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The WindBelt as a Low-Cost Energy Generator: Low Energy Consumption Sustainable Solutions within the Framework of Modelling Pedagogy

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Abstract

The multitude of low-energy applications extend from wireless sensors, radio-frequency transceivers, charging devices, cameras and other small-scale electronic devices. The energy consumptions of these devices range in the milliwatt and microwatt scale which is a result of continuous development of these technologies. Thus, renewable wind energy harnessed from the aeroelastic effect can play a pivotal role in providing sufficient power for extended operation with little or no battery replacement. The paper deals with the development of clean and alternative low-cost energies for low-energy applications. The presented prototypes are accomplished during science lessons. An aeroelastic belt as a simple device composed of a tensioned membrane coupled to electromagnetic coils and power conditioning components were explored. Further improvement towards the integration of energy harvester into the real world and its possible applications were studied too. While teaching author of this text used the backward design, unfold learning and modelling pedagogy as she considered them as much more efficient approaches to course design then traditional methods.
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Keywords:	Windbelt; Aeroelastic flatter; Wind induced vibration; Energy harvesting; Low-energy generator; Low-power consumers; Targeted intervention in education; Modelling pedagogy

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1. Introduction

The aim of this paper is not to prototype an energy harvester in order to develop a framework for a modeling pedagogy. The aim was to build device that harvest ambient energy and convert it into electric energy. The Windbelt – low-cost energy generator for low energy consumers and zero-waste circular economy, is chosen as main topic. The term “modelling pedagogy” in the title of this paper is used in the context of the framework within modeling and designing of an energy harvester was placed. Actually, by “modelling pedagogy” we refer to the “tool” that enabled author of this paper to deal with development of clean and alternative low-cost energies for low-energy applications within the science lessons.

Different modeling approaches has been combined: a) exploratory modeling, where students investigate the property of a pre-existing model by engaging with the model (e.g., changing parameters) and observing the effects; b) expressive modeling, where students express their ideas to describe or explain scientific phenomena by creating new models or using existing models; c) experimental modeling (called inquiry modeling originally), where students form hypotheses and predictions from models and test them through experimenting with phenomena; d) evaluative modeling, where students compare alternative models addressing the same phenomenon or problem, assess their merits and limitations, and select the most appropriate one(s) to explain the phenomenon or solve the problem; and e) cyclic modeling, where students are engaged in ongoing processes of developing, evaluating, and improving models to complete comprehensive projects as experts would be.

The following targets were set as learning outcomes: to build a low-cost, energy sustainable and eco-friendly generators, easily maintained, and with zero embedded energy (students are advised to use recycled electronics

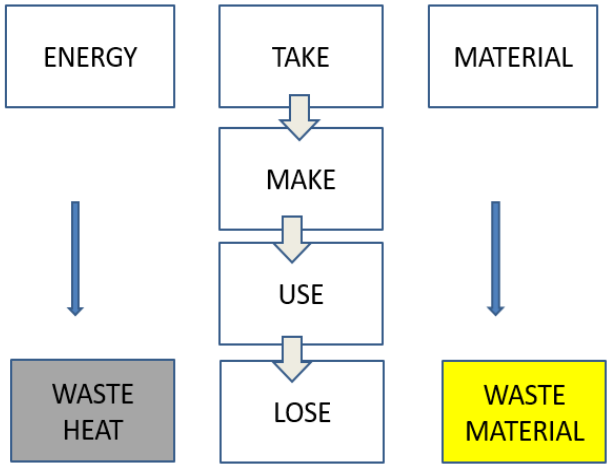

Figure 1. Waste heat and waste material as byproduct of energy production.

– waste energy and waste material). The prototype had to be functional - suitable for low-energy consumers. These boundaries were requested in order to support innovation with the zero-energy waste in the circular economy too, since the industrial system becomes more and more inherently degenerated. A lot of waste heat and waste material have been produced while the extraction and processing of Earth's materials has indeed falling (Figure 1). Reengineering energy would be solution, utilizing energy from embedded energy or designing educational tools or/and small generators from the recycled electronics.

Beside learning targets and learning outcomes above mentioned there are four main arguments that we put forward for the epistemic and social values of such projects. Firstly, in search for a sustainable solution on requested task, students were advice to search for extensive link to their local community what in return can bring an interest of local community to design own sustainable energy solutions. Secondly, evolution design generates content over time and is a response to key questions for energy sustainability in the context of social and environmental change: Can conversation between academic institutions and non-expert communities make us better at understanding different perspectives on sustainable energy solutions? Can collaboration of experts and non-experts in interdisciplinary research reveal seeds of alternative futures? Thirdly, this way we establish foundation for collaborative tool that allows non-experts to actively contribute their ideas during a planning and provides real-time analysis feedback on the emerging design ideas in order to quickly advance the design process and help participants identify the acceptable solutions. Fourthly, we recognized the role of learning through mistakes in the art of delivering development aid to community and consequently believe we have developed a model of professional intervention that reflects enlightenment that can be only obtained through the observing of errors, both through research of own failures and through rigorous prototyping.

This paper is organized as follows. The concept of energy harvesting is introduced in Chapter 2, physics of the wind power is briefly given in Chapter 3, the potential of aeroelastic phenomena as energy harvester are introduced in Chapter 4 and the transducing mechanisms are briefly introduced in Chapter 5. The Faraday's electromagnetic induction and its interplay with aeroelastic flatter are introduced in Chapter 6. The literature overview on Windbelt is given in Chapter 7. The student projects as learning outcomes are presented in Chapter 8. The observed advantages and disadvantages are systemized. Conclusion and further steps are given in Chapter 9.

2. Energy harvesting

Energy harvesting is the capture and conversion of small amount of readily available energy in the environment into usable electric energy. The electrical energy is conditioned for either direct use or accumulated and stored for later use. Energy harvesting is also known as energy scavenging or micro energy or micro energy harvesting.

Harvesting applications should be designed to be self-sustaining, cost-effective, easily maintained and to require little or no servicing for many years. In addition, the power is used close to the source, hence eliminating the transmission losses and long cables. If the energy is enough, the source can be powered directly without need to store and accumulate energy.

In the simplest form, an energy harvester requires a source of energy such as heat, light or vibration and the following three key components: transduced/harvester, energy storage and power management. Transducer is the energy harvester that collects and converts the energy from the source into electric energy. Typical transducer includes photovoltaic for light, thermoelectric for heat, inductive for magnetic, RF for radio frequency and piezoelectric for vibration/kinetic energy as presented in Figure 2.

For instance, piezoelectric transducers produce electricity (see Figure 3), when subjected to kinetic energy from vibrations, movement and sound. Kinetic energy is converted into electric and then rectified, regulated and stored in a thin film battery or a super capacitor.

Generally, energy harvesting suffers from low, variable and unpredictable levels of available power. However, the significant reduction in power consumption achieved in electronics, along with miniaturizing the

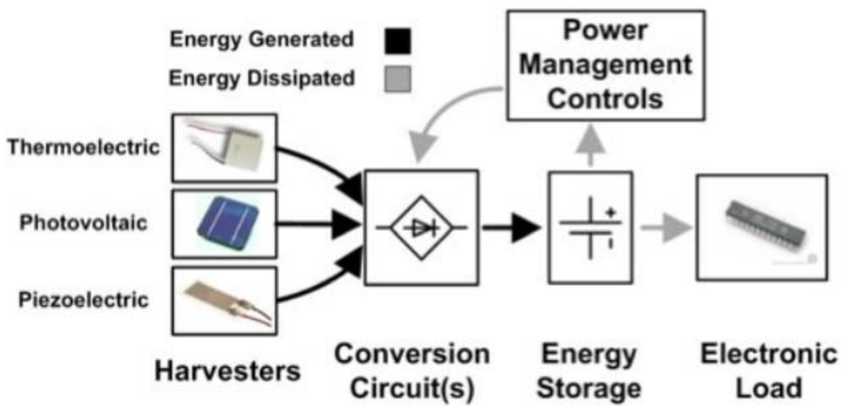

Figure2. Basic components of an energy harvester system

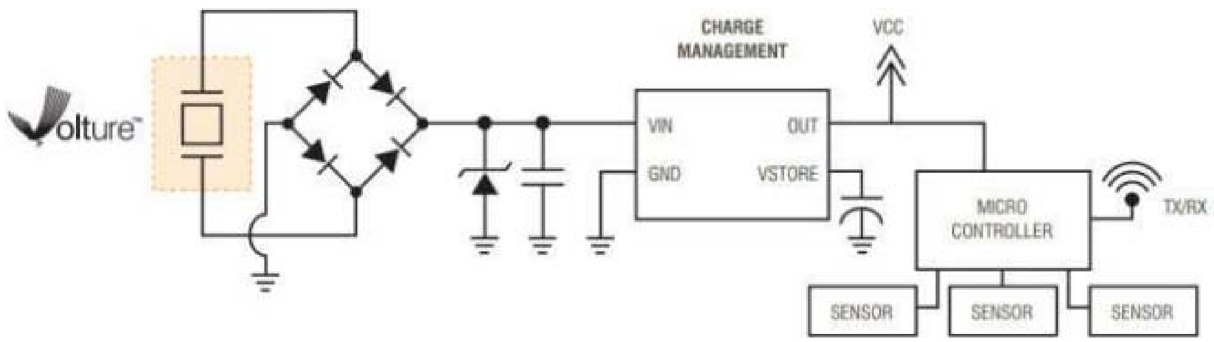

Figure 3. Piezoelectric Energy Harvester Circuit (Image courtesy of eu.mouser.com)

electronics and increasing the number of mobile and other autonomous devices, are continuously increasing the attractiveness of harvesting techniques. Consequently, the number of research paper in this field is continuously increases.

This paper discusses the harvesting energy from wind induced vibrations.

3. Physics of wind power and its limits imposed by Betz law

To estimate the energy in wind, let's imagine holding up a hoop with area *A*, facing the wind whose speed is *v*. We will consider the mass of air that passes through that hoop in one second. Since the mass of this speed of air is the product of its density *ρ*, its area *A*, and its length which is *x* times *t,* the kinetic energy of this peace of air is given by following equation:

$$\frac{1}{2}mv^2 = \frac{1}{2}\rho Avtv^2 = \frac{1}{2}\rho Atv^3 \qquad (1)$$

Dividing equation (1) by time -*t*, we get the estimation of power of wind, for an area *A* – that is, the kinetic energy passing across that area per unit time. Taking into account that the density of air is about 1.3kg/m^3, then the typical power of the wind per square meter of hoop is 140 W/m^2.

It is well known that not all of this energy can be extracted by a windmill. The windmill slows the air down quite a lot. The maximum fraction of the incoming energy that can be extracted by a disc-like windmill was worked out by a German physicist called Allbert Betz in 1919. If the departing wind speed is one third of the arriving wind speed, the power extracted is 16/27of the total power of wind. 16/27 is 0.59. As an example, if we assume a diameter of d = 25m, and a hub weight of 32 m, the power of a single windmill is

$$effociency\ factor\ x\ power\ per\ unit\ area = 50\%\ x \frac{1}{2\rho v^3} x\ \frac{\pi}{4} d^2\ = 34\ kW \qquad (2)$$

Variation of wind speed has crucial impact on the amount of the produced energy. Taller windmills sense higher wind speeds. The way that wind speed increases with height is complicated and depends on the roughness of the surrounding terrain and on the time of day. The win shear formula from the DANISH Wind Industry Association is given by following term:

$$v(z) = v_{ref} \frac{\log(z.z_0)}{\log(z_{ref/z_0})} \quad (3)$$

where z_0 is a parameter called the roughness length, and v_{ref} is the speed at a reference height z_{ref} such as 10m. In one of the UK government studies wind resource is estimated using an assumed wind farm power per unit area of most 9W/m^2. If the capacity factor is 33% then the average power production would be 3W/m^2.

What about mini-turbines? Taking account above consideration, it is obvious that the conventional approach for generating power using wind turbine is, however, difficult to apply to small scale energy harvesters, because small size generators are difficult to make and have low efficiency. Here is an example. Assuming a wind speed of 6m/s, which is above the average the most parts of Britain, and assuming a diameter of 1m, the power delivered would be 50W; that is 1.3kWh per day – not very much. Taking into account the cost for building and amount of energy embedded in micro turbine it is obvious that delivery of energy is much lower than the energy used to build it.

As alternative method we introduced students to concept of aeroelastic phenomena and its potential for harvesting applications.

4. Used aeroelastic phenomena for energy harvesting applications

When a structure is subjected to flow loads the structure may undergo various responses including nonlinear undesirable dynamic phenomena such as: divergence (static aeroelastic phenomenon), flutter (dynamic aerodynamic phenomenon), vortex – included vibration, buffeting (unsteady aerodynamic phenomenon) or limit cycle oscillations (nonlinear aeroelastic phenomenon) [1]. Piezoelectric materials and other actuators have been mostly used as active and semi-passive controllers to modify aeroelastic behaviour of wings. Piezoelectric actuators were also used for morphing wings.

In what follows we will focus on aeroelastic flatter. Aeroelastic Flutter involves aerodynamic forces acting on a structure to result in a self-feeding high energy oscillations. Flutter had the potential to occur in any object subject to wind. If there is positive feedback in the structure between the aerodynamic forces and its natural vibration, flutter will occur. This means that the vibrational oscillations of the object coupled with wind, will dive the object to move more faster and faster. Aeroelastic flutter results in 'self-exciting oscillations' and will build up until the aerodynamic or mechanical damping of the system matches the energy input. At this point, large amplitudes are occurring which can cause rapid failure in structure. In other words: aerodynamic force acting on a surface are divided in two parts: the component that support the structural motion of the body and the other that resist the movement; when the aerodynamic and structure loads are in balance it will produce harmonic oscillations. Above the critical flow speed there is an unbalance of energy flowing to the structure that cannot be dissipated and as the consequence the oscillations grows divergently.

To conclude, the flutter occurs as result of interactions between aerodynamics, stiffness, and inertial forces on a structure as shown in Figure 4.

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5. Controlled aerodynamic instability phenomena for energy harvesting

Flatter phenomena can be effectively used to convert wind energy into electricity, since the deflection caused by flatter is large and the oscillating frequency of the flatter is adjustable. The critical flow speed at which destabilizing aerodynamic effect cause self-excited vibrations of the structure to emerge is essential to the design of the energy harvester because it sets the lower bound on the operating wind speed and frequency range of the system.

The general approach to harvesting energy from these "aeroelastic" vibrations is to attach the beam to a secondary vibrating structure, such as a wing section. Such design eliminates the need for the secondary vibrating structure because the beam is designed so that

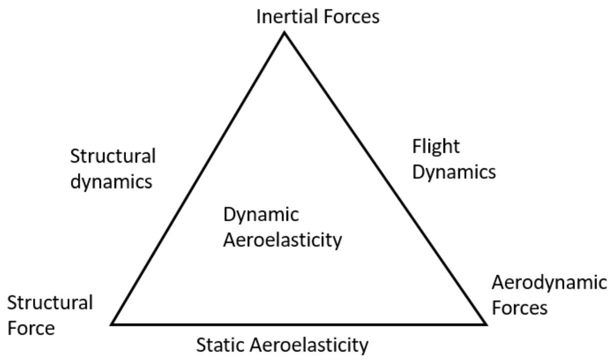


Figure 4. Figure demonstrates the interaction of inertial, structural and aerodynamic forces on surface vehicles

it produces self-induced and self-sustaining vibrations. As a result, the new system can be made very small, which increases its efficiency and makes it more practical for applications, such as self-powered sensors.

The different methods and materials used for energy harvesting are as follows: a) piezoelectric transduction; b) electromagnetic Induction; c) electrostatic transduction and d) electroactive polymers. We employ the electromagnetic induction.

6. Interplay of Faraday's law and aeroelastic flattering

In practice a changing magnetic field applied through a conductive wire in a closed circuit will generate electricity. The voltage induced in the electromagnetic transducer is expressed by the Faraday' s law as follows:

$$V = N \frac{d\phi}{dt}\frac{dz}{dt} \tag{4}$$

where *z* iz the relative displacement between a magnet and the coil and *N* is the number of coil turns and *Φ* is the magnetic flux. Thus, the induced voltage is proportional to the product of a magnetic gradient which is determined by the geometries of the coil and the magnet as well as their relative configurations, and the relative velocity between the magnet and the coil. The electromagnetic force F_{em}, which is proportional to the induced current in coils, acts against the environmental excitation force, and is given by following term:

$$F_{em} = D_{em}\frac{dx}{dt} \tag{5}$$

Where D_{em} is the damping coefficient. It is important to note that there are three dumping contributions: the aerodynamic damping, the mechanical and the electrical damping.

The dissipative power extracted by electromagnetic force can be describe as follows:

$$P = \frac{V}{R_L + R_c + jwL_c} \tag{6}$$

where R_L, R_c are load and coli resistance and L_C is coil inductance.

It is important to note that the current produced from aeroelastic flatter is an alternating current, with a frequency typically between 50 and 60 Hz, depending on the wind speed and construction dimension for the unit.

7. Birth of WindBelt: The phenomenon of aerodynamic flatter from flexible belt subjected to an airflow

Figure 5 shows the concept of aeroelastic flatter designed by Shown and his group which was later commercialised by company Humdinger [3].

The idea is very simple and low-cost. The magnets are fixed directly on the belt, and coils are placed around the magnet. The basic design is like that of an Aeolian harp and the oscillation of the belt resembles that of a vibrating string. The principle of aeroelastic flatter works here as positive feedback loop, in which the vibration of the oscillating belt causes an increase in the aerodynamic load, which in turn causes the belt to move/flatter further. The oscillating magnets that are attached to the belt create oscillating magnetic flux and change in magnetic flux further induce voltage and current which can deliver AC current. Thus, an electromagnetic transducer is used to convert flatter induced vibration into electricity. Prototypes have generated 40 mW in 10 mph slivers of wind, making his device 10 to 30 times as efficient as the best microturbines.

Fei Fei and Wen J. Li in their article [4] addressed a few problems. They said that "the vibrating belt may encounter the coils when its amplitude is increased at high wind speeds, and the location of magnet on belt should be systematically designed to ensure maximized magnetic flux linkage between the magnet and coils". A modified method of harvesting energy from flatter windbelt is proposed and an electromagnetic resonator which works as a piston inside a cylinder was implemented instead of heavy permanent magnet embedded on the belt. Furthermore, the resonator is placed near the end in the belt to make use of bandy stiffness. Thus a power of 1.3 mW is achieved at wind speed of 3.1 m/s. In order to increase efficiency, the longitudinal versus torsiorel flatter oscillations were explored. It was shown that adding the magnet at other points along the belt's length adds weight to the belt in the middle of its natural oscillation and creates a standing wave pattern that results in self-dampening.

Furthermore, David Eisen and his colleagues exploited two types of architectures and present in their paper [5]: a conventional design with an adjustable belt that uses weight for tension control and a revised design with a belt oscillations perpendicular to the coil axes. This is illustrated in Figure 6.

P.Balaguru and his group primarily settled on the conceptual design based around of Shown's design [6] and they gave cost and recent data (see Figure 7) that can be used for comparative studies.

More interesting approach is presented in [7], see Figure 8, where Seong-Hyok Kim and his group designed two devices: a) a windbelt-based vibratory linear micro-generator targeting strong airflows, and 2) a Helmholtz resonator based generator capable of scavenging energy from weaker airflows, i.e. environmental airflows. Both devices consist of two tightly coupled parts: a mechanical resonator, which produces high-frequency mechanical oscillation from quasi-constant airflow; and a permanent magnet/coil system, which generates electrical power from the resonator's motion.

A Helmholtz resonator is simply a gas filled chamber with an open neck, in which a standard second-order (i.e. spring-and-mass) oscillation occurs. The air inside the neck acts as the mass and the air inside the chamber acts as the spring.

There is many more examples but no one used for teaching purpose. For further study in this field we recommend extensive and comprehensive review written by A. Abdelkefi [8].

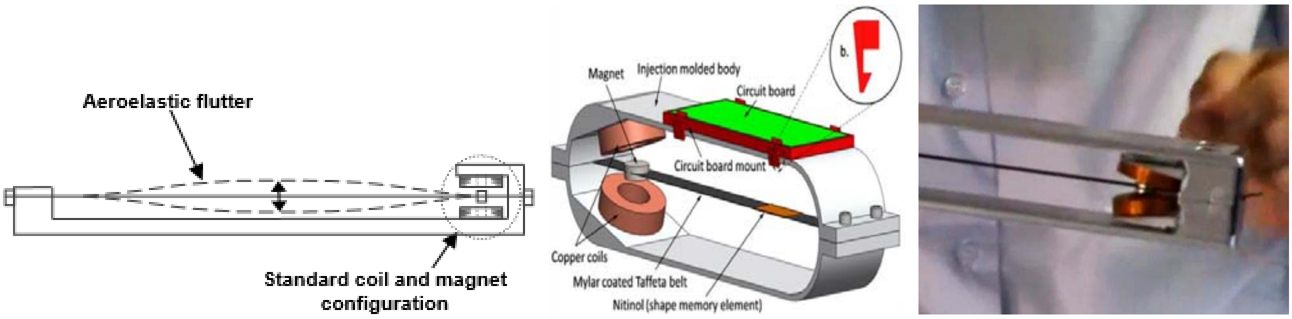


Figure 5. Basic WindBelt design: Driven by the fluttering belt, the magnets oscillate between two coils and generate AC electrical signals to their wire terminals [3]

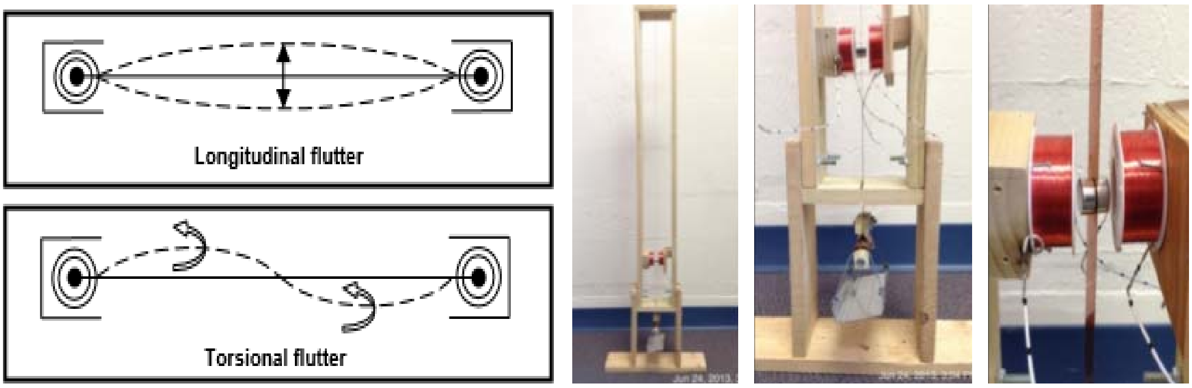


Figure 6. Image on the left: Longitudinal versus torsional flutter oscillations.
Image on the right side: Vertical test bed (parallel magnet-to-coil orientation) full-view, carriage and coil close-ups [5].

Wind Speed (m/sec)	Current(mA)
3	2
3.4	2.2
3.8	2.3
4.2	2.5
4.4	2.7
4.8	2.9
5.2	2.9
5.4	2.9

Figure 7. WindBelt design [6]

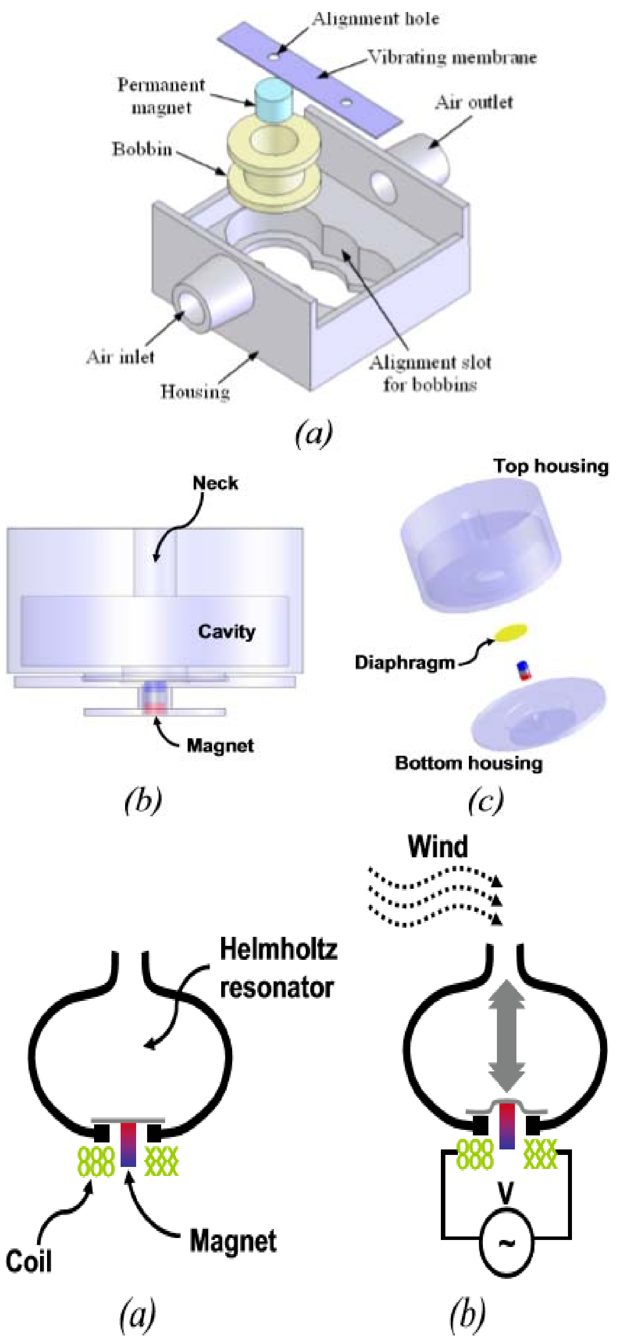


Figure 8. Top : 3-dimensional schematics of the proposed energy scavengers; (a) exploded view of the widbeltased micro-generator, (b) cross-sectional view and (c) exploded view of the Helmholtz resonator based micro-generator.
Bottom: Schematics showing the operation principle of the proposed energy scavenger (a) at rest and (b) at resonance by external air flow. [7]

8. Our results

The project "Pedal Generator was" was introduced to the student at the Faculty of Philosophy (the Department for Teacher Training) in 2016. In 2017

Figure 9. The basic concept of the construction model

students worked on understanding of another concept, the WindBelt concept. Since there was no sufficient budget for innovative solutions we decided to make very simple design and explore physics behind.

Our students, all from Teacher training department, settled on a conceptual design based around American engineer Shawn Freyn's Windbelt. Table 1 lists the working principle on which their design was based.

Further, the students are given the list of parameters in order to study the energy efficiency design. The list of parameters is given in Table 2.

Students were advised to use abandoned waste to reduce cost. The components used from recycled electronics are listed in the Table 3.

Construction Model & Circuit Architecture

Students applied the concept of construction model that is shown in Figure 9. The main components are the copper coils, a few strong magnets, a ribbon with higher elastic property. The bracket holds together the entire unit. It can be fabricated from any available material such as treated timber, aluminium or plastic. The bracket requires a top and bottom piece and four spacer pieces. It is important to consider the lifespan of the material since exposure to the elements is imminent. Weather treatment and protection will need to be applied, or else the Wind-belt can be sheltered in an environment that channels wind through the capture zone. The ribbon is the platform for the entire functionality of the Wind-belt. When exposed to wind above 3m/s the ribbon in our Wind-belt will experience aero elastic flutter. Wind will cause the ribbon to move up and down with high frequency oscillating motion. Students explored different material that can be used for the ribbon. They concluded that It is key for the ribbon to be as light as possible so that the cut in wind speed for flutter is minimized. Another outcome of learning was observation that the ribbon needs to be torsional strong so that the oscillation is as linear as possible, with little twist during the motion.

Three working subsystems can be distinguished: i) A wind-to-vibration converter, which is here a direct conversion system taking advantage of the fluttering effect on a thin ribbon. ii) An electromagnetic

Table 1: List of working principles (learning outcomes)

<table>
<tr><td>Structural instability:</td><td>Structural instability caused by self-exciting aerodynamic forces (flutter) can be used as an effective input source for small scale energy harvesters.</td></tr>
<tr><td>Aero elastic Flutter

Theoretical background:</td><td>Aero elastic Flutter involves aerodynamic forces acting on a structure to result in a self-feeding high energy oscillation. Flutter has the potential to occur in any object subject to wind. If there is positive feedback in the structure between the aerodynamic forces and its natural vibration, flutter will occur. This means that the vibrational oscillation of the object, coupled with wind, will drive the object to move farther or faster.

A structure becomes aerodynamically unstable through a coupled motion in the vertical bending and the torsional direction as shown in Figure below.

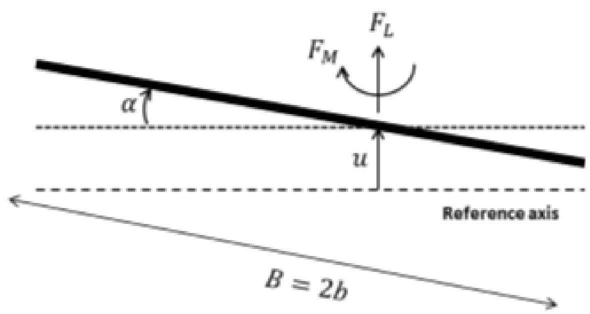
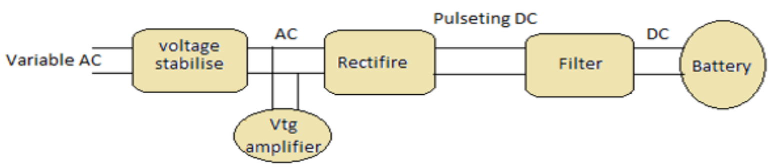

</td></tr>
<tr><td>Electromagnetic Induction</td><td>The second principle behind the Wind-belts design is that of Michael Faraday's electromagnetic induction. Electromagnetic induction is the production of voltage across a conductor in a changing magnetic field. In practice, a changing magnetic field applied through a conductive wire in a closed circuit will generate electricity. The current produced in the Wind-belt is an alternating current, with a frequency typically between 20Hz and 30Hz depending on the wind speed and construction dimensions for the unit.</td></tr>
<tr><td>Vibrations due to air flow</td><td>Vibrations deal with behaviour of bodies under the influence of oscillatory forces. These forces are caused frequently by dynamically unbalanced masses in rotating machines or by the motion of the body itself. Vibrations can be used the way wind, say, we use for making the belt flutter. In our case, as we are trying to harness energy from vibration, high amplitudes will actually be beneficial. Higher the amplitude, more the belt will flutter, and more will be the output of the system.</td></tr>
<tr><td>Use of Belt for Power Generation</td><td>It vibrates as wind flows over it – this movement, triggered by airflow, is what is known as aeroelastic flutter.</td></tr>
<tr><td>Designing the power conditioning circuit: to amplify, rectify and filter signal</td><td>Power conditioning circuit uses the parallel of connection to achieve higher voltages for low wind speed. The circuit uses rectifier, a smoothing capacitor a step up supply and a power storage device such as rechargeable battery or a super capacitor. The function of rectifier is and capacitor is to convert the output of the coils, which is in the form of alternating current, into smooth direct current. The dc current is then fed into the step up supply, or a device storage device is provided to buffer between the current drawn by the application and the supply from the coils of the generator. Therefore there is requirement of diode in the circuit board to control flow of current.</td></tr>
<tr><td>Circuit architecture
Block diagram of power conditioning circuit</td><td>
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Table 2: List of parameters used to study energy harvester

Parameters for the energy harvester	
L (length)	I (moment of inertia)
t (thickness)	K (stiffness) [N/m]
E (Elastic modulus)	m (mass)
The flutter critical wind speed, at which flutter is initiated (v_c)	The oscillating frequency (f)
The information about the maximum tip displacement of the magnets for estimating the power output from the harvester	The influence of the electromagnetic transducer, which imposes an additional electrical damping to the system
Natural frequency) [rad/sec]	The damping ratio
Torsional stiffness	Tensions T

Table 3: The components used from recycling electronics

Electronic waste	There are copper coils and electromagnets in almost all appliances such as televisions and speakers. Any of these coils worked well in the WindBelt.

transducer to convert the vibratory mechanical energy into electricity. Rather than a piezoelectric transducer, an electromagnetic one is chosen. This one is more suitable in the case of large amplitude oscillations like the ones induced by fluttering. Some students decided to implement a fixed magnetic circuit coupled with permanent magnets induces a static electromagnetic field while the copper coil, lighter than the magnetic circuit is chosen to be mobile, attached to the ribbon. Others decided opposite: to use small magnets glued on the foil. In this case vibration of foil caused by wind had an effect on changes in magnetic field and as consequence the current was induced in coil. When there is a relative displacement between the coil and the magnetic field, a voltage is generated across the coil ends according to Faraday's law of induction. The third part was an extraction circuit used to rectify and regulate the generated voltages. Two button magnets were attached to the ribbon in line with the centre of the copper coils. To capture the power output from the Windbelt, the wires from the copper coil were connected into a rectifier for AC to DC conversion, and then the DC power was plugged into a appropriate applicant. It was important that ribbon was tightly clamped in one end of the frame by tightening. To find the right tension in the belt, a fan was used to provide a constant stream of air while the belt was pulled tighter. When the belt fluttered with the most effective amplitude and frequency then it's fixed. We tested a number of materials for the belt ranging from simple fabric ribbon, to videotape. Insulation tape was the chosen medium as it had the least torsional rotation.

Successfully accomplished projects

Students were encouraged to make scrap book: to document each step of their designing process by providing video record or the set of photographs following the chronological order in order to further enable critical discussion and knowledge sharing. It is important to note that all students were female-students and they did not have skills in engineering. However, curiosity, patience, perseverance and high ability of creativity overwhelmed the initial lack of engineering background knowledge. Figures 10 presents work done by student Edona Cejovic. The copper wired were used from an old and abandoned washing programmer. Her projects was the first one who was fully functional. Figures 11-14 present other successfully finished projects. Figure 17 shows a work done by student Scepanovic Teodora where a voice coil actuator was used. Changing the amplitude and polarity of the current in the coil causes an in-out force that 'plays' the diaphragm on the speaker. The spring tension on the diaphragm keeps the voice coil actuator centered when no current is applied. The hard disk voice coil actuator is used to position disk heads across the platter of the disk. This set up shows different variations in the static magnetic field which were due to: flux-leakage, nonlinearities in the B-H curve of the pole steel, field variations caused by DC coil current, other effects caused by the rate of change of flux, effects on the drive electronics caused by coil motion, changing resistance due to heating, changing inductance and other problems.

In order to measure the generated voltage, an attempt for digital voltmeter was built and shown by students done by Jelena Susic and Mira Djukovic (Fig. 13). The digital voltmeter is built using microcontroller and 7-segment LED display. Instead of wooden constriction (in order to hold belt) a PVC material (pipe) was used. Coil and magnets were used from hard driver disk. Magnets were not vibrating but wires in solenoid were moving inducing variable strength of magnetic field.

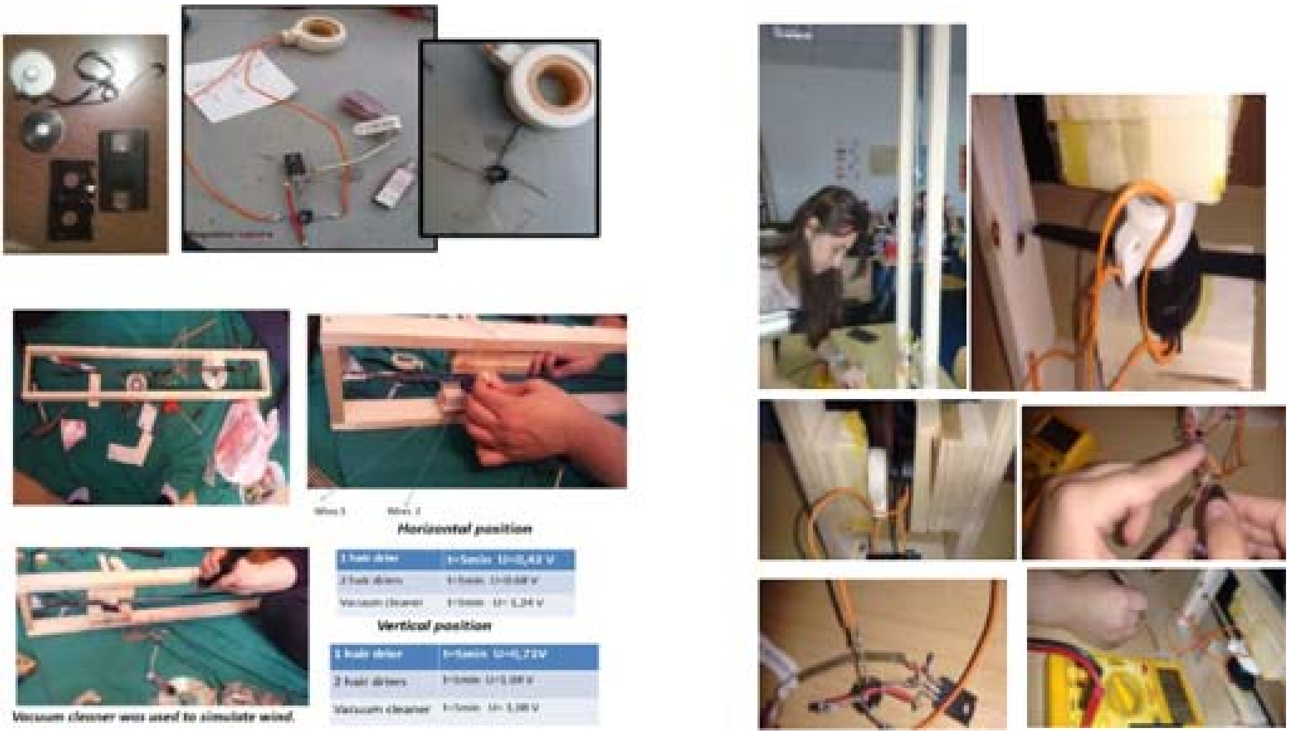


Figure 10. WindBelt prototype designed by Edona Cejovic.
The various positions of apparatuses were tested and results included in shown Table. An increase in generated voltage was recorded when was unit was hold in vertical position

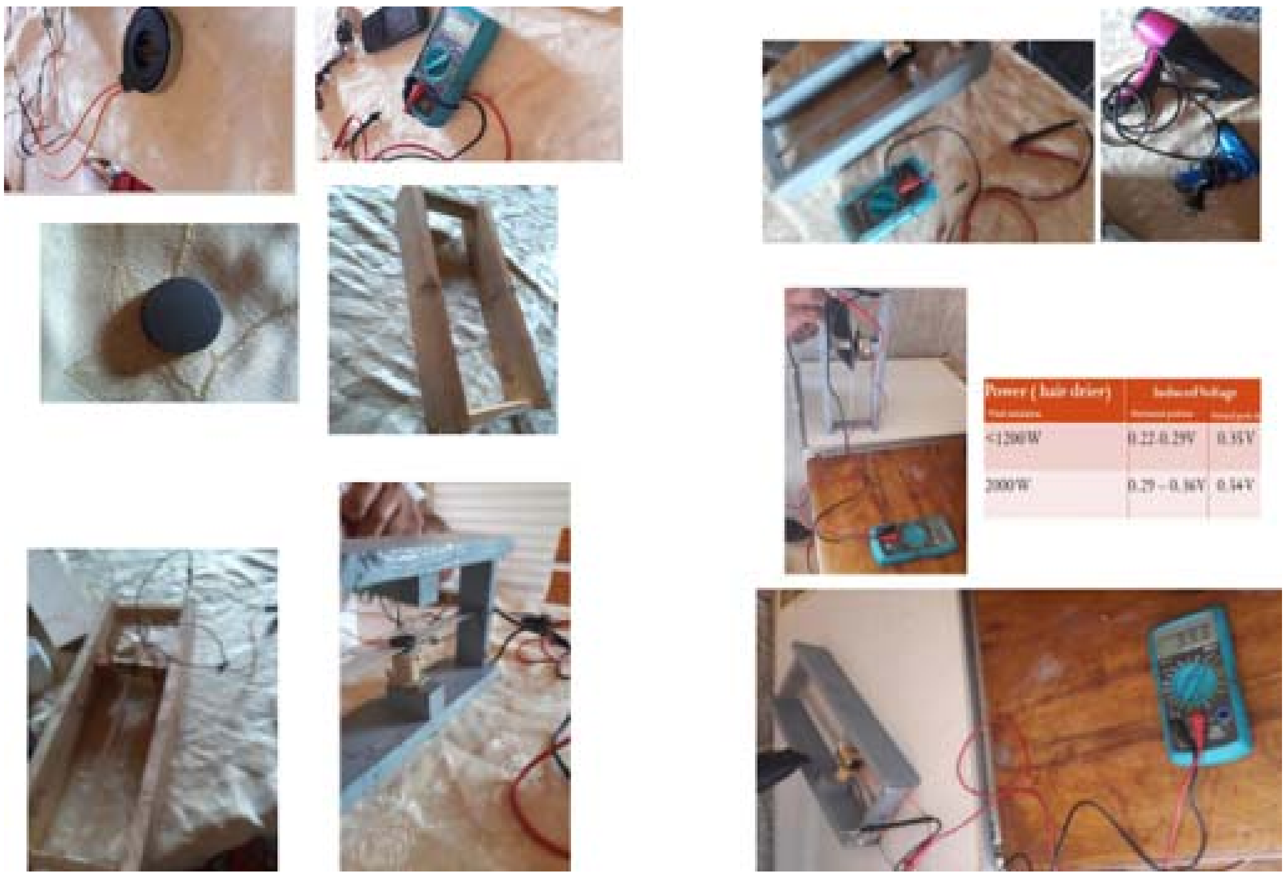
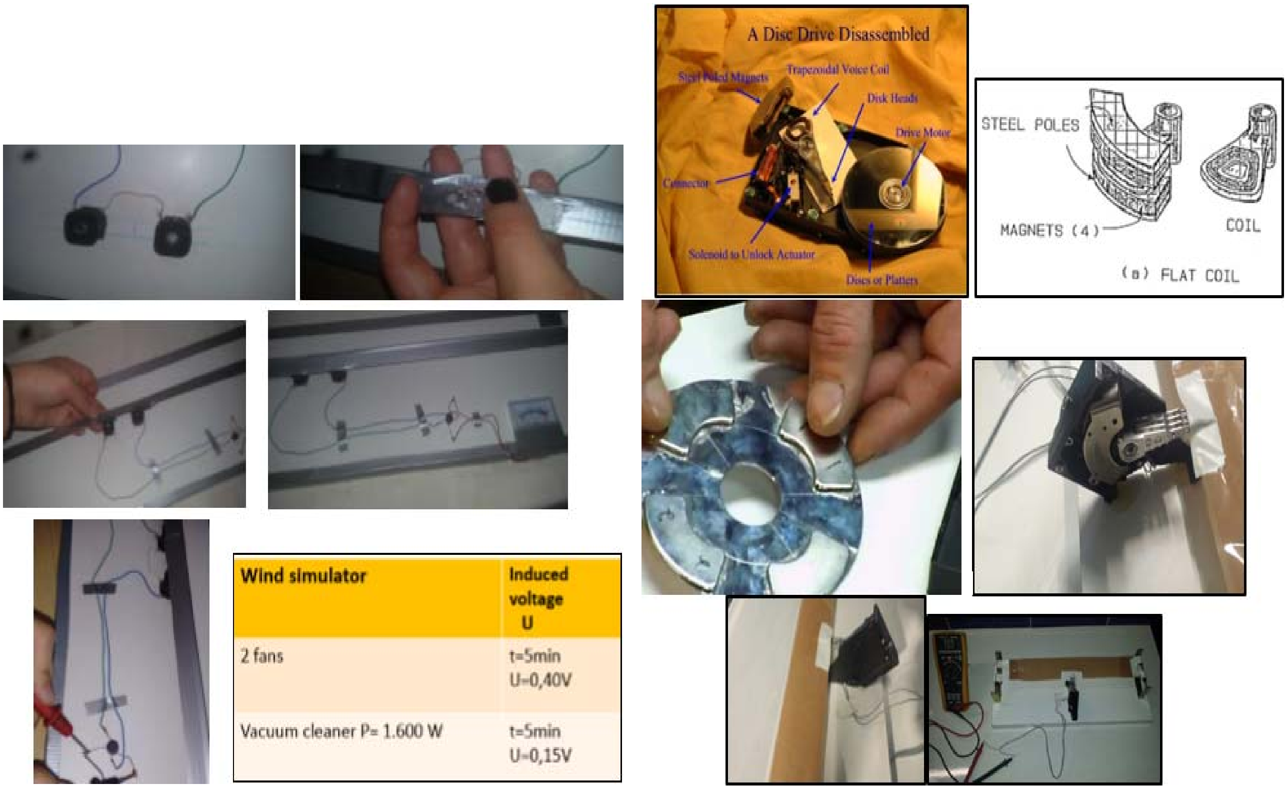


Figure 11. A student project: WindBelt prototype designed by students Vujovic Nebvena and Djukanovic Nadja



Wind simulator	Induced voltage U
2 fans	t=5min U=0,40V
Vacuum cleaner P= 1.600 W	t=5min U=0,15V

Figure 12. Figure presents a project completed by Konatar Lidija (images on the lleft) and Scepanovic Teodora (images on the right)

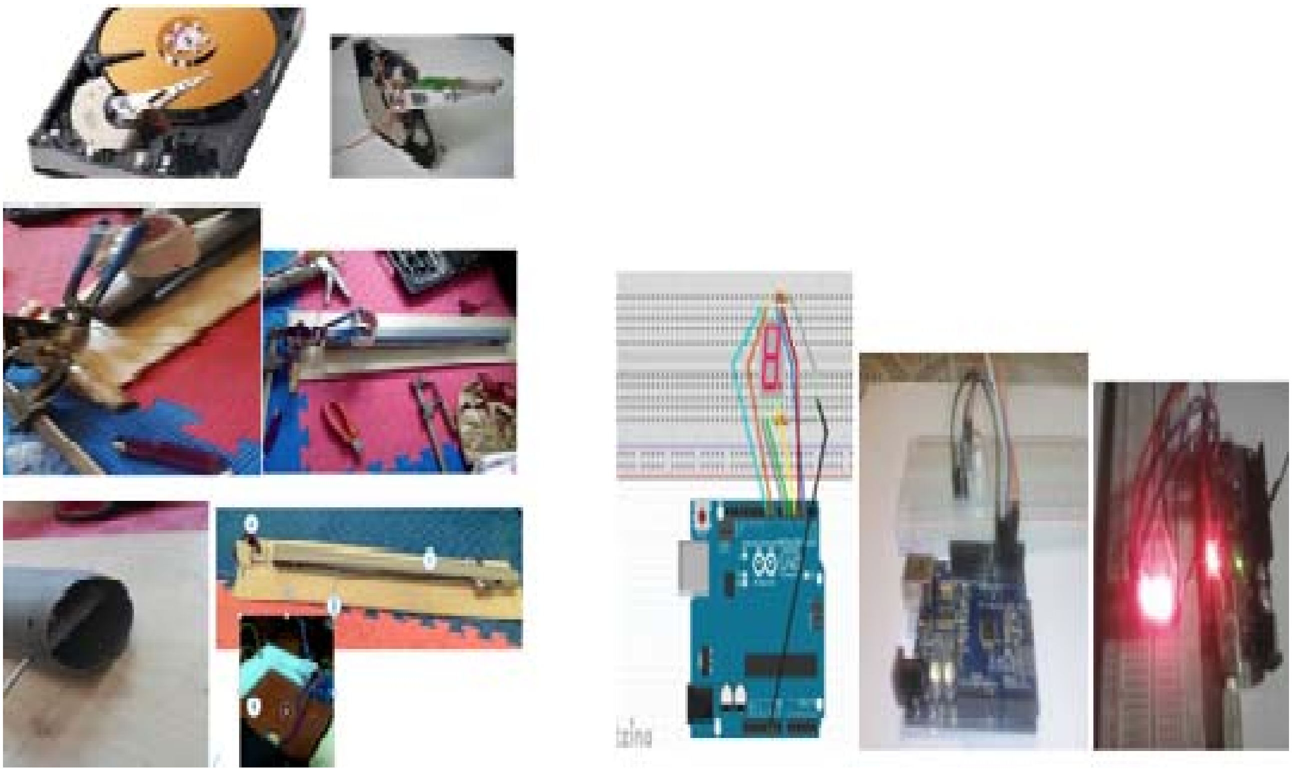


Figure 13. The seven segment LED display and the microcontroller were additionally used to advance the prototype design

Figure 14. The photos are taken during the demonstration lesson (academic 2016/2017).
Figure shows also an prototype of WindBelt installed outside the flat

Table 4: A few vibration tests performed to estimate the damping ratio

A few vibration tests are conducted to estimate the damping ratios:	- Mechanical and electrical damping of the energy harvester. - In the tests, the voltage time series generated by the interaction between the coils and the magnet is recorded. - Then, the damping ratio is estimated form the exponential decaying rates of the amplitude peaks in the time series.

Table 5. The wind speed of fan is depending upon the rating of a fan motor

Different ratio of speed of fan (in m/s)	Output power using neodymium magnets
3 m/s	38 mW
4 m/s	41 mW
5 m/s	60 mW

Validation, testing, and learning about interdependence of physical parameters

Table 4 lists the tests students performed in order to validate feasibility and potential of their apparatus (prototype).

The results averaged over presented projects are given in Table 5.

Findings, discussions and future steps

The findings of students' projects were consistent to each other in the following: The „Stiffness of the belt‟ and „Length of the belt‟ are the some of the crucial factors for the amount of energy produced. The tension adjustment had important role in maximizing the fluttering/inducing voltage efficiency too. Smaller belt produced more fluttering in high speed wind so longer belt is best suitable for harvesting power from low wind speeds and for high wind length of the belt should be less. Therefore, belt length can be maintained from 50cm to 100cm according to wind speed. Further, In order to target low-speed winds, this increase has to be compensated by slightly reducing the ribbon tension for instance. Further works could be focus on including the electromechanical subsystem and on studying the influence of the electromechanical coupling on the critical flutter frequency, in order to develop a global model of the harvester. Ffurthemore mechanical and electrical dumping were tested too.

Furthermore, we found that one way to improve and stabilize the output of a wind belt generator across wider range of wind speed would be to dynamically increase the tension of the membrane as the wind speed increases. Thus, students explored the membrane length ad its relationship to the generated electricity as well as the relationship between the wind speed and the load resistance. It became soon obvious that the tension of membrane is limited by the length and aeroelasticity features of membrane. Another idea that we tested was ribon tension. The adjustment of the tension of the ribon was done manually, in order to adapt the generator to the wind speed. It was obvious that further study od optimisation is crucial.

The results of investigation on optimisation are summersied as follows. Optimization of this harvester can be approached in three directions:

- **To maximize the harvested power**: Tests studies have shown that maximizing the power generated by an electromagnetic generator can be reached by improving the electromechanical coupling coefficient and reducing the electromagnetic generator losses coefficient (reducing the coil resistance for instance);
- **To increase the input vibration acceleration**;
- **To maximize the power density**: This can also be seen as minimizing the size. In our case, reducing the harvester size mainly means reducing the ribbon length which is much bulkier than the electromagnetic device itself. The effect of scaling the ribbon can be theoretically studied;
- **To enlarge the range of wind speeds at which it is harvesting energy**: This aim can be translated as reducing the minimal wind speed at which the flutter starts. In this objective, the critical flutter wind speed will be studied as a function of several design parameters;
- **To model the fluttering ribbon**: We consider a thin and long ribbon clamped at both ends, and pre-strained by a tension force T. The ribbon is subjected to an incompressible fluid flow of speed U. When this velocity reaches the flutter critical velocity v_c, a self-sustained dynamic oscillation of large amplitude and stable frequency fc occurs. The model comprises a finite elements modal analysis performed with software, which determines the first uncoupled heaving and torsion modes frequencies. When the ribbon tension is varied then an evolution of v_c and f_c as a function of T is recorded, for several lengths L, comparable to results found in literature. The frequency is, as expected, an increasing function of the tension, as is the flutter limit speed. Both increase as well when the ribbon length is decreased. If all the ribbon dimensions are scaled by a certain factor our model predicts an increase of the critical wind speed together with an increase of the flutter frequency with the miniaturization. Note that v_c is increasing at a faster rate when the length only is reduced. So when miniaturizing such a system, one should reduce the width and thickness at least at the same rate at the length;
- **To get a fixed and reproducible tension of the membrane**: A mass, in this case two symmetric wound coils, is fixed on the ribbon close to the top edge. It would be good to use a laser displacement sensor pointing towards the coil in order to measure its vibration amplitude and frequency. However we wrere limited with equipment. We observed a minimal wind speed at which the flutter starts. The critical wind speed at 0.45 N is measured between 1 and 2.5 m/s, and the recorded flutter frequency is 39.5 Hz at low wind speeds. It was also observed that the flutter frequency slightly increases with the wind speed. It also increases with the ribbon tension. Another point is that the more tensioned the ribbon, the higher the wind speed necessary to induce flutter. This too corresponds to the theoretical results. When the ribbon length is decreased from 55 cm to 25 cm, the critical wind speed increase. Some discrepancies we observed between the theoretical and experimental results might be due to the difficulty to measure critical velociy in some cases, probably because of the not perfect balance of the two hand-wound coils;
- **The direction of wind**: As a wind simulator we used hair drier so the directioncan can affect measurements. This should be invetigate more.
- **An array of WindBelts:** It could be assembled to generate more energy.

9. Conclusions

This work presents a windbelt-based energy harvester made of a fluttering ribbon and an electromagnetic transducer. The arrangement of coils and magnets are analysed for the desirable output. Findings presented in previous chapter confirms significant potential of Windbelt's prototyping. Significance nan be valueted through efficiency of acquiring and mastering knowledge students needed to sove problem and build energy harvester. Furthemore, significance of presented projects can be valueted through applicatins and possible integrations of Windbelt. Windbelt can be integrated into buidings as energy harvester. For example, HVAC systems can be chosen since they offer an attractive environment for energy harvesting from fluid flow due to the predictable nature of their flow and their prevalence in buildings. Airflow in HVAC systems is typically unidirectional with a slug-shaped velocity profile and operating speeds from 2 to 5 m/s. While other environments such as liquid or gaseous water pipes and natural gas lines also exhibit similar characteristics, they offer a more challenging environment in which to work. Experimental testing in an HVAC system would be beneficial as it is the simplest and safest system for conducting research. For instanc, authors in [9] present study as a novel step towards integration of the aero-elastic belt into buildings. They emphasize the significance of using numerical analysis with Computational Fluid Dynamics (CFD) which can give field results to optimize location before conducting field experiments to obtain the actual performance. Another paper we refer here confirms significant interest of developing Windbelt in scientific community. The paper [10] extended “WindBelt” study by providing tools for the optimization of a flutter-based energy harvester. A theoretical model is derived from Theodorsen flutter theory and allows the simulation of the flutter frequency and critical wind speed evolution as a function of the ribbon parameters. We hope that our research will be extended in this diection too.

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