# Roadway Kinetic Energy Capture and Conversion


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16. Abstract

Alternative energy generating assets, such as solar, piezoelectric, electrostatic and electrodynamic generators and wind turbines in and along the highways can capture and convert otherwise wasted ambient energy, which may provide an opportunity to reduce cost, prepare for future needs and even generate revenue. In this Phase-1 project, a review of technologies for energy harvesting is presented, along with an analysis of possible assets and relevant applications, to indicate how ODOT can benefit from this rapidly expanding and maturing field. Following brief background information framing the nature and relative density of ambient energy sources, general requirements for energy harvesting and principles adapted for this report are introduced. Subsequently, three major tasks for the project are used to analyze the potential and challenges of energy harvesting technologies for ODOT.

It is emphasized that energy harvesting within the transportation infrastructure presents new challenges and opportunities, which can be adequately tackled not by a single technology or device but an energy-harvesting ecosystem in which a range of more established as well as up and coming technologies, each of which have unique strengths and particular weaknesses, are integrated side-by-side. Particularly, solar and wind-based devices have a significant lead in power density, installation and operational cost and total energy potential that set them apart from newer, more compact devices that truly benefit from vehicular driven vibrational energy sources such as piezoelectric and linear electromagnetic generators.

It is recommended that ODOT continues to invest in energy harvesting technologies in general as they are maturing and expanding rapidly to offer viable energy solutions, especially in hybrid schemes that co-integrates several technologies such as solar, wind and piezoelectric in a complementary fashion. This will not only initiate the learning curve for adaption of energy harvesting toolset, it will also provide data for critical decisions for large-scale projects necessary for smart transportation systems with embedded sensors and self-driving electric vehicles expected to proliferate significantly in the next decade. It is further recommended that ODOT determine intended locations for eventual field testing, since energy harvesting will always require a degree of custom design and a truly effective hybrid solutions will be dependent on intended locations.

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# 1 Executive Summary

According to the Department of Energy (DoE), the transportation sector consumes almost one-third of the total energy production in the US. ODOT alone spends more than $12 million each year to power the transportation system. Yet, considering the vast roadway network it manages, a large amount of kinetic energy from vehicles wasted through friction heat, vibration and wake air currents is available to ODOT. Alternative energy generating assets, such as solar, piezoelectric, electrostatic and electrodynamic generators and wind turbines in and along the highways can capture and convert some of this *vehicular kinetic energy,* which may provide an opportunity to reduce cost, prepare for future needs and even generate revenue. In this project, a review of technologies for energy harvesting is presented, along with an analysis of possible assets and relevant applications, to indicate how ODOT can benefit from this rapidly expanding and maturing field.

The project included three tasks. **Task 1** presents an extensive literature survey of devices and technologies in the context of transport infrastructure. Based on this review, **Task 2** establishes that solar and wind-based devices have a significant lead in power density, installation and operational cost and total energy potential that sets them apart from newer, more compact devices such as piezoelectric and linear electromagnetic generators that truly benefit from vehicular driven vibrational energy sources. Significant potential of thermal generation does not translate to practical applications due to low efficiencies and installation costs at this time. **Task 3** identifies four most suitable infrastructure elements for ODOT to explore integration of EH generators are *signposts, bridge decks, overhung sign decks* and *median gaps*. Moreover, it also brings three major classes of applications into focus for EH technologies: i) Extended arrays of generators for large scale power & utility applications such as solar noise barriers, ii) Mobile power units with hybrid generators that can be used for emergency and field power needs, and iii) Embedded mini harvesters to power novel safety sensors and information displays in smart infrastructure applications.

It is emphasized that energy harvesting within transportation infrastructure presents new challenges and opportunities, which can be adequately tackled not by a single technology or device but an energy-harvesting ecosystem in which a range of more established as well as up and coming technologies, each of which have unique strengths and particular weaknesses, are integrated side-by-side. Depending on the target applications in mind and unique locations in the state, both in metro or rural areas, a specific energy harvesting solution can thus be pursued using this compendium of devices.

It is recommended that ODOT continues to invest in energy harvesting technologies in general as they are maturing and expanding rapidly to offer viable energy solutions, especially in hybrid schemes that co-integrates several technologies such as solar, wind and piezoelectric in a complementary fashion. This will not only initiate the learning curve for adaption of energy harvesting toolset, it will also provide data for critical decisions for large-scale projects necessary for smart transportation systems with embedded sensors and self-driving electric vehicles expected to proliferate significantly in the next decade. It is further recommended that, prior to a Phase-2 study, ODOT must determine intended locations for eventual field testing, since energy harvesting will always require a degree of custom design and a truly effective hybrid solution will be dependent on the location.

## 2 Project Background

The world is forever growing and evolving, as is the demand for new energy resources and sustainable infrastructure. Costs and risks associated with exploration of new energy resources lead us to seek means to tap into readily available ambient energy sources that are otherwise completely wasted. This would especially be meaningful in the transportation context: According to the DoE, the transportation sector consumes almost one-third of the total energy production in the US. Yet, considering the great number of lane-miles of the roadway network in the U.S., a huge amount of kinetic energy from vehicles is wasted through friction heat, vibration and wake air currents. Therefore, the utilization of such naturally occurring sources of energy does not only offer environmentally friendly and sustainable energy alternatives but can also help reduce the energy bill and improve smart transportation infrastructure facilities.

Ohio has a vast highway infrastructure that is comprised of thousands of roadway miles. The Ohio Department of Transportation (ODOT) is the primary entity responsible for the design, construction, and maintenance of this essential component of the state's infrastructure. This includes spending more than $12 million each year to *power* its transportation system. Alternative energy generating assets, such as solar, piezoelectric, electrostatic and electrodynamic generators and wind turbines in and along the highways to capture and convert *vehicular kinetic energy*, provide an opportunity to power some of the essential road information systems, signage and illumination, hence reducing costs and even generating revenue for ODOT.

The economic viability of harvesting energy from moving traffic is dependent largely on several factors: 1. Types of energy capture and efficiency of conversion devices chosen; 2. Availability and accessibility of road infrastructure for sufficient energy capture; 3. Effective placement of energy harvesters and power storage for utilization; and 4. Identification of sustainable applications and suitable applications worthy of the investment. While some of these factors (1 & 4) are easier to control through proper design, the other two factors (2 & 3) are site specific and are beyond the control of the engineer. For example, while one can confine energy capture only to existing road surfaces and superstructures such as bridges and posts, it is also possible to conceive unique structures under and over the road surface to effectively capture kinetic energy, especially from heavier/larger vehicles.

As a vehicle moves along the highway, it produces vibration and drags air in its path. Depending on the road type (concrete vs. asphalt), structural details (barriers and bridges) and vehicle type, different amounts of energy can be harvested. EH can be done via most forms of energy including piezoelectric generators that produce charge displacements in response to structural deformations, electro-static or electro-magnetic generators that convert motion to current with the aid of interdigitated capacitors or inductors, electro-thermal generators, photovoltaic (PV) cells, and micro/mini scale wind turbines as well as novel devices that integrated several of such elements in a single system or body. However, not all of these energy sources are equally efficient or abundant. Hence, it is crucial to re-assess the potential of energy harvesting, based on reliable engineering data, observed trends and road infrastructure.

## 3 Research Objectives

The primary objective of this study is to review and present the technological options to capture and convert kinetic energy from transport infrastructure in the state of Ohio induced by moving vehicles. To do so, very basic scientific background and a detailed review of the state-of-the-art and relevant literature on technologies capable of energy harvesting from roadway infrastructure are presented. The principles and requirements that should guide such a survey are also elucidated and presented in this report. Both established and upcoming technologies harvesting ambient energy sources such as vibrations and wind produced by passing vehicles are considered to determine their feasibility to power specific needs such as lighting, signage, deicing and smart sensor systems that are integral part of the modern highway systems. Hence, Phase-1 of this study included the following tasks to achieve the outlined objectives:

- **Task 1:** Conduct a comprehensive survey of the state-of-the-art in technologies relevant for kinetic energy harvesting
- **Task 2**: Identify suitable EH technologies and generic ODOT assets/locations relevant for capturing and converting kinetic energy from vehicular traffic in Ohio.
- **Task 3:** Identify applications that will readily benefit from EH technologies, along with their essential figures of merit such as peak power, power density and cost-benefit.

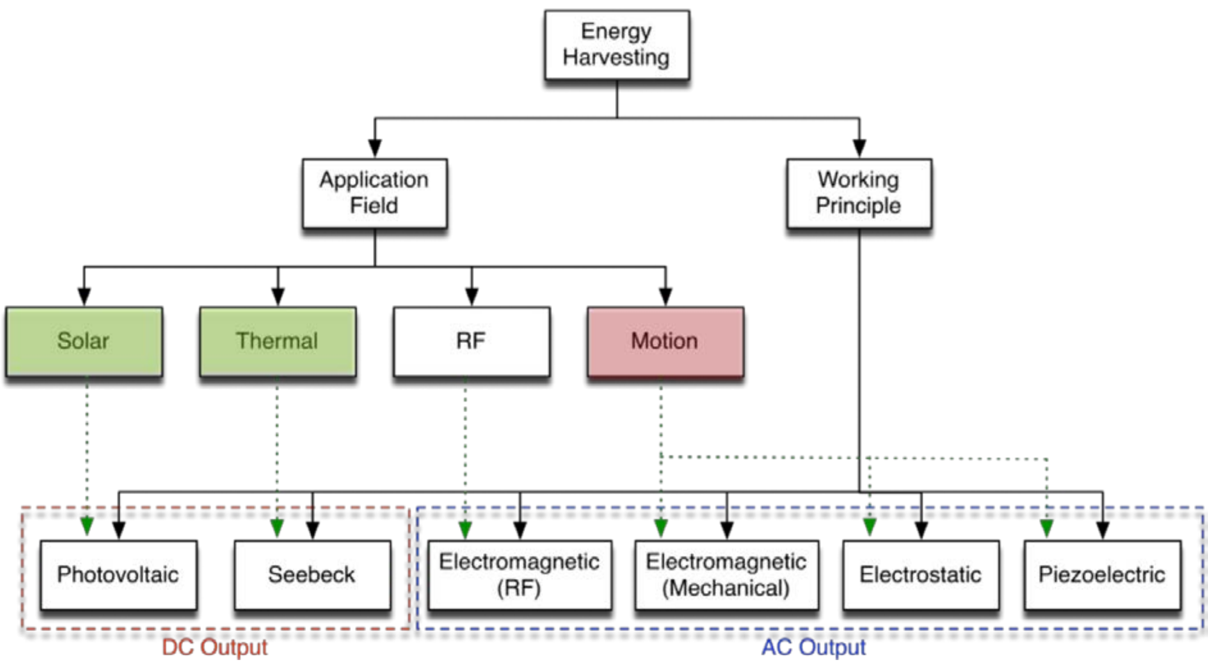


*Figure 1: Main principles of energy harvesting and their relationship*

## 4 Energy Harvesting Background

Thanks to many material and technical advances in the last three decades, the most critical question in energy harvesting today is not the viability of power conversion from ambient sources, but their relative efficiency and scalability to different contexts. A list of viable and significant energy harvesting approaches that can be employed for this purpose, i.e. powering personal electronic devices and electrical sub-grids, are shown in Figure 1 [1]. In this taxonomy, the relationship of energy sources and working principles are indicated with dashed arrow as well as the AC/DC nature of the power output, which would have implications for both design and use of EH systems. Also highlighted in this picture are the motion, solar and thermal sources that has the highest relevance for the report and ODOT infrastructure. Although motion is the basic interest to this report, for completeness and inherent complimentary potential, solar and thermal sources are also considered.

*Table 1: Power density extractable from different ambient energy sources*

| Energy Source | Power Density | Comments |
|---|---|---|
| **Light** | **10-100 μW/cm²**<br>**10-100 mW/cm²** | Indoors Office Illumination<br>Outdoors Solar |
| **Motion** | **200 μW/cm³**<br>**4 μW/cm²**<br>**200-1000 μW/cm²** | Vibration (*Piezoelectric*)<br>Vibration (*Human - Hz*)<br>Vibration (*Machines -kHz*) |
| **Thermo-Electric** | **1-10 mW/cm²**<br>**30-60 μW/cm²** | Machinery<br>Human |
| **Acoustic Waves** | **0.96 μW/cm³**<br>**0.003 μW/cm³** | Noise @100dB<br>Noise @75dB |
| **Electro-Magnetic Waves** | **0.1-1 μW/cm³**<br>**1-10 μW/cm³** | Indoor RF sources<br>Outdoor RF sources |
| **Wind** | **0.4-1 mW/cm²**<br>**3.5 mW/cm²** | Indoors (Airflow)<br>Outdoors |

Practical density levels for different forms of energy sources are summarized in Table 1 [2], [3], which is crucial to understand at the onset of any EH study. Clearly, there are substantial differences among practical *power density* (amount of power that can be extracted in per unit area or volume of a given approach) levels among energy sources. *Given that both solar and wind power has typically one to two orders of magnitude advantage in power density, as well as propensity to achieve higher energy output and cost efficiency in larger structures/areas, motion/vibration (including kinetic activity via passing vehicles) would always trail in power output, especially in outdoors context.* Luckily, all these approaches are typically complimentary in power output, which could be used cleverly and judiciously while powering electrical loads. For instance, in lighting and anti-icing applications lack of solar and heat energy sources make kinetic energy harvesting very valuable and unique. Or relatively low energy output in small-sized and low-frequency piezoelectric generators can be used to power embedded sensors or electronic monitoring/warning systems in hard-to-service locations and embedded structures [4], [5]. Thus, uninterrupted power generation may be possible. In other words, Table 1 calls for a diverse and hybrid EH solution right from the start, one that utilizes existing solar and wind-based solutions as integral elements, while also extending the power output and availability much further by other forms of energy driven by vehicular traffic and/or extracted from roadway elements. Therefore, as we look into alternative kinetic power generation schemes, we shall emphasize how solar and wind solutions can be implemented either as add-on or integrated elements that can enable a truly flexible, scalable and efficient EH solution. Such hybrid solutions would be especially attractive and helpful if one considers the huge benefits (cost/space savings) that would be resulting from minimization of energy storage and distribution elements necessary to maintain and deliver power if each solution was adapted separately.

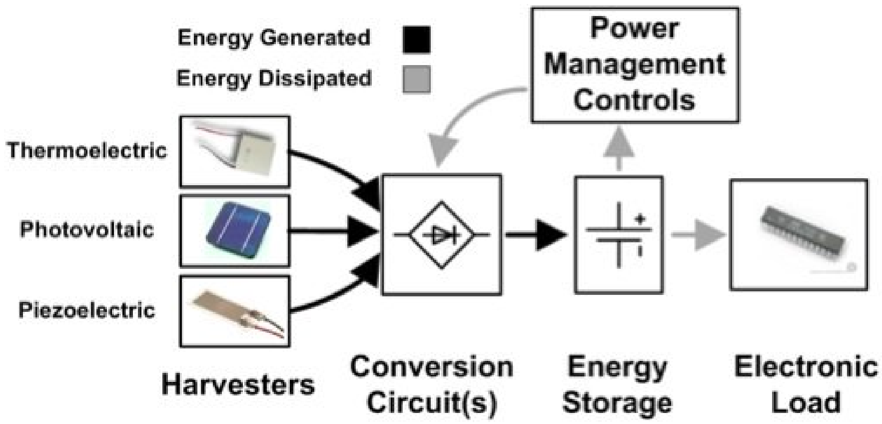


*Figure 2: Basic electric components and layers of engineering required for a complete EH solution*

Also relevant for any complete study of EH is the appreciation of all basic electrical engineering layers involved in practical applications, as described in Figure 2. Harvested energy must be first converted to an appropriate electrical (AC/DC) form and may need to be stored (using battery or supercapacitor banks) for some time interval to even out sparsity and maximize peak power levels for high-powered loads such as electric motors, lifts, actuators as well as sizeable displays and signage. For overall efficiency and safety of the electric load the entire system must be monitored via digital controller interfaces.

Even the most suitable energy harvesting devices for a given locale or application can quickly become inefficient, inadequate or costly if all engineering layers (power conversion/inversion, storage and distribution) are not designed in the right manner. In many cases, these additional engineering layers can be just as expensive and bulky as the harvesters. While these layers are not the focus of the present review, they can be crucial in choosing the right solution eventually. This is especially true for hybrid solutions that integrate multiple harvesting pathways and share these power engineering elements.

## 5 Research Context

As ODOT is continuously searching for ways to reduce the operating costs of its highway infrastructure and increase its reliability, capturing and converting kinetic energy from moving vehicles is a very attractive option. Kinetic energy is currently wasted, and conversion of this latent energy to electric form could ensure that critical elements in the infrastructure are powered even during power outages. Similarly, several states have explored the use of various energy-harvesting technologies or roadside power generation to tap into available energy sources such as solar, heat, vibration, wind and friction [6]–[9]. Roadway surfaces and bridge decks are continuously exposed to vehicle loading and solar radiation, which induces mechanical vibration and thermal gradients in pavement layers [10], [11]. Mechanical energy can be converted into electricity via magnetic field for electromagnetic generators or strain field for piezoelectric materials. Solar energy can be harvested through photovoltaic cell, heat flux, or thermoelectric fields [10], [12]–[14]. However, like all engineering problems, each of these different conversion approaches have its own context and design parameters, which must be re-considered for roadway structures and elements. Therefore, EH, as a whole, presents unique opportunities as well as new challenges.

***Opportunities:*** Figure 1 shows that EH approaches may include both conventional micro/mini wind turbines and novel solar panels integrated to the road infrastructure elements as well as newer methods such as thermoelectric harvesters exploiting temperature differentials between the asphalt pavement surfaces and its surroundings, novel piezoelectric elements tapping into vibrations and/or structural bending, electromagnetic generators driven by passing vehicles or tribological harvesters converting frictional energy to electricity via engineered surfaces. In many cases, these approaches are not available all at once. Thus, a mature and well-designed EH platform may employ several of these sources to maximize power and extend service time.

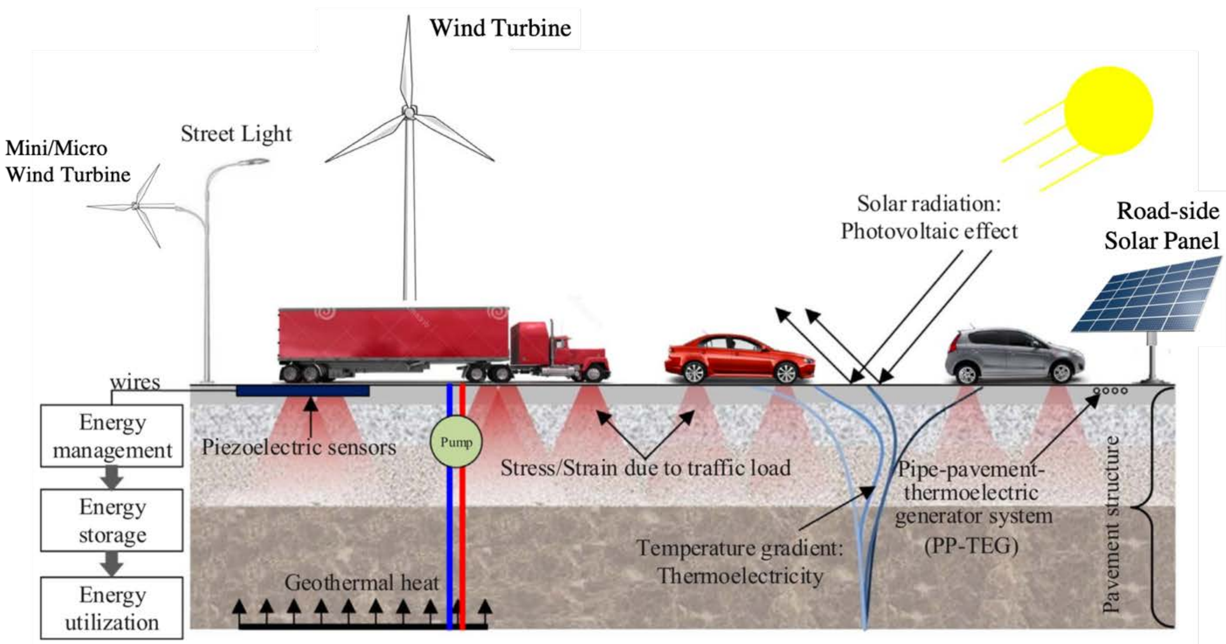


*Figure 3: Energy harvesting platforms that can tap into the kinetic energy of moving vehicles [14]*

Every passing vehicle on the highway typically generates significant levels of vibration, wind movement or friction that can be converted into usable power and stored using appropriate electro-mechanical devices. In the following sections, we present available techniques and ODOT infra-structure elements to harvest this energy in an economically viable manner suitable for potential field deployment.

***Challenges:*** Use of EH to power support and safety systems in transportation is indeed a promising approach to save resources, prevent accidents and improve travel experience as a whole. However, since EH technologies have been initially developed mostly for portable electronics, the existing literature must be re-considered for larger power needs and re-framed from the perspective of transport applications and highway infrastructure. As was evident from Appendix A, not all energy sources are equally easy to capture and convert, with several orders of magnitude difference in density. Thus, it is necessary to ascertain if ***common EH approaches can be practically***

***enhanced/degraded when scaled up to larger structures or power levels and integrated to the roadway elements***.

A second and equally important perspective for this ODOT review is the need to ***identify technologies with known 'off-the-shelf' solutions that can be adapted without major scientific research & development work.*** Such R&D efforts would be very demanding in terms of time and cost involved, and more importantly, are also not included in ODOT's mission. As a result, while we list all reasonable and useful technologies in the summative tables in this review, a thorough evaluation must pay special attention to how easy and likely to realize the proposed technologies with mostly off-the-shelf components in a low-cost manner and in large volumes.

## 6 Research Approach

Although a great majority of efforts in EH is focused on energy capture and conversion devices, a realistic analysis must also consider other aspects of power generation and usage that can be critical for an efficient solution and lasting impact. As such, there are *three* main components that all efficient and useful energy harvesting systems share:

A. ***Available & Complimentary Sources***: Readily accessible free energy sources that are complimentary in nature are needed so interruption to service can be avoided. While the kinetic energy of moving vehicle is a unique resource available within the transport infrastructure, hence an ODOT asset, there is no reason <u>not</u> to couple it with the other sources such as solar, wind, (geo)thermal in an effort to maximize cost and service benefits.

B. ***Suitable & Efficient Conversion Devices:*** Efficient, appropriately-sized and sustainable (carbon-neutral and life-cycle positive) energy capture and conversion devices are required for immediate and long-term gains in energy production from the environment. These may include uni-modal devices optimized for conversion from a single source and multi-modal or hybrid devices that may combine several technologies to maximize power generation.

C. ***Energy Storage and Distribution Network:*** If peak power levels are insufficient, EH systems will require compact and long-lasting electric storage solutions, with two-way reconfigurable re/dis-charging circuitry and power regulation to supply different loads and locations. Hence temporal and spatial distribution of average and peak power demand is needed so EH generators can be properly sized and strategically placed.

*In an effort to present an accurate perspective, we draw critical insights from all three aspects above. However, focus is on B since it is most readily impacted by recent technological advances.* A is site specific and B is heavily impacted by ODOT's vision and organizational decisions beyond the scope of this work. Thus, we ensure that the report is neither a mere academic review of advances for EH technologies and nor is it tilted toward a specific solution or location.

The following subsections summarize the specific research tasks used in this study to investigate the EH solutions for ODOT.

### 1.1. Task1: Literature Review

A comprehensive literature review of pertinent studies on the EH technologies applicable to transportation in general and kinetic energy harvesting in particular was conducted between November 2018 and March 2019. The literature review covered: 1- Common approaches and their principles of operation; 2- Example applications in the literature, especially in the context of transport infrastructure; 3- Summative tables summarizing and comparing notable works. The survey is conducted using academic library resources as well as citation databases on the web. The relevant literature has been cataloged by a Mendeley® folder with actual PDF articles that can be shared with ODOT. For the sake of continuity and brevity of the main report, the conducted survey is incorporated as a separate appendix at the end. Due to scope and page limitations the survey does not necessarily exhausts all possible approaches, focusing on latest works and promising approaches related to *Kinetic* and *Hybrid* energy harvesting. The outcome of the survey is presented in the following sections (Tasks 2 & 3), along with potential applications and recommendations. The Table is generated as a collective summary of a large number of research articles as well as comprehensive reviews on energy harvesting [12], [14]–[19].

*Table 2: Energy harvesting technology matrix for transportation applications*

| Technologies vs. Figure of Merit | Solar (S) | Wind (W) | Thermal (TE) | Vibration (V) | |
|---|---|---|---|---|---|
| | | | | Piezo (P) | eMag (EM) |
| Available Power ($W/m^2$)* | 1200 | 350 | 10-20 | 300 | 300 |
| Average Output ($W/m^2$)* | 150 | 100-150 | 0.5-2 | 9 | 20-50 |
| Harvest Density ($kWh/m^2$)* | 600-800 | 120-240 | 1-1.5 | 7.2 | 28.8 |
| Typical Efficiency (%)* | 15-22 | 20-30 | 5-8 | 10-30 | 25-50 |
| Base Cost ($/W)* | 0.1 - 0.2 | 0.07 - 0.15 | 60-200 | 90-150 | 100-200 |
| Installation Cost ($/ln/mi) | 1-4 | 3-6 | 100 | 106 | 279 |
| Ease of Implementation | High | Medium | Low | Medium | Low |
| Reliability | High | Medium | High | High | High |
| Load/Grid Interface | DC | DC/AC | DC | DC | DC/AC |
| Market Penetration | High | High | Medium | Medium | High |
| Negative Env-Social Impact | Low | Medium | Low | Low | Low |
| Sustainability | Medium | High | Medium | Medium | High |

** Depends on* ***many*** *environmental, operational and design factors, hence range of numbers*

### 1.2. Task 2: Suitable EH Technologies and ODOT Assets

Table 2 summarizes the outcome of the literature survey presented in Appendix A. It takes into account established industrial trends and as well as available products and has deliberately omitted speculative and novel research-grade developments that cannot be implemented in the short-run. As such, it identifies three technologies (solar, wind and piezoelectric generators) as most suitable alternatives for integrating energy harvesting into transportation infrastructure as a whole. Besides their marked advantages in terms of density (see Table 1), solar and wind-based solutions also offer significant lead in installation and operational cost, efficiency and ability to scale up to large installations, with shortest possible return of investment and high sustainability potential. Among the vibrational technologies, piezoelectric solution is a more scalable, simpler to implement and lower cost solution, as compared to the electro-magnetic generators. The latter option, despite its high efficiency and relatively high-power output, suffers mostly from high installation and design cost. Thermal approaches, which rely on maintained temperature differentials, suffer from limited efficiency, low power and large cost.

Although the solar technology is not strictly driven by vehicular kinetic energy, its maturity, scalability and ease of integration with truly kinetic technologies (wind and vibrational), without negatively impacting them, make a compelling case for its inclusion in the transport infrastructure.

In fact, additional cooling of the solar panels by air-wake currents, sharing crucial resources such as battery packs, having generally complimentary climatic dependencies with respect to wind and its non-exclusive use of space as compared to alternative technologies (especially as noise barriers) further strengthen this case in favor of solar. Similar arguments can be given for the wind-based technologies, except that they can actually benefit directly from vehicular kinetic energy if positioned appropriately and sized correctly. Hence a truly kinetic enhancement of wind-based solutions would require and optimization study for a given locality so that air-wake by the vehicles is properly harvested without becoming an impediment to the users or the infrastructure elements' primary functions. If a large amount of power is the only criterion, it may be possible to integrate existing large-scale wind-generator solutions in a straightforward manner, much like the solar case, and without any optimization, however, this will not benefit from any kinetic enhancement.

*Table 3: Transportation infrastructure assets suitable for energy harvesting technologies*

| ***Technologies vs. Generic Locations*** | ***Solar (S)*** | ***Wind (W)*** | ***Thrm (TE)*** | ***Piezo (P)*** | ***EMag (EM)*** | ***H1 (WS)*** | ***H2 (WP)*** | ***H3 (SWP)*** |
|---|---|---|---|---|---|---|---|---|
| ***Bridges*** | ***H*** | ***H*** | ***L*** | ***H*** | ***H*** | ***H*** | ***H*** | ***H*** |
| ***Signposts*** | ***H*** | ***H*** | ***M*** | ***H*** | ***H*** | ***H*** | ***H*** | ***H*** |
| ***Underpasses*** | ***L*** | ***M*** | ***M*** | ***L*** | ***H*** | ***L*** | ***M*** | ***M*** |
| ***Embankments*** | ***H*** | ***H*** | ***H*** | ***L*** | ***L*** | ***H*** | ***M*** | ***H*** |
| ***Overhung Sign Deck*** | ***H*** | ***H*** | ***M*** | ***H*** | ***M*** | ***H*** | ***H*** | ***H*** |
| ***Noise Barrier*** | ***H*** | ***H*** | ***H*** | ***L/M*** | ***L*** | ***H*** | ***M*** | ***M*** |
| ***Median Gap*** | ***H*** | ***H*** | ***M*** | ***L*** | ***L*** | ***H*** | ***H*** | ***H*** |
| ***Median Barriers*** | ***H*** | ***H*** | ***L*** | ***M*** | ***L*** | ***H*** | ***H*** | ***H*** |
| ***Tunnels*** | ***L*** | ***M*** | ***L*** | ***L*** | ***L*** | ***L*** | ***L*** | ***L*** |

Scalability, lower cost and ease of implementation at (especially in existing structures and smaller size elements) put Piezoelectric generators give an advantage as compared to more established electro-magnetic generators in purely vibrational techniques, even though EM devices can deliver significantly larger power and efficiency. Since they are commonly used in wind generators, EM generators already play a significant role in EH devices. However, linear EM generators in small vibrational systems without tightly coupled magnetic loops (as in rotational counterparts) cannot offer substantial efficiency or power advantages as compares to piezo elements that have no (large) moving parts and take much smaller space.

### 1.3. Task 3: Significant Assets & Applications for ODOT

Following the evaluation of EH technologies, an assessment of basic ODOT infrastructure elements and possible target applications have been undertaken in Task 3. Hence it is intended to indicate *where* EH technologies are most likely to find an efficient platform or to be best exploited, as well as suggesting practical examples of devices or applications that can make an impact for ODOT. Moreover, besides indicating the relative qualitative importance of the basic EH (solar, wind, thermal, piezo and electro-magnetic) technologies as applied to different infrastructure elements, Table.3 also includes three hybrid technologies (wind-solar, wind-piezo and wind-solar-piezo). These are listed as alternatives to maximize the power output while lowering resources to implement each one of them separately. Four infrastructure elements come to fore as the most suitable venues to implement EH technologies: *Signposts, bridges, overhung sign decks* and *median gaps*. Three of these naturally occur in higher densities in metro areas, while median gap and signposts are the main assets in the rural areas to utilize EH technologies.

In terms of applications that can be implemented in these unique ODOT assets, three categories are identified to be relevant and important, as shown in Figure 4: i) Large scale power & utility applications to lower energy costs; ii) Mobile power units for blackout preparedness, emergency backup and field operations; and iii) low-power and deeply integrated mini harvesters for safety and smart infrastructure applications. The first application requires more substantial investments with greater power returns that can offset energy costs for ODOT. Solar noise barriers (Fig.4d) are an example to this approach. Mid-level power units that integrate multiple EH methods in a hybrid approach (Fig.4c) can be moved to different locations at will, which can make them especially useful for a variety of tasks such as emergency power needs during blackouts or while operating in remote locations. The final example for applications is on smart road system such as bridge deicing that can integrate smart sensors and heaters that can keep a bridge deck from dangerous ice build-up by use of solar and wind harvesters. [20], [21] Obviously, these examples can be greatly expanded, especially in the upcoming era of autonomous vehicles and intelligent road systems that will have require many wireless sensors and smart signs to be part of the road infrastructure. [22]

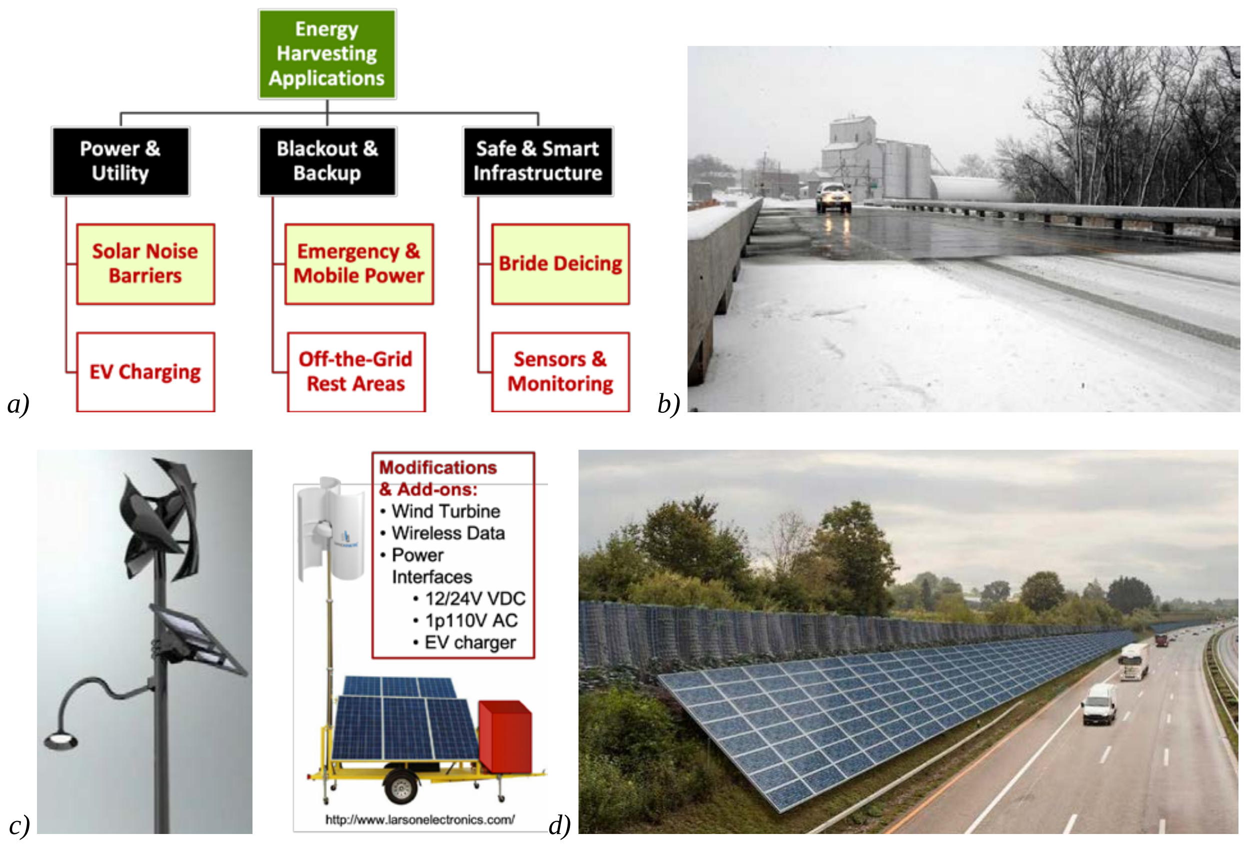


*Figure 4: Energy harvesting applications interest to ODOT. a) Taxonomy of applications, b) Bridge de-icing example by NE-DOT c) Off-the grid illumination and energy banks and d) Solar noise barriers.*

# 7 Research Findings and Recommendations

Based on the above discussions, data and additional information presented in the appendices we summarize our specific findings and recommendations below

## *7.1 Energy Harvesting Technologies*

- Energy harvesting technologies has both mature and developing elements that can meet energy needs at many levels, if sufficient area/space and infrastructure development are provided.
- Purely *kinetic* energy harvesting due to vehicular traffic is possible only with vibrational and wind harvesters, which is a limited spectrum of available EH technologies.
- Wind & Solar based techniques can offer significant energy at a reasonable cost if sized and situated in an optimal manner. However, size and up-front cost for wind-turbines can be relatively higher at small power ratings as compared to solar technology.
- Piezoelectric and electromagnetic generators techniques are *primary* technologies for *purely* vibrational energy harvesting. As compared to more scalable and mature solar and wind technologies, they have up to three orders of magnitude cost disadvantage and significantly (10 to 100 times) lower power output.
- Hybrid solutions that integrate mature wind and/or solar technologies with a vibrational, preferably piezo based, generator for power boost and reduced climatic dependences appears to be the most optimal approach for kinetic energy harvesting.
- Unlike the more mature solar and wind-based solutions that have off-the-shelf products, vibrational and hybrid solutions will require some level of custom design and development for a given location and application

## *7.2 Energy Harvesting Applications*

- Four most suitable infrastructure elements for ODOT to explore integration of EH generators are *signposts, bridge decks, overhung sign decks* and *median gaps*. Although opportunities for EH generation exist in other ODOT assets as well, these four elements have capacity to address most locations and maximize the impact of energy produced with minimal installation costs.
- Three major classes of applications are identified for EH technologies: i) Extended arrays of generators for large scale power & utility applications, ii) Mobile power units with hybrid generators; and iii) Embedded mini harvesters for safety and smart infrastructure applications.
- Specific applications that can have large impact in ODOT's mission include i) EH integrated onto noise/median barriers utilizing solar panels as structural elements, ii) portable power bank with hybrid generators and wireless data access; iii) bridge de-icing systems with integrated EH-driven heaters and smart sensors.
- As important and generational changes in transport systems such as explosive growth in electric and self-driving vehicles and smart roadway systems are expected to take place in the next decade, use of EH devices may provide additional flexibilities in designing and powering these novel features without substantial investments and initiate the learning curve necessary to adaption of any novel technology.

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## Appendix:  Literature Review

Having introduced the context and sources of modern energy harvesters earlier, we provide in this appendix a general literature review on the state-of-the-art in techniques used to convert vehicles' kinetic energy into electric power. We also include in this review approaches for hybrid integration of more established *non-kinetic* generation techniques such as heat and solar energy that may be available in the immediate surroundings, can improve overall power levels significantly and are often complementary to kinetic methods.

### A.1. Solar/PV Energy Harvesting

The immense potential, existing industrial base and excellent scalability of today's photovoltaic power generation devices require very little introduction. Widely considered to be a low carbon footprint solution for energy-challenged developed world as well as off-the-grid solutions in remote and less-developed parts of the world, it is becoming ever cheaper and more efficient, thanks to sustained efforts in the last two decades [23]. High-efficiency PV cells utilize single or multiple diodes (*p-n junctions*) to capture light energy to convert it to a direct electric current thanks to energy band-gap of the semiconductor materials. *The objective in this section is **not** to review solar generation in general, but to recast it as an integral element of EH toolbox for transportation system in particular.* Even in this limited perspective, it may appear as odd that why and how solar power generation could even be considered for *kinetic* energy harvesting, which is briefly justified as follows.

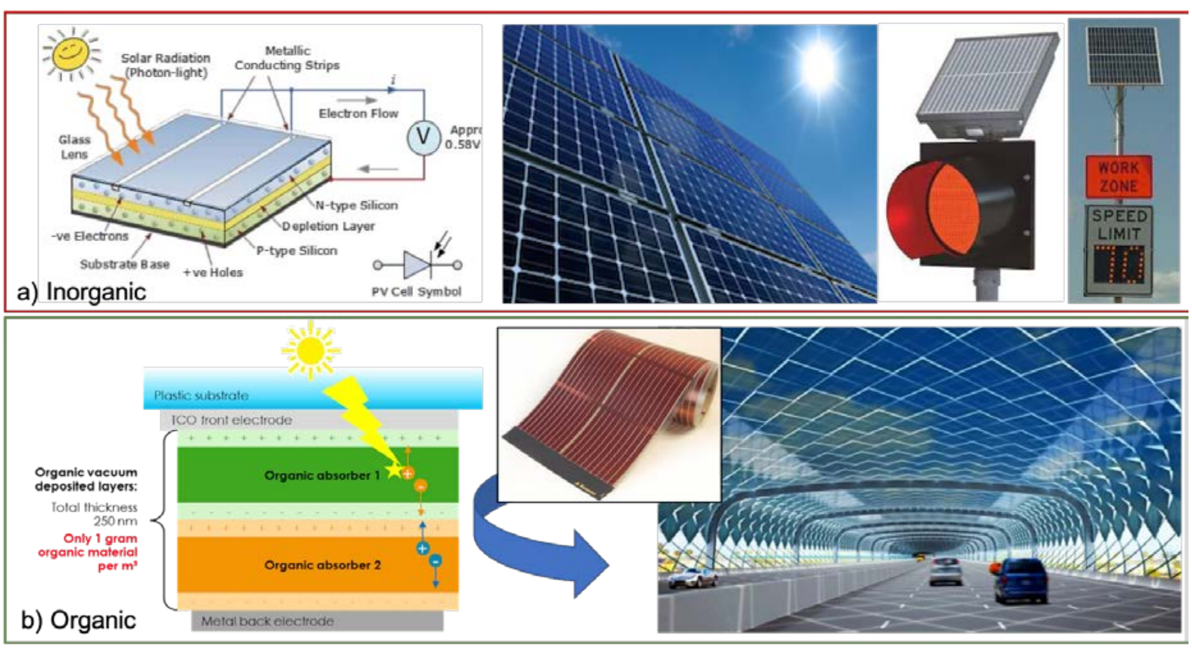



*Figure A1: a) Conventional (inorganic) versus b) flexible (organic) solar energy harvesters that can be utilized for energy harvesting in transportation.*

Solar power generation has a unique status due to the fact that there are existing solar power elements in and around the ODOT infrastructure, typically in the form of isolated solar panels atop or on the side of sign-posts and by emissive (LED-based) traffic warning signs, similar to ones in Figure A1 (upper right). Given the availability of large exposed surfaces on many ODOT structural elements and large power density of sun, it is necessary to consider how solar energy can be uniquely useful in the context of kinetic energy harvesting. Three reasons can be given:

- **Basis for Hybrid Solutions:** Since ODOT already owns and deploys solar power posts/banks, other kinetic energy harvesters can be readily built on top and in the vicinity of these existing resources. As such these PV islands/stations can be a practical testing and integration platform for different kinetic solutions considered in this report, increasing the chance of their adaption and reducing deployment costs significantly, especially if/when a local battery storage is present. Thus, in addition to increasing the overall power production and service hours, solar/PV technologies can be considered as a catalytic or enabling agent for unique hybrid EH solutions to be developed, especially for many alternative technologies that would not otherwise be cost effective or power efficient alone.
- **Kinetically-cooled PVs:** It is very-well known that power output of a typical PV cell increases by about +0.5% with every degree Celsius drop in temperature [24]. In fact, the rated peak power of PV cells is seldom achieved in actual outdoors conditions, since module temperature can easily climb up to +50°C. Thus, kinetic EH can be used to cool, either directly via convection/conduction of heat enhanced by moving traffic and wake currents or indirectly via energy provided by other kinetic approaches. Thus, efficiency of PVs can be improved significantly. In the hybrid approaches that integrate solar and other kinetic approaches (wind, piezoelectric, thermoelectric and so on), the harvester design can be purposely made to cool the PV elements as well, such as those in underpasses, bridges or highway signage.
- **Novel Flexible/Organic PVs:** In the last decade, rapid materials and manufacturing advances lead to the emergence of a new class of low-cost, mechanically flexible, large-area-capable solar panel technology: Flexible and organic solar cells.[7], [25], Although lower in efficiency, typically 5% to 10 %, the unique form factor, low-cost and deployment advantage of the polymer-based solar technologies must be reconsidered especially in the context of kinetic EH technologies. Being so novel and relatively less efficient, flexible solar cells received very little focus especially in the transportation infrastructure. However, they can easily offset efficiency disadvantage by way of low cost and large area capability. More importantly, their ability to assume complex or curved shapes and technology similarity with some existing piezoelectric, battery and display elements, make them especially intriguing solar solutions. Thus, either as a stand-alone or hybrid EH solutions, there appears to be a very unique opportunity in flexible solar technologies for transportation studies.

In the following we illustrate some example works that can be more relevant for the last two arguments only. The first one, the hybrid approach, is to be explored in greater detail in a separate section below, along with wind generators and other kinetic approaches. Given the vast material in conventional solar/PV technologies, this section can be expanded significantly in principle. However, due to the aforementioned ODOT specific needs (scalability, cost efficiency and practicality), the scope and examples are kept limited

**Examples**: Solar generators is one of the most widely studied energy harvesting technologies and many efforts were made to integrated them onto roadway systems. For example, USDOT supported the development of Solar Roadways systems via three phases of SBIR program [7]; recently, a 63,180 sq. ft and 3,670-ft-long photovoltaic roadway was constructed to show the early promise of this technology. However, many of these efforts on PV integration to roadway systems involve straight-forward adaptation of solar panels on road surfaces, around bridge decks or onto noise barriers, without any *kinetic* enhancement. To do so, the key is to design PV cells such that they can benefit from kinetic cooling effect, either alone or as a hybrid solution integrating wind and electro-thermal generators. In the direct case, multiple smaller PV cells must be distributed in closer proximity to the wake currents of passing vehicles, which is not very practical and easy to maintain for conventional PVs with rigid glass body. For organic flexible solar cells this would not be a problem. Therefore, *organic solar cells* would present a unique advantage due to their flexible form-factor, as seen in Figure A2 below, and their hybrid integration potential. In addition, they can be more easily adapted to unique shapes and airfoils that can maximize cooling effect driven by wake currents. *As a result, organic solar cell technology is a very promising alternative to consider for transportation applications, especially for hybrid schemes.*

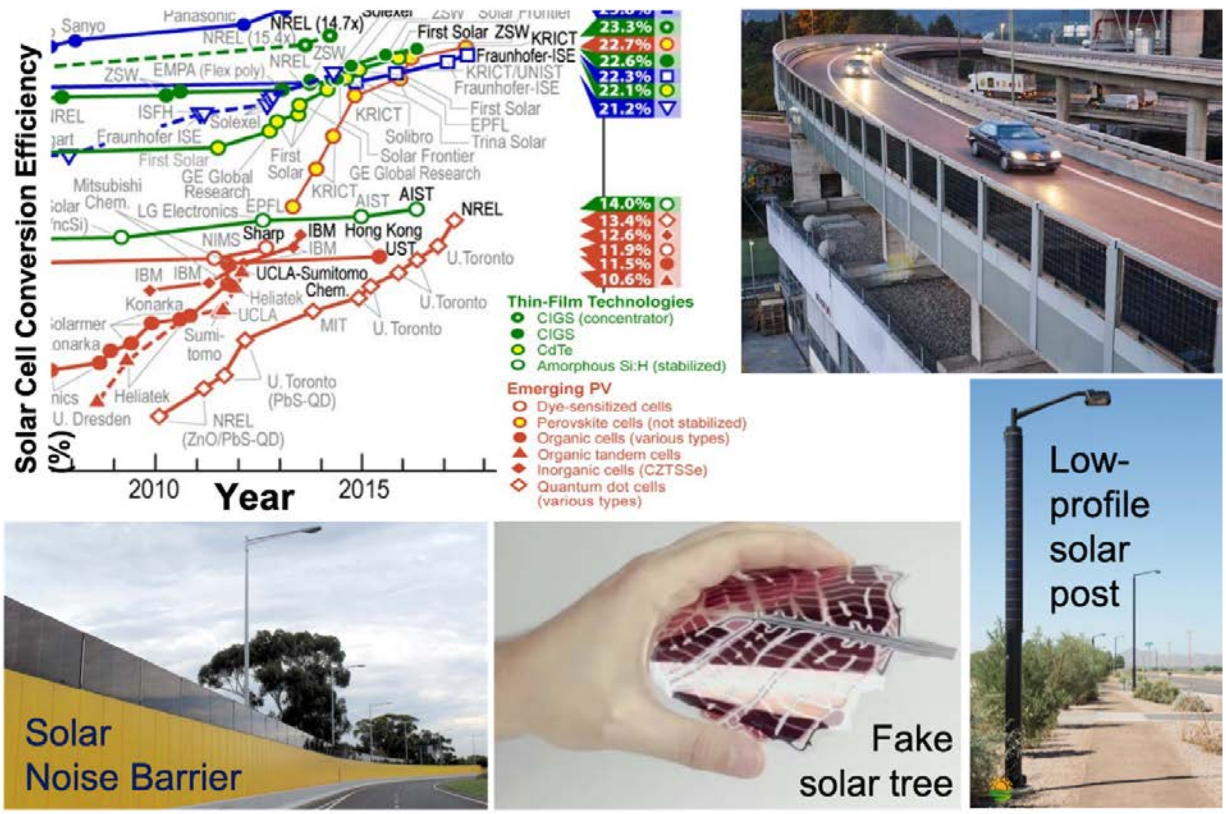



*Figure A2: a) Rapidly rising efficiency of Flexible PV technologies (red & green), rivalling low-end silicon PV cells and potential applications where organic solar cells can be integrated to roadway infrastructures.*

### A.2. Vibration Harvesting

Energy stored in the deformation of mechanical structures (both static bending and dynamic vibrations) has been harnessed for centuries, but it has only started to become a major part of our energy production toolbox in recent years. Over the past two decades, the types and quality of devices that can harvest vibrational energy have increased considerably, making them an increasingly affordable method of energy generation. Recent advances in material science have allowed for deposition of multilayered piezoelectric material structures in a cost-effective fashion, paving the way for ever more reliable and efficient harvesters. Similarly, other electro-static and linear electro-magnetic generators have developed rapidly thanks to advances in the design and fabrication of micro electro-mechanical systems (MEMS), which will be outlined below.

### A.2.1. Piezoelectric Harvesters

Piezoelectricity is the process of converting mechanical deformations within a solid-state matrix into electric potential by the inducement of electric dipoles internal to its structure. Starting with naturally piezoelectric bulk crystals such as ZnO, AlN and quartz, or using high-performance ceramics like lead zirconate titanate (PZT) and polymers such as PVDF, it is possible to induce electric current from physical deformations and vibrations based on piezoelectric effect (see Figure A3). In fact, following its discovery by Curie brothers in 1880, piezoelectric technology has been widely used in different fields, such as sensors, transducers, ultrasonic devices, motors, and MEMS technologies. Lately, several large-scale applications of this technology are also found in the literature, including tide/wave energy harvesting [26], and vibration in aircrafts [27] and under the train-track sleepers to power wireless sensors [13].

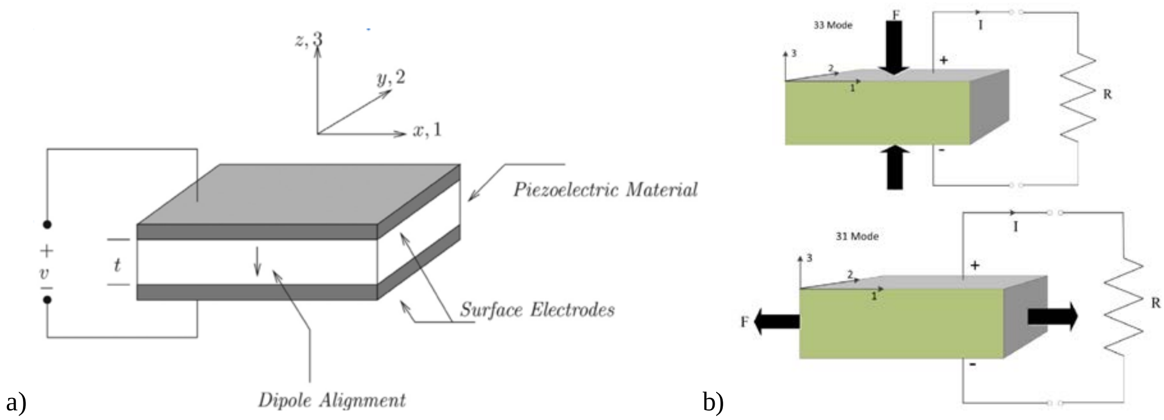



*Figure A3: a) Generic structure of piezoelectric energy harvesters and b) Major coupling modes*

**Operation Modes**: In the case of transportation, the vehicle's kinetic energy will provide the physical excitation ($Y_o$) of piezoelectric material depending on the density and types of vehicles passing. The power output from piezoelectric energy harvesters ($P_{out}$) also varies with the device electric damping coefficient ($d_e$) and must be rectified prior to being used or stored. In general, there are two coupling modes of piezoelectric materials, namely *31-mode* and *33-mode*. In 31-mode, power output reaches its maximum when piezoelectric harvester vibrates perpendicular to the material's poling direction. In 33-mode, the field is produced from longitudinal deformation of the piezoelectric material and increases linearly with increasing load on the poling direction [28]. A schematic representation of both coupling modes is provided in Figure A3. Typically, 31-mode is more efficient for small level forces. However, in case of vehicles load, which is relatively high, 33-mode is more effective and durable.

**Vibration Frequency**: According to the simple linear model of a coupled mass ($m$) and spring ($k$) system with electric ($\zeta_e$) and mechanical ($\zeta_m$) damping, the maximum power is achieved when the device vibrates in its natural frequency $\omega_n = \sqrt{k/m}$. At this peak condition, the total power that can be converted is given as:

$$\max_{\omega=\omega_n}(P_{out}) = \frac{m\zeta_e {Y_o}^2 {\omega_n}^3}{4{\zeta_T}^2}$$

where, $Y_o$ is vibration amplitude and $\zeta_T = \zeta_e + \zeta_m$ is total damping ratio (electric + mechanical). The most essential factor in the design and operation of the piezoelectric device is its natural frequency ($\omega_n$) which in turn depends on the generator size ($m$) and coupled mechanical structure acting as the spring ($k$). Thus, depending on its size, piezoelectric generators can harvest energy on a wide spectrum of frequencies: In fact, both low-amplitude vibrations (e.g., small semi-rigid elements, membranes, posts etc.) and low-frequency large deformations (large beams, a bridge or barrier) are of interest for energy harvesting. The former is more practical to install and operate, yet it is limited in terms of total power. The latter allows higher power levels to be achieved, but, it requires more complex and expensive installations. However, since the high-frequency devices vibrate many times per second and can take a long time to dampen, the energy they harvest can quickly become significant if devices are properly designed and deployed in dynamic mode as opposed to static bending.

**Piezoelectric Materials & Device Options**: A piezoelectric device must be optimized with respect to the mode being designed as well as frequency of operation. For instance, PZT is preferred choice for high-frequency devices and large loads, whereas PVDF polymers may provide an advantage for large areas, wide spectral capture cross-sections and flexible shapes. Similarly, actual range of load, extent of deformation and environmental conditions also play a part. In addition, these thin films, it is imperative to evaluate the potential of novel, artificially-grown and/or composite structures which may offer unique solutions despite their cost, which tend to be higher. Several transition-metal oxides such as ZnO and semiconducting AlN materials are also of interest as they can actually be integrated with the electronic devices and produced in a more cost-effective manner than many other crystalline materials. For instance, high-quality sensor electronics may be built upon ZnO material, which can also serve as a piezoelectric generator. There are several device configurations currently in use, which are relevant for transport applications. These include uni- or bi-morph piezoelectric membranes, large cantilever beams with integrated piezo-flexure arms or micro-machined cantilever arrays. Each configuration offers unique advantages and challenges. For instance, inclusion of additional mechanical or magnetic constraints (see Figure A4) can lead to bi-stable configurations that can take advantage of two degrees of freedom. Due to its broad applications in energy harvesting for other non-transport related applications, there are a large number of designs for these devices in the literature.

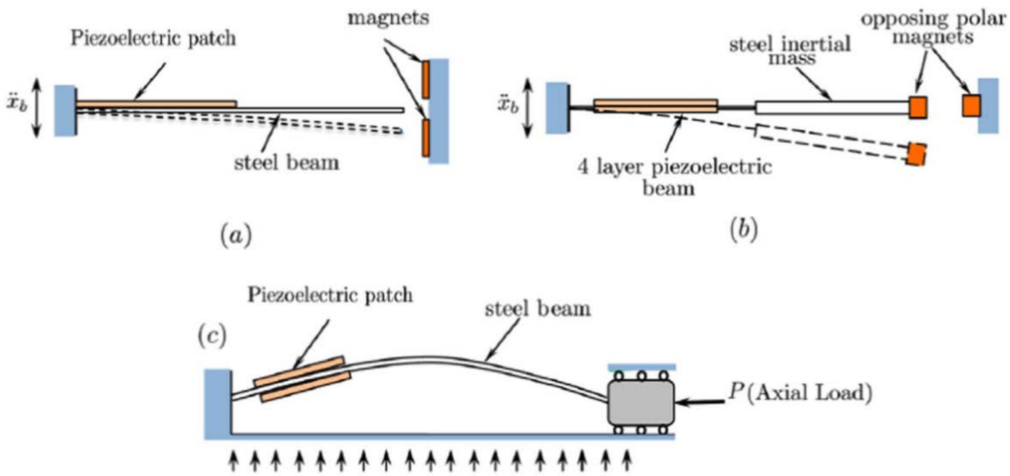



*Figure A4: Example configurations of bi-stable piezoelectric energy harvesters*

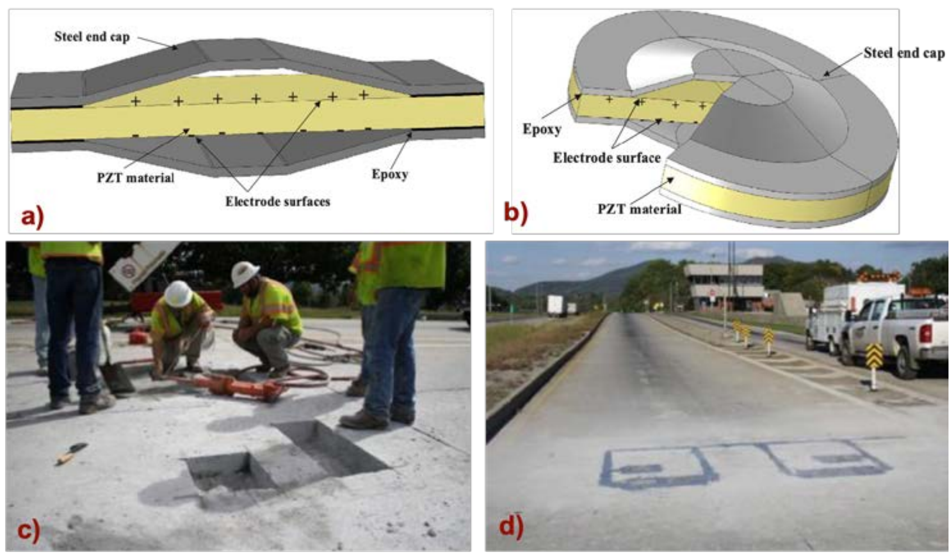



*Figure A5: a) examples to ceramic piezo elements in bridge and cymbal configurations. The installation six piezo-bridge harvesters at I-81 Troutville weigh station [1]*

**Examples:** Several recent examples of piezoelectric harvesters integrated into transport infrastructure may be found in the literature. A study was conducted by Xiong *et al.* on the potential use of piezoelectric devices on public roadways [18]. For an energy harvester under traffic loading, 33-mode configuration was selected, because of its higher efficiency and better durability compared to the 31-mode. PZT from American Piezo Ceramics, Inc. (APC) was selected as the piezoelectric material because of its cost effectiveness. Using finite element analysis, it was found that a cylindrical shape of the material provides better stress distribution and less stress concentration. The devices were then fabricated, protected and waterproofed by plastic packages. Before installation, the harvesters were tested for quality and durability in the laboratory using a model mobile load simulator, which can mimic cyclic loading of vehicles up to 295 kg of loading for four days. It was reported that no damage was found in the device. Also, the average power output was measured under different tire velocities, and it was found that power output increases with increasing tire velocity. Three devices were installed and tested under a pickup truck and dump truck with tire pressures of 544 kPa and 676 kPa, respectively. The harvesters were tested on a rainy day to evaluate water resistance as well, and it was reported that no damage or water leakage was found after applying 80 cycles (40 cycles for each vehicle). Too evaluate the feasibility of using piezoelectric generators under real traffic, six fabricated harvesters were installed along the wheel path in a cement concrete pavement structure at I-81 Troutville weigh station (Figure A5). The weigh station has daily truck traffic of 4000 per day with an average speed of 40 km/h. A maximum instant power output of 0.116 W and the maximum average power of 3.106 mW was reported.

For comparison, several other studies [12] that are conducted on pavements are summarized in Table A1. In majority of these cases, the piezo generators were laid down under the traffic load and integrated into the pavement structure, after being optimized for a specific depth and device configuration. As can be seen from this table, power levels are typically less then 100mW, which is sufficient to power sensors and LED based illumination devices. Beyond pavement integration, another option would be to utilize existing commercial products (such as those shown in Figure A6) to build bi-stable or resonant piezo generators on signposts and plates that can move with traffic generated vibration or air wake current, often using several of these devices in a single design.

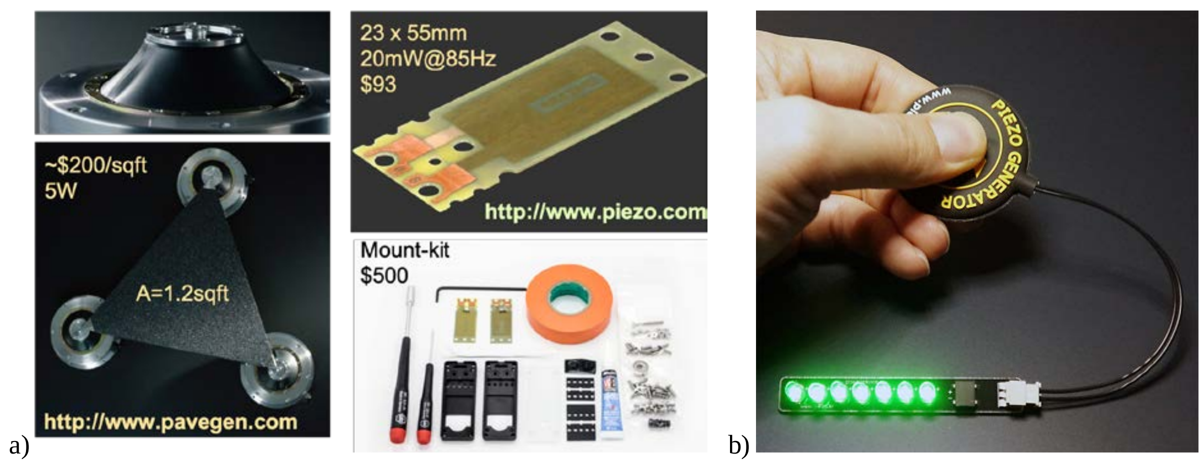



*Figure A6: Commercial Piezoelectric generator examples, a) Pavegen's step-on deformation generators and Piezo Devices low-frequency mini resonators and b) PZT-based hand-clicker mini generator*

*Table A1: Some important trials of piezoelectric harvesters in the transport systems.*[12]

| Year | Researchers | Type | Collector Size | Electric Output | Inputs |
|---|---|---|---|---|---|
| 2006 | Kim et al. | Lab test | 30 mm Dia. | 40 mW / 100 mW | 70 N load in 100- 200Hz |
| 2010 | Innowattech | Field test | N/A | 250 kWh per 1 km | 600 traffic volume |
| 2011 | Rodriguez et al. | Lab test | 29 mm Dia. | 48.2 / 2.6 uW (Signal) | 14 to 116 km/h |
| 2012 | Kim et al. | Lab test | 43×33 mm | 63.9 mW / 7.61 mW | 20 km/h vehicle speed |
| 2012 | Yao et al. | Lab test | N/A | 106 V to 154 V | 0.4 to 0.7 MPa in 5 Hz |
| 2014 | Xiong et al. | Field test | 6×31.6 mm Dia | 3.106 mW | Truck |
| 2015 | Roshani et al. | Lab test | 10 mm Dia. | 40 V to 80 V | 2.1 to 5.6 kN |

### A.2.2. Electro-Magnetic (EM) Harvesters

A more conventional approach for generating power from vibrations is the use of purpose-built linear electro-magnetic generators that are based on Faraday's *Law of Induction*. Much-like any other electro-magnetic generator, external translational motion (vibration) drives an electric coil or magnet with respect one another in a one degree-of-freedom system (Figure A7), thus producing time varying magnetic flux (Φ) or inductive current, which can be related to the output voltage ($E_v$) according to Faraday's equation: $E_v = -d\Phi/dt$. Assuming that the magnet ($B$) and displacement ($x$) are perfectly aligned, and that the $N$-turn coil has a circumference of $l$, the open-circuit potential across the coil can be expressed as $V_{oc} = NBl\frac{dx}{dt}$. By coupling this potential to load resistance $R_L$ and solving for equation of motion for a given level of mechanical damping ($d$) and electric conversion factor ($\delta_c = B_z l$), it is possible derive the electric power dissipated by the load as it is vibrating with a simple harmonic input:

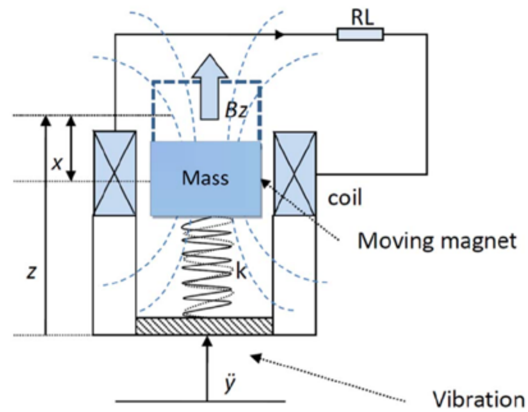


*Figure A7: Generic model of a single degree-of-freedom electromagnetic vibration harvester*

$$P_e(\omega) = \frac{Y_o^2}{2R_L}\left|\frac{j\omega m\delta_c\omega_c}{(\omega_c + j\omega)(-m\omega^2 + j\omega d + k) + j\omega\alpha\delta_c\omega_c}\right|^2$$

where electric coupling force factor is defined as $\alpha = B_z l/R_L$, and the electrical cut-off frequency as $\omega_c = R_L/L_e$ for the inductor coil with self-inductance $L_e$. This equation proves that many design parameters such as the actual design of the coil (via $L_e$), its ability to couple to the vibration (i.e. $\alpha$ and $\delta_c$), extent of mechanical damping (d) and vibration frequency impact the power that can be harvested in the linear electro-magnetic generator.

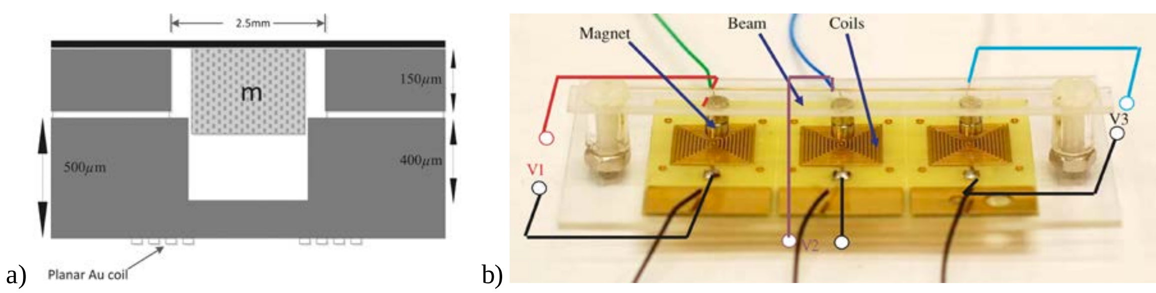


*Figure A8: a) Generic structure of MEMS based planar electro-magnetic energy harvester, b) a practical triplet implementation example.*

**Design & Operation**: As compared to the piezoelectric devices, EM harvesters tend to be larger in size and thickness due to the sizeable magnets needed for larger power levels. However, thanks to MEMS engineering that can fabricate and integrate these elements in an ultra-thin and efficient fashion, EM harvesters have evolved in recent years to very compact dimensions. MEMS process make it possible to miniaturize and flatten the EM generators described above, as seen in

Figure A8 above. Thus, they can be found in different form factors and sizes which make them suitable for various structural elements and locations. They may be especially suitable in solutions where the piezoelectric harvesters are not very effective, either due to the large vibrations involved, cost or frequency of operation.

**Examples:** Depending on the size of loads involved and their (transverse versus longitudinal) orientation with respect to the generators, EM harvesters can be designed in numerous ways. Using the MEMS fabrication processes or micro-assembly, planar and compact generators are available to be laid under the pavement (Figure A8) or built into the other structural elements. The utilization of very compact and strong rear-earth magnets, such as the NdFeB alloy in Figure A8(b), permits the size of the magnet (and the overall system) to be reduced dramatically while also generating notable power for its size. Many compact MEMS-based EM generators can be combined and scaled-up according to the desired application. Depending on the overall size or frequency of interest, the coil size/shape and magnet strength must be optimized in each case.

For applications that demand coupling of small to mid-size linear EM harvesters, several commercial off-the-shelf solutions exists as shown in Figure A9. Many of these devices are optimized for a given force/acceleration levels and can deliver power at 1 to 100 mW level provided a good quality mechanical coupling is achieved.

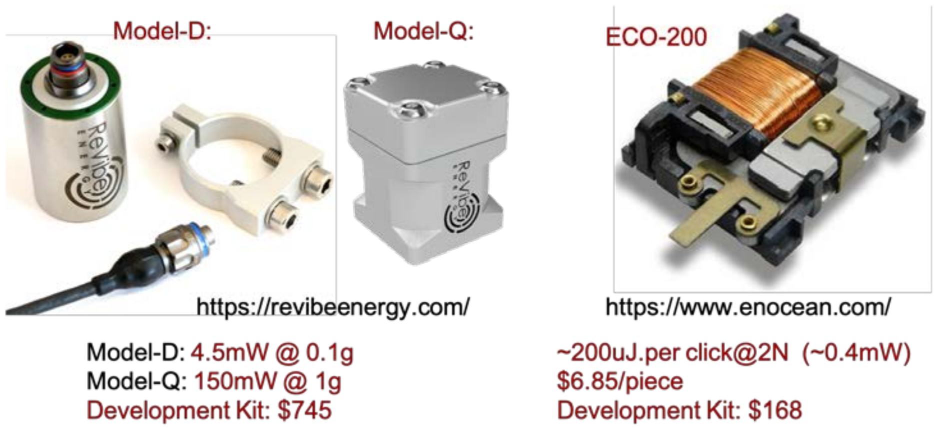



*Figure A9: Commercial examples of linear EM generators by a) Revibe Energy and b) Enocean.*

### A.2.3. Electro-Static (ES) Harvesters

Capacitive devices in which the two electrodes vibrate against one another can be used to generate power in electro-static generators. However, this approach would require an accurate timing and electronic circuit to orchestrate the power extraction. The idea of electrostatic energy harvesting, which can be seen in Figure A10(a), is summarized in three steps: put an electrical charge $Q_0$ on a variable capacitor ($C_v$ ) when its capacitance is high ($C_{max}$ ). Then reduce this capacitance to its minimal value $C_{min}$, thanks to the vibrational motion, and eventually discharge the charge stored in the capacitor ($C_{stor}$) between these extremes [28]–[30]. It is a technique that requires an electronic control interface to ensure switches (SW1 & SW2) are timely opened/closed to transfer the excess charge. It is an approach where energy 'investment' put in forming the initial charge $Q_0$ grows due to change in the capacitor size. The method relies on the proportionality between charge and voltage across a capacitor (C=Q/V) to ensure that either the output voltage (charge-constrained system) or the output current (voltage-constrained system) will increase in response to vibrations driving capacitive extremes. Thus, the power can be stated as

$$P_c(\omega) = \frac{\omega}{2\pi}\frac{U_o^2}{2}C_{max}\left(\frac{C_{max}}{C_{min}} - 1\right)$$

where $U_o$ refers to potential inducing the initial charge across the $C_{max}$ state of $C_v$.[28] When this capacitor is driven by a mass($m$)-spring($k$) system as shown in Figure A10(b), with mechanical ($d_m$) and electrical ($d_e$) damping constants at its mechanical resonance state, the maximum power that can be generated becomes $P_c(\omega) = (d_e m^2 \omega^4 Y_o^2)/2(d_e + d_m)$. This means that larger is the

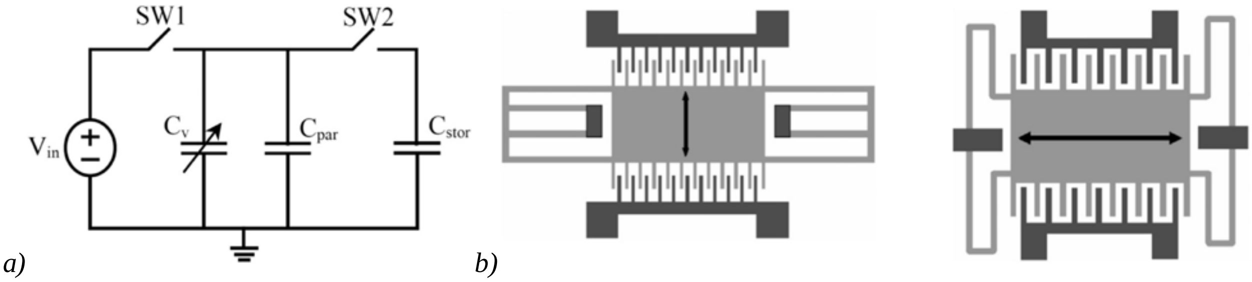
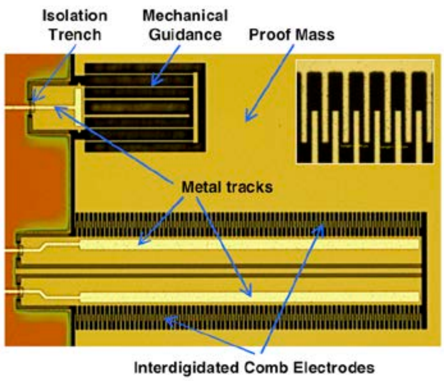



*Figure A10: a) Generic 3-capacitor electrostatic vibration energy harvester circuit b) its MEMS implementation of the variable capacitor Cv in the model, which has 1-D freedom in the direction of vibrations.*

mass or vibration frequency the greater the power that can be generated, as long as $d_e \gg d_m$. Current MEMS-based capacitors provide this conversion efficiently as they have low mechanical losses and high frequency operation. However, ES generators require large capacitors (area and mass) to be more effective, and an electronic interface is needed to 'harvest' the charges due to vibration, which tends to make them more complex at the electrical end. Hence simpler physical structure (moving plates) is traded for more complex electric power extraction, in contrast with the mechanical complexity of the EM generators that are simpler to extract power.

**Examples:** Due to MEMS fabrication processes involved ES harvesters tend to come in small sizes (Figure A11). But they can be replicated across an entire wafer, making it low-cost and easy-to integrate them with the control electronics required. Thus, given their size, they are especially suitable for high frequency operation on small flexures and posts. Since their operation would not interfere with other elements, they can be used alongside EM and piezoelectric counterparts in hybrid schemes. Figure A11 shows two examples from recent literature. Although simpler than the EM counterparts, requiring no magnetic elements, ES harvesters are not practical to scale up to large dimensions, delivers limited power (~mW) and suitable only for battery-based systems.

a) 

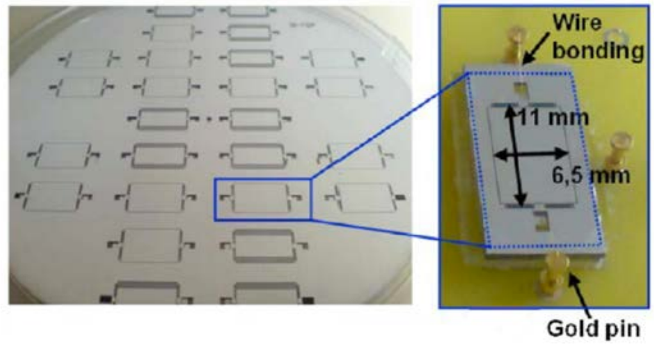

b) 


*Figure A11: MEMS-based ES generator examples a) single device up-close [29] and b) wafer-scale integration example [30]*

### A.3. Micro and Mini Wind Turbines

The traffic driven air-flow in a highway is one wind energy source that can be harvested and used for various purposes, such as highway lighting and powering a nearby micro-grid. The wind induced by the moving vehicles causes a drag force, which is the force induced when an object moves in fluid medium. This wind turbulence along the highways can be captured by the small wind turbines along the highways (Figure A12). Studies have been conducted that place either vertical or horizontal axis wind turbines on the highways. Figure 6 presents the placements of the vertical axis wind turbines on the road divider of a highway.

Today's wind turbines are lighter in weight than the turbines used on windmills in the past. Micro and small-scale (mini) turbines (400 watts to 50 kW) are available. They are intended for remote power, battery charging, or net metering type generation. These turbines can be used in conjunction with batteries and inverters to provide constant power at locations where the installation of a distribution line is not possible or is more expensive. Small wind turbines can even be grid-connected for residential power generation or they can be used in off-grid applications such as water pumping or battery charging. These small turbines are typically installed as a single unit or in small numbers.

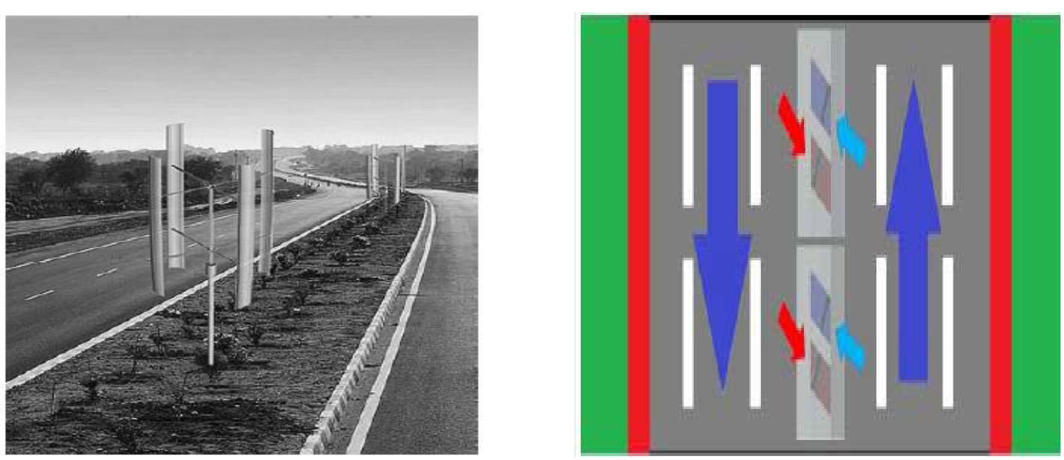


*Figure A12. Placement of the vertical axis wind turbines on the divider of the highway.*

**Power Extraction**: Wind energy is extracted by wind turbines through their blades, and then transferred by the gearbox and rotor hub to the mechanical energy in the shaft. The shaft drives the generator to convert the mechanical energy to electrical energy. The turbine model is based on the output power characteristics, expressed as: $P_m = C_p \rho A v_w^3/2$, where $P_m$ is the mechanical output power in watt, which depends on the performance coefficient $C_p$, air density $\rho$, turbine (or rotor) swept area $A$, and wind speed $v_w$. Area $A$ is important because the rotor is the part of the turbine that captures the wind energy. So, the larger the rotor, the greater is the energy that it can capture. The $C_p$ determines how much wind kinetic energy can be captured by the wind turbine system and has a theoretical limit of 0.593, which is known as the Betz Limit. Depending on the turbine design and the operating conditions, $C_p$ values would vary. Other important factors that impact power production and selection of the turbines include the following concepts:

- **Wind Turbine Rating:** The ratio between the swept area of the turbine's rotor and the specific rating of the turbine, which typically ranges from 0.32 to 0.47 $kW/m^2$ for the best compromise between energy capture, component loading, and cost.
- **Annual energy outpu**t provides a better measure for the performance of the turbine rather than the power. An estimate of the annual energy output from the wind turbine (in kWh/yer) determines if a particular wind turbine would provide enough electricity at a particular site.
- **Turbine Spacing**: The spacing between the turbines is mainly dependent on the rotor diameter and the wind resource characteristics. It is typically selected to increase the energy production and reduce the risks of damaging the rotor due to turbulence and to ensure maximum energy generation while maintaining reasonable inter-connectivity costs.
- **Control Scheme**: A power conditioning unit is necessary to interface wind turbine generator output to the electrical infrastructure. The speed of the wind turbine is controlled dynamically to match the wind speed for the maximum power extraction. Variable speed turbines produce energy at slightly higher efficiencies, over a wider operational range of wind speeds, than constant-speed turbines.
- **Grid vs Stand-Alone Operation:** In a stable grid interface, an energy storage system is desired to filter the fluctuation in the wind energy to provide reliable power to the user. As such, most wind turbine systems interface either to the utility grid or the batteries. The grid-connected systems are considered practical if the wind averages at least 10 mph over the course of the year and the local utility requirements for connecting a small wind turbine are not prohibitively expensive. Stand-alone systems do not require a stable grid interface. The excess power from the wind turbine is stored in the batteries to be used later when there is not much energy produced by the wind turbines. The charge controller controls the charging rate of the battery as well as extracting the maximum available power possible.

Much like the solar generators, wind turbines of today are considerably mature and proven devices for energy harvesting that can be easily adapted for use in transportation infrastructure. Many commercial device examples, both in vertical and horizontal configurations, are available for immediate use (see Figure A13). However, in most cases, this will be a standard use of the devices unless the type, size and position of the turbine is optimized for enhanced output due to kinetic energy of the passing vehicles. This is especially true for compact vertical axis devices that are more likely to be employed by the transportation applications.


*Figure A13. Low-profile micro wind turbine examples that can be readily purchased and positioned on various ODOT highway structural elements*

There are also important recent advances in wind-based harvesters, especially in terms of low-profile turbine design in metro areas and high population density areas. Fig.A14 provides several examples of such structures [31], [32]. Many of these novel wind mills assume the shape of common landscape structures and bring the esthetics as an important design issue. Although having a lower power rating, such inconspicuous turbine designs can be especially relevant for transportation applications due to safety and noise concerns. Another important area of development in wind harvesters is the aero-foil devices [33] that are essentially flexure devices or flaps that are much smaller and easier to integrate to the planar structures with large surfaces. When coupled to EM or piezoelectric devices these can be made to harvest wind and air-wake energy in an efficient manner, as will be discussed in the hybrid devices sections.

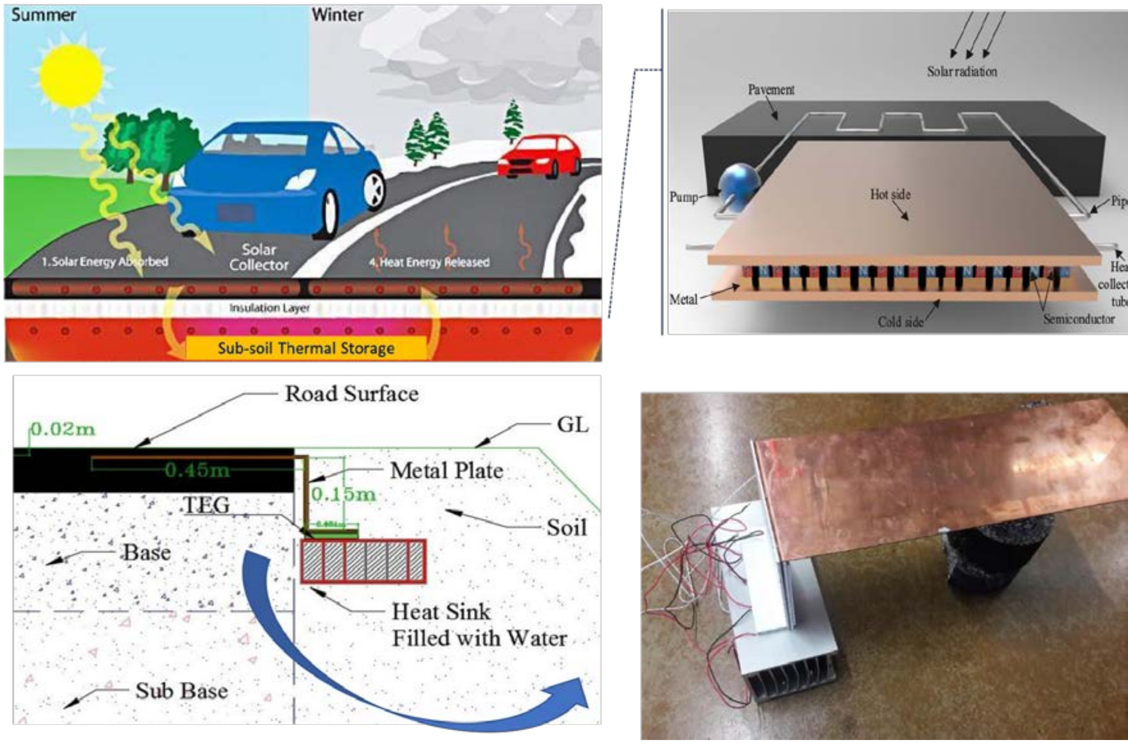



*Figure A14: a) Concept of thermos-electric energy harvesting via road surface using TEGs that may be placed directly below the road surface or nearby using fluidic pipes for heat transfer and b) Example for direct plated system by Datta (2017) [11]*

### A.4. Thermo-Electric Harvesters.

Temperature differentials, either naturally occurring or enhanced by vehicular traffic on the roadways can be used thermo-electric generators to capture and convert energy across the vast ODOT infrastructure. The state of Ohio, with four distinct seasons and large variations in the weather daily and between seasons, should be able to take advantage of this effect. Since recent advances in material science have resulted in novel thermoelectric generators (TEGs) with higher efficiencies and new device designs that can be integrated into structural elements, this technology has become more attractive. TEGs, be easily scaled to different shapes and sizes, as long as two firm thermal boundary conditions can be accessed and maintained during operation. Figure.A14 shows the context of conventional thermal generation via pavement (especially using the high absorption of asphalt) and basic profile of the TEG devices. The main challenge in this technology its relatively higher cost (under-pavement) as well as much lower efficiencies as compared to more established technologies such as solar and wind as well as vibrational (piezo &EM) generators. It is also true that any indirect kinetic enhancement in this technology, via indirect cooling or heating of passing vehicles, is likely to be minimal. Thus, it is not a truly kinetic harvester in essence.

There are two different approaches for thermos-electric generation: TEG plates in direct contact with the heat boundary conditions and generators that are placed convenient nearby location exchanging heat with the environment using a liquid or solid (typically metal) thermal conductors. In the case of liquid, the distances involved can be much larger, thanks to piping installed. Each have advantages and challenges of their own. The direct contact TEGs tend to be smaller in size and power output but cheaper to operate. In contrast, remote exchangers relying on circulation of glycol-based fluidic mixtures (high thermal capacity) can output more energy over larger areas, at a higher cost to build, install and maintain.

**Heat Pumps & Geothermal Power**: The thermal energy from the pavement system can be captured via different approaches. For example, as shown earlier in Figure A14, power can be generated due to spatial variations of temperature via TGs, or due to temporal variations of temperature via pyroelectric materials. Heat pump systems can also be integrated to the TGs to improve the heat transfer in the pavement systems energy [14], [34]. Environmental constrains, space and weather/climatic patterns play a significant role in deciding the type of thermos-electric generators. Geothermal heat has already found applications in home heating and road/bridge deicing, especially in locations with confirmed geothermal potential (i.e. Western US). Not being seismically active, such locations are typically non-existent in Ohio, hence geothermal EH is *not* a practical approach for ODOT. In some cases, typically in SE Ohio, limited options might exist for deicing bridges. Therefore, solar absorption via asphalt-based road surfaces, may present opportunities, especially during the spring/fall when heat differentials may be higher. By the same token, it appears that compact TEG devices integrated to specific surfaces such as bridge decks/embankments and exposed hill-sides are likely locations to explore for conventional TEG installations. Regardless of locations, TEG technology is likely to be competitive base technology due to its low efficiency and relatively high cost for installation.

If any, hybrid use of TEG devices in combination with solar assemblies and wind-based generation may become a more relevant option to consider. Because, in both solar and wind-based power harvesters integrated to transportation infrastructure, a natural boundary exists for heated (solar) and cooled (wind) surfaces that can make use of TEG devices. Even in hybrid solar-wind generators (see next section), depending on the size, geometry and power needs TEG can be exploited to provide some additional power. This limited potential may grow in near future, however, due to many polymer composites and ceramic alloys with highly engineered thermal properties being explored heavily in the last decade [35]. Such novel high capacity materials are especially useful for hybrid integration efforts as shown in Fig.A15, which utilizes shape memory effect to increase pyro-electric energy conversion. [36] In this case, ambient heat or cooling from vehicles can drive the bi-morph membrane that also integrate piezoelectric device for extra power.

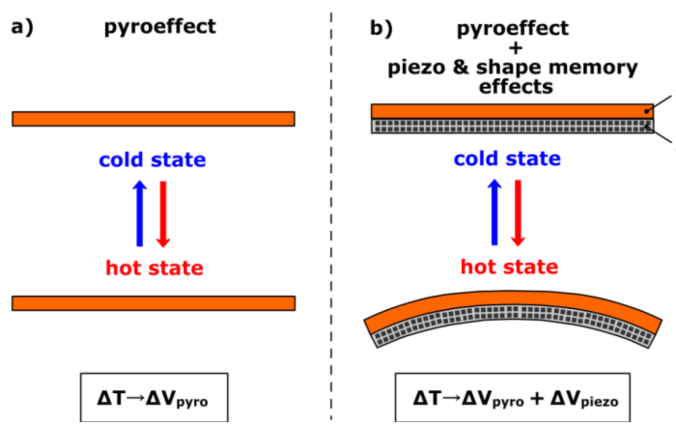



*Figure A15: TG devices combined with a bi-morph piezoelectric device for hybrid generation that results in 50% increase in energy production [Zakharov 2013]*

### A.5. Novel Approaches and Hybrid Systems

Given the varying nature of traffic flows (i.e. traffic jams, rush hours), it is necessary to develop a resilient energy harvesting solution that can integrate established solutions with other alternative energy options such as solar, wind and thermal sources. Since such alternative systems already come with energy storage capacity, power inverters and grid connectivity, it may be especially suitable to integrate or 'piggy back' kinetic energy-driven harvesters onto their platform. In particular, wind-solar integration is a unique option since they tend to complement each other's weaknesses climatically. For instance, mini solar farms that may be built in specific ODOT assets such as cloverleaf intersections, rest areas, or embankments, can be furnished with mini wind turbines that will take advantage of vehicular wake currents. Also, actual micro wind turbine elements that can be mounted at the underpasses, bridges or posts can also feature solar arrays. Another example to this approach is the vibration harvested via piezoelectric elements in a well-known high-traffic metro area can be coupled to a nearby solar panels installed onto noise barriers. Hence, hybrid approaches are exploring a composite and integrated approach that can improve the amount of energy scavenged while also reducing the dependence on any one form of energy for harvesting. Another advantage in implementing hybrid generators with shared resources is that fact that ODOT can test and compare novel harvester technologies, as they become available, on a single platform and generate valuable field data for future plans. Therefore, novel and hybrid approaches can offer both capacity enhancement and future development base for EH solutions.

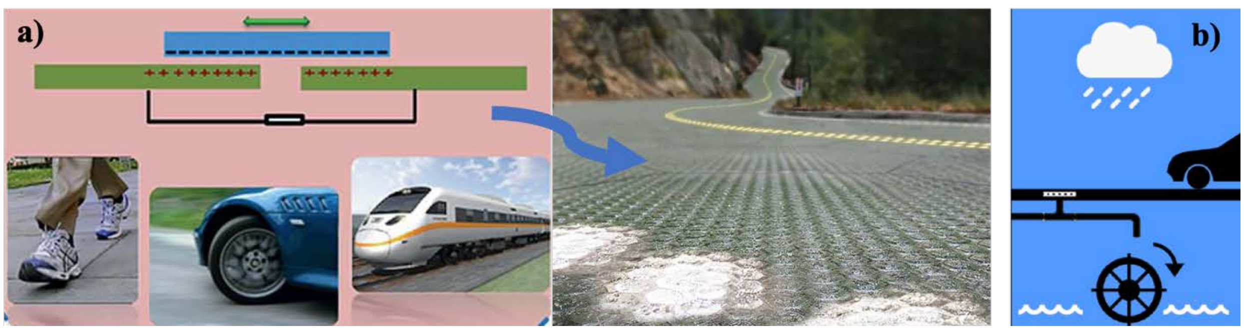



*Figure A16. Alternative energy harvesting systems. (a) Triboelectric "mats" (Wang 2014) [9] that convert friction generated by vehicles and pedestrians into static electricity (b), Drainage turbines under roadways (Williams 2017) to use water run-off to generate electricity*

**Alternative Approaches:** In addition to kinetic energy waste, there are other waste energy sources that can be exploited in the roadway systems as indicated earlier in Figure 1 and in Figure A16. Some of these alternative approaches include:

- **Triboelectric Generators**: In addition to piezoelectric and electromagnetic generators, the kinetic energy due to traffic can also be scavenged via triboelectric nanogenerators (TENG). The triboelectric effect is the phenomenon that a material becomes electrically charged after it contacts a different material through friction (Wang, 2014) [9]. Recently, there has been fast development in the area of TENG which can lead to high power density (up to 1200 W/m$^2$), high volume density (up to 490 kW/m$^3$) and very high energy conversion efficiency (50%–85%). It can be applied to harvest all kinds of mechanical energy that is available in our daily life, such as walking, vibration, wind as well as flowing water (Wang, 2014). Harvesting mechanical energy induced by moving vehicles in roadway systems can be a very promising application for TENG, as indicated in Figure A16(a).
- **Drainage Water Turbines**: The movement of water through the drainage systems also provide an opportunity for energy harvesting in roadway systems. Similar to mini hydropower

generation, the flowing water can generate electricity via a rotational turbine in the drainage/sewage conduit systems shown in Figure A16(b). [37]

Majority of novel energy harvesting approaches are currently in the development stage and each one has advantages and disadvantages. At present, the cost and payback period for developing an individual energy harvesting approach is prohibitive, hence they may not become an effective EH solution for ODOT in the short run. However, as they mature and become more accessible, they can be readily integrated onto *hybrid integration platforms*, examples of which will be provided below.

**Hybrid systems** including different types of energy harvesting components is a viable way to reduce the systematic cost and increase the overall power output [38]. By combining several EH device types on a single power engineering platform it is possible to share power inverters, battery storage elements, structural framework, micro-controller and wireless access, resulting in significant cost savings [39]. Moreover, it is possible to make a very fair and extended comparison of these alternative technologies under the same conditions when they share resources and physical location. Finally, hybrid energy harvesting platforms also results in the complementary features of these energy conversion technologies and synergistic advantages such as solar panels serving as structural support, wind turbine cooling solar panels and doing heavier work at night, vibrations benefiting from wind turbine and heated solar panels serving as boundary condition for thermoelectric generators and so on. Clearly, hybrid solution possibilities are numerous as many combinations between EH devices are possible.

Examples of possible combinations include, hybrid solar-wind generators (see Figure A17) shows several examples of, piezo-wind coupled generators or integration of TGs with solar systems. Hybrid system can typically operate in two modes: simultaneous and sequential. In the former case, power delivery can be maximized, while the latter ensures that power delivery is uninterrupted. For instance, hybrid solar-wind generators that can be placed along roadways. Hybrid solar-tribo nanogenerators can individually or simultaneously scavenge solar, kinetic and wind energies [16]. Figure A15 already provided an example hybrid piezo-thermal generator that also use shape-memory metal bi-morphs. Moreover, most piezoelectric materials are also pyroelectric in nature. Thus, it is possible to explore the possible interactions between the two effects without an adverse interference between and the total energy harvested is the algebraic combination of the piezoelectric and pyroelectric energy [40].

*Figure A17: Solar-Wind hybrids concept systems and example devices, including both commercial illumination systems, designer concept for a portable system and prototype solar sail based on flexible solar cells.*

#### A.5.1. Solar-Wind (SW) Hybrids:

Several examples to practical solar-wind hybrid technologies are provided in Figures A17. Bringing together two most abundant energy sources in a synergistic fashion ensures that SW hybrids can deliver even greater power densities in broader range of weather conditions. Moreover, they are mostly based on commercial products that are already exist or in the prototype stage, which makes SW hybrids most attractive and low-cost option to consider. The types of SW hybrids will greatly expand as flexible solar elements become unique structural elements harnessing wind power while also harvesting solar energy in fairly large dimensions as in the case of solar sail in Figure A17. Bringing solar out of rigid panels and forming unique extended surfaces will be an extremely attractive proposition for transportation infrastructure and wind energy generation. It is important to treat SW-hybrids also as a development platform. In most cases such 'hybrid' SW-base systems can be altered to integrate one or two additional EH devices. In other words, SW-hybrids are not only valuable as practical low-cost power generators, they can also serve as a development platform for expanding hybrid integration efforts for ODOT in the near future.

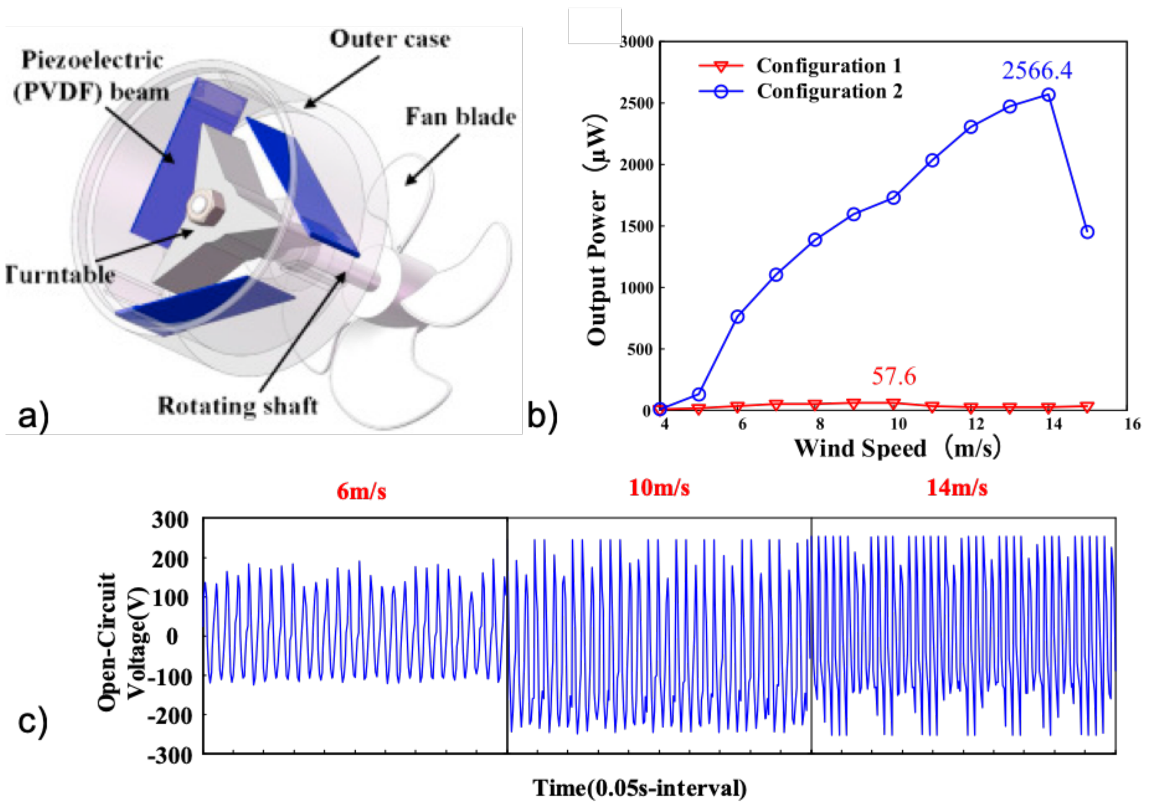



*Figure A18: a) Concept device for demonstration of Wind-Piezo coupled hybrid generators. Turning wind turbine also vibrates PVDF-based piezo elements, b) power levels produced in two configurations of blades and c) voltage levels recorded under three different wind speeds.*

#### A.5.2. Wind-Piezo (WP) Hybrids:

It is already established, earlier in this literature review, that piezoelectric elements have unique and superior features as a technology for harvesting static deformations and vibrations. Depending on the size, operation mode and placement of the piezo elements, they can be easily coupled to wind turbines that naturally generate their own vibrations and amplify structural resonances. Hence a very synergistic hybrid device can be built in a variety of forms. Piezo elements integrated onto the blades, posts and bases can be used to generate additional power or enhance the electro-magnetic interactions so that the overall system operates with higher efficiency. More importantly airfoils [33] can use adapt PVDF-based polymers as the primary flap/foil element as the system is driven by wind or vibrations, as shown in Figure A18. In fact, 'artificial trees' where aero-foil 'leaves' are actually piezo elements (PVDF or AlN) are also being studied in the context of urban friendly and low-profile WP hybrids. [32]

Another unique example for hybrid integration that involves piezo and wind-based devices is shown in Figure A19, where PVDF again serves as the flexible piezo device for power generation. In this case a 'flexible' polymer-based battery is also integrated on the flap that oscillates. This is possible because, both PVDF and battery technology share the same fabrication technologies and a number of common elements such as substrate and one electrode, thus lowering cost and increasing functionality [41]. To operate this device successfully, the thickness and overall dimensions of the 'flap must be carefully optimized so one can generate the maximum power while also having sufficient volume and good lifetime for energy storage.

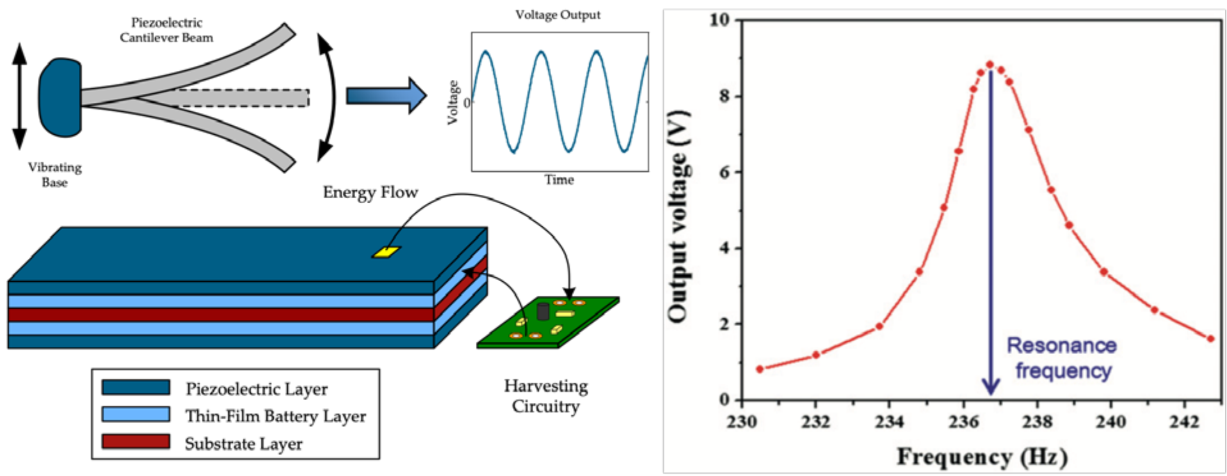



*Figure A19: A hybrid aero-foil example that integrate flexible piezo and battery elements, saving considerable weight and cost in the process. The aero-foil is driven by structural vibrations and/or air flow to generate a maximum voltage output at its natural frequency of 237Hz. [40]*

### A.5.3. Solar Wind-Piezo (SWP) Triple-Hybrids:

A superior option for hybrid development would be to pursue integration of three EH technologies (solar, wind and piezoelectric generators) on a common framework. The basis of this integration is likely to be a commercial SW harvester introduced above (see Figure A17). Essentially, this would involve replacing the wind turbine with a coupled WP-hybrid harvester (see previous section) or placing piezo harvesters on the pole and other structural elements of the commercial base system. In other words, one hybrid technology can be easily integrated onto another synergistic device, leading to higher power capacity and overall energy production with minimal development and investment costs. Other design details in such a triple integration problem can be easily addressed after the dimensions, performance and placement of the base SW system is known. It is best to attempt the triple integration after establishing the optimal use for the hybrid SW and WP devices and ensuring that the overall triplet does bring the best in all devices.