing up from a squat. The vibrational movements are mainly converted into energy by piezoelectric devices. Piezoelectric systems consist of semiconductor crystals that release voltage in response to pressure changes. In addition, there are electrostatic solutions where the energy is collected by varying the distance or overlap between the two conductors, causing a voltage difference. The energy from these can also be used to power wireless sensors [7]. Larger movements are typically collected by coils moving in a magnetic field using the principle of electromagnetic induction. In this case, both the magnet and the coil can be the moving element, the point is the change of the magnetic field around the conductor. The greater the movement, the greater the energy that can be collected [5].

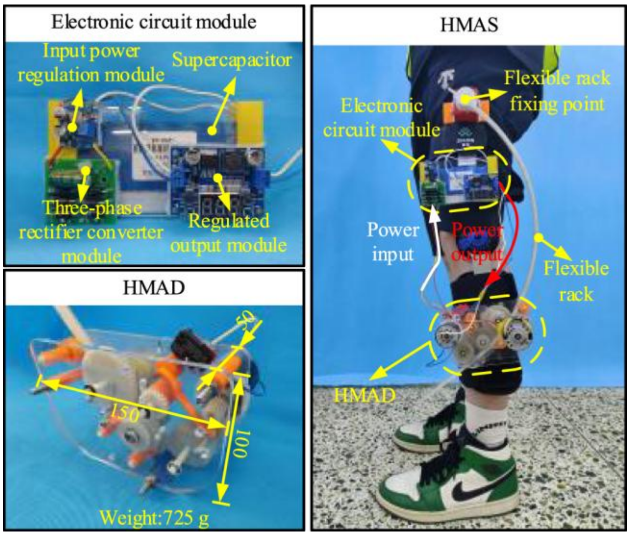
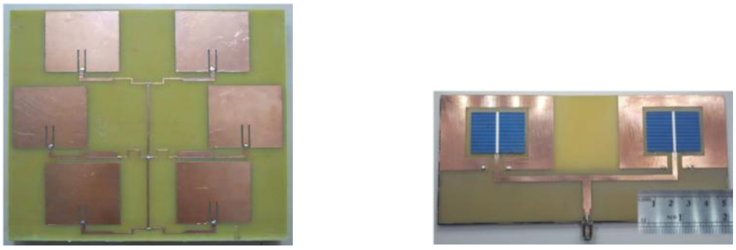


Figure 1. HMAS prototype and installation. Source [6]

3.2. Use of electromagnetic (RF) energy

The latest energy harvesting solutions harness radio waves from various devices. The energy that can be extracted from radio waves is typically low but constant. Radio waves emitted by electrical engineering and network devices in the environment can be collected by antennas and used to help power low-power IoT devices [8]. Energy from radio waves is typically used in warehouses and production halls in confined spaces. In order to collect energy more efficiently, it is necessary to collect energy from multiple sources with different frequencies. An example of these solutions is shown in Fig. 2, which shows so-called multiband radio frequency collectors. However, due to the specificities of the technology, prior assessment is important, as metals and liquids absorb radio waves to a large extent, so the amount of energy that can be extracted varies from one area to another. Care must also be taken to ensure that the energy harvesting systems do not interfere with the communication that takes place using the radio waves to be used.



a) Microstrip antenna array. Source [109] *b) SCR-AR prototype. Source [110]*

Figure 2. Multiband RF rectennas

3.3. Use of temperature difference

The Seebeck effect can be used to use the heat difference. For the physical realization, blocks of two semiconductors with different impurities are formed in a special arrangement, so that the temperature difference measured on both sides of the element generates an electric current [11]. In addition to the Seebeck effect, recent research has led to the emergence of solutions that exploit the temperature difference between the two surfaces, which operate on different principles. One of them is based on materials that generate electric current during the solid-liquid phase change [13]. Fig. 3 shows the principle of operation. In this solution, nanotubes are used to form a composite material to enable energy harvesting.

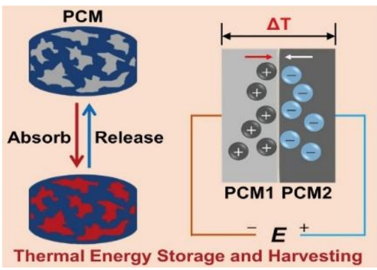


Figure 3. Theoretical operation of Phase Change Material (PCM). Source [13]

3.4. Use of natural resources

Light-based energy harvesting is achieved by using the well-known solar panels. The energy can be used outdoors, where we can mainly use the energy from sunlight, while indoors the energy is based on lighting and incident light. Obviously, less energy can be collected indoors, but increasingly efficient low-power electronics can still collect enough energy to keep the system running. Significant energy can be recovered by using polymers and water-based gels to harness the internal light [14].

In the case of wind and fluid flow, the principle is similar, with some kind of rotating or alternating motion mechanical device using an electromagnetic generator to produce useful energy from the motion. They can be considered among the earliest energy harvesting systems, as wind and water mills existed centuries ago. The electricity generated by modern wind turbines can be used to power logistics systems or run production lines, but locally installed low-power wind turbines can also help reduce electricity costs. In the field of transport, a turbine installed close to the rails can help power rail transport sensors by generating power from the winds of passing trains [15].

3.5. Comparison of technologies

A comparison of the different solutions and their applications is summarized in Table I. As can be seen, the different technologies have different advantages and disadvantages, so it is important to assess the potential of each technology before applying it to the task at hand in order to choose the optimal solution for energy harvesting. Energy from natural resources is also compared, as it can also reduce the required grid energy consumption, although it is not considered as an energy harvesting solution. Energies from vibrations, kinetic energy, radio waves and temperature differences can be considered as relatively constant, predictable and stable sources.

Table I.

Comparison of energy collection systems (own editing)

Type	***Place of application***	***Benefits***	***Disadvantages***
Vibrations, movements	Power supply for conveyor belts, sensors for production machines	Energy generated locally, no need for cabling	Limited use and low power
Radio waves (RF)	Warehouses, manufacturing plants	Continuously available	Low power, communication interference, absorption
Thermoelectric	Use of waste heat from manufacturing to power sensors	Provides constant power	Limited range of applications
Solar panels, wind energy	Charging warehouses, electric vehicles	Available everywhere	Power output is weather dependent

However, the efficiency of all three systems depends on the location of the application, as it is not the same whether the vibrations of a small engine are used or those of a large press.

The power that can be extracted also depends on the amplitude of the movement or vibration, and the higher the amplitude, the greater the energy that can be extracted. The use of radio waves must also take into account the smooth operation of communication systems, which requires prior assessment and planning. For thermoelectric systems, low power can be a limitation, since in logistics processes it is rare to find a case where a large heat difference occurs at an interface.

4. ENERGY HARVESTING IN MONITORING SYSTEMS

Two technologies in logistics tracking systems currently require their own power source. Semi-active RFIDs and the TAGs of RTLS systems contain a power source, while the other identification and tracking solutions operate without external power supply. The power source in these devices can be either a single-use battery or a rechargeable battery, whose charge is indicated in some way by the device [16]. However, a discharged TAG cannot perform its function and if its last position is not known, its location can be problematic. In devices with batteries, the use of energy harvesting systems may be relevant to extend the operating time. TAGs placed on transport vehicles or on workers can use two types of energy harvesting solutions: systems based on vibration and motion, and systems using radio waves. With the development of Industry 4.0 and digitalization, the use of smart devices is essential for more accurate and efficient operations, and their power supply is becoming increasingly important. With IoT systems, there may also be a need to support the powering of smart sensors using energy harvesting technologies. The results of the literature survey show that currently the power supply of these devices is not or very rarely supported by energy harvesting systems. As IoT devices typically consume more energy, it is important to ensure that their charging is provided by energy harvesting systems, knowing the limited battery capacity. Small, combined devices are now available on the market that can harvest energy from multiple sources (vibration, light and radio waves) simultaneously, making them more efficient than single-source devices [17].

The use of energy harvesting systems is essential for Industry 4.0, especially when it comes to complying with increasingly stringent environmental regulations. Currently, there is no methodology to support the use of energy harvesting solutions in tracking systems, so in our future research we will investigate the criteria and analysis needed to select the right system, the solutions it should include and the resources and improvements needed in logistics systems to implement it. In essence, our aim is to develop a methodology that can be used to conceptualize the design and operation of an ideal tracking system for a given logistics system. In order to do this, it is necessary to consider not only the logistics system but also the conditions of the application site.

5. REQUIREMENTS FOR ENERGY HARVESTING SYSTEMS

For energy harvesting systems, the first step is to assess the area. This involves using test equipment with different technologies to see how much energy can be recovered. In addition, it is important to assess the energy demand of the components of the monitoring system used, which devices can be assisted with energy collection and at which locations. The survey should also examine the spatial and temporal distribution of the energy that can be collected with each technology. Once these have been summarized and analyzed, planning should start, where possible, with the power supply of the most important devices. For existing devices, such as RTLS tags, the problem may be how to modify the enclosure, even if it is waterproof, so that the energy harvested can be connected to the power supply circuit without damaging the original protection. It is also important to ensure that the devices to be installed are placed in the correct position and are adequately protected. It is enough to consider that devices on a pallet lifted by a forklift truck may be subject to physical stresses during material handling. It must be ensured that the equipment does not move or fall off the supported equipment or container. The implementation of this is also under consideration, as it makes a difference whether the energy harvesting equipment is placed on a metal drum containing a liquid or on plastic products on a wooden pallet.

6. Summary

In this thesis, a detailed literature analysis was carried out to investigate which energy harvesting systems are relevant in the field of logistics and which solutions have advantages and disadvantages. Furthermore, some applications and solutions have been described. We have also looked at energy harvesting in a broader sense by examining the use of natural resources. In the field of monitoring systems, the review of publications did not identify any developed methodology that would provide a solution for the optimized design and operation of monitoring systems, taking into account the potential of energy harvesting systems.

In our next publication, we will explore in detail the requirement framework for the application of energy harvesting systems and the optimization opportunities that can be achieved through their application. We will examine the differences between the possibilities of upgrading an existing system and those of a greenfield investment. The requirements for the application of energy harvesting systems in each application area will be explored.

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