Novel Energy Harvesting Solutions for Powering Trackside Electronic Equipment

Cristian Ulianov, Zdeněk Hadaš, Paul Hyde and Jan Smilek

Abstract Recent developments in different areas have enabled the improvement and development of new energy harvesting technologies that could potentially be successfully employed for various railway applications. The state of development of energy harvesting solutions potentially suitable for integration in the railway environment to power trackside equipment has been reviewed and assessed. The general harvesting capacities and characteristics of potential energy harvesting technologies have been discussed, along with the general power usage requirements and characteristics of common types of trackside equipment. Conclusions have been drawn about the most suitable energy harvesting technologies, or combination of technologies to be incorporated into a combined energy harvesting and storage power supply for different trackside equipment.

Keywords Energy harvesting · Railway systems · Signalling · Trackside electronics

1 Introduction

Trackside equipment used to control and monitor the movement of train and monitor the railway infrastructure are currently generally powered through cables from the electricity grid. This has significant impacts on overall infrastructure reliability, availability, maintainability and safety (RAMS), as well as on its life cycle costs (LCC). Developments in energy harvesting technologies, and low-power and cost-efficient sensors and communication equipment

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, have made the development of self-powered energy harvesting trackside systems a realistic possibility. The development of energy harvesting technologies that could be easily integrated into the track system is a potentially viable alternative powering solution for trackside equipment, particularly if combined with more power efficient trackside equipment.

Such energy harvesting solutions would allow minimising the use of cables and provide infrastructure managers with alternative technologies that could be used for the next generation of low-power trackside electronic equipment.

In this paper, the energy harvesting capabilities and technology characteristics have been considered, with respect to the energy requirements of common trackside applications. An overview of combinations of energy harvesting technologies and applications that could be potentially viable is presented.

A commonly used definition of energy harvesting technologies (Mateu and Moll 2005) is:

> An energy harvesting device generates electric energy from its surroundings using some energy conversion method. Therefore, the energy harvesting devices here considered do not consume any fuel or substance. On the other hand, as the environment energy levels are very low (at least for today's electronic devices requirements).

The energy harvesting concept is based on converting some type of available ambient energy into usable electrical energy using a dedicated device (energy harvester). The amount of available power and the ease or difficulty of its extraction and conversion are crucial limiting factors for independent devices, especially those of small size. Most of the current remote electronic applications rely on the battery or mains supply as a primary source of power. Energy harvesting, if implemented, serves mostly as a secondary power source meant to extend the service life until the next battery replacement or recharge. However, with the ongoing miniaturisation of the electronic devices, their increasing power efficiency and decreasing power consumption, the energy harvesters could serve as the primary power source for some low power applications. Larger energy harvesting and storage installations could be also considered for the primary power source of some trackside applications with moderate or high power requirements. However, the main determining factors for such large power supplies are likely to be life cycle cost and reliability rather than their technical viability.

2 General Considerations on Energy Harvesting Technologies

2.1 Background of Trackside Energy Harvesting Technologies

For nearly 20 years energy harvesting has been investigated as a possible source of power for wireless applications, which would be for one reason or another difficult

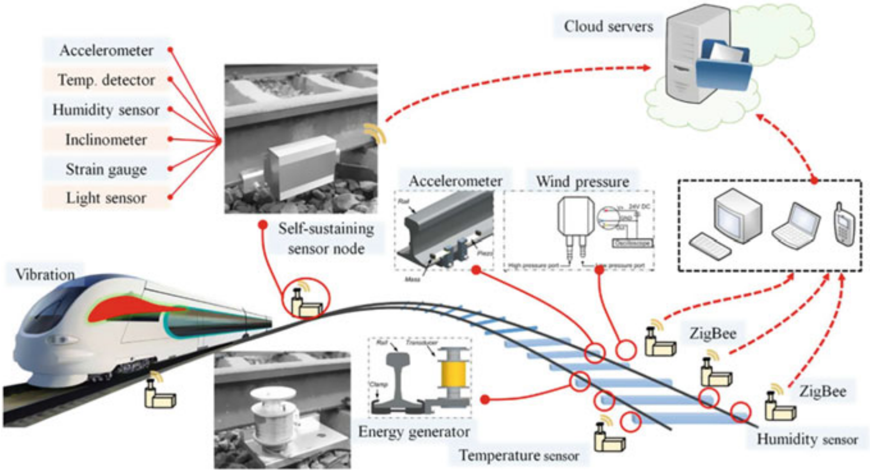


Fig. 1 Illustration of proposed solution for intelligent monitoring of underground railway (Gao et al. 2017a, b)

to connect to the power grid. These applications currently include mainly wireless sensor nodes for structural or health monitoring systems (Aktakka and Najafi 2014), in aerospace (Hadas et al. 2014) or transportation (Yoon et al. 2013). Figure 1 shows a solution proposed for intelligent monitoring of railways, which is based on energy harvesting technologies (Gao et al. 2017a, b).

Energy harvesting solutions also cover common renewable energy technologies, which are integrated in an original object. In case of trackside energy harvesting applications, it could be, e.g., a photovoltaic cover on trackside objects, trackside wind turbines, sleepers with integrated photovoltaic panel or sleeper with integrated wind turbine, etc. Wind turbines and solar panels are commonly used as autonomous sources of energy for various remote applications. These technologies can be exploited and integrated for the trackside power source solutions and turbines or solar panels provide alternative source of energy for trackside objects.

Kinetic energy in a form of mechanical deformation, vibrations, shocks, and thermal energy in a form of waste heat sources are exploitable inputs for autonomous power sources in several engineering applications related to energy harvesting. Waste heat sources are not readily available in the trackside environment. However, they could be useful for on-board solution (e.g., waste heat caused by friction). On the other hand, a passing train provides a non-negligible source of input mechanical energy, which could be converted into electricity by various transducer setups. Although a typical train does impart a large amount of mechanical energy into the infrastructure, the energy is distributed and dissipated over a large area, therefore, capturing this energy efficiently in a relatively small device is a complex problem. The amount of harvested energy from vibrations is usually very low, and the output electrical power

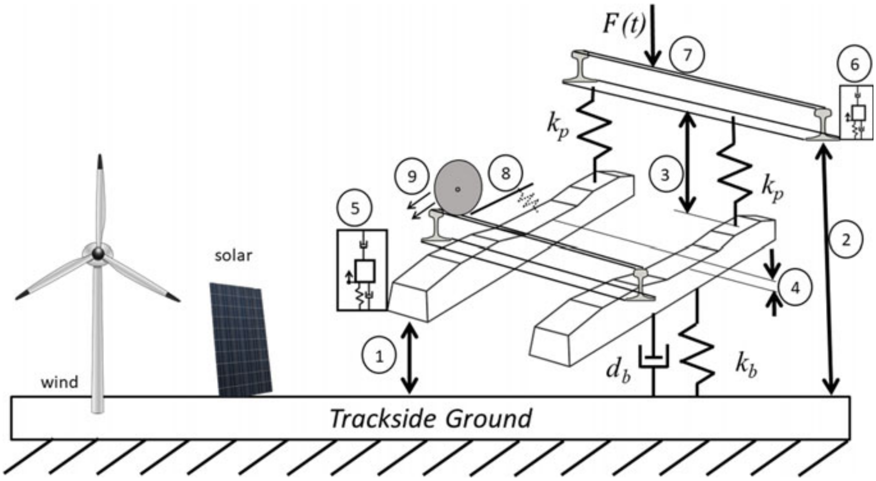


Fig. 2 Potential trackside energy harvesting technologies

has to be predicted and compared with the power requirements of intended ultra-low power applications.

Figure 2 shows potential application and integration of trackside energy harvesting technologies, including:

- Commercial solar and wind power products
- Displacement, strain and deformation energy harvesting—type ***1***, ***2***, ***3***, ***4***, ***7***, ***8***
- Vibration energy harvesting—type ***5***, ***6***
- Change of magnetic field by passing wheel—***9***
- Thermal gradient between in trackside environment (if available).

2.2 Physical Principles of Energy Harvesting

The scope of energy harvesting is to convert energy from one form to another, so that it could be used to power electronic devices. In general, energy harvesting relies on both ambient and external sources. Ambient sources such as radio frequency (RF), solar, thermal, wind, etc. are accessible within the environment, without any external energy supply. External sources (e.g., mechanical) are those that emit energy to the environment, with the intent for this energy to be harvested by specifically designed devices.

The underlying physical and technological principles, which can be applied to deriving power from various energy sources for the purpose of harvesting energy, are briefly summarised in this section.

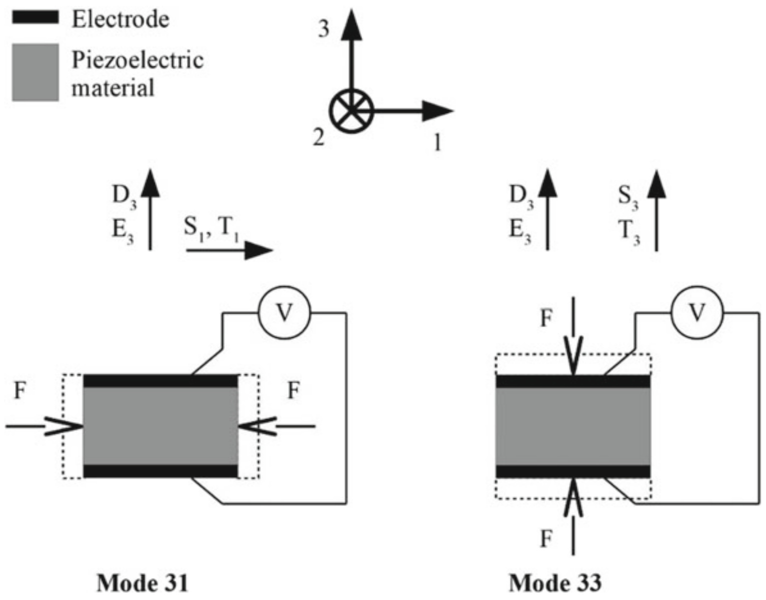


Fig. 3 Operation modes of piezoelectric material for energy harvesting

2.2.1 Piezoelectric Conversion

Piezoelectric materials have the property of converting a mechanical stress or strain applied to them into a change of electric field or electric displacement within the material and vice versa. Conversion from mechanical to electrical energy is called the direct piezoelectric effect, and the conversion from electrical into mechanical domain is known as reverse piezoelectric effect (Batra and Alomari 2017). The piezoelectric phenomenon is based on the fundamental structure of a crystalline network—certain crystalline structures have a charge balance with polarization, which must be oriented in one direction to produce piezoelectric behaviour of the material.

Two operation modes of piezoelectric materials are important for energy harvesting (Ambrosio et al. 2011), i.e.: mode 31 and mode 33, which are depicted in Fig. 3. In these modes, the external force is applied only in one direction, which is the most common case in energy harvesting devices and electrical potential is observed on electrodes.

A cantilever design of energy harvester, which uses the mode 31 of piezoelectric effect to harvest energy for bridge monitoring purposes was developed by Cahill et al. (2018) (Fig. 4).

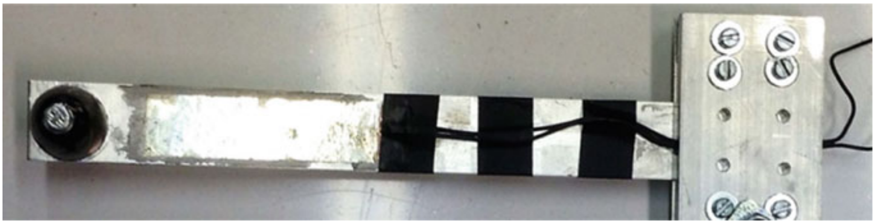


Fig. 4 Piezoelectric cantilever for energy harvesting (Cahill et al. 2018)

2.2.2 Electromagnetic Induction

Electromagnetic induction is the production of an electromotive force (EMF) across an electrical conductor in a changing magnetic field. The EMF generated due to relative movement of a circuit and a magnetic field is the phenomenon underlying electrical generators and is based on Faraday's law of induction. When a permanent magnet or magnetic circuit is moved relative to a conductor, or vice versa, an electromotive force is created. If the wire is connected through an electrical load, current will flow, and thus electrical energy is generated, converting the mechanical energy of motion to electrical energy.

2.2.3 Electrostatic Conversion

The principle of electrostatic energy conversion lies in exploiting a capacitor with variable capacitance value. The two electrodes of the capacitor, separated by air, vacuum or any dielectric material, move with respect to each other due to mechanical excitation. That leads to a change either in the active surface of the electrodes, or their distance from each other, causing a variation in the capacitance (Boisseau et al. 2012). Energy harvesters based on electrostatic conversion are related to Micro-Electro-Mechanical Systems (MEMS) technologies and provide very low output power.

2.2.4 Magnetostriction

A characteristic property of magnetostrictive materials is that a mechanical strain will occur if they are subjected to a magnetic field in addition to strain originated from pure applied stresses, Fig. 5. Also, their magnetisation changes due to changes in applied mechanical stresses in addition to the changes caused by the changes of the applied magnetic field. A coil is integrated for energy harvesting operation (Kaleta et al. 2014). Commonly used magnetostrictive materials include Terfenol-D alloy (Fan and Yamamoto 2015), Galfenol (Berbyuk 2013) and Metglas.

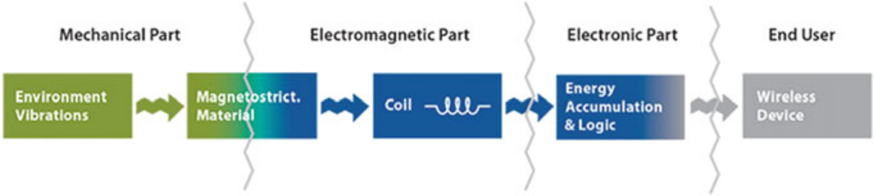


Fig. 5 Magnetostriction energy harvester as combination of smart material and electromagnetic induction

2.2.5 Triboelectric Effect

Triboelectric nanogenerators (TENG) are based on two principles such as triboelectric effect and electrostatic induction. The theory of this type of energy harvesters is described by many researches (e.g. Jiang et al. 2016), and follows from the structure of TENG device. TENG has shown advantages such as high output voltages, high energy-conversion efficiency, abundant choices of materials, scalability and flexibility (Zi et al. 2015). There is a potential to use as a power-generator floor or bed (Zhang et al. 2015).

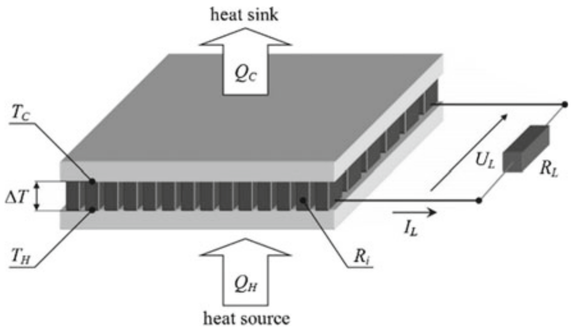
2.2.6 Photovoltaic Effect

The photovoltaic effect occurs when photons are absorbed at a junction between two dissimilar materials (a heterojunction), inducing a voltage. Materials used for fabricating such heterojunctions are generally semiconductors, which are responsive to light of various wavelengths. A typical photovoltaic device mainly consists of a large area semiconductor p-n junction.

2.2.7 Thermoelectric Conversion

Thermoelectric generators consist of a thermoelectric module, a heat source (hot side) and a heat sink (cold side). The thermoelectric module utilises the Seebeck Effect to convert a temperature difference between each side of the device to an electromotive force. A schematic representation of a thermoelectric module is shown in Fig. 6. This phenomenon is based on diffusion of electrons through an interface between two different materials—usually semiconductors; the diffusion is achieved by applying heating at the junction of the materials, which make a thermocouple.

Fig. 6 Thermoelectric energy harvesting module



3 Implementation of Energy Harvesting Technologies in Trackside Applications

Development of effective implementations of energy harvesting for trackside applications depends on three main categories of factors. These are: the energy consumption of the device or devices being powered, the energy harvesting characteristics and capacity of the energy harvester, and the characteristics of the trackside environment.

3.1 Potential Trackside Applications of Energy Harvesting Technologies

The scope of trackside energy harvesting applications is to power trackside equipment locally and avoid the need for power cables from the electricity grid to the equipment. Associated with this, is the replacement of communications cables with radio communications, also powered by energy harvesting. The objective of reducing or eliminating trackside cables is to reduce installation, commissioning, maintenance and repair costs, as well as reducing the vulnerability of the system to copper cable theft. The main potential applications envisaged are for powering, wireless communications, wireless command and control data links, local interlocking and trackside object control, train detection, condition monitoring systems, signals and signalling equipment, route switching (point motors), level crossing equipment (monitoring and actuation), and point heaters. The energy harvesting profiles of the technologies discussed previously are all subject to variation in terms of the energy output from the devices, according to the availability of the energy source they are harvesting energy from. For the power supply (energy harvesting and storage combined) to be reliable, the energy harvester must capture more energy on average than is used, and the storage capacity must be sufficient to accommodate the cycles and variations in energy harvesting and usage, and also include an element of redundancy to ensure reliability.

Modern micro-electronic wireless communication and data links, which could be used for communications and command and control functions, with relatively low data rates have fairly low power consumption (less than 1 W). These could need to be active almost continuously in order to verify the status of equipment with similar latency to conventional wired systems, or power saving procedures, could be implemented when revising railway signalling procedures to be more power efficient. Local signalling control and interlocking, and the command and control of trackside equipment has many features in common with communications and data links in terms of the power consumption, particularly as communications and data links are often an integral part of their function. Current devices used in this application have moderate levels of power usage (tens of Watts) but there is potential for replacing them with modern micro-electronics with power usages an order of magnitude lower.

Train detection systems are used to verify track occupancy so that traffic control systems can safely authorise train movement. Traditional track circuit train detections systems require a moderate amount of power continuously. Axle counters which detect and count each wheel entering or leaving a section of track so that the occupancy of a section of track can be established use less power than track circuits but also need to be responsive and therefore active continuously in current railway signalling practices. Current trackside signals require a low to moderate amount of power continuously (about 10 W), with signals based on LEDs.

The setting of routes on railways is actuated by electrically powered devices (some have a hydraulic power transfer stage) known as point motors. These have a large momentary power requirement, of about 3 kW for 20 s, which occurs intermittently when the route is changed, with an additional low continuous power requirement to confirm the status. Equipment installed at level crossings to prohibit the passage of road traffic ranges from flashing lights, to half or full barriers (with flashing lights as well) and might include a monitoring system. The power consumption of the flashing lights if fairly low and intermittent, the power usage of the barriers is moderate to high and is also intermittent, monitoring systems might be active continuously or only activated when required and would have fairly low power requirements.

In some locations, according to the climate, heaters are installed prevent the moveable rails at junctions from being frozen in place by accumulations of snow and ice. The power usage of these “point heater” devices is very high, in the order of magnitude of kilowatts, is seasonal, and can be active for prolonged periods. Various monitoring systems might be applied to the trackside infrastructure at various locations depending on requirements, these might include noise or landslide detection systems for example. The energy usage of monitoring systems would generally be quite low depending on the type of equipment, and might be very low for devices which are largely passive and only activate a low energy usage process when trains are passing or intermittently, but are otherwise in a dormant state.

3.2 Energy Harvesting Concepts for Trackside Applications

In general, it is envisaged it might be feasible to power applications with very low or low intermittent energy usage might with energy harvesting techniques, which derive their power from the passage of trains, with or without supplemental energy harvesting from a very small solar or wind installation. This could be useful in situations such as tunnels and cuttings, where limited solar radiation or ambient air flow are available. It might be feasible to power applications with low or intermittent moderate energy usage using small installations of wind, solar or combined wind and solar energy harvesting techniques possibly supplemented with additional energy from harvesting techniques which derive their power from the passage of trains. Applications which have large energy requirements would require large solar, wind or solar and wind installations along with a very high capacity energy storage system to make powering them with energy harvesting feasible. Although perhaps technically possible is likely to be impractical and economically unfeasible to power equipment with very large energy requirements, such point heaters, using energy harvesting techniques.

3.3 Development of Trackside Energy Harvesting Solutions

A preliminary analysis and a feasibility study of an trackside energy harvesting solution are necessary development steps in the design of these autonomous systems (Hadas et al. 2018). Mathematical models of the physical principles employed and performance data for commercial energy harvesting systems can be used, in combination with analysis of the energy requirements of the applications, to conduct a feasibility study of useful energy harvesting systems. The waterfall development diagram, shown in Fig. 7, can be used to describe development steps for the design of fully autonomous energy harvesting systems.

3.3.1 Railway Network Parameters

The parameters of the railway environment which affect energy harvesting vary according to the particular geographic characteristics of the railway route and location, railway infrastructure characteristics, and railway traffic characteristics. Variations in particular parameters have different effects on different physical principals of energy harvesting. The geographic conditions of the route mostly affect environmental energy harvesting methods, such as solar and wind, the geographic position of the location affects the solar exposure throughout the year and the pattern of wind conditions. Solar based energy harvesting methods need to be aligned with the sun for optimal energy harvesting although will harvest some energy in other orientations. Also the ground profile and vegetation of the location affect the incident solar and

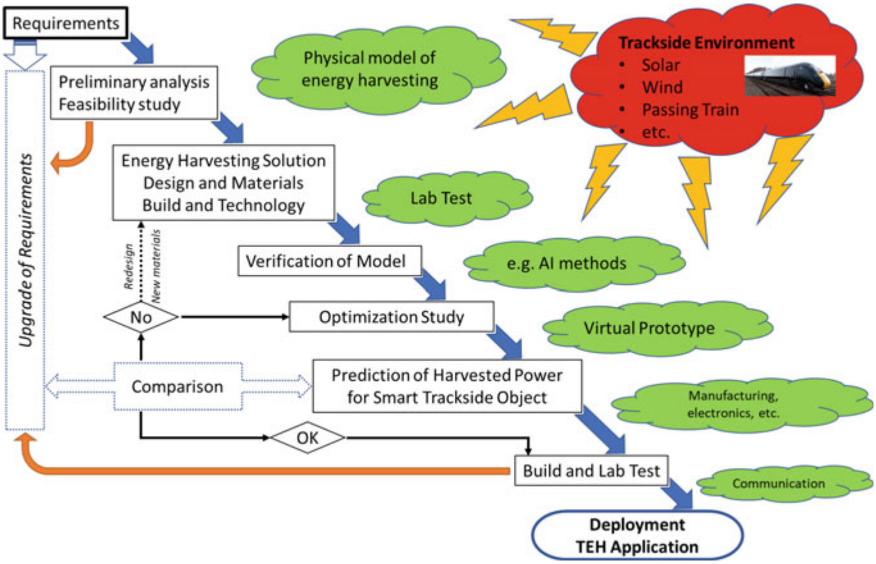


Fig. 7 Waterfall diagram showing the development of energy harvesting system for trackside application

wind energy at the trackside, the local landscape increasing the shading or sheltering the energy harvester compared to an flat open site.

Railway infrastructure characteristics mostly affect energy harvesting from train induced vibration and displacement. Track construction, components and materials; different types of rail, fixing, and rail support (sleepers etc.) affect the dynamic behaviour of the track and therefore the dissipation of the energy imparted by a passing train, which in turn affects the quantity and form (in terms of frequency and amplitude for example) of energy available at a location for the energy harvesters to collect. Also the quality of the maintenance of the alignment affects the interaction between the train and the track and hence the energy input to the track. Other features such as switches and crossings present a disturbance to the support of the wheel, leading to impacts and locally higher energy input into the track. As well as the characteristics of the track, the track support and ground conditions affect the dynamic behaviour of the track.

A factor which affects energy harvesting based on train induced vibration and displacement, and train aerodynamics based wind generators are the railway traffic characteristics, traffic pattern. This includes the length and number of trains, the speed of the trains, the load condition and the vehicle dynamics of the types of vehicles.

3.3.2 Reliability, Cost and Maintenance Considerations

In addition to the physical environment and the practical viability of a TEH design, the reliability, cost and maintenance requirements of the TEH (and track) need to be considered. In general they should be at least as reliable as current power supply, and have lower life cycle costs considering procurement, installation and maintenance. Also they should be easily maintainable at track-side, self-diagnostic and easy to inspect, the components or modules should be easily replaceable to minimise downtime and time staff on site to correct faults. The impact of the energy harvesters on the maintenance of the track and railway infrastructure, such as inspections, tamping, and rail-grinding should also be considered, as should the vulnerability to theft, and other external factors such as extreme winds and flooding.

4 Overview of Existing and Emerging Trackside Energy Harvesting Technologies

4.1 Solar Energy Harvesting Technologies

Various solar panel products are commercially available for general use to supply power to different applications; the range in power output and size varies from very small to panels which have a power output of a couple of hundred Watts and areas of a couple of square meters. Specialist panels could be integrated or applied to structures of various shapes if a particular situation requires it. Small solar panels of around 0.1 m^2 can be applied to equipment or a suitable surface almost anywhere on or around the track and harvest a small amount of power. Larger panels of a couple of square meters could be installed on posts, or similar mountings, next to the track to provide a low to moderate average power output. Larger arrays of solar panels with higher power ratings might require installation on land further from the trackside, possibly outside the normal railway boundary. The performance of commercial solar panels in terms of how much power they generate for each unit of sunlight is well established, e.g., the nominal maximum power rating of crystalline silicone solar panels is approximately 150 W/m^2. The average power output of the solar panels is affected by their orientation, local shading, the geographic location of the installation, seasonal variations, and the weather.

As an alternative to conventional solar arrays the start-up Greenrail recently presented an eco-friendly sleeper, which integrates a photovoltaic (or piezoelectric) module onto a lightweight composite sleeper. Information on the power output or other parameters is not yet available, as the product is still under development; product samples and trial installations are shown in Figs. 8 and 9.

Fig. 8 Solar sleeper (Greenrail Project No. 738373—H2020-SMEINST-2-2016-2017)

Fig. 9 Solar sleeper installation (Greenrail Project No. 738373—H2020-SMEINST-2-2016-2017)

4.2 Wind Turbine Technologies

Various commercially available designs and products for energy harvesting from environmental air flows are suitable for general use supplying power to multiple applications. These conventional wind turbines are most commonly either bladed designs rotating about a horizontal axis, or designs with vanes rotating about a vertical axis, and are available in a variety of sizes with varying power output ratings. Wind turbines of moderate power rating and size, for example power ratings of hundreds of Watts and major dimension of around 1 m, could be installed at most trackside locations, although performance in locations sheltered by buildings or the landscape will be less than optimal. Larger wind turbines with higher power ratings might require installation on land further from the trackside, possibly outside the normal railway boundary. The power ratings of wind turbines can be expressed as either the maximum power output at the optimal wind speed, or more usefully the nominal monthly average power output, although this would vary according to the month, conditions at the installation location in terms of sheltering and exposure, and the profile of the wind conditions at the geographic location throughout the year. Examples of commercially available wind turbines include:

- a three bladed model with a 1.17 m diameter rotor with a swept area of 1.07 m^2, optimum wind speed range is 4.5–22 m/s, and has a 40 kWh/month average output based on an average annual wind speed of 5.8 m/s (Primus Windpower);
- a design with vanes rotating about a vertical axis, which has a rotor of 0.27 m diameter with a height of 0.918 m; it has a momentary power output of 24 W at a wind speed of 8 m/s, and the peak output is 200 W (Leading Edge—Vertical Axis Turbine).

In the context of this paper, devices intended to make use of the aerodynamic effects of passing trains are included in the category of wind turbines. Devices that harvest energy from the aerodynamic effects can either be focused entirely on harvesting energy from the air currents caused by passing trains, or a combination of this and environmental wind. The advantage of the latter approach is that one device can harvest energy from both sources with air currents from trains supplementing he environmental wind, particularly on days where there is little or no environmental wind. By necessity wind turbines which use air currents generated by trains have to be fairly small to fit in the railway environment around the area when trains pass where the air currents are strongest, and consequently of moderate power rating. The disadvantage of these types of wind turbines is that they might not be ideally placed to take advantage of the environmental wind.

An example of an energy harvester focused entirely on harvesting energy from the air currents induced by the aerodynamic effects of passing trains is the T-BOX Wind Power Generator (T-BOX Wind Power Generator). The device, shown in Fig. 10,

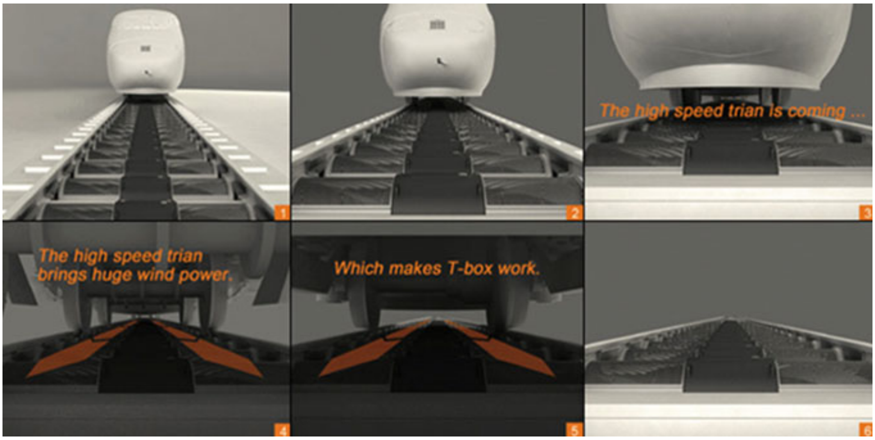


Fig. 10 T-BOX wind power generator (T-BOX Wind Power Generator)

is installed between railway sleepers, and is partially buried underground. As the train passes over the device, the air currents generated from the train aerodynamics spins the turbine inside the T- box to generate electricity. The T- box contains all the mechanical components required for harnessing, storing and supplying converted power. It consists of a durable metallic cylinder with vents, which allow air to flow through and rotate turbine blades housed inside. The Hetronix wind turbine system consists of a 2.5 m long rotor system and a generator which is 35 cm in diameter. The 58 kg wind turbine is rated at 2000 W with a 12.5 m/s airflow.

4.3 Technologies Based on Linear Displacement Electromagnetic Generator Concept

One concept for harvesting energy from the trackside environment is to use the linear displacement induced by the passage of trains and transfer this motion to an energy harvesting component. The displacement could be captured either from contact with the wheel directly or from a connection to the track that is displaced by the train. Some examples of different concepts for capturing energy from train induced displacements are presented further on in this section.

Geared electromagnetic generators prototypes

Most of the concepts and prototypes that have been developed so far are based on devices fitted to the track and operating on the principal of transforming vertical displacement of the track caused by the passage of a train, via racks, gears and clutches, to a rotary motion to drive a rotary electromagnetic generator. The main distinguishing feature between these designs is whether the device is connected to

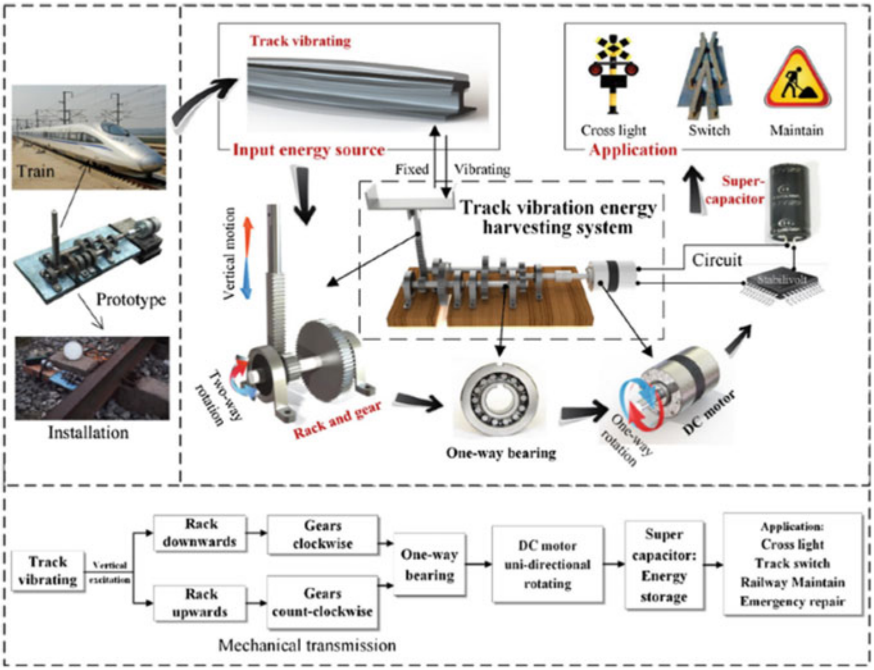


Fig. 11 Design and prototype of the energy harvester with output energy peak voltage of 58 V at 1 Hz with a displacement of 2.5 mm (Zhang et al. 2016)

some form of ground anchor to utilise the relative motion between the track and the ground, or if the device is only connected to the track and utilises the relative motion between different locations on the track.

A team from Southwest Jiaotong University, China, presented a portable high-efficiency electromagnetic energy harvesting system (Zhang et al. 2016), depicted in Fig. 11. It consists of two main parts: mechanical transmission and the electrical regulator. With a displacement of 2.5 mm at 1 Hz, the peak output voltage is 58 V, which is close to being practically useful for supplying trackside applications, such as safety devices and emergency repairs in areas lacking power, indicating that the proposed system has potential as a renewable alternative energy source.

Another prototype of mechanical rectifier based harvester has been developed by a team from Stony Brook (Wang et al. 2012). The results of laboratory testing show that sufficient power can be harvested, as well as the features and benefits of the motion rectifier design, which is shown in Fig. 12.

A novel direct motion-driven harvester has been reported by TTCI (Lin et al. 2018). The harvester shown in Fig. 13 is anchorless and harvests energy without requiring special preparation during installation. Compared to any traditional anchored device, this design is more practical, as it does not require a long interruption to the operation of trains during its installation.

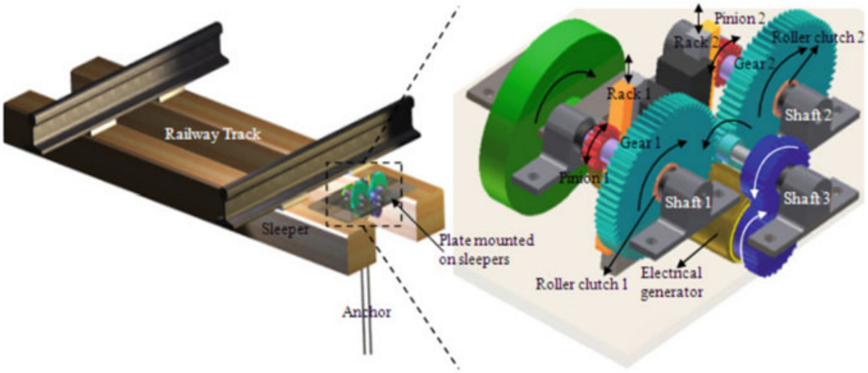


Fig. 12 Electromagnetic energy harvesting from train induced railway track displacement (Wang et al. 2012)

Linear electromagnetic generator concept

Linear generators produce electricity from the relative movement of the components using the electromagnetic effect. They use the same electromagnetic principles as rotary generators. However, linear generators are potentially more suitable for some applications as they do not require complex mechanisms to transfer linear motion into rotary motion to harvest energy. Figure 14 shows a schematic representation of a linear generator.

A novel concept that considers different designs and installation options has been proposed within the EU Horizon 2020 project ETALON by the team at Newcastle University, for integrating linear generators into railway infrastructure. The concept is based on the principle of capturing energy from displacements induced by either the train itself, or the movement of the track under the train and transferring those displacements to a linear generator.

Schematic representations of various potential configurations for linear generator harvesters are shown in Figs. 15 and 16, where the black rectangle in each concept represents the mover of the linear generator, which contains permanent magnets, located within open box representing the stator coil and protective case. In Fig. 15 an actuating arm is connected at one end to the linear generator such that the contact element on the other end is positioned next to the inside of the railhead just below the running surface. When the wheel of a train passes, the flange of the wheel, which extends below the running surface of the rail, makes contact with the contact element and displaces it downwards. This linear (or arc segment) motion is transmitted either directly, as in Fig. 15a, or via a pivot (fixed to the track) to the linear generators (also fixed to the track), with the lever arrangement, as in Fig. 15b, c, amplification of the displacement is possible depending on the length of the levers.

In Fig. 16a, the linear generator and pivot are fixed to the sleeper and the linear generator is connected to the rail through the pivot via a lever to transmit the vertical displacement of the rail relative to the sleeper to the linear generator for energy

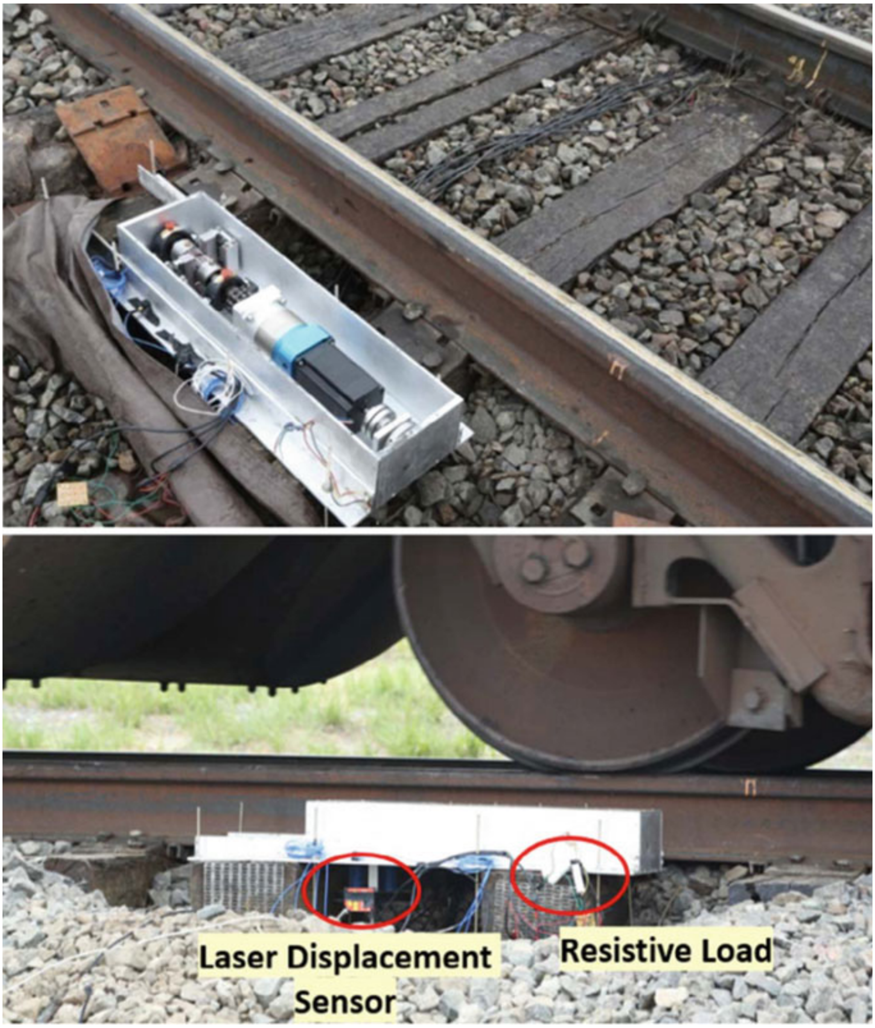


Fig. 13 Harvester installed and tested at TTCI test track, with fully loaded freight train running at 64 km/h (40 mph) (Lin et al. 2018)

harvesting. In Fig. 16b the linear generator and pivot are fixed to the ground and the linear generator is connected to the track through the pivot via a lever to transmit the vertical displacement of the track to the linear generator for energy harvesting. In this concept it is expected that there would be a large differential in the lengths of the lever either side of the pivot in order to amplify the small displacement and large forces from the track into a larger displacement at the linear generator.

A prototype has been designed (Fig. 17) for being manufactured and tested within the EU Horizon 2020 project ETALON.

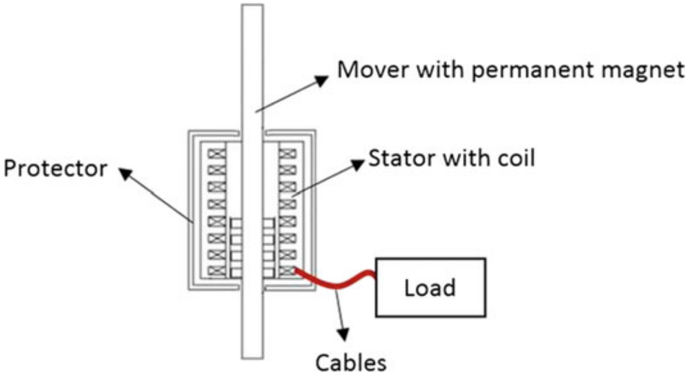


Fig. 14 Schematic representation of a linear electric generator

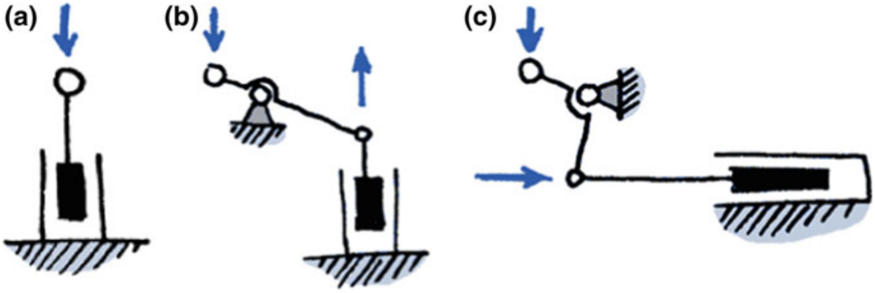


Fig. 15 Schematic representation of linear generator energy harvesters mounted on the track and displaced by the wheel

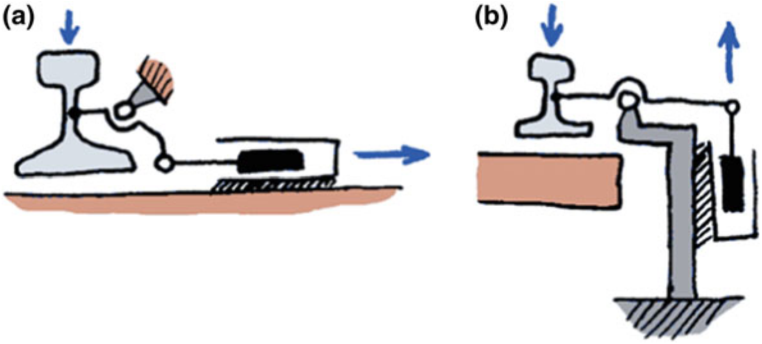


Fig. 16 Schematic representation of linear generator energy harvesters fixed to the ground and displaced movement of the track

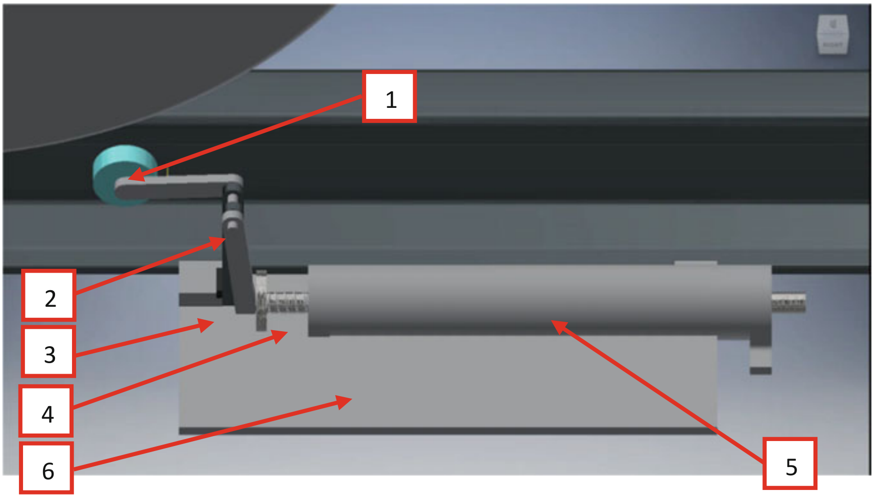


Fig. 17 Concept outline design of linear generator for trackside application. Key: (1) Contact element, (2) actuation mechanism, (3) limit mechanism, (4) return spring, (5) linear generator, (6) base plate/frame

4.4 Variable Reluctance Harvester Concepts

Electrical energy can be generated by an electromagnetic induction, caused by a change in magnetic reluctance induced by a passage of a train wheel, momentarily forming part of the magnetic circuit.

A team from University of Freiburg developed a variable reluctance harvester (Kroener et al. 2013). The test set-up for the harvester measured mean power output with respect to the velocity for three different clearance widths between the moving and the static parts of the reluctance circuit was published.

Magnetic flux from a permanent magnet in the variable reluctance generator, which is shown in Fig. 18, passes through the fixed part of the magnetic circuit, rail and air gap. The value of magnetic flux density is minimal when a train wheel is passing through the magnetic circuit of the generator. The path of the Magnetic flux in the magnetic circuit changes when the wheel of the train interrupts the normal path at a portion of it passes through the air gap. This causes a change in the magnetic flux within the wire coil which induces a voltage in the coil in accordance with Faraday‘s Law.

A rail concept of the variable reluctance harvester was analysed under the EU Horizon 2020 project ETALON. The simulation results shown in Fig. 19 present the calculated potential energy output of this design. Each passing wheel provides only one positive and one negative peak of voltage in a short time. The magnitude of the voltage peaks is proportional to the train speed and depends on the change of magnetic flux density through magnetic circuit. Due to range of the variation in the

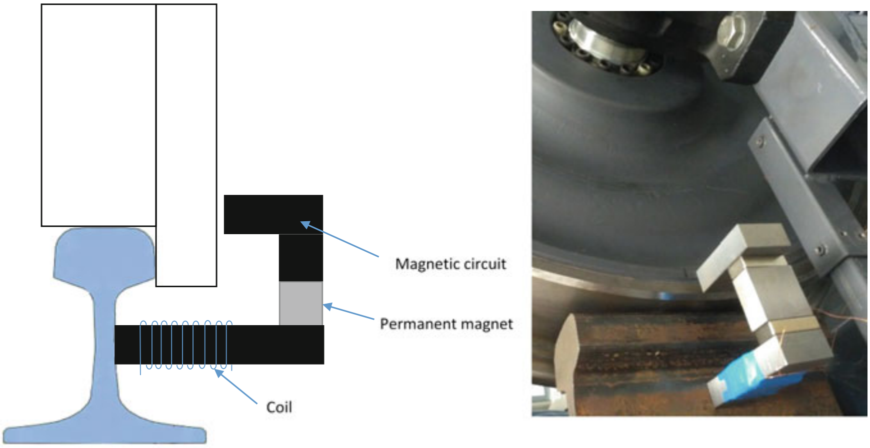


Fig. 18 Variable reluctance rail harvester; model and test concept of ETALON project

lateral position of the wheel relative to the rail, minimal allowed distance between the magnetic circuit and rail to avoid contact between the wheel and the magnetic circuit is 58 mm. Therefore, the change of magnetic flux density due to the presence of a wheel is in range of 100–250 mT, the actual value for any particular wheel pass depending on the actual lateral position of the passing wheel within the range of possible positions.

4.5 Vibration Energy Harvesting Technologies

The applications of vibration energy harvesting technologies are well established in the fields of structural monitoring of civil structures and aircraft. Passing train induce huge mechanical vibrations in the track and trackside environment. Several concepts of trackside energy harvesting technologies were investigated and published. The paper by Cleante et al. (2016) reported on an investigation into how much mechanical energy could potentially be harvested from the vertical vibration of a sleeper induced by trains passing at different speeds. Basic information about the very low outputs of different piezoelectric energy harvesting systems have been reported for a proposed piezo-drum design (Tianchen et al. 2014), a piezoelectric circular membrane array (Wang et al. 2014), piezoelectric vibration cantilever harvester (Gao et al. 2016), and piezoelectric patch-type and stack-type energy harvesters (Wang et al. 2015).

Vibration energy harvesters based on the electromagnetic principal provide more promising source of energy from trackside vibration which could be used for wireless sensor networks. Design of electromagnetic energy harvester by Gao et al. (2018), which converts rail vibrations into electricity, is shown in Fig. 20.

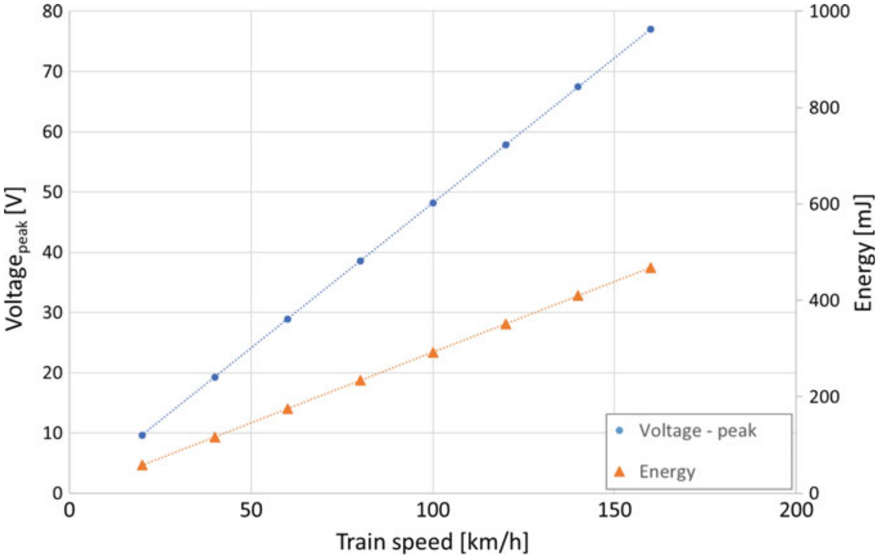


Fig. 19 Variable reluctance rail harvester; simulation results for coil with 2000 turns and an assumed change of magnetic flux density of 100 mT

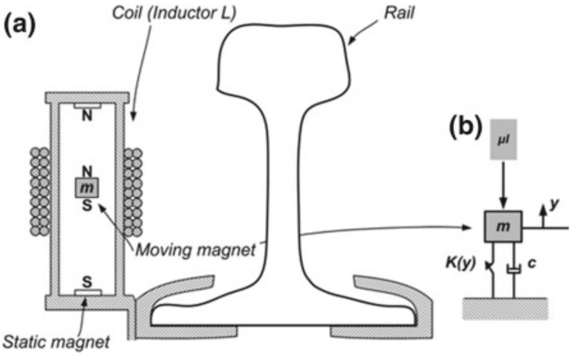


Fig. 20 Electromagnetic energy harvester by magnetic levitation: **a** physical model, **b** representative mechanical schematic (Gao et al. 2018)

The research by Southwest Jiaotong University (Gao et al. 2017a, b) investigated the possibility of establishing a self-powered wireless sensor network by integrating the ZigBee stack protocol together with an energy harvesting power source. Field test of self-sustaining sensor nodes with local energy harvesting is shown in Fig. 21.

Swedish company ReVibe Energy has developed electrodynamic vibration energy harvesters of various sizes. Their pilot project in cooperation with Deutsche Bahn AG includes adaptation of in-house developed inertial energy harvesting units for the trackside environment.

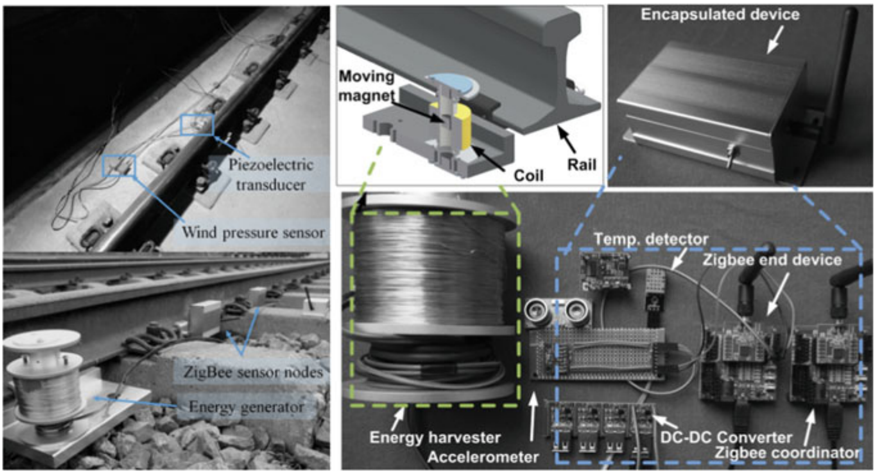


Fig. 21 Field test of self-sustaining sensor nodes with local energy harvesting (Gao et al. 2017a, b); Illustration of hardware prototype of self-sustaining sensor nodes for urban rail transit (Gao et al. 2018)

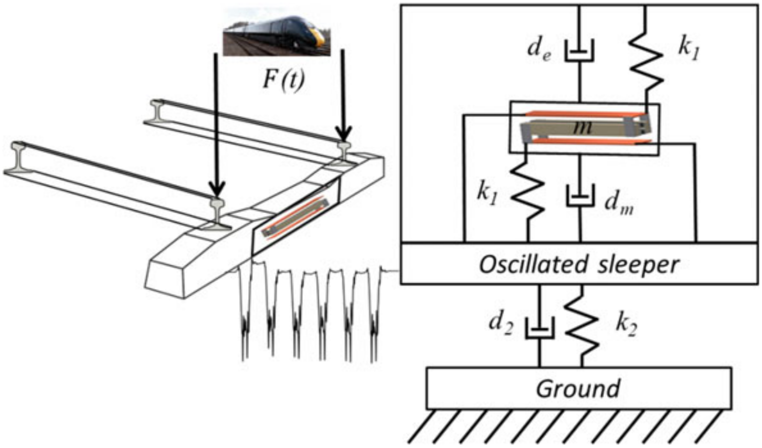


Fig. 22 Principle of pulse excitation by passing train of electromagnetic vibration energy harvester

ReVibe Energy and Southwest Jiaotong University energy harvesting solutions convert vibration of the rail into electricity. The energy harvesting team at Brno University of Technology, Czech Republic, is developing an electromagnetic vibration energy harvester for a sleeper application under the EU Horizon 2020 project ETALON. The principle is shown in Fig. 22 where pulse excitations of the sleeper provide a vibration response of electromagnetic energy harvester.

The cantilever design of electromagnetic harvester is shown in Fig. 23. This system is designed for use with a traditional sleeper design with a simple mounting,

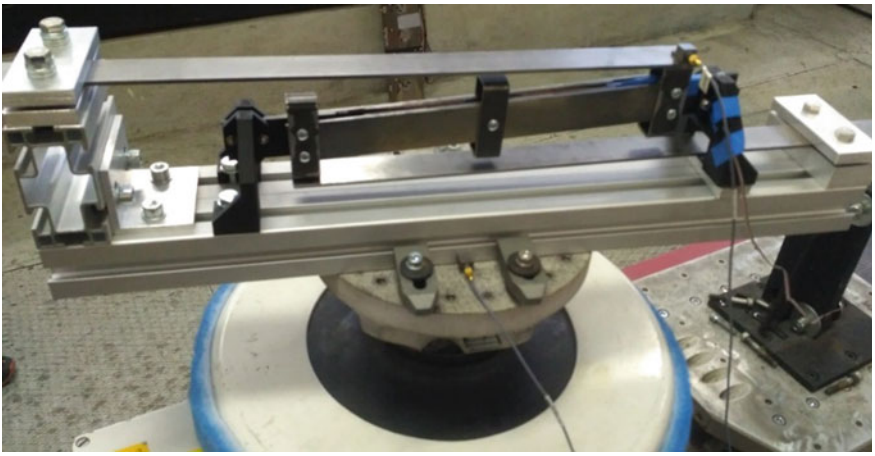


Fig. 23 Shaker test of electromagnetic vibration energy harvester for sleeper

or it could be integrated inside new generation of smart sleepers. This harvester was excited by shaker in laboratory environment using a vibration profile based on real measurement of sleeper vibration and the voltage and power output recorded.

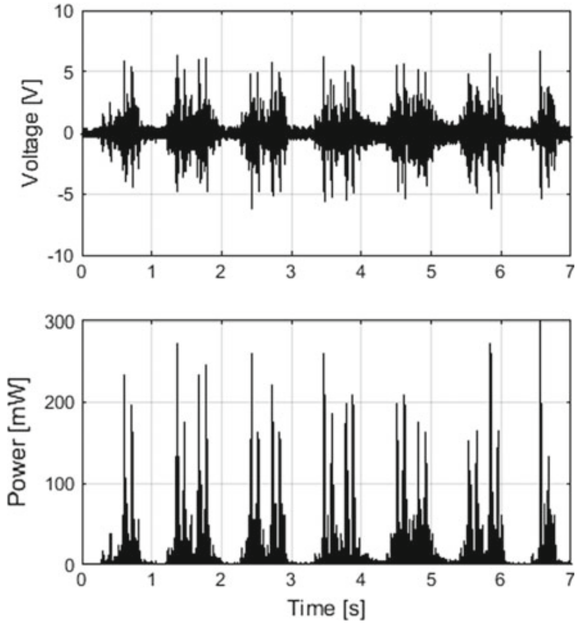
Experimental results of shaker test with the acceleration of sleeper induced by the shaker being representative of a passing regional passenger train are shown in Fig. 24. The harvester power output depends the harvester response to track dynamics, which, in turn, depend on a number of parameters related to the interaction between the track and train dynamics, including the track alignment quality, train speed, weight and suspension type. A freight train passing a harvester of this design mounted on low quality track could provide very high output power peaks (more than 1 W). Whereas, lightweight trains on a high quality high-speed track provide a specific vibration spectrum, which is not suitable for this system, and the response of the harvester will be lower.

5 Conclusion

In conclusion, this paper showed research results that are broadly positive. There are a large number of technologies and systems in development, which have demonstrated the feasibility of powering trackside low-power equipment using energy harvesting.

The identified technologies and potential applications show a wide variety of energy harvesting solutions and energy usage, respectively. Therefore, development of a particular power supply for a specific installation needs to take into account the energy harvesting capacity and characteristics of the energy harvester, along with the energy storage, and the energy requirements of the connected equipment.

Fig. 24 Experimental results of shaker test of electromagnetic vibration energy harvester. Vibration of sleeper during passing of regional train



Since the energy harvesting capacities of the technologies range from a few microWatts up to a few kiloWatts, there should be a viable solution for most applications, although cost, maintainability, reliability, robustness and redundancy would need to be taken into account. Also the variations in the characteristics of the energy harvesting technologies, such as annual cycles and dependence on passing trains, need to be considered to ensure a reliable power supply is developed, the optimum solution might vary between locations depending on local conditions and requirements. For example, piezoelectric systems are suitable for sensing and monitoring application; electromagnetic resonators seem to be suitable for maintenance free powering of wireless sensor nodes, while variable reluctance harvester could be used for traffic monitoring applications. Displacement linear harvester and geared systems provide interesting source of energy for local electronics. Wind and solar technologies are commonly used renewable sources of energy for wire spectrum of engineering applications.

Hybrid systems harvesting energy from two or more sources and utilising different principles would offer a diversity of energy sources which would increase the robustness of the power source. In general, it was shown that applications with large power requirements would need to at least include a large installation of one or both of solar and wind, combined with large capacity energy storage, in order to meet the requirements. The current technologies which harvest energy from the passage of trains would only be suitable for applications with low power requirements, intermittent moderate power requirements, or as supplemental energy harvesting to other systems.

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