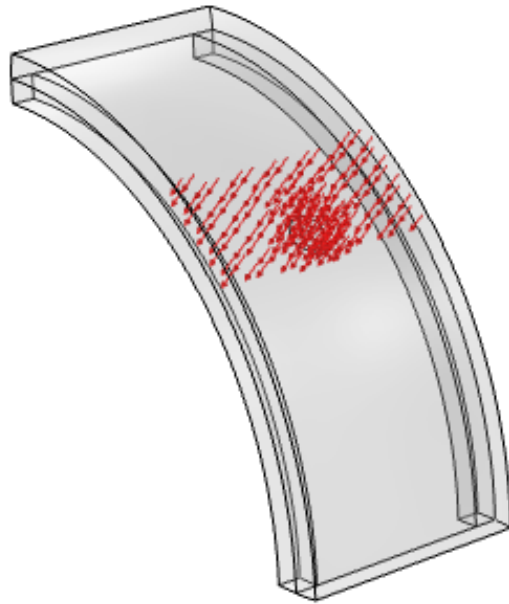




# CHALMERS

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## **Design of flexible piezoelectric microenergy generator for automotive tire application**

MASTER THESIS 2022

**Design of flexible piezoelectric and triboelectric  
microenergy generator for automotive tire  
application**

*Author*

Simon Matsson, MPAME, [simmat@student.chalmers.se](mailto:simmat@student.chalmers.se)

*Examiner*

Peter Folkow

*Industrial Supervisor at RISE*

Henrik Staaf



**CHALMERS**

Department of Mechanics and Maritime Sciences  
Chalmers University of Technology  
Gothenburg, Sweden 2022

Design of flexible piezoelectric and triboelectric microenergy generator for automotive tire application

Master's thesis in Applied Mechanics 2022:52

Simon Matsson

Department of Mechanics and Maritime Sciences

Division of Dynamics

Chalmers University of Technology

## Abstract

One of the largest technological challenges of the 21:st century is the increased need for electrical energy. For large systems they need to be powered by an external electrical power source but smaller systems and especially sensors may be powered by energy harvesting modules. This thesis aims to investigate the use of piezoelectrical PVDF harvesters in car tires via pre-study, experiments and **COMSOL Multiphysics** simulations to determine if it is possible to power wireless sensors, what the requirements may be and what the optimal harvester would consist of.

The experiments have compared different sized and shaped harvesters in real tires to evaluate the available voltage. Simulations are then performed for the same shapes and sizes to investigate if there are any similarities and if any conclusions can be drawn from simulations for future development. These simulations have involved the design of a simple tire model, applying the right loads on the tire and choosing the right material properties to match real life experiments as much as possible.

From experiments and simulations the results show a clear size and shape dependency of the harvester. Approximately 40 % more voltage is available for shapes with smoother edges without sharp corners for example a circular harvester. These characteristics are the same for both experiments and simulations. The results also show that for these more energetically profitable harvesters there is enough energy available to power a sensor and transmit data from that sensor. A 2 cm diameter circular harvester need 15 layers at 20 km/h but for every increase in area and velocity the number of layers decrease. This is gratifying and indicate that there is likely a future where real life implementations of this type of energy harvester is near. For future development more experiments with more different sizes and geometric shapes need to be performed in real tires and the simulation model may be built upon to further match real life.

**Keywords:** Energy Harvesting, Piezoelectric, Tires, Simulations, Experiments, Applied Mechanics



# Preface

## Acknowledgments

All things must come to an end. Now as I near the end of my 5 years at Chalmers and end of my 17 years in school I would like to take the time to acknowledge those who have helped me along the way. If you have been a part of my life in any way or form you deserve a mention and just because you are not mentioned by name, know that I appreciate every single one of my friends and family for helping me to this point in life.

First of all, my work colleagues, Peter Folkow and Cristina Rusu for your supervision and guidance through this project. Through your questions and progressive attitude you have given me an opportunity to develop and compile the best results possible. To Henrik, it has been a pleasure to have you as the primary supervisor. You have given me a satisfactory liberty while at the same time always being there to discuss or answer any thoughts and questions. Our chats about things outside of work and our common memories from school have been a highlight of this spring and made the days all the more enjoyable. To the rest of the RISE employees, thank you for including me and making me feel like part of the team. It has been a pleasure working with all of you and thank you for giving me this opportunity.

Second of all, my friends from school, Ludde, Ida, Preisko, Stålis and the rest from ph7. Your friendship and company have made the time at Chalmers the best of my life. At Gasquen, in ÖG or at Prippsko I have enjoyed your company endlessly and hope we have built friendships for life.

Thirdly a massive shout out to my Bandy club SK Höjden. To drop work and go and play Bandy was exactly what I needed most nights when things did not work out. The A-team in Höjden have been like a second family the last years (most likely spend more time with you than my own parents during season) and your friendships and the joy we have shared on the pitch have kept me going through work.

Last but probably largest of all. My family and relatives, Grandma, Grandpa, Aunt, Nisse, my dear cousin Emilia, Mom and Dad, you have always stood by my side no matter what. You have helped me with homework, driven to every practice and every game and done everything for me. I do not take that for granted and am eternally grateful for your help. Without you I would not be here today. I love you all.

Gothenburg, June, 2022





# Nomenclature

BLE - Bluetooth Low Energy

BOB - BreakOut Board

E - Young's Modulus

J - Harvester developed by Joanneum.

$\nu$  - Poissons ratio

PVDF - Polyvinylidene fluoride polymer.

PZT - Lead Zirconate Titanate

R - Harvester developed by RISE.



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# 1

## Introduction

### 1.1 Background information

One of this generations greatest technological challenges is the ever increasing energy requirements. The energy use of humans increases with  $\approx 1-2\%$  each year and the majority of the energy comes from fossil fuels [1]. In order to cater for this increase in energy demand but reduce climate change, alternate sources of energy is starting to appear. One of these technologies are energy harvesters which can convert mechanical energy into electrical energy to drive products which require low energy power, such as sensors of different kinds. One of the most common examples of these harvesters, and the one which will be examined in this project are piezoelectric harvesters [2]. These use deformation of charged materials to generate energy. The trigger for these deformations are mechanical energy and as such these are suitable in systems which contains a lot of motion. Vehicles, structures and even the human body are examples of such systems. Using this otherwise wasted energy and converting it into electrical energy is one step in solving the energy problem.

Harvesters may not be able to replace any of the major energy sources such as fossil fuels or nuclear power but instead reduce the need for these in certain situations. These harvesters could be used to prolong battery life time so that it will reach beyond the life time of the sensor. If one does not need to replace a battery as often then the global demand for batteries is lessened as well. It is also beneficial to avoid replacing batteries in hard to reach places and where a large number are required [3]. Such a hard to reach place is inside the human body, more specifically for a pacemaker. A standard pacemaker battery has a lifetime of  $\approx 5-8$  years before it needs replacing [4]. This involves going through a surgery which is not only inconvenient for the patient but also carries additional risk of infections and a great cost to society. If the pacemaker battery could be replaced by and or work in conjunction with an energy harvester this could reduce or remove the number of surgeries required thus saving both money and lives. In that case the energy harvesters would use our bodily motions, both that of the heart and intestines as well as our outer body movements like walking etc.

This project aims at finding usage of piezoelectric harvesters in tires. This can be considered as a hard to reach place and also one which may require plenty of batteries. Since 2007 it is mandatory for newly produced cars sold in the USA to have tire pressure sensors installed on them. These would either require batteries or cables from the main body of the car. Such a thing would increase the complexity of the car which in turn increase the risk of failures and the cost and possibility of changing tires [5]. At

this point there is only mandatory with tire pressure sensors but this could change with more sensors and even without mandatory installation some companies may desire to install other sensors to measure things like tire temperature, tire forces etc [6]. Each of these new sensors would require an additional battery or an extra cable thus escalating the problems many times over. By using the tire compression, deformations and vibrations when driving, the piezoelectric harvesters could power these sensors.

Since the uses for this new type of energy technology are both plentiful and promising there is a current European project working with these harvesters and other energy solutions. The project is called "Energy ECS for future mobility" and is funded by the H2020 ECSEL project. One of the goals of this thesis project is to contribute to the project on the usage of piezoelectric harvesters in tires. It is also of great importance that this thesis project is part of a cooperation between RISE and Nokian Tyres in Finland. Nokian Tyres are a tire manufacturer which wants to research and examine the usage of piezoelectrical harvesters in their tires. RISE are helping them with technical expertise on harvester types, locations and shapes as well as circuit and connections. Nokian have a tire testing rigs so some experiments will be conducted on site in Nokia, Finland and minor testing has been performed on RISE in Gothenburg. There are several other parties involved in this project, for example the University of Bologna who will focus on circuit boards for the final harvester set up. This thesis project does not involve the development or analysis of these circuit boards and hence no discussions or cooperation will be performed directly with Bologna.

Powering tire sensors with an energy harvester has not yet been achieved with the specifications worked after in this thesis. To achieve a full comprehension about the effects and influences at play it is crucial to be broad in the approach. This project will therefore involve both physical experiments and computer simulations. By comparing these and taking both into account the conditions are as good as possible for a successful project.

## 1.2 Previous Research

### 1.2.1 Energy Harvesters

The research about energy harvesters has seen a large increase during the last 20 years. In the year 2000 only one technical document about piezoelectric energy harvesting was available and in 2019 that number was 1172 [4]. As mentioned above this is most likely due to the need for renewable energy sources.

Sezer and Koç have collected a comprehensive review of the state-of-the-art piezoelectrical harvesting [4]. In this they cover the basic theory behind the technology, material choices and some implementations. This article was released in 2020 and the majority of it is concerned with piezoelectric films showing the technological progresses made from the basic PZT cantilever beam to films and patches.

Another study which collects the most recent advances in piezoelectrical harvester films was written by Sukamaran et al. [7]. They give further information about how to handle

and transform the harvester output signals to be able to power sensors etc.

Wang et al. have tried combining piezo and triboelectric harvesters into a hybrid harvester [8]. They combined piezoelectrical materials as the differently charged materials used in triboelectric theory allowing for different types of harvesting depending on the level of compression. Furthermore they found that the triboelectric part of the harvester generated more energy than the piezoelectrical part and that the distance between the triboelectric materials was the variable which influenced the most.

### 1.2.2 Implementation in Tires

When the idea of implementing energy harvesters into tires was first starting to be investigated the main type of harvesters were the PZT based cantilever beam [6]. These were able to give a certain amount of energy but have two major drawbacks. The first is the lack of available space between a tire and the actual wheel. It is not a large space which in turn limits the possible length of the PZT cantilever beam. While the length of the beam is not the only metric which effects the energy output it does effect it in some way and generally speaking a longer beam means a further displacement which means more generated energy [9]. The second is that beams are easier to break as a tire moves and deforms compared to a pliable PVDF harvester film.

Kubba and Jiang [10] studied three different piezoelectric PZT cantilever designs for tire implementation. They found that the shape of the PZT cantilevers are of great importance but note that they were not actually tried or simulated in a tire model.

Since the PZT cantilever approach is severely limited by the tire dimensions and risk of damage it is more appropriate to use a flexible PVDF film in a tire. The thickness of the film is significantly smaller than the available space and the flexibility reduce the risk of damage. This was researched by Lee and Choi [11] and they managed to obtain 380  $\mu\text{J}$  per revolution at 60 km/h and 500 kg load. From this they were able to convert and use approximately 9.7 % of the available energy.

Esmaeeli et al. have also tried using piezoelectrical harvesters which follow the shape of the tire like a film or patch would [12]. They managed to obtain 95  $\mu\text{J}$  per revolution at 41 km/h and  $\approx$  600 kg load. From this the efficiency in using the energy was  $\approx$  5 %.

Zhang et al. have designed an alternate triboelectric harvester which uses Single-Electron technology which periodically comes into contact with the other dielectric material [13]. They managed to obtain an output of 2.25  $\mu\text{J}$  per revolution from a bicycle tire but they made it clear that the technology could be used in an automotive tire also.

Lee and Taheri have used PVDF harvesters to analyze the tire characteristics for handling and breaking via the friction and moments acting on the tire [14]. This is not a true energy harvesting but shows a further implementation of piezoelectric materials.

The strain curves shown in the report show the same shapes and characteristics as the voltage graphs seen in this report. The linearity between strain and voltage for piezoelectric materials show highly similar results.

There are three major ways to utilize energy harvesting from tires which have been tested before. One may use PZT cantilever beams or piezoelectric PVDF films on the flat part of the surface or place the harvester on the side walls of the tire. In the interest of robustness of the connection together with weight and size limitations from Nokian this thesis apply a piezoelectric PVDF film on the flat inside of the tire. For further information about the weight and size limitations from Nokian see Table 2.3.

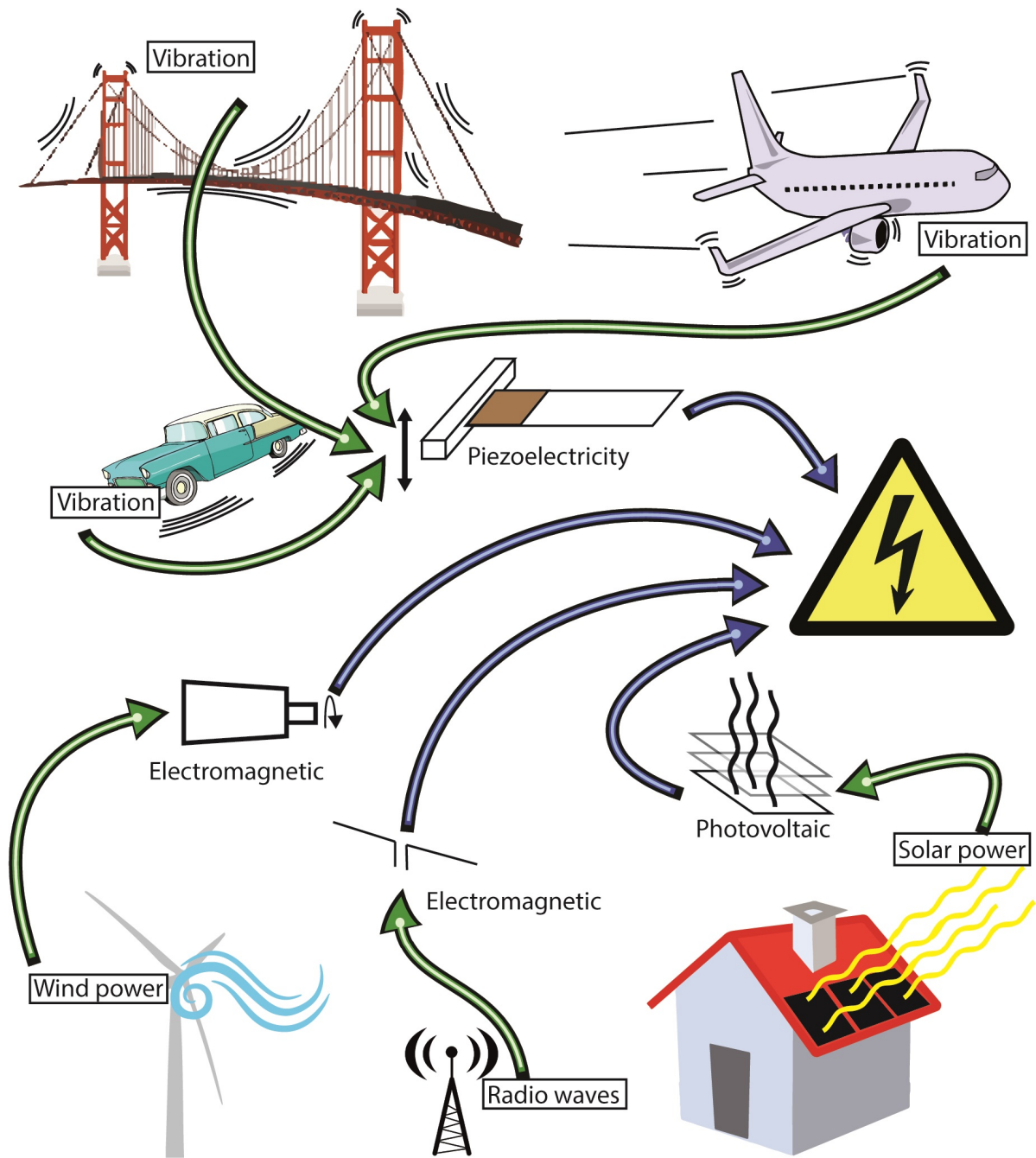
# 2

## Softwares and Theory

### 2.1 PVDF energy Harvesters

In this section the basic theory behind the workings of the two type of harvesters are presented. Note that the scope of this thesis is to implement the harvesters into a COMSOL model and that the structural mechanics behind their workings are more important than the electrical couplings.

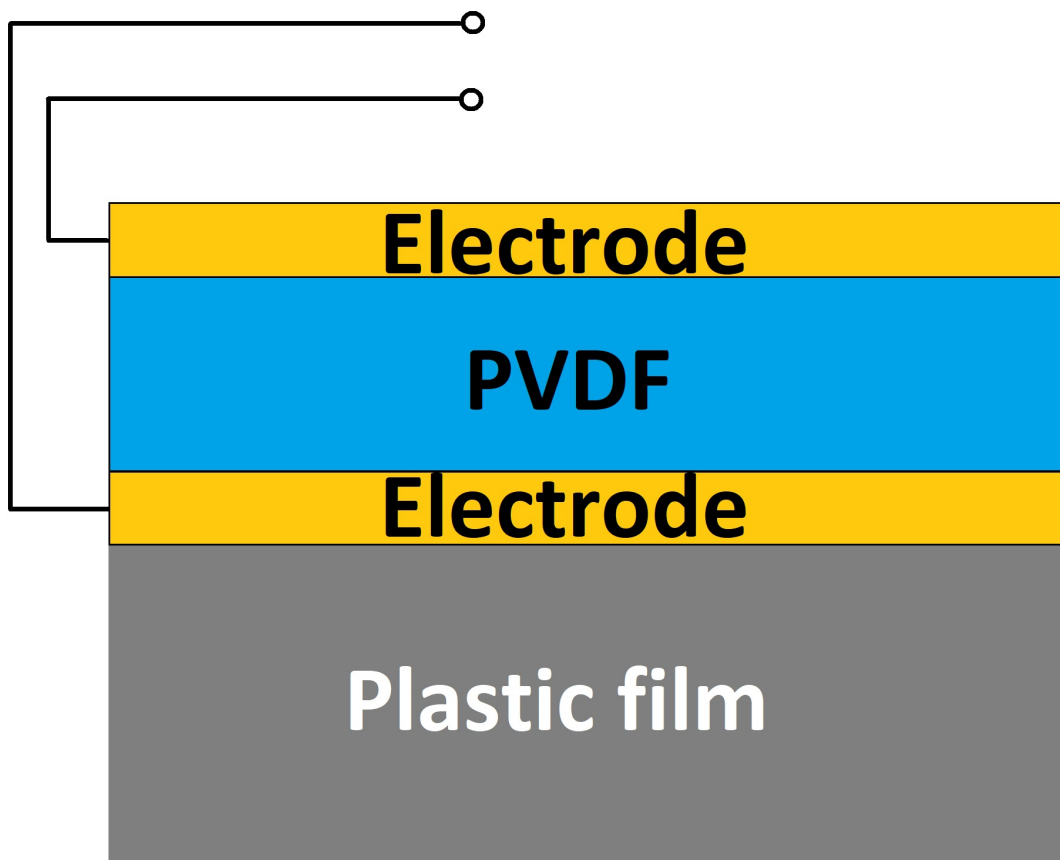
The basic idea behind energy harvesters is to use residual energy and convert it into useful electrical energy. This residual energy can be everything from thermal to mechanical and come from any part of a system. A number of examples can be seen in Figure 2.1. It is crucial that the harvester does not affect the system of attachment and instead harvests the residual energy which would otherwise go to waste.



**Figure 2.1:** Visualization of energy harvesting from different sources. Used with permission from [15].

### 2.1.1 PVDF Piezoelectrical harvesters

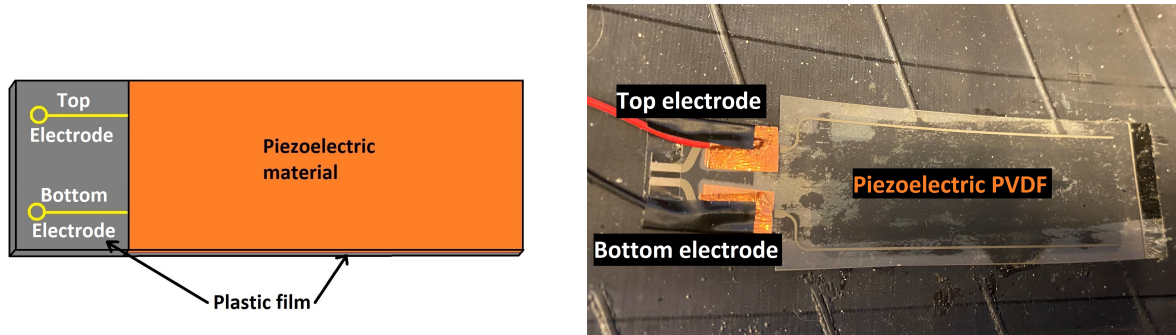
A piezoelectric harvester is made up of several layers. In theory only three layers are needed, two electrodes on either side of a piezoelectric material. In our case this layout is printed on a plastic film or flexible substrate for ease of application and structural integrity. An image of this very basic layout can be seen in Figure 2.2.



**Figure 2.2:** Graphical representation of a piezoelectric harvester. Note that the layers are not drawn to scale and that the blue region denoted "PVDF" could consist of other materials, see below.

Note that the layers in Figure 2.2 are not drawn to scale and that the blue region denoted "PVDF" could consist of other materials, see below. This Figure represents one piezoelectric harvester but one can use several harvesters together in parallel connection. One just places a similar harvester on top of the other one so that the plastic film is in connection with the topmost electrode of the lower harvester. If one then connects each of the lower and upper electrodes together respectively one has built a combined harvester consisting of many simpler harvesters. One must remember here that increasing the number of harvesters on top of each other will decrease their flexibility and how much they can deform. At the same time more harvesters can generate more energy so there is a balancing act to find the optimal number of harvesters. The physical layout of the combined harvester does not involve any gluing or connecting layer between the simpler harvesters, instead they are connected at the end where the

electrodes are connected by wrapping electric tape around the entire structure. This should not increase dampening since the electric tape is not actually in contact with the piezoelectric material but only on the plastic film on which only electrode connections are fitted. See Figure 2.3a for a simple sketch view and Figure 2.3b for a real harvester placed in a tire.



(a) Sketched view of piezoelectric PVDF harvester. Note the two electrodes connected to each of the two electrode layers. Also note that the piezoelectric material do not cover the entire plastic film.

(b) Real rectangular PVDF harvester with top and bottom electrodes connected to wires.

**Figure 2.3:** Comparisons of sketch and real version of a PVDF Piezoelectric harvester. Note the strong similarities, especially the two different electrodes clearly visible.

In Figure 2.3a one can see a simple sketch of a piezoelectric harvester, note that the piezoelectric material combination of PVDF and electrodes do not cover the entire plastic film. In theory the plastic section which extends beyond the piezoelectric material could be very large but it is often large enough to comfortably connect wires to electrodes and there is plenty of room for a electric tape strip to be placed over it.

There are a number of materials which could be used to construct a piezoelectric harvester. They can be collected into inorganic, organic, composite, ceramic etc. All of these types vary heavily in terms of strength, toughness and other parameters. Piezoceramic materials for example are known for being very brittle but also have large dielectric and piezoelectric coefficients. As such it is very useful and can generate a lot of energy but not for major deformations. On the other hand piezopolymers generate less energy but are very flexible and can withstand higher impact forces [4]. In this project it has been chosen to use piezoelectric polymer comprising of polyvinylidene fluoride polymer or henceforth known as "PVDF". This material can be shaped to follow curved surfaces which is ideal for a tire implementation.

Most polymers contain different types of crystalline structures and the same is true for PVDF. It contains structures known as  $\alpha$ -,  $\beta$ -,  $\gamma$ -,  $\delta$ - and  $\varepsilon$ -phase. The most piezoelectric of all of these structures are the  $\beta$  variant which is a fairly regular and structured dipole. Each individual  $\beta$ -phase polymer is clearly bipolar but a piece of piezoelectric material consists of many of these chains, all of which are oriented in different directions. This could reduce the available output energy drastically. In order to increase the output energy one can do what is known as poling to the piezoelectric material. By applying a strong electric field together with a temperature increase to the

material one can redirect the electric dipoles so they all align in the same direction. This is known as polarizing the PVDF harvester. Removing the electric field will still keep the majority of the dipoles locked in a near- perfect alignment which means that the available energy from piezoelectric energy has been increased. If one knows that the majority of load will come from one specific direction this is a popular way to ensure that the available load generate as much energy as possible [7].

Piezoelectricity is associated with the deformation of a piezoelectrical material. The way that is used in this thesis is that a deformation of the material generates an electrical current, voltage and energy. This is called the direct piezoelectric effect, a deformation which generates power. The opposite to this is an applied voltage which generates a deformation of the piezoelectrical material. This is called the converse piezoelectric effect [7]. Both these effects can be described by the two following equations [4]:

$$D = d \cdot \sigma + \epsilon \cdot E \text{ Direct effect,} \quad (2.1)$$

$$\varepsilon = s \cdot \sigma + d \cdot E \text{ Converse effect.} \quad (2.2)$$

Here  $D$  [ $\frac{As}{m^2}$ ]vis the electrical displacement,  $d$  [ $\frac{As}{N}$ ] is the piezoelectric coefficient,  $\sigma$  [ $\frac{N}{m^2}$ ] is the stress,  $\epsilon$  [ $\frac{s^4A^2}{kgm^3}$ ] is the electric permittivity of the material,  $E$  [ $\frac{N}{As}$ ] is the electrical field over the element,  $\varepsilon$  [-] is the strain and  $s$  [ $\frac{m^2}{N}$ ] is the mechanical compliance. Note that in the case of no electric field present, as is the case for a tire, one can neglect the  $E$ -terms which simplify the equations to:

$$D = d \cdot \sigma \text{ Direct effect,} \quad (2.3)$$

$$\varepsilon = s \cdot \sigma \text{ Converse effect.} \quad (2.4)$$

Here one notes how the equation is linear between the electrical displacement and the stress on the piezoelectrical element. Note that these equations are in turn matrix equations of a size dependent of the dimensions of your problem. In 3D one often talks about  $d_{33}$  and  $d_{13}$  which describe piezoelectric coefficient in the direction of the polar axis (33) and orthogonal to it (13). The chosen harvester variants both have  $d_{33}$  piezoelectric coefficients in the same span of -25 to -38 pC/N [16]. There are no data available for  $d_{13}$  values but since the harvesters are polarized so that the loads will act in the 33 direction these can be approximated without influencing the results drastically.

Now that the electrical displacement is calculated one can define the output voltage from that and it is given by:

$$U_{OC} = \frac{d_{ij}}{\epsilon_r \epsilon} \sigma_{ij} g_e. \quad (2.5)$$

Here  $\epsilon_r$  [-] is the relative dielectric constant and  $g_e$  [m] is the distance between the top and bottom electrodes. With the output voltage known one can use Ohm's law to calculate the output current as long as one knows the impedance in the circuit [17]. This gives:

$$I_{OC} = \frac{U_{OC}}{R_{OC}} \quad (2.6)$$

and the output energy can be calculated by the classical electrical energy equation:

$$E_{OC} = Pt = U_{OC} I_{OC} t = \frac{U_{OC}^2}{R_{OC}} t. \quad (2.7)$$

Here  $E_{OC}$  is the output energy,  $P$  the output power,  $U_{OC}$  the output voltage,  $I_{OC}$  the output current,  $R_{OC}$  the output impedance and  $t$  the time. From Equation 2.6 it becomes clear that different impedance affect the output current, voltage and energy from the harvester. Thus it is important to know what one wishes to power with the energy so one can tune ones parameters after that. It is also important to have a calibrated energy management that can handle a wide range of input and still output the required amount of power. From Equation 2.7 it is clear that one also needs to keep track over how long time the applied stress acts since the time comes into the equation. Note that **COMSOL Multiphysics** does all of these calculations automatically.

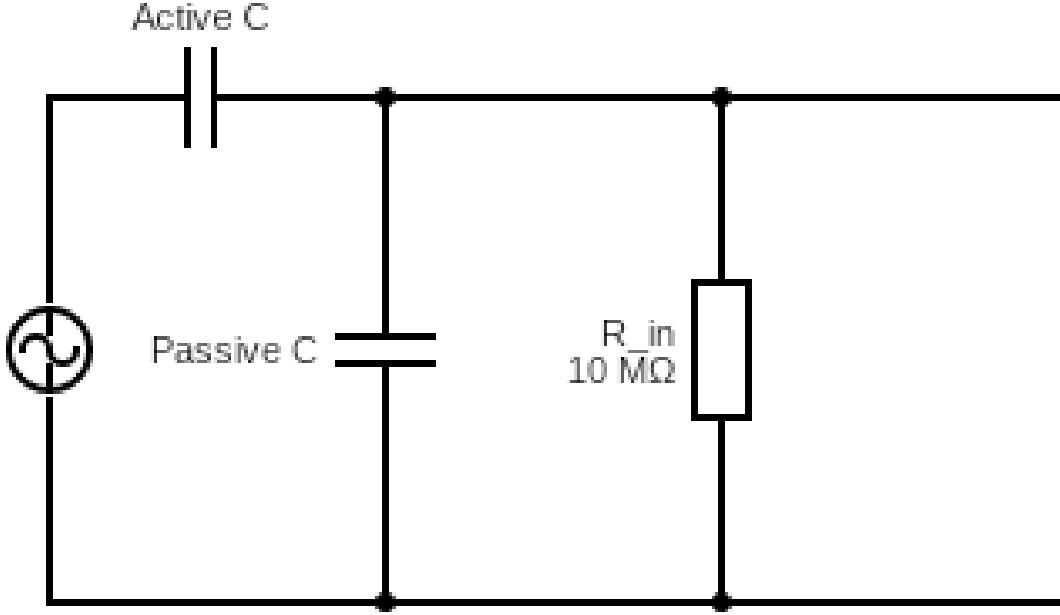
One of the geometrical aspects which influence stress the most are holes or sharp edges. In this case holes do not come into play but sharp edges may occur. It is desirable to keep these at a minimum since these stress concentrations will not only complicate the calculations but could also provide faulty data. The stress at these sharp edges can be described by the stress concentration factor  $K_T$ . It can be described by the following equation:

$$K_T = \frac{\sigma_{max}}{\sigma_{nom}}. \quad (2.8)$$

Here  $\sigma_{max}$  is the maximum stress over a cross section and  $\sigma_{nom}$  is the nominal stress over the same cross section. For an edge or a crack it is the relation between the radius of the edge or crack tip vs the thickness of the geometry in question which becomes interesting. They are often compared by the factor  $\frac{R}{T}$ , where  $R$  is the radius and  $T$  is the thickness. One must note that for a sharp 90 degree edge the radius is 0 which means that the factor also becomes 0. Such a 0 value factor indicate an infinite stress factor:  $K_T = \infty$ . Obviously this is not a true representation of reality but instead of a stress concentration factor one can use the stress intensity factor  $K$ . Once again the governing equations are not entirely interesting, the main part is that one tries to avoid sharp edges on surfaces where loads are applied. The most prominent appearance of this was found during the simulations on the plastic film. The sharp edges of the plastic piece gave stress concentrations which called for a very fine mesh in that region to compensate for it. By rounding out any sharp edges or corners into smoother curves, severe stress concentrations can be avoided and the system becomes less sensitive to loads. An almost equally important point is that the plastic films on which the piezoelectric material is printed have rounded edges. So to round them in the **COMSOL Multiphysics** simulation with rounded edges is not only positive from a calculation perspective but also from replicating the real world as much as possible.

Other geometrical aspects which appear to affect the output energy and voltage is how much of the PVDF harvester which actually deforms or bends. When a deformation between the curved tire and the flat surface in contact with the ground occurs it is a relatively small area that bends. This bending motion is what generates the majority of energy and is of the most interest. However, the rest of the harvester which contains none to negligible bending will in this case not only fail to contribute but could actually dampen the output voltage. This is due to the non-bending area containing an inner impedance. By having a varying width of this so called passive area one can minimize this build up of internal impedance while a constant width will significantly influence this. These calculations with active and passive zones are not something which **COMSOL Multiphysics** does automatically so to gain an understanding about this one must model

it directly. In this case it has been attempted by implementing a circuit which can be seen in Figure 2.4.



**Figure 2.4:** Circuit to account for passive and active zone. Note the active and passive capacitors.

Note the active and passive capacitors which have to be calculated based on the bending zone of the PVDF harvester. The AC voltage generator is the output from the actual PVDF harvester. When it comes to characterizing the different capacitors and their values as well as the inner resistance real life measurements were made. By measuring the capacitance and resistance in a 2x5 single layer PVDF harvester they were found to be  $17 \mu\text{F}$  and  $\approx 10 \text{ M}\Omega$  respectively. These values were used as base values for the circuit values.  $R_{in}$  was simply set to  $10 \text{ M}\Omega$  and then the following equations were used to describe the values of  $C_{Active}$  and  $C_{Passive}$ :

$$C_{Active} = C \frac{A_{Active}}{A_{Active} + A_{Passive}} = C \frac{A_{Active}}{A_{Total}} \quad (2.9)$$

and

$$C_{Passive} = C \left(1 - \frac{A_{Active}}{A_{Active} + A_{Passive}}\right) = C \left(1 - \frac{A_{Active}}{A_{Total}}\right) = C - C_{Active}. \quad (2.10)$$

Here  $C$  is a constant which is chosen to  $17 \mu\text{F}$ . Thus the total capacitance of the system is always  $17 \mu\text{F}$  as was measured. The resistance value of  $10 \text{ M}\Omega$  comes from experimental measurements of the impedance of real life harvesters to ensure a correct voltage measurement after "U vs I" connector.

### 2.1.1.1 Utilized versions of piezoelectric harvesters

There were two types of piezoelectric harvesters considered for the tire implementation from two different manufacturers. The first is manufactured by the Austrian research institute Joanneum and the second is manufactured by RISE in Norrköping. Both of these have a PVDF material between their electrodes. For further reference these will be denoted 'J' and 'R'. While the basic layout of the two harvesters are very similar there are some crucial differences. Firstly they do not have exactly the same electrode material or PVDF crystalline structure which could be ground for potential differences. Secondly, they come in different shapes and sizes. As of writing the J harvester can be found in 1x3,5,7 cm<sup>2</sup> sizes while the R harvester is only available in 1x1 cm<sup>2</sup>. When putting things into production there is obviously a possibility to construct the optimal sized harvester for that implementation. Thus it is more important what each harvester does per unit of length/area rather than as a whole. To get the same dimensions it is possible to cut a J harvester to approximately the same dimensions as the R harvester. This will not damage the remaining PVDF material but will just shorten the active zone. The last but certainly not the least difference between the harvesters is the material on which the actual harvester is printed. Both manufacturers have opted for a thin plastic film but have used different plastics and slightly different thicknesses. The R harvester is printed on a thicker and stiffer plastic than the J harvester. This obviously increase the stiffness and thus could possibly decrease the available energy. An increased thickness does however mean that the harvesting materials are more protected from extreme stress concentrations and hard hits.

Joanneum provides specifications over their harvesters parameters. These parameters are collected in Table 2.1 and have been used as a base when implementing harvesters into the **COMSOL Multiphysics** model.

Min thickness [ $\mu\text{m}$ ]	Max thickness [ $\mu\text{m}$ ]	$d_{33,min}$ [pC/N]	$d_{33,max}$ [pC/N]
3	15	-25	-38

**Table 2.1:** Joanneum harvester specs

## 2.1.2 Circuits

### 2.1.2.1 Rectifier circuits

The first tries with a circuit were conducted with the MIDE EH0003 rectifier circuit. This is a very simple circuit which consists of only a single rectifier and nothing else. There are two inputs into the circuit but only one output since the two inputs are combined and taken with absolute value. Thus one only needs to measure the singular output vs ground to obtain the output voltage.

### 2.1.2.2 Harvester circuits

In the initial tests at Nokian Tyres in Finland an off the shelf harvester circuit was used to indicate how good the harvesters would be at driving a real life harvester setup. This harvester circuit is the BOB 09946 circuit. This circuit can be calibrated to have a constant output of 1.5, 3, 3.3 or 3.6 V as long as the input voltage is high enough. In

the case which was used in Nokian the calibrated output was set at 3.3 V. The input voltage into the BOB harvester can be either AC or DC since the BOB harvester contains a voltage rectifier. The threshold value for the BOB harvester to be able to fully charge up to 3.3 V it requires a minimum input voltage of 5.43 V. For voltage just below 5.43 V the circuit can start and give some output voltage but it will not reach 3.3 V and for input voltages significantly below 5.43 V the circuit will try to start and immediately shut off.

As a finished product the harvester system will utilize another harvester circuit. This circuit needs to be designed after the specifications provided by Nokian Tyres. Based on data from Nokian Tyres they have a desire to perform 15 measurements and data transmissions per 24 seconds using their Intuito component. Each of these sequences require  $\approx 41.14 \mu\text{J}$  of energy or  $\approx 11.25 \mu\text{C}$  of charge. The time for one of these transmissions is  $\frac{24}{15} = 1.6$  seconds. The harvester circuit will therefore need to provide these required energies and be designed thereafter. The design of these circuits are outside the scope of this project and is something which RISE will do in discussion with other parts in the European project.

## 2.2 COMSOL Multiphysics

**COMSOL Multiphysics** is a simulation tool used in both industry and research projects. One of the major advantages of **COMSOL Multiphysics** is that it allows for easy integration of different physics into the same system. Hence the name "Multiphysics". This allows the user to for example integrate electrical applications into structural system without exporting models or simulations between different software. This has been a crucial tool in this project.

The workflow is similar to other types of mechanical software with the main difference that other types of physics can be included. One first define the actual model geometry in 1D, 2D or 3D. Once the geometry is in place each surface and section of the geometry must be given its corresponding material properties. Materials can be chosen from a list with predefined material of different types. These material properties can still be modified and altered to further optimize the model. One major property which was subject to change in this project is the Young's modulus of the rubber material chosen for the tire rubber. After the material one needs to define which types of physics to be included, for example solid mechanics and electrical mechanics. If one assumes solid mechanics as the chosen physics then the variables solved for include deformations, stresses and strains and these are predefined by **COMSOL Multiphysics**. One must also define what type of study one should perform, stationary, frequency domain or time dependent. This project is about rotating tires which is easiest described in the time domain, so the study is a time dependent study. The variables solved for will be calculated for each time step defined. Note that more than one type of physics and study can be implemented into a single model.

When using different physics, **COMSOL Multiphysics** will define a multiphysics node automatically. This node allows the user to chose which physics to be connected and

influence each other. In the case of this project the two physics working in cohesion are solid mechanics and piezoelectric effect. So the piezoelectric effect and voltage depends on the loads and displacements from the solid mechanics node according to the piezoelectric theory in Equations 2.3 and 2.5. To extract and display the generated voltage one must have an electrical circuit. A circuit can be connected to a terminal and ground, one to either side of the PVDF film. In our case it consists of a simple resistance between the two sides over which a voltmeter measure the generated voltage via Equation 2.6. If one would like to represent the generated energy instead of the voltage one must do so in Matlab by utilizing Equation 2.7.

When adding materials to the model one obviously wants to chose materials as close to real life as possible. When it comes to the tire it is not a uniform rubber throughout the entire thickness, to obtain the correct stiffness for a safe and effective tire metal meshing and wires are used. These are placed inside the tire like fibers in a composite material and help with stiffness and bending properties. These meshes and wires can not be modeled in this simple tire model and instead one can modify the Young's modulus of the chosen rubber to a higher value. This will simulate the added stiffness from the metal wires even if they are not present in the entire tire. The approximation is deemed reasonable and to still give useful data for analysis.

As a part of simulations the tire can be modeled as a straight, level tire instead of a curved, circular tire. The level tire model is modeled as an arch of rubber but instead of a solid hub it simply uses a fixed boundary on the lower edges of the rubber walls. Furthermore, a fixed boundary is applied to the edges of the rubber to force any displacement upwards or downwards (which would match the radial direction in the curved model). The speed with which the load moves over the tire model is easily given in m/s but in order to properly compare this to the circular model or physical rolling tire experiments this needs to be converted to an angular velocity rad/s. To do this one remembers that the tire model has a radius of  $\frac{70}{2} = 35 \text{ cm} = 0.35 \text{ m}$ . If the velocity of the moving load is  $v_{load}$  m/s and the tire has a radius  $r = 0.35 \text{ m}$  then the angular velocity  $\omega$  rad/s becomes:

$$\omega = \frac{v_{load}}{r} \text{ rad/s} = \frac{v_{load}}{0.35} \text{ rad/s}. \quad (2.11)$$

Here it may also be worth to note the conversion between m/s to the more commonly used km/h scale:

$$km/h = 3.6 \cdot m/s. \quad (2.12)$$

When parallel connecting  $i$  number of harvesters which each has an output voltage of  $V_i$  the total output voltage also depends on their internal resistances  $R_i$ . The resistances become in a parallel connection and by using the superposition principle the output voltage becomes:

$$V_{Tot} = \sum_{i=1}^n V_i \cdot \frac{R_i}{\sum_{i=1}^n R_i}. \quad (2.13)$$

If, for example, one has two harvesters with the same dimensions (Same internal resistance  $R$  and voltage  $V$ ) the total output voltage becomes:

$$V_{Tot} = 2 \cdot V \cdot \frac{R}{R + R} = 2 \cdot V \cdot \frac{1}{2} = V. \quad (2.14)$$

So for two identical harvesters with the same loads at the same time the output is the same as one harvester. The key point here is "at the same time" for if two harvesters are placed one after the other they will not have the same loads at the same time so the voltages will be different which will give a lower output voltage than  $V$ .

When using **COMSOL Multiphysics** one must use an "I vs U" connector to extract the voltage potential generated from the piezoelectric material to the electrical circuit. The observant reader will note that this extraction method seems to contain a current I. The connector I vs U reads the voltage and converts it into a current which is inputed into the circuit. Thus, one must include resistances to be able to read the actual voltage generated from the PVDF harvester. In previous iterations of **COMSOL Multiphysics** a connector called "U vs U" was available which did read a voltage and inputed a voltage. This conversion from voltage to current also means that one cannot connect several "I vs U" connectors from several harvesters via parallel connection directly in the circuit module. If this for example is performed with 2 identical harvesters under identical load the result will be a doubled current, one from each harvester. The resulting final voltage would be two times the individual voltages but for parallel coupled voltages the resulting voltage can at the most be as high as the two individual voltages. To circumvent this problem one can perform two separate voltage measurements over each "I vs U" connector with corresponding, individual resistors. One can then input those individual voltages into Equation 2.13 via Matlab and the actual parallel output from the harvester system is given.

When implementing the PVDF harvester with the chosen material into the **COMSOL Multiphysics** model one wants to ensure such a close resemblance to the real harvester as possible. Below follows a table with the PVDF harvester and material parameters. Note that the shape of the harvester may vary between simulations but the thickness does not. See Table 2.2

Thickness [ $\mu\text{m}$ ]	Density [ $\text{kg}/\text{m}^3$ ]	$d_{33}$ [ $\text{pC}/\text{N}$ ]	$d_{31}$ [ $\text{pC}/\text{N}$ ]
10	1780	-33.8	13.58

**Table 2.2:** COMSOL Multiphysics PVDF harvester parameters

## 2.3 Wheel physics

The scale of this project is sadly not enough to encompass tire forces and tire physics in any great detail. Thus, the model of the tire will be a simplified one. This may not influence the results drastically but it is worth noting. For further descriptions of the model see the methodology section.

Wheels consists of two primary components, an outer tire made from primarily rubber materials and a wheel hub on the inside which consists of harder, less deformable materials such as steels or in some cases carbon fibers. To say that the tire consists of primarily rubber, while not technically wrong, is a significant simplification. The tire also consists of metallic meshes, wires and belts of different metals and structures [18]. These different extra layers and components in the rubber structure are mainly there for

stability and structural reasons and this makes the structure non-homogeneous. All these different components and metallic nets and meshes are not included in the **COMSOL Multiphysics** model but the material properties are significantly changed with their real life inclusion. For example Young's modulus is not homogeneous in the entire tire but this is assumed in the simulations. Thus, the Young's modulus used in the simulations is an approximation of the entire tire structure with all the different components and not the exact value of tire rubber. Under load the inner wheelhouse will remain almost entirely undeformed while the outer, softer material will deform more (under the conditions that the applied load is great enough to warrant a deformation). One can find a similar feature in everyday life in a poorly inflated football. If you have ever played football on a break in school you know the ball which was very deformable due to the bad inner pressure. As this ball lay on the ground the lower surface became very flat and the contact surface with the ground became larger. As the ball rolled the flat contact part, and thus the deformation, moved around the ball. Obviously the tire deformation and flattening will be less extreme than on a football but the principle remains the same. As the wheel spins the tire deformation will move around the wheel (while obviously remaining at the contact point to the ground) and as the piezoelectric elements move over the deformed zone they will also deform and bend resulting in generated energy.

The deformation of the tire is not only dependent on the material choices but also on the internal pressure. Similar to the school ground football a higher pressure means a stiffer system and smaller deformations. Trivially however, the pressure in the tire still needs to be enough to maintain the vehicle's drive qualities and is often specified by the tire manufacturer at  $\approx 30$  psi or 2 bar.

It is stated above that rubber is a more deformable material than steel which is intuitively easy to understand, however if one wish to quantify what the deformation depend on it gets slightly more complicated. If one looks at the deformation compared to the original size one can determine the material strain  $\varepsilon$ :

$$\varepsilon = \frac{\delta}{L}. \quad (2.15)$$

Here  $\delta$  is the displacement and  $L$  is the original size in the direction of the displacement. If for example a beam of original length 1 m is extended in that direction with 1 cm then the strain becomes  $\frac{0.01}{1} = 0.01$  or 1 %. There is another way to determine the strain which is via the generalized Hooke's law:

$$\boldsymbol{\sigma} = \vec{\mathbf{C}}\boldsymbol{\varepsilon} \quad (2.16)$$

where  $\boldsymbol{\sigma}$  is the 3x3 load matrix (In 3D modeling),  $\boldsymbol{\varepsilon}$  is the 3x3 strain matrix and  $\vec{\mathbf{C}}$  is a 3x3x3x3 stiffness tensor. To avoid working in 4 dimensional matrices one can rewrite the equations in Voight notation. Voight notation use the anisotropy (material properties are direction dependent) to simplify this equation to:

$$\vec{\sigma} = \mathbf{C}\vec{\varepsilon}. \quad (2.17)$$

Here  $\vec{\sigma}$  and  $\vec{\varepsilon}$  are 6x1 vectors given by:

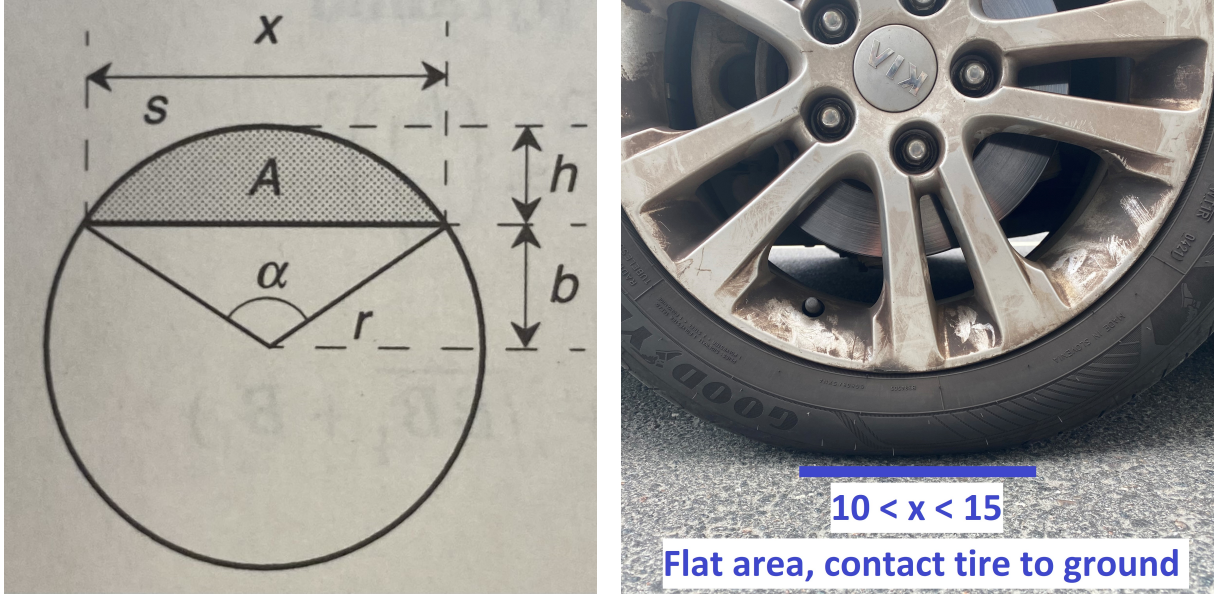
$$\vec{\sigma} = \begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{bmatrix}, \quad \vec{\varepsilon} = \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{12} \\ \varepsilon_{13} \\ 2\varepsilon_{12} \\ 2\varepsilon_{13} \\ 2\varepsilon_{23} \end{bmatrix}, \quad (2.18)$$

and  $\mathbf{C}$  is a 6x6 matrix given by  $C_{ij}$ ,  $i,j=1-6$ . The different components of  $\mathbf{C}$  are as such a connection between the stress and the strain. These equations described above are true for every orthogonal coordinate system  $\hat{e}_1, \hat{e}_2, \hat{e}_3$ . Thus it can be used in a wheel which could be easily described by a cylindrical coordinate system. COMSOL performs these calculations automatically when solving for solid mechanics. Another noteworthy part is that as long as the  $\mathbf{C}$ -matrix is invertible, its determinant is non-zero, then one can rewrite the equation to give the strain instead of the stress:

$$\vec{\varepsilon} = \mathbf{C}^{-1}\vec{\sigma}. \quad (2.19)$$

One of the things which affect materials the most is the environment in which they are located. Here such things as contacts, forces and stresses are not included but rather temperatures and humidity. Especially temperature is one of the greatest variables when it comes to material properties and how they change. Since temperature is highly irregular and can change drastically, especially over an entire year, this may cause troubles. In this thesis project it has been assumed that the wheel is located in a constant, optimal temperature. This is done in the interest of time and complexity even if it may influence the connection to real life tests. In most countries with varying temperatures between summer and winter it is mandatory to change tires on your car from softer during the winter to harder during the summer. This is done to try and keep the material properties variation in a smaller spectra and could justify the approximations done here.

One can approximate the displacements in the tire by approximating the contact area between the tire and the ground based on the theory displayed in Figure 2.5a. In Figure 2.5b one can see a real tire to ground contact with a flat contact surface.



(a) Theory describing geometrical representation of deformed tire. (b) Wheel on real car. Note flat contact surface between tire and ground.

**Figure 2.5:** Simplification and real life tire to ground contact

Using the nomenclature laid out in Figure 2.5a one can describe the contact area as  $x$ . Then it is possible to approximate the displacement  $h$  using the following equation [19]:

$$h \approx \frac{x^2}{8r} \text{ if } h \ll r. \quad (2.20)$$

Since the displacements in a rolling tire is significantly smaller than the radius of the tire this is a reasonable approximation. The contact length between tire and ground is approximated to being between 10 and 15 cm long which renders displacements  $h$  as follows:

$$h_{10} = \frac{0.10^2}{8 \cdot 0.35} = 0.0036 \text{ m} \quad (2.21)$$

$$h_{15} = \frac{0.15^2}{8 \cdot 0.35} = 0.008 \text{ m}. \quad (2.22)$$

Thus the displacement of the tire should be between 3.6 and 8 mm. Now, keeping these displacements in mind it is of interest to know the angle difference between the original angle and the compressed angle of the PVDF. To do this one can once again use an approximation. By approximating the shaded area in Figure 2.5a as an equilateral triangle the angle of one of the corners represent the angular difference between the undeformed and the deformed angle. The angles are given by:

$$\alpha_{10} = \tan^{-1}\left(\frac{h_{10}}{\frac{0.01}{2}}\right) = \tan^{-1}\left(\frac{0.0036}{0.05}\right) \approx 4.12^\circ \quad (2.23)$$

and

$$\alpha_{15} = \tan^{-1}\left(\frac{h_{15}}{\frac{0.015}{2}}\right) = \tan^{-1}\left(\frac{0.008}{0.075}\right) \approx 6.09^\circ. \quad (2.24)$$

From Equations 2.23 and 2.24 one can conclude that there is a difference of less than  $2^\circ$  for the two approximated extreme values for ground to tire contact.

### 2.3.1 Nokian harvester specifications

Should a final product eventually be discovered and put into production it would be Nokian Tyres who would utilize it in their products. Therefore it is their wishes and specifications who decide on the final product. These specifications include the geometrical dimensions and weight of the harvester system along with the required energy production.

Variable	Maximum value
Weight harvester unit [g]	25
Weight harvester electronics [g]	20
Length [mm]	100
Width [mm]	100
Height [mm]	50
Full functionality [mW]	15
Limited functionality [mW]	5
Charge for full measure and transmission [ $\mu\text{C}$ ]	11.25

**Table 2.3:** Nokian specifications for harvester implementation.

# 3

## Methodology

### 3.1 Physical experiments

Physical experiments was conducted both at RISE laboratories on Chalmers Campus in Gothenburg, Sweden as well as in the Nokian facilities in Nokia, Finland. The experiments in Nokia was performed on full tires in a mechanical and repeatable setup while the experiments at RISE were of a smaller scale on a halved tire using hand power to bend the tire.

#### 3.1.1 RISE experiments

Since the Nokian experiments was carried out in Finland and during machine-applied load it was of great importance that connections, test methods and applications were as good as possible when the tests were conducted. With limited time on site and risk of lack of tools for any major repairs it was of the highest priority that the setup was tested to make sure that cable and harvester connections were firm and measuring equipment worked before the Nokian tests. In order to achieve this smaller, less formal experiments have been carried out at RISE in Gothenburg. Obviously there are significant differences between the Nokian and RISE experiments, especially in load and stress magnitudes as well as test speed. These initial test gave a good idea of different connection types and was a good way to ensure that measurements were possible before the Nokian experiments.

To summarize all measurements used for the results Table 3.1 has been compiled.

Harvester type	Area [cm <sup>2</sup> ]	Shape	Layers	Capacitor [nF]	Velocity [km/h]	Exp. Type
J	42	Rect	3	470	10-100	Nokian
J	$\pi$	Circ	1	470	10-40	Nokian
R	1	Rect	1	470	10-60	Nokian
R	1	Rect	1	N/a	Hand	RISE
J	1	Rect	1	N/a	Hand	RISE
J	2	Rect	2	N/a	Hand	RISE
J	3	Rect	3	N/a	Hand	RISE
J	3	Rect	1	N/a	Hand	RISE
J	5	Rect	1	N/a	Hand	RISE
J	$\pi$	Circ	1	N/a	Hand	RISE

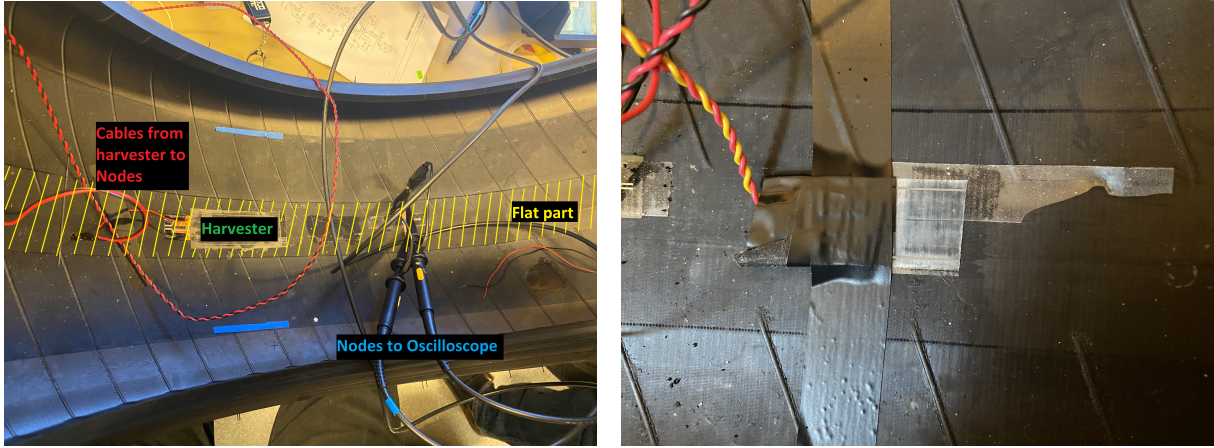
**Table 3.1:** Different harvester combinations used for RISE and Nokian experiments.

#### 3.1.1.1 Piezoelectric experiments

The two harvester types, J and R, were compared when it comes to voltage, connection with tire and prize/availability. To protect the PVDF surface on the harvester and make for easier removal plus application onto the tire the harvester was fixed to a plastic film which in turn was then connected to the inside of the tire. This was done with either double-sided tape and/or with the glue "Loctite 401". Case 1 was to glue the tire and the harvester with Loctite 401. In this case the piezoelectric material was directed inwards the circle center of the tire away from the tire surface to protect it from glue and any friction or destruction from contact. Thus the glue was only in contact with the plastic film on which the PVDF material was printed on the other side. Case 2 was to use double sided tape and tape the tire and harvester in the same way as in case 1. The harvester was directed as in case 1. Case 3 once again used Loctite 401 and a plastic film but this time the harvester was also covered in electric tape. First a thin plastic film was placed on the PVDF side of the harvester to protect it before electric tape was wrapped around the entire harvester, enclosing it in a tape layer. This bundle was then glued against the tire.

Initially, the double sided tape used for the connections were an ordinary office style tape found at the RISE offices. Nokian had used another, industrial style, double sided tape when connecting other objects to tires and it was their wish to use this during the experiments in Nokia. Nokian sent a packet with these tapes to the RISE offices and after this point they were used to connect the harvesters instead of the office style tape. One initial thought about this except for that the tape may have been designed for rubber connections was that the tape was round instead of the ordinary rectangular strips one obtains. The circular shape reduced the stress concentrations that previously occurred at the corners of the rectangular shape in the tape and therefore enhanced the connection between tape and tire.

Stated by Nokian, the harvesters were placed on the flat central part of the tires as seen in Figure 3.1a. Connecting the harvester with the tire was relatively easy since this part of a tire does not have any ridges or uneven surfaces. Aligning the harvester placement to the flat center enables to avoid any side to side unbalances in the tire. Since the weight of the harvesters were relatively small this did not have a large influence on the physics of the tire with further impact on the car, but it could still affect the results slightly. Especially with the circuits attached to the harvesters. One must always aim to have the balance of the tire as equal as possible. See Figure 3.1a for setup.



(a) Harvester placement on flat part of tire using double-sided tape. (b) J harvester cut into  $\approx 1 \times 1 \text{ cm}^2$  size. Notice some of the double-sided tape remaining on the tire.

**Figure 3.1:** RISE experiments harvester setup.

In order to determine the size dependency of the harvesters the J harvester was measured in its full size as well as cut into  $\approx 1 \times 1 \text{ cm}^2$  size. The cut harvester can be seen in Figure 3.1b.

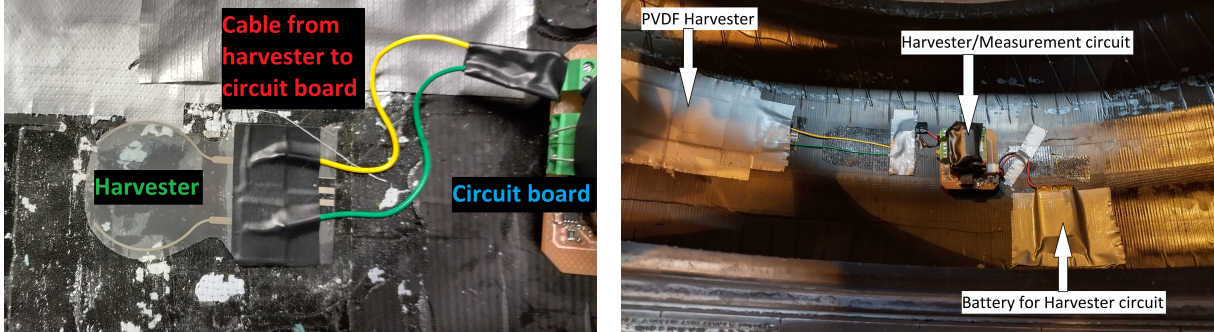
The most desirable option was to use the R harvester since it is produced in closer cooperation with the RISE office and could as such be obtained at a lower cost and could easily be modified to any shape desired. However, should it prove that the J harvesters are significantly better in the future, they should be used instead. The initial test thus used both harvesters and their performances was analyzed and compared.

To stimulate the harvesters on the tire, hand power was used. The tire was rolled backwards and forwards over the area where the harvester was connected using hands. For each measurement the initial speed of the roll was slow and then it was increased to obtain the entire roll frequency/velocity span in one measurement. The harvesters were connected using copper tape to probes on an oscilloscope from which the data was extracted. In some measurements a rectifier circuit was connected between the copper tape and the probes since a similar circuit was needed for real world applications. When the circuit was applied both channel outputs go into the rectifier and only one signal was measured out against ground from it. When obtaining the power output from the harvester, both with and without rectifier, Equation 2.7 was used and the time-factor was ignored.

### 3.1.2 Nokian experiments

The double sided tape sent from Nokian Tyres showed promising results so the harvesters used in the Nokian experiments were prepared for that tape connection. Initially the harvesters were uncovered, however during experiments on site it was chosen to cover them anyways to add an extra protective layer. Harvesters from J were most prominently used but a few R types were also tried. Since J has both rectangular and circular harvesters, both geometries were also analyzed. Some harvesters were also designed which contain

several layers but these were only done for the rectangular J harvesters. Under the electric tape around the electrodes ordinary wires have been connected and extended outside the electric tape. These wires were initially meant to be pushed into the measurement circuit via pins but as several wires came loose at low velocities this was changed to them being soldered onto the circuit board. This can be seen in Figure 3.2a.



(a) Wire connections used during Nokian Tyres experiments. Note the electrical wires pushing out through the electric tape.

(b) Picture over the experimental setup in the Nokian lab. Note the covering duct tape over PVDF and battery.

**Figure 3.2:** Nokian experiment harvester setup.

In Nokia the tires were placed in a test rig which spun the tire with a desired speed (the rolling speed of the tire) while applying pressure over that same contact surface (the ground force / pressure). While some different ground forces were tried during some measurements, the majority of experiments used a ground force of  $200[\text{kg}] \cdot g$ , where  $g$  is the gravitational constant of  $\approx 9.82 \text{ m/s}^2$ . This would compare to a car weighing a total of 800 kg which is low but in the right order of magnitude. The internal tire pressure was set to 2 bar for each experiment since it is the most commonly used tire pressure. Note that the same value was used for the **COMSOL Multiphysics** simulations as well. To connect the harvesters to the tire surface the double sided tape was used and as mentioned before electrical tape was used to push down and protect the PVDF material. Furthermore the cables between circuit battery, circuit and harvester had to be held down with duct tape as well. A full, general representation of the experimental setup can be seen in Figure 3.2b.

Initially, the experiments varied the load pressure up towards 500 kg but it became apparent at this point in time with the current setup that it could not handle the loads that came with that. 200 kg was the maximum safe load and was therefore the chosen load for these experiments. The goal is to increase this load for future experiments. As more and more runs were performed it became clear what the problems were with the setups and these were progressively fixed as the experiments moved further. One of the major adjustments was the inclusion of duct tape over the cables between the components. It was clear that the cables and circuit contacts were weak spots and thus they were reinforced.

When the internal setup of the harvesting system was in place the tire was mounted on a rim and inflated to correct pressure so an entire car wheel was obtained. This wheel was then pushed against a large, rotating drum. The rotation of the drum gave the rotation of the tire and the pressure between them simulated the car to ground load. Using a

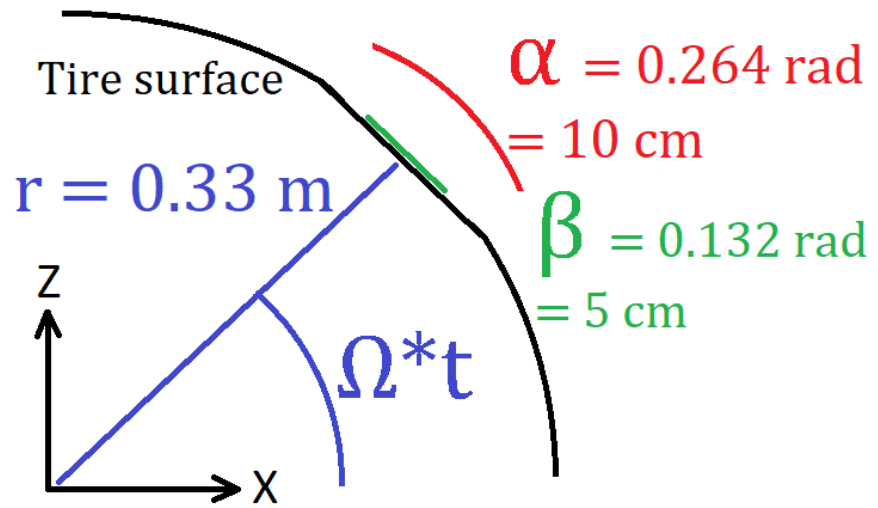
drum in this way is a common test rig for Nokian Tyres and gives accurate measurements and control over speed and pressure which makes it ideal for this type of harvester. By utilizing a BLE (Bluetooth Low Energy) hot spot it was easy to send the harvested voltage and store it on a file outside the tire which also removes the use of cabling or wires into the tire from outside.

## 3.2 COMSOL Multiphysics simulations

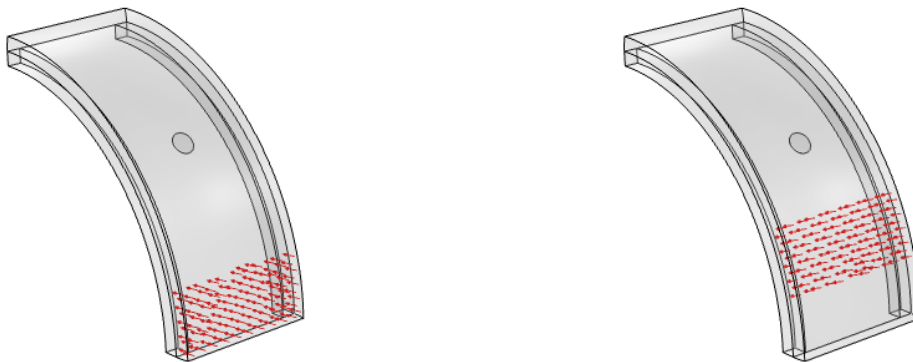
The initial COMSOL Multiphysics simulations were of a very simple wheel model to determine it's mechanical properties. The first model consisted of a structural steel cylinder surrounded by a thin layer of rubber with Young's modulus 50 MPa and Poissons ratio 0.3, the entire wheel was resting on ground. The wheel was here modeled without a cavity or space between the tire and the wheelhouse to give an idea of how a basic tire will act. To replicate a real tire and to avoid straight 90 degree angles a slight angle was modeled between the roll area and the side wall.

This wheel was initially simulated in a stationary state with a body load of 500 kg. Attempts were here made to make the wheel roll on the ground by adding angular velocity, initial velocities along the ground and a constant velocity along the ground. These experiments were extremely time consuming and required many iterations to work even with very low velocities. To prevent this the decision was made to alter the car load on the tire. Instead of moving the tire itself over ground the load was moved over the edge of the tire.

By using an if statement to define over which area the load was to be applied in the simulations the load of 500 kg could be applied in the correct directions using cosine and sinus factors. The load area was defined by approximating the contact area to the ground and converting that to an angle. It was approximated that the contact length with the ground was 10 cm long. By knowing that the entire circumference of the tire is 2.39 m and corresponds to  $2\pi$  radians, the 10 cm length was converted to an angle  $\alpha \approx 0.264$  radians. When one knows the angular velocity  $\Omega$  with which the load will move over the tire then one can make sure that the load is applied only in an area defined by  $\alpha$  and the current position. For example the load was applied in the x-direction in the area defined by  $x = r \cdot \cos(\Omega t \pm \frac{\alpha}{2})$ . Here  $r$  is the radius to the outer edge of the tire. The variable  $t$  stands for time and ensures a movement over the surface as it increases. In the interest of keeping the model simple the car load was applied to only one quarter of the tire. Note that the load should not be strictly radial due to the outer deformation of resting against ground. To ensure a non-radial load the angle of the load was defined by the normal to the middle of the surface defined by  $\alpha$ , see Figure 3.3. How the load was applied in the **COMSOL Multiphysics** simulations can be seen in Figures 3.4 - 3.6. In these figures the time was incrementally increased, causing the load to move from bottom to top top of the tire. Note that there are several time steps between the chosen screenshots.



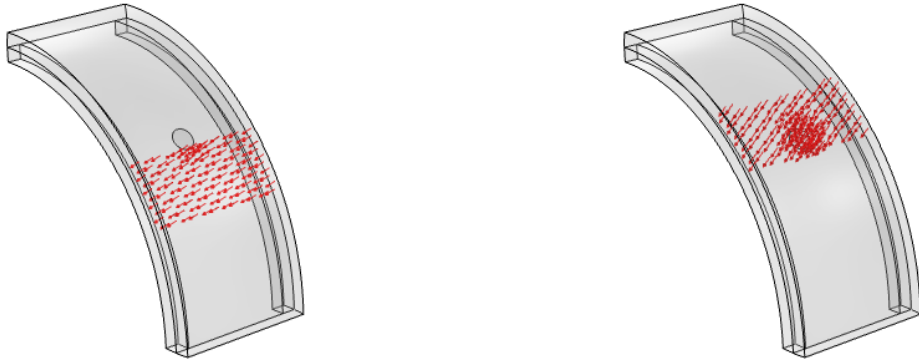
**Figure 3.3:** Visualization of the load/displacement in COMSOL Multiphysics



(a) Ground contact at bottom of tire.

(b) Ground contact has moved slightly as time moves forward.

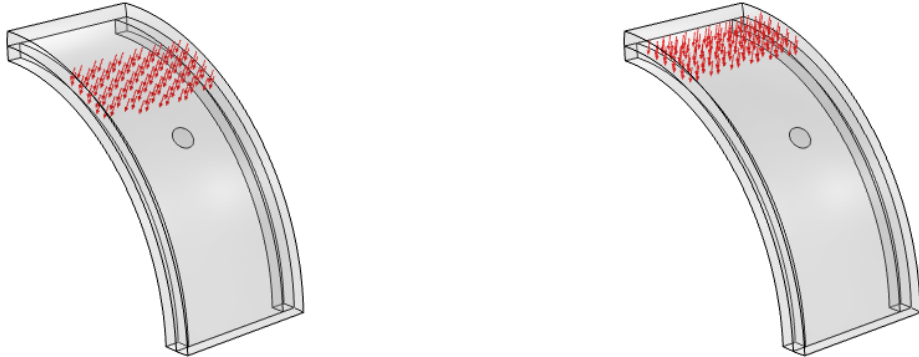
**Figure 3.4:** First two ground contacts.



(a) Ground contact continues to approach circular harvester.

(b) Ground contact has moved entirely over the circular harvester.

**Figure 3.5:** Middle two ground contacts.



(a) Ground contact has moved passed the circular harvester.

(b) Ground contact has moved to the top edge of the tire quarter.

**Figure 3.6:** Last two ground contacts.

To further resemble a real tire a cavity was added in the middle between the tire and hub. This is where air would be inflated on a real tire and thus it contains a pressure. This pressure was modeled outwards in a radial direction with a value of 2 bar. Once again this pressure was only applied in a quarter of the tire, the same quarter as the car load was applied.

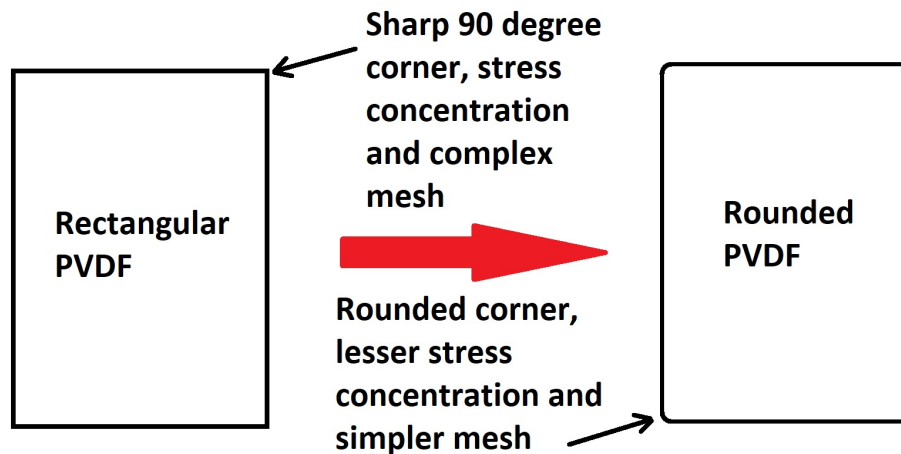
When a simulation with an entire wheel model existed which contained all the basic elements of a real life wheel the next step was to add the external harvester components. The first step of this part was a small layer of plastic film which represent the plastic film on which the harvesters would be connected before applying them to the tire. This was modeled using two tauruses to determine its angle from the center of the tire and a thin and narrow cylindrical strip in the width and thickness of the plastic piece. Their overlapping areas defined a thin plastic film on the inside of the tire. Trivially, this was placed in the same quadrant as the applied loads were. The dimensions for the plastic film were as follows: For now the angle corresponds to a 5 cm strip which give an angle of  $\beta = 0.132$  radians, the width was determined to be 2 cm and the thickness was set to 1 mm. When this thin geometry was added to an otherwise quite bulky model it set higher demands on the chosen mesh size. A finer mesh was required to be able to properly evaluate the thin plastic film. As the harvesters would be replace these films it was of great importance that the deformations and stresses were correct on that small area. It was important that the deformations could propagate through the tire and then the plastic film as well to the harvester. This set some requirements on the Young's modulus of the rubber which was here drastically increased into to the GPa scales. The entire meshed geometry, both wheel and for a rectangular harvester can be seen in Figure 3.8

As deformations could be seen on the plastic film when simulating, the choice was made to convert the plastic film into a PVDF piezoelectric element and reduce the thickness of the film to 0.01 mm instead of the previous 1 mm. The thickness  $10 \mu\text{m}$  is in the middle of the specified span from Joanneum, see Table 2.1. When choosing the material parameters for the PVDF element the initial choice was an arbitrary piezoelectric material and not specifically a PVDF material. This was corrected later as stated below and no data obtained before this switch has been used in the report. One must also define a ground potential which in this case was chosen as the inner edge of the piezoelectric harvester which means that the part in contact with the tire will have the electric potential. In order to obtain a better measured voltage from the now present harvester an electrical circuit component must be added to the geometry. The connection between geometry and circuit is done via a terminal. The connected circuit was simple and consisted of a  $10 \text{ M}\Omega$  resistor connected between the two different electrodes of the harvester. By measuring over this resistance the data became comparable to the measured data from the oscilloscope which has an internal resistance of  $10 \text{ M}\Omega$ .

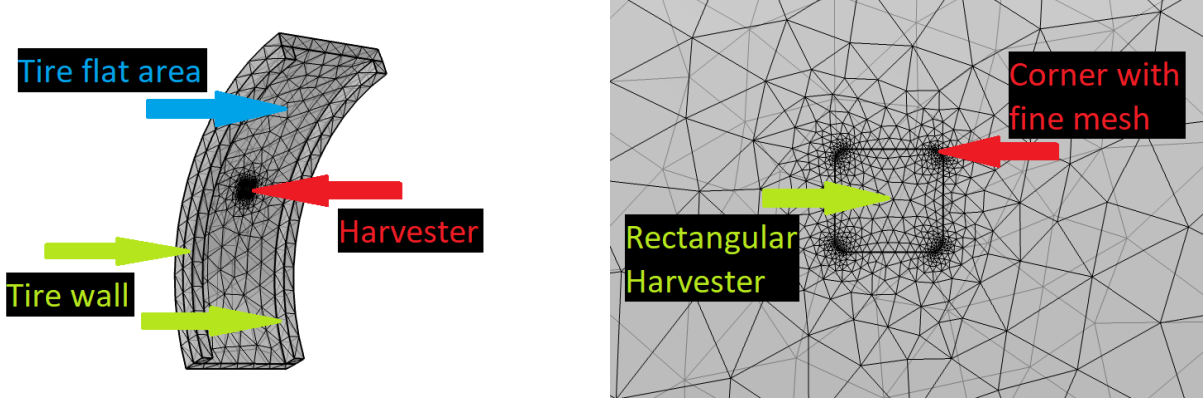
As these steps were taken there were several instances when the system did not solve or was unable to mesh. These problems have since slowly been worked away but to obtain quicker results a straight/flat tire model was developed. This was a model with the same dimensions as the circular one but stretched into a flat plane. This eliminated any curvature and made the model easier to solve. A straight model was not a true representation of a real life tire but it could be used to obtain an idea of different harvesters and their characteristics while the problems with the circular model were resolved.

The problems with the circular harvester model finally came down to a few key points.

The worst was material parameter errors which made the harvester material too brittle and more similar to a ceramic rather than a PVDF harvester. This was a great representation why ceramic materials are badly suited for a curved tire implementation since they cannot handle those deformations before snapping. The simulations obviously failed when the material broke and when an appropriate material was chosen that problem was eliminated. When the material was changed from an arbitrary piezoelectric material to a PVDF material the chosen variant was denoted "PVDF" in **COMSOL Multiphysics**. This was the most standard PVDF material available with predefined values for  $d_{13}$ ,  $d_{33}$ , density etc. Piezoelectric parameters have a major influence on the available output so the material cannot be chosen completely at random. This predefined, standard material had parameters within the established boundaries with a  $d_{33}$  value of -33.8 pC/N since the real life harvesters have  $d_{33}$  values between -25 and -38 pC/N, see Table 2.1. One further improvement was the introduction of rounded corners when rectangular harvesters were examined. By avoiding 90° corners and their stress concentrations the system not only solves easier but was also easier to mesh. The difference is schematically shown in Figure 3.7.



**Figure 3.7:** Graphical representation of the alterations with the rounded edges of the harvester.



(a) Meshed wheel geometry. Note the finer mesh around the harvester.

(b) Meshed rectangular harvester. Note the finer mesh needed at the corners compared to straight section

**Figure 3.8:** Meshed geometries, entire tire and rectangular harvester.

The curved edges could easily be modeled using the fillet function which automatically curves edges over a given radius. The radius of the corners were varied based on the desired geometrical shape. To model and examine circular shapes the same basic theory as before was used. By keeping the arc length of the harvester the same as the width one obtained a square. Applying a fillet with radius of half the harvester width will then provide a circular harvester. Both these harvesters have been examined via simulations and the dimensions have mostly been dictated by the dimensions of the real life harvesters used in the physical experiments.

When performing simulations on the curved tire the angular velocity was calculated to match the velocities used in the Nokian tire experiments. To calculate their relationship Equation 2.11 was used. The radius of the tire is 0.35 m. This gives the values provided in the following table, Table 3.2.

$v$ [km/h]	$v$ [m/s]	$\omega$ [rad/s]
10	2.78	7.94
20	5.56	15.89
30	8.33	23.8
40	11.11	31.74
50	13.89	39.69
60	16.67	47.63
70	19.44	55.54
80	22.22	63.49
90	25	71.43
100	27.78	79.37
110	30.56	87.31
120	33.33	95.23

**Table 3.2:** Linear velocity to angular velocity for the velocity span tested in Nokian.

When these values are tested one can compare the maximum voltage drops to the

measured voltage in Nokian for each velocity and see if there is a correlation.

As, to our knowledge, **COMSOL Multiphysics** could not calculate and take active and passive zone into account, attempts were made to simulate them by implementing the circuit seen in Figure 2.4. To calculate the different values of  $C_{Active}$  and  $C_{Passive}$  the given equations were used along with a fixed deformation zone. At that point in time there was no knowledge of how to extract which points had the most bending deformation. Thus, as an analytical start, an area with a width of 5 mm in the middle of the deformation zone was prescribed as the active area. As long as that active area was over the same area as the PVDF harvester then the different capacitors had values given by Equations 2.9 and 2.10.

As an attempt to reduce the passive area in each harvester narrow strips were investigated. By printing narrow strips of PVDF material on the plastic film instead of a large continuous area each strip would act as its own harvester with its own active and passive zones. By aligning the strips so that they are orthogonal towards the rolling direction and trying to keep them as wide as the active zone they would have none to a very small passive zone. Thus, one could cover the same area as before with many smaller harvesters, all of which should have a very small passive zone and each strip parallel connected with the rest. This was the same theory which would include parallel connecting several regular harvesters after each other to have a more continuous energy output. The only practical difference was that for this case the strips were said to be part of the same harvester.

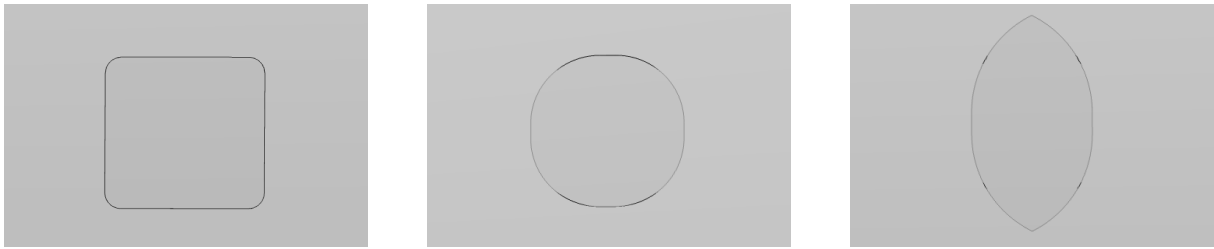
For the initial simulations with strips they were chosen to be 3 mm wide each with a space of half the strip width (1.5 mm) between them. The number of strips was allowed to vary between 1-8 and they were analyzed at speeds of 30, 50, 70 and 90 km/h. By comparing these data to simulations at the same speeds with a single rectangle with the same area as the different amount of strips one could compare them and analyze the effect of splitting a harvester into strips versus keeping the original, one element dimensions.

As a further step in optimizing the model an angled polarization was introduced for the piezoelectric element. This angle polarize the piezoelectric material inwards towards the center of the wheel as the  $d_{33}$  direction. By doing this the same deformation could generate more voltage as long as the polarization direction is correct. As external parameters had changed one must once again reevaluate the right Young's modulus of the rubber. Thus, initially a parameter sweep between 0.1 and 1 GPa was performed to determine the best value. The best value was the value which corresponds the generated voltage for a fixed velocity to the voltage obtained for the same velocity at the Nokian experiments. In this case the chosen velocity was 10 km/h with a circular harvester with a 2 cm diameter. With the best Young's modulus chosen one can then move on and perform a parametric sweep over the velocity span 10 to 120 km/h and determine the output voltage.

One subject which had not been examined so far was the choice of resistance in the

electrical circuit when running the simulations. Simple measurements were performed on regular harvesters using voltmeters which showed that the inner resistance was in the order of  $\approx 10 \text{ M}\Omega$ . However the value was not exactly that. Bearing this in mind the inner resistance was examined and allowed to vary between 10 and 100  $\text{M}\Omega$ . Intuitively this should influence the output voltage with a higher resistance giving a higher voltage output, especially since the chosen connections convert from voltage to current and then use it into the circuit. All according to Ohms law.

One subject analyzed at the Nokian and RISE experiments was the dependency on the geometrical shape of the harvester. Rectangular were compared to circular with interesting results which raised the question if any other shape might be more beneficial. Any other shape of harvester was at the time unavailable for real life experiments but there were possibilities to perform **COMSOL Multiphysics** simulations of the different shapes. By varying the fillet radius of any corners one could modify the harvester shapes into rectangular, circular and elliptical shapes. These shapes can be seen in Figure 3.9. By keeping their footprint area the same and performing the same simulations with them one could analyze their characteristics. In these simulations the PVDF polarization angle described above was used since it showed a higher correlation to real life data.



(a) Rectangular harvester. Note the slightly rounded corners to avoid disastrous mesh requirements but still match reality.

(b) Circular harvester. Note the near perfect circular shape.

(c) Elliptical harvester. Note the slightly pointed corners at the top and bottom. These are unavoidable with the current way to model the harvesters and are deemed to not influence the mesh too much.

**Figure 3.9:** The rectangular, circular and elliptical harvesters used in the **COMSOL Multiphysics** simulations. Note that the area for each harvester is the same ( $4.011 \text{ cm}^2$ )

If one had decided on a final geometric shape it was still of interest to analyze how the size of that shape would influence the output voltage. To determine how the area of a harvester affects it the circular harvester seen in Figure 3.9b was chosen. With this shape chosen the area was allowed to vary and be analyzed. Since a circle grows equally in all directions one could analyze the area dependency and not only the length or height dependency.

To conclude the setup which was used for the **COMSOL Multiphysics** simulations the

final values are here collected in Table 3.3. The values used here are the ones used when results are extracted from the simulations.

Load [kg]	Young's Mod. [GPa]	Velocities [km/h]	Harvesters	Mesh
500	0.19	10-100	Figure 3.9	Figure 3.8

**Table 3.3:** Simulation setup for all simulations.

# 4

## Results

### 4.1 Physical experiments

#### 4.1.1 RISE experiments

##### 4.1.1.1 Piezoelectric harvesters

As the different type of connections were examined it became clear that it was non-trivial to determine which was best. The initial double sided tape connections gave good results with very little dampening but the connection between harvester and tire was not as optimal as it could be. As the tire rotated and deformations occurred over and over there was a risk that the tape was worn out and come loose. The usage of Loctite 401 was not trivial either since it was found that initially the connection between harvester and tire was excellent but as a few days went by the glue was allowed to set entirely. The glue setting entirely made it lose the connection to the plastic film material. It was unclear what this depends on but it could be a chemical reaction between the glue and the plastic. To prevent this the third case was examined where the glue connected rubber tire to a rubbery electric tape rather than directly on the plastic film. This drastically increased the connection between the harvester and the tire while at the same time dampening the displacements. The extra layer of a rubber material dampened the available energy but it may be necessary to obtain the desired connection. There was also a difference between the sensitivity and type of load which was best for the different types of connections. For the double sided tape it was found that the higher the rotational speed and intensity of it the more energy was available for extraction. While for the electrical tape covered harvesters it was more important that the deformation of the harvester was smooth and over the entire harvester surface.

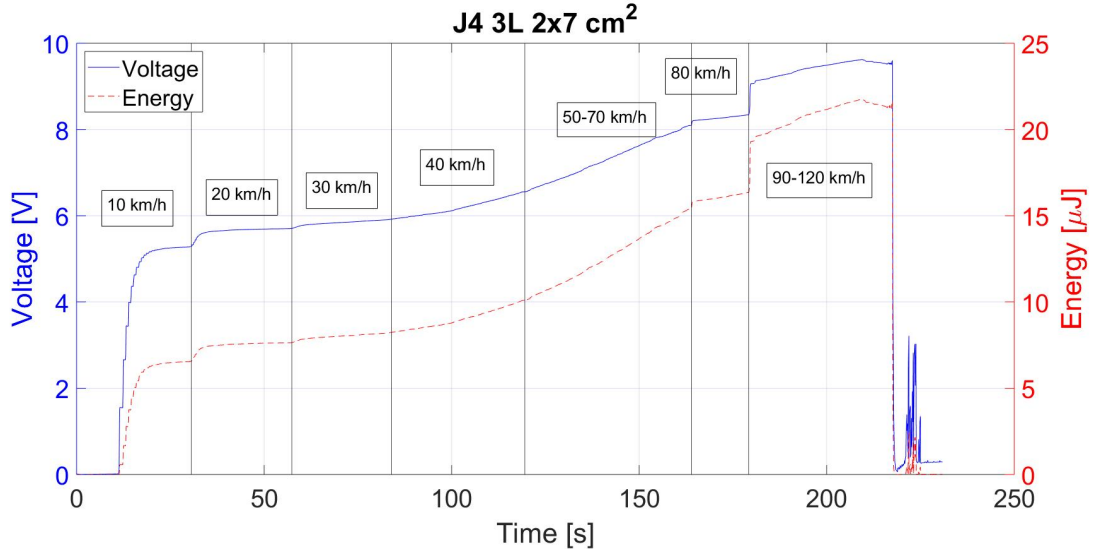
When the Nokian double sided tape was tested it became clear that this was a more optimal tape than the previously used office tape. This new tape had a higher grip against both the tire surface and the harvester during pulling tests and it showed the same negligible dampening of the output voltage.

By keeping the width of the harvester constant at 1 cm and varying the length of it to 1 and 5 cm one can compare the output from these two lengths. The peak values were slightly higher for the 5 cm long harvester and they were also significantly wider than for the shorter harvester. For a rectangular 1x1 cm<sup>2</sup> vs a 2 cm in diameter circular voltage and power a significant difference was found. The values were significantly higher for the circular PVDF compared to the rectangular. The actual energy peak

values were 6.7163 and  $0.991 \mu\text{J}$  respectively. With these values one took into account that the circular PVDF had a higher area ( $\pi \text{ cm}^2$ ) compared to the rectangular PVDF ( $1 \text{ cm}^2$ ) which gave a smaller difference in  $\text{J}/\text{cm}^2$ . The difference was however still almost a factor 2 in the circular PVDFs advantage.

### 4.1.2 Nokian experiments

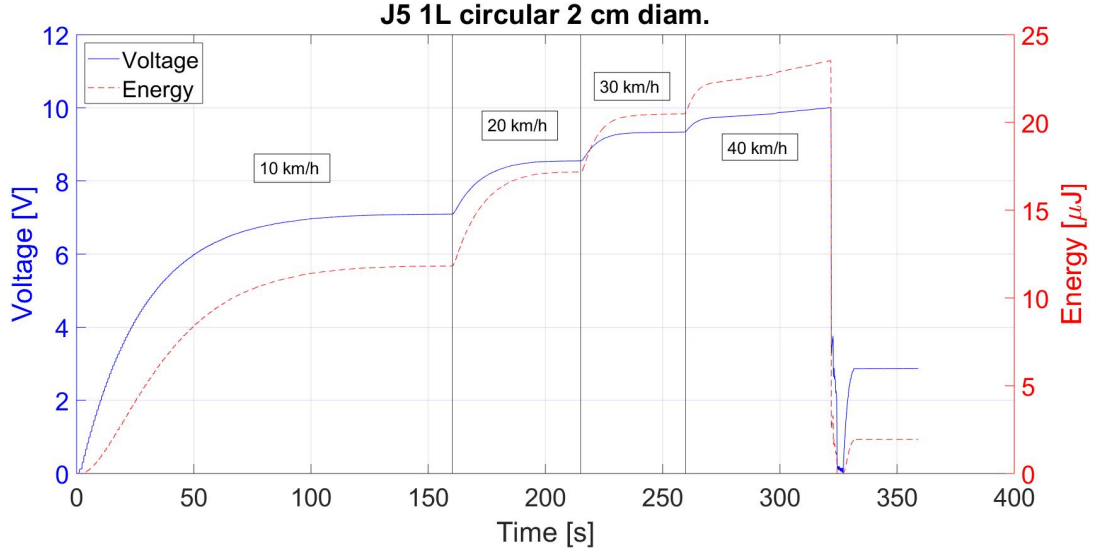
Here below the most promising results from the Nokian on-site experiments are presented. These were the experiments which gave good and clear data unaffected by broken equipment or connectors. The first graph shows the output voltage and energy for a three layer  $2 \times 7 \text{ cm}^2$  harvester with 2 bar tire pressure and a ground load of 200 kg. The velocities were allowed to change from 10 to 120 km/h. The results can be seen in Figure 4.1.



**Figure 4.1:** Voltage and energy for three layer  $2 \times 7 \text{ cm}^2$  harvester with 2 bar tire pressure and 200 kg ground load. Velocities change from 10 to 120 km/h, note the saturation levels for lower velocities and the cable failure at the end.

The saturated voltages for 10 and 20 km/h were 5.2 V and 5.7 V respectively. These values were of importance since the threshold value for the BOB harvester circuit was in between them at 5.43. The maximum energy was also  $\approx 22 \mu\text{J}$  which is below the required  $41.14 \mu\text{J}$  to power the Intuito.

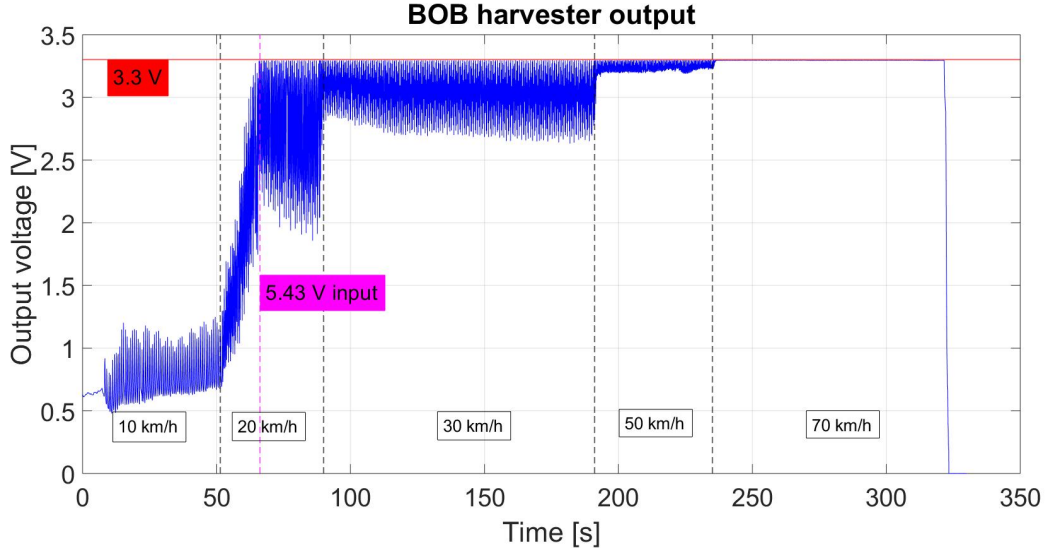
The second highly interesting measurement from Nokia was over a single layer, circular harvester with 2 cm diameter. This measurement used the same tire pressure and ground load but only ran for 10 to 40 km/h before cable failure. The results can be seen in Figure 4.2.



**Figure 4.2:** Voltage and energy for single layer 2 cm diameter circular harvester with 2 bar tire pressure and 200 kg ground load. Velocities change from 10 to 40 km/h, note the saturation levels for lower velocities and the failure when increasing to 50 km/h.

The saturated voltages for 10, 20, 30 and 40 km/h were  $\approx 7.1$ , 8.3, 9.1 and 10 V respectively. These were all above the required voltage to start the BOB power management circuit. However, the maximum energy was still below  $41.14 \mu\text{J}$ . So that size, speeds and loads could not power the Intuito. At the increase to 50 km/h a connection cable to the harvester snapped making it impossible to make further experiments for the circular harvester.

The third interesting measurement was running experiments with the BOB power management circuit connected. There it became clear how the harvester works and what parameters were needed for it to operate as desired. As long as the voltage input to the circuit exceeded  $\approx 5.43$  V the output from the circuit was 3.3 V according to its calibrations. It was also clear that as the speed increase, the frequency with which the piezoelectric harvester hits the ground increase which lessened the available time for a discharge. This meant that the voltage drop for the discharge from 3.3 V decreased and the voltage became more and more constant at 3.3 V. This data can be seen in Figure 4.3.



**Figure 4.3:** BOB voltage output for 10 to 70 km/h. Note the calibrated output 3.3 V and when the input voltage goes above threshold value 5.43 V. Also note the more and more constant voltage for higher speeds.

By running a measurement without the BOB harvester and looking at the circuit measured voltage the velocity when the generated voltage (which would be the input voltage to BOB) reaches above 5.43 V could be found. It was found that for 10 km/h the generated voltage leveled out at  $\approx 5.2$  V and for 20 km/h the generated voltage levels out at  $\approx 5.7$  V. It was clear that somewhere between 10 and 20 km/h was the minimum speed to generate enough voltage to drive the power management circuit if one used a  $2 \times 7$  cm<sup>2</sup> J harvester with 3 layers. It was also possible to power the BOB harvester with the 1 layer circular harvester at 10 km/h and above since their saturated voltage was 8.3 V.

By comparing simulation results for a single layer R harvester with an area of 1 cm<sup>2</sup> to a J 3 layer harvester where each layer has an area of  $2 \times 7$  cm<sup>2</sup> one could calculate the charge generated per second. At 20 km/h the charge rate for the R harvester was 1.65 nC/s and for the 3 layer J harvester it was 69.3 nC/s. Remembering that the total area of the 3 layer harvester was  $3 \cdot 2 \cdot 7 = 42$  cm<sup>2</sup>. This was of great interest since  $\frac{69.3}{1.65} = 42$ . Thus one could conclude that the charge rate nC/(s·cm<sup>2</sup>) was the same for both rectangular J and R harvesters independent of dimensions and number of layers. The overview of this can be seen in Table 4.1.

Geometry	Area [cm <sup>2</sup> ]	Sat. V	V/cm <sup>2</sup>	Charge rate nC/(s·cm <sup>2</sup> )
$2 \times 7$ cm <sup>2</sup> rectangle	42	5.7	0.136	1.65
1x1 cm <sup>2</sup> square	1	N/a	N/a	1.65
2 cm diam. circle	$\pi$	8.5	2.71	16.8

**Table 4.1:** Table comparing the available voltage and charge rate per area for 20 km/h. Note the identical values per area for the R and J harvesters with different geometries and layers. Also note the significantly higher available voltage per area for the circular harvester.

Table 4.1 also shows the saturated voltages for different geometries. The saturated voltage per  $\text{cm}^2$  was  $\approx 20$  times higher for the circular PVDF and the charge rate was  $\approx 10$  times higher for the circular PVDF. The same identical 470 nF capacitor was used in all three cases.

One of the final aims of the EU Project is to provide Nokian Tyres with the possibility of performing a measurement sequence once every 1.6 seconds. One could calculate the required sizes of those harvesters at 20 km/h. Since the required charge was  $11.25 \mu\text{C}$ , see Table 2.3, and there was data available for the charge per second per  $\text{cm}^2$  the equation became as follows:

$$A = \frac{11.25}{C_{Rate} \cdot t}. \quad (4.1)$$

Here  $A$  was the required area,  $C_{Rate}$  = charge rate given in Table 4.1 and  $t$  was the required time in seconds. Given Equation 4.1 one obtained the two required areas for rectangular or circular areas, at 20 km/h speed and only 200 kg car load as:

$$A_{Circ} = \frac{11.25}{0.0168 \cdot 1.6} \approx 420 \text{ cm}^2 \quad (4.2)$$

and

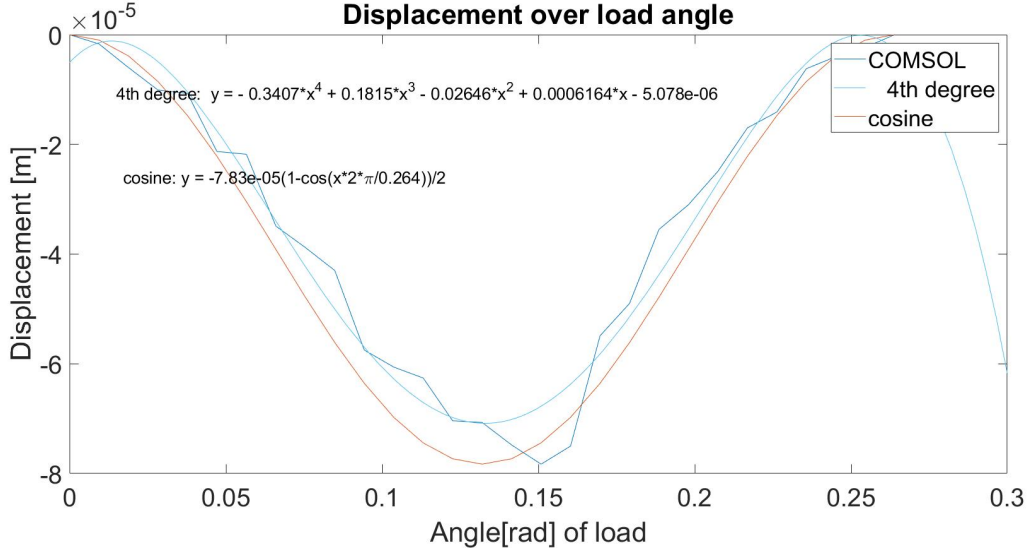
$$A_{Rect} = \frac{11.25}{0.00165 \cdot 1.6} \approx 4260 \text{ cm}^2. \quad (4.3)$$

If one approximated the available space to place a round harvester in the tire the diameter of the harvester could be at a maximum  $\approx 6$  cm. This meant that each layer would have an area of  $\pi 3^2 = 28.27 \text{ cm}^2$ . This would require  $\frac{420}{28.27} \approx 15$  layers.

## 4.2 COMSOL Multiphysics simulations

The initial simulations when there existed both a wheel and a physical, geometrical ground showed an extremely high solution time of  $> 5$  hours for low velocities  $< 0.5$  m/s. The contact between the tire and the ground was giving the system difficulties and gave a high degree of complexity.

When simulating using the chosen model one obtained the pressure and displacement over the plastic piece corresponding to the PVDF harvester. By collecting all the displacements as the load moved over the film one could get a graph over the total displacement. From this graph one could curve fit to obtain equations which described the displacement. Attempts were made to prescribe displacement of the plastic film using these equations but the attempts were unsuccessful. The graph and curve fits can be seen in Figure 4.4. Note that the plastic film angle was 0.132 radians and thus shorter than the load area.



**Figure 4.4:** Displacement graph and corresponding curve fits over the car load angle. Note that the plastic film angle is 0.132 radians and thus much shorter than the load angle.

As can be seen in Figure 4.4 the best curve fit was a 4th order polynomial:

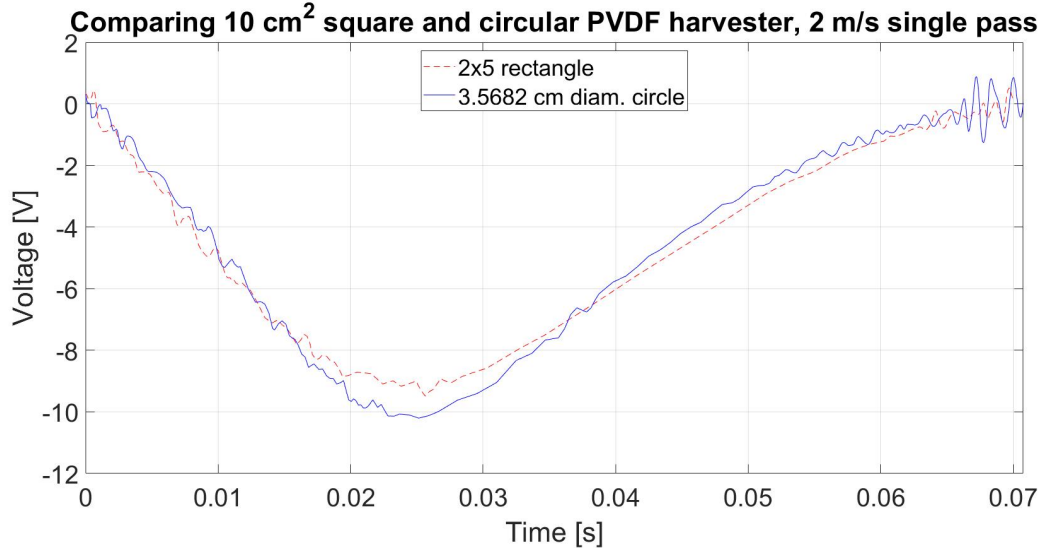
$$d = -0.3407 \cdot \Theta^4 + 0.1815 \cdot \Theta^3 - 0.02646 \cdot \Theta^2 + 0.0006164 \cdot \Theta - 5.078 \cdot 10^{-6} \quad (4.4)$$

and a cosine equation:

$$d = -7.83 \cdot 10^{-5} \frac{\cos\left(\frac{\Theta 2\pi}{0.264}\right)}{2} \quad (4.5)$$

Here  $d$  was the displacement in meters and  $\Theta$  was the angle in radians over which the load was applied. When using these equations back into COMSOL for the prescribed displacement one used either of these equations above here. However, both these equations took the angle within the load slice as input so the x- or z-coordinates had to be converted to that angle. Note that because the displacement was zero at the borders of the angle the continuity between the displaced or zero displaced areas was accounted for automatically.

When performing a simulation using the flat theory model at 2 m/s with 2 bar tire pressure and 200 kg ground load for round and rectangular PVDF models with the same area the resulting voltages can be seen in Figure 4.5. Note that the amplitude and shape was near identical for both geometries and any difference was very minor.

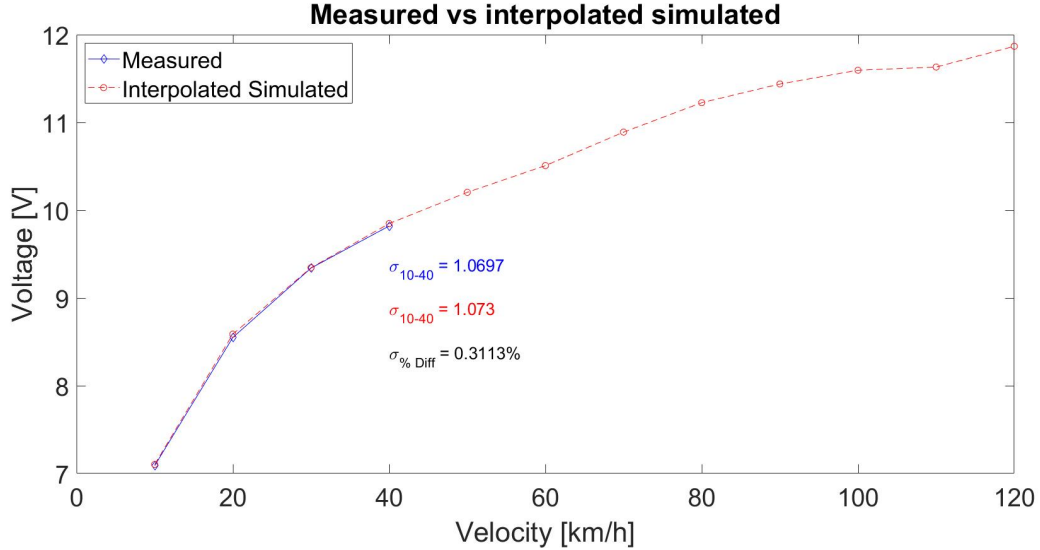


**Figure 4.5:** Voltage drop for 2 m/s pass over circular and rectangular PVDF in flat tire model.

By simulating at different loads it became clear that the output voltage given by **COMSOL Multiphysics** was scalable to the load over the surface. When the car load was increased from 200 to 500 kg the voltage output also increased with a factor 2.5.

By increasing the velocity with which the load was moved over the tire surface (increased driving speed) the generated voltage from the PVDF harvesters also increases. The increase is non-linear but rather follow a 2nd order equation up to a fixed value where it does not increase or decrease. This can be seen in Figure 4.10.

When performing simulations with the model harvester dimensions as close to the real life harvesters as possible there were significant differences in voltage amplitude between the simulation data and the measured data from Nokian. This was most likely due to the differences in geometry which exist and the chosen Young's modulus which symbolize many different materials combined into one. By utilizing the simulations and measurements for the same harvester geometry and velocities one could plot the factors between the two data sets. Then one could find an equation which described the factors between simulated and measured data as a function of the velocity. This function could be multiplied to the simulated data for a single layer, 2 cm diameter, circular harvester which shows how the measured voltage would be on a real tire. Results can be seen in Figure 4.6.



**Figure 4.6:** Graphs showing the Nokian measured voltage for 10-40 km/h and the simulated data multiplied with the factor equation for 10-120 km/h. Note the significantly similar standard deviations and how well the first 4 data points align.

In Figure 4.6 one can see graphs showing the Nokian measured voltage for 10-40 km/h and the simulated data multiplied with the factor equation for 10-120 km/h. Note how well the first 4 data points aligned and how the values started to converge towards a maximum value of approximately 12 V. That was when the velocity did not influence the voltage anymore. Also note how the standard deviations for the first 4 data points for the two data sets were extremely similar. There was a difference of just  $\approx 0.3\%$  which in practice meant that they were identical. Since the standard definition is a measurement of how far the average data point are away from the average of all data points a similar value for two data sets does not mean that they are exactly similar. However, by looking at the actual points in the graph one can see how similar they were there as well. Thus one can say without doubt that at least the first 4 data points were near identical.

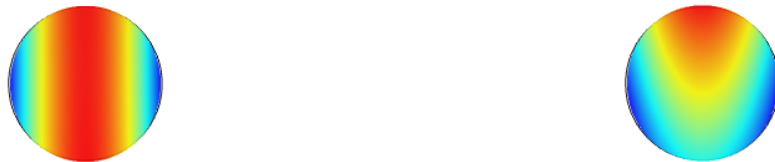
To try and simulated the active and passive zones by implementing the circuit in Figure 2.4 proved to be highly difficult. At the time of writing the **COMSOL Multiphysics** simulations could not solve with the attempted circuit implemented. This may show that the attempted circuit was wrong or that something more must be added for a successful integration into the model. Whatever the reason for the failed simulations it is clear that there is of now no known solution to account for the active and passive zones in **COMSOL Multiphysics**.

In the Methodology section 3 it was discussed how using several narrow strips to construct a PVDF harvester may be beneficial. The hope was that these strips will reduce the passive zone while maximizing the active zone of the harvesters. When using multiple strips as a harvester in **COMSOL Multiphysics** one could see a clear increase in voltage when using 5 mm wide double strips compared to 2 mm double strips. The values were almost 2 times as high. However one must also note that the voltages were significantly noisier for the wider strips. It was also found that at the

moment it was very difficult to analyze the effect of strips vs larger harvester since it was unknown how to include the passive and active zones in **COMSOL Multiphysics**.

To ensure the closest match between simulations and reality the polarization angle of the PVDF harvester was analyzed and altered according to mentioned in Section 3. When simulating using the angle polarized PVDF harvester the initial results were to determine the correct Young's modulus. This value turned out to be 0.19 GPa for 500 kg load and 0.028 for 200 kg load. With this value used, a parametric sweep over the velocity from 10 to 120 km/h showed a difference between the measured Nokian data and the simulated data. The simulated data reached the maximum voltage output for a lower velocity than the measured data. The simulated data also reached a lower final voltage than the measured data, even if the voltage for the lowest velocity matched up between the two data sets. Here one must note that for 0.028 GPa and higher velocities the model failed. Most likely this was because the tire became too pliant so higher velocities would result in displacement waves propagating through the rubber. So to match a 200 kg load for Nokian experiments the 500 kg simulations have been used.

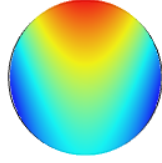
By observing the deformations over just the harvester in the circular tire model one could see the clear passing, movement and subsequent deformations of the harvester as the load moved over it. In Figures 4.7-4.9 one can see these displacements. The load moved from bottom to top as the harvester was placed in the text. A red color symbolized larger relative displacement and blue meant smaller relative displacement.



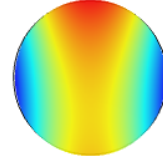
(a) Displacement over circular harvester before ground contact reach it.

(b) Ground contact has moved slightly as time moves forward and is now starting to deform the harvester.

**Figure 4.7:** First two harvester displacements due to ground contact.

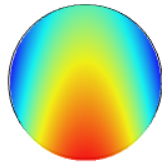


(a) Displacement over circular harvester before ground contact reach it.

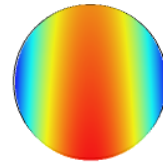


(b) Ground contact has moved slightly as time moves forward and is now starting to deform the harvester.

**Figure 4.8:** Second and third harvester displacements as load moves close and over the harvester.



(a) Displacement over circular harvester before ground contact reach it.



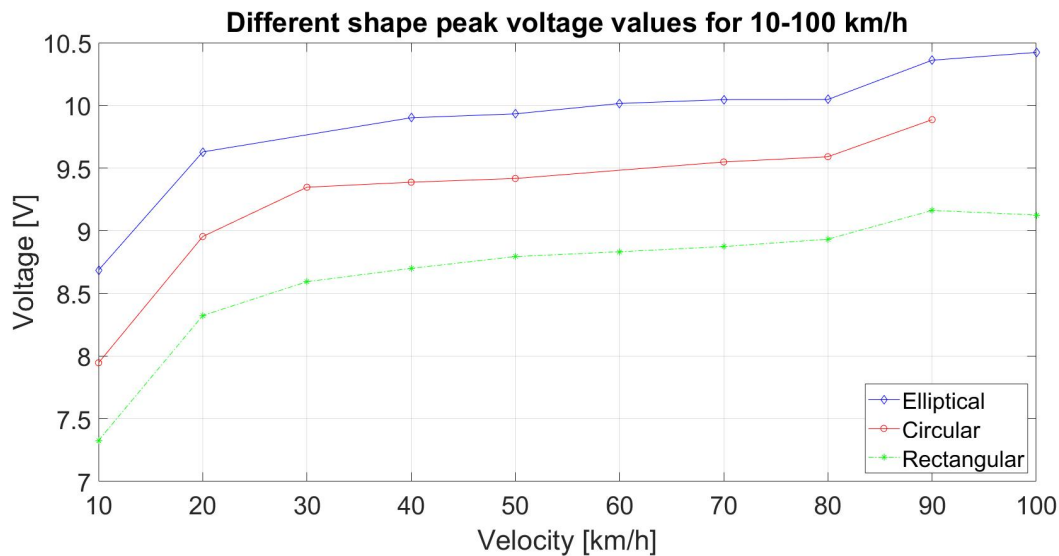
(b) Ground contact has moved slightly as time moves forward and is now starting to deform the harvester.

**Figure 4.9:** Final harvester displacements as the load pass out and away from the harvester.

Varying the resistance in the electrical circuit of the **COMSOL Multiphysics** showed significant differences between the different values, but not as expected. The higher the resistance value, the more the voltage curve was offset from the old 10 M $\Omega$  curve. The

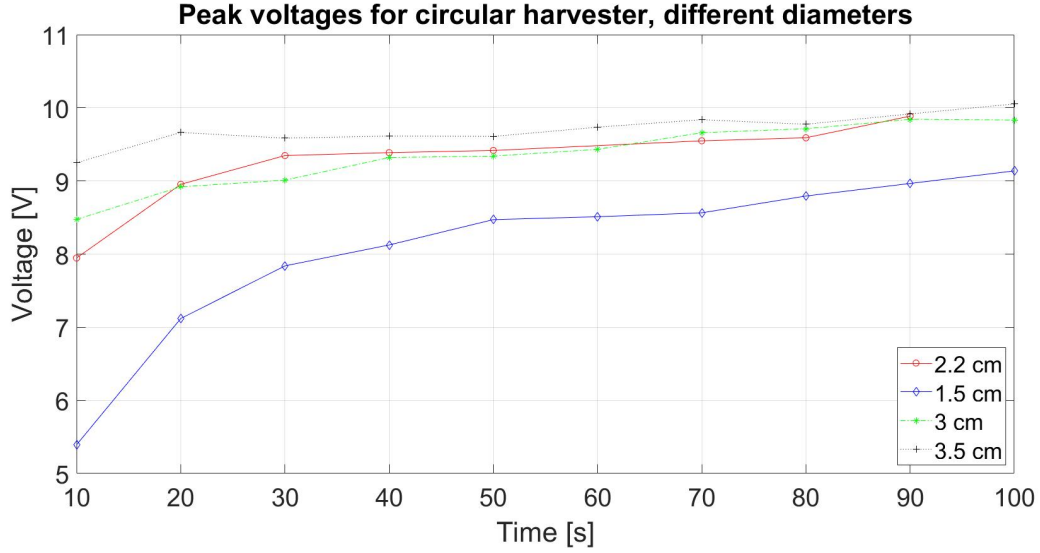
actual voltage drop in peak to peak value was independent of the resistance value. The value of the offset was significant compared to the actual voltage with the 100 M $\Omega$  offset being 0.7 V when the maximum drop for 10 M $\Omega$  was 0.5 V. An offset of 120 % of the maximum voltage drop made it necessary to adapt the resistance to the model while no difference in actual drop amplitude showed that the drop was independent of the resistance values.

Since different geometrical shapes were analyzed using real life experiments the same shapes were simulated in **COMSOL Multiphysics** as well. These simulations have been performed with the PVDF polarization described above since it showed the highest similarities to real life. They were also performed with the same harvester footprint areas and single layers. Thus the only variable changing was the geometric shape. The resulting voltages can be seen in Figure 4.10



**Figure 4.10:** Peak voltage values at different velocities for different geometrical shapes. It is clear that elliptical is the best option, next comes circular and lastly rectangular. Note that the total area of each shape is the same at 4.011 cm<sup>2</sup>.

A further variable discussed in the real life experiments was the area of the harvester. To investigate this circular harvesters were analyzed with different areas. Once again the PVDF was polarized as above and the only variable allowed to change between simulations were the areas. The resulting voltages can be seen in Figure 4.11.



**Figure 4.11:** Peak voltage values at different velocities for different circular harvester sizes.

A further measurement to extract from the harvesters was the electrical power which they can generate. Here a comparison was made from between the best (elliptical) and worst (rectangular) harvesters from the **COMSOL Multiphysics** simulations. Note that both simulations had the same resistance of  $10\text{ M}\Omega$  and, as described above, the only changing variable was the geometric shape. The electrical power for the different shapes can be seen in Table 4.2

Velocity [km/h]	Elliptical [ $\mu\text{W}$ ]	Rectangular [ $\mu\text{W}$ ]	% Rect. of Ellipt.
10	7.54	5.37	71.2
20	9.27	6.93	74.8
30	9.62	7.38	76.7
40	9.80	7.57	77.2
50	9.86	7.73	78.4
60	10.03	7.80	77.8
70	10.09	7.88	78.1
80	10.09	7.98	79.1
90	10.73	8.39	78.2
100	10.86	8.33	76.7

**Table 4.2:** Electrical power for elliptical and rectangular harvesters of same area ( $4.011\text{ cm}^2$ ) and load. Note the higher values for elliptical which also has higher voltages, Figure 4.10. Furthermore note the scale which is in  $\mu\text{W}$  and relatively low.

a

# 5

## Discussion

### 5.1 Experiments

#### 5.1.1 RISE experiments

There are a number of discussions to be stated about the RISE experiments. First and foremost one must remember that the stimulation of the tires has been performed by hand and without any constraint about movement or twisting. The degrees of freedom in the system is higher than for a tire fixed to a hub. This introduces a number of variables which affect the data and especially when comparing two different data sets. Attempts to keep stimulation as equal as possible for each new measurement was made but the human factor can not be overlooked here. As such all of these result should be seen more as indications than factual results.

At first the harvester dimensions aspect are examined by comparing output for the 1x5 cm<sup>2</sup> J-harvester against the 1x1 cm<sup>2</sup> J-harvester respectively. These comparisons indicate that there is a dependency. The most prominent difference between the two different sizes are significantly narrower voltage spikes for the smaller harvester. The second most prominent difference is the absence of spikes for the smaller harvester when the stimulation is less intense. This indicates that as the size of the harvester decrease it becomes more sensitive to the frequency and intensity of the simulations. It would seem as if a larger harvester is better for lower rolling frequencies which means that it could be useful for a slower driving car. In the same way one can note that the amplitude of the voltage (and power) is larger for the larger harvester but in the same order of magnitude for both sizes.

To determine the influence of the connected rectifier circuit one just compares the output voltages with and without the circuit connected. These comparisons show a difference in amplitude which indicate a loss of  $\approx 50\%$  when connecting the circuit. This is expected as more components will generate more losses to heat and in connections. Still, this needs to be taken into account when calculating how much energy is available. Furthermore one can see that the spikes narrow when passing through the rectifier which is most likely due to the rectifier having a threshold value at which point it starts to rectify and provide an output voltage. This would mean a straighter, vertical jump from 0 to that threshold value which would narrow the peaks by cutting off any volume present below the threshold value. For the R harvester another significant difference when adding the rectifier circuit is the absence of peaks at low intensity stimulation. This is most likely also due to the threshold value in the

rectifier. If that value is higher or approximately the same as the amplitude of the earlier spikes they will be zero.

As different connections between harvester and tire are examined one must remember that these are all simplified connections which would be perfected if this was to be put into production. For example, when the electric tape is wrapped around the harvester it is not done perfectly. There are overlapping zones and possibly too many layers of tape (could be enough with just one layer). When one says the best connection one should also include the available energy for each connection. As the results showed this can depend both on the type of load and on how frequently it is applied. In the end it is a combination of all parameters when determining the best connection but it is important to remember that if the harvester do not stay on the tire it does not matter how much energy that is available from it.

Comparisons between circular and rectangular experiments at RISE and later performed at Nokian both show the same characteristics albeit on slightly different orders of magnitude. For both set of experiments the circular harvester gave higher voltages than the rectangular but the percentile difference was smaller for the RISE experiments. The Nokian experiments were performed in a more controlled environment and using a wheel test rig, the RISE experiments were performed using hand power with significantly more uncontrolled variables. The fact that the overall characteristics are similar is gratifying but there is no surprise that there are changes in the relative difference between the two set of experiments. The test rig load is significantly higher and applied in a higher velocity than the hand applied load at RISE. These trivial differences makes them negligible in this analysis.

### 5.1.2 Nokian experiments

The result that a single layer, smaller, circular PVDF generates more energy and charge than a triple layer, larger rectangular PVDF is highly unexpected. Intuitively, more layers should generate more energy especially if they are in parallel connection. In the same way, a larger area should intuitively generate more energy since it is a larger area which can deform. And still, for all these intuitive thoughts the experiments demonstrate the opposite effect. The most likely explanation for these characteristics is that as a dynamic load moves over the rectangular PVDF an inner impedance is built up over the harvester. This is referred to as the active and passive zones. Since the width of the rectangular PVDF is constant there is no variation in this internal impedance and it can become difficult to add additional impedance and energy to the harvester. While for the circular harvester there is constantly changing width which makes the built up impedance vary which allows for more energy to be harvested.

Due to an unfortunate turnout of events there are no available measurements for a single layer  $J$   $2 \times 7$  cm<sup>2</sup> harvester to compare to the single layer 2 cm diameter from the Nokian experiments. Thus it is at the moment no possibility to analyze how a similar number of layers compare between different shapes and sizes. Since new measurements will be conducted in the future in RISE's time schedule this can be obtained for their progress in their project. Unfortunately these new measurements will not be conducted

until this Master Thesis Project is finished which means that they are unavailable for analysis and usage here. This may lead to some guesswork and potential errors in the analysis and conclusions.

When analyzing the BOB harvester results presented in Figure 4.3 it is rather clear what happens when the circuit becomes active, that is after the input voltage crosses 5.43 V. However, before this there is a charge up period which may appear strange. This is when the voltage comes closer and closer to 5.43 which means that the circuit attempts to start and output voltage. During this period the circuit does actually start and output some voltage. The voltage is not enough to power the circuit fully so the circuit also dies quickly which means a constant charge and discharge for values lower than 3.3 V. Before this section, in the 10 km/h region the output is even lower and here the input voltage is significantly lower than 5.43 V which means that the circuit tries to start and output some voltage but fails and shuts down directly. This region is of little to no interest other than to try and minimize it by reaching 5.43 V promptly.

Since it has been found that the R and J harvesters have the same available energy per  $\text{cm}^2$  it is trivial that either can be chosen as harvester. Bearing this in mind it is the most beneficial to use the R harvesters since they can be easily obtained from other RISE offices and are therefore cheaper and easier to modify. Modifications are desirable since it has also been proven that a circular geometric shape generates 20 times the available energy per  $\text{cm}^2$  compared to a rectangular one. Another interesting thought here is if it is possible to layer multiple round harvesters to multiply the generated energy as was shown in the case for rectangular harvesters. At this point in time there is nothing suggesting that this is not possible but it has not been tested experimentally. Since the multiplications were possible for rectangular harvesters and every other metric has proven to be scalable between rectangular and circular harvesters it is here assumed that this is possible in practice as well and should increase energy production. Since the available energy per  $\text{cm}^2$  is 10 times higher for the circular harvesters one may utilize much smaller harvesters to generate the same amount of energy. There are two extreme solutions here, either one determines the acceptable time at which one would like the circuit to start harvesting and then scale the harvester after that. This could possibly save some money since the harvesters may not need to be large. The second option is to maximize the harvester area in the available space in order to extract the maximum amount of energy for any given time. While this option will generate a lot of energy it is also the most expensive option. The majority of the production cost comes from the harvester area which is applied. In practice it is not impossible that the real life choice is to compensate by having as much harvesters as is allowed by the economy. Hopefully that economy corresponds to enough area for an acceptable charge time.

The calculated areas required to obtain the desired sensor rates may seem very high but one must remember three major caveats. The first is that this area can be distributed over multiple layers and if one can add several of those the contact area with the tire can significantly reduce. The second is connected to the velocity of the experiment. 20 km/h is a relatively low speed for cars. Special locations excluded the lowest maximum speed limit is often 30 km/h and this is in close proximity to houses on narrow streets. Often the speed limits are 50 or 70 km/h and on the freeway 110-120 km/h. The majority of driving will therefore most likely be performed at higher velocities and therefore more energy will

be available. The last caveat is the car load acting on the tire. As was previously discussed the load was set to 200 kg but a more realistic weight at a real life implementation would be closer to 500 kg. This would increase the deformations which would increase the generated energy as well. These required areas therefore seem promising for the future and show that a real life application is highly probable.

## 5.2 COMSOL Multiphysics Simulations

### 5.2.1 Model development

As attempts were made to roll the wheel over a fixed ground it was found that the complexity of the simulations was very high. Even at low speeds ( $< 0.5$  m/s) the computational time was very high ( $> 5$ h). This is slightly surprising as the geometry and connection is not overly complex and should have potential to connect. However, that is the situation at hand which dictated that a new type of load or movement of the load must be found.

By moving the load over a stationary tire instead of the tire over a stationary ground the computational time was decreased significantly to sub 30 minutes. There is no physical connection and disconnection between two solids in the new model. This is because the ground is modeled as an applied force over a moving area which reduce the complexity. One other major culprit when it comes to reducing calculation time was incorrect material properties. It was mentioned that incorrect properties made the system unsolvable but even in the cases where the system is solved the material properties can often be further optimized to give the best and fastest results.

When applying the curved corners on the plastic film piece one can compare it to Figure 3.1a which also shows a small, smooth corner rather than a sharp one. Efforts have been put into keeping these corners equal and in this case the use of the curved corner is deemed reasonable since it allows for the geometry around the plastic film to use a less complex mesh.

Some attempts were made to prescribed pressure or displacements over just PVDF films when the circular model failed to solve. It became apparent that the measured pressure from when the plastic film was placed on the circular model gave a nonphysical displacement of some hundreds of km. This is because that pressure is applied on a much stiffer system when the tire rubber is present. When only modeling the thin, plastic film that same pressure will escalate the displacements to absurdness. To prescribe the displacement also turned out to not work well since COMSOL had problems accepting an equation as displacement input. The result often just showed a constant displacement in part of the film. When the problems with the circular model were solved these simulation attempts were abandoned and it is the view of the author to not attempt these but use an entire wheel model. This may increase computational time but will give results comparable to reality.

The simulations performed on the flat tire model show that the two different voltages are near identical for circular and rectangular harvesters. From Nokian experiments it

has been clear that the circular PVDF give more energy/voltage per  $\text{cm}^2$ . This should give a higher voltage for circular PVDF harvesters for identical loads and areas but this is not what appears in the **COMSOL Multiphysics** simulations. These simulations instead show a near identical output which can be contributed to several different aspects. The first is that **COMSOL Multiphysics** doesn't include the real life physics with active and passive zones. The second is that this is the flat tire model. It is very likely that a curvature on the tire will influence the two different harvesters in different ways. The flat tire model was used as a step in analyzing the system and as soon as the curved tire model ran without errors the flat model was abandoned. These results should not be taken into account extensively but can be seen as partial results.

### 5.2.2 Model parameters analysis

Since the output voltage is scalable with the load amplitude over the harvester one can conclude several things about the mechanical properties of the system. Given Equations 2.3 and 2.5 the output voltage is theoretically linear towards the applied stress  $\sigma_{ij}$  which in turn is linear towards the displacement via Equation 2.17. Thus one can conclude that in theory the voltage is linear towards the displacement. This theory can now be confirmed by the simulations since an increase of stress (load) given a matching increase in voltage.

One might want to compare the displacements seen in Figure 4.4 and the voltage drops seen in Figure 4.5. The graphs are in general similar but they are not identical as one might could imagine. The most prominent difference is the shift of the minimum voltage towards an earlier time instead of when the middle of the load passes over the middle of the harvester. The theory here is that the minimum voltage actually occurs when the center of the load pass in the center over the harvester. The reason for the longer and slower voltage return after the peak value is the inertia in the tire. The compression goes fast but as the load has passed it takes longer to flex back to the original position of the tire.

If the characteristic of a maximum available voltage independent of speed is true then they are the subject for discussion. Instinctively it could be a negative thing if one could not generate more than a certain amount of energy but as long as the maximum energy or voltage is high enough to power any sensor or system for data handling this is acceptable. In most countries the maximum speed limit is  $\approx 120$  km/h so to have an increase of voltage up to that speed is a satisfying coincidence. One must remember that if the speed is increased further the voltage still remains high so one does not loose anything by increasing the velocity, one just don't gain significantly in terms of energy. The most optimal thing in fact would be if the maximum voltage was reached for a significantly lower speed so that for example everything above 30 km/h could power the system satisfactorily. Now, this is not realistic and it is highly unlikely to be able to design such a system. However it is possible by using multiply layers of harvesters to generate more energy for lower speeds as well.

Here it is once again a good idea to mention some of the difficulties found during the

measurements in Nokian. Unfortunately there is only one measurement with useful data for a circular harvester and that data is only true for 10-40 km/h. If there were data available for higher velocity measurements from Nokian one could trivially compare the data further and allow for a more accurate factor equation. As it is now one must keep in mind that the interpolated values in Figure 4.6 which may contain incorrect values. However, they appear to have reasonable values and those which one can compare show a high similarity so they are deemed reasonable in the grand scheme of things.

When looking at the results for the strip-based harvester implementation the expected results would be voltages fairly close to equally sized rectangular harvesters. It is reasonable that the resulting voltage is slightly lower because each strip will not provide their maximum output values at the same time but in slight succession. Instinctively it may seem like a negative to lessen the voltage but as mentioned before, the current is improved by parallel connections, so as long as the voltage is high enough it is not a negative to use parallel connection. In the case that the voltage does become too low one can just serial connect a few of the strips to bump up the voltage again. As shown in the Results section there is no implementation of active and passive zones which is what the strip-theory is based on.

By implementing the polarization of the piezoelectric element, as discussed in Section 3, one can note that the Young's modulus values which have been calculated for 200 and 500 kg are significantly lower than the previously used values. These values have been calculated with the goal of replicating the experimental values from Nokian. That does not mean that a higher value is incorrect when it comes to the overall characteristics of the harvester setup. The higher value will not replicate the experimental value but it may still indicate whether a harvester is better or worse than another harvester, or a velocity is better than another velocity. One must also take into account that for no polarization the **COMSOL Multiphysics** model could not handle small Young's modulus values without finding singularities. When simulating for different velocities it became clear that there is no perfect match between simulation and experimental data with the current iteration of our model. The lower final voltage is most likely due to simplifications in the model where velocity is less influential than it is in real life. There is a possibility that this depends on the way the load is applied on the wheel. If the actual wheel was rotated it would include more mobility and movement to the system which would for example push the tire outwards through centrifugal force. As the model is designed now the only motion is the load on the still wheel. If this is the case then the problem would be solved by implementing a moving wheel over a fixed ground. At the moment that is unrealistic due to the complexity and the computational time but one may consider this a possibility for future development of these **COMSOL Multiphysics** simulations. This could further increase the similarities between simulations and experiments.

Varying the resistance of the implemented circuit did not have the effect which was expected. The two things which needs to be discussed is the offset of the voltage and the unchanged amplitude of the voltage drop. Amplitude not varying with the resistance (in the scale of 10s M $\Omega$ ) means exactly as the results show, that at this amplitude of resistance there are no benefits or losses of varying the resistance. The most likely reason is that the electrical circuit doesn't actually run any current through the resistance before measuring the voltage. It has previously been stated that the

connector converts the voltage to a current which is inputted into the circuit. Since the connector and resistance are parallel connected the current will not pass through the resistance until it flows around down through the resistance and once again through the circuit loop.

It has already been stated from the real life experiments that there was a strong dependency on geometrical shapes. From the **COMSOL Multiphysics** simulations one can conclude that the dependency holds true for the simulations also. Elliptical appears to be the best shape before circular and finally rectangular or quadratic as seen in Figure 4.10. At the time of writing there are no elliptical harvesters available for real life experiments so one can only compare the circular vs rectangular for simulations and experiments. The overall characteristics that a circular harvester is better than a rectangular is the same for both simulated and experimental data but the difference is smaller for the simulated case. For experiments the difference was  $\approx 40\%$  and for the simulated case it was instead close to  $10\%$ . Any difference can most likely be attributed to the way **COMSOL Multiphysics** solves the problem and any faults therein, as discussed elsewhere.

With the geometrical dependency discussed one can also discuss the area dependency based on **COMSOL Multiphysics** simulations. The results seen in Figure 4.11 show that the area influences the resulting voltages. As the area increases, the voltage also increases, but not linearly. There comes an area where the increase in area is no longer reasonably matched by an increase in voltage, at which point it is no longer beneficial to increase the area. No longer beneficial is subject to discussion since an increase in area shows an increase of generated voltage at lower velocities. The maximum voltage for all velocities do not change but as the area of harvester increase the peak values become more and more equal independent of any velocity. This may be useful, especially in densely populated areas with lower speed limits. Intuitively there should be a constant increase of voltage as the area increase but apparently that is not the case. This may be attributed to the way **COMSOL Multiphysics** solution and methods to find that solution. Another explanation may be that as the area reach it's maximum value the internal impedance in the harvester reach a value which cannot be bridged by the generated energy. To obtain a full view of the problem and make a final analysis some real life experiments are needed for different sized circular harvesters. An order has been placed on this but they were sadly not delivered before the conclusion of this Thesis project. In the future RISE will be able to perform experiments with these new harvesters and so get a full picture of the size dependency.

If one compares the desired specifications from Table 2.3 to the simulated power values in Table 4.2 one can see a clear difference. The simulated power values show significantly lower values than the specs from Nokian which is unfortunate but in no way unexpected. The simulated values show a certain characteristic based on the chosen model and the chosen parameters for example of the inner resistance. Furthermore these values come from a certain harvester area and shapes which can be varied and increased.

As the measured and simulated data follow such similar characteristics it is a strong indicator that the simulation model and performances can be used to gain an idea over how a real life test would react. This is a gratifying discovery since it could be desirable to simulate experiments before performing them in real life to save both money and

time. These simulations may not show the exact same values as the experiments but will show the correct characteristics. This opens up for comparisons between different types of harvesters and different velocities.

# 6

## Conclusions

One of the most prominent and important conclusions for future development are the clear advantages with using a circular or possibly elliptical PVDF harvester instead of a rectangular one. The advantages are more available energy per  $\text{cm}^2$  and stress decrease in the harvester. Since this allows for a more energy-effective construction of a harvester there is also the possibility that this is more economical and trivially decrease weight in the tire since less material can be used compared to a rectangular harvester.

A further conclusion from the experimental data is that as the speed increases the output voltage also increases. However a higher speed also means a shorter peak (contact with ground) compared to a slower speed. Thus, the available energy in each rotation remains relatively unchanged with a slight increase for higher speeds. A higher speed does also mean an increased number of rotations per unit of time so the available energy per second increase as the speed increase. The conclusion from this becomes that it is energetically profitable to drive the car at a higher speed (up to a certain maximum velocity).

A conclusion which is crucial for any future research and simulations are regarding the **COMSOL Multiphysics** model. It is the experience of the author and supervisors that the model is sensitive for any major changes or that **COMSOL Multiphysics** is not optimized for a pushing and moving load over a piezoelectric film. Therefore the conclusion is to take the raw resulting data from the simulations as well founded indications. They can and should be used as indicators of results and characteristics but can as of now not be compared directly to experimental data. This may be solved with a more advanced model with more steps or components, for example by adding more complex circuits, the active vs passive zone characteristics and adding movement to the actual wheel.

The biggest conclusion from this thesis is that there is a bright future for piezoelectric energy harvesting, especially in tires. It is clear that enough energy can be obtained to power sensors and or transmitters. Furthermore the RISE research team now has further understanding about the different geometrical shapes and how each individual variable affect the output energy. By utilizing this knowledge and making the right choices for harvester geometry, harvester layers, speed, etc one can design a system which can generate, store and utilize enough energy to be useful. Implementations of piezoelectric elements in tires feel closer than ever and a large step on the way to a finished product has been taken.

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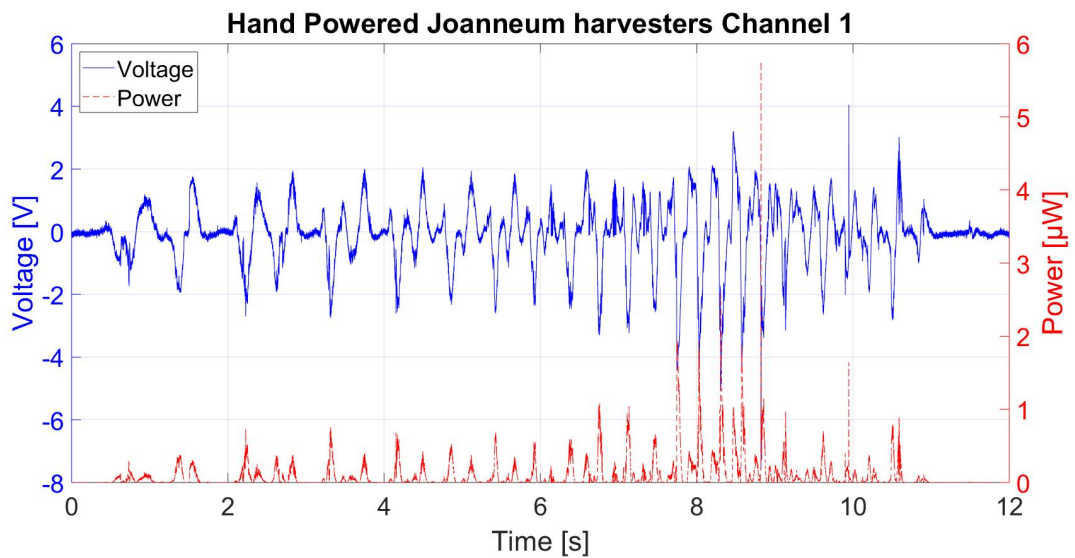
# A

## Appendix

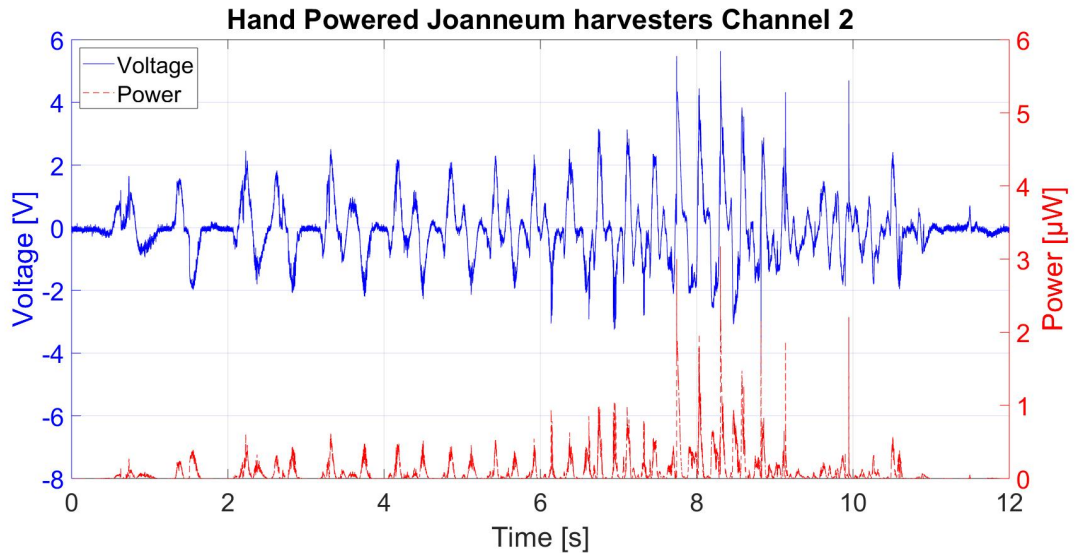
### A.1 Graphs

#### A.1.1 RISE experiments

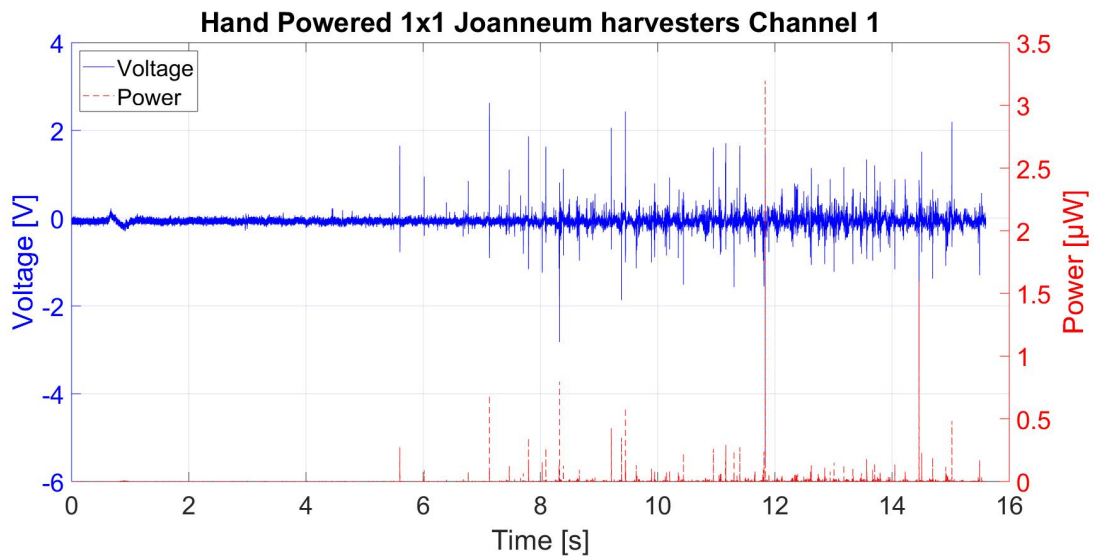
##### A.1.1.1 Piezoelectric experiments



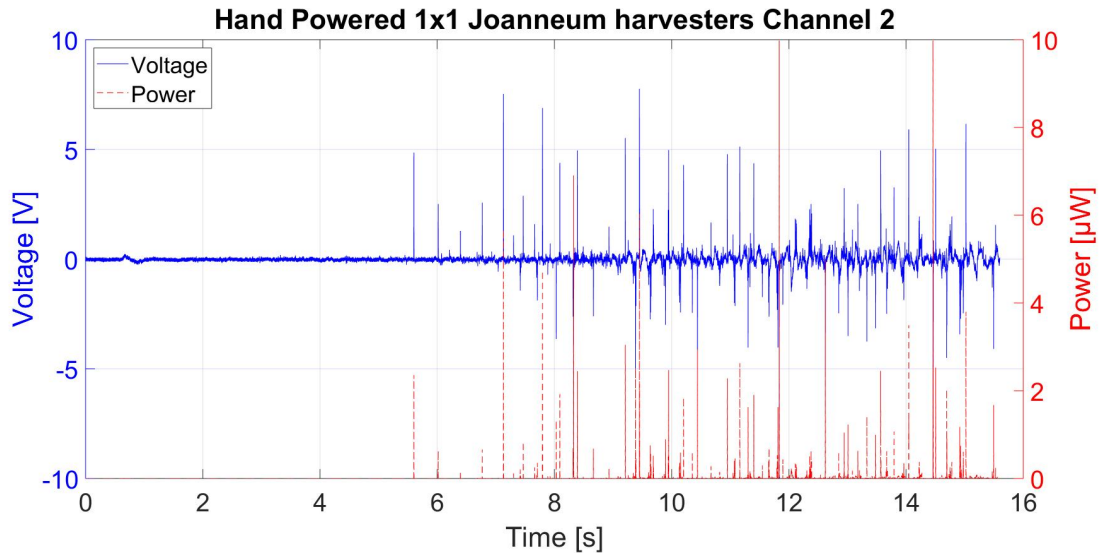
**Figure A.1:** Channel 1 Voltage and Power for the full Joanneum harvester without any circuit attached. Note the spike correspondence between Voltage and Power.



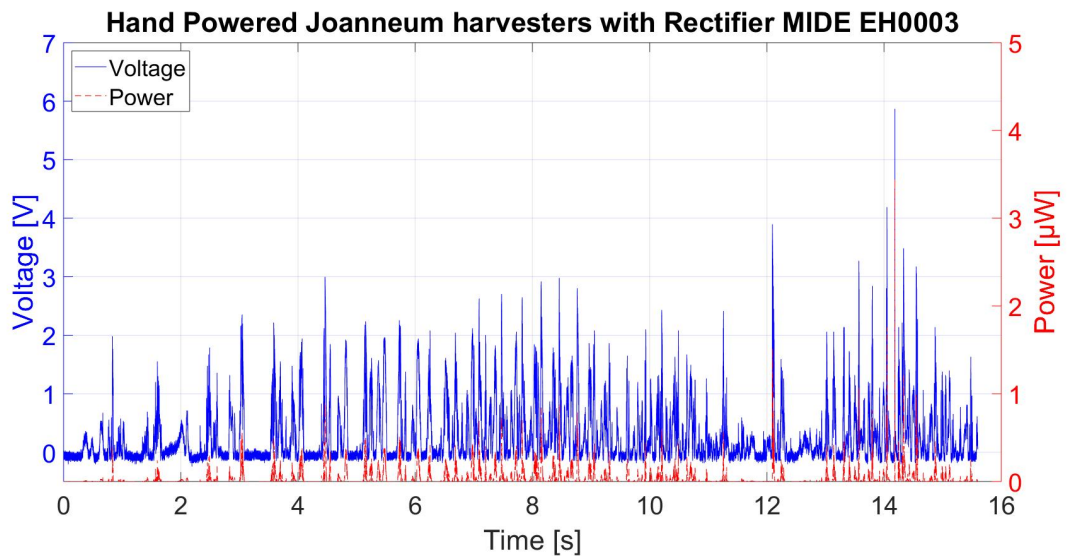
**Figure A.2:** Channel 2 Voltage and Power for the full Joanneum harvester without any circuit attached. Note the spike correspondence between Voltage and Power.



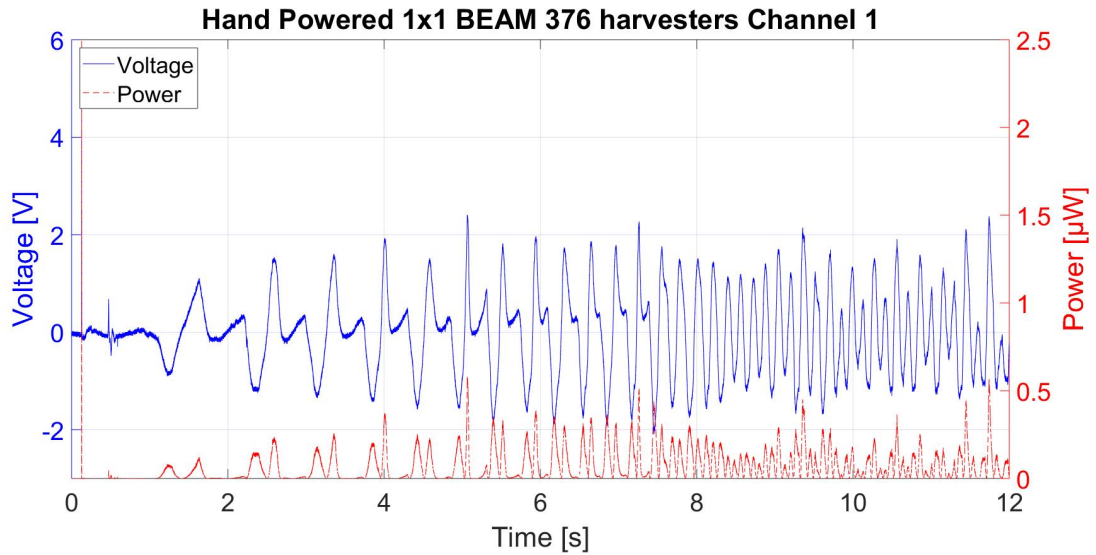
**Figure A.3:** Channel 1 Voltage and Power for the 1x1 cm<sup>2</sup> Joanneum harvester without any circuit attached. Note the spike correspondence between Voltage and Power and the slender spikes.



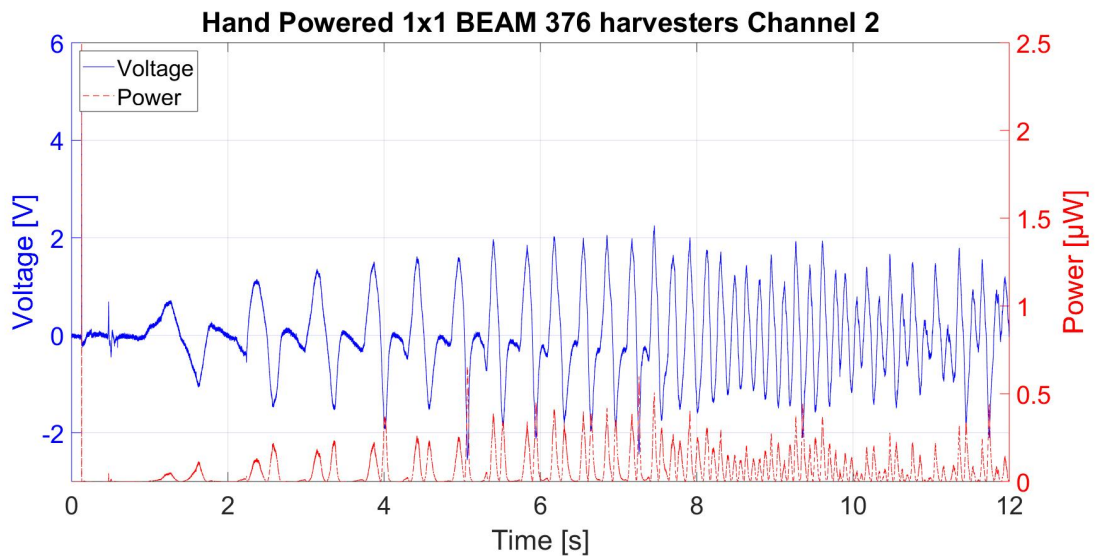
**Figure A.4:** Channel 2 Voltage and Power for the 1x1 cm<sup>2</sup> Joanneum harvester without any circuit attached. Note the spike correspondence between Voltage and Power and the slender spikes.



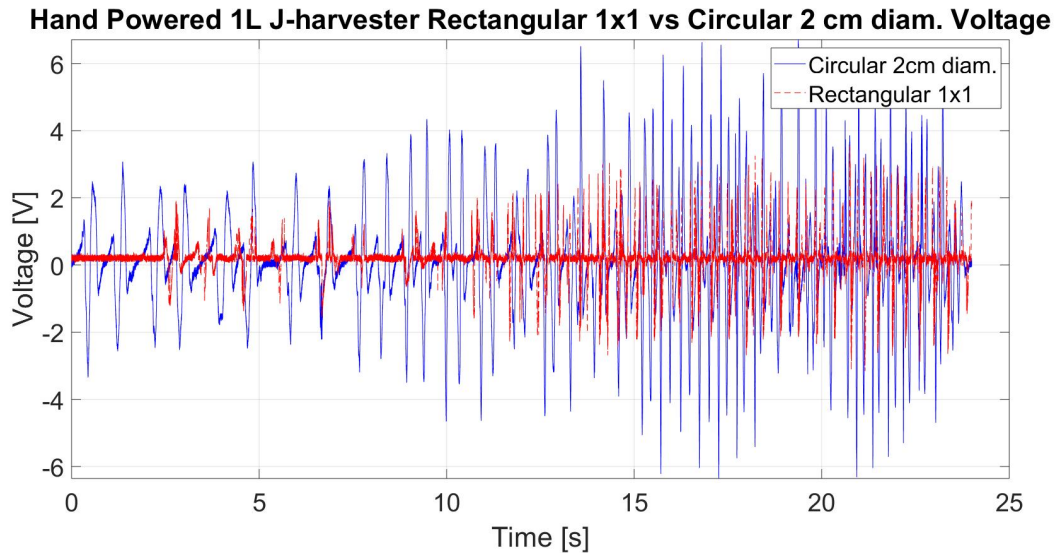
**Figure A.5:** Output Voltage and Power for the full Joanneum harvester with a rectifier circuit attached. Note the singularly positive values which indicate that the rectifier has done its job.



**Figure A.6:** Output Voltage and Power for the 1x1 BEAM 376 harvesters Channel 1 without a rectifier circuit. Note the relatively wide spikes.

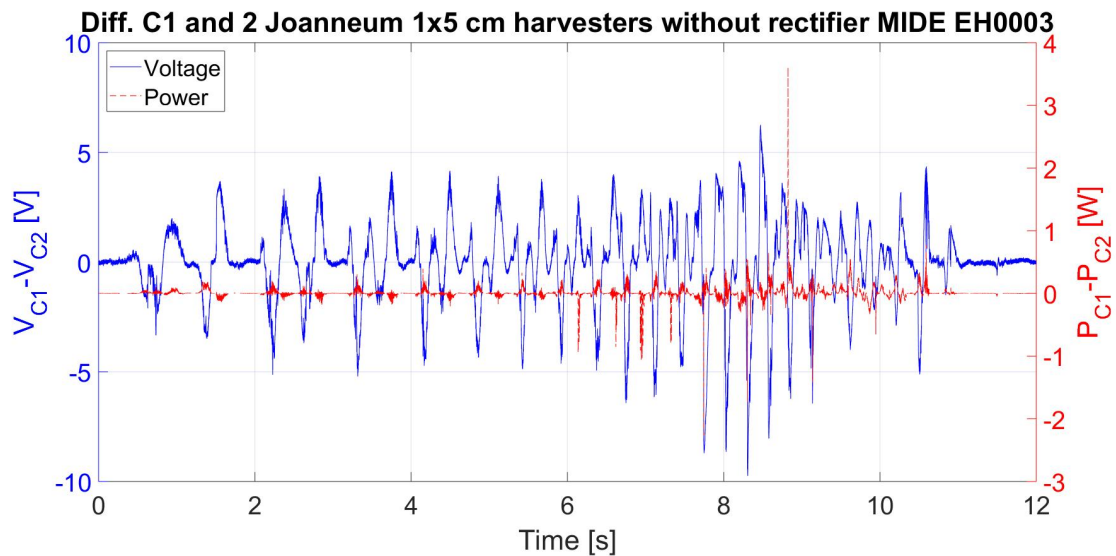


**Figure A.7:** Output Voltage and Power for the 1x1 BEAM 376 harvesters Channel 2 without a rectifier circuit. Note the relatively wide spikes.



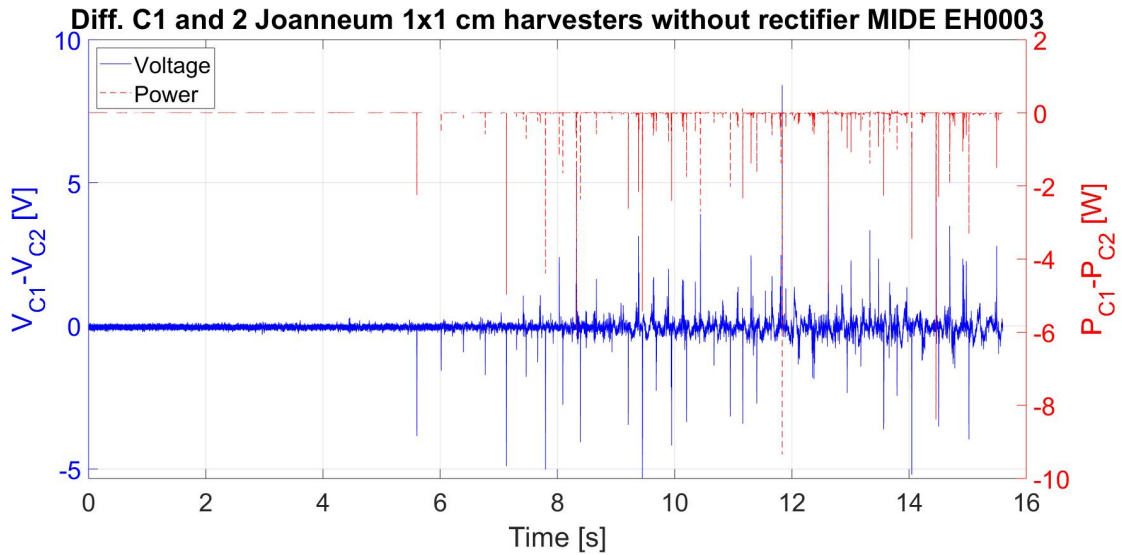
**Figure A.8:** Graph showing the voltages for a 2 cm diam. circular vs 1x1 cm rectangular PVDF harvesters. Note the significantly higher voltages and slightly wider spikes for the circular PVDF.

In Figure A.9 one can see the output Voltage and Power from the full 1x5 cm<sup>2</sup> harvester without any rectifier circuit connected. Note the periodic values representing the movement back and forth of the tire.

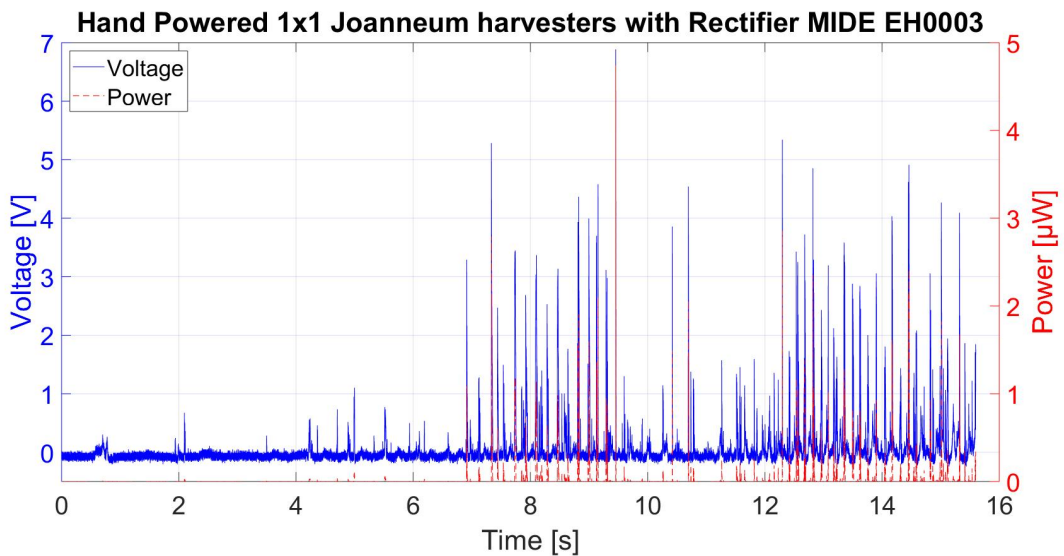


**Figure A.9:** Voltage and Power difference between Channel 1 and 2 for the 1x5 cm<sup>2</sup> Joanneum harvester without a rectifier circuit.

In Figure A.10 one can see the output Voltage and Power when the Joanneum harvester have been cut to an  $\approx 1 \times 1$  cm<sup>2</sup> area. This is still without an attached circuit.

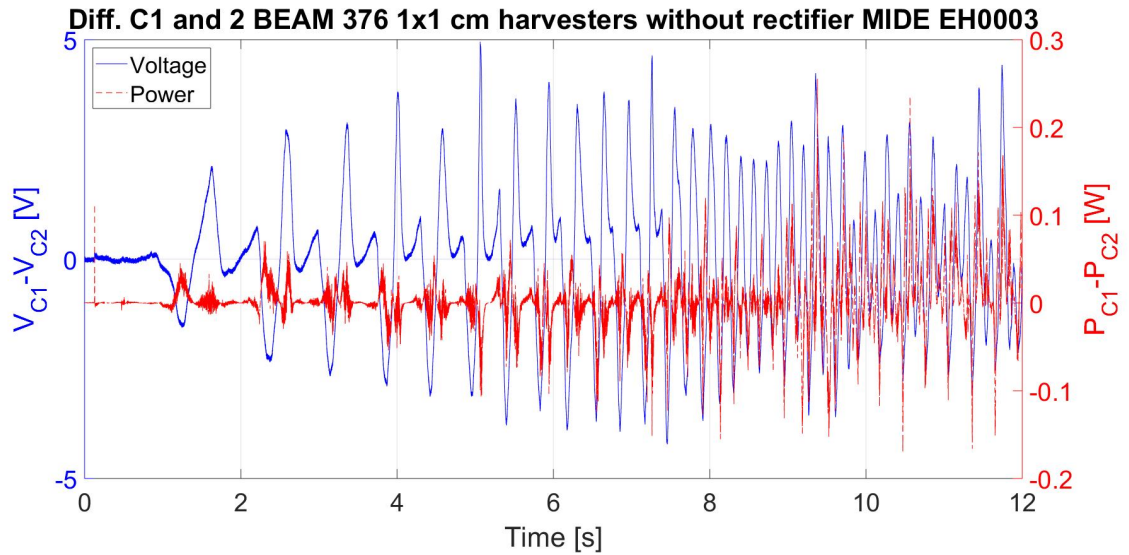


**Figure A.10:** Voltage and Power difference between Channel 1 and 2 for the  $1 \times 5 \text{ cm}^2$  Joanneum harvester without a rectifier circuit.



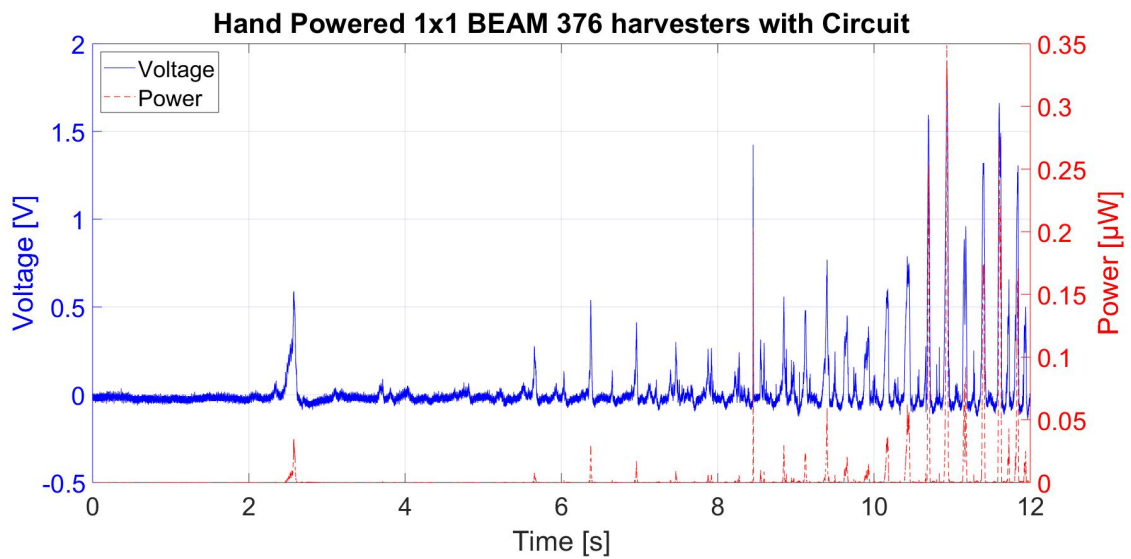
**Figure A.11:** Output Voltage and Power for the  $1 \times 1 \text{ cm}^2$  Joanneum harvester with a rectifier circuit attached. Note the singularly positive values which indicate that the rectifier has done its job. Also note the slender spikes.

In Figure A.12 one can see the output Voltage and Power for the BEAM 376 harvesters in the area of  $\approx 1 \times 1 \text{ cm}^2$ . This is without a connected rectifier circuit. Note the relatively wide spikes.



**Figure A.12:** Voltage and Power difference between Channel 1 and 2 for the 1x1 cm<sup>2</sup> BEAM 376 harvester without a rectifier circuit.

In Figure A.13 one can see the output Voltage and Power for the 1x1 BEAM 376 harvesters with a rectifier circuit. Note the relatively narrow spikes and only positive values.



**Figure A.13:** Output Voltage and Power for the 1x1 BEAM 376 harvesters with a rectifier circuit. Note the relatively narrow spikes and only positive values.

## A.1.2 Nokia experiments

### A.1.2.1 Piezoelectric experiments

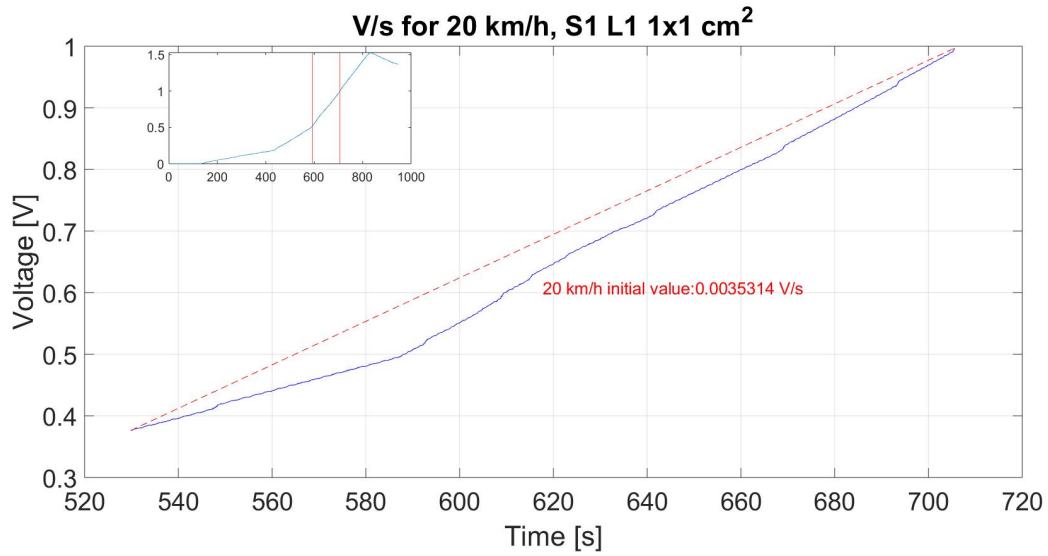


Figure A.14: Volts per second for rectangular harvester

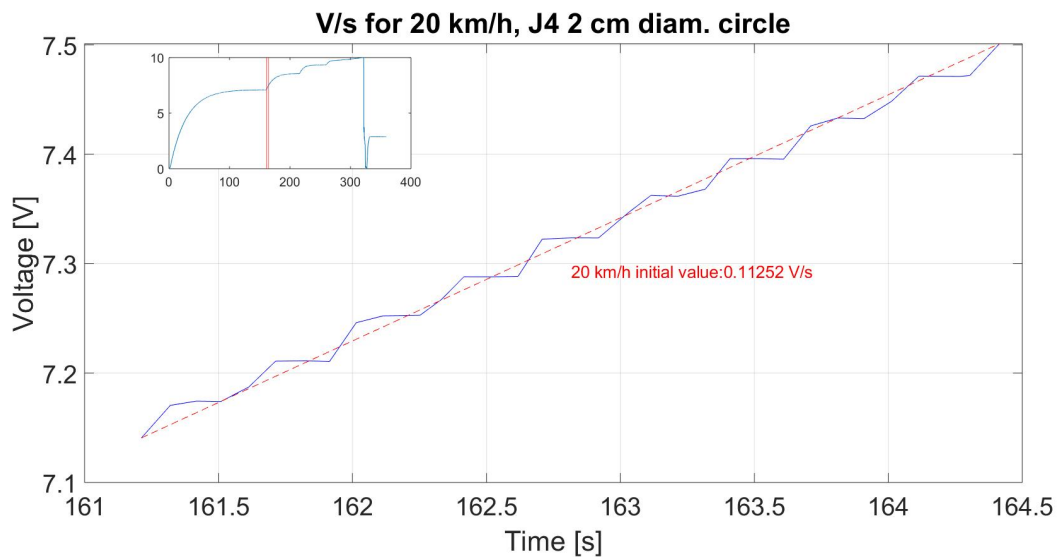
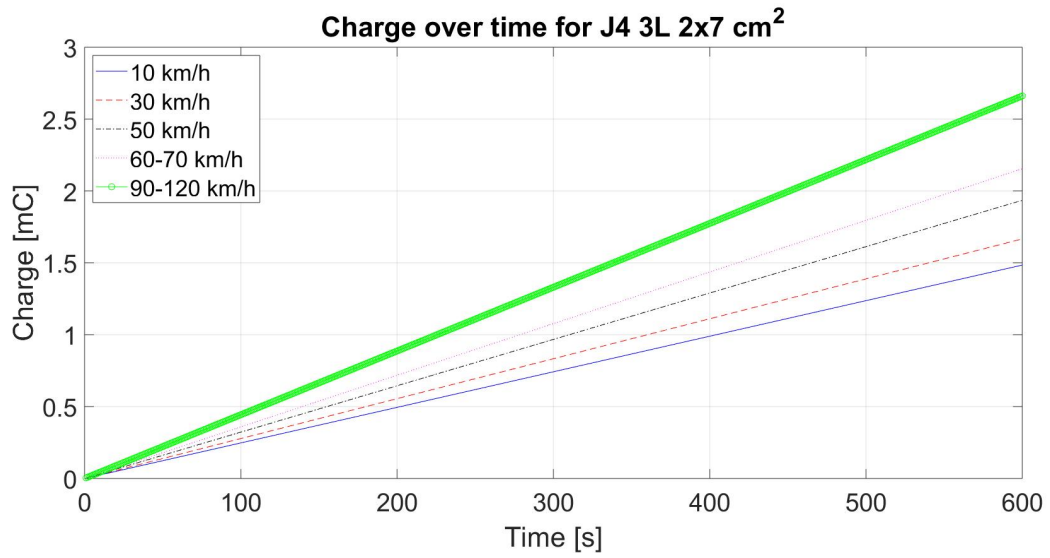
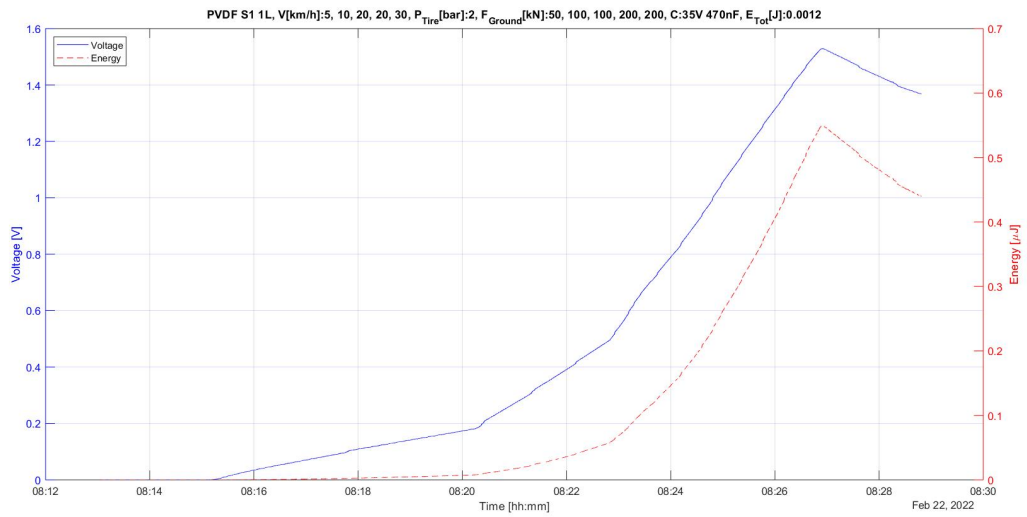


Figure A.15: Volts per second for 2 cm diameter circular harvester



**Figure A.16:** Charge rate for odd velocities for rectangular J harvester



**Figure A.17:** Measurement from first Nokian day

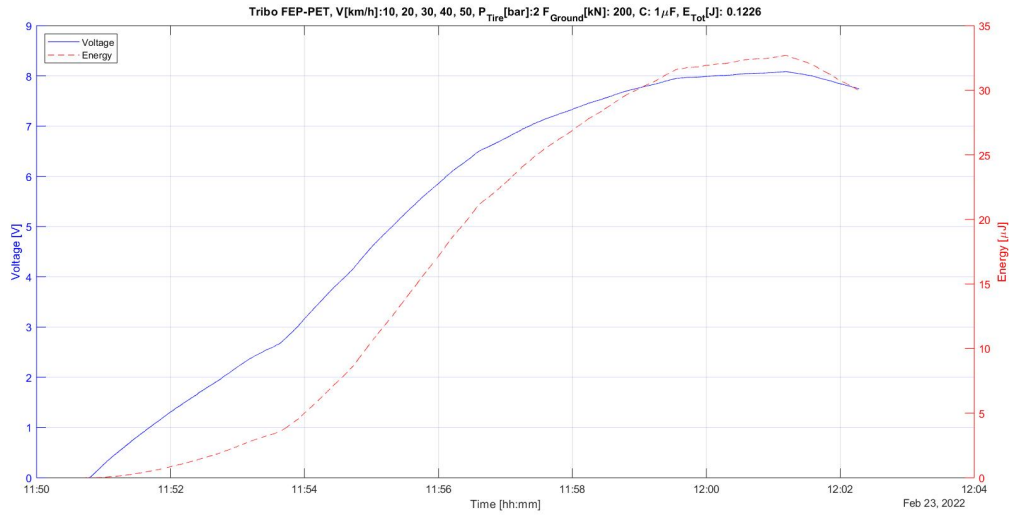


Figure A.18: Measurement from second Nokian test day

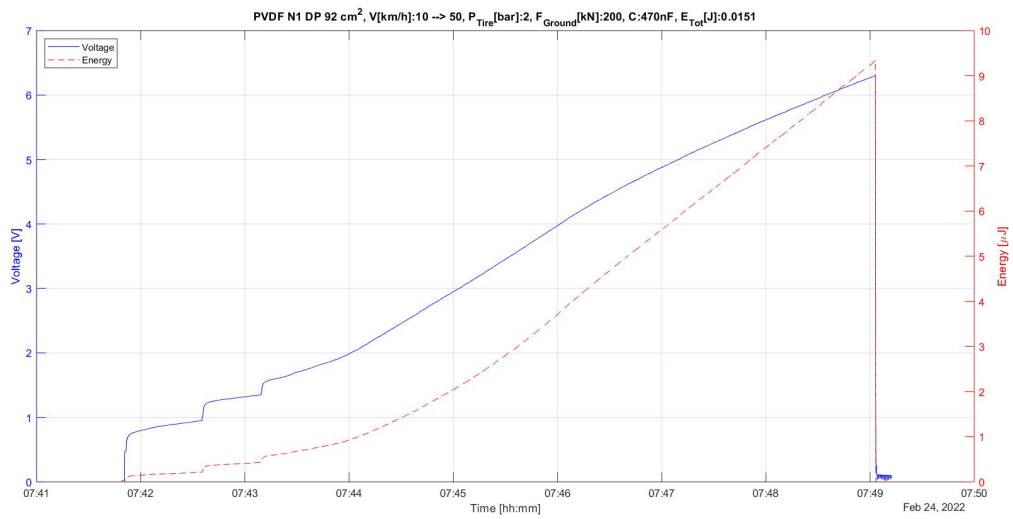


Figure A.19: Measurement from third Nokian test day