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Energy for IoT and Other Electrical Devices E4IoT

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Preface

This project was carried out at the University of Vaasa and the Vaasa University of Applied Sciences during the years 2020–2022. The project was founded by Pohjanmaan liitto and twelve Finnish industrial companies. The participating industrial companies were ABB Oy, Ensto Oy, Safegrid Oy, Sähkötukimuspooli, TJK Tietolaite Oy, UTU Oy, Vaasan Sähköverkko Oy, Vaisala Oy, Wapice Oy, Viimatech Digital Oy, Wärtsilä Oy. Essential part of this work, ”The study of the internet of things, IoT” was performed by Technology Centre MERINOVA.

The main aim of the project was to develop energy autonomous system level technology for clean energy harvesting, recovering, storing and utilization in sensors, sensor networks, condition monitoring, electronics, communication technologies, safety technology, IoT and Industrial IoT.

When energy harvesting is used, the equipment generates operating energy from dynamic phenomena in the environment, such as vibration, mechanical motion, temperature differences, electromagnetic field, RF signals and electrochemical phenomenon. This way, renewable and clean energy can be used to power sustainable electronic devices. A reliable self-powered device will remain functional virtually as long as ambient energy is available. Self-powered devices are perfectly suited for long term applications looking at decades of monitoring.

There are several advantages of energy harvesting:

- Clean and environmentally friendly energy for electrical devices
- Reduction in electrical wiring and the number of batteries
- Improved cost effectiveness, the maintenance work and costs reduced
- More reliable and safe of electronics, sensors and IoT devices
- Automatic long-term condition monitoring
- Measurements in places where the batteries or the electrical cables cannot be used

Five different energy harvesting platforms were developed in this project. The platforms were successfully tested in laboratory and field circumstances.

Capacitive method – Energy harvested from the electric field around the high and medium voltage power lines. Tested and functioning verified in the laboratory and field tests (TRL 5)

Inductive method – Energy harvested from the magnetic field around the low voltage power lines. Tested and functioning verified in the laboratory and field tests (TRL 5)

Thermoelectric method – Energy harvested from the temperature differences for instance on the surface of engines and electrical devices. Functioning verified in the laboratory and field tests (TRL 5).

Kinetic method – Energy from mechanical vibration and movement. Functioning verified in the laboratory tests (TRL 4).

Electrochemical method – Energy from mechanical vibration and movement. Functioning verified in the laboratory tests (TRL 4).

1 Introduction

The monitoring of systems and components, wireless communication, data processing and analytics, utilization of measurement and sensor technologies and automation are all increasing rapidly. A huge number of pieces of equipment will be connected to IoT or IIoT. When using traditional technology, a large amount of wiring and batteries are needed, increasing energy consumption and hazardous waste. However, the energy needed by sensors and electronics can be generated locally using energy harvesting technology. This radically reduces the wiring and the need to change batteries. The growth of harvesting technology is believed to be exponential. The main aim of the project is to develop and demonstrate generic solutions for energy harvesting and storage, which enable energy-autonomous industry applications. The Project will be carried out in close cooperation with industrial enterprises. Companies are expected to start their own R&D projects already during the course of the project. The secondary targets of the project are to increase the cooperation between companies and between companies and universities, and to develop the expertise and service capability of the universities in Vaasa (IoT Competence Center).

The project was carried out as a public joint effort of the University of Vaasa and the Vaasa University of Applied Sciences during 2020–2022. The results can be utilized by all companies. The expected concrete results of the project were the following:

- Generic prototypes of independently operating (no changeable batteries or wiring needed) electronic and IoT devices have been developed and demonstrated
- Several industrial enterprises have started to apply or have plans to apply the developed technology in their R&D projects
- New partnerships or cooperation between companies have emerged
- The expertise and service abilities of the universities in Vaasa have developed in the energy harvesting and IoT technology areas.

1.1 Structure of the project and work packages

The project consists of five different work packages, WP 1, Industrial needs and applications, WP 2, Energy sources, WP 3, Energy conversion modules, WP 4, Energy management electronics and WP 5, Generic demonstrations of energy harvesting systems. Figure 1.1

shows the work packages and the structure of the project. Figure 1.2 shows the ecosystem of the project. The ecosystem consists of the research platform, industrial companies, research laboratories and research cooperation.

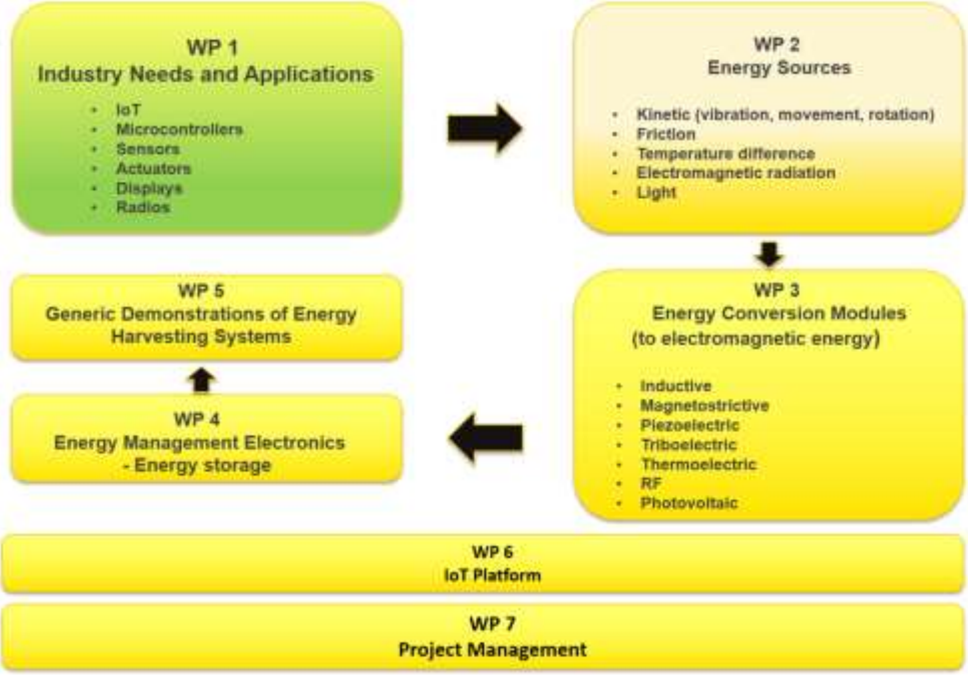


Figure 1.1 Structure and work packages of the E4IoT project.

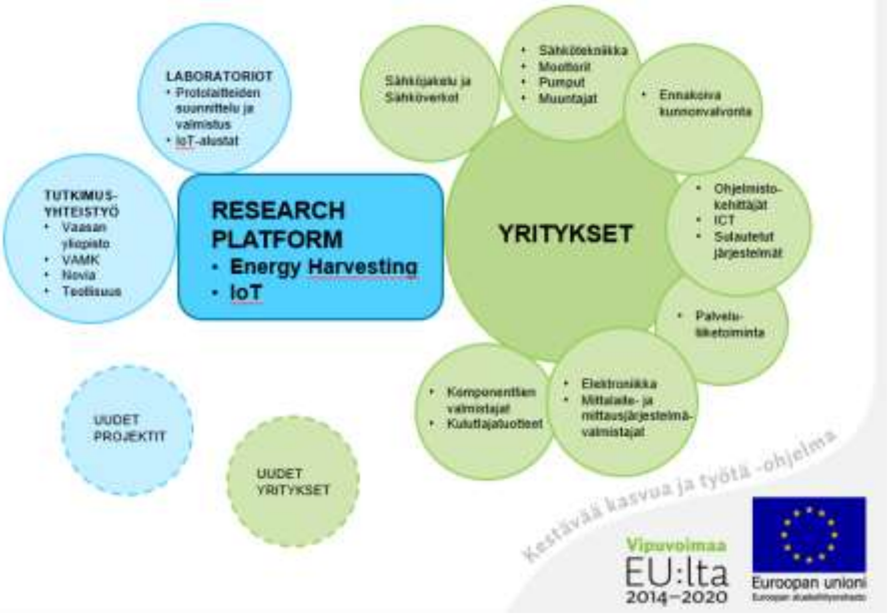


Figure 1.2 Ecosystem of the project.

1.2 Industry needs and application

The market research and mapping of industrial needs are based on telephone conversations with persons at the participating companies. Eleven companies and Sähkötutkimuspooli are participating in and funding this research project. Sähkötutkimuspooli consists of ten industrial parties. This project is also funded by the Regional Council of Ostrobothnia (Pohjanmaan liitto) and the University of Vaasa. The companies participating in this project are potential component producers and end users. They represent widely and with versatility the Finnish electrical, electronics and ICT industries as well as service and maintenance businesses. In the future, we also wish to encourage other industrial companies to join this development work. These industries will include machine, metal, mining, and transportation industrial companies, which are all very important for the Finnish economy. Most of the present companies are geared toward international business. The companies include medium and six large enterprises as well as small start-ups.

The companies represent widely different business sectors in Finland:

- ICT
- Electric distribution
- Electrical technology (engines, generators)
- IoT
- Electronics
- Manufacturing of measurement and analysis instruments
- Service and maintenance
- Manufacturing of industrial components
- Manufacturing of consumer products
- Embedded electrical systems
- Software development
- Design and planning of components and products

The most important requirement for the participating companies is the opportunity to obtain electrical energy from the surrounding environment without batteries and electrical cables (energy harvesting). This is because the monitoring of systems and components, wireless communication, data processing and analytics, utilization of measurement and sensor technologies and automation are all increasing rapidly. A huge number of pieces of equipment will be connected to the IoT or IIoT. When using traditional technology, a large amount of wiring and batteries are needed, increasing energy consumption and hazardous waste. However, the energy needed by sensors and electronics can be generated locally using energy harvesting technology. This radically reduces the wiring and the need to change batteries. The growth of harvesting technology is believed to be exponential.

The companies find it important to develop and demonstrate generic solutions for energy harvesting and storage which enable energy-autonomous industry applications. Cooperation between different companies and research organizations is also important for the companies. The developed energy harvesters and energy management systems should be cost-effective and capable of retrofitting and their energy consumption must be small. The developed devices should be commercially competitive. The following list presents the generic, general needs of industrial companies:

- No electrical cables and batteries
- Cost-effectiveness
- Reduction in maintenance costs
- Increased reliability of the electronics
- New generation solutions
- Opportunity for retrofitting
- Energy
- Size of the components
- Maximum power produced
- Automatic condition monitoring
- Environment monitoring
- Networking and new partners

- Cooperation between the University of Vaasa and the University of Applied Science of Vaasa
- Commercially competitive electronics
- Opportunity to participate in the work planning
- Increased understanding of harvester technologies
- Ready-to-use prototypes for testing in industrial environments
- Ideas for new technologies and operational models

Table 1.1 presents details of different technical needs and application environments. For the companies, the generic applications are condition monitoring, environment monitoring, powering measurement electronics, energy storage and transferring the collected data wirelessly to the IoT-platform. Important quantities to be measured include temperature, humidity, air pressure, vibration, acceleration, and magnetic and electric fields.

Table 1.1 Technical needs and applications.

- Condition monitoring of the electrical power network (low, medium, and high voltage)
- Measurement and condition monitoring of the distribution transformers
- Condition monitoring of electrical devices and electrical machines – engines, generators, pumps (temperature, vibration, and electrical quantities)
- Powering of field sensors
- Measurement and monitoring of the temperature of electrical instruments
- New remote monitoring solutions
    - measurement and monitoring of operational environments (temperature, humidity, wind)
- Sata analytics (data processing)
- Powering of measurement electronics
- Connecting the measurement electronics with IoT devices
- Prototypes of functional energy-autonomous energy harvesting systems include:
  energy harvesters + power management electronics + energy storage + measurement + IoT instrumentation
- Electrical quantities in electrical engines + temperature and vibration
- Humidity, wind
- Powering of IoT sensors
- Intelligent actuators
- Equipment inside electrical transformers
- Cost-effective, small and low-power data communication sensors
- Measurement of electric discharge
- 3-D acceleration sensors
- Development of reliable and energy-efficient electronics for the harvester modules
- Development of energy storage solutions for the harvester
- New environmental technology
- Following the development of energy harvesting technologies

2 Capacitive energy harvesting from the high-voltage line

With the capacitive harvester, it is possible to obtain energy from high-voltage power lines. Figure 2.1 presents the 110 kV power line. The capacitive energy harvesting platform developed in this project is shown in Figure 2.2. The main components of the harvester include a harvesting module, electronics, energy storage, a measuring and data transfer IoT unit and a data receiver. This platform is based on harvesting energy from the electric field around a high-voltage power line. The harvester is on the low-potential side of the line.

Figure 2.1 High voltage power line.

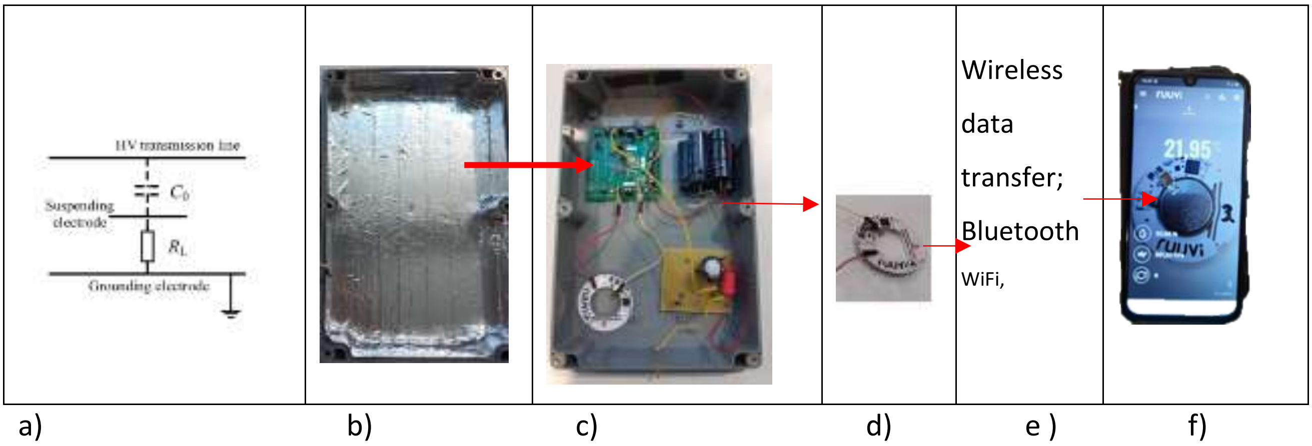


Figure 2.2 Capacitive energy harvesting platform, a) low potential coupling of the harvester, b) harvesting electrode, c) energy management electronics, d) measurement and data transfer unit (RuuviTag), e) wireless data transfer (Bluetooth), f) data receiver (cell phone).

Figure 2.3 shows the distribution of the electric field strength around a high-voltage power line. Energy can be harvested from this electric field basically using four different types of harvesting modules. Schematic pictures of these modules are shown in Figure 2.4. These include: a) direct-mode harvester, b) low-potential harvester and c) high-potential harvester. There was also the option of a two-plate harvester, shown in Figure 2.5.

Basically, the harvester consists of one or two harvester plates. The plates create a capacitor that is charged in the electric field. In the high-potential model, the harvester plate is in contact with the power line, and in the low-potential harvester, the harvester plate is not in contact with the power line. The harvester developed in this project is based on the low-potential model.

Figure 2.5 shows a complete concept of a two-plate harvester module between a ground and a conductor. Energy is collected from the electric field by placing two capacitor plates close to each other. The plates create a capacitor that is charged in the electric field. The plate that is closer to the conductor is charged positively, and the other plate will be negative. The plates are short-circuited with the conductor, and between the plates is the capacitance C_2. The capacitance C_2 depends on the voltage difference and distance between these two plates. The capacitance C_3 is the capacitance from the lower level plate to the ground. C_3 depends on the voltage difference between the lower plate and the ground and the height of the lower plate from the ground.

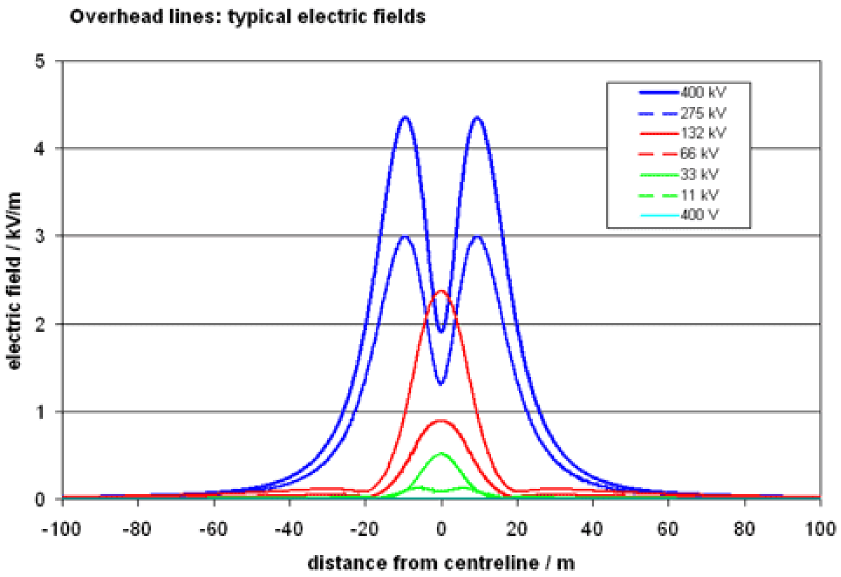


Figure 2.3 Typical electric field distribution under a high voltage power line (2).

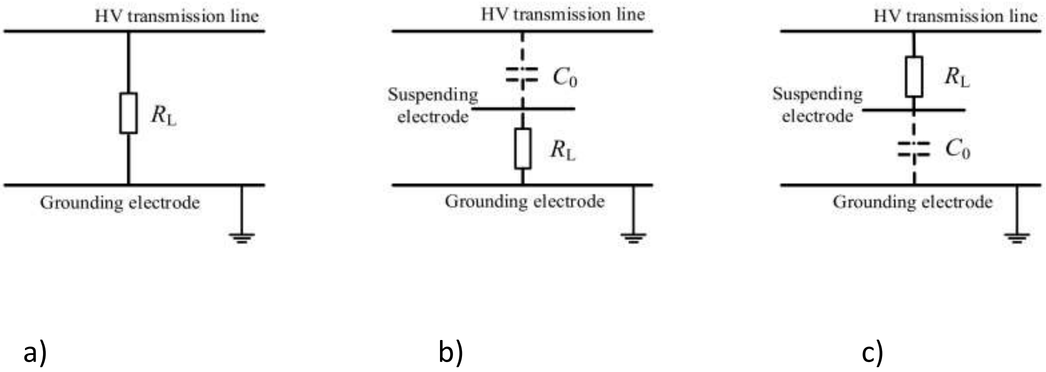


Figure 2.4 Schematic diagram of energy harvesting modules under electrostatic field; (a) direct mode, (b) low potential, (c) high potential (4).

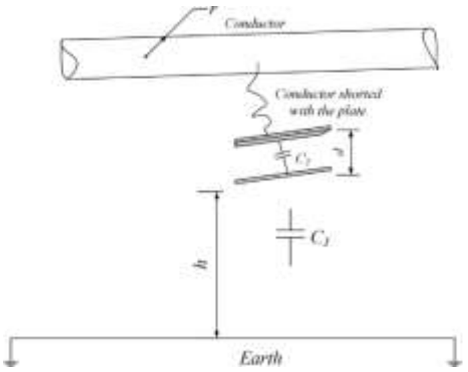


Figure. 2.5 Parallel plate harvester: two plates are placed near each other between the conductor and the earth, which is grounded. (5)

Several variables can affect the harvested power in capacitive harvesters. For example, in the parallel-plate harvester, shown in Figure 2.5, the effect of the plate separation, plate size, displacement current, and the voltage across the plates in relation to the potential harvested power was theoretically analyzed. These results are presented in Tables 2.1 and 2.2.

As presented in Table 2.1, the higher the plate separation is, the higher the power that is obtained (95.2 mW). Moreover, the larger the plate surface is, the higher the power that is obtained, as presented in Table 2.2.

Table 2.1 Theoretical effect of the separation of the electrode plates, displacement current, voltage across the plates and harvested power in a two-plate harvester. (5)

Plate separation d (cm)	Displacement current (μA)	Voltage across the plates (kV)	Harvested power (mW)
1	52.7	7.02	29.5
3	47	18.77	70.2
5	42.4	28.22	95.2

Table 2.2 Theoretical effect of the size of the electrode plates, displacement current, voltage across the plates and harvested power in the parallel plate harvester. (5)

Plate size (cm)	Displacement current (µA)	Voltage across the plates (kV)	Harvested power (mW)
3	7.1	23.7	13.5
5	13.7	16.4	17.9
7	20.8	12.7	21.1

2.1 Capacitive energy harvesting electronics

The power management electronics are based on the Texas Instruments evaluation board PQ25504. This was connected to the harvester electronics developed in the Technobothnia laboratory. Three different versions of a capacitive energy harvester were developed. Each version utilizes a different design and components to convert ambient energy into usable electrical power. These designs were created through research, experimentation, fixing errors and changing components. After two versions, it was possible to construct a multi harvester which includes the possibility to use, for example, capacitive, thermoelectric, electrochemical, inductive or kinetic energy.

Figure 2.1.1 presents the capacitive energy harvester platform. The RuuviTag was used as an IoT device. This IoT device measures, for example, temperature, humidity, air pressure and acceleration and sends the measurement result via wireless Bluetooth data transfer to the data receiver. The data receiver can be, for example, a mobile phone.

Later a voltage regulator was added to the electronics to increase the output voltage from 5 V to 12 V. This solution requests a delay circuit that gives time for the capacitors in the voltage regulator to increase before the output activates. Otherwise, the output device might take all the available energy before the voltage reaches 12 V.

Harvester module | Harvesting circuit | TI evaluation circuit | Energy storage | IoT device RuuviTag | Data receiver

a) **b)** **c)** **d)** **e)** **f)**

Figure 2.1.1 The capacitive energy harvester platform. a) Capacitive energy harvester module. b) capacitive energy harvester electronics. c) Energy management circuit for all the harvesters. d) Energy storage, capacitor. e) RuuviTag as an IoT device. f) Data receiver, for example, a mobile phone, as here.

Version one capacitive energy harvester

The Version one capacitive energy harvester circuit made for the proof-of-concept idea for this circuit is originally from an old patent. The patent is over 20 years old, and its basic idea is still interesting. Because the patent did not show any measurement or test results, there was no true information on how much energy could be harvested, if this even could harvest energy. Version one was only tested with some new components and it was estimated how much energy it could harvest.

The first version was made in the laboratory on FR4 board material. The patent's component list was not perfect; some old components were no longer being produced, so slightly different components were used. Version one was not planned in the most optimal way. Some Cu paths were unnecessarily long, and some component pads were the wrong size. These are not optimal, and there might be some current losses.

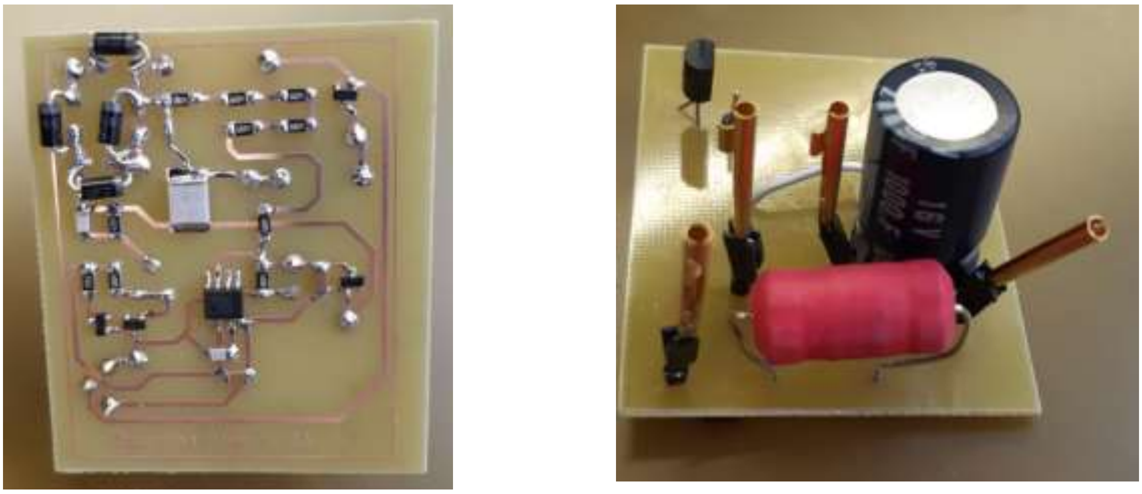
The tests with the Version one capacitive harvester were run in the Technobothnia high voltage laboratory. The test arrangement was not comparable with the other tests. But these tests can give us a hint about how a harvester works. The high-voltage power line was connected to the harvester, and a suspended electrode was very close to the grounding point. Without a load on the circuit and when the high voltage was 5 kV, the output voltage was 1.5 V. When the high voltage was 5 kV, and an 8 kΩ load was connected, the output power was 1.1 mW.

a) **b)**

Figure 2.1.2 Version one of the capacitive energy harvester electronic board. a) electronic and trace side. b) big components and pins.

The Version two capacitive harvester is shown in Figure 2.1.3. Components for this harvester were more optimized based on research and what was available from electronics stores. This version of the capacitive harvester was more carefully designed, so current losses via Cu paths were hopefully decreased. In addition, the shorter Cu paths make this harvester circuit much more efficient than the Version one capacitive energy harvester.

Compared to the proof of concept Version one, Version two was planned to be a test circuit. Because of this, separate connectors were added to the circuit to help perform the measurements of the device's functioning. This was also the first harvester to be connected to the energy management circuit. This new connection would allow it to collect more energy and store it.

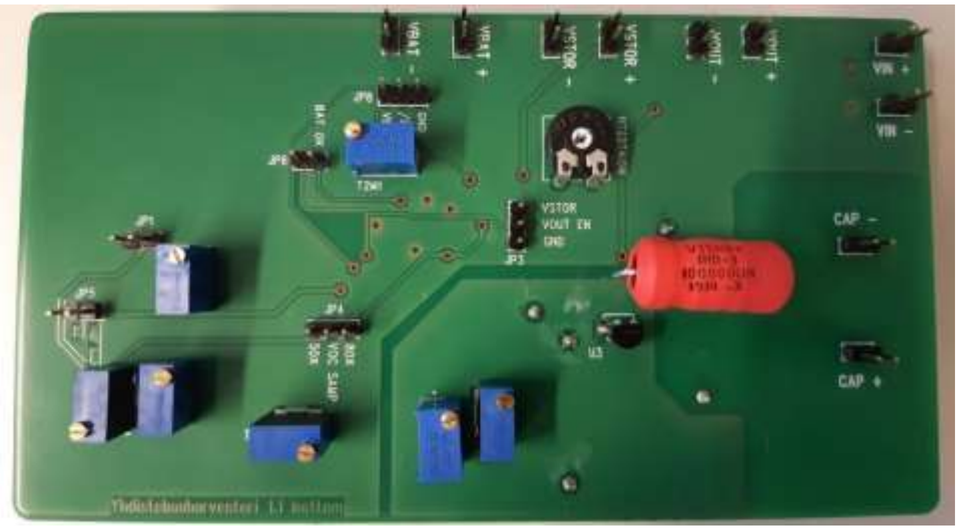


a) b)

Figure 2.1.3 Capacitive harvester electronics, a) Version two of the capacitive harvester with components and copper traces, b) Capacitive harvester from the other side with larger components and pins.

Version three of the capacitive harvester is shown in Figure 2.1.4. The energy harvesting circuit and energy management were added to the same PCB. Some of the resistors were changed to potentiometers so it was possible to tune the value of the resistors to optimize the functioning of the electronic circuit. In this way, it is possible to adjust how the harvesting circuit works, which affects how fast it recharges the energy storage capacitor or the battery. The voltage required to start up the electronics is 3.7 V. Also, with these tunable resistors, it is possible to select different types of energy harvesting modules to connect with the power management electronics.

The energy management circuit can also be optimized to determine how high the energy storage voltage rises and how low it can decrease before the power supply cuts out the power. With these adjustments, it is possible to optimize the circuit to work with different kinds of devices that are using power.



a)

b)

Figure 2.1.4 Version three of the capacitive harvester circuit and energy management circuit in the same PCB. a) Bottom side with pins and potentiometers. Blue boxes are potentiometers. b) Top side with small components and capacitive harvester circuit capacitor.

During some tests with Version three of the capacitive harvester, shown in Figure 2.1.4, some unwanted (EMI) electromagnetic interferences were noticed, and the harvester was not working properly. After a couple of tests, it turned out that the problem was related to the potentiometer resistors taking disturbance from the high-voltage power line. This disruption made these boards work a little bit erratically. Usually, the energy storage voltage did not increase to as high as it should. After the energy management circuit started to power the device, the voltage was too low, and there was not enough energy to start the IoT device.

Because of this, electromagnetic interference shielding was used. The first option covered some parts only with aluminum tape placed over these potentiometers. This is shown in Figure 2.1.5. It worked, but there was concern that the tape would accidentally cause a circuit shortage. A better solution was a 3D-printed case which was surrounded by aluminum tape. The tape was also grounded to the circuit, so the disruptions dropped almost to zero. This interference suppressor with the aluminum tape is shown in Figure 2.1.5.

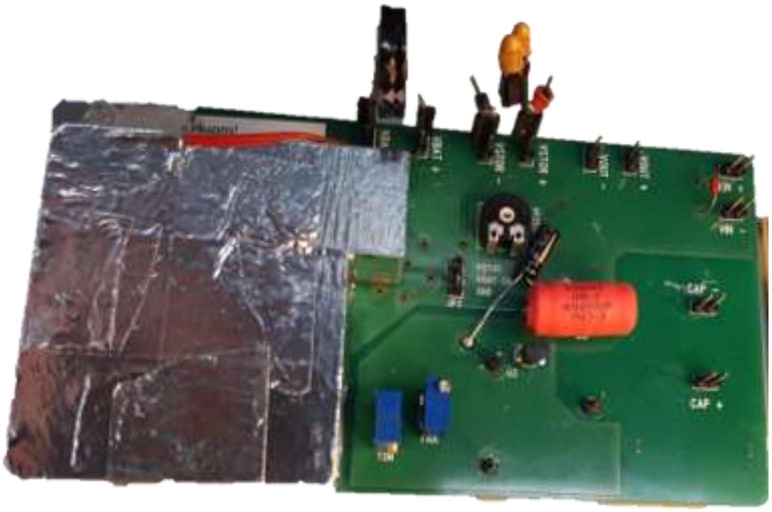


Figure 2.1.5 Energy harvester electronic and voltage regulator with EMI shielding.

Some more advanced IoT devices use a higher voltage than a regular energy management circuit can give. For this reason, a voltage regulator was added to increase the voltage from 5 V to 12 V. However, this basic voltage regulator was too fast and tried to start IoT devices with too small energy capacity. This problem was solved with a delay circuit which gives the voltage regulator more time to recharge enough energy to start the IoT device. The final capacitive energy harvester platform is shown in Figure 2.1.6.

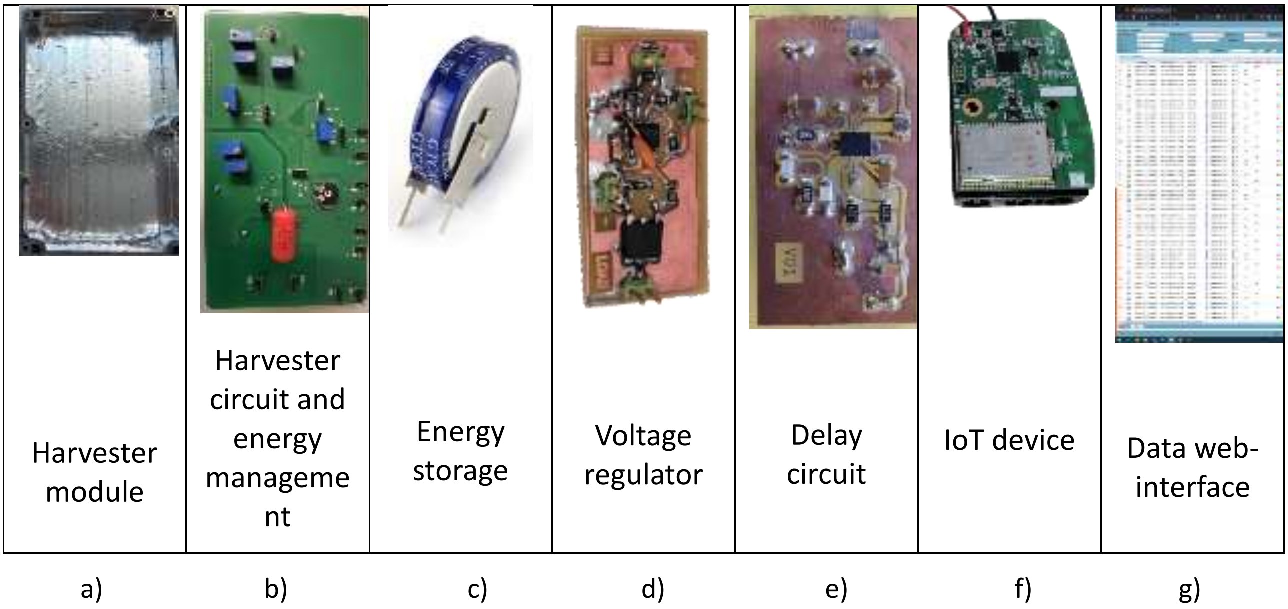
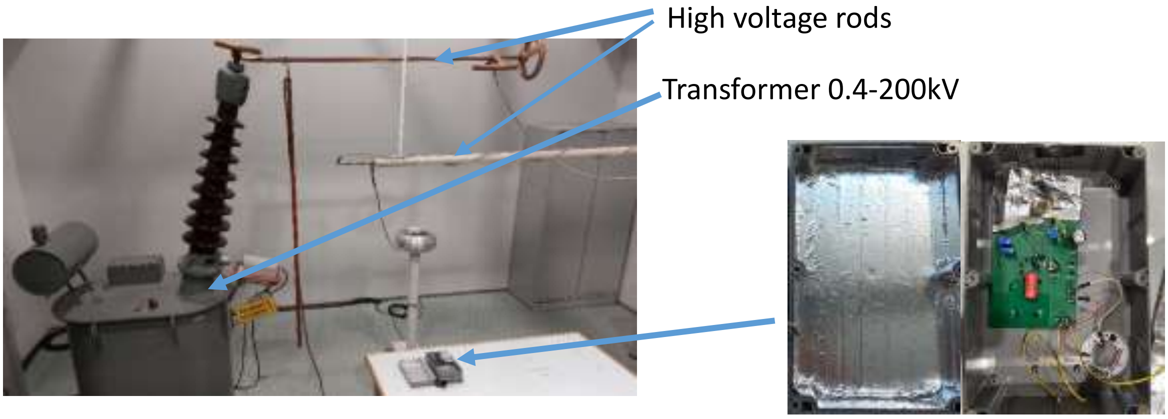


Figure 2.1.6 Final capacitive energy harvester platform. a) capacitive energy harvester module. b) Capacitive energy harvester circuit and energy management circuit in the same PCB. c) Energy storage, here a supercapacitor. d) Voltage regulator that increases the voltage from 5V up to 12V. e) Delay circuit, give voltage regulator time to collect more energy before starting the IoT device. f) IoT device. g) Collected data from an IoT device.

2.2 High voltage testing of the capacitive energy harvesting

Figure 2.2.1 shows the high-voltage laboratory in the Technobothnia research laboratory in Vaasa. The figure shows a transformer which can generate high voltage from 0.4 to 200 kV. The transformer is connected to the high-voltage rods, which simulate high voltage at the power line. A grounding stick is hanging from another high-voltage rod. On the grounded table is the capacitive harvester, and the harvester module is directly under the high-voltage rod. The other electrode of the harvester is grounded straight to the table ground point. The distance between the table and the overhead power line is about 1.2 meters.



a) High voltage laboratory in Technobothnia

b) Harvester

Figure 2.2.1 High voltage laboratory area in Technobothnia. a) High voltage laboratory and all main components. b) Capacitive energy harvester on the laboratory table.

2.2.1 Testing of the Version one capacitive harvester

Figure 2.2.1.1 shows the first version of the capacitive harvester circuit is in direct contact with the high-voltage power line. Connection to the ground is made through a 15 cm x 15 cm Cu plate. Some of the Cu is scratched away from the plate. The circuit and Cu plate are on top of the insulated plate. The Cu plate is in a capacitive connection with the ground. The voltage meter measures the output voltage from the harvester. The table is made of insulating material with only one grounding point. This grounding point is about 20 cm from the Cu plate, which is in a capacitive connection with it.

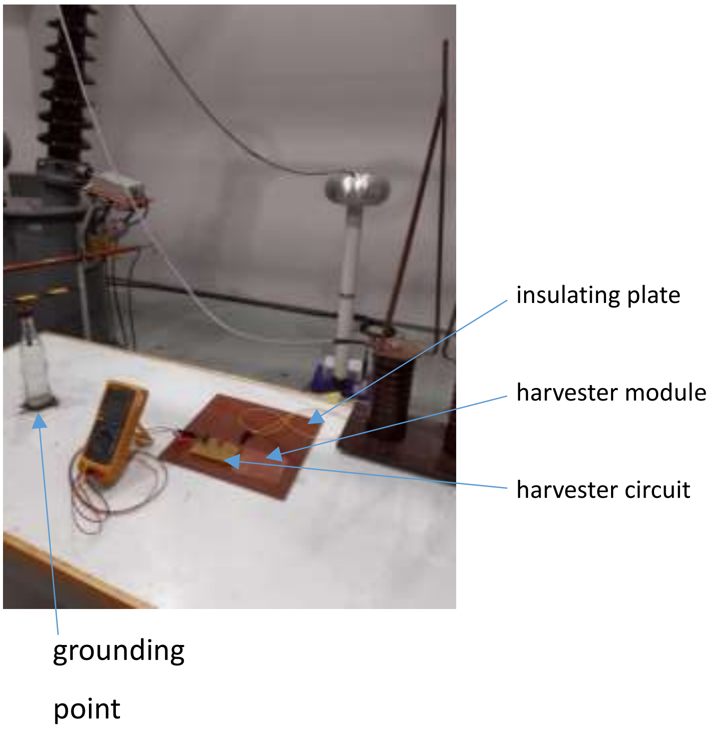


Figure 2.2.1.1 Test arrangement of Version one capacitive energy harvester. The harvester circuit is in direct connection with the high voltage.

The capacitive energy harvester measurement arrangement is shown in Figure 2.2.1.1. The harvester electronics are in galvanic contact with the high-voltage line. The harvester module's output voltage is 1.03 V when the input is 1.2 kV. With these results, a load was added to calculate the estimated power. The output voltage is 2.95 V with an input voltage of 5.0 kV. The resistance is 8 kΩ.

Power is calculated by $P=UI,\ I = \frac{U}{R},\ P = \frac{U^2}{R},\ P = \frac{2.95^2}{8\,000} = 0.0011\ \text{W} = 1.1\ \text{mW}$

To compare, the harvester was placed on top of the high-voltage power line. The resistor is 5.0 kΩ. When the high voltage input is 5.0 kV, the output voltage is 0.03 V. When the high voltage is increased to 11.7 kV, the output is 0.12 V. So, the power can be calculated using the previous formula. The results are shown in Table 2.2.1.1.

Table 2.2.1.1 Test results of the version of the capacitive harvester in high potential.

Voltage	Power
5.0 kV	0.00018 mW
11.7 kV	0.00288 mW

A test with Version two of the energy harvester circuit was performed in the Technobothnia laboratory. How the size of the Cu plate affects the energy that can be harvested was tested. Table 2.2.2.1 shows two 30 cm x 21 cm Cu plates that are at different distances from each other. The overhead voltage varied, and this also affected the output voltage.

The test arrangement is shown in Figure 2.2.2.2. The power line is about 1.2 meters above the higher Cu electrode plate. The grounding point is located under the lower Cu plate. An insulating block of wood keeps these plates separate. Another variable is the high- voltage on the overhead power line. The results of these tests are shown in Table 2.2.2.2.

Figure 2.2.2.2 Test arrangement for harvester plates. The distance between the copper plates is 30 cm. The size of the copper plate is 30 cm x 21 cm. The overhead power line is cut out of the figure. The power line is about 1.2 m above the upper copper plate.

In this measurement, the expectation from Table 2.1 was tested in terms of how the harvested power changes when the distance between the two Cu plates changes (Figure 2.2.2.2). The Cu plates are 30 cm x 21 cm, and the distances between them are 30 cm and 11 cm. The results are shown in Table 2.2.2.1.

Table 2.2.2.1 Test results with variable plate distance and overhead voltage. The size of the Cu plates stays the same, 30cm x 21cm.

Distance between plates (cm)	Overhead voltage (kV)	Output voltage (V)	Power (mW)
11	2.8	0.009	
11	11.5	0.889	0.16
30	2.8	0.033	
30	11.5	1.11	0.2

Table 2.2.2.1 shows how the output voltage variables when the overhead voltage changes and the distance between the Cu plates changes. The harvesting module also affects the power, as shown in Table 2.2. Table 2.2.2.2 shows the results when the test arrangement was the same as the previous one, but the Cu plates were connected to each other, so, the lower Cu plate is added next to the upper plate. The upper Cu plate size is now 42 cm x 30 cm, and the harvester is connected directly to the ground.

Comparing the result from these two tables confirms the effect of higher overhead voltage on the power. Distance also increases the output power and the effect of the harvesting module on the harvested power. So larger harvesting modules, long distances between electrode plates and higher voltage on the overhead power line all increase the harvested power.

Table 2.2.2.2 Test results when the upper copper plate is 42 cm x 30 cm and the ground is connected to the harvester.

Distance between plates (cm)	Overhead voltage (kV)	Output voltage (V)	Power (mW)
30	2.8	0.127	
30	11.5	1.612	0.5

2.2.2 Testing of the Version three capacitive energy harvester

Figure 2.2.3.1 shows the Version three capacitive harvester measurement arrangement. The high-voltage power line is in capacitive connection to the harvester module, and is connected to the harvester circuit. The harvester circuit is directly connected to the ground. On top of the harvester box is a 30 cm x 21 cm Cu plate used as the harvester module. The harvester circuit and the energy management circuit are both in the same PCB.

The test results are shown in Tables 2.2.3.1 and 2.2.3.2. Different phase voltages from 20 kV and 110 kV overhead power lines were used. A 1.5 F supercapacitor served as the energy store. The output power was calculated by average because the capacitor’s recharging ability changes as it increases.

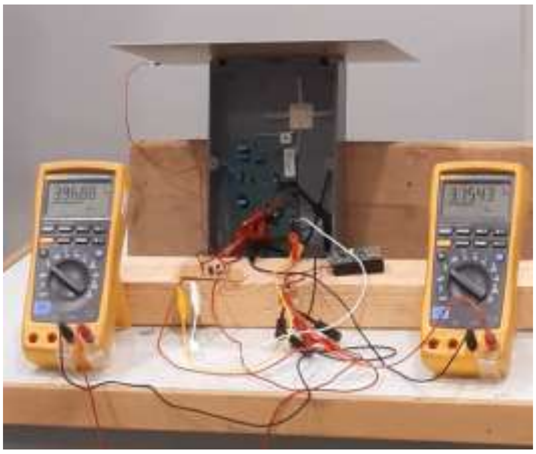


Figure 2.2.3.1 Test arrangement for Version three of the energy harvester circuit and energy management. The top of the electronic box is a 21 cm x 30 cm Cu plate that is the harvesting module. The voltage meters are measuring the input voltage and battery voltage. The left circuit on a wood block is the voltage regulator, and the right circuit is an IoT device.

Table 2.2.3.1 Test results when phase voltage is 11.5 kV.

Phase voltage	**11.5 kV**
Rechargeable capacitor	1.5 F
Time	60 s
Change of energy over time	65 mJ
Average power output	1.09 mW

Table 2.2.3.2 Test results when phase voltage is 63.5 kV.

Phase voltage	**63.5 kV**
Rechargeable capacitor	1.5 F
Time	35 s
Change of energy over time	262 mJ
Average power output	7.50 mW

2.2.3 Capacitive harvester field tests

The first field measurements were made under 110 kV and 400 kV overhead power lines. The main result from these tests is that the developed Version one harvester circuit works and can be used to collect energy from real high-voltage power lines. In these tests, the distance between the harvester and the voltage lines is about 14.5 m, and it can be assumed that more energy can be collected by bringing the harvester module closer to the lines.

Figure 2.2.4.1 shows the version of the capacitive energy harvester used in the field tests. It consists of one Cu plate measuring 21 cm x 30 cm. Figure 2.2.4.1 shows a field test under a

110 kV overhead power line. The energy harvester module is placed on the roof of the van at a height of about 2.5 m above the ground. The distance of the power line from the harvester is about 14.5 m.

a) b)

Figure 2.2.4.1 Field test arrangements, a) 110 KV power lines and a capacitive harvester on the roof of the van on the right, b) a capacitive harvester module.

The experimental arrangements shown in Figure 2.2.4.2 were used to charge a capacitor connected to a charging electronics board. The measurements showed that the voltage on the capacitor increased steadily by 0.1 V/min. It took about 15 minutes to charge the capacitor to 1.5 V. After the capacitor voltage had risen to 1.42 V, a voltage decrease was measured over a period of 13 seconds with a consumption of 10 mA with a load of 5 kΩ. The result was that the voltage decreased to 1.32 V.

With the same experimental design, the harvester was also measured under the 400 KV line. The result was that the capacitor was able to maintain a voltage of 0.69 V with a continuous consumption of 0.1 mW, with a load of 5 kΩ. When using the van as part of an energy collector, the capacitor was charged to a voltage of 2.46 V.

Version three of the capacitive energy harvester was field-tested at the local electricity substation. The test arrangement is shown in Figure 2.2.4.2. The test field harvesting box was attached to the grounded pole under the 110kV overhead power line. Inside the box were Version three of the capacitive energy harvester and a RuuviTag measuring and sending data. The RuuviTag had no direct connection to the internet, so Bluetooth was used to transfer data. The data receiver was a Raspberry Pi which collected and saved data the RuuviTag sent. The Raspberry Pi was connected to the electricity grid, saving all the data locally. The saved data is shown in Figure 2.2.4.3.

a) b) c)

Figure 2.2.4.2 Experimental arrangement for the field test at the local electrical substation in Vaasan Sähköverkko. The energy harvester module, harvesting circuit and energy management were placed in the box. The box was then installed under the 110kV overhead power line. The harvester took a capacitive connection to the overhead power line, and another electrode was connected to the grounded pole.

Figure 2.2.4.3 shows the collected data. The orange line is air pressure, and because of the scale, it looks like the pressure is stable, although it changes slightly. One drop that shows in the middle happened because energy storage went too low, and data measurement and sending ended. In this graph, it looks immediate, but actually, it took about 5 hours to reconnect. The same effect happened with humidity. The scale in the graph is too big for small changes, and after restarting, it looks like an immediate drop.

The blue line represents the energy storage voltage level. The system starts when the voltage level is about 3.3 V and then increases close to the maximum value of 3.4 V. After the highest point, the battery level starts to decrease, which indicates that the capacitive harvester cannot produce enough power to run the RuuviTag. After a battery voltage drop below 2.7 V, the energy management circuit cuts the power supply and gives the harvester time to increase the battery voltage level back to 3.3 V. This took about 5 hours to recharge.

Figure 2.2.4.3 Battery voltage (blue), air pressure (orange), air temperature (gray) and humidity (yellow) at the different data points during the test period. The x-line is the sequence of data points.

3 Inductive energy harvesting

Inductive energy harvesting is a process of generating electrical energy from magnetic fields utilizing electromagnetic induction. It involves using an inductor or coil to harvest energy from the changing magnetic field in these experiments produced by a nearby alternating current.

One potential idea for the application of inductive energy harvesting that companies wanted to support was to insert the harvester into a location with high electrical current, such as a power line or an electric motor cable. However, it is important to note that the harvester should not be connected directly to the system as this could cause safety hazards for the installers. Instead, the harvester can be placed near the current-carrying conductor to harvest the energy from the magnetic field generated by the current, which can then be used to power low-power electronics or stored in a capacitor or battery for later use. This approach can offer a cost-effective and maintenance-free solution for powering remote or hard-to-access devices. Such devices could have the benefit of multiple companies having devices in the same spaces without having to connect their systems electronically together, thus avoiding bureaucracy between companies.

3.1 Measurements

The theory of inductive harvesting is based on electromagnetic induction. The working principles are like in a transformer. To make use of the same energy harvesting and storing module from Texas Instruments as was used in the other harvesting modules tested in this project, the impedance of the winding should be high enough. Different wire diameters were tested to make working examples to achieve an impedance value both low enough to be useful and high enough not to break the TI energy harvesting and storing module. The recommended minimum resistance for DC input for the module was mentioned to be at least 20 Ω (when the energy storage is full and the excess input current is shorted to an internal low-impedance resistor).

The local electrical store had polyurethane varnish-coated copper winding wire at diameters from 0.05 mm to more than 1 mm with a certain wire weight on offer. 100 g of wire was selected as a suitable-sized roll for testing the impedance of the harvesting coil. The thinnest wire with a diameter of 0.05 mm, corresponding to a cross-sectional area of about 0.002 mm², was not selected for the test as it was too thin. The thickest wire taken for the test was 0.5 mm in diameter, corresponding to a cross-sectional area of 0.2 mm. All the wires used in the tests are presented in Table 3.1.1.

Table 3.1.1 100g wire roll properties used in the inductive harvesting coil tests.

Order code	Diameter [mm]	Cross section [mm²]	Length about [m]	Resistance [Ω] (calculated)
EL100-0.1	0.1	0.0078	1 370	2930
EL100-0.15	0.15	0.018	612	582
EL100-0.2	0.2	0.031	345	185
EL100-0.3	0.3	0.071	152	36
EL100-0.5	0.5	0.2	55	4.7

As the magnetic field was not strong enough with air as the sole magnetic medium, a ferrite of suitable size was found in the EMC laboratory in Technobothnia. The characteristics of that ferrite as 50 Hz are not well documented as it was made for MHz to GHz frequency ranges, but it was certainly better than air. All the wire rolls were tested with the same ferrite; it was good in size and easy to use in the tests to compare the different wire properties. Later, ferrite that was documented in more detail was used for the selected wires. The selected ferrite was found in a local electrical store with a closed round shape. It had to be cut into two halves, and it succeeded. The properties of the ferrite are listed below in Table 3.1.2. The two ferrites used can be seen in Figure 3.1.3.

Table 3.1.2 Ferrite material for inductive harvester coil.

Order code:	FE36-3E25
Material:	3E25
Coating:	epoxy
Permeability (µ):	5 500 ±20 %
AL-value:	7 390 nH ±25 %
Insulation voltage:	2 000 Vdc
Max Temperature:	+200 °C
Outer diameter:	36.25 mm
Inner diameter:	22.75 mm
Height:	15.4 mm

Figure 3.1.3 The tested inductive harvesting coil structures. First, the right with full winding wire rolls and round split ferrite from the EMC laboratory glued to a plastic grip, then the left later used ferrite cut in two halves with wire wound around one of the halves.

For prototyping purposes, two different diameters of wire were chosen out of the larger diameters. One was 0.2 mm and the other 0.3 mm in diameter and both wires were wound up about 300 rounds. The DC resistance for the wires was calculated and estimated from the data of the wires. However, the AC resistance is different, including both capacitance and inductance and therefore the resulting reactance, with 50 Hz as the test frequency.

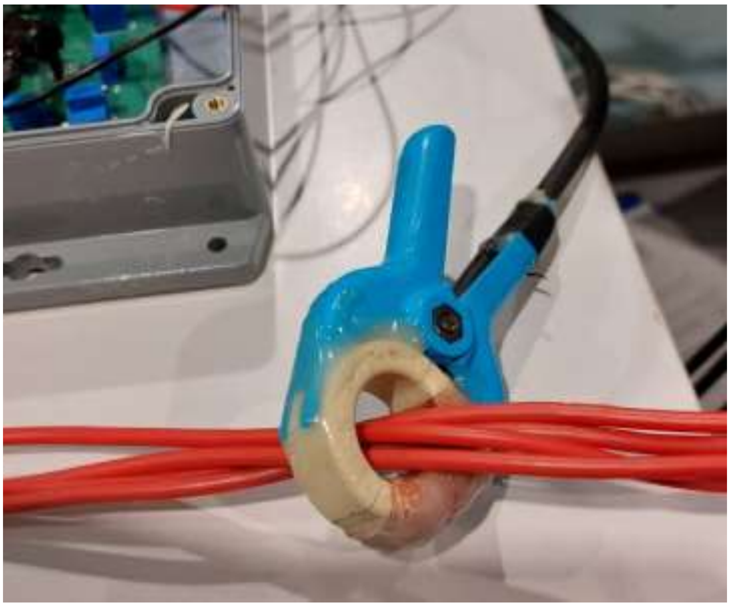


Figure 3.1.2 One of the inductive harvesting coils used in the prototype tests.

After checking that construction of the harvesting coil was working properly, it was tested to determine whether it produced a high enough voltage for harvesting electronics carrying a current of 1 A. The minimum cold-start voltage was mentioned to be around 600 mV to start and over 100 mV to continue harvesting. (28) Also, for the field tests, the maximum current to withstand was required to be 100 A. That was also tested not to break anything.

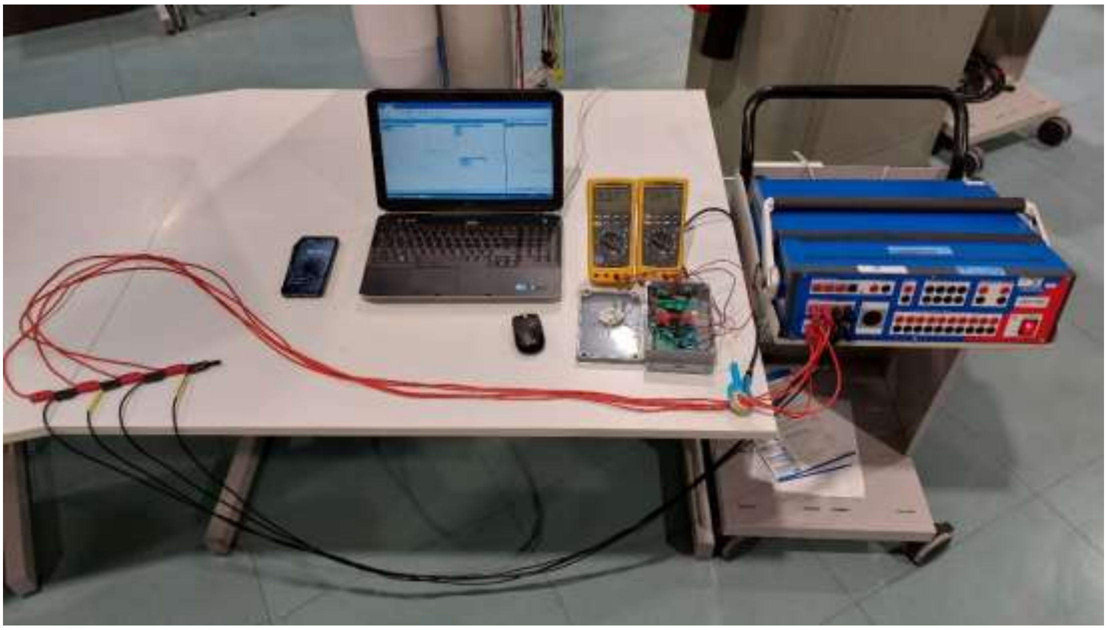


Figure 3.1.3 Inductive harvesting prototype test setup with Omicron CMC-356 and RuuviTag IoT device.

The full proof-of-concept for inductive harvesting was achieved using the self-made inductive harvester coil, the TI energy harvesting electronics involving the TI circuit and the RuuviTag as an IoT device. The same front was also tested to power more power-demanding ESP-01, including the ESP-8266 chip. It was found that the current consumption of that Wi-Fi module was more than 400 mA peak current at startup. To overcome the problem, some large capacitors were utilized because the TI chip is only capable of feeding 50 mA constant and 100 mA peak.

3.2 Results from inductive harvesting with different winding dimensions

The initial tests for the inductive harvesting module build-up involved finding suitable wire rolls with compatible properties. First, the different coils as a whole were tested with different currents as primary and different loads and the current and voltage of the load measured, thus calculating the power. Figure 3.2.4 shows that the maximum power point was relatively constant for the wire with different currents. The thinnest wire was found to match about 100 kΩ impedance. This was too much to obtain a decent amount of power with such a low voltage, as the TI chip was enabled to use voltages of 0.1–5.0 V as input.

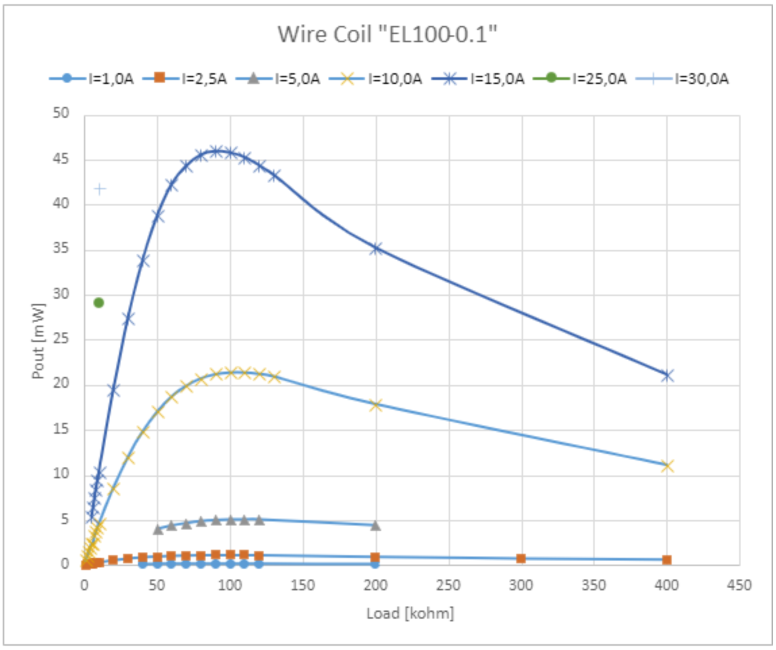


Figure 3.2.4 Power output of the coil using “EL100-0.1”wire, which is 0.1 mm in diameter with different load resistances and different load currents.

When comparing the different wire diameters (and length, as the weight was 100 g for all rolls), the matching impedance was found to be as in Figure 3.2.5, all measured with the same current levels. Also, it was found that the maximum power was not affected by the wire properties but more constant with the ferrite properties and, of course, affected by the current. Looking more closely at the measurements of the EL100-0.1 wire, the matching impedance was found to be about 80 kΩ. The current meter range was found to affect the measurements as the current from the coil was in the microampere range, and the resistance of the current meter in that range was quite high as well.

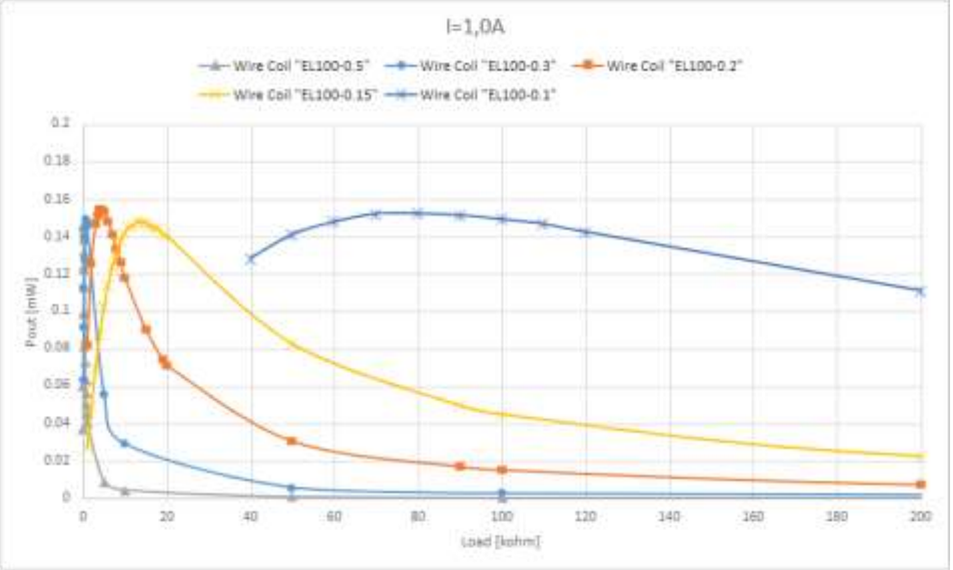


Figure 3.2.5 Power output of the coil using different “EL100-x” wire diameters where “x” is the diameter in mm, with different load resistances and different load currents.

Rejecting the EL100-0.1 wire as having too high impedance and being still too thin wire to play with, zooming in on the results in Figure 3.2.6 shows that there was slightly more power output with EL100-0.2 wire than the others. The resistance was also getting closer to the usable range.

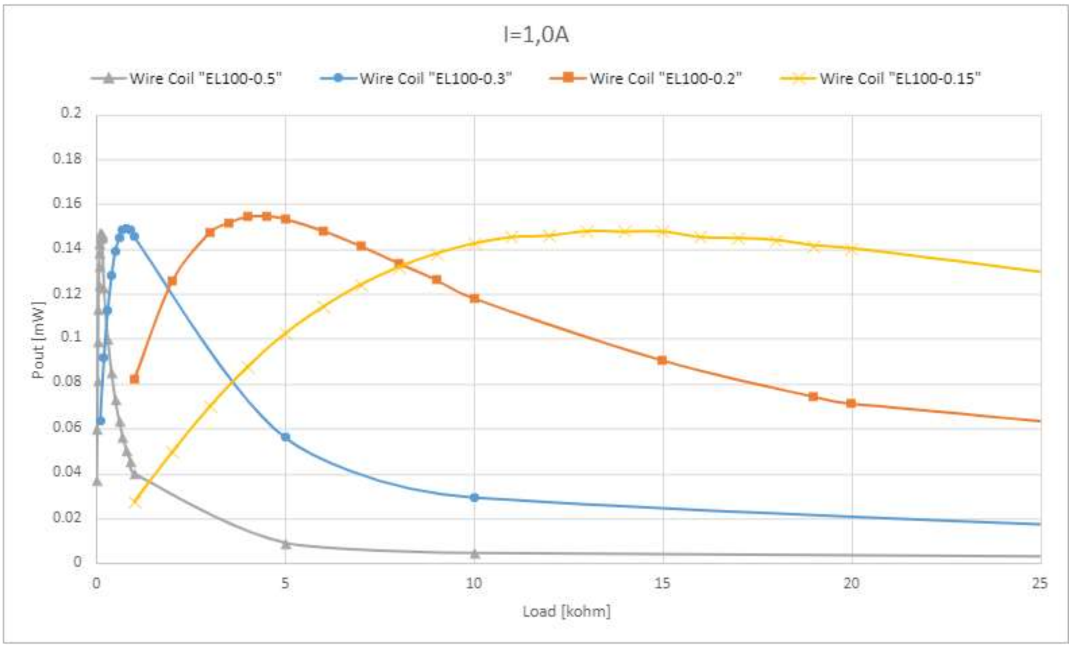


Figure 3.2.6 Power output of the coil using different “EL100-x”wire diameters, where “x” is the diameter in mm, with different load resistances and 1 A current.

The impedances were too high if using the whole wire in a roll, so it was estimated to be a better match with the other ferrite material and only part of the wire. The selected wires used were 0.2 and 0.3 mm in diameter – one for each coil. The power output peaks can be seen in Figure 3.2.7: about 4 kΩ for 0.2 mm and 750 Ω for 0.3 mm whole rolls.

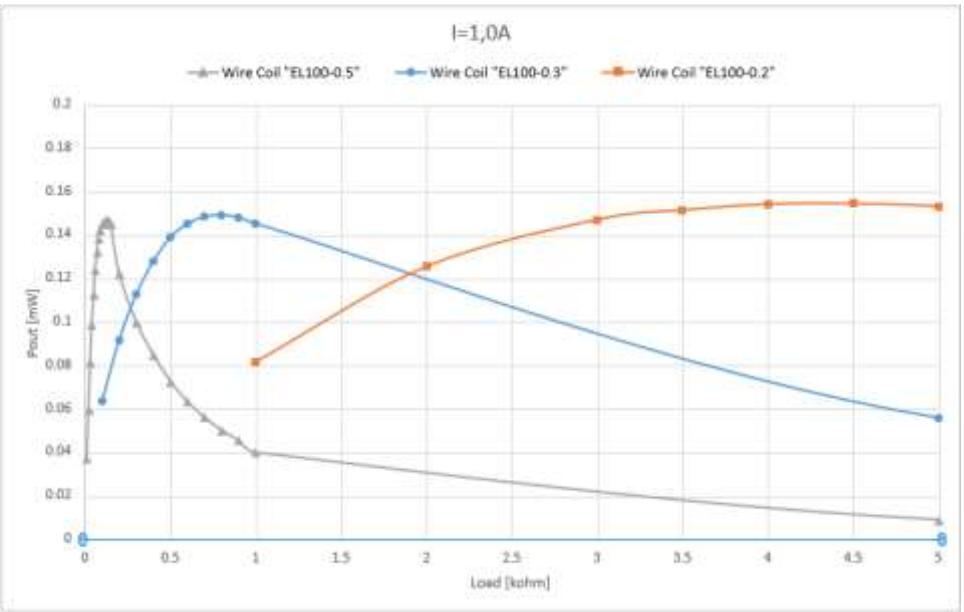


Figure 3.2.7 Detailed curve of the power output of coils with 0.2, 0.3 and 0.5 mm diameters and 1 A current with different load resistances.

3.3 Field measurements

Figure 3.3.8 Measurement at Viimatech Digital Oy powering the nrf9160 development kit

In the field test conducted at Viimatech Digital Oy, the goal was to establish easy connectivity between our inductive harvester and the power line of a water pump in a real environment. Two tests were conducted for this purpose.

In the first test, the harvester was connected to the 1-phase wire of the pump motor, with our harvester electronics powering a RuuviTag for measuring temperature and sending data over Bluetooth to a Raspberry Pi. This first test aimed to verify the working of the setup using an extremely low-power device that had been previously tested.

In the second test, the harvester was connected to the same phase wire of the pump motor while running the code that performed generic calculations to simulate a worst-case scenario in terms of power consumption, using an nrf9160 development kit shown in Figure 3.3.8. The data collected from this test was then sent over an LTE-M network to the test database. The test showed that the harvester electronics did not operate well with over 100 mA peak current at the startup process of the development kit’s data connection.

These tests were conducted to gather empirical data and validate the functionality of the setup in a real-world environment. Further development of the harvester electronics is needed for high-peak current applications.

4 Thermoelectric energy harvesting

Thermoelectric effects and harvesters have been widely studied. Coolers that use the Peltier effect are widely used in everyday life. In addition, some commercial applications of thermoelectric harvesters are available for small electrical devices, such as Seiko’s Thermic watches.

According to Paradiso and Starner, TEGs can deliver significant power when the temperature difference is high enough, but low-power applications may be viable with small temperature differences. (16)

Thermoelectricity research done in the past can be divided into three categories: material science, device-level design, and system-level design. Material science mainly focuses on the performance of thermoelectric materials. In device-level design, the focus is on keeping the thermoelectric devices as close as possible to their nominal performance. Applications and improvements of thermoelectric generator systems have been a concern in system-level design. (19)

4.1 Thermoelectric operation principle

The Seebeck Effect is the physical process responsible for the function of the thermoelectric element. Practical applications are based on the construction of the modules using a negative charged (n-doped) and a positive charged (p-doped) semiconductor. The harvester works as a thermocouple where heat energy flows from the higher temperature to the lower temperature side. This causes the flow of a current in the closed circuit.

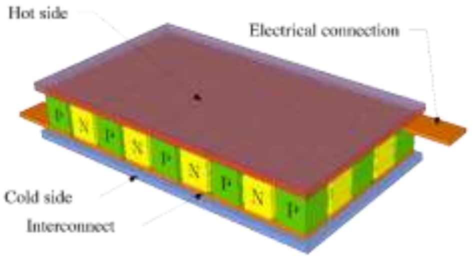


Figure 4.1.1 Construction of a thermoelectric module consisting of a negative charged (n-doped) and a positive charged (p-doped) semiconductor. (25)

4.2 Practical examples of thermoelectric harvesters

One widely researched area with a TEG is human body temperature. Ramadass and Chandrakasan tested different power management circuits for thermal energy harvesting on the human body temperature range. A thermal harvesting module of 7.5 cm^2 was able to output 10 µW of electrical power with 25 mV input voltage. (18)

In industrial applications, the thermal differences can be much higher than human body temperatures. According to the proof-of-concept work, a high-temperature energy harvester could power even a Wi-Fi module with seven 1 cm^2 and 0.4 g thermal couples if difficult-to-build parts could be made. (26)

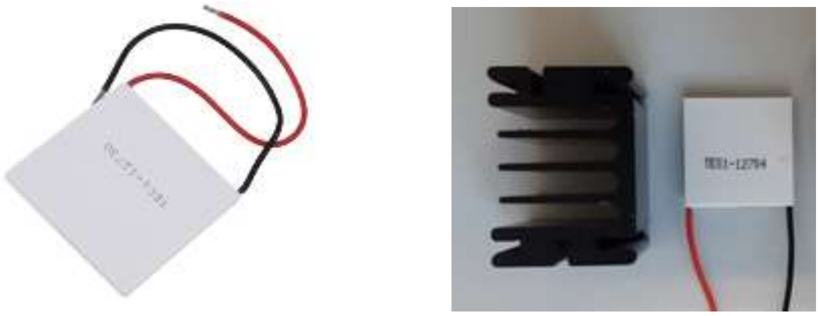
Thermoelectric harvesters can also be used instead of solar panels, as shown in (17). A fully autonomous multisensor system was developed consisting of a bismuth telluride thermoelectric generator sandwiched between a 40 cm x 40 cm sized aluminum panel and a heatsink. The TEG worked with as low as a 7 °C temperature difference between the opposite sides. On sunny days, up to 7 J of energy could be collected.

The amount of power harvested from thermoelectric harvesters scales up relatively high for IoT use cases if the temperature differences between the cold and hot sides are increased. For example, Coulibaly et al. report that when they had a difference between 25 °C ambient temperature and a hot-side temperature of 200 °C in full-disk brakes, they were able to produce up to 4.25 W. (23)

4.3 Laboratory measurements of the thermoelectric harvester

The thermoelectric harvesters were tested in the Techbothnia laboratory. The test setup is shown in Figure 5. The TEG element chosen was a commercially available Peltier element. The used Peltier element had a voltage tolerance of 14–16.1 Vdc and a current of 3.3 A. With the maximum temperature difference (Delta T) of 66–75 °C, the nominal power output is 34–37 W. The maximum operating temperature for this Peltier element is +138 °C.

Figure 4.3.1 a) presents the TEG harvester module. The dimensions of the element are 30 x 30 x 3.3 mm. A heat sink was connected to the harvester, as shown in Figure 4.3.1 b).



a)

b)

Figure 4.3.1 a) Commercially available Peltier element. b) Heat sink connected to the Peltier element.

The thermoelectric element was connected to the base of an electrical motor with heat-transfer tape. During the running of the electrical engine, the temperature of the connection point of the engine base increased to about 35 °C.

The experimental arrangement shown in Figure 4.3.2. consists of an electrical engine, a TEG with a heat sink, a current meter, energy harvesting electronics, a RuuviTag as an IoT measurement device and a cell phone used as a data receiver. The battery-operated RuuviTag is a commercially available IoT device. With this tag, it is possible to measure temperature, humidity, air pressure and acceleration. This data is sent wirelessly to the data receiver. A cell phone was used as a data receiver. In the tests, the battery was removed from the tag, which was powered with the energy produced by the TEG and the energy harvester platform. The tests showed that with the energy harvesting platform, it is possible to obtain enough energy for the harvesting electronics and the RuuviTag IoT device. In these tests, the temperature data was measured and sent wirelessly to the cell phone.

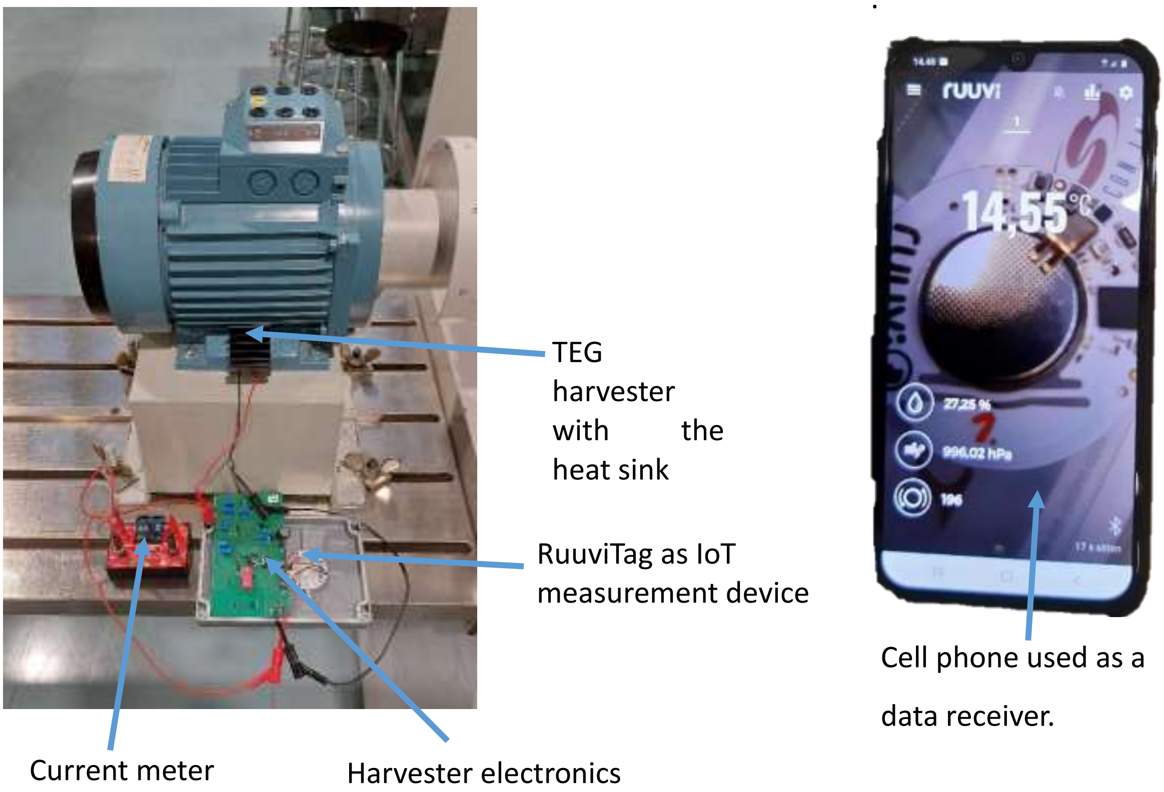
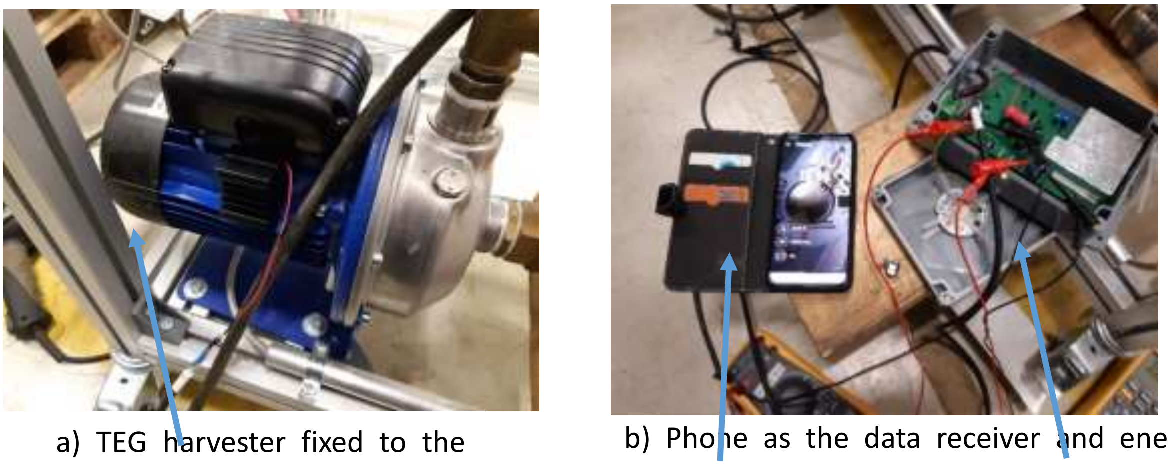


Figure 4.3.2 Experimental arrangement to test the energy harvesting platform consisting of an electrical engine, a TEG with a heat sink, a current meter, energy harvesting electronics, a RuuviTag as an IoT measurement device and a cell phone used as a data receiver.

4.4 Thermoelectric harvester field tests

The thermoelectric energy harvesting platform was also tested in an industrial environment to demonstrate that there are real spots in the real operating environment where a TEG-based harvester can be installed with minimal effort. Figure. 4.4.1 shows the experimental arrangements for the TEG harvester testing at Viimatech Digital Oy. The TEG harvester is connected to the electrical engine of the water pump and the energy harvesting electronics. This test also showed that it is possible to harvest enough energy from the small electrical engine for the harvesting electronics and the RuuviTag. Data was sent wirelessly to the phone used as a data receiver. The test showed that commercial TEG elements can be used for power measurement with IoT devices and data transfer even without optimal installation.

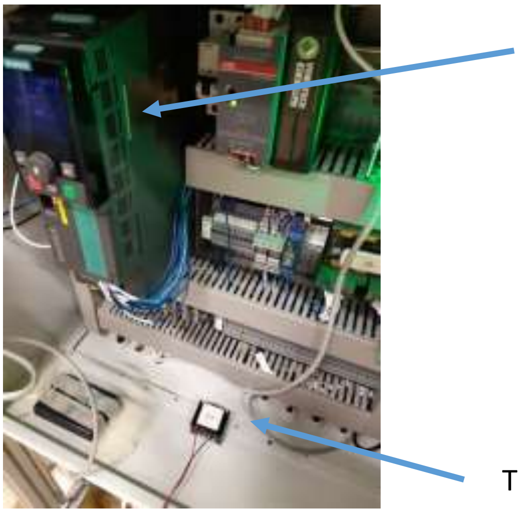
Figure 4.4.2 shows the Siemens variable-frequency drive. The TEG harvester was connected to the flat metal surface on the side wall of the unit. The temperature of this metal plate increased enough to get energy for the harvester platform. This test also showed that the TEG energy harvesting platform worked and sent the measurement data to the data receiver.



a) TEG harvester fixed to the electrical engine.

b) Phone as the data receiver and energy harvesting electronics

Figure 4.4.1 Testing of the TEG – harvester at Viimatech Digital Oy, a) the TEG harvester fixed to the electrical engine of a water pump, b) the energy harvesting electronics and the data receiving cell phone.



point of TEG attachment

TEG harvester used in the test

Figure 4.4.2 Testing of the TEG harvester in Viimatech Digital Oy, TEG harvester was fixed to the flat metal plate on the side wall of the Siemens variable-frequency drive.

4.5 Tests of the thermoelectric harvester below the ground surface

The objective of the measurement was to explore the possibility of using the temperature difference between the ground surface and the air for energy harvesting. The experiment involved using aluminum rods with different thicknesses and lengths, as specified in Figure 4.5.1 a), which were embedded in a 50 mm x 50 mm x 50 mm aluminum cube. Figure 4.5.1 a) displays the configuration of the rod used for the measurement, featuring a passive aluminum heat sink, a Peltier element and an embedded aluminum cube on the left. In Figure 4.5.1 b), the bottom part shows the components joined together with thermally conductive adhesive, while the top image reveals the bare aluminum sections coated with insulation material. 100 mm of the lower end of the pole was left uninsulated.

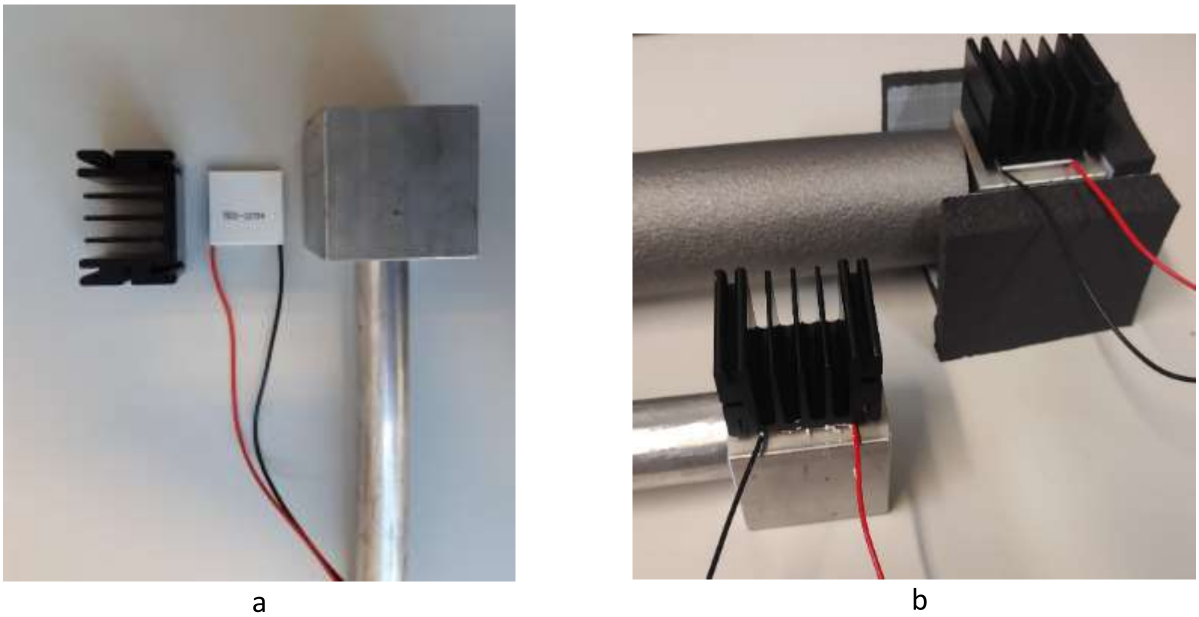


Figure 4.5.1 Field measurement arrangements, a) The parts used in the test, starting from the left: the heat sink, the TEG Peltier element and an aluminum cube with an aluminum rod implanted inside. b) The aluminum rod was covered with the pipe insulation shown in the picture, and the empty sides of the cube covered with adhesive insulation.

Table 4.5.1 Dimensions of the used aluminum rods.

	Aluminum rod 1	Aluminum rod 2	Aluminum rod 3	Aluminum rod 4	Aluminum rod 5
Diameter (mm)	10	15	20	20	20
Length (mm)	500	500	500	300	1000

Measurement was carried out in a grass field where the poles were placed, as illustrated in Figure 4.5.2. To measure the voltage, a Raspberry Pi was utilized.

Figure 4.5.2 Holes were made in the lawn for aluminum rods of different lengths, into which the rods were inserted. The bottom 100 mm of the aluminum rod was without pipe insulation.

During the thermal harvester test, the voltage from the TEG element dropped to around 10 mV as the temperature difference equalized. The measurement was discontinued as the accuracy of the voltmeter used was insufficient. The outside temperature was between 3 and 7 degrees Celsius during the measurement. The thermometer readings taken from different depths below the ground indicated that the temperature difference was sufficient for the operation of the harvester if the heat could be conducted to different sides of the TEG element. The companies funding the project did not prioritize the development of the thermal harvester, as other aspects of the project were considered to be more important. However, the potential for further development of the harvester exists, but the project focused more on other aspects of the project.

5 Kinetic energy harvester

Electromagnetic induction is a well-known phenomenon. But still, practical induction-based small-scale energy harvester technologies have not been studied on a large scale.

The harvesters studied can essentially be divided into two categories: a) harvesters using motion and b) devices that directly utilize the magnetic field caused by an electric current in the conductor.

5.1 Working principle of a linear induction harvester

The induction harvester's generic principal model was introduced by Williams and Yates. (6) As shown in Figure 5.1.1, their model mechanically consists of a moving mass on a spring inside a housing wrapped in a coil. When the harvester is vibrated, mass *m*, attached by spring *k*, starts to move, and its displacement is represented by *z(t)* and cases displacement by *y(t).* Damping is depicted by *d*. Damping consists of mechanical and electrical damping of the system.

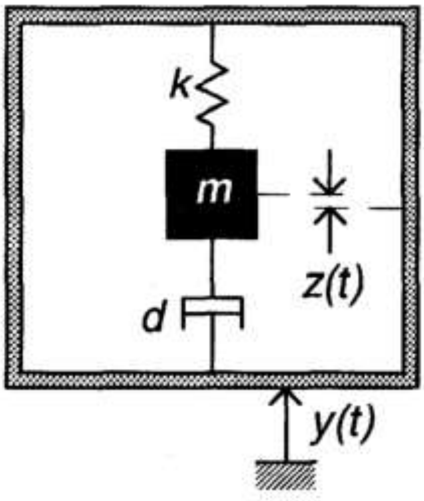


Figure 5.1.1 Schematic diagram of the generator. (6)

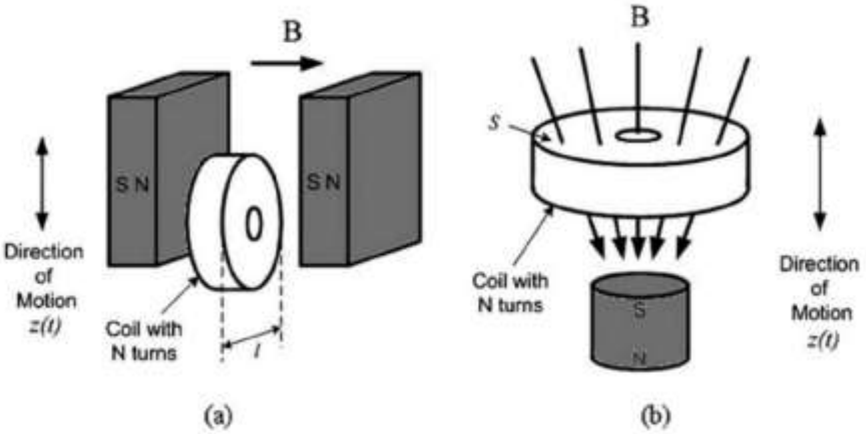


Figure 5.1.2 Working principles of an induction generator. In Figure a), the magnetic field strength remains constant, but the magnets and the coil move relative to each other, changing the magnetic flux through the coil. In Figure b), the coil and magnet move relative to each other, changing the magnetic field's strength with increasing distance. With this change, the permeable magnetic flux of the coil changes. (7)

When the vibrating mass is a permanent magnet, it moves inside of the coil, as in Figure 5.1.2 b), based on Faraday's law of induction, magnetic flux changes and current induced to the coil.

5.2 Practical examples of linear harvesters

Induction-based harvesting devices are not widely available to consumers. However, some devices are available for specific applications.

One researched application of harvesters using vibration as an energy source is from trains. According to an article in Energy Reports from 2021, there is a lack of energy for devices monitoring railway areas. However, many kinetic energy sources are available in railway areas, and harvesting is possible with multiple types of harvesters. (20) Depending on the frequency and forces, the maximum range of power that could be collected from trains and carts was 10–100 mW. Gao states that powering ZigBee-based Internet of Things nodes is possible with a magnetic levitation-based energy harvester in combination with a battery management system. However, it is suggested that vibration energy should be combined with other energy harvesting technologies. (21)

A good example of a simple linear harvester design was presented in Jarkko Välitalo's diploma. (7) Two devices were made with the approximate dimensions of standard AA and AAA batteries (8,34 cm^3 and 6.77 cm^3). The design principle was to keep the build as simple as possible so the harvester could be built by hand. Testing was carried out with multiple different vibrations. In the best-case scenario, the larger harvester was able to produce a maximum power of 349.6 mW and an average continuous power of 139.7 mW. Smaller harvesters produced a maximum power of 212.4 mW and an average continuous power of 76.46 mW.

Similar design principles have been studied for much smaller vibration environments, such as the human body, as in Morais's article on hip prosthesis. (22) Morais evaluated the power budget in a working period of 300s at about 360 µJ, with an average power of 1.21 µW. In another study, a prototype with a spring-mounted magnet and self-biased Ni/PZT/FeNi magnetoelectric composite was capable of harvesting from low-frequency vibrations. (27) The harvester was able to produce a power density close to 14.44 µW on a 10 kΩ load worn on humans.

5.3 Harvester prototypes built for measurements

The aim was to build prototype coils for measurements, as used by Jarkko Välitalo in his thesis "Energy harvesting from mechanical vibration using electromagnetic methods" (7). We used springs like the ones used in Välitalo's thesis, as well as different sizes and different spring constants for the measurements.

The purpose of the measurements was to establish that a vibration harvester could be used to electrify a generic IoT device in practice.

Two versions of harvesters were built for the tests, in which the structure consists of a PTFE tube wrapped with 500 rounds of a 0.1 mm copper wire coil, as shown in Figure 5.3 a). One tube had a diameter of 12 mm externally and 10 mm internally and a height of 40 mm, and the other had a diameter of 10mm externally and 8 mm internally and a height of 38 mm. The copper wire was attached with electrical tape. One-millimeter holes were drilled in both ends of the tube to allow air to escape.

The inner part of the tube consists of two NdFeB magnets, shown in Figure 5.3.1 b) The magnets in the smaller harvester had a diameter of eight millimeters, and in the larger one, a diameter of 10 millimeters. Both magnets had a height of 10 mm. The manufacturer reports holding the weight of 2.4 kg for an 8mm and 3.9 kg for a 10 mm magnet. Between the magnets was an iron spacer 3 mm high. Magnets were attached with cyanoacrylate adhesive to the spacer, with the same poles facing each other. The outer ends of the magnets were attached to 3D-printed PLA retainer discs, with the parts joined with adhesive. The holders at the ends of the magnet had holes for springs of different sizes. The tube ends also had corresponding 3D-printed retaining plugs, shown in Figure 5.3.1c.

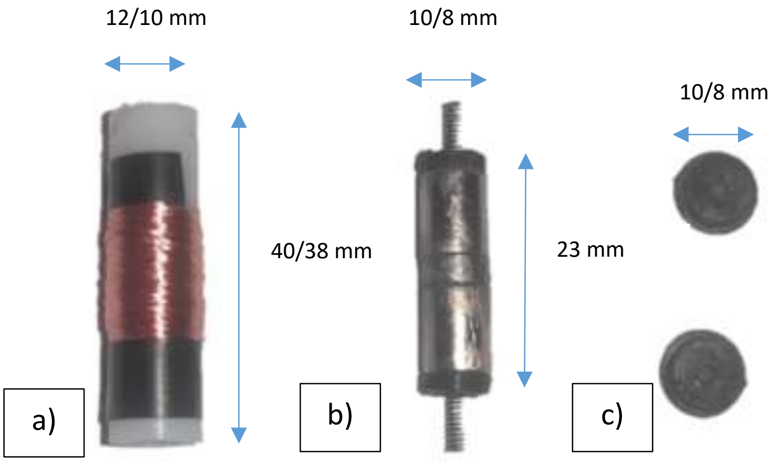


Figure 5.3.1 Vibration harvester parts: a) PTFE tube wrapped with 500 rounds of 0.1 mm copper wire b) magnet part with loose spring, a 3D-printed spring holder glued to an NdFeB magnet glued to an iron spacer. The other end is the same. Equal polarities are turned toward each other. c) Two 3D-printed retaining plugs from a top-down view.

For the measurements, the frame shown in Figure 5.3.2 was 3D-printed from PLA plastic for the harvester tube, and the harvester was pressed into the frame with a friction clamp to allow easy replacement of the springs inside the harvester between tests. Electrical tape was used to prevent lateral movement during vibration testing. The frame had holes for attachment to the vibration shaker device.

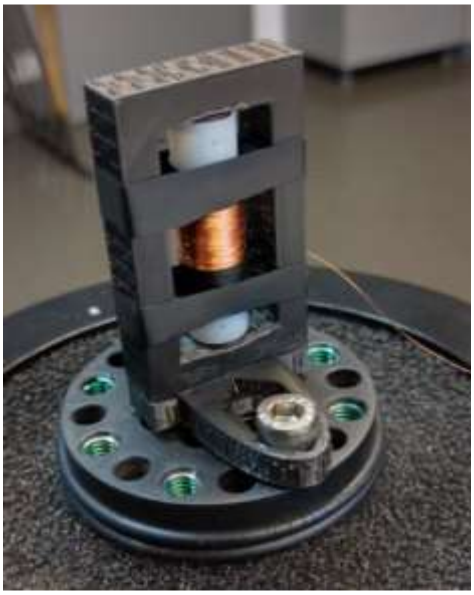


Figure 5.3.2 PLA 3D-printed holding frame for harvester with attachment points to vibration unit.

5.4 Testing the kinetic energy harvester

Vibration measurements were carried out with two types of shaker devices, as shown in Figure 5.4.1. The vibration harvester shown in Figure 5.3.2 is attached to shaker devices. All the used springs had an unloaded length of 8.70 mm; other properties varied between different springs.

a)

b)

Figure 5.4.1 Vibration testers, a) first vibration tests were done with a DynaLabs DYN-PM-250 shaker b) LDS V850-44T-Lin-Air shaker with horizontal testing position and the harvester also in a side-mounted position.

The initial tests aimed to determine which spring would be the most effective for use in future measurements with the harvester. The experiment was carried out using the DynaLabs DYN-PM-250 shaker, as depicted in Figure 5.4.1 a), with the 8 mm diameter kinetic energy harvester described in Chapter 5.3 attached in the vertical position. The test was performed within a frequency range of 30–105 Hz, the same range used in previous measurements reported by Jarkko Välitalo. (7) A 50 Ω resistor was employed to measure the peak-to-peak voltage generated by the harvester. To prevent the magnet inside the harvester from hitting the maximum compression of the spring, the shaker control voltage was adjusted visually to a level where the magnet part could move without hitting the maximum compression with different springs. All tests were carried out with the same control voltage. Different springs were used in the experiment with spring constants of 0.63, 0.86, 1.83, and 2.20. It was observed that the magnet easily compressed the springs to their maximum, resulting in multiple broken springs. Hence, the strength of the harvester needs further development. The spring with the smallest spring constant was too loose for the weight of the moving parts inside the harvester. This can be seen from the measurements when the spring was breaking; therefore, the actual spring constant suddenly changed. This phenomenon also happened when the magnet hit the end caps of the harvester. When hitting the end cap, the output frequency is probably twice the vibration frequency. This can be seen in Figure 5.4.2, where the k = 0.69 curve splits suddenly into parts. The frequency in these graphs is measured from the output voltage.

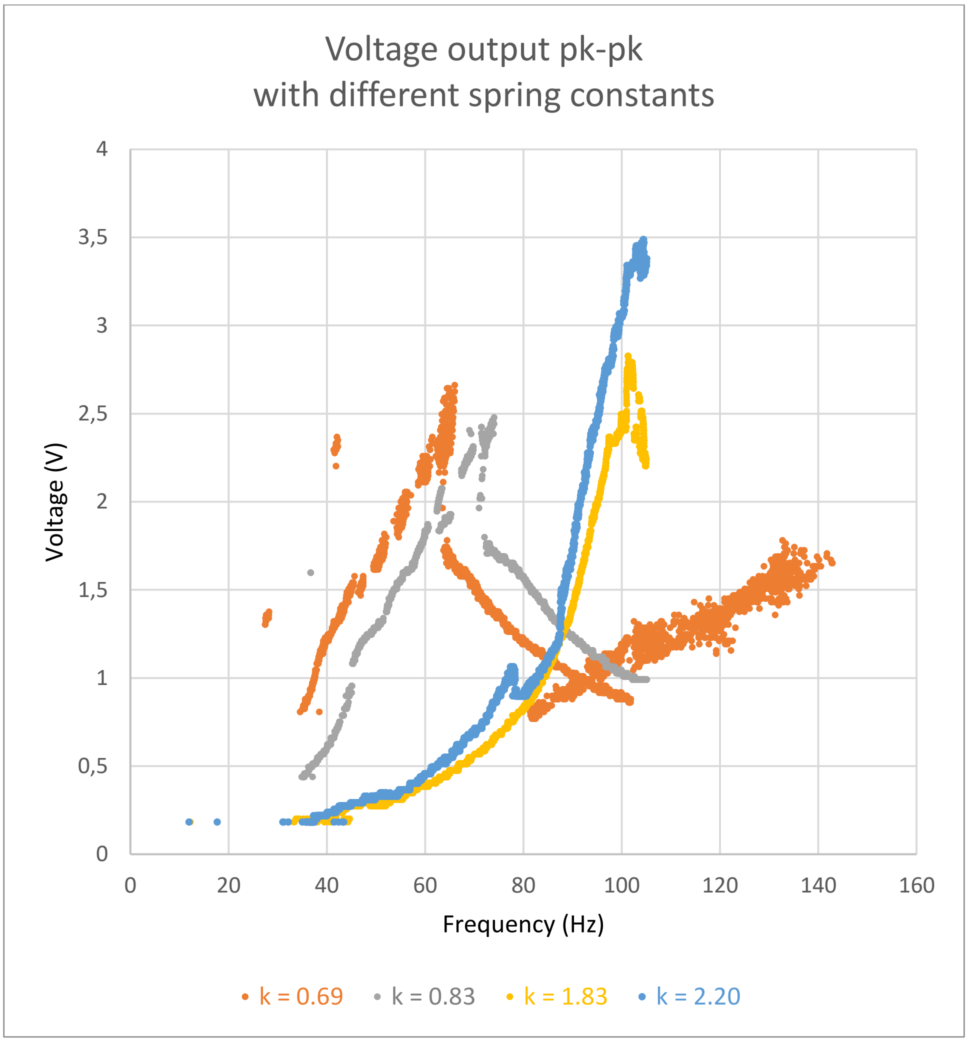


Figure 5.4.2 Voltage output with different springs and constant acceleration.

The second experiment was done with a different shaker, the LDS V850-44T-Lin-Air shaker, shown in Figure 5.4.1 b), which was employed to test the kinetic energy harvester arranged in a horizontal position. The experiment was carried out using an 8 mm diameter harvester, and the frequency range used was 30–105 Hz, consistent with previous measurements reported by Jarkko Välitalo. (7) The peak-to-peak voltage generated by the harvester was measured over a 50 Ω resistor, and the test was performed with three different constant accelerations of 4G, 8G, and 10G. However, similar to the previous test, the harvester's spring broke during the 10G test sweep. At least the hitting to the end cap can be seen from the measurements in Figure 5.4.3 as the 10G curve is splitting and the frequency doubling.

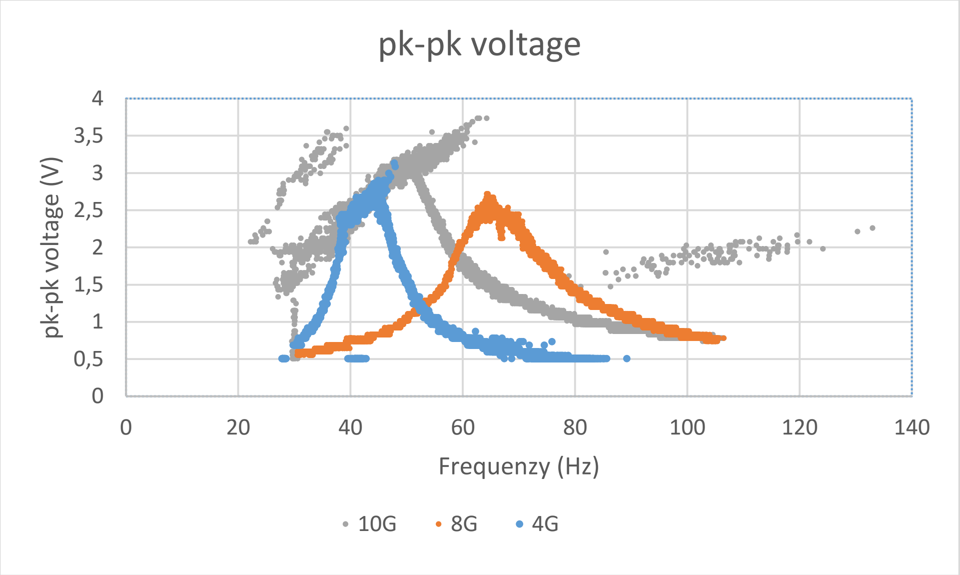


Figure 5.4.3 Voltage output with different vibration accelerations.

Although the tests carried out on the kinetic harvester were promising, the companies funding the project did not consider it to be the main focus of the project's development. The potential for further development of the kinetic harvester was recognized, but the project was primarily focused on the general development of harvester electronics and capacitive energy harvesting. As such, the tests were considered indicative for further development, but the project's priorities lay elsewhere. Despite this, the positive results from the tests highlight the potential of the kinetic harvester for future development and application.

6 Electrochemical energy harvesting

6.1 Background

The electrochemical phenomenon occurs, for example, in the corrosion of metals, and it is also exploited in batteries. The electrochemical phenomenon is a chemical reaction in which chemical energy is converted, typically without external force, into electrical energy. The basis of the reaction lies in the physical properties of metals, oxides or molecules. Devices utilizing this phenomenon are often called electrochemical or galvanic cells. Figure 6.1.1 shows the basic structure of the electrochemical or galvanic cell. The cell has three distinct parts: the anode, cathode and electrolyte. An anode is a negative electrode, and a cathode is a positive electrode. The anode is where the oxidation reaction takes place. The reduction reaction happens in the cathode. The electrolyte is a substance which allows the flow of ions between electrodes. The reactions of this chemical cell are the following (in Figure 6.1.1.):

- The electrolyte is a mixture of salt (NaCl) and water (H2O). In the water, the salt dissolves into ions (Na+ and Cl-): $NaCl\ (s) \rightarrow Na^+\ (aq) + Cl^-\ (aq)$
- The oxidation reaction happens on the surface of the anode between zinc metal and chloride ions: $Zn(s)+2Cl^-(aq) \rightarrow ZnCl2(aq) + 2e^-$
- The zinc atoms from the anode dissolve in the electrolyte and are combined with negative chloride ions while losing two electrons. The molecule formed is ZnCl2.
- The reduction reaction occurs in the cathode between water and electrons from the oxidation reaction. At the surface of copper cathode: $2H20(l) + 4e^- \rightarrow H2(g)+2OH^-$
- The water is reduced to gas H2 and OH ions.

The external conductor is required to transfer the electrons from the anode to the cathode.

The reactions on the surfaces of the copper and zinc electrodes are due to their electrochemical properties. Electrochemical properties are described as electro-potential series (or galvanic series) in which metals are arranged based on their standard electrode potential (nobility). Figure 6.1.2 shows the galvanic series. When two different metals or alloys are connected by an electrolyte, the difference in standard potentials causes corrosion. The less noble (lower electrical potential) will corrode. The larger the difference between the standard potentials, the larger the corrosion rate and electric current.

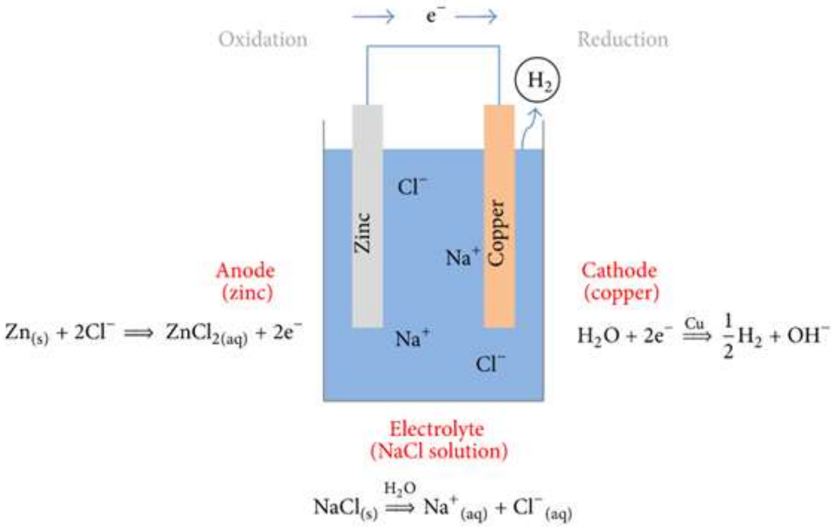
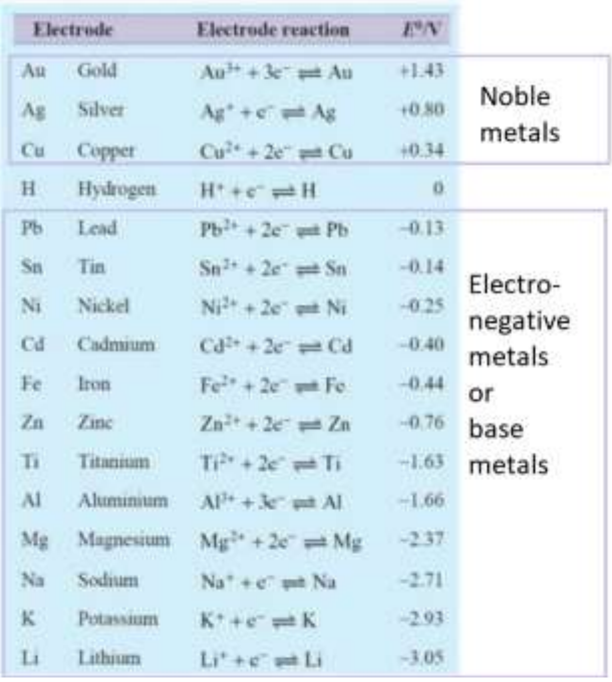


Figure 6.1.1 An electrochemical cell consists of two electrodes (a zinc anode and a copper cathode), an electrolyte (NaCl solution) and an external circuit (conductor). (25)

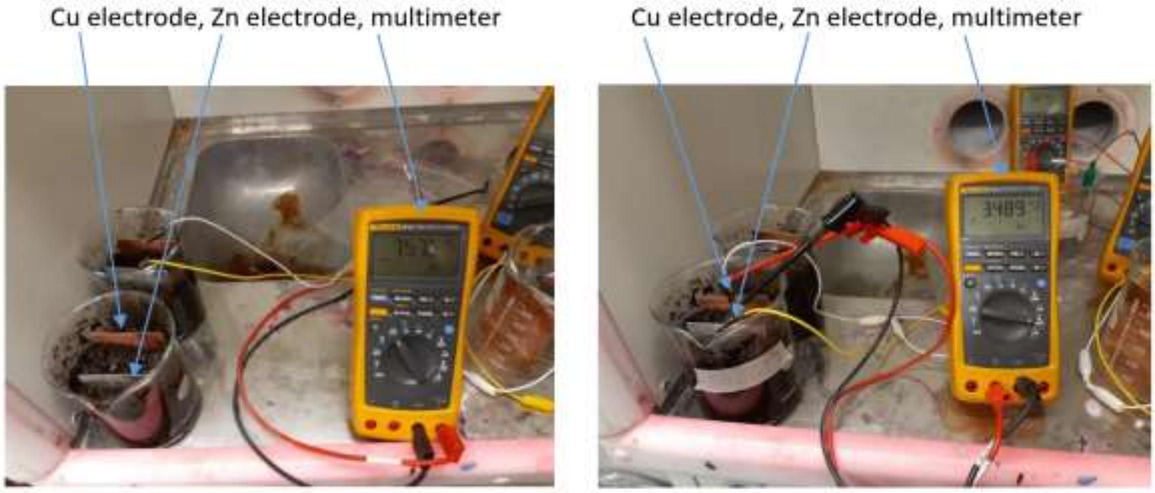


Electrode		Electrode reaction	E°/V	
Au	Gold	$Au^{3+} + 3e^- \rightleftharpoons Au$	+1.43	Noble metals
Ag	Silver	$Ag^+ + e^- \rightleftharpoons Ag$	+0.80	
Cu	Copper	$Cu^{2+} + 2e^- \rightleftharpoons Cu$	+0.34	
H	Hydrogen	$H^+ + e^- \rightleftharpoons H$	0	
Pb	Lead	$Pb^{2+} + 2e^- \rightleftharpoons Pb$	−0.13	Electro-negative metals or base metals
Sn	Tin	$Sn^{2+} + 2e^- \rightleftharpoons Sn$	−0.14	
Ni	Nickel	$Ni^{2+} + 2e^- \rightleftharpoons Ni$	−0.25	
Cd	Cadmium	$Cd^{2+} + 2e^- \rightleftharpoons Cd$	−0.40	
Fe	Iron	$Fe^{2+} + 2e^- \rightleftharpoons Fe$	−0.44	
Zn	Zinc	$Zn^{2+} + 2e^- \rightleftharpoons Zn$	−0.76	
Ti	Titanium	$Ti^{2+} + 2e^- \rightleftharpoons Ti$	−1.63	
Al	Aluminium	$Al^{3+} + 3e^- \rightleftharpoons Al$	−1.66	
Mg	Magnesium	$Mg^{2+} + 2e^- \rightleftharpoons Mg$	−2.37	
Na	Sodium	$Na^+ + e^- \rightleftharpoons Na$	−2.71	
K	Potassium	$K^+ + e^- \rightleftharpoons K$	−2.93	
Li	Lithium	$Li^+ + e^- \rightleftharpoons Li$	−3.05	

Figure 6.1.2 The galvanic series shows the electrochemical potential or nobility of metals and their alloys. (Original image from the Open University, https://www.open.edu/openlearn/science-maths-technology/engineering-technology/introduction-structural-integrity/content-section-2.3)

6.2 Experimental arrangements

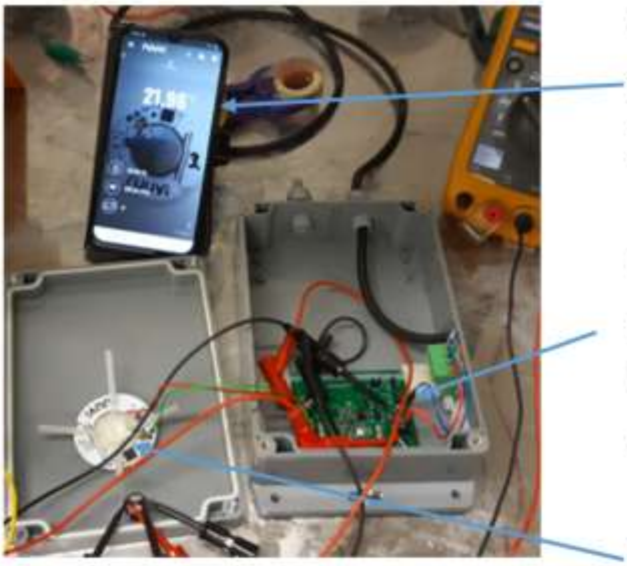
The experimental arrangements of the electrochemical energy harvesting method are shown in Figure 6.2.1. The basic setup consists of a decanter glass, Zn and Cu electrodes and an electrolyte soil+water+NaCl or seawater. The open circuit current and the voltage between the electrodes were measured with a multimeter. The voltage between the electrodes in both electrolytes was measured to be about 0.757 V.



a) b)

Figure 6.2.1 Experimental arrangements in the electrochemical energy harvesting method, a) Zn and Cu electrodes, electrolyte soil+water+NaCl in the decanter glass, the measured voltage between the electrodes 0.757 V, b) Zn and Cu electrodes, electrolyte soil + seawater in the decanter glass, measured current 3.489 mA.

A close look at a test application for the energy harvesting system is shown in Figure 6.2.2. A RuuviTag sensor sends the information wirelessly to a mobile phone using the RuuviTag app. The energy harvesting is controlled via power management electronics. Figure 6.2.3 displays the whole chain from energy harvesting to the display of measured temperature data.



Mobile phone data receiver (measured temperature 21.96 °C measured with the RuuviTag)

Power management electronics, connected to the electrochemical energy harvester shown in the Figure. 6.2.1. a) and b).

Bluetooth RuuviTag for measurements and data transfer.

Figure 6.2.2 With the electrochemical method shown in Figure. 6.1.1, it is possible to obtain enough power for power management electronics, measurements and wireless data transfer.

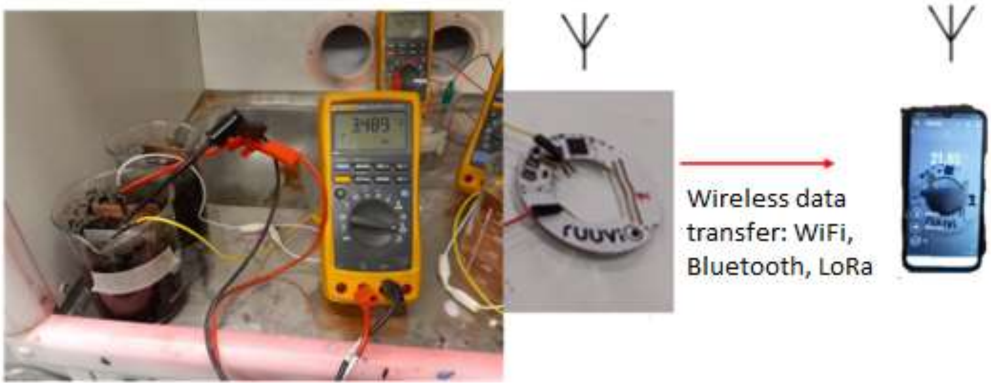


Figure 6.2.3 The electrochemical energy harvester, RuuviTag Bluetooth measurement tag and data receiver cell phone.

The current and voltage between the electrodes were measured as a function of time using the theoretical arrangements explained in Section 6.1 and shown in Figure 6.1.1. Three different electrolytes were used: a mixture of seawater and soil, a mixture of water and NaCl, and only seawater. The measurement results are shown in Figure 6.2.4 a) and b). When using water and NaCl as an electrolyte (Figure 6.2.4 a)) the voltage decreased rapidly from 0.5 V down to 0.13 V. With the seawater + soil electrolyte, the decrease of the initial voltage was lowest, from 0.85 V down to 0.52 V. The decrease of the voltage at the beginning of the measurement is most probably caused by the fact that an ionic layer is formed on the surface of the electrodes which prevents the movement of the ions to the surface of the electrodes. When seawater was used as an electrolyte, the voltage first decreased from 0.89 V down to 0.21 V, and then it increased rapidly to 0.78 V. This is because just before the last measurement, the decanter glass with the electrodes and seawater was moved, causing the seawater to move, which in turn removed the ionic layer from the surfaces of the electrodes.

Figure 6.2.4 b) shows the corresponding electrode current values measured simultaneously with the electrode voltages. It is interesting to note that seawater and soil being an electrolyte, the current increases as a function of time from 3.21 mA up to 4.17 mA. With seawater, the current decreases from 2.24 mA to 0.5 mA; with water and NaCl, the current remains nearly constant at about 1.75 mA.

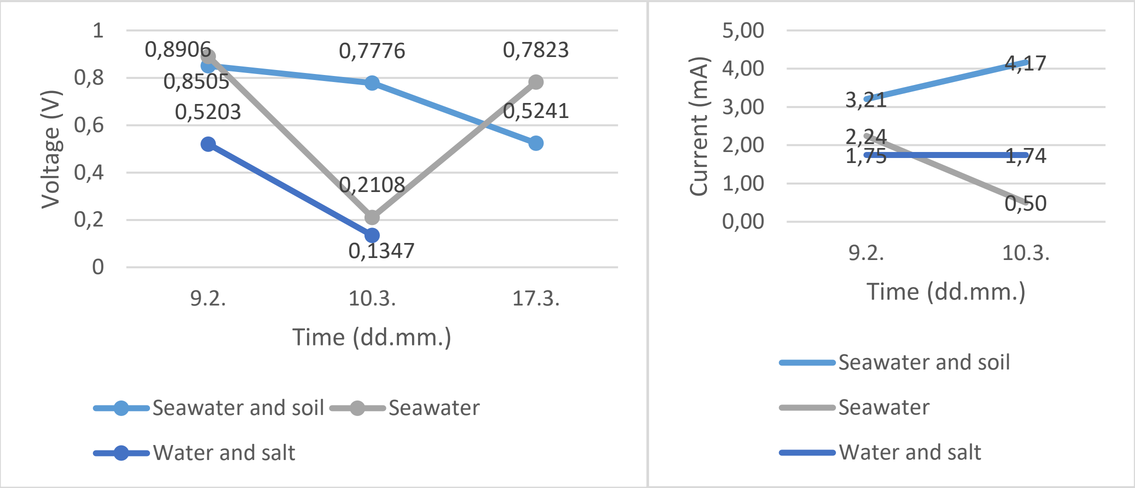


Figure 6.2.4 Measures values for a) voltage and b) current when the measurement period was more than one month. The measurement circuits were left open when no measurements were made.

6.3 Laboratory measurements, current measurement, parallel coupling

The arrangements of the electrochemical measurements are shown in Figure 6.3.1. Figure 6.4.1 shows the measured current values as a function of time. The electrode plates are made of Zn and Cu. Table 6.3.1, lists the electrode plate materials, as well as the dimensions and the number of the electrode plates. There were two plates of Zn and two plates of Cu. Both Zn plates were 19.8 cm x 10.0 cm. The Cu plates were of different sizes, one the same size as the Zn plate (19.8 cm x 10.0 cm), and the other 15.9 cm x 15.4 cm.

The electrodes were embedded into the seawater in a plastic container shown in Figure 6.3.1. The distance between the plates was 2 cm. The electrodes were not in contact with the container walls. The Zn electrode was located below the Cu electrode. The measurement cables were soldered into the electrodes. In Figure 6.3.1, a) the electrodes are connected with two plastic clamps, and in Figure 6.3.1, b) the plates are kept together with tape. In Figure 6.3.1 c), there are four electrode plates that are listed in Table 6.3.1. All the plates are in one straight pile and kept together by tape. In Figure 6.3.1, d) the plates try to cover as large an area as possible.

Table 6.3.1 Materials and the dimensions of the electrodes

Material	Dimension	Number of electrode plates
Zn	19.8 cm x 10.0 cm	2
Cu	19.8 cm x 10.0 cm	1
Cu	15.9 cm x 15.4 cm	1

a) b)

c) d)

Figure 6.3.1 Experimental short-circuit current measurement arrangements in the electrochemical energy harvesting method. Different arrangements of electrodes are in the container filled with standing seawater. The distance between the plates is 2cm. a) One Cu and one Zn electrode are lying on top of each other; the dimensions of both plates are 19.8 cm x 10.0 cm. Two plastic compactors are used to keep the plates together. b) One Zn 19.8 cm x 10.0 cm and one Cu 15.9 cm x 15.4 cm electrode are kept together by tape that goes over the Cu plate. c) Two Cu plates on the bottom (19.8 cm x 10.0 cm and 15.4 cm x 15.9 cm) and two Zn plates on the top (both 19.8 cm x 10.0 cm). The electrodes are kept together by tape in the middle. d) Two Cu and two Zn electrode plates covering as large an area as possible, the sizes of the plates are the same as in Table 6.3.1.

Figure 6.3.2 shows all the measurements from the Figure 6.3.1 arrangements. All current values start from a high level and stabilize over time. This first value is high because the water was still moving. When time passed, and the water was standing, the electric current stabilized. The test time was quite short, only 30 min with the first two tests, then expanded to 40 min with tests 3 and 4. But as Figure 6.4.1 shows, after an initial phase, the current value started to stabilize. Tests 1 and 2 were done only with two electroplates, so the highest value of the current is lower than the highest values from tests 3 and 4. The current was about the same in all tests when the water stabilized. However, measurements after even a small movement of water show a rise in current value.

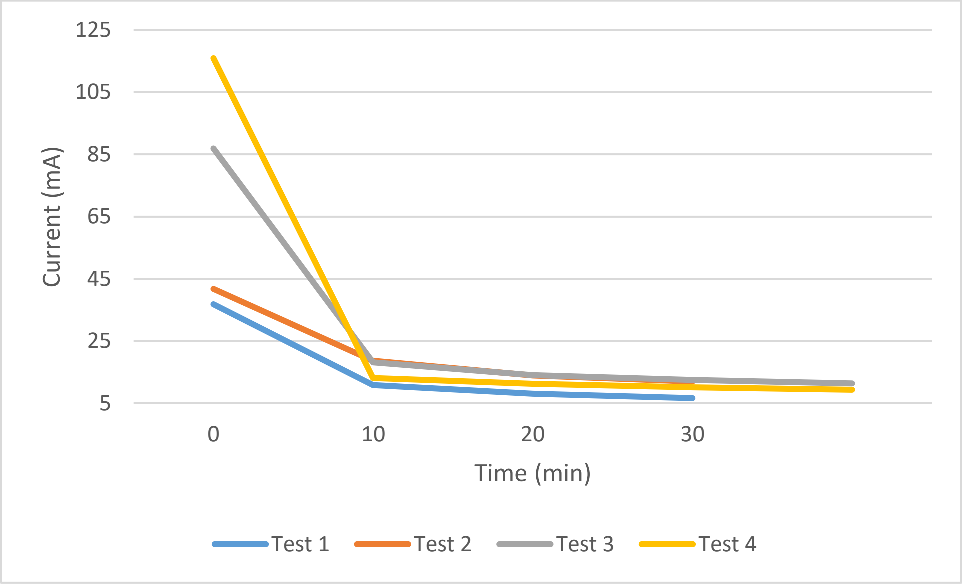


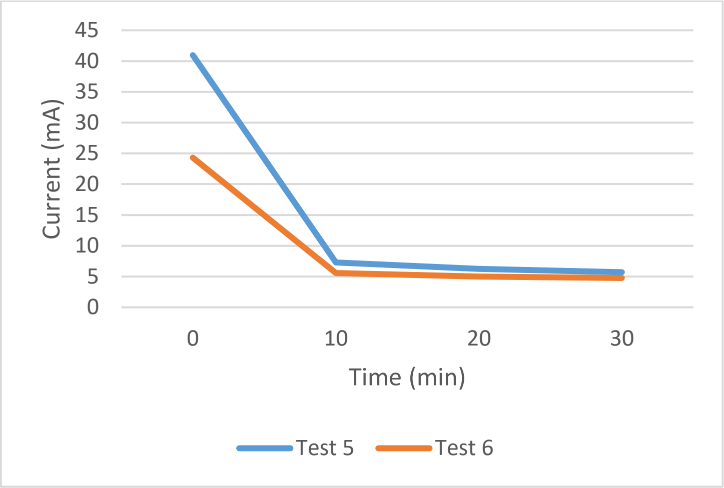
Figure 6.3.2 Current value as a function of time in the parallel coupling measurements.

6.4 Current measurements, series coupling

Two setups for the series coupling current measurements are shown in Figure 6.5.1 a) and b), and the measured current values are presented in Figure 6.5.1 c). Two Cu and two Zn plates were connected in series, and the distances between the plates was 2 cm. The plate dimensions can be found in Table 6.3.1. The measured current was a short-circuit current.

a)

b)



c)

Figure 6.4.1 Current values in the series coupling as a function of time in the electrochemical energy harvesting method. Electrolyte: seawater. The distance between the plates is 2 cm. The dimensions of the electrode plates are shown in Table 6.3.1 a). Two Cu plates are on the top, and two Zn plates are on the bottom (test 5). b) Electrode plates cover as large an area as possible (test 6). c) Current as a function of time for tests 5 and 6.

6.5 Voltage measurements, series coupling

Figure 6.6.2 presents all the measured data obtained using the arrangements shown in Figure 6.6.1. All the voltage values were low at first, but then they started to increase and stabilize. This first rapid increase is due to the fact that the first measurements were made just after the electrodes were placed into moved water. Over time, the water will no longer move; the voltage will increase slightly, and its value will stabilize. The test time was quite short, only 30 min, but as shown in Figure 6.2.2, the voltage values started to stabilize. Tests 7 and 8 were made only with two electroplates, so their voltage values were lower in the beginning than those obtained from tests 9 and 10 with more plates. When the water was not moving, the voltage values of all the tests went to a similar level. Still, a higher number of electrode plates produced a slightly higher voltage value.

a)

b)

c)

d)

Figure 6.6.1 Open circuit voltage measurement arrangements in the electrochemical energy harvesting method. The electrodes are placed in the container filled with standing seawater. The distance between plates is 2 cm. a) One Cu and one Zn electrode are placed on top of each other; the dimensions for both are 19.8 cm x 10.0 cm. b) One Zn 19.8 cm x 10.0 cm and one Cu 15.9 cm x 15.4 cm. c) Two Cu plates on the bottom 19.8 cm x 10.0 cm and 15.4 cm x 15.9 cm, and two Zn plates (19.8 cm x 10.0 cm) on the top d) Two Cu and two Zn electrode plates covering as large an area as possible, sizes of plates are the same as in Table 6.3.1.

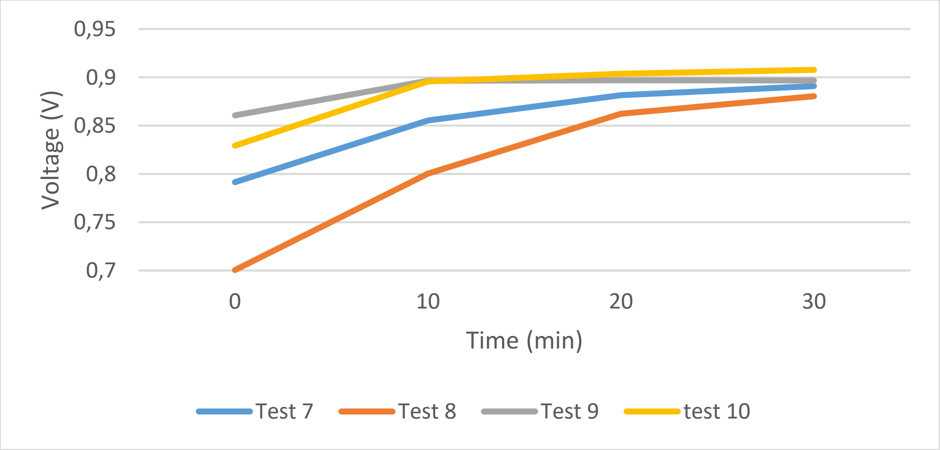


Figure 6.6.2 The voltage measurements were made using the setups shown in Figure 6.6.1: the setup shown in a) corresponds to test 7, b) corresponds to test 8, c) corresponds to test 9, and d) corresponds to test 10.

6.6 Voltage measurements with a load

Figure 6.7.1 presents the measurement arrangements for the electrochemical energy harvesting method with a load. The value of the load was calculated to be 47 Ω. As shown in Figure 6.7.1, the electrode plates were placed upright. One plate of a different material than the other plates was placed in the middle. The two other plates were put on either side of it.

The measurement results for a time period of 40 min are shown in Figure 6.7.2. The plate setup of Zn-Cu-Zn produced higher voltage values than the setup of Cu-Zn-Cu. However, the voltage values stabilized during this period, as indicated in Figure 6.7.2. The Zn-Cu-Zn arrangement produced a power of 3.4 mW after 40 min. The measuring circuit was closed throughout the whole 40 min period, so the current passed through the load continuously.

These laboratory experiments indicate that the mixture of wet soil and water is a good option as an electrolyte material. So even soil from the backyard could be used to produce enough power to operate a small IoT device with low power consumption. Moving seawater is also a good option for this purpose, as the previous experiments produced the highest output with moving water.

Figure 6.7.1. Two Zn and one Cu electrode plates are upright in the container filled with standing seawater. The distance between plates is 2 cm. Cu plate is in middle and Zn plates are on both side of it. Under the plates are 2 plastic tubes that hold plates in this upright position

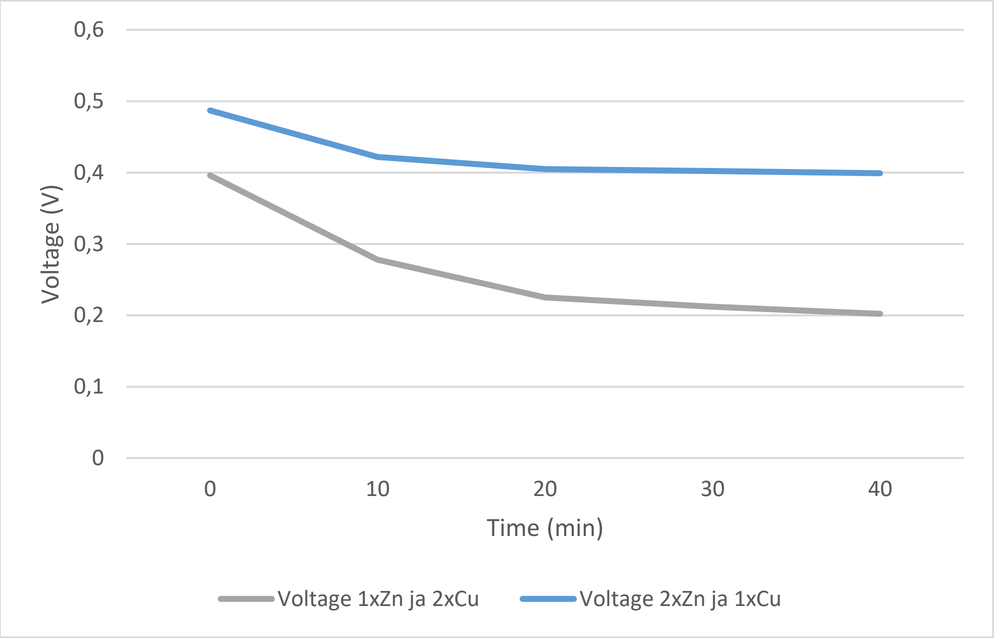


Figure 6.7.2. Voltage values for plate set-ups of Cu-Zn-Cu and Zn-Cu-Zn when the load was 47 Ω and time period 40 min. The set-up of Zn-Cu-Zn is displayed in Figure 6.7.1. The set-up of Cu-Zn-Cu is similar.

6.7 Field tests in the seawater

Field experiments of electrochemical harvesters were carried out on the coastal side of the Gulf of Bothnia. The purpose was to verify the performance of the whole harvesting system under field conditions. The harvester modules were placed at a distance of 2 meters from the seashore and slightly below the sea surface. Figure 6.8.1 a) shows the experiment location and b) the positions of one harvester module, power management electronics and the LoRaWAN transmitter.

The experimental system consisted of energy harvesting modules, energy management electronics (inside a protective box), “The Things Node” microcontroller with a temperature measurement sensor, a capacitor as energy storage and a LoRaWAN transmitter module. The measured temperature and the voltage data of the capacitor were sent to the DIGITA network with the LoRaWAN transmitter. This measured data can be downloaded from the DIGITA network for further analysis.

Figure 6.8.2 displays the electronic components of the seawater energy harvesting platform. The system consisted of two electrode plates: one Zn plate and one Cu plate; the size of both plates was 19.8 cm x 10.0 cm (Figure 6.8.2 b)). The plates were separated by 5 mm thick electrically non-conductive plastic wafers. The plates were held together with two clamps. The electric box was attached to the plates using soldered copper wires. The electronics were installed inside an IP54-rated box, as shown in Figure 6.8.2 a). The electronics consisted of energy management electronics and energy storage. The energy storage was a single electrolytic buffer capacitor (5.5 V, 1.5 F).

The capacitor was used as an energy source for “The Things Node” microcontroller, which is shown in Figure 6.8.2 d). The used microcontroller was the SparkFun Pro Micro 3.3V/8Mhz. “The Things Node” has a low-power microchip, ATmega32U4, and an RN2483 868 MHZ LoRAWAN module. In the first experimental test, the seawater temperature was measured and sent to DIGITA’S LoRAWAN network. This experiment included connection tests to the LoRaWAN network. The second energy harvesting experiment was done with a similar setup to the first except that the number of electrodes was changed to four: two Zn plates (19.8 cm x 10.0 cm) and two Cu plates (19.8 cm x 10.0 cm and 15.9 cm x 15.4 cm). The plates were separated 5 mm from each other with plastic wafers. They were placed in a vertical position using plastic screws (Figure 6.8.2 c)). This second setup also had two parallel-connected electrolytic buffer capacitors (5.5 V, 1.0 F) instead of the single capacitor (5.5 V, 1.5 F) used in the first experiment. The harvester module (the plates) was placed in an upright position under the seawater surface (at a depth of approximately 20 cm–30 cm), as shown in Figure 6.8.2 c). The electronic box was placed into rock cavities around 1 m above the seawater surface. The first and second experiments were performed in the same coastal location shown in Figure 6.8.1 a).

The measurement data was sent wirelessly to the LoRAWAN network every 5 minutes in the first experiment. The microcontroller was put into sleep mode between data transmissions. According to the manufacturer's datasheet (29), the current of a typical LoRaWAN module drops to 0.0016 mA (3.3V) in sleep mode from the typical current of 2.8 mA of idle mode. The RN2483 LoRa module's typical current in transmission mode is 38.9 mA (at 3.3 V), and in reception mode, 14.22 mA. In the second experiment, the data was transmitted every 30 minutes, so the sleep mode was longer.

Figure 6.8.1 Measurement of the efficiency of the harvesters in seawater. a) Preparation of the field measurements of the electrochemical harvesters in seawater. b) Position of the harvester module and the power management electronics in the test area**.**

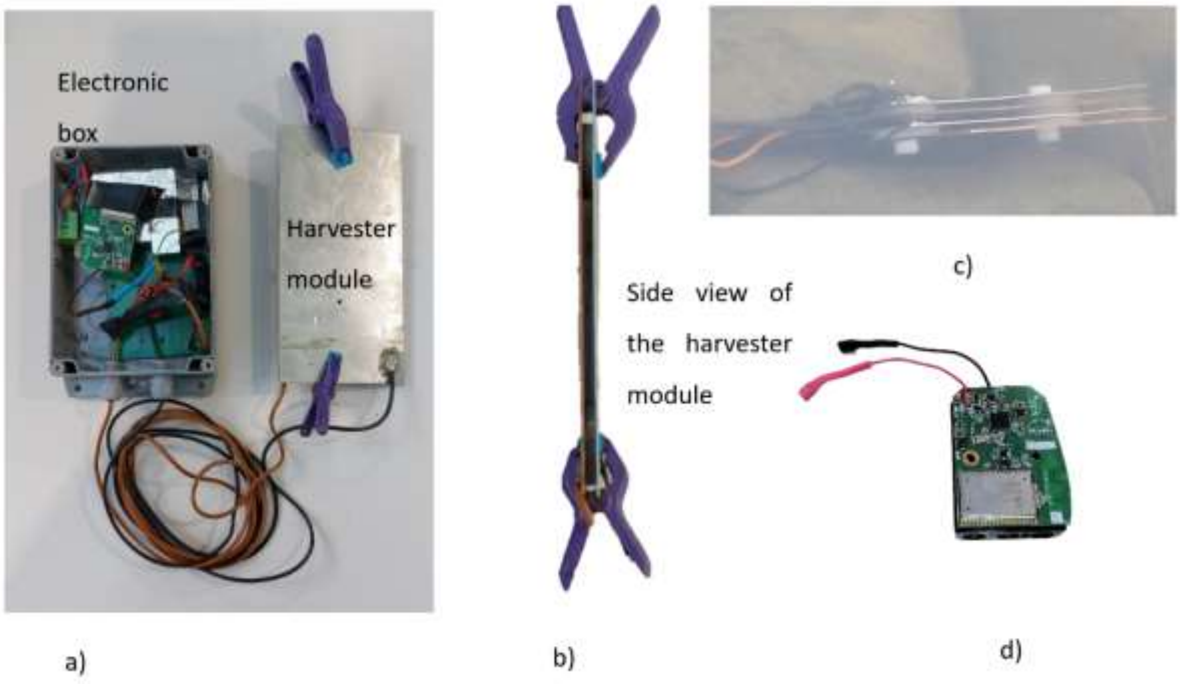


Figure 6.8.2 Components used in the energy harvesting experiment with seawater: a) electronic box (17.1 cm x 12.1 cm x 4 cm) and harvester module. b) Side view of the harvester module,(19.8 cm x 10.0 cm). The plates are separated by two plastic discs 5 mm thick. The plates are held together by two clamps at the ends of the module. c) A harvester module under the seawater surface. d) The microcontroller used in the experiments is “The Things Node”, which is on the SparkFun Pro Micro - 3.3V/8Mhz board. This board includes a Microchip LoRaWAN module and temperature sensor, NXP’s digital accelerometer, a light sensor, a button and an RGB LED.

The results from the first experiment are presented in Figure 6.8.3. The main goal of this experiment was to validate that the harvester module will produce energy from seawater. Another goal was to demonstrate the capability of the IoT device to connect to the LoRaWAN network with energy harvesting.

In the first tests, it was found that it was possible to generate enough energy for the harvester platform to start working. There was also enough energy to start up the IoT part of the device and measure the temperature and voltage of the capacitors, connect to the LoRaWAN network and send the measured data to the DIGITA network.

Figure 6.8.3 shows the first measurement results. The energy harvesting platform is operational and can power itself.

The temperature curve in Figure 6.8.3 has several gaps. At these points, the device was unable to send the data. The failure to send data can be for several reasons, such as a busy network or temporary loss of network connection. In our lab tests, we measured that “The Things Node” consumed more power during LoRaWAN connection establishment than during the measurement procedure. If the connection fails, the device automatically tries to reconnect. The voltage curve in Figure. 6.8.3 shows that the device behaves as expected when the voltage drops. However, when the voltage drops simultaneously, a gap in the temperature curve appears, indicating that the IoT device has tried several times to establish a large energy consumption LoRaWAN connection.

During the several hours’ pause between 15.00 and 18.00 in the temperature reading, the LoRaWAN connection was established only once, and only one voltage reading was sent. In this case, the voltage reading was the highest (4.768 V) of the whole measurement sequence, probably because of the long charging time without a successful data-sending connection via LoRaWAN. The lack of connection was more likely caused by the programming and the behavior of the “The Things Node” IoT device, not the electrochemical harvester electronics.

However, as shown in Figure 6.8.3, the voltage decreased steadily toward the end of the measurement period. There may be several reasons for that, such as the slowing down of the water movement, contamination of the surface of the harvester plates, moisture inside of the electronics box or the weakening of the soldering connections between the harvester plates and the electrical wires in the seawater environment.

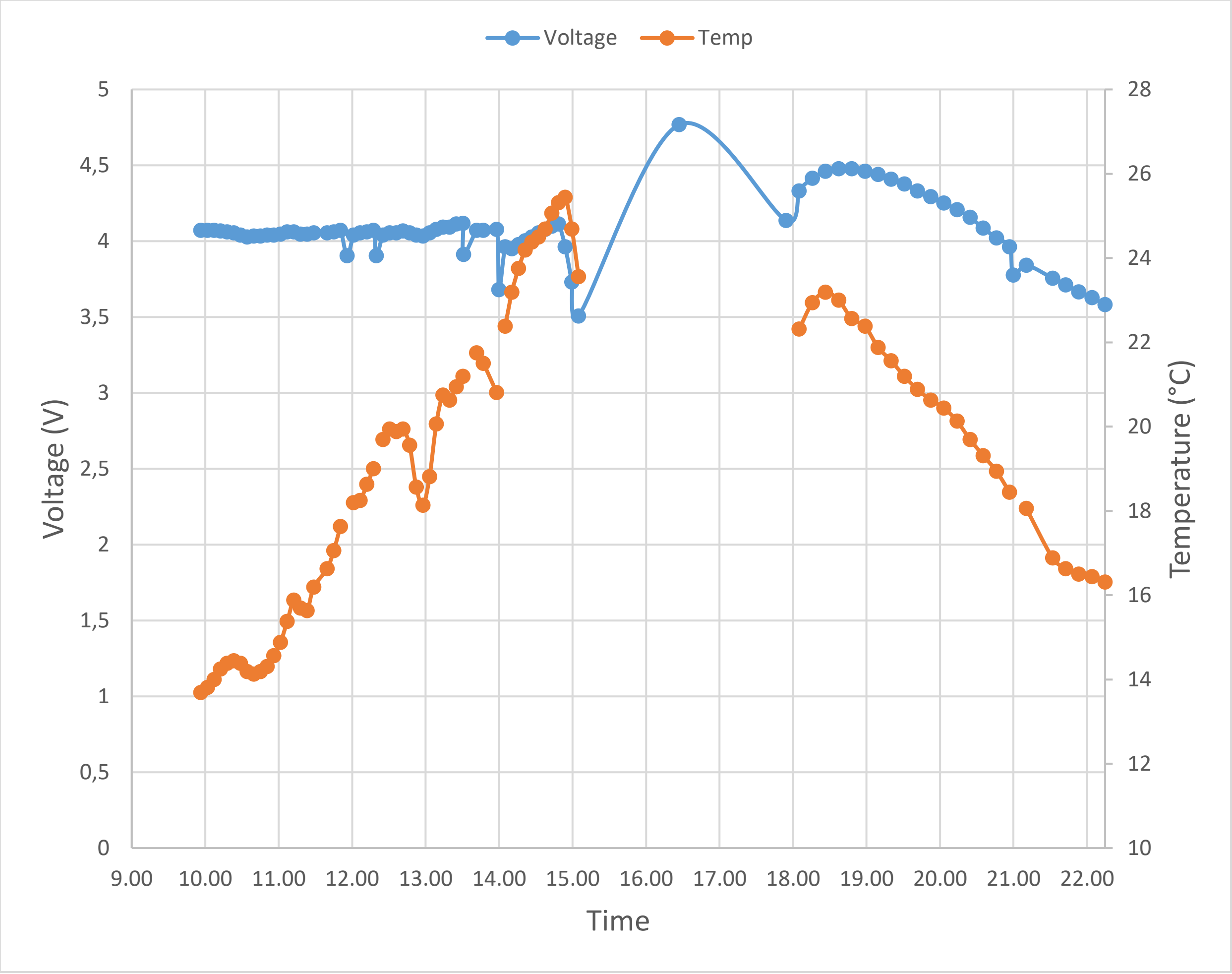


Figure 6.8.3 The first measurement results show the operating voltage of the "Things Node" and the temperature reading from inside the electronic box. The IoT device was programmed to send data after every 5 minutes. The gaps in the temperature curve are in line with the dropped voltage readings. At the dropping points, the IoT device has lost the connection to the LoRaWAN network and has had to perform a high-consumption reconnection to the network.

The results of the second measurement are shown in Figure 6.8.4. In these measurements, the frequency of the measurement and data-sending sequence was decreased from 5 min to 30 min. In this way, the overall consumption could be decreased, and the platform could be made to operate continuously.

As the curves in Figure. 6.8.4 show, the device managed to send the measurement result approximately every 30 minutes from the first transmission at 10.23 until the last data point at 21.04. After that, the device did not work, and the next data arrived at 04.50 on the next day. The same kind of problem was detected in the first measurement, as shown in Figure

6.8.4. Either the device failed to establish a LoRaWAN connection or the voltage level was not sufficient.

However, Figure 6.8.4, shows that the harvesting electronics were working as intended. The device again woke up at 04.50. This was because the device had managed to harvest enough energy to complete the new transmission.

There can be several reasons for the data loss. The laboratory measurements found that “The Things node” device consumes significantly more energy if the device fails to establish a LoRaWAN connection on the first attempt and is left trying to establish a connection several times. Moisture was also found inside the device, which could cause the malfunctioning of the device. The circuits used in the test were not specifically protected against moisture.

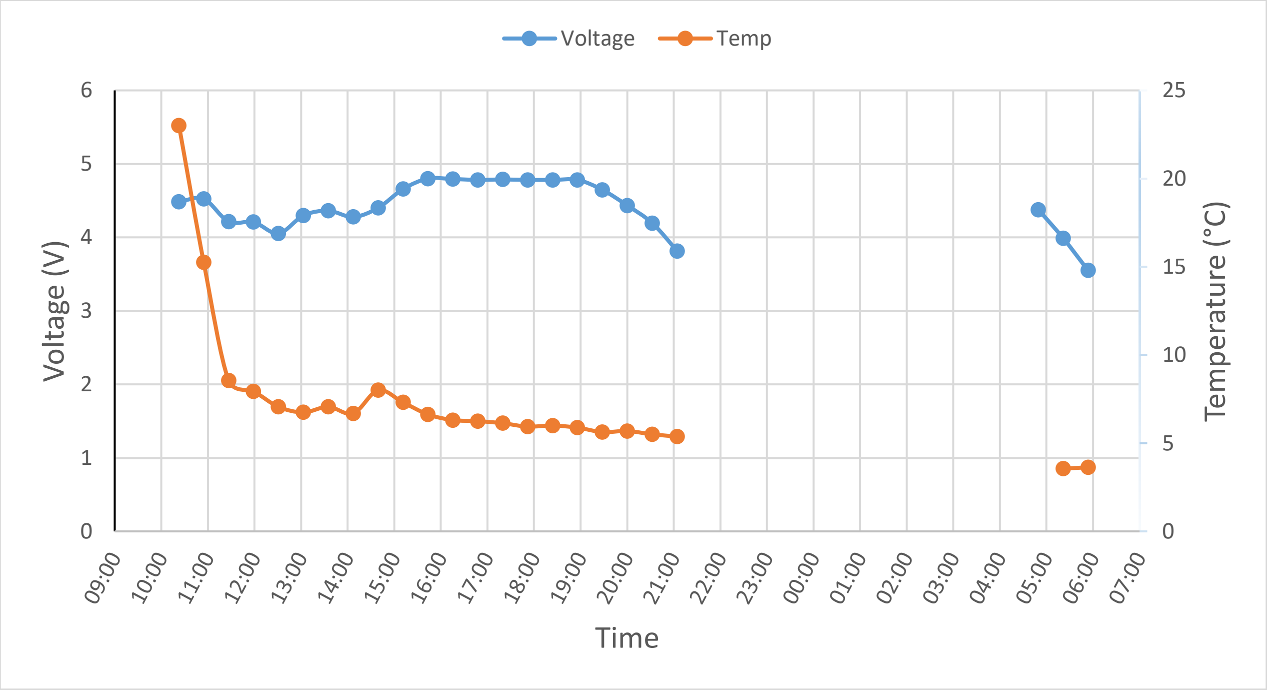


Figure 6.8.4 The measurement result of the measurements performed at a time interval of 30 min. The high initial temperature is due to the assembly of the measurement setup inside the laboratory at room temperature. At 21:00, after the measurement, the voltage has dropped so low that the device has shut down. However, the harvester electronics have managed to collect enough electricity to successfully wake up and start the unit by 4.50.

7 Conclusions

The energy harvesting technology developed in this project will offer an easy-to-deploy, energy-efficient, sustainable and scalable solution for the low energy power needs of electronic devices, enabling massive amounts of wireless battery-free industrial IoT sensor nodes and networks.

The objectives of this project were 1) further development of the technology to TRL6 level, 2) testing of the POC (proof-of-concept) in a real customer environment, 3) implementation of market research and validation of product demand and initial business model hypothesis, 4) registration of intellectual property rights for our solution.

The number of sensors on the Internet of Things (IoT) will grow rapidly – we are talking of billions of sensors. As most of the sensors will be connected wirelessly, the technologies for powering the growing number of sensors have to be rethought. Otherwise, the demand for batteries will increase indefinitely and billions of lithium batteries will end up in landfill every year around the world. Lithium mineral resources will not be enough to meet the predicted growing demand, driven by, for example, the electrification of transport. Battery maintenance is labor-intensive and a constant expense. The energy harvesting-supported battery-free sensor networks will be the sustainable solution for industrial IoT.

Using our battery-free wireless IoT sensor network platform, we will enable end-to-end condition monitoring-as-a-service solution.

End users will be the electrical industry, the electronics industry, the technical facility management in various industry sectors, including Oil & Gas, Pulp & Paper, Steel, Water & Waste, Energy grids & Utilities and other industries running ‘heavy machinery.’ We are targeting a growing market of wireless industrial IoT solutions for condition monitoring. The smart factory and industrial IoT trends are driving the growth of the predictive maintenance market. A recent IoT Analytics report estimates that the market will reach $28.2 billion by 2026. More and more condition monitoring systems will be battery-free, supported by energy harvesting and wireless power. According to market research by IdTechEx, the battery-free electronics market is forecasted to grow dramatically – from under $8 billion today to over $120 billion in 2041.

In this research project, five different energy harvesting platforms, including harvesting modules, power management electronics, power storage and wireless data transfer, were developed:

1. Inductive + electronics + wireless data transfer
2. Thermoelectric + electronics + wireless data transfer
3. Capacitive + electronics + wireless data transfer
4. Kinetic + electronics + wireless data transfer
5. Electrochemical + electronics + wireless data transfer

All these technologies worked in laboratory conditions. With all these technologies, it was possible to collect energy from the environment, store the electrical energy in the supercapacitor, perform measurements (for instance, temperature, humidity, air pressure, and acceleration) and send the data wirelessly to the IoT devices. LORA, Bluetooth and Wi-Fi were tested in the wireless data transfer.

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Appendices

1 The study of the internet of things, The current state of IoT expertise and services at Technobothnia

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The report was made for project E4IoT, University of Vaasa.

1.1 Background to need of an IoT laboratory.

At Technobothnia there is various projects ongoing and are under plan by VAMK, Novia and the University of Vaasa, which require measurements and data collection, as well as analysis of the collected data. Different projects have different levels of expertise in electronics, information technology and data analysis. Each project spends a considerable amount of time thinking about which sensors to measure, which technology to use to transfer the data to the databases, and how to analyze the data, for example, for a final report or for practical action. Centralized IoT expertise, as well as data management and analysis services, could speed up the progress of projects, as well as ensure the accuracy of data and the security of data management. In the future, data analysis will be more important in projects, including how to find new services or cost savings on basis of the data.

There would also be a great need to collect open data that could be used for both exercises and research. Data could come from industry, electricity networks (smart grid), the city, different projects as well as users of different services. Automatically collected data can also be combined with manually recorded data. When the data can be used in research, either freely or through agreements, it is likely that new start-up activities will also emerge in higher education. There is also a need for data analysis training in data analysis education done in all three universities.

Technobothnia can also be used to collect data from the building itselves, and this is already being done, for example, for the building's ventilation systems and other energy systems, for building automation. At the campus area there are several buildings under renovation, and data collection points could now be implemented there.

Iot is one of the major components in the implementation of Industry 4.0 as well as in people’s daily lives when monitoring smart homes or information used by personal applications on your mobile phone.

Gartner defines the industrial Internet of Things (IIoT) platform market as a set of integrated software capabilities to improve asset management decision making within asset-intensive industries. IIoT platforms also provide operational visibility and control for plants, infrastructure and equipment.

IIoT Platforms

The IIoT platform is differentiated from legacy operational technology (OT) by its ability to cost-effectively collect higher volumes of high-velocity, complex machine data from networked IoT endpoints. The IIoT platform also orchestrates historically siloed data sources to enable better accessibility and improve insights and actions across a heterogeneous asset group through specialized analysis of the data.

The IIoT platform:

- Monitors IoT endpoints and event streams
- Supports and translates a variety of manufacturer and industry proprietary protocols
- Analyzes data at the edge and in the cloud
- Integrates and engages IT and OT systems in data sharing and consumption
- Enables application development and deployment
- Can enrich and supplement OT functions for improved asset management life cycle strategies and processes

1.2 What exists (mainly at Technobothnia) at Novia, VAMK and the university at the moment (Experts, facilities, equipment, systems, training, research, services)

Currently, there is an actual IoT laboratory facility at Technobothnia, that is shared with the energy laboratory.

The space itself does not have IoT measuring devices or the like, but the space has been used in IoT training and projects. The space does have different energy technology processes that can be used for IoT measurements and to calibrate the IoT sensors in a simulated process.

Hans Linden is in charge of the laboratory space and his office is directly connected to the room.
(Contact informations can be found in the appendix to this report and as an Excel file).

His office also has various IoT sensors, circuit boards with communication units and training materials and measuring equipment. There is also storage boxes made for IoT courses where you can find ready-made laboratory training equipment.

The measurement results of Novia's various projects can be viewed at iot.novia.fi

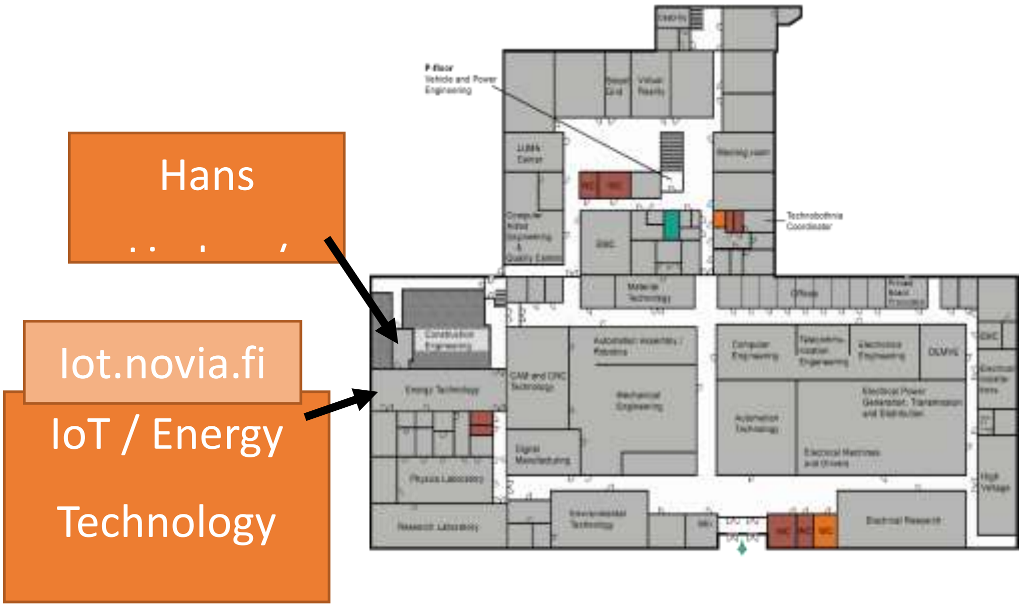

Figure 1.1.2.1 map of Technobohnia

Expertise in how to develop business using IoT and data-analysis could be sold as an service for companies by Technobothnia!

Functions supporting the IoT laboratory on different levels at the moment are:

- Automation Laboratory
- Electrical power distribution, power transmission and power generation laboratory
- Electrical machines and drives laboratory
- DEMVE laboratory
- Electrical automation laboratory
- EMC laboratory
- VR / AR laboratory
- Digital Twin laboratory
- Computer engineering laboratory
- Telecommunication engineering laboratory
- Energy technology laboratory
- Environmental laboratory
- Smart grid laboratory
- PCB Manufacturing space
- Additive manufacturing laboratory (3D Printing)
- Robot Laboratory
- Factory Automation Laboratory
- High Current and High Voltage Laboratory
- Indoor positioning test environment

In Technobothnia there is also workshops for upper comprehensive school under Luma Center in Ostrobothnia. They have a classroom at Technobothnia.

Contact persons are: Janne Koljonen, Sanna Söderlund, Kukka-Maaria Kallio

More information about the different laboartories and contact information can be found in attached excel file.

Technobothnia also has wireless networks in use for IoT communication

- Wi-Fi

- LoRaWAN
- DigiMesh
- Zigbee
- Bluetooth
- 4G LTE, 5G

Digita is giving for educational use, Digita’s LPWA (Low Power Wide Area) network that covers the whole of Finland, uses LoRa (Long Range) technology, which is the first technology in the world developed specifically for the Internet of Things. Data produced by measuring sensors that use a minimal amount of energy can be transferred long distances wirelessly.
Digita estimates that, by 2023, almost 20 million IoT sensors will have been installed across Finland
https://www.digita.fi/en/services/iot/iot-services/

Wapice IoT ticket is possible to use as platform for IoT projects in both Novia and VAMK. Wapice has provided the system free of charge.

Technobothnia has also IoT ticket devices from RuuviTag in installed on different positions.
RuuviTag is also used by Digitalisation Academy for education.

More information on how IoT devices can communicate with gateways and cloud services:
https://www.digi.com/blog/post/how-do-iot-devices-communicate

Technobothnia has also industrial communication networks mainly using OPC UA and Modbus.

OPC Unified Architecture (UA)
https://opcfoundation.org/about/opc-technologies/opc-ua/
Modbus
https://modbus.org/
Cabling at Technobothnia is done in a way that is easy to change and add cables.
Technobothnia does also have a wide ethernet cabling, that can be used for data transfers.

1.3 Education and research

- IoT course, Open course. Hans Linden, Novia
- Software Engineering Project. Timo Kankaanpää, VAMK
- https://ops.vamk.fi/fi/IT/2018/IITS3303/
- IoT is included in both IT- electrical- and automation engineering studies in both VAMK and Novia.
- Digital Economy, an open research platform for interdisciplinary research on innovations enabled by new technology. Include IoT. (University of Vaasa)
- https://www.uwasa.fi/en/fundraising/research-platforms/digital-economy
- The Smart Electric Systems (SES) Research Group (University of Vaasa)
- https://www.uwasa.fi/en/tutkimus/ryhmat/smart-electric-systems
- workshops for upper comprehensive school, Luma talks worhskops (University of Vaasa)

1.4 Projects

Internet of Things (IoT) is a collective name for applications where physical devices or people are equipped with sensors. The sensors collect data from its surroundings and delivers data via the internet to a data cloud or to another storage device that processes the data and then can control or monitor it the environment in which the sensor is located.

In the next few years, various services and products designed around IoT based technology to increase significantly. Society streamlined and new forms of services and products will be offered to more and more. For our region, it is extremely important that we establish one knowledge and an opportunity for our college students and companies to become involved in global development. Companies and especially SM companies in Ostrobothnia lacks a test environment to be able to develop its own IoT ideas and applications. The project's primary goal is to build a learning and test environment in Technobothnia that acts as a hub for the development of IoT applications in Ostrobothnia. Because Technobothnia is already a gathering place for different technologies, it is natural to build an IoT test environment here.

The test environment is supported by the existing knowledge that already exists in the three universities that collaborate on Technobothnia. Researchers, teachers and students everyone can be involved and contribute to the project's activities. IoT test and the learning environment will be built on the basis of initiated case studies. Different cases serves as an example of what problems can be solved with the help of IoT technology and the goal is to inspire SM companies to come to Technobothnia to test your own IoT applications and ideas.

The project is funded by the European Regional Development Fund (ERDF)
Project owner: Yrkeshögskolan Novia
Samarbetspartners: Vasa Yrkeshögskola, Vaasan yliopisto
Project partners: VAMK, University of Vaasa
Projekt leader: Tom Lillhonga

1.5 OboDigI 4.0 - Ostrobothnia Digitalization Industry 4.0

Duration of the project: 1.8.2021-31.7.2022
Project manager: Centria University of Applied Sciences
Collaboration with: Yrkeshögskolan Novia and Vaasa University of Applied Sciences
Project homepage:
https://obodigi.fi/iot/internet-things

Project description
Mitigating the effects of the corona epidemic and maintaining international competitiveness will require companies to pay particular attention to digitalization. In this situation, companies need the latest information on the opportunities and risks associated with technology and digitalization.

In collaboration with the region's polytechnics, webinars, workshops and demonstrations on robotics, artificial intelligence, the Internet of Things and cybersecurity will be conducted for the direct benefit of companies. This will create a wave of digitalization in the region, which will speed up the recovery of companies from the corona crisis and improve their international competitiveness.

OboDigI 4.0 Project has received funding from European Regional Development Fund and Regional Council of Ostrobothnia.

The project is funded by the REACT-EU Instrument as part of the European Union’s response to the COVID-19 pandemic.

Personnel:

Joni Jämsä, Project manager, Cyber security in Finnish (Centria)

Tom Tuunainen, Cyber security in Swedish (Centria)

Sören Mattbäck, Project leader (Ai, IoT and Robotics program for Novia and VAMK)

Hans Linden, Project worker

1.6 Energy for IoT and Other Electrical Devices (E4IoT)

The main aim of this project is to develop and demonstrate generic energy autonomic solutions utilising energy harvesting and energy storage for various industry applications.

Potential application areas for the developed technology are e.g. IoT, wireless communication, ICT, electronics, measurement technology, automation and maintenance. The reaching of the main target requires that the following tasks are carried out:

- Development of new type of harvester modules (e.g. inductive and thermoelectric). The modules convert energy from e.g. vibration, rotation or temperature difference into electric energy.
- Development of reliable and energy efficient electronics for the harvester modules.
- Development of energy storages for the harvester modules.
- Integration of the harvester modules, electronics, energy storages and wireless IoT into energy autonomic prototype systems.

The project also aims at increasing the cooperation between the companies and developing expertise and expert services of the local universities in this technology area. The research project is carried out in close cooperation with industrial companies and Vaasa University of Applied Sciences.

Duration: 1.9.2020-31.8.2022

Organisation coordinating the project: University of Vaasa

Project partners: Vaasan ammattikorkeakoulu VAMK

Project leader: Pekka Ruuskanen

Project researchers: Lauri Kumpulainen (until 1.1.2022), Birgitta Martinkauppi, Tuomas Rauta, Jussi Keskikuru
Contact persons: Pekka Ruuskanen
Research group/platform at the University of Vaasa: Smart Electric Systems, Renewable energy, Technology and Innovations
Project funding from: European Regional Development Fund ERDF, The Regional Council of Ostrobothnia
Project partner: Vaasa University of Applied Sciences
Co-operation partners: ABB, Ensto, Safegrid, Sähkötutkimuspooli, TJK Tietolaite, UTU, Vaasan Sähköverkko,Vaisala, Vaspec, Wapice, Viimatech Digital, Wärtsilä

1.7 Digitomkku - Big Data testbeds for wireless sensors in tomato and cucumber production

The main goal of the Digitomkku project is to (1) create and run a Big Data trial and learning platform for production of tall greenhouse vegetables based on test beds and managed by a multi-actor network. Project tasks include creation of sensor networks in greenhouses, data transfer, data management, data analysis and data use in decision making. The data architecture produced and the experience of its use are the basis for evaluating the benefits of data-driven cultivation for internal and business development of the test beds and the multi-actor network. In addition, the project will provide information on (2) the significance and controllability of intra-greenhouse variability of the greenhouse climate and (3) the usefulness of direct measurements of plant physiological status in irrigation control. The focus is on refining irrigation control through measuring physiological responses of plants and the effects of plant water management on the quality of end products.

Duration: 1.9.2019 – 30.6.2022
Organisation coordinating the project:

Financiers: EMR_Maaseudun innovaatioryhmät EIP
Project owner: Projektägare: Österbottens Svenska Producentförbund (ÖSP)

Partners: Österbottens Svenska Producentförbund (ÖSP), Natural Resources Institute Finland (Luke), University of Tampere
Project leader at Novia: Viveca Öling-Värnå

https://www.luke.fi/en/projektit/digitomkku/
https://vakra.fi/projektit/digitomkku/?lang=fi
https://www.novia.fi/forskning/fui/specialkunnande/hallbar-energiteknik/projekt-inom-hallbar-energiteknik/digitomkku-big-data-testipedit-langattomille-antureille-tomaatin-ja-kurkun-tuotantoon

1.8 Digital Twin

DigitalTwin refers to using a digital copy of the physical system, such as machinery, factory, control system, supply chain to conduct real-time experimentation and performance improvement. DigitalTwin project applies simulation software technologies to build virtual environments for industry.

Project duration: January 2020 - December 2020
Project actors at the University of Vaasa: Networked value systems NeVS, Technology and Innovations
Organisation coordinating the project: University of Vaasa
Project leader: Petri Helo
Funding from: Direct funding
Contact persons: Petri Helo, Rayko Toshev
Research group at the University of Vaasa: NeVS
Research partners: Companies
Collaboration partners: Several companies.

Reference:
Shamsuzzoha, A., Toshev, R., Vu Tuan, V., Kankaanpaa, T., & Helo, P. (2019). Digital factory–virtual reality environments for industrial training and maintenance. Interactive Learning Environments, 1-24. https://www.tandfonline.com/doi/abs/10.1080/10494820.2019.16280

1.9 FUSE: Future Smart Energy

In the FUSE project (Future Smart Energy) advanced methods basing on artificial intelligence and use of hierarchical communication system are being researched and developed for the operation and monitoring of Smart Grids.

This is a Finnish-German joint project where the partners in Finland focus on predictive maintenance and early indication of faults in medium voltage grids. The University of Vaasa participates in this project utilizing its expertise on power systems and defines the technical specifications for the condition monitoring system. Also the various applicable sensor techniques will be surveyed.

In Finland the project is primarily funded by Business Finland and the other partners include ABB, Jubic and VTT.

Project duration: August 2018 - July 2021

Project leader: Kimmo Kauhaniemi

1.10 TULEVA –Logistics and resource management of the future via ubiquitous precision positioning methods

The project will produce open source software and solutions for smart logistics, widen the future competence within smart logistics in the regions of Ostrobothnia and Southern Ostrobothnia, accelerate the application and service development on the basis of novel technology solutions and assist the development of projects within industrial internet and the related international funding application activities from international programs. This project is funded by the European Regional Development Fund.

The TULEVA project ensemble consists of four work packages, of which the first one (WP1: Building pilot environments: putting up test environments to Technobothnia and Frami) will be implemented in the investment project kicked off in conjunction with the development project. The other three work packages (WP2-4) are part of the actual development project and they are as follows:

WP2: Precision positioning in smart logistics: algorithm development and programming for precision positioning methods with satellite navigation signals, dual-frequency Galileo and wireless network measurements with UWB;

WP3: Logistics and mobile platforms: definition of the logistics processes and concepts that utilise precision positioning; as well as

WP4: Demonstrations and fostering of innovation ecosystem: demonstrating seamless precision positioning solutions for industrial internet, smart logistics and resource management as well as supply chain source authentication.

Project duration: September 2020 - August 2022

Units and groups involved at University of Vaasa

- Project actors at the University of Vaasa
- Digital Economy
- Technology and Innovations
- Smart electric systems
- Networked value systems NeVS

Organisation coordinating the project

University of Vaasa

Project partners

Seinäjoen ammattikorkeakoulu SeAMK

Funding partners

European Union - European Regional Development Fund

Personnel:

Petri Helo, Principal investigator at the University of Vaasa

Project leaders: Petri Välisuo and Heidi Kuusniemi

Other researchers at Univaasa: Heidi Kuusniemi, Timo Mantere, Ahm Shamsuzzoha, Mohammed Elmusrati, Mahmoud Elsanhoury, Dalbert Oneybuchi, Akpo Siemuri, Kannan Selvan

https://www.uwasa.fi/en/research/projects/tuleva-logistics-and-resource-management-future-ubiquitous-precision-positioning

1.11 H2C - Highway 2 Code

The partners of the project are Centria University of Applied Sciences (UAS), Oulu UAS, Kajaani UAS, Vaasa UAS, Jyväskylä UAS and Turku UAS. The student seeks to study at the option that looks most interesting for his/her career. The aim is for the student to study at the chosen UAS, but it is also possible for the student to choose courses from other partnering universities. Student performance is supported by local mentoring and it is possible to form study groups with other students of the same university.

The target group of the training are the people interested in programming and the existing stereotypes are aimed to be removed to respond the need of employees of the industry. The goal is especially to train the immigrants and female, both underrepresented in this professional field.

At the same time, fresh perspectives are being brought to the industry: business-minded and user-driven future actors. Previous work or study background in the non-IT sector is an opportunity that opens up a new kind of innovation and user-orientation in product development.

Each of the participating universities of applied sciences offers its own variety of courses based on the needs of regional industries.

The projects devised ways in which Wapice Oy's IoT-Ticket® platform and Techat Oy's sensor can make life easier, reduce energy consumption and keep food fresh.

The project ended in 2021, but may continue in 2022.

https://h2c.fi/highway-2-code-in-english/

(Article in finnish) https://www.vamk.fi/fi/news/kahdeksan_kuukauden_koodausrutistus

1.12 Older projects

SG Platform (2018-2019)

https://www.uwasa.fi/en/tutkimus/hankkeet/sg-platform

Workshop: Open Innovation for Digitalization: Industry 4.0, Internet of Things, CleanTech and Energy Systems

https://www.uwasa.fi/fi/events/openinnotrain_workshop

1.13 Upcoming projects

Pohjanmaan liitto on tulevaisuuden tiekarttana osoittanut, että heille osoitettavat projektit koskisivat yhdessä luotuja ”tiekarttoja” joihin ollaan yhdessä oppilaitosten ja yritysten kanssa katsottu seuraavat aihealueet tarpeellisiksi.

1.14 The needs and expectations of companies and educational institutions from the IoT knowledge platform

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The report was made for project E4IoT, University of Vaasa.

1.14.1 Interviews with companies in the E4IoT project

Through questions and discussion, we try to find out in the survey about IoT and the use of data in companies, what their prospects are and whether they need services for IoT and data usage.

The questions also include energy harvesting, whether it is a familiar term to companies, whether they have a need or even already use IoT equipment or the like that uses some form of harvesting as an energy source.

The questions and interview as well as the discussions were conducted in Finnish or Swedish and answers translated to English for the report

The questions that laid the groundwork for the interviews were as follows:

The current situation of the company?

- What IoT platform are you using?
- IoT devices, what self-developed and purchased IoT devices do you have?
- Do you have IoT as part of process monitoring and product development?
- Future needs, eg in terms of competence, training needs?

Other skils?

- IoT staff, finding staff?
- Product development, do you have your own product development R&D?

- Cooperation (eg Cooperation or university cooperation. Do you have cooperation with other companies)?
- Vision, how do you see IoT in the future?
- The need for an IoT laboratory, what would you use an IoT laboratory with on Technobothnia?
- What IoT networks do you use (Sig Fox, LoRa, NB-IoT, Wi-Fi, etc.)?
- What cloud services do you use?
- Do you do Data Analysis? What tools do you use?
(R, Python, Apache spark / Storm, PIG / HIVE, MATLAB, Simulink, Tableau, Power Bi, Qlik View, Splunk, Google Data studio?)
- Do you have IoT based apps?
- Open Data. Is there a need / can you provide open data for research use?
- IoT harvesting, is there a familiar concept, are there needs, would it be helpful?
- Open feedback?

The length of the interviews was about 45 minutes to 1 hour. The interviews were conducted mainly remotely via Zoom. A few interviews were also conducted on site.

The interviewed companies received the questions in advance so that they had time to discuss the issues internally and find out, for example, about the technology used by the company, etc.

1.15 Results of interviews

The results of the interviews are presented as observations collected from the discussions. We did not ask in the form of a form to answer between 1-5 how important you consider things, but we asked companies to tell us how they work and what their opinions and needs are.

The discussions were recorded as memos of a few pages. The most important issues have been selected for the report, and efforts have also been made to open what is at stake and to make remarks on various issues at a general level as well. At the outset, it is also good to note that IoT is a commonly used term, however, in industrial use, the term IIoT should be used, i.e., Industrial Internet of Things.

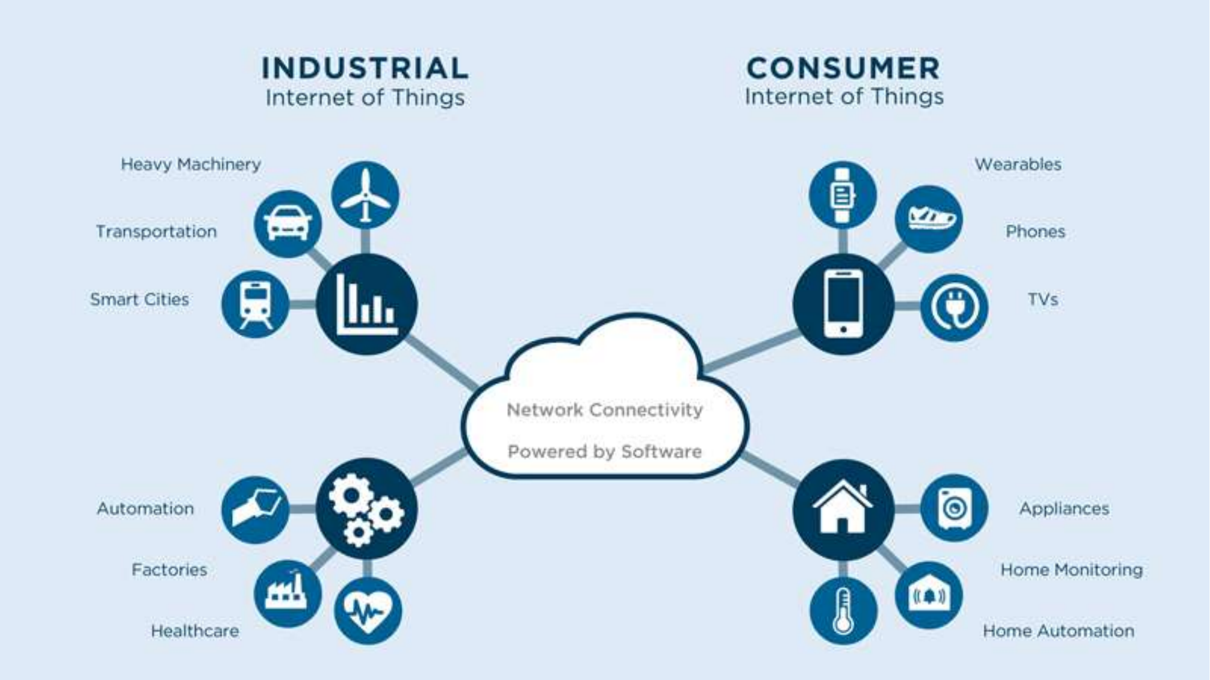

Figure 1.2.2.1 (Picture: https://intellinium.io/why-iiot-is-different-from-iot/)

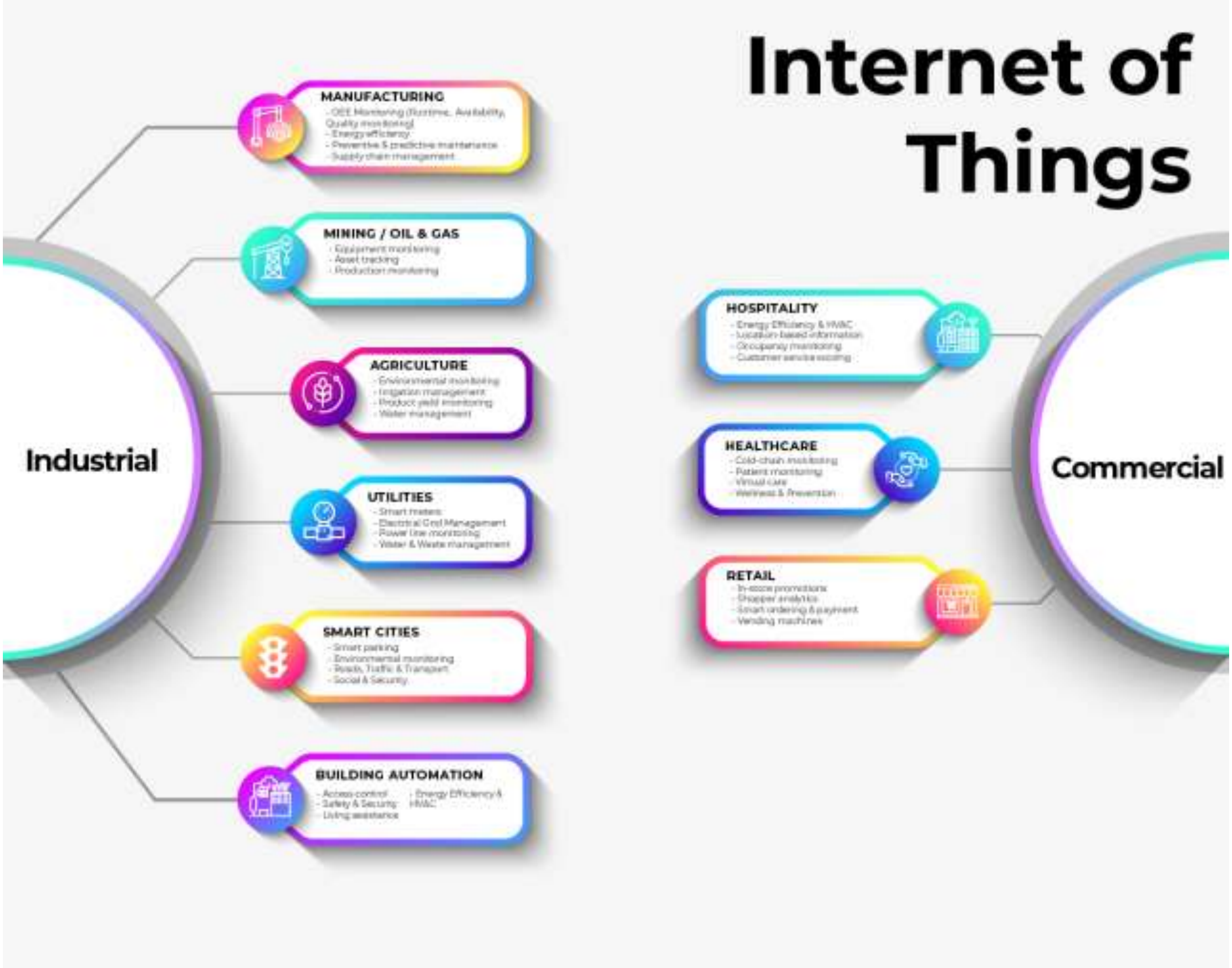

Figure 1.2.2.3 Industrial and commercial (personal) use should also be considered. (Picture: https://ubidots.com/blog/iot-consumer-vs-commercial-vs-industrial-main-overview/)

1.16 IoT platforms, what is used?

Many companies have their own IoT platforms developed for their own needs. Most programmed in Python or C (C ++), and the necessary functionality added over the years.

Some companies had ready-made systems such as the Wapice IoT ticket or the Fliq platform, in which case the development of the system is mainly done by the developers of those platforms. ABB also has an ABB Ability platform.

The reason for creating our own platforms has been that ready-made platforms that are easy to use and scalable as needed have only been available in recent years. The transition from one's own platform, especially made for one's own needs, to a finished one would require a rather big decision from the company, as well as taking into account old customers, i.e. in a way, at the same time, we should continue to maintain our own platform.

There are also open-source platforms, in which case it can be difficult to know if the platform will be able to sell as part of your own system when you have your own software this problem does not exist.

In terms of cost-effectiveness and maintaining competitiveness, the decision to deploy a ready-made system is likely to have to be taken sooner or later, especially if a lot of additional development is needed on its own platform, which may be unprofitable due to the difficult availability of additional resources.

The advantage of ready-made IoT platforms is that they can usually import third-party IoT data without any problems. Products from different manufacturers usually have the necessary settings, etc., so that you can create functional entities in a “select and drop” style via the graphical user interface, without even having programming skills, it is enough to know what functionality you want to create. In other words, it takes advantage of previous projects that have been done by yourself or that another client on the platform has done on the same platform.

1.17 IoT devices, whatever self-developed devices in use

Some companies have their own self-developed IoT sensors or devices. Usually, however, IoT sensors are purchased from a “catalog,” meaning that commercial finished products are used, especially on the sensor side. The sensors may be used to make IoT systems suitable for personal use, e.g. to measure things. However, only a few companies had their own IoT systems made for commercial use.

As it is not so important to measure and produce different data, it is better to use an IoT sensor that can be easily replaced with another one from another manufacturer, e.g. if there is a shortage of components and that sensor cannot be purchased. What matters is how the data is transferred and the platform on which it is used, i.e., the software side in a more important role than the HW.

1.18 IoT as part of process monitoring and product development?

Companies that have their own products manufactured mainly do product development as a subcontractor.

Only larger companies may have their own product manufacturing and product testing on their own premises.

That is, companies often do not directly have IoT devices themselves in production, product development, and testing. For example, some companies had testers with sensors that collect data in the cloud.

Data have been collected in both testing and manufacturing before the concept of IoT, e.g. in process automation. So, this is not a completely new thing. Data has been exported via fieldbuses to various production control systems, perhaps the novelty with IoT is that data is transferred through various edge and gateway devices to cloud services where data can be processed as needed and different data sources can be connected to BI systems, making business-critical decisions based on data.

When discussing process maintenance, maintenance, etc., especially in companies with older generation owners, it can be difficult to make them understand the benefits of data collection. The first steps may be to manually record information on paper, eg because some maintenance was done, who did it, and downtime, eg during maintenance and repair. Being able to demonstrate the benefits of even simple manual data in developing functionality, moving forward with the installation of IoT sensors, the deployment of ERP systems, etc. Change management and demonstration of commercial benefits play a key role! It is also important to make companies aware of how data can be used to manage a company's operations. The data itself rarely provides added value but understanding the data and combining the collected data with other data sources, e.g., to provide services.

1.19 Future needs, e.g. in terms of competence or training needs?

Digitalisation brings challenges to companies in terms of know-how. VAMK has conducted a competence survey in which several of the interviewed companies have participated, i.e. more detailed information can be found in that survey.

A few commented that it would be good if someone else thought about what kind of “skills packages” it would be good to offer to staff, especially with regard to digitalisation. These are certainly based on the VAMK competence survey.

Here are comments on what companies have responded to that they hope for:

- In general, what is and what is coming from current technologies
- Bootcamp, ie the practical use of, for example, the use of the Wapice IoT ticket platform together with students. Ready-made entities, experimental activities.
- Cyber security
- Design and project expertise
- Productization, development of service business
- The role of the product manager
- The courses could be “General level” because you can apply for in-depth information yourself if necessary.
- About network technologies, eg LoRa and other networks.
- Low power Bluetooth
- Electronics design, circuit board design, etc.
- Electronics skills in general, Embedded systems (prototyping, testing, etc.)
- How to add value to the customer using IoT / data (technical + commercial)
- Data Mining, data analytics
- Radio technology, IoT communication wirelessly with various technologies.
- IOS and Android development
- Go language
- Mathematical simulation / modeling
- New protocols
- Should training have some direct benefit to the company, customized training?
- Ui / UX design
- How to create added value for the customer must increasingly be considered in teaching as well!
- How to trust data (cyber security, data analytics)
- Value generating algorithms (mathematical + commercial)
- How to transfer data cost-effectively (commercial) and reliably (cyber security)

- Data-based decision making (management)

1.20 IoT staff, finding staff?

The comment is that few companies are looking for an IoT expert, but staffing is sought with a slightly broader concept such as a programming, IT or electronics specialist. However, almost all companies agree that it is difficult to find experts, especially if you want to find experts with enough suitable experience and skills to be productive right away. Most of the new employees come directly from the school bench, which means that the skills are very variable and the employee's stay in the company for a longer period may be less.

Another common comment is that one often seeks a “good guy” who has a desire to learn and can work independently, meaning that technical know-how can be acquired over time, making it more difficult to change a person to fit the company’s work atmosphere.

There are also varied experiences of foreign workers, in general it seems that a person stays in the company for 1-2 years, after which he or she often applies to leave Vaasa.

Here, it would be important to be as well integrated as possible into Vaasa and jobs in Vaasa during my studies. If a circle of friends is missing, the student will easily apply elsewhere.

1.21 Product development, do you have your own product development R&D?

Several companies have their own product development. However, many of these do product development in connection with customer projects, ie there is a customer project where new products or services are developed. These projects can also result in products or services that can be sold to other customers in the future.

Thus, few software companies had their own product development, but product development is outsourced, and the know-how and lessons learned from it.

Larger companies have the full scale, product development, service production, manufacturing, and testing, as well as the distribution channels needed for this.

In smaller companies, co-operation with others is emphasized when it comes to product development, ie the network is utilized in, for example, electronics design, programming and testing. Your own resources would not be enough to do everything. It should be noted that it would be worthwhile to invest in the formation of networks in small and medium-sized enterprises, it could also bring benefits to the emergence of new products and services in terms of IoT and data collection and analysis.

1.22 Cooperation – with companies or universities?

There is certainly cooperation between all companies at varying levels. For small businesses, operations are often based on an extensive subcontracting network. However, very few companies have co-operation-style activities, not even larger ones.

There is cooperation between universities, especially in larger companies, and smaller companies wanted more cooperation with universities.

The remark here may be that there was less co-operation with local universities than might have been expected, especially in larger companies there was more co-operation with Aalto and the University of Tampere than with Vaasa universities.

Collaboration with Novia was least encountered in this interview from universities.

1.23 Vision, how do you see IoT in you in the future?

Quite unanimously, the response from all companies was that they see IoT and data collection increasing, the benefits of data increasing, and that, to a very large extent, it will be critical for many companies to continue to operate. This is a competitive advantage and a requirement from customers to obtain data that can be used, for example, to optimize their own operations or to show energy consumption, carbon footprint, etc.

Here, perhaps, it can be said that digitalisation is gaining momentum in industry now faster than ever, but also in areas such as construction and home automation, and it is precisely energy monitoring and process efficiency that will certainly bring the greatest benefits and demands in the future.

In personal life, too, digitalisation and data collection have increased and will certainly continue to increase. The collection of personal data has already been common in sports, but is also increasing in medicine, especially in home care, housing, transport (motoring, cycling, public transport) and monitoring one's own carbon footprint.

When discussing with the city, carbon neutrality becomes clear and how a lot of different data on traffic, real estate, etc. activities are needed to achieve this, where energy can be saved, and operating methods changed.

Space data may be a novelty in how ground-based data can be combined with data provided by small satellites, such as images showing the growth of fields and forests, etc. When these are analyzed, new practices and services can be created, optimized, e.g.. The University of Vaasa studies a lot of issues related to space data.

1.24 What would you use an IoT lab with on Technobothnia?

One of the questions was what services you would like to have in an IoT lab with Technobothnia.

Listed below in a vague order are the suggestions that emerged from the interview. That is, they are not in any order of priority. Some responded that the services needed are directly depending on what projects are underway and what tests their clients require. It was generally hoped that the price level should be affordable for services, otherwise it would be easy to start doing it on your own premises or by a subcontractor.

- EMC tests, electronics
- Calibration of meters and equipment
- Calibration of production testers
- Data anomalies in different data sets
- Testing of algorithms and modeling if ready-made suitable data sets can be found, ie collected data.
- Finding limit values should be able to be manually simulated, tested, and adjusted.
- Life cycle and maintenance modeling, e.g. proactive analytics, to support decision making. “Data wizard decision”.
- The IoT laboratory could do research and development in general, from which companies would benefit as new opportunities in products and services.
- Could act as an expert in different wireless networks, ie advise on which network to use, including location technologies (e.g. BT mesh, Wirepass mesh, UWB)
- 3D modeling and visualization of IoT systems
- Simulation of rare things, e.g. in MATLAB environment. As an example, in cable networks, partial discharges that indicate abnormal behavior.

It can take up to decades for this to happen in a live environment.

- IPR service on how to fund the data collected
- Data analysis service.
- Prototyping
- If there was a working PCB router, use it (milling Proto circuit boards)
- Labra Data Bank on regulations, frequencies, etc. Which would help in product development.
- Competence in standards in general, especially performing tests according to standards

One thing that might have to be mentioned separately was if there was a working environment in place where one could test, for example, the functionality of a sensor or the use of a wireless network. In other words, an IoT platform, various wireless networks, connections to industrial data networks, etc. would be ready, especially if one could build, for example, demo entities that can be presented to the customer or decision-makers. In other words, visualization and modeling would also be part of the service.

Building a simple operating environment to test a single component can be a tedious process, especially if you need to take network measurements.

Modeling was another that came up several times on how to be able to model the operation of sensors or the functionality of entire systems.

1.25 What IoT networks do you use?

According to the interview, LoRa is the most used, but all IoT networks are used.

The use is largely dependent on the project, ie the customer-defined network. Costs also affect what communication can cost. In the case of large amounts of data, certain networks may not be able to transmit or may be expensive to use.

Some also had country-specific local area networks in place.

1.26 What cloud services do you use?

It uses all the most common cloud service platforms, ie Microsoft Azure, Amazon Web Services (AWS), Google Cloud. The most special mention was the testing of Alibaba's cloud service.

Some also had their own cloud-based data collection platforms.

In principle, there are no European cloud services yet, i.e. GDPR issues must be taken into account when using cloud services.

1.27 Do you do Data Analysis? What tools do you use?

Some companies performed the Data analysis themselves, but these were in the minority.

The tools used were mostly Python or C ++ programs, and MATLAB + Simulink software was used for modeling and data analysis. BI tools were also used on the business side. The Python language and R were mentioned if building your own modeling’s.

In Azure cloud games, Data Bricks is used by some to manipulate data, at least for testing purposes.

Apache spark and Scala were mentioned in the same context.

As a comment, analytics software varies as needed, especially in customer projects, and some software is out of date, as exemplified by Qlick View software. That is, learning how to use certain software may not be essential.

Larger companies have basically all the most common software for analyzing data.

1.28 Do you have IoT based apps?

Many companies had apps that presented IoT data or apps that could track alerts or the like, for example. Usually, though, those apps were made for a customer. IoT platforms also usually include the ability to use the App for tracking. In any case, the use of apps in industry may not be as common as it is on the “consumer” side, e.g. in the monitoring of health devices.

1.29 Open Data. Is there a need / can you provide open data for research use?

The first point is that a lot of data is already being collected. Especially in customer projects, data is used and utilized within the project, but for example, sharing customer data with a third party can be challenging. Even the fact that raising an issue with a customer can be delicate, and without a direct benefit to the customer, it certainly won’t materialize.

The customer does not usually want to share the data, even if it does not have a direct immediate value in money, they still want to ensure that the data is not accompanied by critical information for the company, or that someone can use the data to determine factors related to competition and profitability (reverse engineering).

Looking the other way around, open data would benefit businesses. If you could find ready-made data sets that are suitable for the company's operations, you would not need to collect data for the tests yourself to get started. The same goes for research, new projects could immediately start testing ideas and see if they work through the right test data. If simulated data is created, it is very difficult to make it real, especially when it comes to large amounts of data.

That is, if open data is desired, the first step is probably to convert it to a format from which the origin or, for example, personal data cannot be identified. The data collector should also have well-secured servers and good management tools to manage and secure the onward distribution of data. For example, if you are researching something, you should first make agreements to ensure information security, etc.

However, several companies stated that they could, at least in principle, share data, and that it might be easiest to think with universities what data is needed and where it could be obtained. For example, data for certain selected properties could be collected at the beginning, it would be quite easily accessible and shared.

Technobothnia itself collects data together with Vaala technologies and Tammi Kiinteistötekniikka Oy to improve home automation. The data is exported to the Wapice IoT ticket system.

Vaala specializes in collecting data from old systems that do not themselves have “intelligence” and converting the data to modern systems for use.

1.30 IoT energy harvesting

For most companies, “IoT energy harvesting” was a familiar concept, some had also done their own experiments, or the technology was familiar, at least on a theoretical level.

However, according to the interview, none of the equipment used for energy harvesting was in use. Here, for example, the solar panels on the roof of the property are not considered, but the energy collected from the surrounding area at the sensor level or to the transmitter module was specifically asked here.

Several companies saw direct benefits and needs. Especially if there is a need to take measurements on the high voltage side or in places where cable routing is challenging. The same applies if replacing the battery is difficult and expensive. Post-installation of sensors is often also easier and cheaper if energy could be harvested nearby, eg from engine vibration, than installing wires and the like.

Everyone understood the problem with battery usage is that you need to think carefully about the measurement frequency, that Data can’t be real-time and not necessarily even every day to have enough battery power for years, even ten years.

In the future, however, more and more data will be needed, and real-time or near-real-time data!

Open feedback?

- In general, there is a need for software expertise and project expertise. HW's expertise is not so critical, it can also be found as a purchasing service if needed, but experts are also needed. More knowledge of mathematics and statistics is needed.
- Educational institutions should give students the opportunity for startup activities, entrepreneurship in other cities much more!
- Productization and earnings logic, especially on the service side, would be important to get better in companies. Would there be a solution to this through training?
- Build additional services on top of basic services in the future.
- Starting service sales is a challenge.

The interview and nice conversation were generally praised.