COMPUTE-PROXIMAL ENERGY HARVESTING FOR MOBILE ENVIRONMENTS: FUNDAMENTALS, APPLICATIONS, AND TOOLS

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Thanks to my parents and wife who allowed me to dream

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SUMMARY

Over the past two decades, we have witnessed remarkable achievements in computing, sensing, actuating, and communications capabilities of ubiquitous computing applications. However, due to the limitations in stable energy supply, it is difficult to make the applications ubiquitous. Batteries have been considered a promising technology for this problem, but their low energy density and sluggish innovation have constrained the utility and expansion of ubiquitous computing. Two key techniques—energy harvesting and power management—have been studied as alternatives to overcome the battery limitations.

Compared to static environments such as homes or buildings, there are more energy harvesting opportunities in mobile environments since ubiquitous systems can generate various forms of energy as they move. Most of the previous studies in this regard have been focused on human movements for wearable computing, while other mobile environments (e.g., cars, motorcycles, and bikes) have received limited attention.

In this thesis, I present a class of energy harvesting approaches called compute-proximal energy harvesting, which allows us to develop energy harvesting technology where computing, sensing, and actuating are needed in vehicles. Computing includes sensing phenomena, executing instructions, actuating components, storing information, and communication. Proximal considers the harvesting of energy available around the specific location where computation is needed, reducing the need for excessive wiring.

A primary goal of this new approach is to mitigate the effort associated with the installation and field deployment of self-sustained computing and lower the entry barriers to developing self-sustainable systems for vehicles. In this thesis, I first select an automobile as a promising case study and discuss the opportunities, challenges, and design guidelines of compute-proximal energy harvesting with practical yet advanced examples in the automotive domain.

Second, I present research in the design of small-scale wind energy harvesters and the

implementation and evaluation of two advanced safety sensing systems—a blind spot monitoring system and a lane detection system—with the harvested power from wind. Finally, I conduct a study to democratize the lessons learned from the automotive case studies for makers and people with no prior experience in energy harvesting technology. In this study, I seek to understand what problems they have encountered and what possible solutions they have considered while dealing with energy harvesting technology. Based on the findings, I develop a comprehensive energy harvesting toolkit and examine its utility, usability, and creativity through a series of workshops.

CHAPTER 1
INTRODUCTION

In 1991, Weiser envisioned the computer for the 21st century, launching the field of ubiquitous computing [1]. Since then, many of his associates have realized three core technologies Weiser emphasized: 1) cheap and low-power computing; 2) software for ubiquitous application; and 3) wireless networks that tie all the devices together. Achievements in these fields have been remarkable over the past three decades. However, the 21st century is here, and we are not yet living in the world he foretold. Computers do not blend naturally into everyday objects. We may find the reason for this in the areas Weiser missed.

In 2005, Paradiso and Starner pointed out that the overriding limiting factor for mobile and ubiquitous electronics is the slow progress in the development of energy density and battery technology [2]. They proposed energy harvesting modes as a way to solve this problem, which include ambient radio, light, heat, vibration, and motion energy. Although energy harvesting has shown great potential in some cases (e.g., heel-strike harvesting in shoes or solar cells in a bright environment), it has not been widely adopted in the real world due to the limited amount of power it can harvest in wearable computing environments.

In 2020, Abowd argued for computational materials as a field that needs to be further studied to complete Weiser's vision [3]. He insisted on the simultaneous importance of three core areas—*power, scale, and form factor*—in designing computers. My thesis deals with *power*. From a user's point of view, power management can cause problems such as frequent charging and replacing batteries. From a researcher's perspective, limited energy may bring restrictions on functionality, computational power, or form factor. Therefore, *power* is one of the critical challenges hindering the completion and expansion of the ubiquitous computing vision.

As long as there is an appropriate target environment, energy harvesting is a promising way to solve the power-related problems. For example, researchers have examined various ambient energy sources (i.e. light [4, 5], heat [4], vibration [5], wireless communication signals [6, 7, 8], power lines [9], and kinetic energy [5, 10, 11]) as alternative power when developing computing devices. The harvested energies have been used in a variety of computational applications ranging from intelligent sensors [12, 13] to augmented everyday objects [14, 15].

In stationary settings, it is not as difficult to find power sources. However, if something or someone moves—automobiles, humans, or bicycles, for example—power harvesting may be in demand. Unlike in other mobile settings, energy harvesting in automobiles has not been exploited beyond replenishing the main power supply. The most obvious examples are regenerative braking and engine heat recovery systems. The former allows for the conversion of kinetic energy to electric energy, while the latter can turn wasted heat energy from a motor or an engine into electric energy. Both approaches store the harvested energy in the main battery and later supply it for driving. In other words, the past approaches in automobiles have been done without considering which computing needs exist and what benefits can be derived.

One possible reason why there are limited applications is the assumption that any systems installed on automobiles would be able to easily and reliably receive electrical power anywhere from the main battery. However, there are many situations in which this assumption is not true. In fact, a major cost, inconvenience, and source of failure for adding or retrofitting sensors and electronic accessories to automobiles is wiring the systems into the main battery of the car[16]. Therefore, I first select an automobile as a promising case study and investigate the ways of using different energy harvesting modes in the automobile. After that, I develop a toolkit for wind energy harvesting, which has not yet been studied much yet in automobiles and other means of transport. Then I evaluate how confident and creative people with no prior experience in energy harvesting can use the toolkit.

To repurpose energy harvesting technologies in mobile environments, I propose a new concept called *compute-proximal energy harvesting*, which is an approach that allows us to consider the development of energy harvesting hardware where computing, sensing, and actuation are needed. In this approach, *compute* refers to sensing phenomena, executing instructions, actuating components, and communication. *Proximal* considers harvesting energy available around the specific location of where computation is needed. Under this concept, the purpose of energy harvesting is not to recharge a vehicle's battery, but to start from the computing needs and implement complete wireless, self-sustainable systems.

1.1 Thesis Statement and Research Questions

In this dissertation, I conduct a focused study on the emerging opportunities, roles, design guidelines, applications, and tools of energy harvesting for mobile environments. The systems, experiments, and user studies presented in the remainder of this dissertation address my thesis statement:

A clear process and supporting tools for designing compute-proximal energy harvesting solutions for mobile environments enable users to confidently and creatively develop systems that are self-sustaining and easily installed.

I break down each aspect of this thesis statement into a research question that provides evidence for my claim. I explore the following questions:

- **RQ1:** What are the opportunities, limitations, and guidelines to harvest heat, wind, vibration, and solar energy for self-sustainable computing systems in a specific mobile environment—the automobile?
- **RQ2:** How can we leverage a small-scale wind energy harvester to develop self-sustainable sensing systems and retrofit them to automobiles?

- **RQ3:** What kinds of challenges have researchers and makers experienced while working on energy harvesting technology in their previous projects?

- **RQ4:** How can a tool allow people with no prior experience in energy harvesting to confidently and creatively prototype wind energy harvesting solutions for automobiles and other mobile environments?

Table 1.1 presents a concise summary of the research activities I completed, along with the evaluation methods employed for each research project.

Table 1.1: Summary of research questions, employed methods, and brief descriptions of all the projects in this dissertation

Research Questions	Chapter	Methods	Study Overview
RQ1: What are the opportunities, limitations, and guidelines to harvest heat, wind, vibration, and solar energy for self-sustainable computing systems in a specific mobile environment—the automobile?	Chapter 3	Analytical and empirical evaluation of energy harvesting modes field deployment	Conducting a comprehensive analysis of heat, wind, vibration, and solar energy harvesting and developing design guidelines and practical examples
RQ2: How can we leverage a small-scale wind energy harvester to develop self-sustainable sensing systems and retrofit them to automobiles?	Chapter 4	Controlled experiment, simulation, field deployment	Investigating the design space of inch-scale wind turbines and implementing two wind energy harvesters with advanced driving assistant systems
RQ3: What kinds of challenges have researchers and makers experienced while working on energy harvesting technology in their previous projects?	Chapter 5	Semi-structured interviews with qualitative analysis	Investigating the challenges and requirements of an energy harvesting toolkit
RQ4: How can a tool allow people with no prior experience in energy harvesting to confidently and creatively prototype wind energy harvesting solutions for automobiles and other mobile environments?	Chapter 6	User study with people who do not have any prior experience in energy harvesting with pre- and post-study quantitative and qualitative measures	Developing and evaluating an energy harvesting toolkit for self-sustainable computing

1.2 Contributions

In this dissertation, I make the following contributions to the field of self-sustainable computing and compute-proximal energy harvesting as shown in Table 1.2.

Table 1.2: Contributions for each research question

Research Question 1
• A comprehensive evaluation of theoretical and empirical limits on compute-proximal energy harvesting for automotive applications, • Step-by-step design guideline to adopt the most appropriate energy harvesting mode and integrate it into the place in which computing is required, and • Development of self-sustainable automotive applications that run intermittently
Research Question 2
• First ever explorations of high-speed inch-scale wind energy harvesting systems, and • Development of self-sustainable advanced automotive sensors that run continuously
Research Question 3
• An investigation of the challenges that makers or researchers have faced when using energy harvesting technologies with possible solutions for them
Research Question 4
• Design and development of a wind energy harvesting toolkit to expand the concept of compute-proximal energy harvesting, • Evaluation of perceived difficulty and confidence through a hands-on experience study with people who have no prior experience in wind energy harvesting, and • Assessment of how creatively people can design self-sustainable systems with the proposed toolkit.

1.3 Dissertation Overview

The remainder of this dissertation is organized as follows (See Figure 1.1 for a visual overview): in Chapter 2, I provide a survey of related literature on energy harvesting and self-sustainable sensing systems in automobiles and review relevant approaches that have been performed in the area of ubiquitous computing. In Chapter 3, I present the opportunities, challenges, and design guidelines of compute-proximal energy harvesting with practical examples. Chapter 4 analyzes the details of compute-proximal wind energy harvesting further in depth and implements self-sustainable driving assistant systems with inch-scale wind turbines. In Chapter 5, I discuss the challenges that makers and researchers have experienced in the utilization of energy harvesting technology and present possible solutions to those problems. In Chapter 6, I design a wind energy harvesting toolkit, called Exergy, the design of which is influenced by the findings of the previous chapters. Exergy is then evaluated with novices in energy harvesting to determine if it increases both confidence and creativity. I conclude this dissertation in Chapter 7 with contributions and suggestions for future direction for the ubiquitous computing and human–computer interaction research communities.

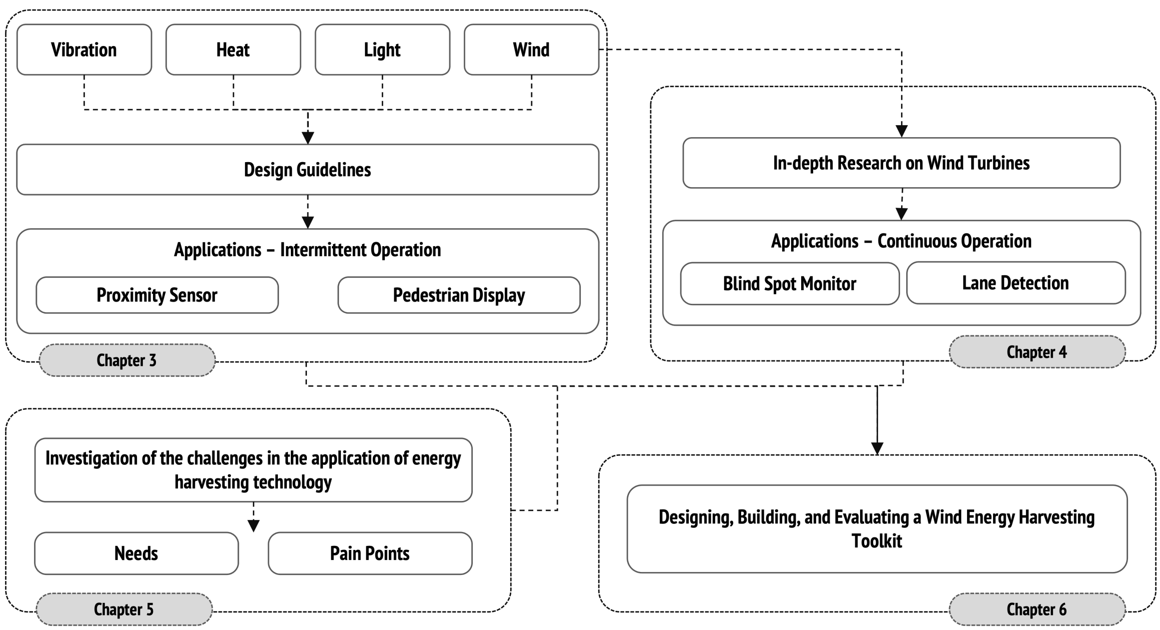


Figure 1.1: Overview of the dissertation

1.4 Acknowledgment of Collaborators

This thesis presents multiple projects that I have led during my Ph.D. program. However, this would not have been possible without the support of my advisers, mentors, and numerous internal and external collaborators. I recognized their contributions in the Acknowledgments section of this thesis. However, I use only the first person singular for the remainder of this thesis.

CHAPTER 2

BACKGROUND AND RELATED WORK

In this section, I present a brief background on conventional energy harvesting approaches and how they affect basic system operations in automobiles. Second, I review the emerging trends in energy harvesting and novel sensor design and operation in the automotive domain. Third, I explore how energy harvesting can advance the design of sensor systems in nonautomotive domains. Finally, I share the latest examples of two core technologies—energy harvesting and low-power sensing—in ubiquitous computing.

2.1 Conventional Energy Harvesting in Automobiles

Research on energy harvesting in automotive systems has drawn attention for decades. With the increased adoption of hybrid and electric vehicles, there has been a focus on energy harvesting for the purpose of recharging the main battery. To achieve this goal, researchers have explored energy harvesting in different locations of the vehicle, including heat energy recovery from the engine compartment [17], regenerative power from braking [18], and kinetic energy harvesting from the suspensions near the wheels [19, 20]. In particular, thermoelectric harvesters have been a notable energy harvesting strategy, as the majority of fuel energy is converted to heat energy and dissipated around engine parts or in the exhaust [21, 17, 22]. The first application of my work builds on the latter and exploits thermoelectric harvesting at the exhaust pipe for the design and implementation of self-sustainable sensor systems.

2.2 Self-powered Automotive Sensors

In recent years, innovative sensing approaches have been introduced through materials science and engineering communities. Jin *et al.* developed a self-powered three-axis acceleration sensor using a polarization-free, high-crystallization β-PVDF-based piezoelectric nano-generator for real-time collision monitoring [23]. To monitor a driver's behavior, Meng *at al.* mounted pressure-sensitive triboelectric nano-generators (TENG) on the accelerator, brake, and on the driver's glasses [24]. Novel self-powered sensors and nanogenerators were also explored for a variety of applications, including tire-pressure, humidity, and fluid level [25, 26]. However, most of these approaches did not fully consider other necessary factors such as computing and communication when it comes to self-sustainability. For example, the TENG pressure sensor can operate without any power sources and provide surplus energy to other components (e.g., microprocessor or radio-frequency module), but this may not be enough to reliably compute and communicate the sensing data. Therefore, the system may requires additional power sources (e.g., the main battery of a vehicle or other energy harvesters). Although the advanced material-based self-powered sensors open up new possibilities, they also illustrate the need for new approaches that take into account other pressing factors. My work bridges this gap by investigating how harvesting, sensing, and computing can be streamlined into a practical system.

2.3 Computing Needs in Automobiles

Low-power sensing has not been fully exploited in automobiles due to the misconception that energy is always readily available from the fuel and engine. Recent work has adopted low-power systems such as the Raspberry Pi platform [27] to demonstrate "add-on" functionalities such as driver assistance. V^2iFi [28] demonstrated in-vehicle monitoring of occupant respiratory rate, heart rate, and other vital signs using a compact impulse radio and Raspberry Pi platform running in real-time. Verma et al. [29] explored signaling intent to pedestrians using an LED display controlled by Raspberry Pi attached to the front of a shuttle. I am inspired by these works that utilize readily available open source hardware platforms and would like to demonstrate additional compelling automobile applications.

2.4 Proximal Harvesting for Self-sustainable Systems in Nonautomotive Domains

A critical lesson we learned from previous studies in other domains is that computing, sensing, and actuating should be considered together when developing or applying an energy harvesting technology. In 2001, Shenck and Paradiso integrated a flexible piezoelectric foil into the insole of a shoe and scavenged electricity to identify people using RFID in a smart environment [30]. All the required elements were in one place where the function was needed. Later, Krupenkin and Taylor generated electricity up to 15 W [31], which has led to innovation in many areas including personal healthcare [32]. Paradiso and Starner examined how energy generated from human motion and heat could be used for wearable devices such as watches and shoes [2]. Yun *et al.* examined a velocity damped resonant generator as a wearable energy harvester and found that it continuously could power many body-mounted wireless sensors and medical telemetry devices [33, 34]. Beyond wearable computing, researchers have also studied harvesting approaches in the home environment. Campbell *et al.* designed, built, and deployed a self-powered water activity sensor (WATTR) [14]. Zhang *et al.* augmented everyday objects with self-powered sensing tags in home and building environments [15].

2.5 Ubiquitous Computing Applications Based on Energy Harvesting

In ubiquitous computing, power source maintenance has remained a long-standing challenge for the deployment of computing devices in everyday physical environments. Owing to this challenge, energy harvesting technologies have been studied as a promising solution and have been explored by taking advantage of everyday environments and/or activities. For example, various ambient energy sources in everyday environments have been studied as a way to harvest energy and deploy self-sustainable computing devices (e.g., temperature sensor, humidity sensor, and/or light intensity sensor) in different environment applications, including light [4, 5], temperature [4], vibration [5], wireless communication signals [6, 7, 8], and power lines [9]. Moreover, everyday activities such as body movements [10, 11] or tool usages [5] have been explored to demonstrate the application of energy harvesting techniques to power computing devices such as activity sensors and modules to communicate sensed activities.

2.6 Low-Power Sensing in Ubiquitous Computing

To create sustainable ubiquitous computing systems, low-power or self-powered sensing is a critical foundation. Researchers have explored low-power or self-powered sensors such as photodiodes for gesture and activity sensing [35], triboelectric nanogenerators for acoustic sensing [36], piezoelectric films for touch sensing [37], electric motors for water pressure monitoring [38], and optical fibers for room-scale vibration monitoring [39]. These sensors either transduce other types of energy into electricity or require no power to operate. Many researchers have adopted low-power embedded computing platforms [35, 38] or aggressive power saving schemes [40, 41] in distributed sensing systems.

2.7 Democratized Technological Practice

In the field of human-computer interaction, researchers have attempted to democratize their skills and intellectual findings by turning them into a tool that could empower other researchers, makers, designers, or even the public [42, 43, 44]. These efforts started with manufacturing tools for nonfunctional objects but later expanded to more intelligent things such as interface design for websites [45], accessibility in surface computing [46], self-expression in wearable computing [47], kinetic motions for architecture and product design [48], paper craft for inductive power transmission [49], shape-changing displays [50], and cardboard machines for prototyping devices [51]. Although energy harvesting has been studied for a long time, the tools to support its practices were very limited [52]. Therefore, energy harvesting tools are needed to enable broader research on energy harvesting and make it more approachable.

CHAPTER 3

PRINCIPLES, OPPORTUNITIES, AND DESIGN GUIDELINES FOR COMPUTE-PROXIMAL ENERGY HARVESTING

A major cost, inconvenience, and source of failure for adding sensors and electronic accessories to automobiles is wiring the systems into the car's power. I propose an alternative approach, *compute-proximal energy harvesting*, which harvests power locally, so wiring is not needed. In this chapter, I provide an overview of the principles and empirical evaluations for harvesting energy in and around the automobile, exploring the role that wind, light, vibration, and heat play in this process. To better explore the proposed approach, I demonstrate two prototypes—a thermoelectric energy-based parking assistant (RearSense), which is attached to the exhaust pipe; and a wind-powered external pedestrian display (PedDisplay), anchored to the front bumper of a car. Note that I explore the proposed energy harvesting concept in the context of the automobiles; however, in Section 3.4 I also discuss about how energy harvesting would be different for other environments.

This chapter is an extension of a full paper published by Park et al. at IEEE Pervasive Computing magazine and a doctoral colloquium paper by Park at the 18th ACM Conference on Embedded Networked Sensor Systems (SenSys 2020) [53, 54].

3.1 Energy Harvesting Opportunities in and around the Vehicle

This section presents both theoretically and practically derived estimates of energy harvesting in automobiles. I cover the relevant modes of wind, heat, light, and vibration. While the evidence provided in this section is not comprehensive, it does provide a realistic estimate of harvested power by mode, as well as a framework for extending my findings.

Figure 3.1 (a) shows where each mode of harvesting was measured. Analytical estimates of harvesting use theoretical models from the literature that have parameters (e.g.,

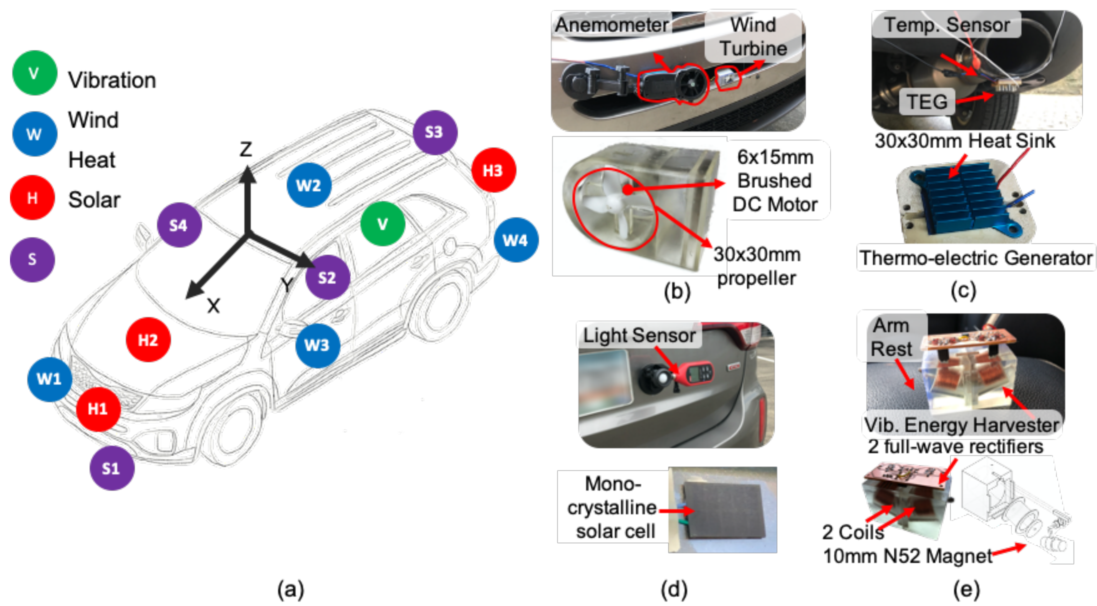


Figure 3.1: (a) Locations of each energy monitor and harvester, (b) Anemometer and wind turbine at the front bumper, (c) Temperature sensor and thermoelectric generator at the exhaust muffler pipe, (d) Light sensor and solar cell at the trunk door, and (e) Vibration energy harvester at the arm rest

wind speed and temperature) I can measure with commodity sensors. Practical harvesting results are measured with mode-specific harvesters I either built or purchased. Figure 3.1 (b)-(e) shows for each mode the sensors used to feed the theoretical models and the specific harvesters used for practical measurement. This approach allows me to illustrate both the potential for harvesting (through theoretical models) and the comparison for what can be achieved “off-the-shelf” today.

To collect realistic data for theoretical models and practical harvesting results, I drove an instrumented vehicle (i.e., a 2014 KIA Sorento) repeatedly along a three-mile path in a neighborhood of the Atlanta metropolitan area in the United States. For each trial, I controlled the time of the journey (about 13 minutes) and overall speed of the car. Table 3.1 summarizes my findings, which I describe in more detail below by each energy harvesting mode.

Table 3.1: Summary of Theoretical Estimates and Practical Measurements of Energy Harvesting by Mode and Location. (TE: Theoretical Estimation, PM: Practical Measurement)

Mode	Parameter					
Wind	Location		W1 (Front Bumper)	W2 (Roof)	W3 (Side Door)	W4 (Rear Bumper)
	Wind Speed (mph) [Avg/Max]		6.2/18.8	15.5/43.6	10.5/36.7	2.6/10.7
	Driving Speed (mph) [Avg/Max]		14/42	13/35	13/41	14/47
	Power (μW)	TE	840	13100	4100	62
		PM	311	732	461	0
Heat[1]	Location		H1 (Front Grill)	H2 (Engine Cover)	H3 (Exhaust Pipe)	
	Temperature (°C)		43.5	51.7	55.4	
	Power (μW)	TE	8767	13584	16101	
		PM	19	59	240	
Light	Location		S1 (Front Bumper)	S2 (Side Door)	S3 (Rear Bumper)	S4 (Windshield)
	Daytime[2] (lux)		24209	37920	24529	62223
	Nighttime[3] (lux)		18.4	18.2	24.4	16.5
	Power[4] (μW)	TE	34801	54407	35259	89158
		PM	2390	5173	2541	14603
Vibration	Location		V1 (Arm Rest)			
	Axis		x	y	z	
	RMS[5] (g)		0.077	0.072	0.066	
	Resonance Frequency (Hz)		0.5	23	13	
	Power (μW)	PM	11.9			

[1]The ambient temperature during the experiments was 10 °C. [2]The average of illuminance measured between 9 and 10 AM. [3]The average of illuminance measured between 6 and 7 PM. [4]The light energy harvesting was performed during the daytime. [5]RMS is the square root of the mean value of gravity.

3.1.1 Wind

Theoretical model and limits of harvesting

Using Newton's second and third laws of motion, the electrical power available from wind energy is expressed as

$$P_{available} = \frac{1}{2}\rho A\bar{u}^3, \tag{3.1}$$

where ρ is the air density, A is the swept area of blades in a propeller, and $\bar{u}$ is the mean of the wind speed [55]. Since I cannot control the air density in our target environment, a higher wind speed and a larger blade size can lead to higher electrical power generation. Equation 3.1 represents an ideal harvester. However, in a realistic scenario, there can never be a mechanical device possible that harvests all the energy calculated in Equation 3.1, available from the air flow. So, the power that is harvested by a wind turbine can be represented as P_w or $P_{harvested}$ such that

$$P_{harvested} = \frac{1}{2}\rho A\bar{u}^3 C_p, \tag{3.2}$$

where C_p is an adjustable efficiency factor. The theoretical maximum power of wind turbine, to recapitulate, is simply this:

$$P_{harvested} = C_{eff} P_{available}, \tag{3.3}$$

where C_{eff} is the efficiency factor for the wind turbine. In 1919, Albert Betz defined a limit for this efficiency factor as 59.3%, known as the Betz limit [56]. To measure the wind speed at various places around the vehicle, I used a Holdpeak 866B anemometer. My analytical results demonstrate a theoretical average power range of 13.1 mW at the roof, which considers the average wind speeds from Table 3.1. For the analytical estimation, we consider that the efficiency factor (C_eff) of the wind turbine (system of blades and the enclosure) is 0.15, along with an assumption that the mechanical efficiency of the motor connected to the turbine blades is at least 80%. The process takes the density of air to be 1.225 kg/m^3 We also produced an aerodynamics simulation based on the 3D model of the test car using Autodesk Flow Design. As illustrated in Figure 3.2(a)-(c), the airflow patterns (assuming ambient wind speed of 35 mph) in the simulation were similar to those measured in our experiments.

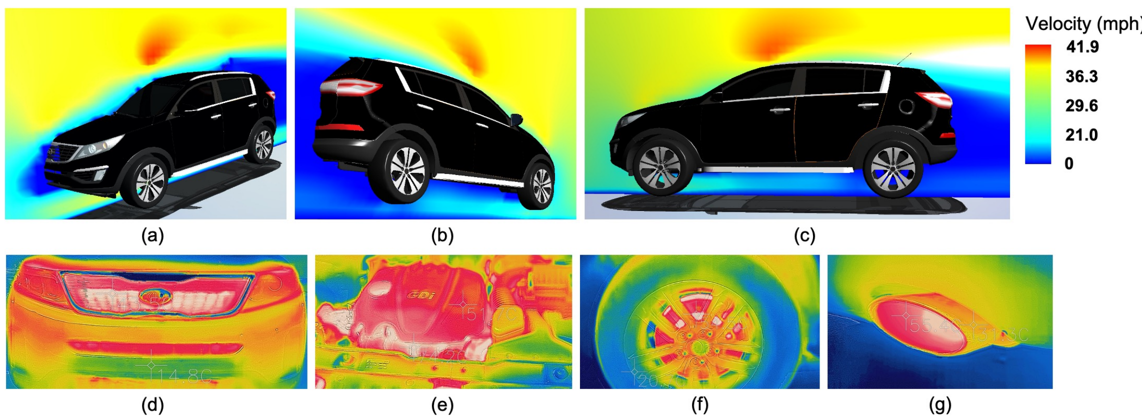


Figure 3.2: (a–c) Simulation results of wind-speed measurements around the test vehicle based on an aerodynamics model. (a) is the front-left side, (b) the rear-right side, and (c) the side view. (d–g) Thermal images captured by FLIR One Pro reveal where temperature differential between the exterior surface of the vehicle and outdoor temperature is maximized (red is the hottest part of the vehicle). Images displayed for (d) the front bumper, (e) the engine, (f) the front wheel, and (g) the exhaust pipe.

Practical harvesting results

Since a small-size wind turbine is not commercially available, I designed and manufactured an inch-scale wind energy generator using off-the-shelf parts developed for a quadcopter, Figure 3.1(b). My results show an empirical power range of 0 to 732 μW. Due to the rotational inertia of the turbine blades, the custom turbine only worked when the wind speed was higher than 11 mph. Thus, the amount of harvested energy was zero at the rear bumper. The results summarized in Table 3.1 illustrate that the roof and side doors of the vehicle are the best locations for wind energy harvesting with a yield of 732 μW and 461

μW, respectively, at the average driving speed of 13 mph.

3.1.2 Heat

Theoretical model and limits of harvesting

Generating electrical power from heat is determined based on temperature differential between the *target* area and its *surroundings*. In this context, all the components connected to an internal combustion engine should be considered to generate some amount of thermal energy. The temperature difference may also happen in the areas where friction occurs, such as a braking disc and pad. While the harvesting potential arising from heat differential can be explained using a number of theories (e.g., the Seebeck, Peltier, conduction, and Joule effects), the Seebeck effect is the core part of thermoelectric generators (TEG) [57]. A TEG module consists of P-type / N-type semiconductor blocks, an electrical insulator, and ceramic substrates. Without the optimization of heat sink and electrical load resistance, the performance of thermoelectric energy harvesting can be estimated using basic equations. The output voltage of TEG is

$$V_{TEG} = \frac{N\bar{\alpha}(T_{Source} - T_{Ambient})}{4}, \tag{3.4}$$

where N is the number of couples in TEG, $\bar{\alpha}$ is Seebeck Coefficient, and T_{Source} and $T_{Ambient}$ are the source and ambient temperature, respectively [58]. The power generated by the TEG can be estimated as

$$P = \frac{{V_{TEG}}^2}{R_{Load}}, \tag{3.5}$$

where R_{Load} is electrical load resistance. As in Equation 3.4, the temperature difference is the crucial factor when estimating the amount of the harvested power in thermoelectric energy harvesting. To estimate the power limits, I first continuously measured the temperature using a BOLYFA BF117 temperature logger while driving on the experimental route. I then computed the limits of the electrical power based on the estimated properties of a typical TEG module [58]. My results illustrate that the theoretical limits of heat energy harvesting ranges between 8.7 and 16.1 mW, see Table 3.1). For a more holistic review of heat sources, I also captured thermal images using a FLIR One Pro camera, see Figure 3.2(d-g))

Practical harvesting results

In my proposed approach, the *target* area can be an engine block, a front grill, or an exhaust pipe, and the *surroundings* are the relatively colder air that sweeps past the car while driving. Although there may be some differences depending on the seasons and weather conditions, the vehicle is quite an interesting platform when it comes to heat energy harvesting. As illustrated in Figure 3.1(c), I deployed a TG12-4-01LS TEG module to three different heat sources and found that the exhaust muffler pipe was highly feasible for heat energy harvesting with a yield of 240 μW. The difference between theoretical estimations and practical results can be explained by two factors: 1) I assume that $T_{ambient}$ in Equation 3.4 is the outdoor air temperature (10 °C) in the estimations, but the actual $T_{ambient}$ (i.e., the temperature of heat sink) is much higher than that in the practical measurements due to the limited air flow of the locations such as inside the engine bay. 2) I use a thermal conductive pad when attaching the TEG module to the heat source, but its contact may not be secure.

3.1.3 Light

Theoretical model and limits of harvesting

Since photoelectric effect was discovered, light (or solar) energy harvesting has been extensively studied [59]. Light consists of photons γ, and the energy of single photon is

$$E_\gamma = \frac{hc_0/n}{\lambda}, \tag{3.6}$$

where h is Plank's constant, c_0 is the vacuum speed light, n is the refractive index of the medium, and λ is the wavelength of the incident light [60]. From Equation 3.6, an irradiance I_e can be derived as

$$I_e = \int_0^\infty E_\gamma \phi_\gamma(\lambda) d\lambda, \tag{3.7}$$

where $\phi_\gamma(\lambda)$ is the photon current density that is normally considered as a constant for fixed illumination [61]. The total radiant power on a surface of A from the light source is

$$P_{rad} = I_e A. \tag{3.8}$$

The capability of light energy harvesting is proportional to the amount of light reached on a given surface. In reality, the actual electric power harvested from a solar cell is also limited by a solar cell's efficiency, and the average solar cells on the market have an approximately 22% efficiency rating. I measured the luminous intensity using UT383 BT and calculated I_e using the light energy simulator proposed by Michael [62]. The theoretical power ranges between 34.8 and 89.1 mW in the daytime (See Table 3.1).

Practical harvesting results

To convert solar energy to electricity, I used a 35 $\times$ 22 $\times$ 1.7 mm mono-crystalline solar cell, IXYS SLMD600H10L, which has a spectral sensitivity range from 300 nm (near-ultraviolet) to 1100 nm (near-infrared) with 22% solar cell efficiency, see Figure 3.1(d)). Solar (or light) energy is feasible in some contexts and not in others. Specifically, I expect that light energy on the rear bumper side can also be strong at night because cars to the rear of the vehicle turned on their headlights as they followed us on the road. The intensity of illumination measured on the rear bumper was higher than other positions, but the difference was not perceptible. Note that the harvested power at night time was less than 1 μW across all the locations; therefore, I did not report the results in Table 3.1. The difference between the given theoretical estimation and practical measurement may occur due to various factors such as load impedance, wavelength, time of day, latitude, climate, and surroundings (e.g., buildings and trees). The results indicate that the power harvested from all the locations examined in this experiment ranged from 2.4 mW to 14.6mW.

3.1.4 Vibration

Theoretical model and limits of harvesting

Piezoelectric, electromagnetic, and electrostatic mechanisms are used to convert vibration (or kinetic) energy to electricity [63, 64, 65]. Among these, I consider electromagnetic conversion since it offers design flexibility while allowing us to implement it in a centimeter-scale [66]. The essential operation of the electromagnetic harvester can be understood using Faraday's Law. The voltage induced in a coil can be expressed as:

$$V = -NAdB/dX\dot{x}, \tag{3.9}$$

where A indicated the coil area with N turns, $\dot{x}$ is the moving velocity of the magnetic, and B is magnetic field. The current generated in the coil is:

$$I = \frac{NlB}{R_{load} + R_{coil}}\dot{x}, \tag{3.10}$$

where l is the coil axial length, R_{load} and R_{coil} indicate the resistance in the magnetic and the coil respectively. The maximum average output power can be expressed as:

$$P_{max} = \frac{mA^2}{16\zeta_m\omega_n}(1 - \frac{R_{coil}}{R_{load}}), \tag{3.11}$$

where m is the magnet mass, ζ_m is the mechanical parasitic damping ratio and ω_n is the natural frequency of the undamped system [66, 67]. Thus, the design parameters of the electromagnetic system include the properties of the magnet, the number of turns, the wire diameter of the coil, and the structure of the module. To accommodate the wide range of vibration in automobiles, I selected a low frequency transducer with a self-powered automatic frequency tuning mechanism [66]. However, the characteristics of the vibration energy can be defined by a driver's acceleration and breaking style (X-axis), the curvedness of the driving route or the frequency of lane changing (Y-axis), and the bumpiness and degree of inclination of the route (Z-axis). Figure 3.1(a) displays the axes information. It was challenging to calculate the estimated power in this dynamic environment. Therefore, I only measured the vibration using VibSensor and reported the resonant frequency and root-mean-square (RMS) vibration without a theoretical estimation in Table 3.1[68].

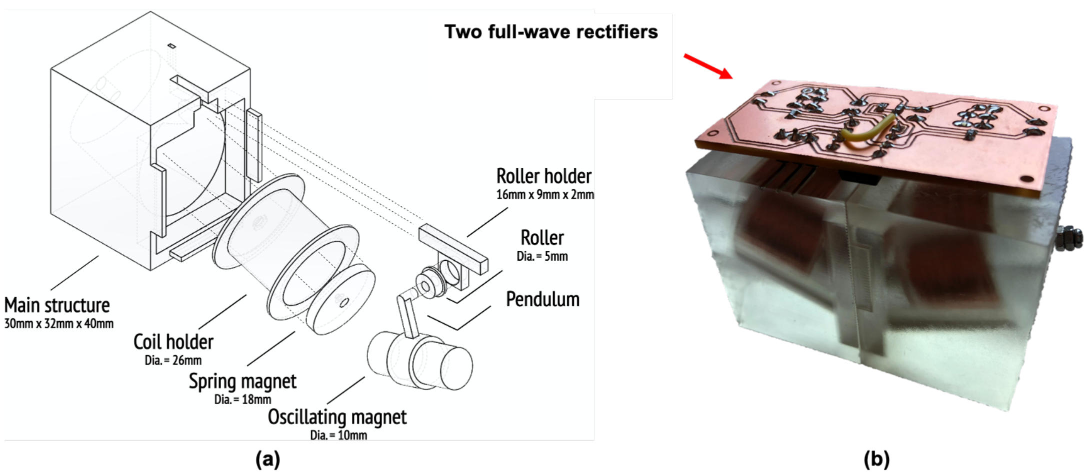


Figure 3.3: (a) The overall structure and (b) Implementation of the proposed vibration energy harvester

Practical harvesting results

Based on the discussion of the design parameters while maintaining the compact nature of the entire device, I designed a $60 \times 32 \times 40$ mm coaxial circular coil vibrator (See Figure 3.3), where the double coil structure is used for the oscillating magnet to have bigger swing. To optimize the final output power of the system, I designed a 28 mm long, 3 mm deep coil holder that allowed us to achieve up to 800 turns of 34 AWG wires. With this compact design, the vibrator could generate an average of 11.9 μW.

3.2 A Step-by-step Design Guideline for Compute-proximal Energy Harvesting

Now that I have explored the harvesting opportunities for a variety of modes and locations around the automobile, I turn our focus toward discovering computing opportunities around the automobile that will respect the harvested power budget. I describe the process for uncovering opportunities to retrofit "smart" computing opportunities at specific locations around the automobile and then design self-sustaining systems at those locations. I use the automobile as a specific environment case study in this paper, but the process prescribed is independent of the specific environment (See Figure 3.4).

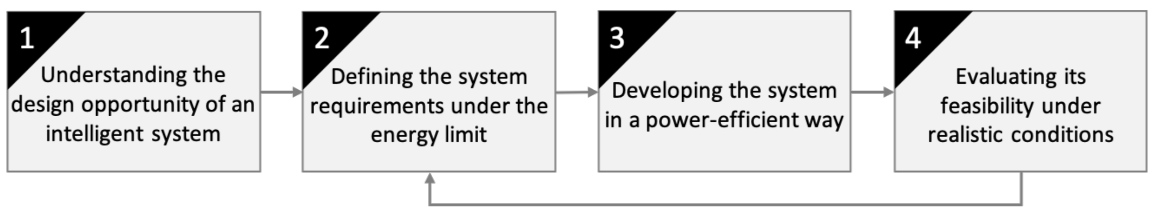


Figure 3.4: A step-by-step design guideline for compute-proximal energy harvesting and self-sustainable intelligent systems

3.2.1 Understanding Design Opportunities

I begin by uncovering opportunities for retrofitting new computational capabilities in a given environment (i.e., the automobile). This can happen in several ways, such as through consulting existing research literature, industry reports, and white papers or by conducting basic human-centered design practices. For example, a recent survey revealed that, while many drivers desire automated parking assistance, the number of cars on the road that have this feature is low [69]. Thus, in Section 3.3.1, I explore a retrofit option that attaches to the back of the car. The example of the pedestrian display on the front of a car is described in Section 3.3.2. In describing the design opportunities, I present the desired computational capability (e.g., what sensing, actuation, logic, and communication is necessary) as well as where it has to be located in the environment (e.g., at the rear or front of the vehicle).

3.2.2 Defining System Requirements Under the Energy Limit

The many design factors that must be considered in meeting the system requirements include sensing, actuating, computing, communication, form factor, installation, energy limit, and power consumption. Compute-proximal energy harvesting provides some hints regarding form factor and installation. To continue the example, the installation position for a parking sensor that is supported by heat power should be on or near an energy source (e.g., exhaust pipe), and the form factor needs to be designed to meet the target condition (e.g., hot, dusty, and possibly wet space around the exhaust pipe). The amount of harvested power may exceed its requirement in some contexts, but this is not always true in other conditions (e.g., solar energy for a driver who parks his car in a parking deck and usually drives at night). In this case, a rechargeable battery or a super capacitor can be considered for an energy storage. Additionally, a comparative analysis of possible energy harvesting techniques with a battery should be considered in this step. If a coin cell battery can operate a target system for a long period, the energy harvester might not be useful (e.g., tire pressure monitoring system).

3.2.3 Developing the System in a Power-efficient Manner

There are two ways of developing a more power-efficient system—either increase the harvested energy or decrease the consumed power during operation. For the former, maximum power point tracking (MPPT) algorithms are an important tactic to maximize the efficiency of energy harvesting [70]. Since almost all the modern energy harvesting integrated circuits already included MPPT, so they can be easily implemented in development. For the latter, system-level power optimization is critical. For example, adaptive duty cycle can be applied to both sensing and communication, which saves a great deal of power in operation. It is also useful if there is a way to reliably wake up and sleep the target system.

3.2.4 Evaluating the Feasibility Under Realistic Conditions

To examine the practicality of the target system, I first needed to be aware of the details of a typical driving situation. For example, if a self-sustaining parking sensor can only be operated after energy harvesting in six hours of driving, the invention will not be usable in the wild. Thus, I created a realistic testing scenario based on the American Driving Survey by the AAA Foundation for Traffic Safety [71]. The survey found that the ordinary driver in the United States travels approximately 14 miles at 37 mph for 23 minutes for a single trip. I had to make sure the target system was feasible under this test condition. If it was not practical, I needed to come back to the second stage for design iterations. Note that this typical driving situation may vary depending on various factors, including traffic congestion and road infrastructure.

3.3 Designing Self-sustaining systems

Having explored the harvesting opportunities for a variety of modes and locations around automobiles and the design guidelines of self-sustainable systems, I next demonstrate and evaluate the proposed design guideline in the process of retrofitting intelligent and self-sustaining computing capabilities in specific locations around the automobile.

I demonstrate two proof-of-concept devices to explain our process of compute-proximal energy harvesting. Figure 3.5 illustrates the configuration details of each of these devices. The core part of the approach is to place an energy harvester in the location where computing, sensing, and actuating are needed, thus greatly simplifying the installation process by means of reduced need for wiring to a central power source.

Although each device described below exploits a different harvesting energy source, they both require common functions: a DC-DC boost charger, a rechargeable energy storage device (i.e., battery), a battery gauge, a processor, and a communications module. For these shared functions, I developed a common core platform and used it for both devices.

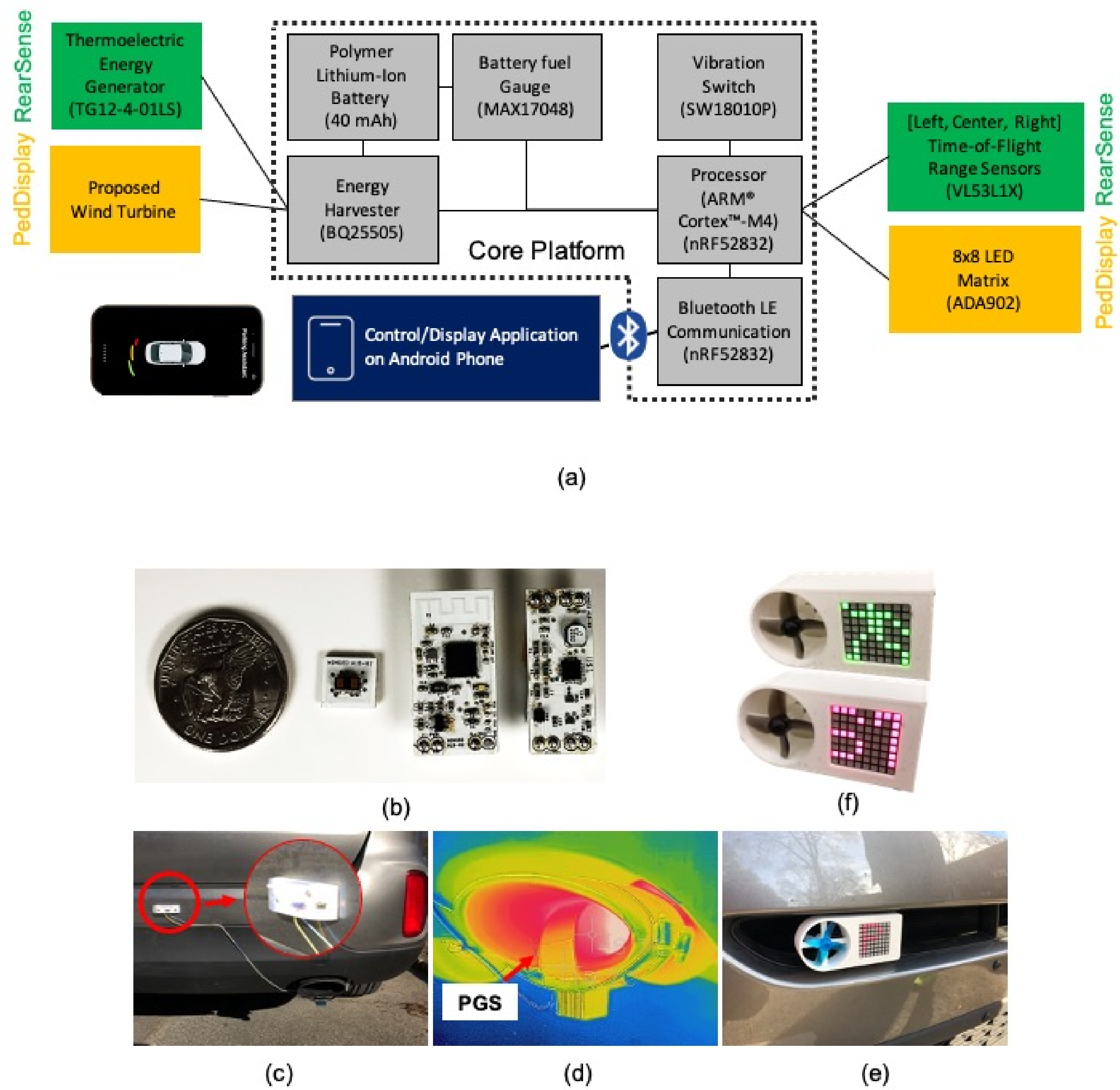


Figure 3.5: (a) Block diagram of two proof-of-concept devices. The core platform and Android application are utilized across all the devices. The green and yellow blocks are used only in RearSense and PedDisplay, respectively. (b-d) Demonstration of RearSense. (b) A time-of-flight laser distance sensor, a processing and communication circuit, and a power management circuit. (c) The field deployment of RearSense for evaluating in the wild. (d) The result of pyrolytic graphite sheet (PGS) deployment. (e) The field deployment of PedDisplay. (f) The demonstration of two animated display messages.

Both examples below require functionality only when the car's engine is on; the entire system can hibernate until switching on the ignition. A control application on a smartphone can remotely turn off all the devices by detecting the car status (e.g., engine-off), and the devices can later wake themselves up using a vibration switch triggered by engine vibration, see Figure 3.5(a)).

3.3.1 RearSense: A Ranging System to Support Backing Up

Step 1 - Design Opportunity

I begin by uncovering opportunities for retrofitting new computational capabilities in a given environment (i.e., the automobile). This can happen in several ways, such as through consulting existing research literature, industry reports, and white papers or by conducting basic human-centered design practices. For example, a recent survey revealed that while many drivers desire automated parking assistance, the number of cars on the road that have this feature is very low [69]. There is an opportunity to provide this retrofit feature mounted to the rear of older cars, thus improving their safety features [72]. However, the expense and complexity of installation for such a sensor as an aftermarket add-on limits wider adoption [69]. I explore how a backup support system, RearSense, could be designed in the rear of a car that would be self-sustaining and simpler to install.

Step 2 - Defining the System Requirements under the Heat Energy Limit

Based on the results in Section 3.1, I selected heat energy harvesting as the best option for RearSense, specifically at or near the exhaust pipe. My practical measurements for thermoelectric energy harvesting showed that there are many opportunities to optimize for more power harvesting. Using a controlled lab setting, I explored relevant parameters of a thermoelectric harvester. The results are illustrated in Figure 3.6 below.

1. I used a heat sink to increase the temperature differential between the exhaust pipe

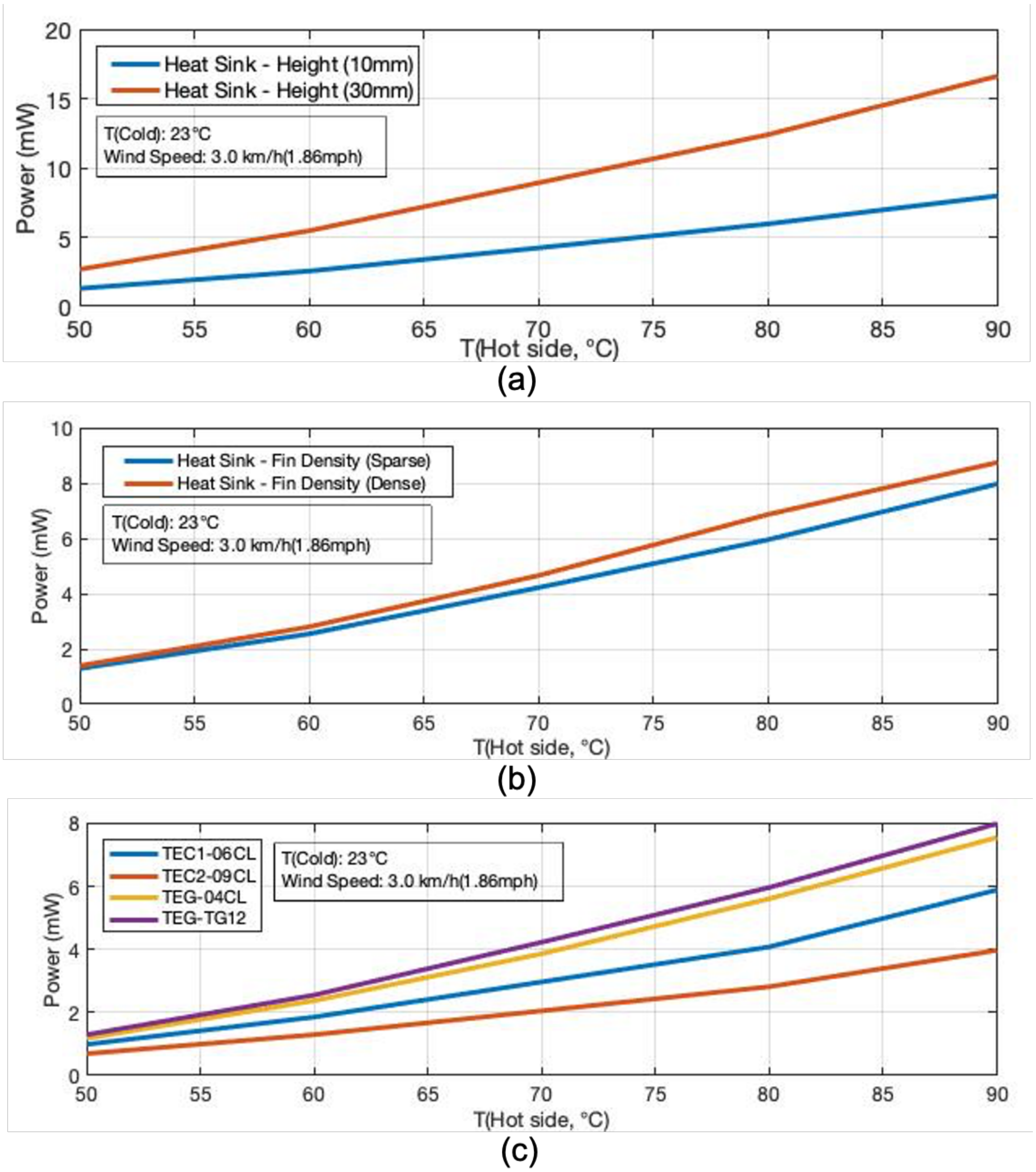


Figure 3.6: The comparison of factors that affect the efficiency of thermoelectric harvesting. (a) A comparison in the height of heat sink fins, (b) A comparison in the fin density, (c) A comparison in different types of thermoelectric modules.

and the external air. The heat sink consisted of numerous fins. Figure 3.6(a) illustrates that a longer fin (30 mm) is better than a shorter one (10 mm).

2. I next investigated the effect of fin density, sparse (8 fins) vs. dense (12 fins). Figure 3.6(b) illustrates that a denser configuration of fins is slightly better than a sparse one.

3. Finally, I tested two thermoelectric generators (TEG) and two thermoelectric coolers (TEC), operating in reverse mode under the same controlled lab setting. Though past studies have indicated that thermoelectric coolers in reverse mode can harvest more energy than thermoelectric generators [73, 74], my results (See Figure 3.6) indicate that the TG12-4-01LS TEG outperforms other modules.

Through this optimization process, I confirmed that we could produce 3900 μWh of energy with a temperature difference of 20 °C.

Key to optimizing the thermoelectric energy harvesting, therefore, is to ensure a minimum of 20 °C difference. Attaching the TEG harvester directly to the outside of the exhaust pipe has a further complication. As illustrated in Figure 3.5(d), the inside of the exhaust pipe is much hotter than its exterior surface. This is because car manufacturers design the exhaust pipe to reduce burn injuries related to direct contact with the pipe. To effectively connect the TEG to the internal surface of the exhaust pipe, I integrated a PGS—an ultra-thin, flexible, graphite polymer film—diffusing heat energy to the "hot" side of the TEG [75].

Step 3 - Developing RearSense within the Harvested Power Budget

Within this power budget, I designed RearSense. Full details of the configuration are illustrated in Figure 3.5. RearSense consists of a core computing and communicating platform with special-purpose, long-range sensors, outlined in gray in Figure 3.5 (a). Table 3.2 shows the power consumption of the computing and communication platform, which I as-

Table 3.2: Estimation of Power Consumption for RearSense and PedDisplay

	Common Core Platform[1]		RearSense[2]	PedDisplay[3]
	Computation	Bluetooth LE	Long-range Sensors	8×8 LED Matrix
Power (μW)	6.27	46.2	158400	50250
Operating time (h)	1	1	1/60	1/60
Power consumption (μWh)	6.27	46.2	2640	837.5
Total (w/ Computation + Bluetooth LE) (μWh)			2692	890

See Figure 3.5(a) for details on the [1]Common Core platform in gray, [2]RearSense in green, and [3]PedDisplay in yellow.

sume operates continuously when the engine is on. Wireless communication is known to be power-hungry [76]. Thus, I optimized the network configurations for the BLE module to reduce its overall power consumption as follows: connection interval is 500 ms, TX / RX payload is 8 bytes, and TX power is 0dBm.

For range sensing, I selected the VL53L1X time-of-flight sensor and configured the system to use three of these components. The power consumption of these sensors is orders of magnitude higher than the compute/communicate platform, but they are only needed when the vehicle is going in reverse. I estimated a usage pattern of 1 minute of back-up driving per hour of overall driving. Under this assumption, and as illustrated in Table 3.2, the harvested power from our TEG exceeded the demand of RearSense. As a comparison, if we were to power RearSense with a 210 mAh CR2032 coin cell, the battery would need to be replaced once every 10 days.

Step 4 - Empirical Evaluation

The results in Table 3.2 represent a theoretical estimate of performance. I ran an empirical evaluation of RearSense using a realistic driving condition (i.e., 14 miles at 37 mph) surveyed by the AAA Foundation for Traffic Safety [71]. I used a MAX17048 fuel gauge to measure how much harvested energy was stored in the lithium-ion battery. This fuel gauge uses a proprietary battery modeling algorithm, ModelGauge™, and I continuously measured the percentage of the battery throughout the driving experiment. The test included

23 minutes of driving with 23 seconds of driving in reverse. The Li-ion battery (total capacity of 40 mAh) measured an increase in stored energy of 2% after this experiment, a net increase with that driving profile. More frequent reverse driving may require an additional TEG module. In contrast to my expectations, PGS did not effectively transfer the thermal energy from inside the exhaust muffler pipe to its outside, so the harvesting can still be improved. As illustrated in Figure 3.5(d), I found that the thermal energy was rapidly dissipated as it approached the outer side. Due to the fuel residues inside the pipe, I was not able to securely attach the film. The vibration switch mechanism I used to detect whether the engine was turned on or off worked effectively.

3.3.2 PedDisplay - External Display for Driver's Intent Communication

Step 1 - Design Opportunity

Drivers often wonder how to communicate their intent to pedestrians. Horns, lights, or turn signals are often not explicit and clear enough. Communication by sight is particularly troubling because the pedestrian often does not have a clear view of the driver; a gesture or facial expression is not intelligible at a longer distance. Some research has explored the use of an external car display to communicate explicit information to those outside the vehicle [77, 78, 79]. Compute-proximal energy harvesting can make the external car display (which I call *PedDisplay*), more practical, feasible, and easy-to-install. I consider this new capability as a way to effectively deliver messages from the driver to pedestrians in front of the vehicle.

Step 2 - Defining the System Requirements under the Wind Energy Limit

I selected wind as the most suitable and reliable energy source for operating PedDisplay placed at the front passenger side of vehicle, see Figure 3.5(e). Since a bright display module tends to consume a great deal of energy in general, I wanted to increase the efficiency of the wind energy harvesting. In Equation 3.3, I described variables (e.g., frictional losses and drag against the air flow) that impact the power coefficient, but their empirical investigation is challenging to perform. Therefore, I relied on theoretical simulations on those variables.

For theoretical analysis, I first identified the fan blade and motor characteristics. Then, I considered geometrical properties such as the shape of the airfoil or airfoil type, chord length, coefficients of lift and drag, and the span of the blade. I designed fan blades with shapes resembling the Drela AG 38 airfoil. The span of the blade is taken to be 15 mm of the 30 × 30 fan, whereas it is 20 mm for the 40 × 40 fan. In the present analysis, the wind speed was 15mph, and the size of the fan was 40 × 40 mm with 4 blades. I theoretically obtained 3.9 mW of electrical power output from the motor. For the same wind speed, a 30 × 30 mm fan, however, generated 2.4 mW of power. It is important to note that the blade geometry and motor used in these two fans were completely different, so there is no correlation in the two results.

In the experimental results, I obtained 0.3 mW in the condition of the 30 × 30 mm fan and 1.7 mW for 40 × 40 mm fan. Note that I adopted a 6 × 15 mm brushed motor with 17500 KV for the 30 × 30 mm fan and a 8.5 × 20 mm brushed motor with 15000 KV for the 40 × 40 mm fan. The difference in the theoretical results and results from the experiments can be associated with several factors, including 1) inaccuracies in the measurement of the blade's geometrical properties such as twist and airfoil characteristics, 2) unknown torque behavior of the motor, or 3) potential sources of the mechanical and electrical losses that are not considered in the theoretical model.

Step 3 - Developing PedDisplay within the Harvested Power Budget

I consider the empirical result of 1.7 mW harvested from a 40 × 40 mm fan connected to a 8.5 × 20 mm brushed motor as the power budget. I designed the external display system from the same core components as RearSense, with a separate display module replacing the range sensors of RearSense. In terms of display, it is critical to select a suitable module with consideration of expressive ability, visibility, and power. Based on the findings from a study of external car displays [77], I selected an 8 $\times$ 8 LED matrix. Similar to RearSense, PedDisplay does not need to operate throughout the driving time. Therefore, I assumed that this system would be needed for one minute out of one hour of driving. As illustrated in Table 3.2, the harvested power could exceed the demand estimated by the specification of each component. In comparison, if PedDisplay were powered by a 210 mAh CR2032 coin cell, the battery would need replacement every 30 days. Although I did not integrate an adaptive brightness feature, it is possible to save even more power by adjusting the brightness of the display from 1 to 15 levels. The host application can measure the environmental illumination level and configure a proper brightness level over Bluetooth LE. Due to the limited space of the display, I developed a character slider and was able to present icons and text messages (e.g., WALK and STOP), as shown in Figure 3.5(e).

Step 4 - Empirical Evaluation

The evaluation condition of PedDisplay is identical to that for RearSense. Under the same driving conditions (a 23-minute journey of 14 miles averaging 37 mph, operating the LED display module for a total of 23 seconds), the Li-ion battery experienced a net gain in stored energy of 5%.

3.4 Summary

Energy harvesting is an area of wide scientific interest that has received little attention in the intelligent vehicles community. I investigated energy harvesting opportunities for sensors and actuators inside and outside the automobile. I proposed a new approach, compute-proximal energy harvesting, which emphasizes the development of energy harvesting where computing, sensing, and actuating are needed. Retrofitting vehicles with new sensor systems has traditionally been expensive due to labor costs [69, 80]. To simplify this and to provide solutions that require minimal on-going maintenance (e.g., eliminating the need to change batteries), I proposed the design of self-sustaining solutions that can be attached at one point in or around the vehicle. The two prototypes I developed as examples can be deployed in under five minutes to the car by someone with minimal car maintenance experience.

The goal of providing self-sustaining solutions through harvesting energy is paramount in my efforts. While I do not claim that I have been exhaustive in my exploration of the different modes of harvesting, I have provided a framework for extending the knowledge on harvesting options around the particular environment of the automobile, highlighting the gap between what is theoretically obtainable and what is currently practically attainable. The compute-proximal energy harvesting approach may be applied to general problems, though it is explored in this paper in an automobile context. I was methodical in my exploration and explanation of each prototype to expose how one should think about this problem in general. It should be clear that the automobile is an environment suitable for compute-proximal energy harvesting, but it is not the only one. Given any environment, a discovery process can reveal a desired computational functionality at a particular location in that environment. A developed catalogue of sensing modalities and their theoretical and practical limits for harvesting power sets a power budget to design against. Understanding the usage context, coupled with expertise in low-power electronics design, results in potential design solutions that can be prototyped and evaluated in practice. As this field matures, I expect more out-of-the-box solutions to emerge.

Some power harvesting modalities are sufficiently mature (e.g., light and heat), so I was able to create solutions from commodity harvesters. Other modalities (e.g., wind and vibration) are not as mature, particularly in form factors that work for attachment to an automobile. In these cases, I had to create my own solutions. As compute-proximal energy harvesting advances, I expect the development of many more commodity solutions for harvesting that satisfy a wider range of design factors. Specific to the automobile, RearSense and PedDisplay should inspire others to consider a whole host of other uses for the compute-proximal energy harvesting approach. I believe that safe driving technology and passenger protection are fertile areas for discovery and exploration.

3.4.1 Limitations and future work

As with any novel approaches, my results have limitations that must be taken into account. My current energy harvesting techniques still result in relatively low-power budgets, which in turn limit the sophistication of the computational solutions that can be supported. Because of this, my focus has been on using self-sustainability for relatively simple, but useful, solutions. Further research on materials and optimizations is needed to maximize the efficiency of energy harvesting. My solutions still assume some other partner functionality (e.g., in-car system or driver's smartphone) to complete the overall use case. For example, RearSense is only useful if the information about approaching obstacles is communicated effectively to the driver. PedDisplay needs a way from inside the car for the driver to signal which display to turn on.

It is currently too difficult to explore the space of compute-proximal energy harvesting because of the level of electronics sophistication needed to make progress. I have substantial industrial experience with electronics design and manufacturing, without which this research would not have been possible. To support researchers in the intelligent vehicles, ubiquitous computing, and human-computer interaction communities, there needs to be significant progress in producing how-to guides (such as presented in Section 3.1) and plug-and-play components to support creative exploration and design. This chapter provides a first step by characterizing the principles for harvesting energy in and around the automobile, exploring the role that wind, light, vibration, and heat can play in this process.

CHAPTER 4

ADVANCED SELF-SUSTAINABLE SENSING SYSTEMS WITH INCH-SCALE WIND ENERGY HARVESTERS IN AUTOMOBILES

Automobiles offer unique opportunities for energy harvesting to support the application of new driver assistance technologies to existing passenger vehicles. In this chapter, I demonstrate compute-proximal energy harvesting for advanced driver-assistance systems with inch-scale wind energy harvesting. I design and evaluate two wind turbines—63 and 92 mm diameter with optimized rotors—and achieve 20.6% and 16.2% power conversion efficiency, respectively. With the harvested energy, I demonstrate a blind spot monitoring system using a novel low-power radar sensor that achieved approximately 90% accuracy and a lane detection system using an off-the-shelf camera sensor and embedded platform that achieved above 90% accuracy in city and highway driving conditions. These applications show a promising path that new sensing capabilities for driver assistance can be added to an automobile with self-sustainable operation.

4.1 Introduction

Building self-sustainable systems is an emerging goal in the ubiquitous computing community [3]. Despite advances in battery technology, battery-powered systems are difficult to maintain, and battery disposal is hazardous to the environment. To this end, energy harvesting and ”battery-free” systems are increasingly exploring various domains, including on-the-body and in-the-built environment. To further advance the topic of self-sustainable computing discussed Chapter 3, I again focus on the automobile in this section.

The first major research objective in this domain is the ability to integrate energy harvesters at any point on an automobile where energy could potentially be harvested. Many automobile manufacturers have begun to produce electric cars, and various energy resources have been explored for the electrification of cars (e.g., heat [81], vibration [82], solar [83], and wind energy [84]). For example, regenerative braking systems allow for the conversion of kinetic energy to electric energy stored in the main battery [85]. Moreover, exhaust heat recovery systems can turn wasted heat energy from a motor or an engine into electric energy, which can be used later in driving. However, little research has been done regarding the utilization of these energy resources, focusing only on recharging the main battery of automobiles. Some studies introduce distributed energy harvesting and storage for aerial vehicles in an attempt to utilize the energy resources for diverse applications [86], but the technology is far from ubiquitous. I apply a novel ubiquitous approach, compute-proximal energy harvesting, to emphasize a more diverse perspective on energy use. While I examine the usefulness of this concept through automobiles in this chapter, the concept can also be applied across various application domains.

In this chapter, I demonstrate two concrete examples based on the compute-proximal energy harvesting approach: blind spot detection and lane detection. Compute-proximal energy harvesting allows us to consider the development of energy harvesting hardware where computing, sensing, and actuating are needed. In this approach, *compute* can be sensing, computing, actuating, or communication. *Proximal* considers harvesting available energy around a specific location if there is a need for computation.

In Section 3.3, I presented simple yet practical examples that either sense the proximity or visualize the driver's intent while communicating the data through Bluetooth LE. In addition to sensing, actuating, and communication, I considered one more aspect when it comes to *compute*—computation. The previous examples presented in this thesis did not include any complex algorithms or local data processing on the proposed devices. However, sophisticated computation capabilities could require more power or power-aware operations. In this context, I implemented local radar and video signal processing functions with their decision-making feature on the blind spot and lane detection systems, respectively.

In automobiles, a high-end modern sedan has about 100 sensors [87], which means there are many places that compute and require energy. Among the sensors, I focus on two essential safety sensor systems—blind spot detection and lane detection. Blind spot detection is a safety feature that warns a driver of approaching vehicles on adjacent lanes in blind spots, while lane detection helps a driver keep centered by triggering an alert when leaving the lane unintentionally. Despite their advantages, these features have not yet been widely adopted. The market penetration of lane keeping assistant and blind spot detection reached only 16.4% and 19.7% in 2015, respectively [88]. I believe that I can lower the barrier to the adoption of these technologies.

I take the following approach: **(1)** I explore the design space for wind energy harvesters and develop two inch-scale wind turbines for each sensing system. **(2)** I examine a pulsed-coherent mmWave radar—for blind spot detection. This is an important example of how advanced low-power sensor systems can become self-sustainable. **(3)** I demonstrate camera-based lane detection on an open-source hardware platform. This example demonstrates the viability of retrofitting widely adopted hardware platforms to become self-powering and perform real-time vision tasks. **(4)** I demonstrate that we can develop self-sustainable intelligent sensors with inch-scale wind energy harvesters in automobiles.

4.2 Inch-Scale Wind Energy Harvesting

With an established need to recycle the lost energy in an automobile to power diverse computing devices, I consider interaction with the wind to be one of the major sources of harvestable energy. Traditionally, wind energy is harvested at a large scale using turbines with blades on the order of 100 m because the energy harvested by a wind turbine is directly proportional to the area swept by its blades. For improving the design of wind turbines for similar power output, there have been efforts to generate novel designs [89] with smaller turbines but much higher rotational speeds. With a decrease in size, the need for a higher rotational speed of the wind turbine increases. That is why small-scale wind turbines are not popular. However, small fans do find an application in space-constrained heat sinks to dissipate heat quickly. Automobiles have similar space constraints. The use of a large wind turbine would introduce aerodynamic drag, offset the energy benefit, and hinder fulfilling the distributed small power needs. Therefore, in this section, I discuss the design space of inch-scale wind turbines for automobiles and design two wind energy harvesters that can meet the power demand of driving assistance devices discussed in Section 4.3.

4.2.1 Principles and Design Factors

The electrical power converted from wind energy can be derived as

$$P_{available} = \frac{1}{2}\rho A\bar{u}^3 \tag{4.1}$$

where ρ is the air density, A is the swept area of blades in a rotor, and $\bar{u}$ is the mean of the wind speed [90]. The air density varies with altitude, temperature, and humidity based on a target driving environment. Wind speed is also affected by the driving speed and aerodynamics of the automobile. Therefore, we can only ensure that a larger blade size can lead to higher electrical power. In reality, it is impossible to harvest all the available wind energy calculated in Equation 4.1 due to frictional losses in the mechanical components, drag force against the air flow, and the shape of the rotor blades in the wind turbine. There are also implicit reasons contributing to the reduction in the power coefficient, such as the induced drag from the mount of the wind turbine and the characteristics of the motor. Accordingly, the practical amount of power harvested from a wind turbine can be represented as

$$P_{harvested} = \frac{1}{2}\rho A\bar{u}^3 C_p \tag{4.2}$$

where C_p is the power conversion coefficient for the wind turbine. Albert Betz delineated the limitation of this coefficient as 59.3%, also known as the Betz limit [91]. Since then, it has been considered as the maximum efficiency of wind-electrical energy conversion for any hypothetical ideal mechanical devices. To achieve the maximum efficiency possible for the wind turbine, we need to consider the following design factors.

Sweep Area

As discussed in Equation 4.1, the sweep area is the most critical design factor since it is proportional to the output of the wind energy harvester. If the sweep area is expanded, the resistance to wind also increases, and the overall vehicle fuel economy might decrease. We need to consider this trade-off. In reality, the sweep area could be also restricted by the available space where a target sensor system is located. In this section, I explore the bottom space of each side mirror and the front area on the roof of an automobile. The shape and size of the target system should be aesthetically appropriate with minimal impact on the overall appearance. If appearance is not important, as on trucks or fleet vehicles, these restrictions on the sweep area may be relatively less.

Airfoil

Airfoil is the cross-sectional shape of the blade. It is also a critical design factor because the amount of lift force could be changed by the shape of the airfoil, and the lift force is directly correspond to the torque. The National Advisory Committee for Aeronautics (NACA) proposed the 63 airfoil series specifically designed for wind energy harvesting, and they have been widely adopted in various research projects [92, 93]. The US National Renewable Energy Laboratory (NREL) also developed efficient airfoil models such as S822 and S834 for small wind turbines [94]. The S822 airfoil is designed for variable speed horizontal-axis wind turbines with 3-10 meter diameter blades, while the S832 airfoil is intended for smaller scale turbines ranging from 1-3 meters in diameter. Note that these airfoils are proprietary to the NREL. In this section, I consider NACA 63-421, S822, and S834 airfoils and compare their characteristics to find the optimal model for the inch-scale wind turbine. Currently, there is little research on airfoil design for inch-scale rotors, hence, this comparative research has critical implications.

Number of Blades

In general, more blades would result in more stability and better mass balance about the axis of rotation with three blades as a minimum requirement when designing a wind turbine. However, in large-scale commercial wind turbines, the incremental costs associated with each blade are high. For example, the blade costs are at least 70% of the total wind turbine expenses [95]. As it is not cost prohibitive to add more blades in a small-scale turbine, I consider the number of blades as a design factor and study the number of blades needed for maximum power output.

Tip Speed Ratio

The tip speed ratio (TSR) is a factor representing the relationship between rotor velocity and relative wind velocity [96]. I need to consider torque, aerodynamics, number of blades, and mechanical stresses to select the optimal TSR [96]. In addition to these aspects, the TSR also affects the possibility of fabrication in the case of inch-scale wind turbines since higher TSRs make each blade narrow and thin. This issue can cause additional problems related to structural integrity.

Revolutions Per Minute (RPM)

If wind approaches an object at 1 m/s and the object is moving toward the source of wind at 1 m/s at the same time, then the relative wind speed incident on the object is 2 m/s. Similarly, when a wind turbine is rotating with a specific RPM value, it has a different value of relative velocity with which it interacts with the air. I need to find the RPM where the maximum power is delivered. When the RPM of the wind turbine changes, the angle of attack with which the air is incident on the blade also changes, leading to a change in the design of twist in the blades. While this value of blade twist can be changed during operation in the commercial large-scale wind turbines, due to space and energy constraints, it is not feasible to have such a capability in an inch-scale turbine. Inevitably, I need to fix a certain RPM at which the turbine will operate and design a target wind turbine based on this RPM. In certain situations where turbine RPM is more than desired or expected, we employ the motor's gearbox to slow the turbine for safe operation and avoid overheating of the components. Thus, I can maintain the turbine RPM, but rotate the motor at higher speed.

Torque

Torque for the wind turbine is analogous to power. If more torque is applied on the turbine, then more power is harvested. Torque and RPM share an inversely proportional relationship and should not be confused. If a wind turbine is rotating with a non-zero RPM but no torque, then it will eventually come to rest. Therefore, while designing the wind turbine, it is important to analyze the value maximum value of torque that can be achieved at the selected RPM and then design the turbine's components and its operation parameters to achieve that value.

Hub

The hub of a rotor is a center disk which interconnects each blade and the motor. As long as the hub is strong enough to hold the connected blades and the shaft of the motor, it should be as small as possible to gain maximum thrust.

4.2.2 Wind Turbine Design

To examine the design factors discussed above, I designed different types of rotors with variations in airfoil, number of blades, sweep area, and tip-speed ratio using Q-Blade, an open-source rotor design and simulation tool [97]. I then performed a series of simulations to determine the optimal design configurations.

First, I compared the expected power of three airfoils (i.e., NACA 63421, S822, and S834), which are widely used in small wind turbines on two scales (i.e., 63 mm and 92 mm diameters). These diameters are determined by taking into account the power requirements of the sensing systems, which will be discussed in Section 4.3. While S384 has slightly higher efficiency in 63 mm diameter, I confirmed that NACA63421 has higher efficiency at 92 mm diameter, see Figure 4.1(a-b)). For example, in the case of a 92 mm diameter, NACA63421 and S384 can produce 36.7 W and 26.8 W of power, respectively, when the wind blows at a speed of 20 m/s. Finally, I selected S384 and NACA6341 for the 63 mm and the 92 mm rotors, respectively. Due to the chord length and blade thickness issue, I chose the value of TSO as 2 when designing each rotor from the two selected airfoils. To optimize my blade design, I adopted the Betz optimization for the chord length of each rotor [96]. As shown in Figure 4.1(c), four blades demonstrated the most efficiency for energy conversion in the 92 mm case of this simulation. I also confirmed that four blades were the most efficient in the case of the 63 mm rotor. Figure 4.2 illustrates the cross section of three airfoils we compared, the 3D models I designed, and the actual appearance of the rotors I manufactured. Note that the simulation configuration for the proposed rotors is as follows: (1) Discrete Blade into N Elements = 100, (2) Maximum Epsilon for Convergence = 0.001, (3) Maximum Number of Iterations = 100, (4) Relaxation Factor = 0.35, (5) Air Density(ρ) = 1.225, and (6) Viscosity = 0.00001647.

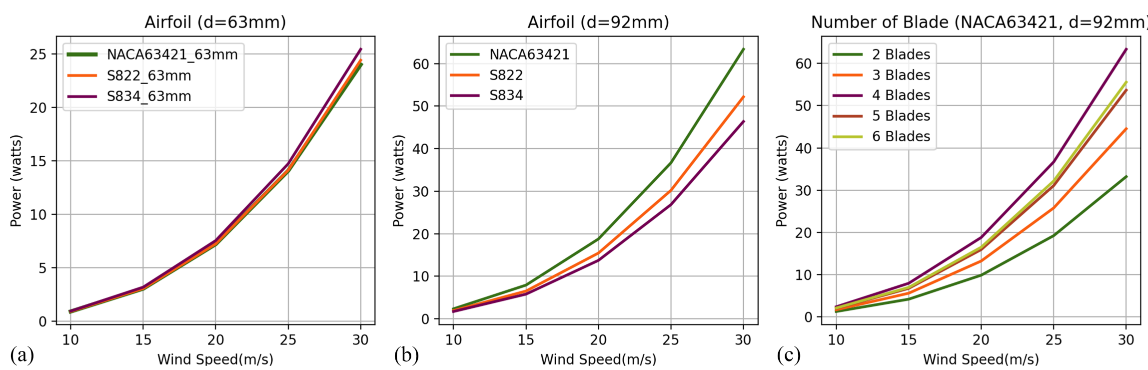
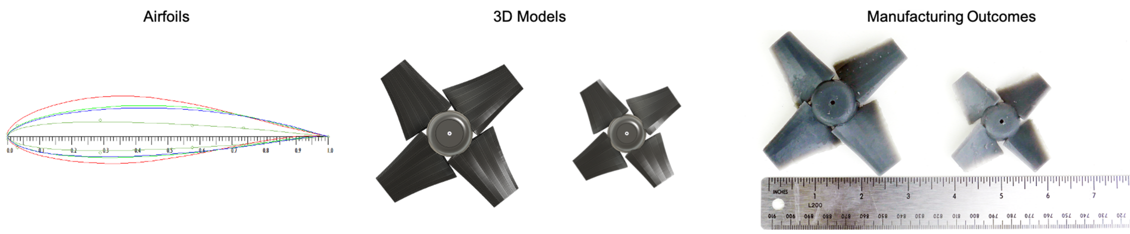


Figure 4.1: Results of rotor simulation. (a) Different airfoils in the diameter of 63 mm, (b) Different airfoils in the diameter of 92 mm, (c) Number of blades in the diameter of 92 mm, NACA63421.



(a) (b) (c)

Figure 4.2: Design of three rotors. (a) Red line: NACA 63421, green line: S822, blue line: S384; (b) 3D models of two rotors in 63 and 92 mm diameters, respectively; (c) 3D printed rotors using Tough 2000 resin of FormLabs 3D.

4.2.3 Wind Turbine Implementation

Based on these simulation results, I demonstrated two wind turbines in 63 mm and 92 mm scales and compared theoretical limits, simulation results, and empirical results of energy conversion in a controlled environment. When manufacturing wind turbines, the selection of motor would be as important as the optimization of the rotor. However, I adopted off-the-shelf motors since it is difficult to implement the custom shape of magnets and mechanical parts which can endure high-speed rotation. These wind turbines are integrated into my proposed sensing systems, as shown in Figure 4.10. Overall, we were able to empirically achieve the power conversion coefficients, C_p in eq. (4.2), of 0.206 and 0.162 for 63 mm and 92 mm wind turbines, respectively (See Figure 4.3).

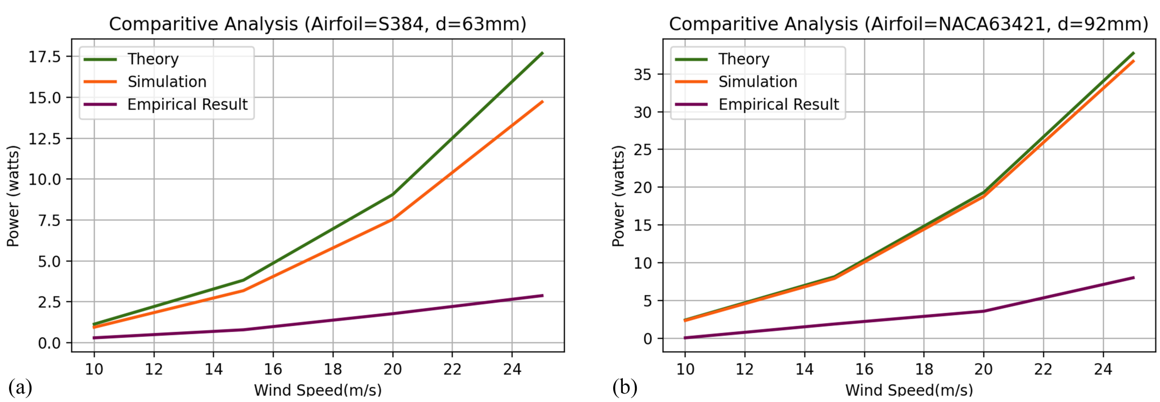


Figure 4.3: Comparative analysis of theoretical limits, simulation results, and empirical results of (a) 63 and (b)92 mm wind turbines.

4.3 Advanced Driver Assistance Technologies

In this section, I examine radar and camera sensing techniques for blind spot detection and lane detection systems, respectively. I first discuss the characteristics of pulsed-coherent radar and evaluate its accuracy in various conditions for blind spot detection. I then measure the power consumption of our blind spot detection system to design an energy harvester. Similar to this, I discuss the implementation of a lane detection system based on a Raspberry Pi 4. I then examine its accuracy and performance with an analysis of power consumption.

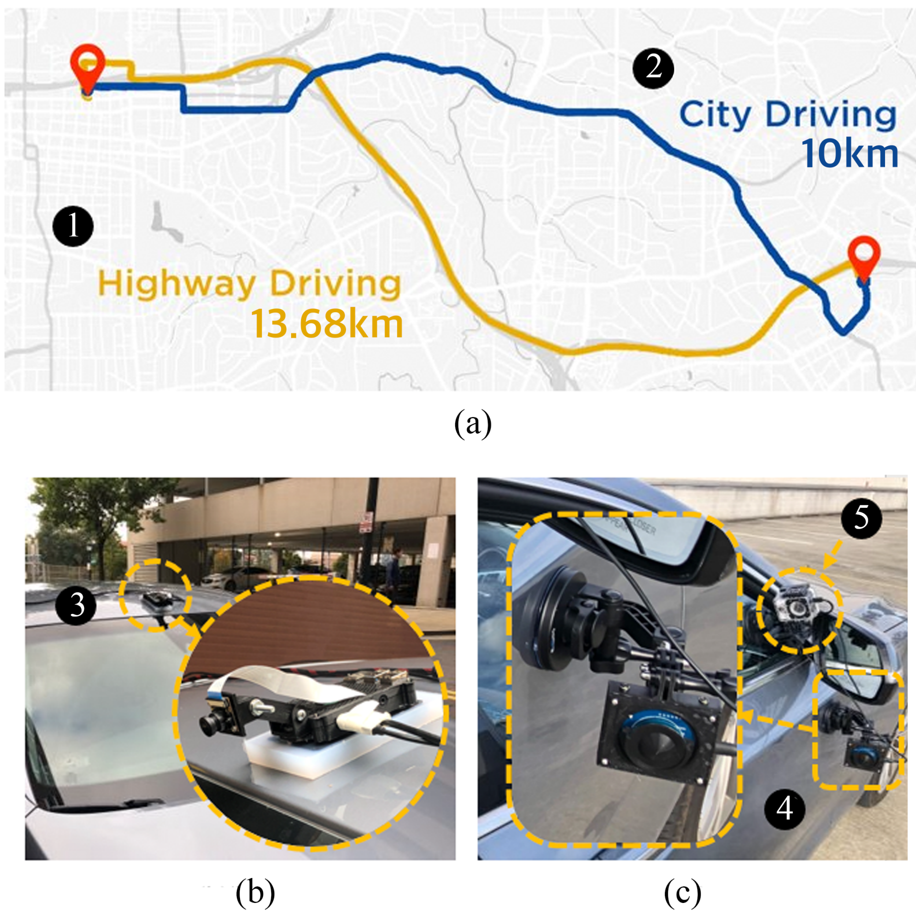


Figure 4.4: Experimental settings. (a) driving paths on a city(2) and a highway(1); (b) a Raspberry PI 4 with a camera(3); and (c) a radar sensor(4) and a wide-angle camera for ground truth(5).

4.4 Blind Spot Detection

Blind spot detection is a safety feature that alerts a driver to the presence of adjacent automobiles in areas that cannot be seen in the driver's rear mirror or side-view mirrors. For this feature, automobile manufacturers have attached radar sensors to the left and right sides of the vehicle's rear bumper, which enable the detection of other vehicles in the blind spot area.

4.4.1 Pulsed-Coherent Radar

I used a pulsed-coherent radar (PCR) sensor for blind spot detection. While frequency-modulated continuous wave (FMCW) sensors which have been widely used for blind spot detection require high power consumption, the PCR sensor consumes low power for object presence detection [98]. The goal of my evaluation is to examine the feasibility of the low-power PCR sensor for detecting an automobile's presence within the region of interest (i.e., the area up to 6 m from each side mirror, ISO-17387) for blind spot detection. I also investigate whether the PCR sensor can be operated in a self-sustainable way with our wind turbine designed in Section 4.2.

4.4.2 Signal Processing for the Pulsed-Coherent Radar Sensor

I applied the Sparse service that Acconeer provided specifically for this PCR sensor to be used to detect an object's presence [99]. This algorithm mainly consists of three parts: (1) noise estimation, (2) intra-frame deviation, and (3) inter-frame deviation. Noise estimation is mainly used to normalize the signal magnitude. This normalization helps detect uprising peaks relative to other signals, which is interpreted to the object presence detection. Intra-frame deviation is part of the Sparse algorithm which detects fast moving objects by recognizing the signal differential within the same frame detection. Thus, a large differential of the signal amplitude within the frame implies a fast moving object's presence.

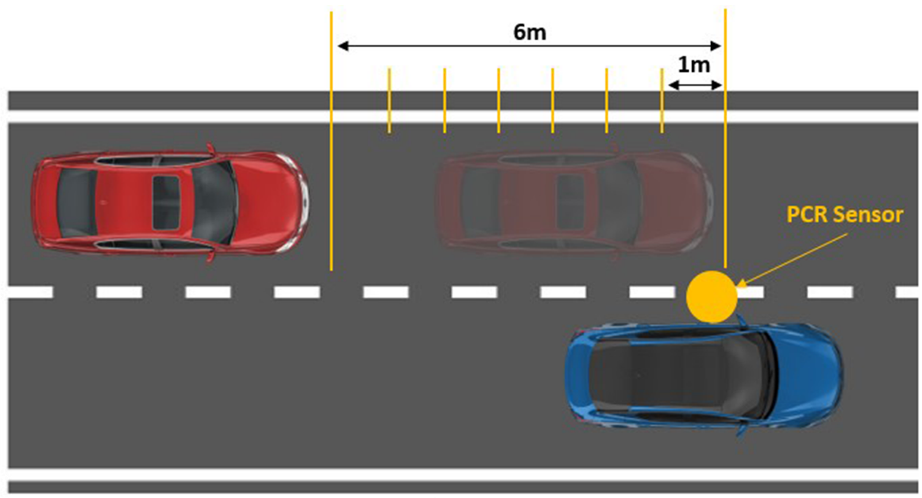
Inter-frame detection allowed me to detect a slow moving object by recognizing the signal differential between frames. Therefore, a large differential of the signal amplitude between frames represents a slow moving object's presence. The Sparse algorithm uses the weighted sum of the intra-frame and inter-frame deviations, and the weights for each deviations are adjusted based on the moving speed of a target object. I empirically found the weights based on the results from my experiments, which I will describe in the following subsections. For the frequency configuration, I used 20 Hz sampling rate for the intra- and inter-frame deviation, while 16 sweeps were measured for each frame. [100].

4.4.3 Evaluation of PCR radar sensor

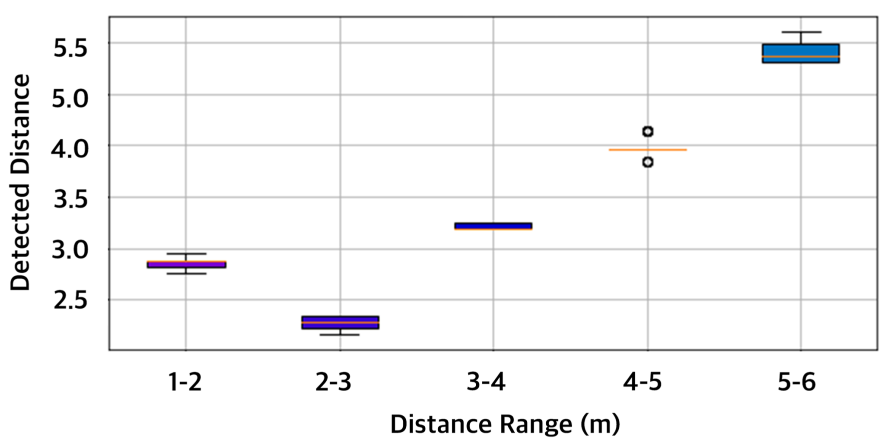
I systemically conducted three-stage experiments. First, I examined the range of the distance where the PCR sensor can detect the car's presence in the controlled setup. Second, I tested if the presence of a car moving at different speed levels could be detected within the range that I examined in the first experiment. Lastly, I assessed whether the sensor configuration that I obtained from the first and second controlled experiments can accurately detect a car's presence in a real driving scenario. To do so, I drove around a city and on a highway for testing, see Figure 4.4(a-c)).

Experimental Setup (Distance) - The goal of my first experiment was to measure the range of distance that the PCR sensor can detect the a car's presence. To do this, I examined how the radar signals from the test vehicle were received in different distance ranges. I conducted an experiment in the controlled setup in an empty parking lot space. As illustrated in Figure 4.5, I fixed the sensor's position and oriented it with 20° facing toward the adjacent lane to replicate the side view mirror's angle and position of the driver's car. I tested 5 different ranges based on adjacent zones illustrated in ISO-17387: (1) 6 m-5 m, (2) 5 m-4 m, (3) 4 m-3 m, (4) 3 m-2 m, and (5) 2 m-1 m. A skilled driver drove a car from the starting point, 6 m away from the sensor, and stopped once the car is moved 1m ahead. The driver repeated the process until he drove in the final range (1 m-2 m).

I recorded raw data that represented a car's presence with its detected distance between the car body and the sensor. The speed of the vehicle was below 1km/h. To measure the accuracy of the distance detection for each test range, I calculated the average and the standard deviation of the detected distance while running three rounds of the experiment process, see Figure 4.5(b). I weighted inter-frame deviations mostly to focus on a slow moving object's presence detection.



(a)



(b)

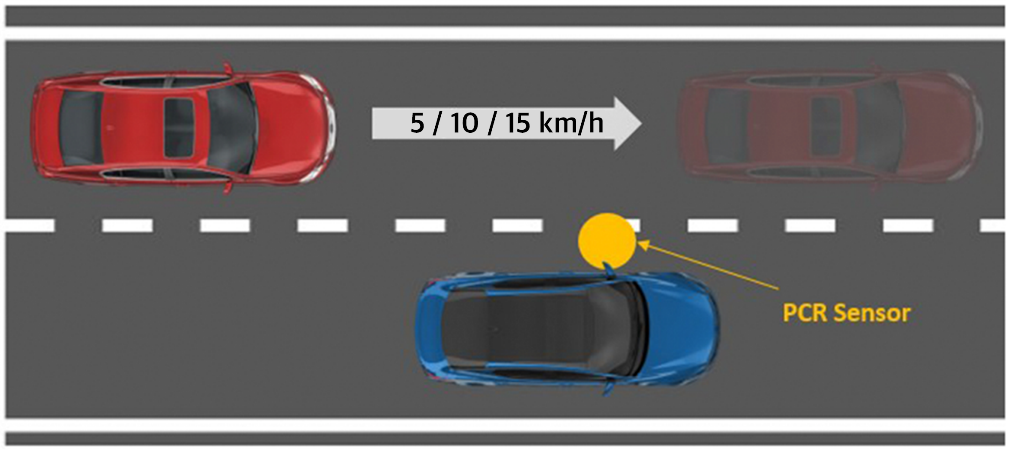
Figure 4.5: I ran the experiment to examine the distance range that the PCR sensor can detect. (a) I set the experiment setup with 5 different distance ranges. (b) The result shows the average and standard deviation of the detected distance for each range test.

Result (Distance) - As illustrated in Figure 4.5(b), the sensor demonstrated the accurate detection rate not just for a car's presence detection but also for the detected distance when the car was positioned within the range between 2 m and 6 m. However, the distance detected when a car was located at a distance between 1 m and 2 m was not accurately measured by the PCR sensor (the result that shows the average and standard deviation). When a car was located within 2 m, there were some errors in range estimation. If the distance between an approaching car and the sensor was within 2 m, the sensor could detect an object's presence at multiple spots (e.g., 1.3 m and 2.8 m) and return one of them as the final distance where the object's presence is detected.

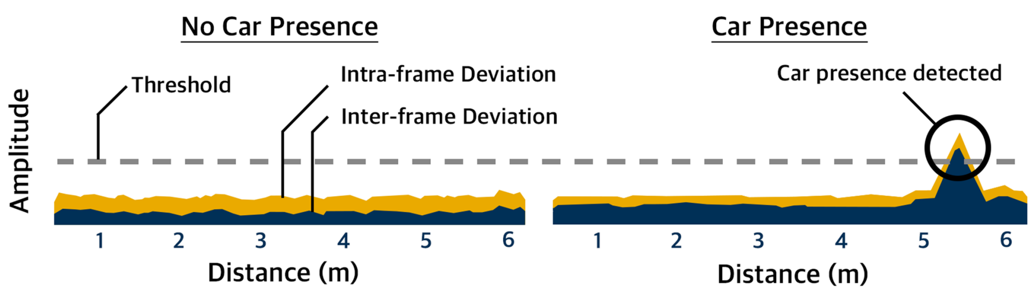
Experimental Setup (Speed) - After examining the accuracy of range detection, I evaluated whether the sensor could detect a moving vehicle passing by at different speed levels. My intention was to replicate the relative speed difference between two cars driving on adjacent lanes in real driving scenarios. To be specific, the experiment was designed to consider the case where a car is passing by the driver's car on the left lane. To simulate the car on the left lane, the skilled driver again drove the car and passed by the PCR sensor at the fixed position at three different speed levels: 5 km/h, 10 km/h, and 15 km/h, see Figure 4.6(a). I set those speed levels considering the fact that a car on a passing lane is allowed to exceed the speed limit by 15 km/h ($\approx$ 10 mph) when it is passing a car on a highway. In addition, roads in cities have generally lower speed limits than highways do.

To collect the ground truth for the distance detected by the sensor, I recorded the car's presence once the car approached from 6 m away from the sensor's fixed position until it passed the sensor's position. I marked a line that represented the 6 m distance from the sensor position and labeled the data once the car started passing above the line. Lastly, to optimize the parameters in sensor configuration, I swept two variables that I could adjust and are critical to achieve accurate detection: (1) threshold for presence detection decision, (2) weight ratio for inter-frame and intra-frame deviations, see Figure 4.6(a-b). I fixed those variables once I found the combination of swept parameter values that achieved the best accuracy.

Result (Speed) - I measured the ratio of the number of frames that the car presence



(a)



(b)

Figure 4.6: I conducted the moving-car detection experiment to examine if the PCR sensor can detect a moving car's presence when the car is approaching at different speed levels. (a) I set experiment setup with three different speed levels (5 km/h, 10 km/h, and 15 km/h). (b) This graph represents the signal profile of intra-frame and inter-frame deviations. The system recognizes a car's presence if the weighted sum of two deviations is above the threshold. Otherwise, the system recognizes no car presence.

was detected to the total number of frames recorded when the car drove within the range between 1 m to 6 m. As illustrated in Figure 4.7(a-c), the results showed that cases of 5 km/h and 10 km/h driving exhibited the high accuracy while the 15 km/h case did not show the promising results since it was less than 80%. Therefore, I found evidence that the PCR sensor can detect well the car presence within 6 m distance away if the car is approaching at less than 15 km/h. Another reason that 15 km/h showed the lower accuracy could be the annotation errors for the cases when the car quickly passed.

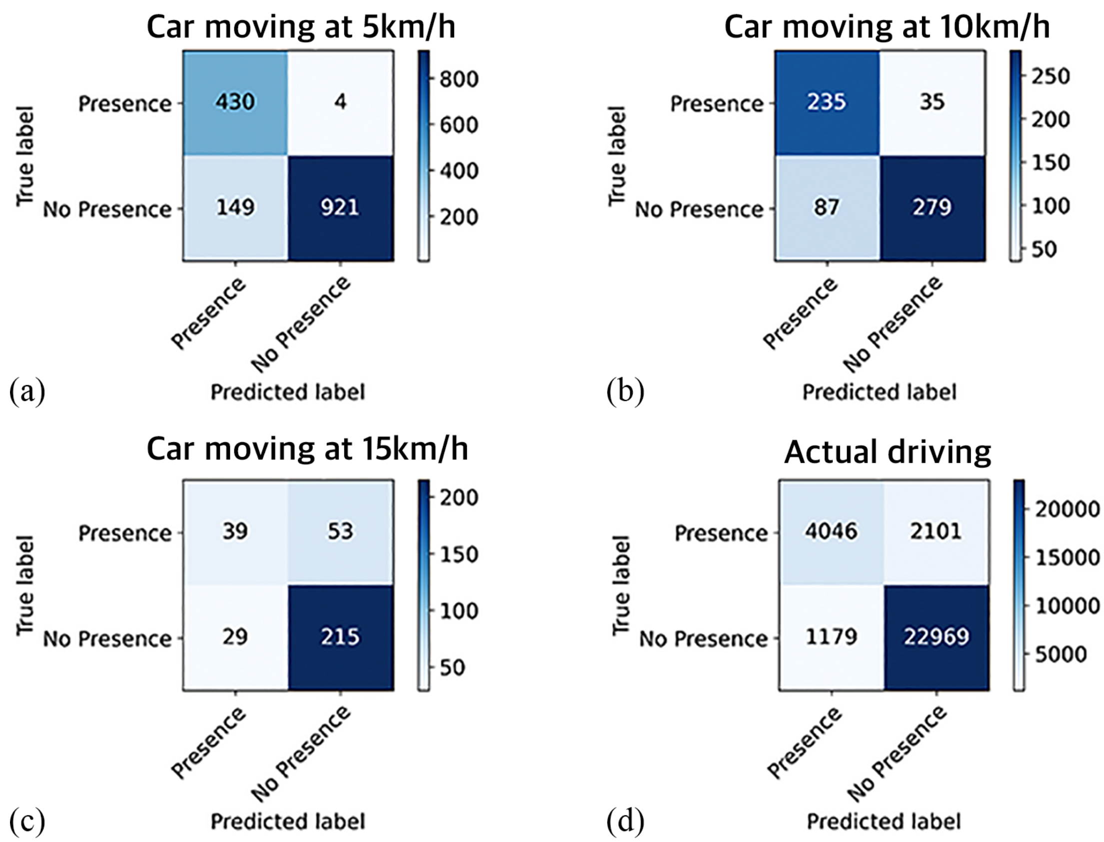


Figure 4.7: The results represent an accuracy of the car's presence detection according to different car speeds and in our actual driving test. (a) Car moving at 5 km/h on an adjacent lane, (b) Car moving at 10 km/h on an adjacent lane, (c) Car moving at 15 km/h on an adjacent lane, and (d) Actual driving.

Experimental Setup (actual driving) - Once I found that the PCR sensor could detect the moving car's presence within the range of 6 m, I tested if the sensor can sense the moving cars' presence in real driving scenarios. For the experiment, as illustrated in Figure 4.4(c), I installed the PCR sensor below the side view mirror and also mounted a wide-angle action camera next to the sensor so that an annotator could annotate the ground truth data of any car's presence within the blind spot area when the driver saw any car moving on a passing lane. I adjusted the camera angle, which allowed the car's presence to be detected from 6m behind the sensor as the ground truth data of a car presence detection. Specifically, when the camera captured any cars, the annotator manually recorded the presence. Otherwise, he annotated non-presence. While driving, the raw data sensed by the PCR sensor was recorded at the same time. To capture various driving scenarios, I selected two driving locations: (1) city driving, (2) highway driving. The skilled driver drove **10** km for city driving and **13.68** km for highway driving to collect data. Lastly, I applied the same weights of intra-frame and inter-frame deviations and threshold value gained from the previous experiment, assuming other cars passing by at most 15 km/h faster than a driver's car.

Result (actual driving) - I measured the accuracy based on how well the PCR sensor can differentiate presence and non-presence of cars passing by on a left passing lane. To do so, I calculated the accuracy as the ratio of the amount of the collected sensor data that is matched with the ground truth to the total number of the collected data. The results showed 89.17% accuracy of the car presence detection for the actual driving scenarios, see Figure 4.7(d). I confirmed the fact that the low-power PCR sensor can be effectively used to detect the presence of adjacent automobiles in the area of blind spot with approximately 90% accuracy.

Power Consumption of Blind Spot Detector - The power consumption in the state of enabling the PCR sensor and the nRF52840 dual-core micro-controller (data processing and Bluetooth LE communication) was measured at 79.25 mW (5 V, 15.85 mA).

4.5 Lane Detection System

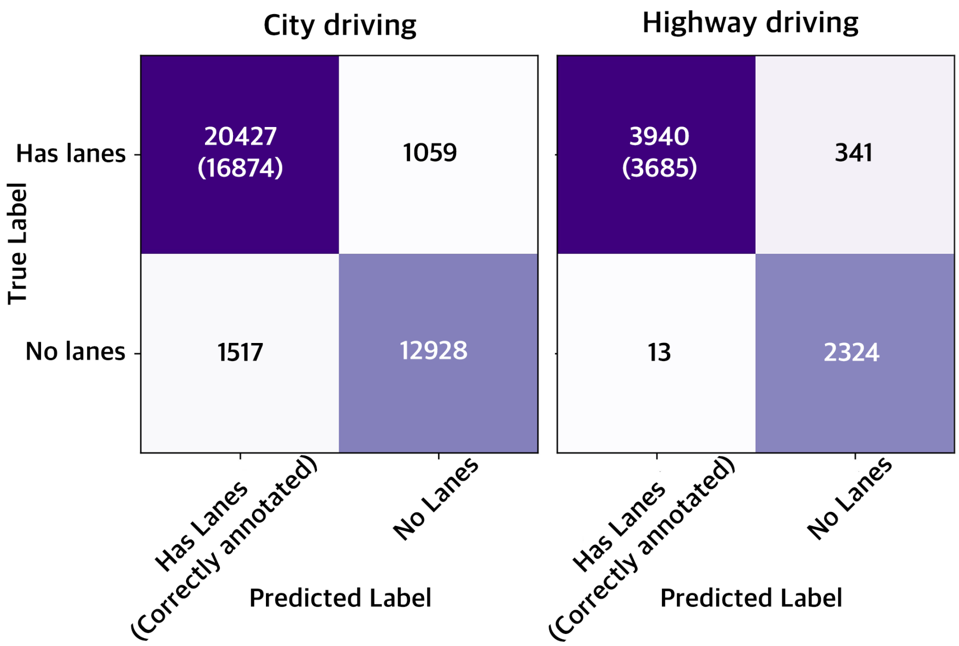
A vision-based lane detection system automatically recognizes the lanes from the input of an on-board video camera and provides lane keeping information for the prevention of accidental lane departures. Vision-based lane detection techniques are quite mature from ongoing research over the years [101], and have been successfully deployed on embedded systems [102]. To date, however, many commercial passenger vehicles are not equipped with this feature. My goal is to develop a self-powered lane detection system with the open-source Raspberry Pi platform and OpenCV library, which serves as an example of many safety enhancing features we can easily added to the automobile.

4.5.1 Development of Lane Detection System on Raspberry Pi

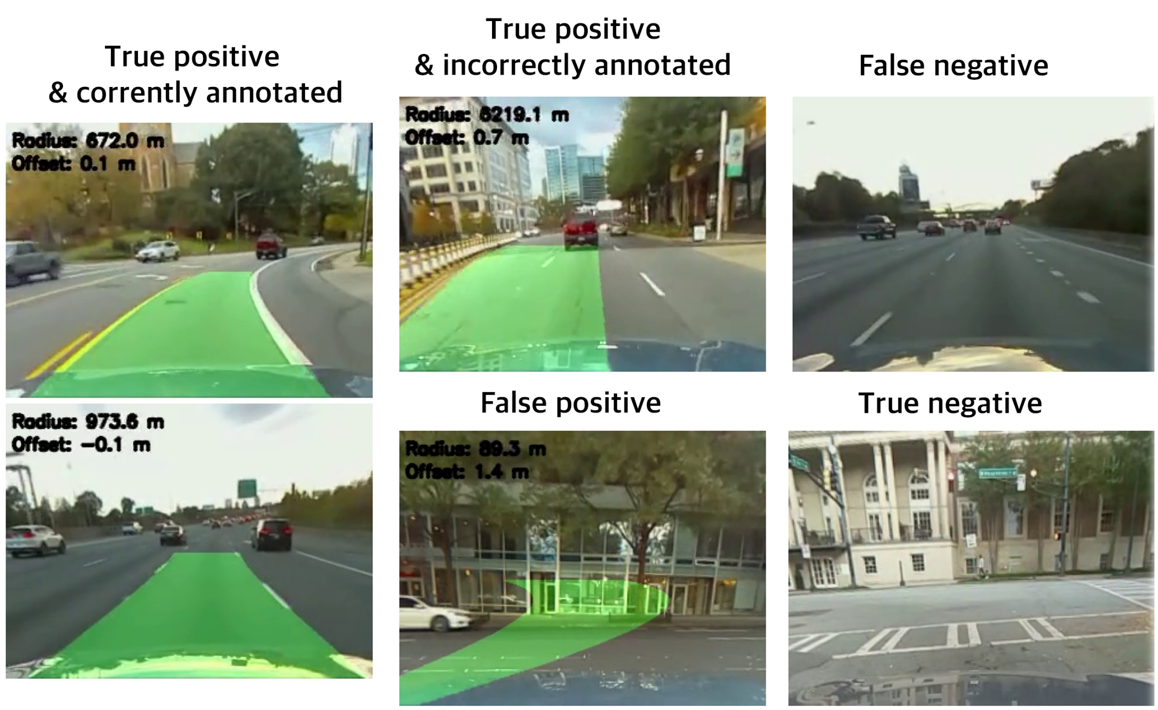
I developed a lane detection system comprised of a Raspberry Pi 4 (1.5GHz CPU, 8 GB Memory) and a camera sensor (5 Megapixels OV5647) with a 160° fish-eye lens, see Figure 4.4(b). The system captures images at 640 x 480 resolution, then applies lane detection algorithms to extract the lane-keeping information in real-time. The extracted information can be communicated via Bluetooth LE to a driver's smartphone or a dedicated display inside an automobile.

My lane detection pipeline runs as follows: 1) For each captured image, I correct the lens distortion using the initial calibration results and identify the region of interest (ROI) based on the fixed camera angle and position. 2) I apply gradient-based edge detection and thresholding in gray-scale and hue saturation lightness (HLS) color space, and transform the perspective to top-view. 3) I use a sliding window to search for lane points from the bottom to the top of the image and fit to them a second-order polynomial curves as the final detection result, for both left and right lanes. Some heuristics, such as lane width and lane curvatures, are used to reject inaccurately detected lanes. The pipeline is adapted from the Udacity course material [103, 104], and implemented with Python 3 and OpenCV [105]. My Raspberry Pi system can achieve a detection rate of 12 frame-per-second running the algorithm described above.

Experimental Setup - I deployed my lane detection system on the roof of a vehicle aligned to the center of the vehicle, with the camera facing the forward and aiming at



(a)



(b)

Figure 4.8: Performance of lane detection, (a) Confusion matrix and (b) Frames of correctly or incorrectly labeled / annotated cases.

the road, see Figure 4.4(b). The system recorded both the raw video and the lane detection result. I collected the data following the same procedure and route as described in the actual driving scenarios, see Section 4.4.3. After the experiment, I analyzed the video frames annotated with the detection result to determine whether the frame contained visible lanes, whether the lanes were detected and annotated, and whether the annotated lanes aligned with the actual lanes.

Result - In total I collected 35,931 frames of city driving and 6,618 frames of highway driving. As Figure 4.8 illustrates, looking only at predicted classes of frames with lanes versus no lanes, I achieved an accuracy of 92.8% and 94.7% for city and highway driving, respectively. Of the correctly labeled frames with lanes, 82.6% of city driving and 93.5% of highway driving were correctly annotated (detected lanes align with the actual lanes). Of the frames with incorrectly annotated lanes, objects and other vehicles were the main reasons for failure. Of the frames with undetected lanes, tunnels, direct sunlight, sharp turns, faded lanes, and obstruction from other vehicles were the main reasons for failure. Overall, I demonstrated a real-time lane detection system using Raspberry Pi platform and OpenCV that can be applied to a wide variety of vision tasks such as traffic light/sign, object, and parking space detection.

Power Consumption of Lane Detector The power consumption in the state of enabling the fish-eye camera sensor, a main processor, and a Bluetooth LE communication module of Raspberry Pi 4 was measured at 4400 mW (5 V, 880 mA).

4.6 Evaluations of Self-sustainability

In this section, I evaluate if the two sensing systems proposed in Section 4.3 can operate in a self-sustainable manner. To manage the harvested energy and store surplus energy if available, I designed two power management systems. First, a buck/boost or boost DC/DC converter was required to convert variable power input and produce a steady constant voltage to a target system. Then, a battery charger was needed to store the remaining energy, if any, and supply the power to the system if the energy generated by the wind turbine was not available. Additionally, a battery fuel gauge might be necessary to check the remaining battery. I described the block diagrams and appearances of blind spot detection system and lane detection system in Figure 4.9 and Figure 4.10 respectively.

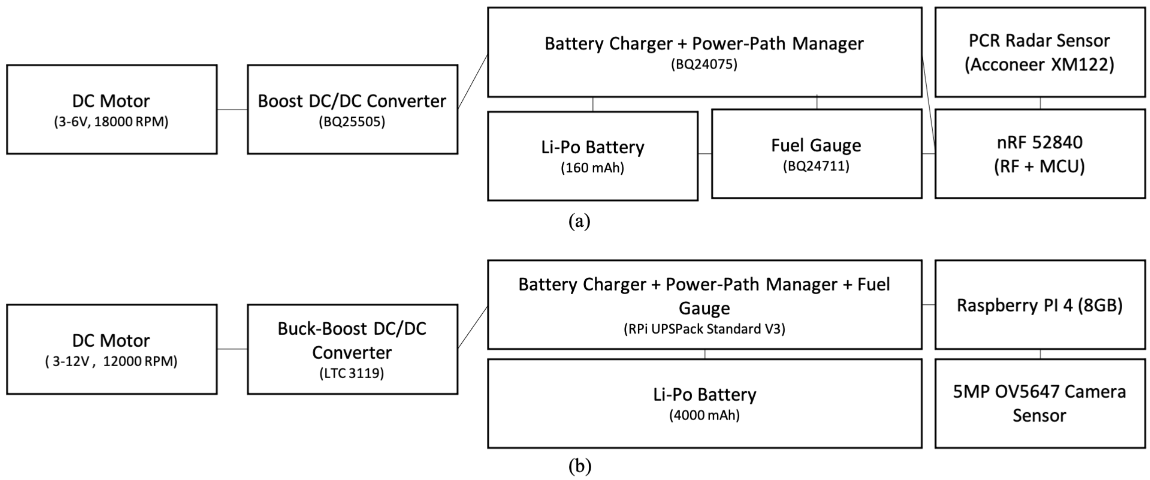


Figure 4.9: Block diagram of the two proposed sensing systems with energy management. (a) Blind spot detection, and (b) Lane keeping system.

Based on my estimation model, the blind spot detection system operating at 79.25 mW can be worked with the use of our 63 mm wind turbine if the automobile is driving at approximately 35 mph, while the lane detection system operating at 4400 mW can be worked by the 92 mm turbine at approximately 47 mph. To validate the self-sustainability of blind spot detection, I drove the same driving course described in Figure 4.4(a) with the average speed of 58km/ ($\approx$ 36 mph). As a result, the 160 mAh Li-ion battery integrated in the system experienced a net gain of stored energy of 2%. I evaluated the self-sustainability of the lane detection system with a higher driving speed of 82 km/h ($\approx$ 51 mph). The battery (4000 mAh) level of the lane detection system did not change during the 10-minute drive. This result means that there was no additional energy to be stored in the battery in this environment. Therefore, I needed to make a larger wind turbine or add one more turbine in parallel, using a diode or current sharing controller (i.e., Linear Technology's LTC 4370) for a more reliable operation in a low-speed environment. Or the system operation (e.g., sensing frequency, frame rate) needed to be optimized in a power-efficient manner.

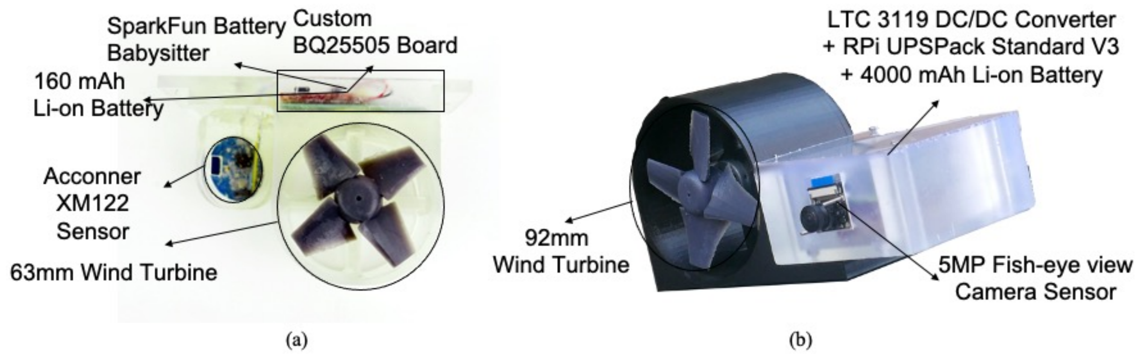


Figure 4.10: Appearance and description of the two proposed sensing system (a) Blind spot detection and (b) Lane keeping system

4.7 Impact of Wind Turbine on Fuel Economy

The presence of the wind turbine increased the amount of aerodynamic drag on the automobile. This led to greater energy consumption and, thus, greater fuel consumption. I performed a computational fluid dynamics analysis to determine the impact the wind turbine would have on energy consumption and fuel economy. By calculating the drag coefficient and frontal area of a vehicle and a vehicle with an energy harvester, I could determine the amount of drag added from the addition of the wind turbine. Ansys Fluent [106] was used to perform this computation. I used a simplified representation of a vehicle, which had similar dimensions to the best-selling passenger car in America, Toyota RAV4. It has a drag coefficient of 0.33929, as computed by Fluent, which falls within the typical range for vehicles sold today. The drag coefficients were determined by setting the velocity of the airflow at 27 m/s and using the Spalart-Allmaras turbulence model [107]. Note that the drag coefficient was relatively consistent across multiple velocities. For the sake of simulation, I defined the dimension of a wind turbine on top of the automobile as 20 x 10 x 10 cm (width, height, and depth) and another wind turbine on the side of the automobile as 10 x 5 x 5 cm.

Afterwards, multiple wind turbines (of my design) were placed on top of the vehicle and underneath the left side mirror. These simplified representations of the turbines showed that the drag forces can vary significantly based on the shape of the turbine. A box shaped turbine, for example, could raise the total drag coefficient over 0.4, while a drop shaped turbine only raised the total drag coefficient to 0.34424. The side mirror mounted wind turbine created a larger amount of drag, even with optimizations, with a best case drag coefficient of 0.35973. After computing the drag coefficients of the automobile and various wind turbine configurations, we can determine the drag force on the car using [108]

$$F_{drag} = \frac{1}{2}\rho v^2 C_D A \tag{4.3}$$

where C_D is a drag coefficient, A is the frontal area computed from Ansys Fluent and ρ is the density of the air, 1.225 kg/m^3. From this equation, I can calculate the drag force in Newtons at varying velocities. To overcome this drag force, I can also calculate how much power is needed because $P = Fv$. As an example, the wind turbine on top of the vehicle created an extra 23.8 N of drag at 27 m/s, a typical highway speed, thus requiring approximately 642 watts of extra power.

Using the methodology described in Mendler [109], I can estimate the impact the harvesters have on the fuel economy of the vehicle. The results provide an Environmental Protection Agency (EPA) city and highway driving figure. Mendler computed the power consumption by summing up the power demand from acceleration, tire friction, hill climbing, and aerodynamic drag on the EPA test cycles. For the sake of estimation, I assumed only aerodynamic drag changes when adding the harvester and left the others as a constant. The aerodynamic power consumption $P_d{}'$ is given by

$$P_d{}' = T_d D_d C_d \tag{4.4}$$

where T_d is 1128.109 for the city and 6569.298 for the highway, D_d, is the frontal area of the car, and C_d is the drag coefficient. Using eq. (4.3) and eq. (4.4), I compared the drag

Table 4.1: Additional fuel consumption for the proposed wind turbines

	Original	Wind Turbine on Top	Wind Turbine on Side
City driving	28.00 MPG	27.68 MPG	27.53 MPG
Highway driving	35.00 MPG	33.94 MPG	33.46 MPG

power consumption for the vehicle with and without the harvester. From that, I determined the additional fuel consumption, in MPG, of the vehicle as shown in Table 4.1. To get a real world understanding of this, I assumed the test vehicle is a Toyota RAV4, which gets an EPA estimated 28 MPG city and 35 MPG highway [110].

4.8 Summary

We are heading toward the era of smart automobiles that consist of many intelligent sensing systems. My proposed approach, *compute-proximal energy harvesting*, can provide a new dimension to the role that energy harvesting techniques play in designing post-factory self-sustainable sensing systems. This perspective enables new paradigms such as ubiquitous sensing systems without energy restrictions when designing automobiles as well as future mobility. The purpose of energy harvesting is not just to recharge the battery of the main system but also to augment new self-sustainable computing and sensing capacities.

As an example of this research vision, I examined inch-scale wind turbines. I reviewed the critical factors of wind turbine design and evaluated their impacts on the efficiency of energy harvesting through three methods—theoretical estimation, computational simulation, and empirical evaluation. We demonstrated two inch-scale wind turbines—63 and 92 mm diameter—with optimized rotors and achieved 20.6% and 16.2% power conversion efficiency, respectively, compared to the theoretical limits. The power budget has much influence when designing a sensing system [3]. For example, in the case of radar or camera sensors, the sensing frequency and resolution of a target system may be limited according to the available power; therefore, this limitation should be considered when developing self-sustainable systems. In particular, it is necessary to apply the power-aware system operations studied in intermittent computing to the applications in compute-proximal energy harvesting. If so, they can be operated in a more reliable manner.

To this end, I demonstrated two advanced safety sensing systems that can be operated in a self-sustainable manner under the energy budget of my wind turbines. First, I examined a novel low-power radar sensor for monitoring blind spots and achieved approximately 90% accuracy with the optimization in signal processing and adoption of a proprietary radar mechanism, called Sparse service, by Acconeer. Second, I implemented a lane detection algorithm using an off-the-shelf camera sensor and embedded platform and achieved above 90% accuracy both in city and highway driving situations. Last, I confirmed that these applications can be operated in a self-sustainable manner while achieving high accuracy. One obvious research direction for the next generation ubiquitous computing is low-power and high-resolution sensing. The PCR sensing system explored in this paper can be a thought-provoking example in this regard. Another research challenge is democratization and deployment. There were various ubiquitous computing examples implemented based on Raspberry Pi 4 [28, 29]. By demonstrating the self-sustainability of this embedded platform, I can inspire other researchers and developers to make more self-sustainable systems in their application domains. For example, as power consumption of Raspberry Pi 4 is comparable to other embedded systems with machine learning accelerators (e.g., NVIDIA Jetson Nano), these systems can also be implemented in a self-sustainable way without modifying our wind turbines.

Automobiles constitute one experimental application domain of our approach; however, the approach could easily be extended to other types of mobility such as electric scooters and electric/regular bikes. There are also additional energy resources (i.e. solar, heat, and vibration) for the extension of my approach. While conducting this research, I realized that there are few tools researchers can utilize for compute-proximal energy harvesting. What types of energy can we harvest in a target environment? What method could be the most efficient method to harvester the energy? If there is variation in the amount of energy, how can this situations be managed? How could a benchmark test related to energy harvesting be possible as in other disciplines (e.g., machine learning or activity recognition)? A toolkit for proper power provisioning is an essential technology that needs to be thoroughly explored.

4.8.1 Limitation

Due to the material limitations of the Formlabs 3D printer used in this study, I could not examine various tip speed ratios when conducting empirical evaluations. This was related to the thickness of blade and endurance force of the rotor. If I could make thinner and more robust rotors using metal or other strong materials, this could affect the performance of wind turbine. The main concentration of this project is not on the best accuracy of each sensing method; I focused more on self-sustainable operation with reasonable accuracy. With more advanced processing and classification techniques, the accuracy of each system can be improved.

CHAPTER 5

UNDERSTANDING THE CHALLENGES AND OPPORTUNITIES ASSOCIATED WITH ENERGY HARVESTING TECHNOLOGY

In the previous two chapters, I demonstrated the potential for creating compute-proximal energy harvesting solutions for an automobile through both analytical and empirical investigation and the development of specific proof-of-concept prototypes that I built. However, I have much experience in electronics and have trained myself extensively during my studies on energy harvesting solutions. In the remainder of this thesis, I examine how others might also explore the design space of compute-proximal energy harvesting without the in-depth knowledge and experience that I possess. I begin this chapter with a qualitative user study to better understand the challenges designers and makers have when considering the application of energy harvesting technologies in mobile environments such as the automobile.

I found that the tools to implement energy harvesting functions are limited and difficult for researchers, designers, and makers to adopt. This problem is compounded for those who have little prior experience with energy harvesting solutions. This leads me to investigate what I, as a researcher in the intersection of human–computer interaction (HCI) and energy harvesting, need to do for makers who have minimal to no prior experience with energy harvesting technology. In this chapter, I explore the challenges faced by researchers and makers who have been using energy harvesting. This step is critical since the problems they have experienced are the ones that novices will face while applying energy harvesting technology. By understanding the issues, I can better understand what possible solutions should be implemented to simplify the process.

5.1 Introduction

HCI has shared a growing interest in the potential of maker culture for the democratization of technology innovation [111, 112]. For instance, the do-it-yourself (DIY) movement has envisioned extending the HCI vision out of the research labs and into the general public [113, 114]. However, very little research addresses how makers work with energy harvesting technologies. I found many energy harvesting-related projects documented in Make: magazine [115], and in online maker communities, such as instructionables.com and hackday.io. These projects employed mature power harvesting techniques, such as solar cells, piezoelectric, and vibrations. The novel energy harvesting materials and fabrications techniques emerging in academic research labs remain foreign to the general maker communities.

This study builds upon the questions raised from the two studies in Chapters 3 and 4. Specifically, when implementing or integrating an energy harvesting function, I realized that it is necessary to consider several factors, including which energy source is most suitable, how much energy can be scavenged, and what design parameters of a specific energy harvesting technology can be adjusted to improve performance. Other design variables address the power requirements for the computing solution, as well as how harvesting and computing varies during a typical use of a mobile environment (e.g., when a car is driving around a city in a rainstorm). To delineate these challenges, I interviewed researchers and makers who have utilized energy harvesting technology. My intent was to investigate what motivated them to use energy harvesting technology, what problems they encountered, and what possible solutions they considered. These insights help me to understand better the requirements of any proposed toolkit support aimed at makers with little energy harvesting experience.

This chapter addresses the third research question of the thesis: *"What kinds of challenges have researchers and makers experienced while working on energy harvesting tech-*

nology in their previous projects?" In addition, I explore what factors motivated them to use energy harvesting technology in the past and what domain knowledge, skills, tools, materials, and resources are needed to overcome the challenges inherent in this endeavor.

5.2 User Study

I conducted an IRB-approved qualitative study (Protocol Number: H20529) consisting of semi-structured interviews with makers or researchers (N=9, see Table 5.1). Participants were recruited by emailing academic researchers and makers across the US and members who actively post related projects on online makers communities such as instructables.com and hackday.io. Each participant received a 15 USD gift card as compensation.

Table 5.1: Demographic and background information of the participants (*EH: Energy Harvesting)

ID	Age	Gender	Education	Number of EH Projects	Experienced EH Modes	Difficulty Level of Working on EH
P1	25-34	Male	Advanced degree	2	Wind turbine, New materials	Moderately difficult
P2	25-34	Male	Advanced degree	3	Solar cell	Slightly difficult
P3	25-34	Male	Bachelor's degree	2	Solar cell, Radio frequency	Slightly easy
P4	18-24	Male	Some college w/o degree	1	Solar cell	Neither easy nor difficult
P5	25-34	Female	Advanced degree	4	Solar cell, Algae systems	Slightly difficult
P6	25-34	Male	Advanced degree	3	Solar cell, Vibration, Heat, RFID	Slightly difficult
P7	55-64	Male	Bachelor's degree	5	Solar cell, Heat, Bio-diesel	Slightly difficult
P8	25-34	Female	Advanced degree	2	Solar cell, Vibration	Slightly difficult
P9	25-34	Male	Advanced degree	4	Solar cell, Wind turbine, Vibration	Moderately difficult

5.3 Data Collection and Analysis

Since in-person meetings were not feasible due to the COVID-19 pandemic, I hosted and recorded the interview sessions through BlueJeans, a Georgia Tech-certified conference call system. All participants provided informed consent before participating in the survey and the interview. The detailed guidelines of the interview session are presented in Appendix-Chapter A. Each interview took approximately an hour. Once I completed the interviews, one of the master students in my research team transcribed the recorded data. I employed a combination of inductive and deductive thematic analyses to infer a list of themes from the data collected and uncover emergent themes [116]. First, I began with inductive analysis by open coding the themes from the data, followed by deductive analysis to look for themes closely related to my driving research questions.

5.4 Results

I identified six themes from inductive/deductive analysis. Three refer to challenges the participants identified, and three describe opportunities for improvement.

5.4.1 Challenges

Challenge-1) Manage the trade-offs among many design constraints: The process of working on energy harvesting is similar to solving a Rubik's Cube. All the participants shared their frustrations about finding the best recipe to balance the trade-offs among design constraints. Primary design concerns included 1) the limited power that can be harvested, 2) the compatible form factor that affords the intuitive user interactions, and 3) the cost of working solutions.

An example is P2's story of installing interactive floor tiles on the campus of NASA's Kennedy Space Center. His team attempted to harvest vibration energy induced by visitors' footsteps using the piezoelectric films on the tiles. P2 mentioned,

> "The tiles should have a certain amount of physical strength because they were not only supposed to interact with kids.... We need to ensure that the size and the shape of the tiles and the strength of the concrete are good enough... But, at the same time, the tiles [should be] interactive with a slight touch from the kids... So that was a very strong challenge for us to ensure that it does not break with heavyweight but is responsive even if the weight is not that much."

Challenge-2) Ensure the reliable energy performance under different usage scenarios: The more practice over time, the more enjoyment people may have in solving the Rubik's Cube. However, this is not the same story as energy harvesting projects because the real world is full of dynamic, unpredictable, or even unknown variables affecting energy performance. When P2 worked with solar panel cells to get the sun's maximum exposure, he had to consider all the changing relationships between the sun's orientation and the site conditions.

> "Every place has a different climate and different context; you have to learn all of that to come up with a more sustainable solution."

P7 shared a similar story when he tried to replicate an experiment described in a publication, but he failed to do so because of differing humidity in the two testing environments. While the variables in nature are difficult to manage, so are the variables in nuanced human interactions. For example, as P9 conceptualized swiping to harvest energy, she noticed that "people might swipe differently."

Challenge-3) Access to tools that are optimized for energy harvesting: With the advancement of material sciences, researchers look for new materials and fabrication techniques to optimize the existing energy harvesting methods. One problem is the access to the specialized tools to facilitate simulation across different application scales. P5, who works on self-sustainable building systems by harvesting energy from algae cultivation, was challenged to translate the energy supply data on the level of algae pond to the urban scale.

> "These two systems remain disparate... and it's hard for us to get these two systems to talk to each other and transfer information between each other."

P9, who adapted TENG technology to develop a self-powered sound or vibration sensor, suggested "more specialized measuring equipment" for ultra-low energy magnitude:

> "if the energy you're harvesting is at nano-watt level or sub microwatt or double-digit microwatt level ... in those extreme cases, you need more specialized measuring equipment to really know what you're working with."

Arduino-based electronic prototyping tools have enabled makers with different knowledge levels in hardware and circuits. However, Arduino is not optimized for energy harvesting technologies and the development practices that accompany those technologies. It consumes much more power than needed since it is not designed for low-power operation or efficient code execution. P8 mentioned,

> "It is not flexible to scale up to suit the needs of more expert energy makers nor scale down to empower novice energy makers. Arduino framework did a lot of abstractions to make it suitable for just any makers, in general, to work on the electronics project. But that same abstraction does not really apply to energy harvesting."

5.4.2 Recommendations

Recommendation-1) Abstract the technical knowledge into "black boxes": Understanding technical concepts and the entangled underlying working mechanism is essential to design, build, iterate, and manufacture energy harvesting hardware and circuits. However, internalizing this knowledge is time-consuming and challenging for novice and average energy makers. To support quick hands-on learning and creative exploration at different scales, the number of technical components should be reduced, and their complex details need to be wrapped into the "black boxes." Thus, the proper hardware parts could be a set of Lego-like pluggable electronic components that support scalability, hack-ability, and mix-and-match. For example, there are "master Legos" each representing the module of a harvester from a particular energy source. Each master Lego comes with a collection of "guest Legos" representing the design variables of this master Lego. Makers could simply mix and match the guest Legos as inputs.

Recommendation-2) Make the technical concepts easy, fun and accessible: The participants suggested building a reference library to comprehend the operations, design variables, materials, and fabrication techniques and tools for each energy harvesting mode. Such advanced information should be delivered in a language that novice users or average makers can easily understand. This information should promote makers' interest by presenting knowledge in an interactive, visualized manner. P6 described his first experience in building an energy harvesting system as:

> "I kind of did a whole bunch of research on YouTube before I built the first one to see what other people did and how they worked."

In addition, P8 argued that

> "Nobody wants to read spec sheets, but that is actually one very, very, very important skill"

Recommendation-3) Integrate simulations into the prototyping process: Participants also suggested creating a simulation tool that could accurately model the energy performance in real-time during the prototyping process. This could lead makers in the right direction to tweak the design variables and find the most optimal energy efficiency. P4 and P5 expressed the need of simulation tools as follows:

> "[P4] I wish that I can make that similar experience in the energy harvesting thing is to say, print out while I'm designing and test it out in some similar

> environment. So, like more proof of concept, I show that this is working in this situation and this is mirroring how it would affect it If I'm using the solar cell space, that would mirror that same effect. "

> "[P5] But having some way to measure how much energy you could really harvest within the day, to be an interesting thing for makers to, you know, how far their design is affected, right?... that's important to know that how much energy you can really harvest and it would be more exciting and fun for people to know that what angle they're putting these things and how they're able to."

5.5 Design Implications for an Energy Harvesting Toolkit

One of the major challenges for energy harvesting is the time and effort needed to gain the expertise to design and deploy a reliable energy harvesting solution for a given context. This resonates with my personal experience (as demonstrated in Chapters 3 and 4) of developing various energy harvesters capable of maximizing the energy conversion efficiency, storing surplus electrical energy, overcoming the cold-start conditions, and monitoring the energy variability. The interview results from this study revealed that researchers and makers who have dealt with energy harvesting experienced similar challenges. Energy harvesting tools are essential to overcome these challenges. Table 5.2 summarizes the design implications of both my own experience and this chapter's study result for tools to support compute-proximal energy harvesting solutions.

5.6 Summary

In this chapter, I identified various problems concerning people who have studied or used energy harvesting technologies. I summarized what tool support is needed to address those problems. In the next chapter, I discuss the design and development of a specific tool, along with an initial empirical evaluation of how it supports a wider audience (i.e., those who do not have experience in energy harvesting) to more confidently and creatively explore the space of compute-proximal energy harvesting for mobile environments.

Table 5.2: Components and requirement sources of the proposed energy harvesting toolkit

Component	Function	Basics	Challenges			Recommendations		
			1	2	3	1	2	3
Design Tool	Help users to find one or more promising energy harvesting modes for a target environment.		•					•
	Provide how-to guidelines and easy-to-follow tutorials for implementing energy harvesters.						•	
	Suggest optimization techniques for improving the efficiency of energy harvesting module.				•			
Hardware	Monitoring the amount of available energy.			•				
	Investigate the variability of an energy source with its contextual factors.			•				
	Convert the target energy sources into electrical power.	•				•		
	Store surplus electrical energy if available.	•				•		
Software	Support the proposed hardware through easy-to-integrate embedded software libraries (e.g., Arduino).					•		
	Predict the possible amount of energy.			•				•

CHAPTER 6
DESIGNING, BUILDING, AND EVALUATING AN ENERGY HARVESTING TOOLKIT

In this chapter, I describe the design and evaluation of a toolkit, Exergy, to provide a means for novice users to manufacture and ideate self-sustainable systems in mobile environments. Exergy is designed to support a broad range of energy harvesting modes, but the first iteration presented in this thesis focuses on wind energy harvesting for a set of mobile environments. The needs, pain points, and insights from prior studies, as well as from my personal experience (see Chapters 3 and 4) and the study results presented in Chapter 5, informed the final structure and requirements of Exergy. Reflecting these requirements, I developed a wind energy harvesting toolkit to expand the concept of compute-proximal energy harvesting. After that, with people who had no prior experience in wind energy harvesting, I evaluated perceived difficulty and technological confidence with respect to the toolkit and assessed how creatively people can design self-sustainable systems with the toolkit.

The part of the toolkit demonstration in this chapter was published by Park et al. at the 19th ACM International Conference on Embedded Networked Sensor Systems (SenSys 2021) [117].

6.1 Introduction

Numerous HCI researchers have tried to transform their own knowledge and skills into tools that empower makers, designers, or the general public [42, 43, 44]. In the past, these efforts were often viewed as helping the hobbyists in the DIY community [111]. However, over the past decade, this viewpoint has broadened, and we now regard the efforts as "democratized technological practice," one of the core topics in HCI [112]. Democratization in DIY started with fabrication tools for non-functional objects, but it has since expanded to "smart" objects that include electronics, metamaterials, biology, and wearable computing [118, 119, 120, 121].

The ideology of the maker culture is to increase access to the means of creating physical inventions. The prototyping tools and the fabrication techniques for energy harvesting should be simplified as a "maker technology" to support and empower more creative minds [3]. There are several examples—Behavior Construction Kits[122], Phidgets[123], The Calder Toolkit[124], and LittleBits[125]—that have improved people's manufacturing skills and expanded the scope of their ideation. However, only a handful of such tools (e.g., Lilypad[126] and the Proximity Toolkit[127, 128]) have been widely embraced by the maker communities.

Successful tools with broad adoption share two characteristics. First, they increase the confidence of users to reproduce solutions that experts produced, but without the prior experience and knowledge of those experts. Second, as a result of this confidence boosting, these tools open up a design space for others to display their creativity. For the proposed energy harvesting tool to be widely adopted, we need to deeply understand these two aspects—ease of use to novices in an area that leads to confidence in their maker skills and the creativity that can be unleashed through access to a broader set of users.

Energy harvesting technology has been studied for a long time in the area of ubiquitous and mobile computing, but efforts to democratize it are still very limited. Thus, I begin this chapter by discussing what makes a tool approachable and usable for a novice population. Then I illustrate how that tool inspires creativity from those new users. This chapter addresses the fourth research question of this thesis: *"How can a tool allow people with no prior experience in energy harvesting to confidently and creatively prototype wind energy harvesting solutions for automobiles and other mobile environments?."* I illustrated the research flow of this chapter and the relationship between this chapter and the previous chapters in Figure 6.1.

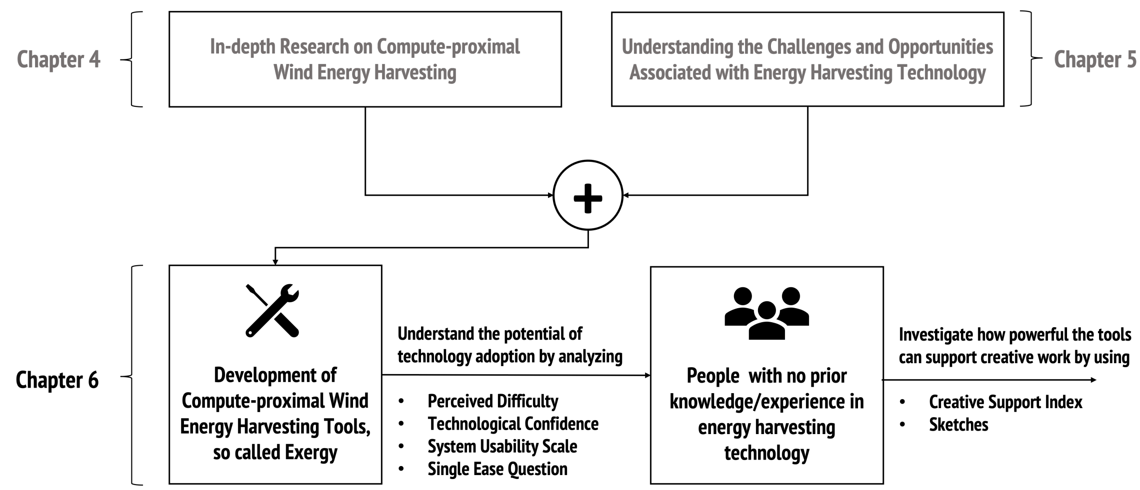


Figure 6.1: Research flow for designing, building, and evaluating the proposed toolkit in Chapter 6

6.2 Exergy - Compute-proximal Energy Harvesting Toolkit

Exergy literally means *"the energy that is available to be used"* or *"the portion of energy that can be converted into useful work"* [129]. In this research, Exergy is a toolkit designed to empower novice users, which in this context means people with no prior experience in wind energy harvesting, to design and develop self-sustainable systems confidently and creatively. Exergy consists of four parts—a simulator, hardware tools, software examples, and ideation cards. In the following sections, I describe each part in more detail. Although I focused only on wind energy while designing and implementing this initial prototype for Exergy, the requirements and design principles of Exergy are relevant to other energy harvesting modes such as heat, vibration, and solar.

6.2.1 Exergy Simulator

Development of Exergy Simulator

One of the first decisions a designer needs to make is where to place the self-sustainable energy harvesting solution. That critical decision will determine how much wind energy can be harvested, so it is important to help the designer see the energy harvesting potential to compare it to the energy needs of the computation. To estimate the amount of electrical power harvested from wind, we first need to know the wind speed at the location a wind turbine will be placed, Equation 4.1. It was not practical to measure the wind speed of all the points around a vehicle in the wild due to uncontrollable variables such as ambient wind and traffic. Thus, I performed computational fluid dynamics (CFD) simulations to predict the wind speed using Autodesk CFD 2019 instead. I used the sedan as an example to explain the details of the development processes. The procedures also apply to all the other vehicle types that Exergy supports—sport-utility vehicle (SUV), heavy truck, motorcycle, and bike (Figure 6.2).

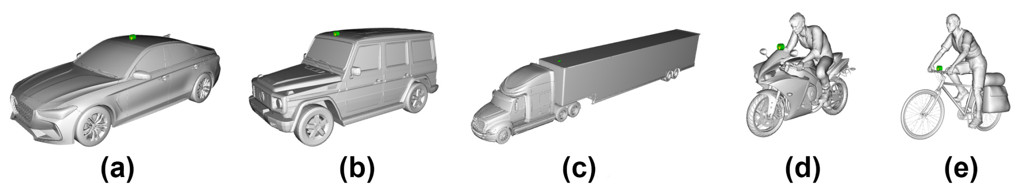


Figure 6.2: Vehicle types that Exergy supports. (a) sedan, (b) SUV, (c) heavy truck, (d) motorcycle, and (e) bike.

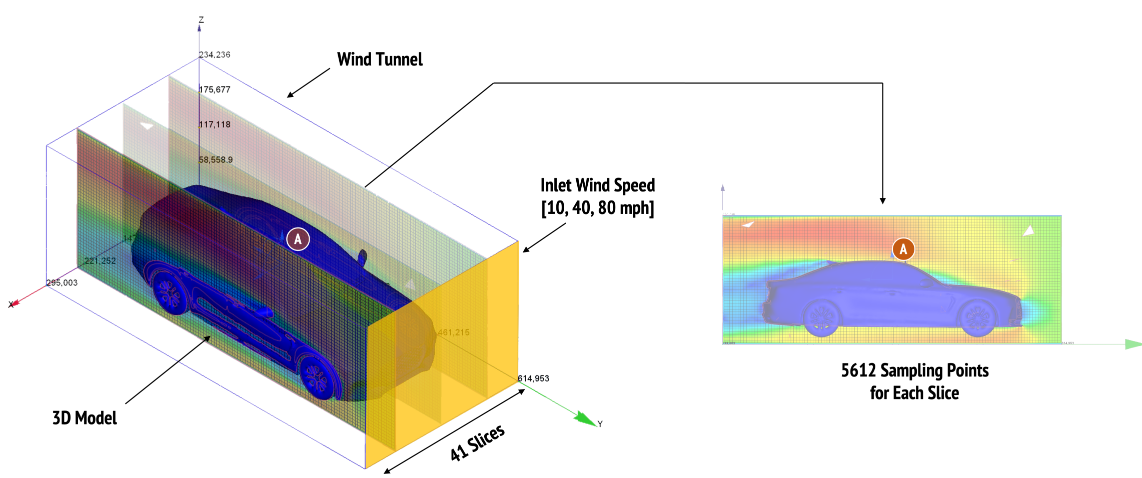


Figure 6.3: Computational fluid dynamics (CFD) simulations were performed for each transportation model, and the results were exported as described in this figure.

As a first step, I imported the 3D model of the sedan into the CFD tool and created a hexahedral wind tunnel with a sufficient margin between the 3D model and the wind tunnel as shown in Figure 6.3. Since the margin was not enough, the airflow around the

3D model could be obstructed, leading to inaccurate simulation results. After creating the wind tunnel, I performed three CFD simulations by setting the inlet wind speed to 10, 40, and 80 mph. The simulated wind data was cut vertically into 41 slices and stored in a database. Each slice contains 5612 sample points, as shown on the right side of Figure 6.3. In total, there are 230,092 wind sample points for each inlet wind speed, which are the purple-colored dots in Figure 6.3.

Let us assume that a user wants to place a wind turbine at Point A in Figure 6.3. The simulator searches the CFD database to find the wind sample point closest to Point A. It then retrieves the inlet wind speed and the corresponding wind speed at the closest sample point, as shown in Table 6.1. Here, the inlet wind speed is considered as the same as the driving speed of the sedan. Thus, the simulator computes the linear regression between the driving speed and the wind speed at Point A as follows:

$$WindSpeed_{PointA} = DrivingSpeed * 1.47 - 0.68 \tag{6.1}$$

Note the R^2 value of the linear regression is 1. Using this equation, the simulator can compute the wind speed at Point A at any driving speed and estimate the harvested power through Equation (4.1) and Equation (3.3). For example, if the sedan is moving at 20 mph, the wind speed at Point A is 28.72 mph. The harvested power at Point A is 1624.13 mW under the condition where the diameter of wind turbine is 4 inches, air density is 1.244 kg/m^3, and the power coefficient is 0.15. All the variables can be modified in the simulator.

Table 6.1: Retrieved wind speed at Point A in Figure 6.3 by the driving speed from the CFD database

No	Driving Speed (Inlet Wind Speed)	Wind Speed at Point A
1	10.00 mph	14.17 mph
2	40.00 mph	58.01 mph
3	80.00 mph	117.24 mph

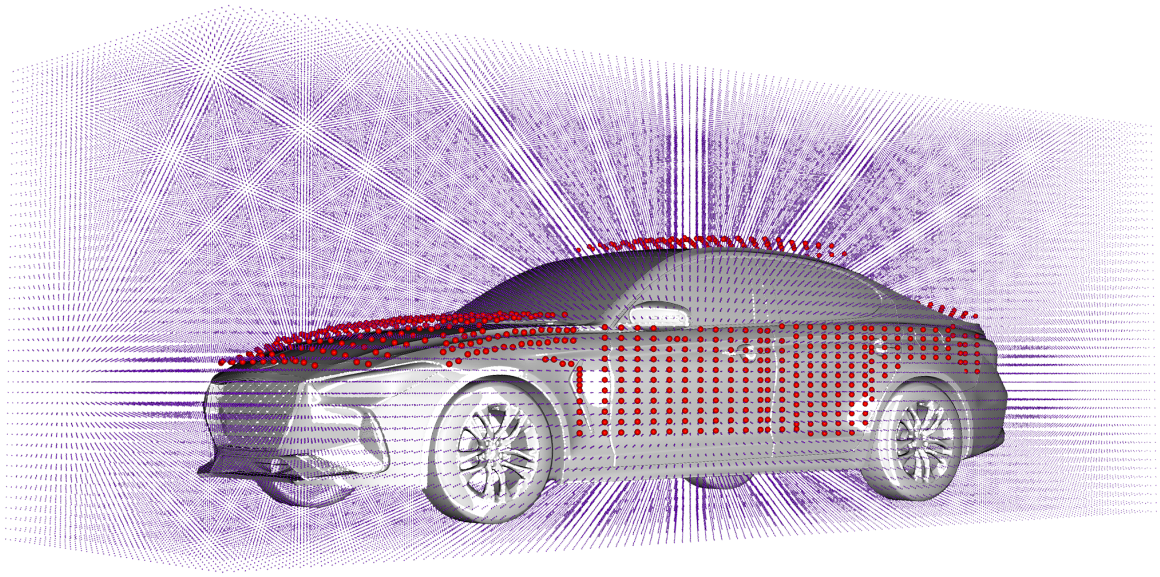


Figure 6.4: Purple dots are the extracted wind sample points from Autodesk CFD 2019. Red dots are the points where the wind turbine can be located. Since it would be difficult to attach a wind turbine to places such as moving windows or glass, I excluded those areas and specified the red dots heuristically. I applied this rule to other vehicles when I integrated the CFD data and 3D models into the simulator.

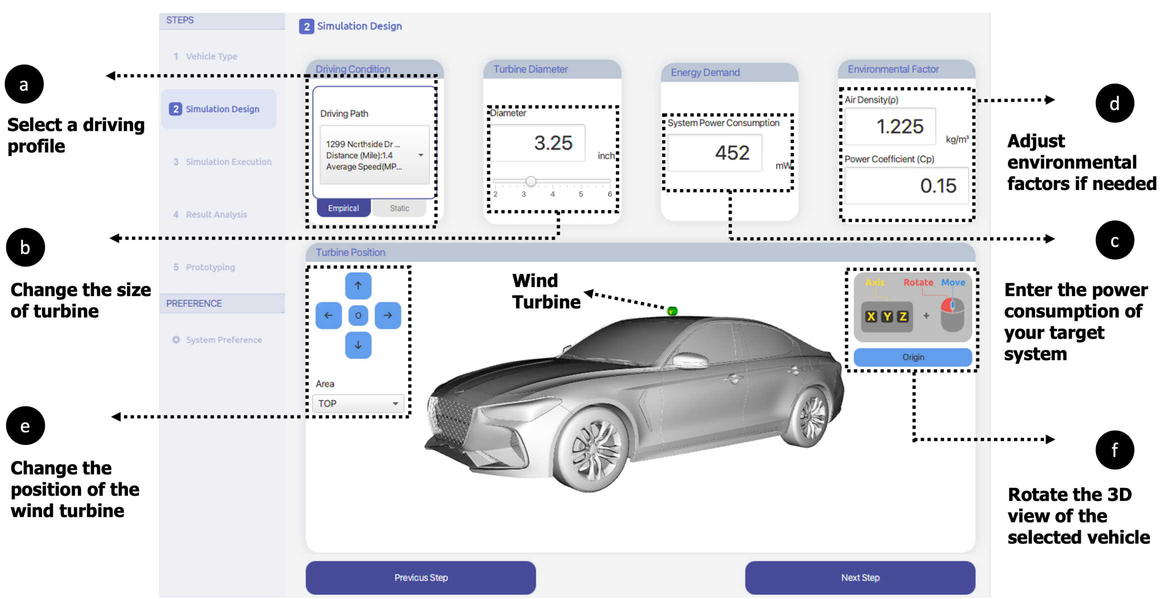


Figure 6.5: Exergy simulator allows a user to design and perform a simulation for wind energy harvesting in vehicle environments.

How to use the simulator

The first step to use this simulator is selecting a vehicle type from a set of options presented in Figure 6.2. After selecting a vehicle, a user can adjust more parameters for energy harvesting simulation. As shown in Figure 6.5. (a) I integrated driving log data collected by our custom mobile application (see Figure 6.6) as well as open-source data sets shared in online repositories such as https://www.kaggle.com for empirical simulation. The user can also select a static driving setting and enter a specific driving speed. (b) The size of the turbine is proportional to the power that the airflow energy harvester can harvest. As each application has different space constraints, the user can enter the preferred size of the turbine. (c) The power consumption of the target system is essential information when it comes to the evaluation of self-sustainable systems. Exergy helps the user to compare the power consumption with the harvested power and visualize whether the target system can be self-sustainable or not (see Figure 6.7). (d) The user can also modify the air density in the target environment or adjust the power coefficient of the energy harvester if needed. (e) The wind turbine can be moved to various positions by the four-way buttons. (f) The user can rotate the 3D view of the selected vehicle and visually check how the wind turbine can be integrated into the surface.

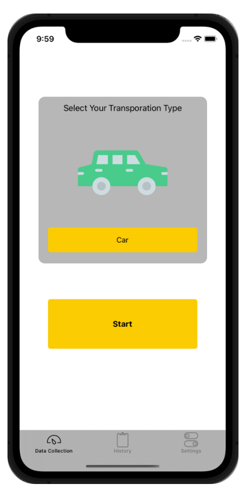


Figure 6.6: Exergy iOS application allows a user to collect actual driving information and transfer it to the simulator through the Google Firebase cloud service.

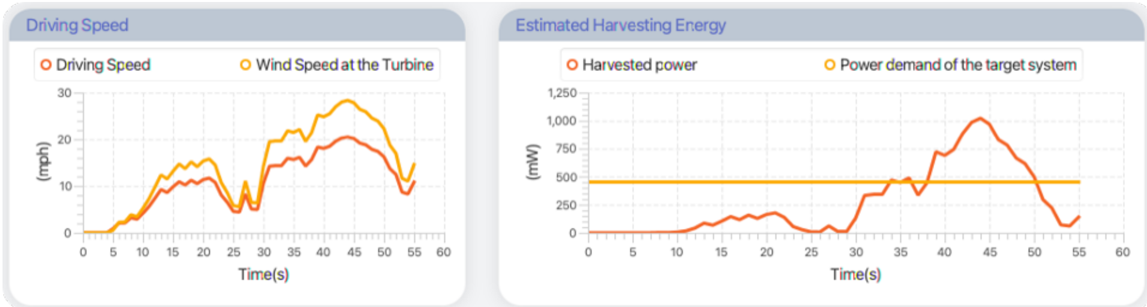


Figure 6.7: An example of the simulation result of wind energy harvesting

Once the user finalizes the simulation factors, Exergy performs the simulation and presents the results with design suggestions. For example, Figure 6.7 shows that the wind energy harvester the user designed can only sometimes meet the power demand. In the case where the average power is below the demand, Exergy recommends the user increase the turbine size. If there is surplus energy, Exergy then recommends an energy storage device such as a rechargeable battery to save it for the time that the harvested power is not enough, see Figure 6.8).

6.2.2 Energy Harvesting Hardware Tools

After completing the simulation and confirming the size of the turbine, the user can prototype the wind energy harvester by utilizing the hardware modules provided in Exergy as follows: (1) The user can adjust the size of the custom propeller model for the target application and manufacture it through a commodity 3D printer. (2) The printed propeller is connected to a DC motor for converting wind energy into electric energy. (3) Since the electrical power from the motor may vary, a Buck-Boost DC/DC conversion is required for a constant, stable power supply. I used LTC3119 and built a custom board, as shown in Figure 6.9(c). (4) I developed another custom board to store surplus power into a rechargeable battery, measure the remaining power in the battery, and control the power path between the connected wind turbine and the battery, as shown in Figure 6.9(d).

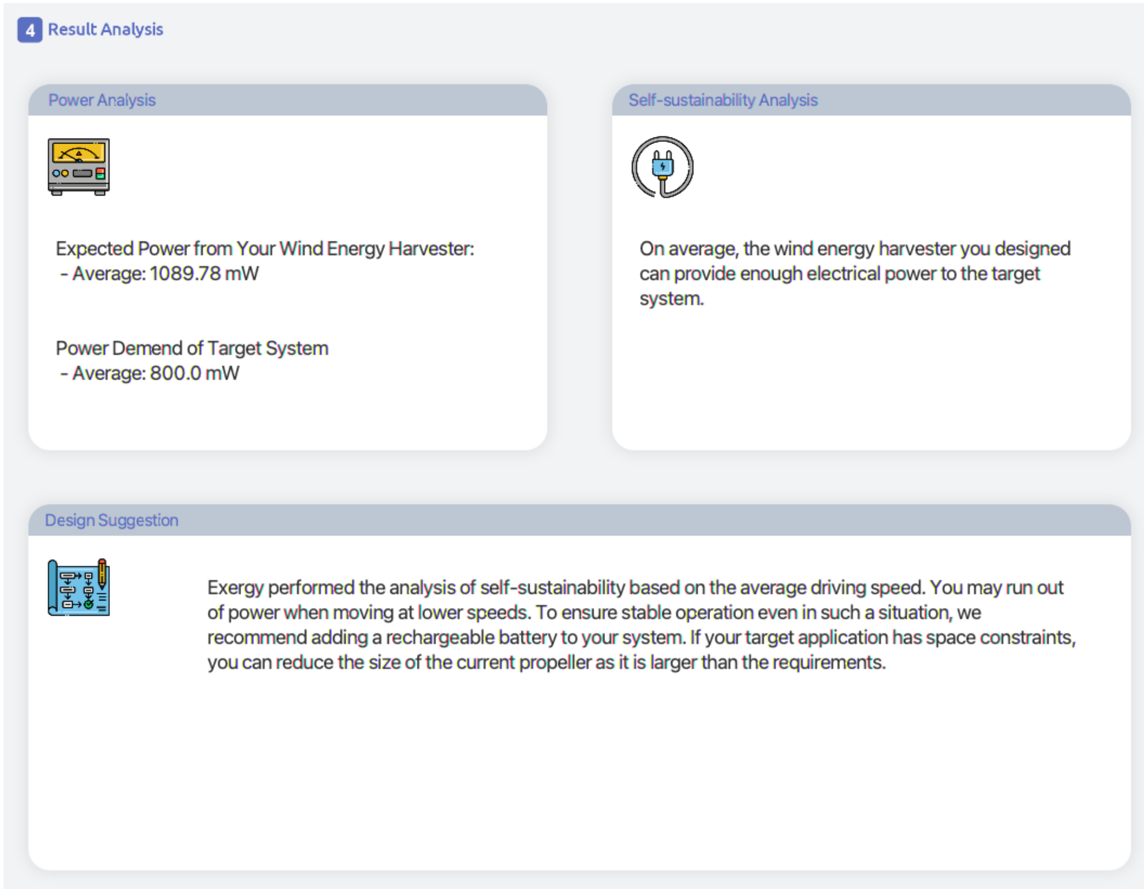


Figure 6.8: Design suggestions based on the simulation result of wind energy harvesting

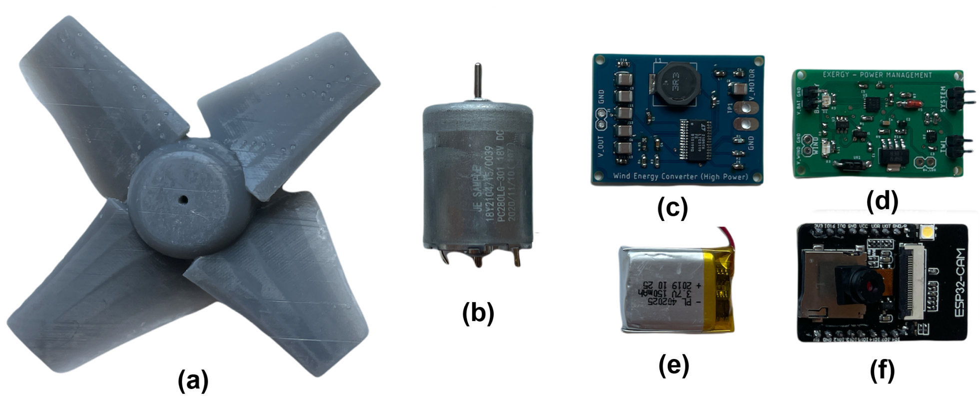


Figure 6.9: Hardware components of Exergy: (a) 3D-printed propeller. (b) DC motor, (c) Buck-Boost DC/DC converter, (d) Power management board, (e) Li-Po rechargeable battery, and (f) ESP32 base platform for the self-sustainable wireless camera application.

6.2.3 Energy Harvesting Software Example

I developed an embedded software example to help users check battery level and power source information (i.e., turbine or battery) while running an application. Applications that use a camera sensor generally require a great deal of power. If wireless communication is needed to transfer the video data, the necessary power to operate the system would be even higher. If I could show that a wireless camera application can be self-powered with a wind energy harvester, I expected that many users would recognize the untapped potential of Exergy. Thus, based on an ESP-32 CAM module, Figure 6.9(f), I developed a wireless camera application that could interface with the hardware parts of Exergy. Figure 6.10(a) describes the system architecture, and Figure 6.10(b) presents an example of the software running on a web browser.

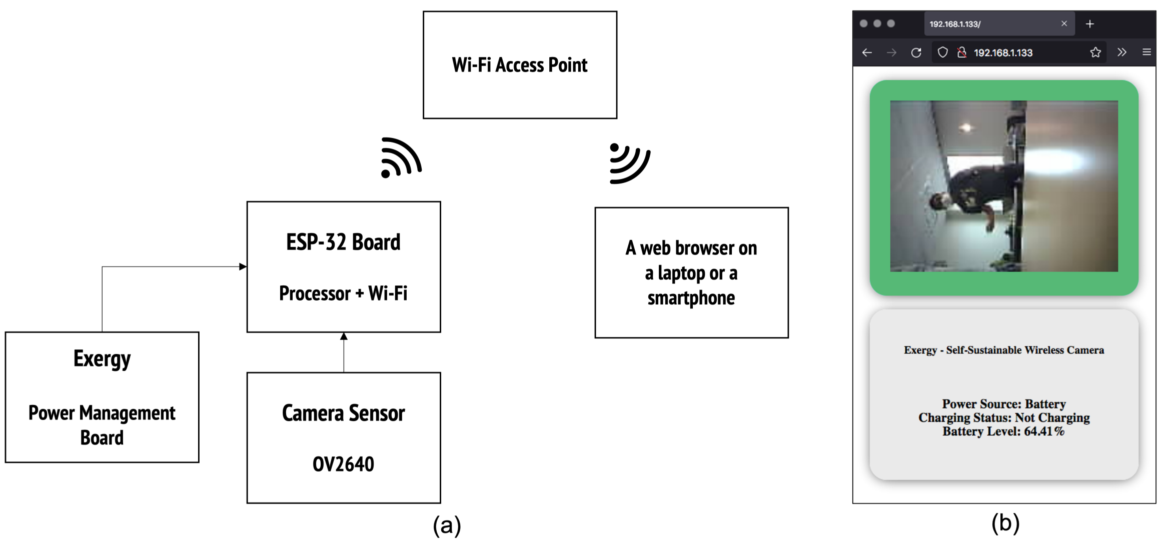


Figure 6.10: (a) The system architecture of the software example in Exergy, (b) Screenshot of the software running on a web browser on a laptop

6.2.4 Energy Harvesting Ideation Cards

In addition to simulation and prototyping features on Exergy, I also aimed to create a component to help users explore novel applications while considering practicalities. Card sets, which are used as a tool for designers to evaluate concepts or prototypes, are also widely adopted in ideation and concept development [130, 131]. In particular, the design card sets allow users to develop and expand novel ideas and share them with others since they can be "tangible idea containers" that promote collaboration and support "combinational creativity" [132]. When it comes to the format of the card sets, I can consider physical, digital, or hybrid cards. A recent systematic evaluation of these three options found that physical cards were more effective in ideation and that people preferred to use the physical type more than the other two options [133]. Therefore, I designed a physical card set including two major card types—transportation and system, as shown in Section 6.2.4. I included power consumption information for each sensor, actuator, processing unit, and communication module for the system cards. By doing so, I could easily estimate the total power consumption of the target system by adding up the numbers on the card.

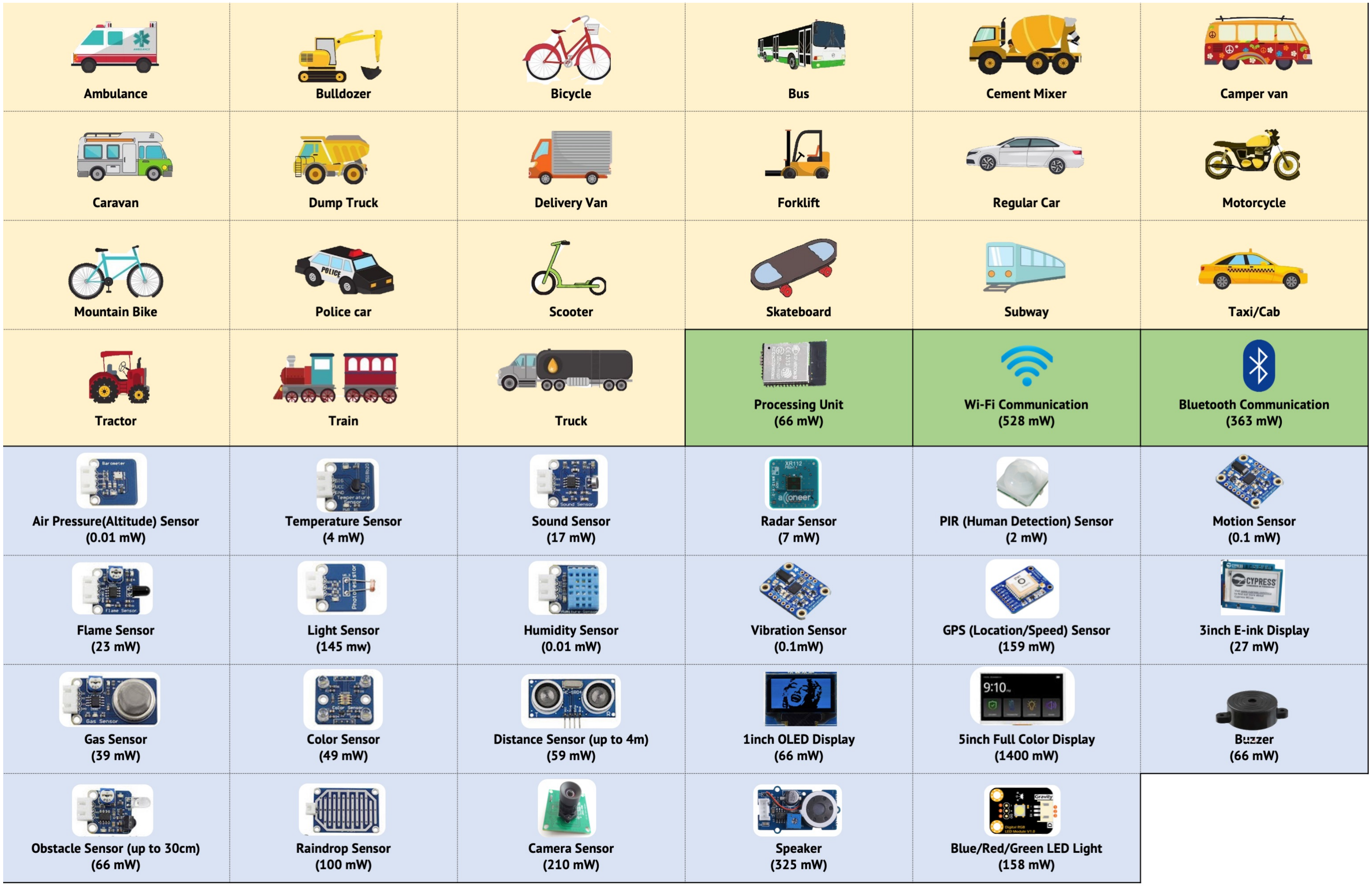


Figure 6.11: Ideation cards of Exergy. Yellow cards describe the type of vehicles. Green cards are either a processing unit or communication modules. Blue cards are either sensors or actuators. Note that I designed the cards by utilizing the images from www.englishstudyonline.org (vehicles) and www.elektor.com (sensors).

6.3 Evaluation of Exergy

To investigate the usefulness and usability of Exergy, I conducted a user study that included a tutorial on wind energy harvesting, a hands-on training course, and an ideation session. I anticipated that it would be challenging to manage more than 10 participants in a single user study since my research team and I needed to help them if they had any issues and observe how they utilized Exergy. Thus, I recruited participants for three different sessions (N=30) by flyers, word-of-mouth, private posts on relevant Slack groups, and announcements in diverse classes at the Georgia Institute of Technology.

Twenty-three individuals participated in three study sessions—6 participants in the first session, 7 in the second session, and 10 in the third session. Participants were offered either a $30 Amazon gift card or an hourly extra credit if they enrolled in the courses in the *People* thread and wanted the credits instead of monetary compensation. The Office of Research Integrity Assurance at the Georgia Institute of Technology approved this user study (Protocol Number: H21284). Before discussing the user study procedure, I present theoretical frameworks that informed the Exergy evaluation.

6.3.1 Understanding the potential of technology adoption

Researchers in HCI have actively studied how an individual comes to accept a new technology. Similar studies have been conducted in the education sector to determine whether emerging technologies such as robots and smartphones are acceptable to students [134, 135]. Across various domains including HCI and education, the technology acceptance model (TAM) is one of the widely accepted theories for explaining an individual's acceptance of a particular technology [136, 137, 138]. Initially, TAM considered perceived usefulness and ease of use as primary factors to confirm technology acceptance. Later, Holden and Rada found that technology self-efficacy had a significant influence on perceived ease of use and usability, which leads to improved attitudes toward using a new technology [138]. The relationship among the components in the revised TAM is described in Figure 6.12.

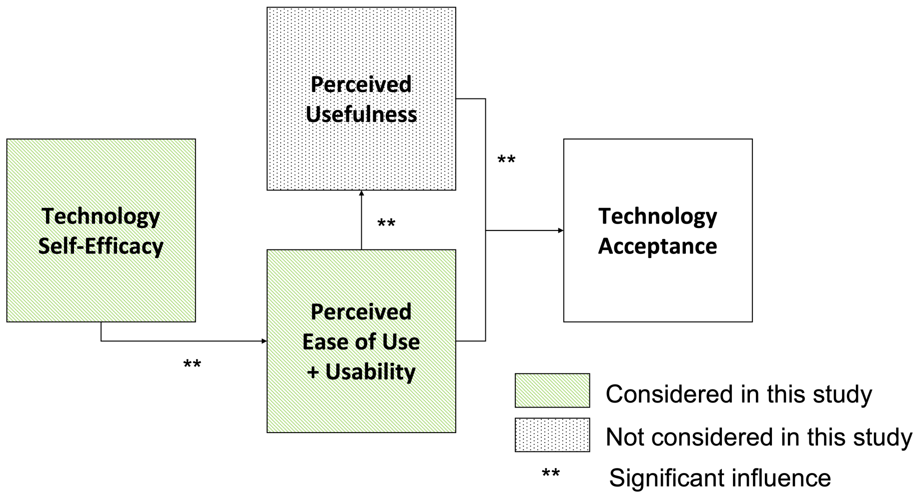


Figure 6.12: Redefined technology acceptance model by Holden and Rada [138]. The concepts of technology self-efficacy, perceived ease of use, and usability were used in this study.

I investigated three critical factors of TAM (i.e., technology self-efficacy, perceived ease-of-use, and usability) to understand the potential adoption of the energy harvesting tools proposed in this study. Technology self-efficacy is defined as "an individual's belief in his or her ability to use a *technology* effectively." I hereafter refer to this concept as *technological confidence* and use it to evaluate the proposed tools in this study. The notion of perceived ease of use is "the degree to which a technology will be free from effort" [136]. I hereafter refer to the perceived ease of use as *perceived difficulty* since the two notions have been used interchangeably [139, 140]. I hypothesize that a toolkit that encapsulates the complexity of small-scale wind energy harvesting and allows flexibility to explore and evaluate self-sustainable applications would decrease the perceived difficulty and increase the technological confidence for people with no prior experience in energy harvesting.

The last factor to discuss is *usability*, "the capability to be used by humans easily and effectively" [141]. Similar to the other two factors above, usability has a significant influence on the technology acceptance (see Figure 6.12). To evaluate usability, various techniques such as the software usability measurement inventory (SUMI) [142], standardized user experience percentile rank questionnaire (SUPR-Q) [143], questionnaire for user interaction satisfaction (QUIS) [144], and system usability scale (SUS) [145] exist. Among them, SUS has been used to evaluate new hardware platforms or many interface technologies [146, 147]. Unlike other techniques, SUS requires only ten questions, which is quick and less burdensome for the participants. Along with this advantage, SUS proved several times that it is a robust method to evaluate usability. Thus, I integrated SUS questions into our post-survey, and the participants answered them right after completing the hands-on experience session. The single-ease question (SEQ) used a seven-point rating scale to examine how difficult users perceive the given task [148]. I designed the survey question regarding the perceived difficulty by referring to the question format in SEQ. By doing so, I could reuse this single question for both the pre-post analysis and SEQ.

6.3.2 Assessing Exergy as a creativity support gadget

A second factor for evaluating the usefulness of Exergy is its ability to elicit creativity in the user. Many toolkit researchers have explored how tools can be applied to diverse areas. For example, Greenberg argued that "good toolkit design can enhance programmer creativity" [149]. Ledo et al. extended his concept and claimed that toolkits should "enable creative exploration of design spaces" [127]. In this context, many prior toolkit studies have focused on exploring novel concepts and design spaces [123, 150, 151, 152]. Similarly, this study evaluates the creativity support Exergy provides participants.

Creativity can be defined in many ways, and most creativity research did not specify its definition [153, 154]. Since the lack of definition can obscure research, I consulted two well-known resources to define and operationalize creativity in this study. First, I referred to Plucker and Makel's definition [153], "the interaction among *aptitude, process, and environment* by which an individual or group produces *a perceptible product* that is both *novel* and *useful* as defined within a social context." Thus, creativity entails the confluence

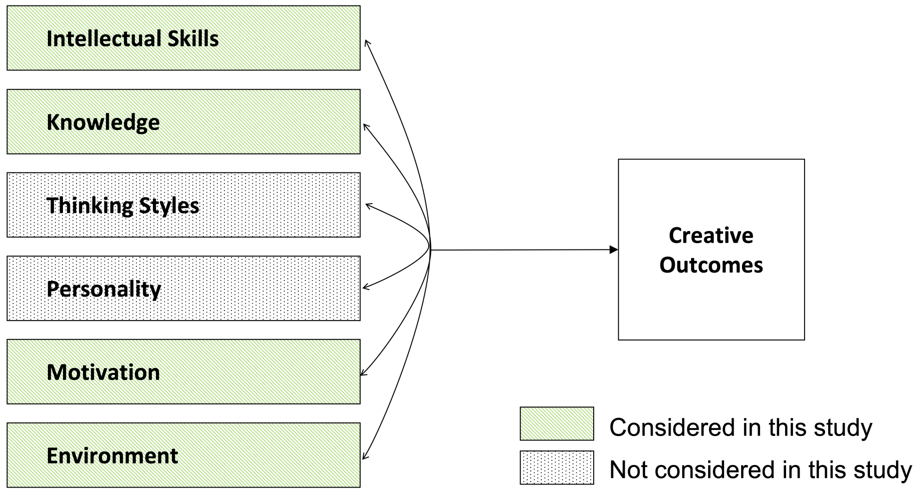


Figure 6.13: The investment theory found that creativity can be influenced by six distinct but interrelated sources [138]. The concepts of intellectual skills, knowledge, motivation, and environment were considered in this study.

of proper skill(s), process, and environment. Second, Sternberg created the investment theory, which explains the factors affecting creativity. As illustrated in Figure 6.13, this theory consisted of six "distinct but interrelated" factors—intellectual skills, knowledge, thinking styles, personality, motivation, and environment [155]. In this study, I consider the role of intellectual skills, knowledge, motivation, and environment.

- **Intellectual Skills**: (1) a synthetic skill to view problems in new ways using the Exergy ideation cards, (2) an analytic skill to evaluate whether one's ideas are worth pursuing by the Exergy simulator;
- **Knowledge**:(1) a tutorial on wind energy harvesting and self-sustainable computing, (2) a hands-on session to demonstrate the knowledge;
- **Motivation**: (1) clarification of the goal of the user study, (2) explanation of how I will utilize their creative outcomes for further research; and
- **Environment**: a supportive and rewarding environment for creative ideas by conducting the user study as a workshop style.

Participants' creativity was assessed by the perceptible products they generated in this user study. In many cases, experienced designers or researchers evaluated the level of creativity of the products. However, it was challenging to argue whether a proposed tool helped users think creatively or whether they were already very creative. A novel and interesting idea can surface from either condition. In 2018, Remy et al. found that 60% of the papers related to creative support tools (CSTs) selected usability testing as a way of evaluating CSTs [156]. They argued that usability testing could raise various questions regarding the link between usability and creative support. To overcome this issue, they suggested more standardized methods for the evaluation of CSTs [156]. In this context, I employed a well-established evaluation method, the creative support index [157]. This allowed the participants to confirm whether Exergy could support ideation and design work in a creative manner.

6.3.3 Overview of the user study

During enrollment, the participants signed a consent form and filled out a survey that provided demographic data and prior knowledge on energy harvesting. Additionally, as a baseline measurement in the enrollment survey, they evaluated how difficult it was to build a wind energy harvester and a self-sustainable system and how confident they were. After that, I introduced the fundamental principles of wind energy harvesting and the purpose of Exergy.

The participants then installed the Exergy simulator on their laptops and used the simulator and hardware parts to examine and manufacture a self-sustainable wireless camera system. Along the way, I presented step-by-step guidelines and helped them if they did not understand any functions of the simulator or any hardware components. During the first phase participant worked by themselves (steps 1-3 in table 6.2). Once each participant completed building the camera system, they brought it to a high-speed wind generator prepared for testing and confirmed its self-sustainable operation. Note that the software example presented in Section 6.2.3 was pre-downloaded to an ESP-32 board for the sake of the user study. Thus, the participants did not need to program any software during the workshop.

After completing the hands-on experience session, participants completed a survey on perceived difficulty, technological confidence, and toolkit usability (i.e., SUS and SEQ) with descriptive feedback on their overall experience. Since they had to concentrate for a long time, I offered a 5-minute bio break after this session. The ideation session began with the introduction to Exergy ideation cards and ground rules the participants had to follow. The rest of the user study was conducted in groups based on their seating arrangement. There was one group of three people and the rest were pairs, (N=10, see table 6.5). Groups were asked to discuss novel self-sustainable systems for vehicles by synthesizing the ideation cards. They presented their sketches to everyone after the ideation session. At the end of the session they completed a post-survey about their perceptions on Exergy's ability to elicit creative solutions. The overall flow of the user study is summarized in Table 6.2.

6.3.4 Participants

Participants could choose to disclose their demographic information—11 identified as female, 11 as male, and 1 opted not to identity a gender. 57% were between the ages of 18-24, 39% between 25-34, and 4% over 65. Most of the participants were students (see Table 6.3). While none of the participants had any prior hands-on experience with energy harvesting technologies, 11 of them had built at least one hardware prototype before. While seven participants stated they had limited or no knowledge of wind energy harvesting, others made several comments regarding its operating conditions, applications, and installation locations, as shown in Table 6.4. Although participants knew the wind energy harvesting technologies would be effective in the area in which wind speeds were constantly high, none of them indicated that the surfaces of moving objects were promising installation

Table 6.2: Study flow diagram illustrating the different steps of the study and the components of each step (total: 3 hours).

Step	Time (mins)	Components
1	15	• Brief overview of the user study, • Consent form, and • Enrollment survey - knowledge on energy harvesting, perceived difficulty and technological confidence. (See Appendix-Chapter B)
2	5	• Introduction to wind energy harvesting and Exergy and • Installation of Exergy simulator on participants' laptops.
3	70	• Individual hands-on experience session with step-by-step guidelines, • Manufacturing a self-sustainable wireless camera system, and • Evaluation of the system that each participant built through a high-speed wind generator.
4	5	• Post-survey - perceived difficulty, technological confidence, system usability scale, and single-ease question, see Appendix-Chapter C.
5	5	• Bio Break
6	55	• Introduction to Exergy ideation cards and ground rules for ideation and • Ideation and sketch session as a group of two people
7	25	• Presentation of ideas and sketches for each group and • Post-survey - Creative Support Index (CSI) and overall experience/feedback (see Appendix-Chapter D)
Total: 3 hours		

Table 6.3: Demographic and background information of the participants (*HW: hardware, Number of HW: the number of hardware prototypes each participant built before this user study, EH: energy harvesting, PNTA: preferred not to answer)

ID	Age	Gender	Number of HW	Prior EH experience	ID	Age	Gender	Number of HW	Prior EH experience
P1	18-24	Male	0	No	P2	18-24	Male	0	No
P3	18-24	Male	0	No	P4	25-34	Female	6-10	No
P5	18-24	Female	0	No	P6	18-24	Female	0	No
P7	25-34	Female	0	No	P8	18-24	Male	1-5	No
P9	18-24	Male	0	No	P10	25-34	Female	0	No
P11	18-24	PNTA	1-5	No	P12	25-34	Male	0	No
P13	25-34	Male	1-5	No	P14	18-24	Female	1-5	No
P15	25-34	Female	1-5	No	P16	65-74	Male	0	No
P17	18-24	Male	> 31	No	P18	25-34	Male	0	No
P19	18-24	Male	> 31	No	P20	25-34	Female	0	No
P21	18-24	Female	1-5	No	P22	25-34	Female	1-5	No
P23	18-24	Female	1-5	No					

locations. Thirteen out of 23 participants mentioned that renewable energy supply to the power grids was the only application.

Table 6.4: Prior knowledge of wind energy harvesting technology. Note that the number in parentheses indicates how many times each item was mentioned in the enrollment survey.

Operating Conditions	Applications	Installation Locations
• Preferably uniform wind speeds (1) • High enough wind level (1) • The high efficient blade design for wind turbines (1) • Good weather conditions (1)	• Generating electricity for small homes, towns, or even cities through power grid systems (13) • Replacing the fossil fuels (1) • Grinding flour (1)	• Areas with a high average amount of wind (9) • Windy and open places with no obstructions (2) • Oceans, seas, or coastal regions (3)

6.4 Results

This section presents the quantitative results of perceived difficulty, technological confidence, usability, and creative support index. I then discuss the qualitative results analyzed by the affinity diagram method. Table 6.2 describes the procedures of the user study.

6.4.1 Manufacturing a self-sustainable wireless camera system

All 23 participants successfully manufactured the self-sustainable wireless camera system. I confirmed this in two ways. First, I asked whether they considered the outcome a success through a question in the first post-survey. They all revealed that they were successful in the given task. Secondly, I examined whether each system they built was working appropriately and found that all the systems worked as expected. The detailed procedures for manufacturing and evaluating a self-sustainable wireless camera system are presented in Figure 6.14.

6.4.2 Perceived Difficulty

The participants were asked to rate how difficult they thought it would be for them to build a small-scale wind energy harvester on a seven-point Likert scale before and after

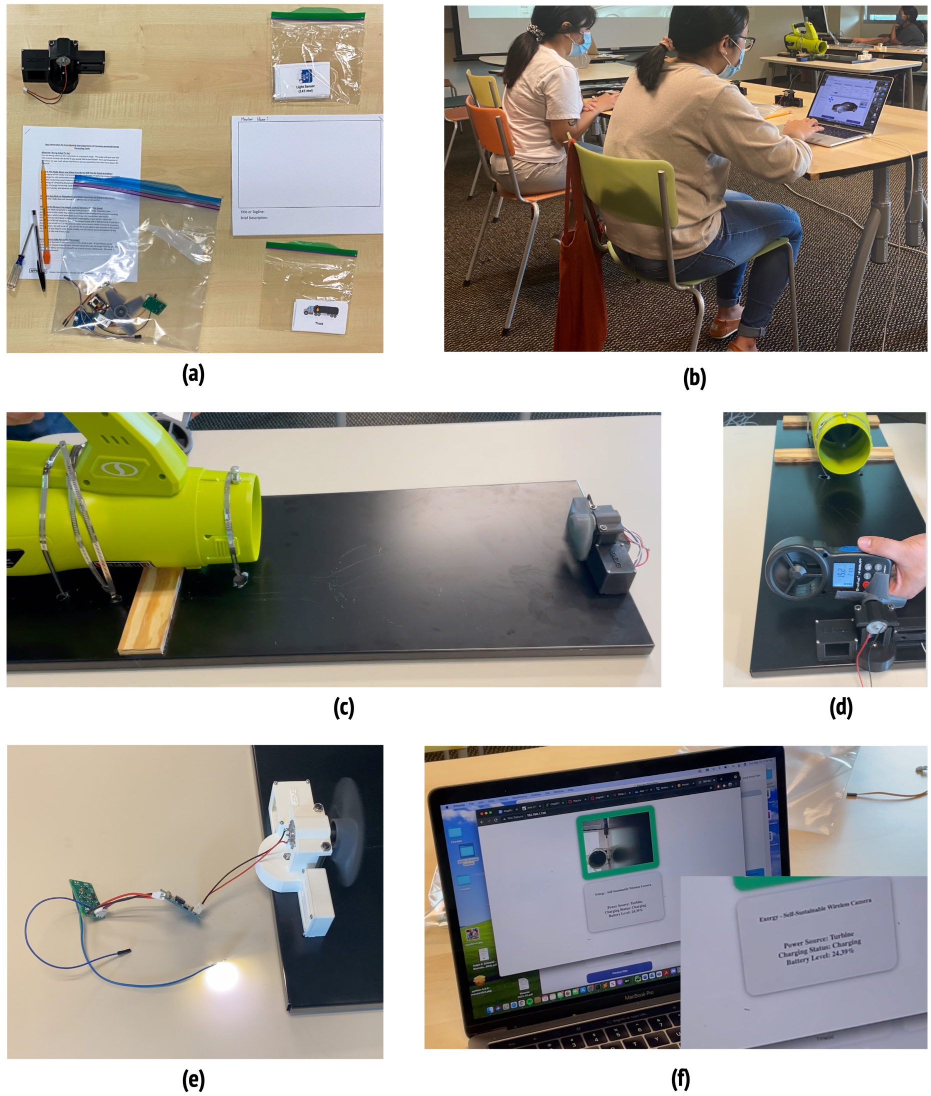


Figure 6.14: (a) I provided all the essential tools and components, including a bracket with a strong magnet at the bottom and a motor at the top, hardware parts, ideation cards, and sketch notes. (b) The participants installed the Exergy simulator on their laptops and used it during the use study. (c) I described the settings of the wind generator used in the study. Once each participant completed manufacturing the given camera system, they brought it to the wind generator and evaluated it. (d) For all the tests with the wind generator, I used an anemometer to inform the wind speed to the participants. (e) To visualize the operation of the wind turbine, I first asked the participants to interconnect the turbine with an LED and check whether they could see the light. (f) After checking the LED light, the participants removed the LED module and added a Li-Po rechargeable battery and an ESP-32 camera module to their system. After completing all of the procedures, they confirmed whether they could harvest wind energy through the turbine while running the wireless camera system.

the hands-on experience session. Since the data collected for the perceived difficulty was non-parametric, I performed a Wilcoxon signed-ranks test to compare the pre (i.e., before using the toolkit) and post (i.e., after using the toolkit) conditions. All statistical analyses were performed using R. The test result indicated that the hands-on experience of Exergy elicited a statistically significant change in the perceived difficulty ($Z = -3.663$, $p = 0.0003$, effect size = 0.78), see Figure 6.15. The ease-of-use that people perceived about the given task significantly increased compared to the pre-condition.

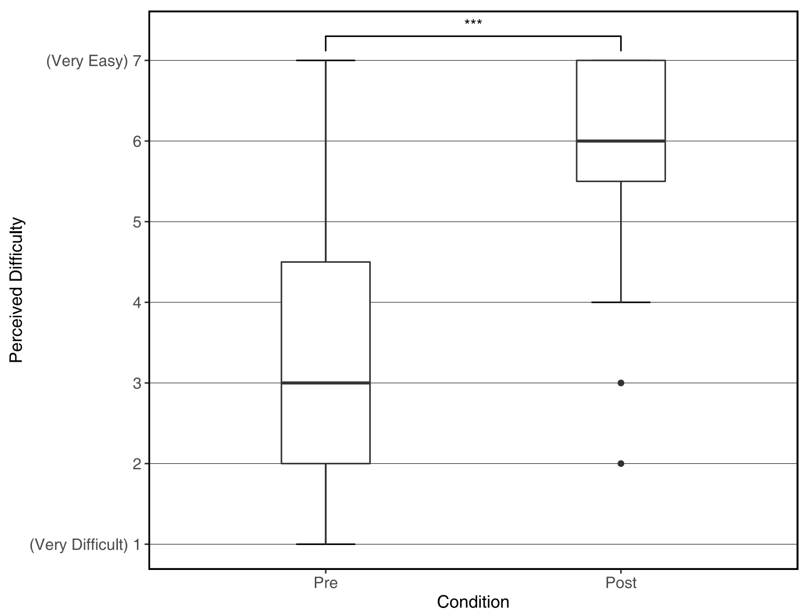


Figure 6.15: Overall changes in perceived difficulty between before and after the hands-on experience session.

I performed a post-hoc test to confirm whether this result could be different depending on the level of prior hardware experience. I divided the participants into two groups—**Novice group** had never built any hardware prototypes, and **Experienced group** built at least one hardware prototype prior to this user study. A Wilcoxon signed-rank test with Bonferroni correction was performed. Since the total number of post-hoc analyses in this study is three, I adjusted the p-value as $.05/3$, which is .0166. The test result indicated that the ease of use was significantly increased in the novice group who had never built any hardware devices ($Z = -3.0365$, $p = 0.0024$, Effect size = 0.92), see Figure 6.16.

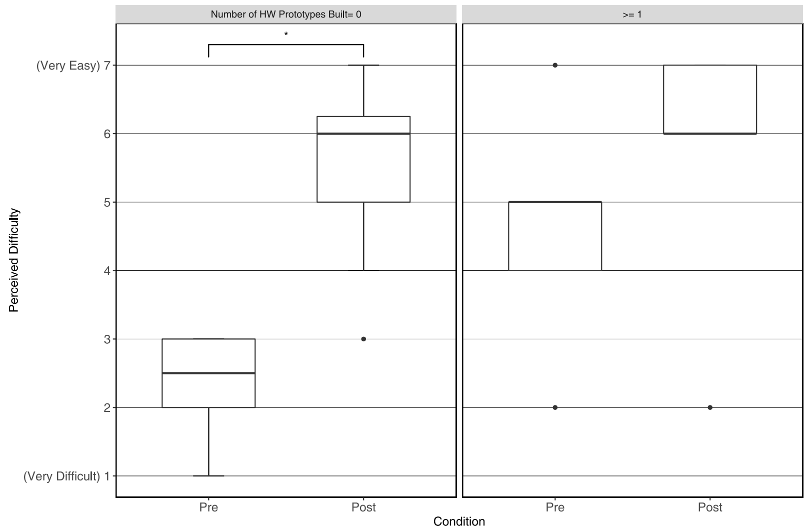
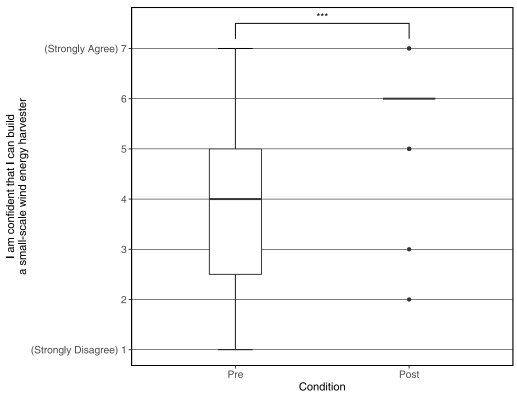


Figure 6.16: Changes in perceived difficulty between before and after the hands-on experience session by the number of hardware prototypes built before.

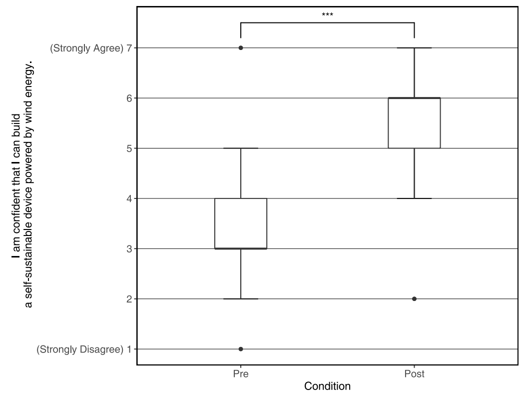
6.4.3 Technological Confidence

The participants were also asked to answer two questions about technological confidence in two tasks—**first task**: building a small-scale wind energy harvester; **second rask**: building a self-sustainable system device powered by wind energy. For those who did not know the exact meaning of "self-sustainability" in this project, I articulated what it meant and how a device could be self-sustainable before they filled out the enrollment survey. I performed a Wilcoxon signed-ranks test to compare the pre and post conditions. The test result indicated that the hands-on experience of Exergy elicited a statistically significant change in the technological confidence for both tasks—(First task: $Z = -3.715$, $p = 0.0002$, effect size = 0.79 / Second task: $Z=-3.784$, $p = 0.0002$, effect size = 0.81), see Figure 6.17a and Figure 6.17b. People who experienced Exergy felt significantly more confident in those two tasks than the pre-condition.

In addition, I performed a post-hoc test to confirm whether the result of technological confidence could be different depending on the level of prior hardware experience. The division of the groups (i.e., novice and experienced) was identical to the one used in the



(a) Building **a small-scale wind turbine**



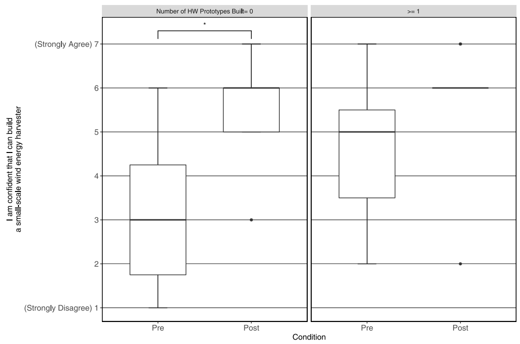
(b) Building **a self-sustainable system powered by wind turbine**

Figure 6.17: Overall changes in technology confidence before and after the hands-on experience session

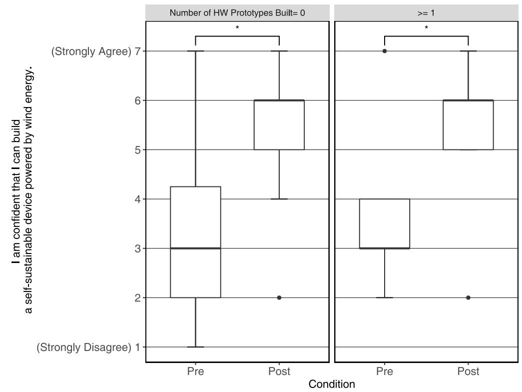
analysis of the perceived difficulty. A Wilcoxon signed-rank test with Bonferroni correction was performed, and the adjusted p-value (i.e., .0166) was used to confirm the statistical significance. The test result indicated that the technological confidence for both tasks was significantly increased in the novice group, who had never built any hardware devices (First task: Z = -2.908, p = 0.0036, effect size = 0.88 / Second task: Z = -2.611, p = 0.0090, effect size = 0.79). See Figure 6.18a and Figure 6.18b. For the second task, the experienced group also showed significantly increased in technological confidence for the second task (Z=-2.6925, p = 0.0071, effect size = 0.85), as shown in Figure 6.18b.

6.4.4 System Usability Scale (SUS) and Single-Ease Question (SEQ)

As presented in Figure 6.12, usability is one of the factors that influences users when they decide to adopt a new technology. From an analysis perspective, SUS returns a single absolute score between 0 to 100, which can help us intuitively understand usability without comparing our toolkit with others. As shown in Figure 6.19, the SUS score of Exergy is 70.8, which is *"Acceptable"* in the acceptability range and *"Good"* in the adjective ranges [146]. Similar to the SUS score, the SEQ score also returns a single absolute value for evaluating the usability of Exergy. The higher the SEQ score, the easier the given task.



(a) Building **a small-scale wind turbine**



(b) Building **a self-sustainable system powered by wind turbine**

Figure 6.18: Changes in technology confidence before and after the hands-on experience session by the number of hardware prototypes built before

Sauro et al. found that the average SEQ score was between 5.3 and 5.6 when they used SEQ for over 400 tasks with 10,000 users. The SEQ score of Exergy is 5.8, which is above the average range of SEQ.

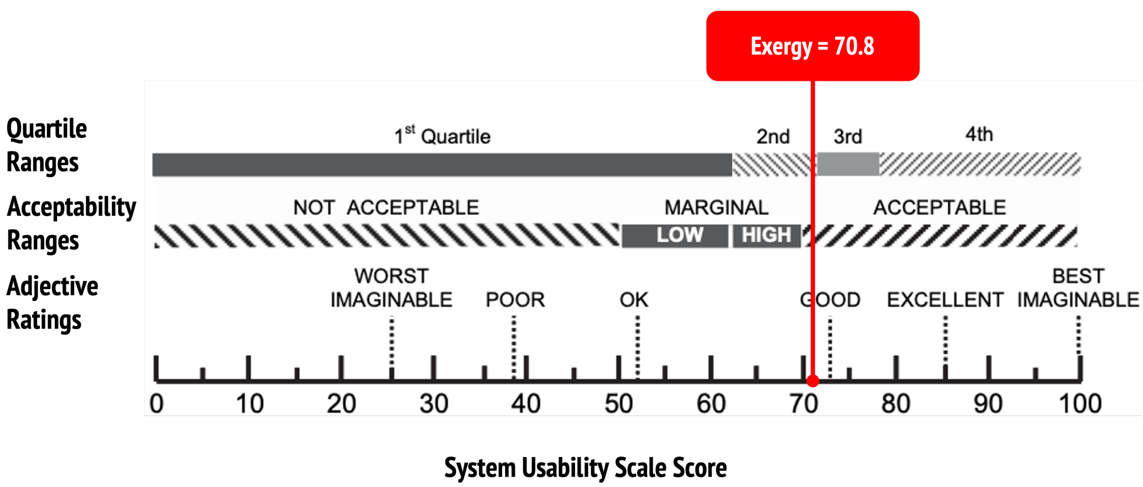


Figure 6.19: The system usability score of Exergy by quartile, acceptability, and adjective ratings. (Exergy SUS Score: 70.8)

6.4.5 Sketches

In the ideation session, the participants drew 103 sketches by combining various sensors and actuators for different types of vehicles (see Figure 6.20). As mentioned earlier, I asked them to make a group by forming pairs. The detailed information about the sketches is described in Table 6.5.

Figure 6.20: An example in which a group of participants freely synthesized the Exergy ideation cards during the user study

6.4.6 Creative Support Index (CSI)

CSI consists of six core factors: results worth effort, immersion, expressiveness, exploration, enjoyment, and collaboration. There are two agreement statements for each factor on a scale between 0 (highly disagree) and 10 (highly agree). A score for each factor (hereafter referred to as ***factor score***) represents the sum of both agreement responses. Thus, the minimum and maximum factor score for each factor was 0 and 20, respectively. Additionally, participants were asked to select which factor contributed the most to their creative work in a paired-factor comparison test, which included 15 comparisons. The minimum and maximum count for any specific factor was 0 and 5, respectively. I hereafter refer to the number of factors selected in the test as ***factor counts***. The higher the average factor counts, the more important the factor. To be more sensitive to the factors that were more important in carrying out the given task, CSI adopted the concept of ***weighted factor score***

Table 6.5: Vehicles and system components used in the sketches per each group. Note that the items marked in red represent things that the participants added, but were not in the Exergy ideation cards.

Group	Vehicle Types	System Components
P1, P4	Forklift, bicycle, train, bus, truck, camper van, caravan, subway, dump truck, tractor	Humidity, gas, camera, PIR, motion, GPS, E-ink display, 5inch color display, buzzer, RGB LED, Wi-Fi, processing unit
P2, P3	Bicycle, bus, dump truck, regular car, police car, train, truck, **helmet, bus stop**	Air pressure, temperature, sound, flame, light, humidity, gas, distance, obstacle, camera, radar, PIR, GPS, **weight sensor**, OLED display , 5inch color display, buzzer, speaker, RGB LED, Wi-Fi, Bluetooth, processing unit
P5, P6	Ambulance, scooter, camper van, regular car, police car, tractor, **marathon runner, fire truck, compost machine truck**	Temperature, humidity, obstacle, camera, motion, **carbon-monoxide sensor, PH/UV sensor, seat warming and rain water flushing toilet, virtual display**
P7, P9	Ambulance, bicycle, bus, caravan, forklift, regular car, skateboard, subway, taxi/cab, **tank truck**	Temperature, light, distance, raindrop, camera, PIR, motion, **weight sensor**, buzzer, RGB LED, Wi-Fi
P8, P11	Bus, camper van, regular car, scooter, subway, truck	Air pressure, temperature, flame, humidity, distance, obstacle, raindrop, radar, PIR, motion, GPS, buzzer, Wi-Fi, Bluetooth, processing unit
P10, P12, P13	Bicycle, bus, camper van, regular car, police car, scooter, skateboard, subway, train, truck	Air pressure, temperature, humidity, color, distance, raindrop, camera, radar, PIR, motion, vibration, GPS, **animal detector**, buzzer, speaker, Wi-Fi, Bluetooth, processing unit
P14, P21	Taxi/cab, skateboard, truck, camper van, bicycle, scooter, mountain bike, ambulance, regular car, subway, bulldozer, forklift	Temperature, flame, obstacle, raindrop, camera, PIR, GPS, 5inch color display, buzzer, RGB LED, Wi-Fi
P15, P20	Ambulance, camper van, skateboard, **door, speed camera on the road, runner, tree**	Gas, obstacle, camera, motion, **oxygen sensor, speed sensor, accelerometer**, E-ink display, 5inch color display, buzzer, RGB LED, Wi-Fi
P16, P17	Bicycle, bus, caravan, forklift, regular car, scooter, skateboard, train, truck	Temperature, flame, light, gas, camera, GPS, **weight sensor, soil chemical sensor**, buzzer, RGB LED, Bluetooth, **air conditioner, mobile hot spot, network stations**
P18, P19	Bulldozer, bicycle, bus, regular car, scooter, subway, truck, **animals**	Air pressure, temperature, light, humidity, raindrop, camera, PIR, OLED display, 5inch color display, buzzer, speaker, RGB LED, Bluetooth
P22, P23	Camper van, regular car, cement mixer, ambulance, police car, bicycle, truck, bus, train	Air pressure, temperature, light, humidity, color, distance, obstacle, raindrop, camera, PIR, GPS, E-ink display, OLED display, buzzer, speaker, RGB LED, Wi-Fi, Bluetooth, processing unit

that can be calculated by multiplying the factor score by the factor count. The total CSI score can be calculated as :

$$\begin{aligned}\mathsf{CSI} = [&\mathsf{ResultWorthEffort}_{\mathsf{weightedfactorscore}} + \mathsf{Immersion}_{\mathsf{weightedfactorscore}} \\ &+\mathsf{Expressiveness}_{\mathsf{weightedfactorscore}} + \mathsf{Exploration}_{\mathsf{weightedfactorscore}} \\ &+\mathsf{Enjoyment}_{\mathsf{weightedfactorscore}} + \mathsf{Collaboration}_{\mathsf{weightedfactorscore}}]/3.0\end{aligned}$$

Table 6.6: CSI Results from our user study using Exergy (N=23). The total CSI score for Exergy was 73.54 (SD = 15.77). SD = Standard Deviation

Scale	Average Factor Counts (SD)	Average Factor Score (SD)	Average Weighted Factor Score (SD)
Results Worth Effort	1.65 (1.64)	16.43 (3.10)	18.09 (3.30)
Immersion	2.00 (1.17)	11.35 (4.50)	23.83 (17.24)
Expressiveness	3.61 (1.53)	15.35 (3.75)	55.22 (27.06)
Exploration	3.91 (1.04)	16.17 (3.13)	64.91 (24.35)
Enjoyment	2.22 (1.24)	15.30 (3.55)	32.83 (18.73)
Collaboration	1.61 (1.44)	16.48 (2.87)	25.74 (22.57)

The mean and standard deviation of factor counts, factor score, and weighted factor score for each of the six factors in our user study are shown in Table 6.6. The CSI score for Exergy is 73.54, which can be interpreted in two ways. First, Cherry and Latulipe found that the CSI scoring system had “a nice mapping to education grading systems.” A score above 90 is an “A” indicating “excellent support for creative work,” and a score below 50 is an “F,” indicating that “the tool does not support creative work very well.” One could argue that Exergy received the “C” grade. Secondly, to address this concern, I compared Exergy with other creative supports tools in Table 6.7. Note that, to the best of my knowledge, there were no CSTs to compare with respect to wind energy harvesting or self-sustainable computing. I confirmed that Exergy is in a comparable range to other tools. To interpret the details of each factor, I referred to the analysis examples proposed by Cherry and Latulipe [158, 157].

Table 6.7: Comparison of CSI score with other CSTs

	Exergy (N=23)	Adobe Photoshop (N=5) Source:[157]	AutoDesk Sketchbook Express (N=11) Source:[157]	MaxOSX Color Exploration Plugin (N=16) Source:[157]	Multimodal Pen-based Interaction (N=26) Source:[159]
CSI Score	73.54	84.20	64.79	76.52	65 *

*The authors did not report the exact CSI score in a written format. Thus, it was extracted from the graph in Figure 4 in their paper [159].

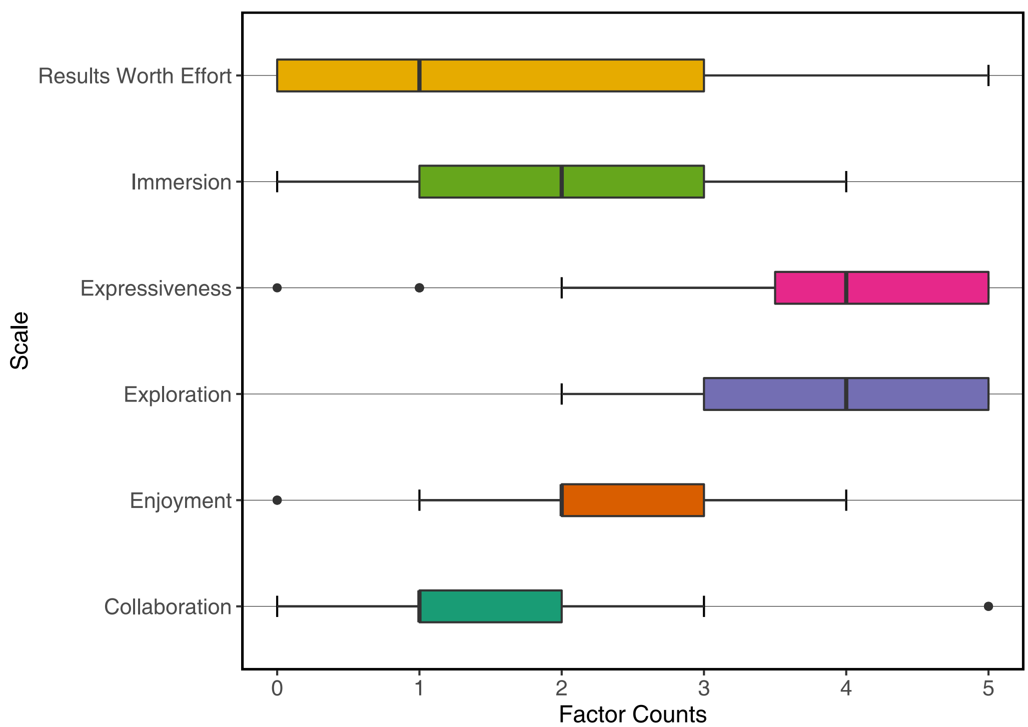


Figure 6.21: CSI factor counts for each scale

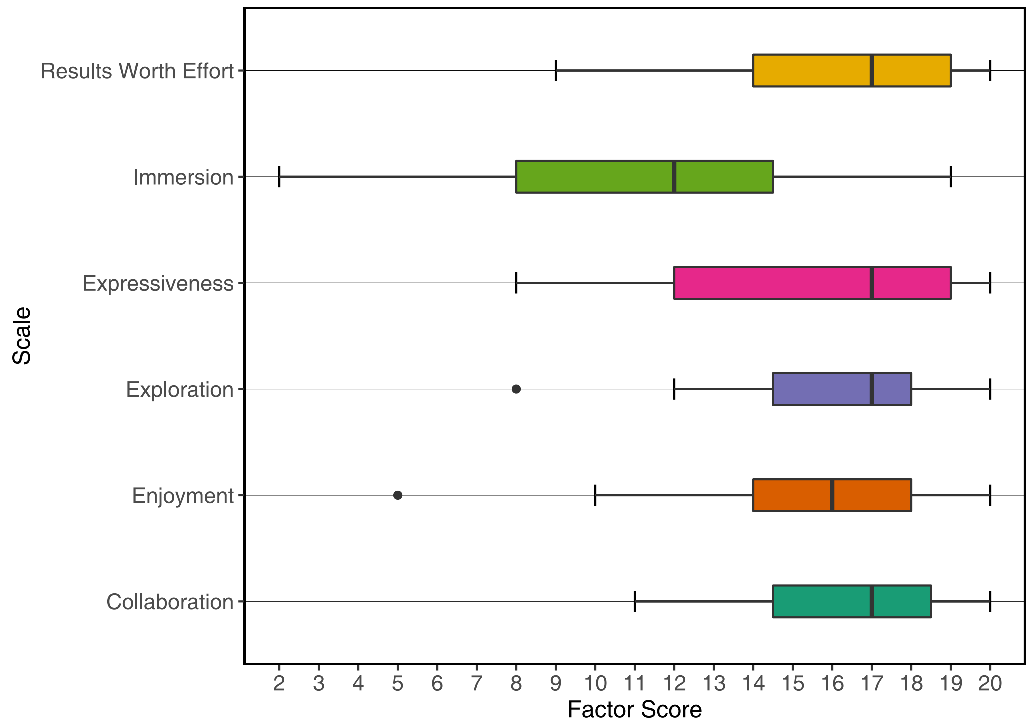


Figure 6.22: CSI factor score for each scale

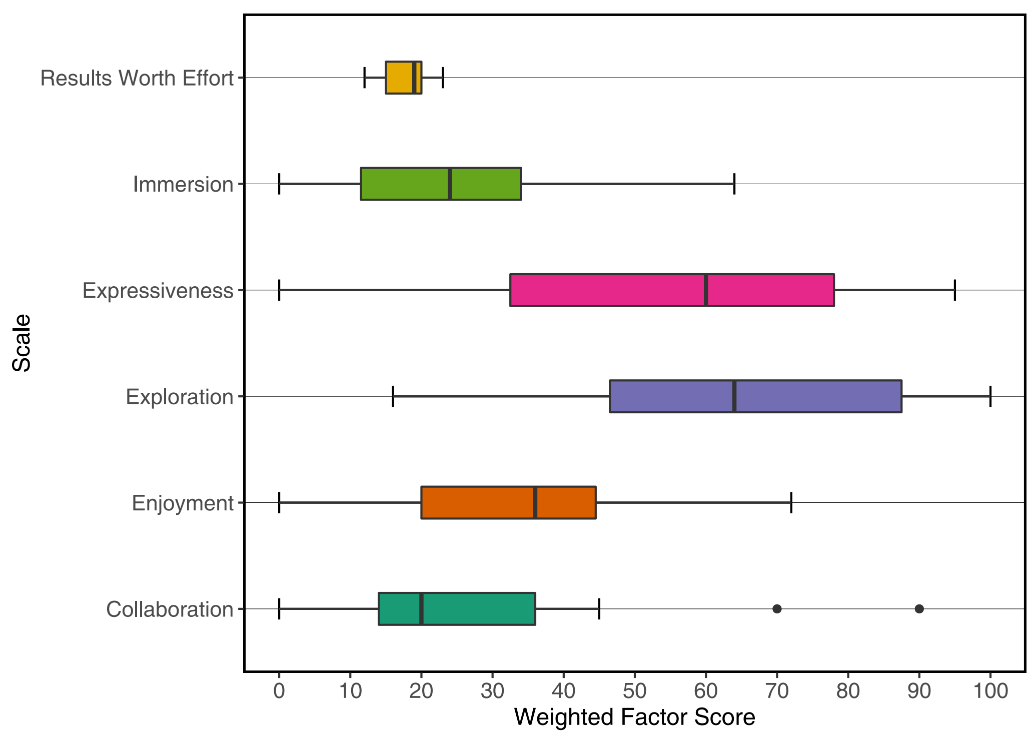


Figure 6.23: CSI weighted factor score for each scale

Results Worth Effort: The average count for the results worth effort was 1.65, which indicates that it was of less importance to the participants engaged in self-sustainable system design. However, its factor score, 16.43, confirms that the amount of effort they had to exert in designing such self-sustainable systems was worth it.

Immersion: The average count for the immersion factor was 2.00, suggesting the immersion possessed moderate importance in a self-sustainable system design. However, the factor score of 11.35 for immersion indicates that the participants had to pay attention to Exergy tools when designing various self-sustainable systems. In other words, they felt that it was difficult to fully absorb in the ideation exercises. The result seems understandable since they could not have enough time to be familiar with the tools that they had never seen.

Expressiveness: The average factor count for expressiveness is 3.61, indicating that it was important to the participants in designing self-sustainable systems. The average factor score of 15.35 for expressiveness means that participants were able to express their thoughts and ideas while using Exergy.

Exploration: The average count for the exploration factor was 3.91, the highest average among all the factors. This count indicates that support for exploration was very important to the participants engaged in self-sustainable system design. Additionally, the average factor score of 16.17 for exploration confirms that it was easy for them to explore and consider different ideas, options, and designs using Exergy.

Enjoyment: The average factor count for enjoyment was 2.22, which suggests that it is of moderate importance to the participants. The average factor score of 15.30 for enjoyment revealed that participants enjoyed the components of Exergy when designing self-sustainable systems. At the same time, it indicated that some improvements were needed to make the experience of using Exergy more enjoyable.

Collaboration: The average factor count for collaboration was 1.61, the lowest average among all the factors, indicating that it was not particularly important to the participants engaged in self-sustainable system design. The average factor score for collaboration was fairly good, 16.48. Since many prior studies proved that design cards are useful for facilitating collaboration [133], the ideation cards of Exergy might also be an effective component that supports collaboration.

6.5 Discussion of Qualitative Analysis

Exergy's CSI score provides quantitative information about the factors that need to be improved for it to become a better creative support tool. Qualitative analysis can allow us to understand the underlying reasons for the scores. Two researchers and I conducted an affinity diagram analysis on the data collected from the user study to understand what participants did to come up with new ideas and how Exergy could support their creative works. Affinity diagramming is an analysis technique used to make sense of unstructured qualitative data [160, 161]. It has been widely used to understand creative sketches and their related implications [162, 163]. The data sources used for the analysis included (1) the sketches drawn by participants as several groups; (2) the challenges, concerns, and overall suggestions of Exergy submitted by each participant via the post surveys; and (3) the notes written by three researchers in my team during the user study.

We converted all the data sources into a list of notes and entered them into a shared board on Miro, an online collaborative whiteboard platform. Since I was interested in confidence and creativity, we took an inductive approach in two rounds of data analysis. Although we already had the overarching focuses, we did not group the notes into predefined categories. Affinity diagrams should be built from the bottom up. Thus, in the first round, two researchers in our team shuffled the individual notes and reviewed them several times. After interpreting the underlying implications of each note, the researchers grouped the notes into more abstract themes and rearranged emergent themes iteratively in the second round. Through these processes, we ended up with three overarching themes and 15 categories.

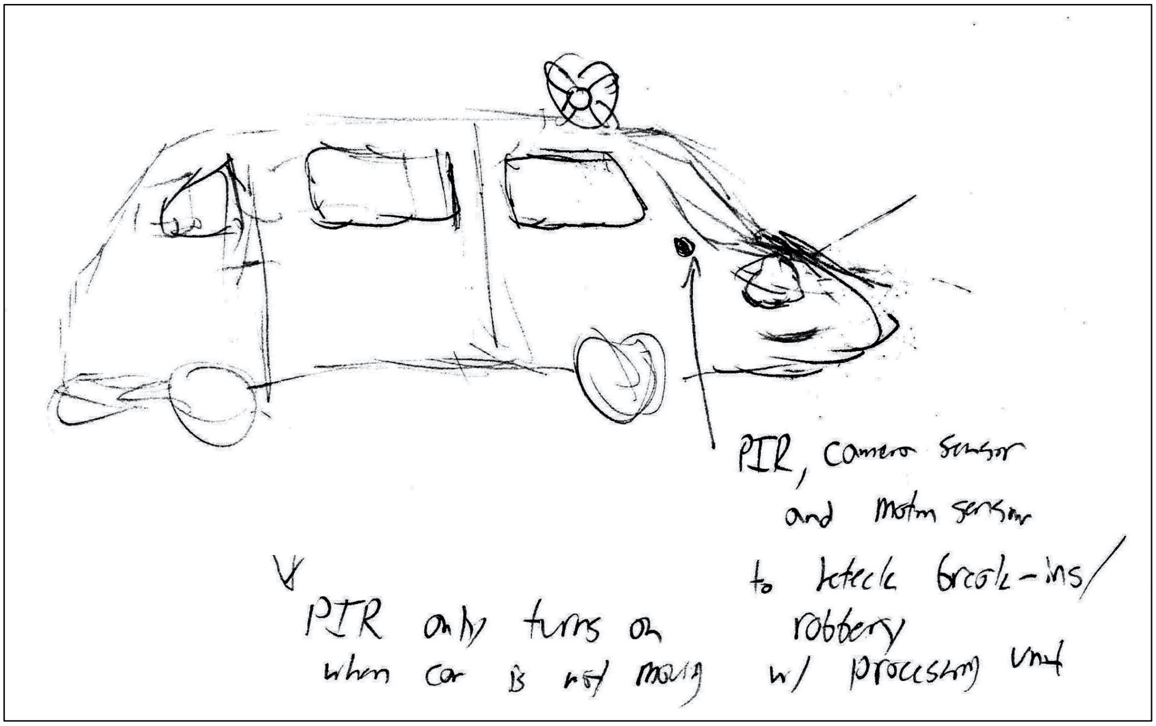
6.5.1 Feedback on Difficulty, Confidence, and Usability

Similar to the results of the quantitative analysis, participants did not find it difficult to use the simulation tool and hardware parts of Exergy. From an experienced user's point of view, P14 and P15 mentioned that "I do think it was easy to create this system" and "It was quite easy and user-friendly to build up the prototype," respectively. However, they both wanted to know more technical details (e.g., internal circuitry or logic) of the hardware parts to boost their technological confidence. From a novice's perspective, P7 and P18 first said, "I wouldn't really know where to get these components or which components would work together" and "there was a bit of a learning curve to connect the wires to the right places," respectively. But, later, they both concluded that "after this demo, I do feel a lot closer to being able to handle this" and "the given instructions were easy to follow and helpful," respectively.

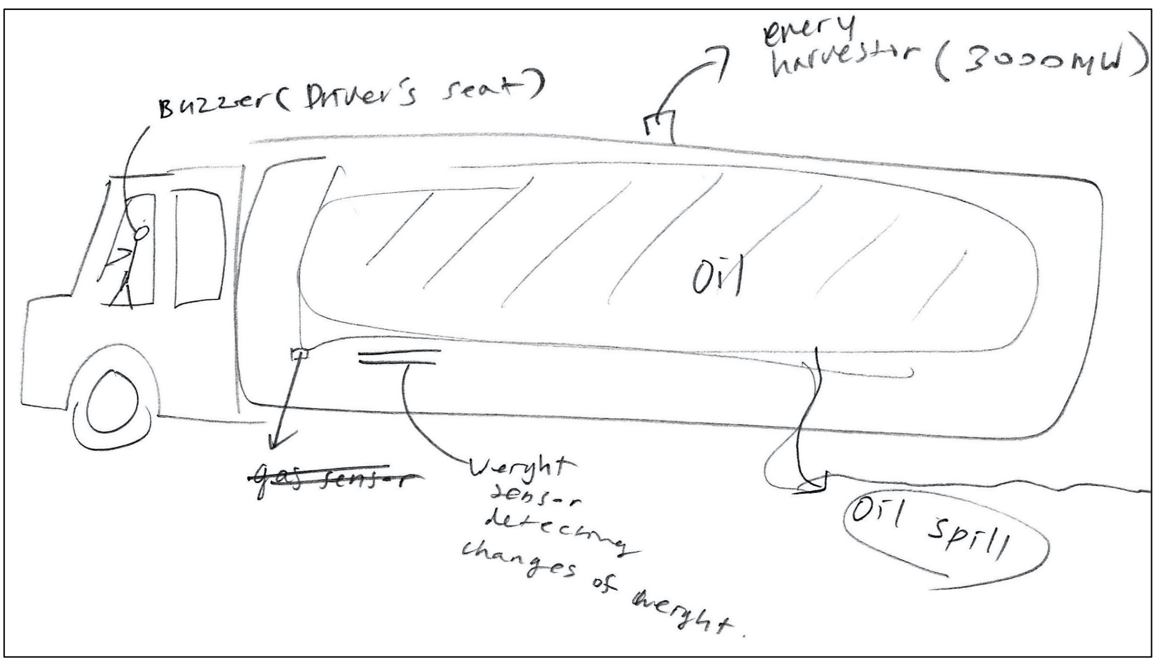
Regarding confidence, there was an interesting case where two participants reacted completely differently to the same perception. Both P2 and P13 felt they were not confident in designing circuit boards for power management and energy conversion. Note that I did not explicitly mention whether they can have these kinds of pre-built hardware parts easily. While P2 said that "I am confident in putting the final products together." P13 complained of difficulties in making the self-sustainable wireless camera example. P13 is one of the two participants who said he lost confidence in building self-sustainable systems powered. P1, P4, and P20 mentioned difficulties in the assembly process, but they felt that it was not a significant issue or would be fine if the manual could be provided.

6.5.2 A Balance of Creativity and Practicality

One might argue that creativity and practicality are contradictory and mutually exclusive. However, a balance between these two aspects is the key to designing innovative products [164]. I found great potential for Exergy to support creative work while considering its practical constraints. Our research team observed that nearly half of the participants



(a)



(b)

Figure 6.24: Sketches that present the balance between creativity and practicality

used the Exergy simulator to confirm whether a wind turbine could support the selected sensors and actuators, power-wise. Some of the practical systems designed were quite novel—based on the SAPPhIRE model, a well-known novelty evaluation metric [165]. For example, in Figure 6.24-(a), P1 and P4 considered the logical sequence to operate a car surveillance system in a power-efficient manner—i.e., (1) a motion sensor to detect whether a car is moving, (2) a PIR sensor to check whether people are approaching the car, (3) a camera sensor is only activated once (1) and (2) conditions are satisfied. P7 and P9 designed a system that can detect a gas truck's oil spill and alert it to the driver through a buzzer. At first, they intuitively selected a gas sensor but realized that multiple gas sensors are required for accurate detection. They became concerned about the power consumption of the system and later applied a weight sensor, which can solve the problem at a single-point detection as shown in Figure 6.24(b). Note that the weight sensor was not an option provided in the ideation cards.

6.5.3 Ideas that lean toward either creativity or practicality

Some ideas generated during the ideation session were very creative but not feasible and vice versa. Some of the participants applied a wind energy harvester to places I never imagined before, including (a) the edge of a door, (b) the wrist area of human body, or even (c) animals such as a bird or a dog, see Figure 6.25. Although these application domains are novel, these ideas are very unlikely to be practical. Additional evaluations are needed to verify whether the amount of wind generated by each movement would be enough for these applications. Other ideas standing in opposition to the creative ones were the practical systems that merely switch the energy source of existing technology from a battery to a wind energy harvester. For example, P8 and P11 connected a set of environmental sensors to a wind turbine in Figure 6.25(d). P7 and P9 changed the power source of the automatic wiper to a wind turbine, and P5, P6, P22, and P23 applied the self-sustained surveillance camera idea to a police car in Figure 6.25(e). These are meaningful and feasible ideas but not very creative, based on the SAPPhIRE novelty metric [165].

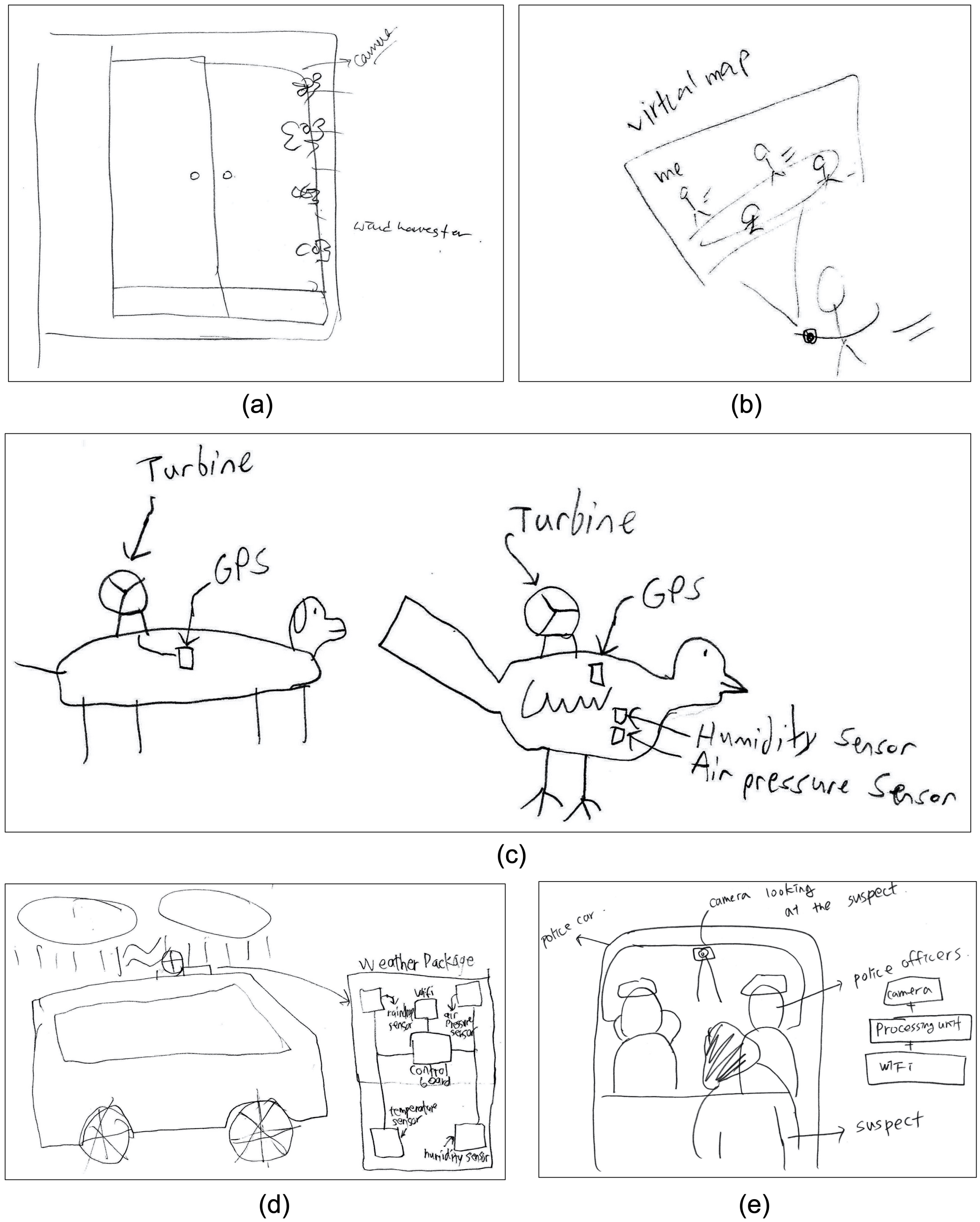


Figure 6.25: Sketches that lean toward either creativity (a-c) or practicality (d-e)

6.5.4 Things that need to be improved

For the hardware parts, P11 and P22 expressed their wish that the attachment and detachment processes of the magnet-based bracket would be easier and safer. P1 and P9 wanted to confirm which energy source (i.e., wind turbine or battery) the target system draws power from in a faster way. These suggestions point out that the quality of hardware parts in Exergy needs to be improved for users to use it more confidently. Additionally, P17 suggested troubleshooting manuals because people without prior knowledge of embedded computing may not know what the error is and why it occurred. For the simulation tool, many participants wanted to explore more design elements with more expert-level features. P4 and P21 mentioned that it would be valuable if Exergy could provide more vehicle types and customization options such as multiple turbines for a single application. P2 and P11 wanted to have some options or hotkeys to change the simulation parameters quickly. I saw many situations where people with no experience in hardware misunderstood the specification and working mechanism of some sensors. So, for accurate and creative ideation, additional research is needed to clearly and accurately inform the users of each sensor's functions and working conditions.

6.6 Discussion and Limitations

For this project, I designed and developed Exergy—a wind energy harvesting toolkit consisting of a simulator, hardware tools, software examples, and ideation cards in this project. The purpose of Exergy was to encapsulate the complexity of small-scale wind energy harvesting and allow flexibility to explore and evaluate self-sustainable applications. Many of our findings point to promising insights about the potential role that Exergy can serve in supporting the design, implementation, and extension of wind energy harvesting and self-sustainable computing.

I evaluated whether the toolkit would be adaptable to participants (N=23) with no prior energy harvesting experience. I used a mixed-method approach to analyze the results. The main findings indicated that Exergy significantly decreased the perceived difficulty and increased the technological confidence when building a small-scale wind turbine and its self-sustainable application. In addition, Exergy was found to be in the acceptable range based on the system usability scale and single-ease question methods. Furthermore, the creativity support index indicated that the toolkit supported creative activities and helped users explore novel yet practical applications ideas for vehicles. Through in-depth qualitative analysis, I found out why and where the toolkit influenced the participants.

Resnick *et al.* presented the three perspectives necessary when designing a toolkit—"lower the floor" to enable easy access for the novice, "widen the wall" to support a broader range of ways to use the toolkit, and "higher the ceiling" to enable progression to increasing complexity [166]. Through the hands-on experience and ideation sessions, we confirmed that Exergy could be an effective toolkit for "lower the floor" and "widen the wall". We designed Exergy based on the pain points and needs of people who have used energy harvesting technology. These requirements are likely to be the essential features for those who will use the technology for the first time. Since Exergy has advantages such as simulating energy harvesting performance and simplifying the manufacturing processes, it might also be able to help those with some energy harvesting experience (i.e., "higher the ceiling"). Therefore, evaluating Exergy with the experienced researchers or the makers who informed us of the requirements would be a fascinating further research topic.

As discussed in Section 6.1, toolkits in HCI were developed to democratize technological practice. In particular, "democratization" required four iterative stages—learning, building, testing, and expanding. Although participants in this study successfully accomplished all the steps, several limitations may influence their performance in the first two stages. First, in the learning stage, participants may have been influenced by my presence, attitude, and rhythm (e.g., Hawthorne effect [167]). The presence of researchers in such user studies can have several positive or adverse effects. The advantage is that I could answer their questions quickly and help with any trouble. However, such agile responses may be a confounding factor in evaluating the perceived difficulty and technology confidence of the toolkit.

Second, I, as a human intermediary, explained Exergy's how-to guidelines during the user study in the building stage. This was not a self-paced learning environment, and the participants were asked to follow along. Building a system by utilizing the toolkit at their own pace may reveal issues that I could not confirm in the format employed. Therefore, to support the self-regulated toolkit learning, we need to consider non-human intermediaries such as online lectures or interactive troubleshooting guidelines. If that happens, people will be able to create and design more diverse applications without time and space constraints.

Third, I designed the hardware components of Exergy in a fail-safe way. For example, each connector shape was unique for each port; thus, it was almost impossible to interconnect the wrong pins while prototyping the example. I also provided only the necessary parts to build the example system. However, suppose Exergy includes more hardware components to increase its design flexibility. In that case, users will be more likely to take longer than the current exercise or even fail due to the increased complexity. It could negatively affect their perceived difficulty and technological confidence. Further studies are needed to confirm and clarify the impact of more design flexibility.

Finally, the fact that it was a physical toolkit required in-person participation. This might have kept some participants away because they thought this was risky during the pandemic. In this respect, I need further research in a more independent, self-paced environment.

CHAPTER 7

CONCLUSION AND FUTURE DIRECTION

Energy harvesting is an alternative to supplement the limited power of batteries in mobile and ubiquitous computing. Specifically, it can be more practical and promising in mobile environments because ubiquitous systems can generate various forms of energy as they move. However, unlike energy scavenging from human movements in wearable computing, other mobile environments have not yet been explored. In this dissertation, I first selected an automobile as a case study in other mobile environments. While energy harvesting in automobiles has primarily focused on replenishing the main battery pack, there is little examination of energy harvesting means for retrofitting automobiles with intelligent devices. To understand opportunities in this area, I proposed a new approach—compute-proximal energy harvesting. I investigated possible energy sources (such as light, heat, vibration, and wind) in and around a vehicle by applying both off-the-shelf and custom energy harvesters. I presented two examples of prototype systems to explain ways of using harvested energy in different locations (Chapter 3).

Even though wind energy harvesting might be the most promising method compared to other harvesting modes in mobile environments, it has not been widely explored on a small scale yet. Thus, I performed an in-depth review of the design space of small-scale wind energy harvester for compute-proximal energy harvesting. I designed and evaluated two wind turbines—63 and 92 mm diameter with optimized rotors—and achieved 20.6% and 16.2% power conversion efficiency, respectively. With the harvested energy, I demonstrated two advanced safety sensing systems—a blind spot monitoring system using a novel low-power radar sensor that achieved approximately 90% accuracy and a lane detection system using an off-the-shelf camera sensor and embedded platform that achieved above 90% accuracy in city and highway driving conditions. These applications show a promising path that new sensing capabilities can be added to an automobile in a self-sustainable manner (Chapter 4).

As a first step to democratize these innovative approaches, I implemented an energy harvesting toolkit called Exergy by incorporating the lessons learned from the automotive case studies as well as the features suggested by the makers and researchers who have used energy harvesting technology (Chapter 5). To examine the potential of democratizing Exergy, I investigated how acceptable the toolkit is and how creatively it can be used. Since it is challenging to directly answer these questions, I analyzed the degree of perceived difficulty and technological confidence that can significantly influence acceptability. I measured the changes of these factors before and after using the toolkit and confirmed that Exergy significantly improved users' confidence while easing their difficulties in building a small-scale wind energy harvester and its self-sustainable application. By analyzing the results generated in the ideation sessions, I also found that Exergy could support people's creative designs (Chapter 6).

Our approaches and examples are not exhaustive. They merely begin to highlight the different ways of applying energy harvesting technology to domains that have not yet received much attention in our research community. More work is needed to better understand the untapped potential of the compute-proximal energy harvesting approach.

Future steps for improving Exergy would include replacing the human intermediary with the non-human intermediaries, incorporating more design factors to extend Exergy, and applying Exergy to the experienced users.

- The first step is to deploy Exergy to potential end-users through non-human intermediaries (e.g., online lectures and interactive troubleshooting guidelines) and ask them to utilize it for various applications over a more extended period. This would allow us to examine the toolkit in a more realistic and self-paced environment. In doing so, researchers should clearly articulate what aspects of learning, building, testing, and expanding are being evaluated.

- The second step is to incorporate other energy harvesting modes that the first version of Exergy excluded, such as heat, vibration, and solar. Unlike wind, these types of energies could be significantly affected by environmental factors such as road condition, ambient temperature, and weather. Thus, it can be challenging to simulate the performance of such energy harvesters accurately. In place of theoretical methods, empirical approaches that consider the diverse affecting factors will be more useful for further research. Even if the energy mode is changed, the core features of Exergy—supporting different vehicle types, incorporating empirical driving data, and helping the users change the design of the energy harvester—would still be effective and valuable. Additionally, the current version of Exergy does not fully support the computation elements in the simulation. More features such as intermittent computing or power-aware system operation should also be incorporated in the future.

- The third step is to foster growth in novice users by increasing the design flexibility of Exergy. This improvement could include adding more energy harvesting circuits, different propellers, various sensors and actuators, and diverse computing platforms. Although the heterogeneity of Exergy may lead to confusion in initial use, I expect that people will use Exergy in various ways over time, which will help them gradually become experts.

- The last step is to understand the potential of "higher the ceiling" for Exergy. In this dissertation, I focused only on enabling easy access for the novice ("lower the floor") and supporting a broader range of ways to utilize Exergy ("widen the wall"). Just as Exergy helped novice users develop easily and confidently through visualized simulation and abstracted hardware, it is expected that Exergy could also support the expert in many ways. Further research is required to determine the potential of Exergy as an expert tool.

I believe this work will inspire other researchers or makers to explore and expand upon our efforts in this area, looking either to the automobile or other mobile environments. With such a collective effort, we can improve the ability to incrementally introduce computation all around us with less constraint on installation and lower maintenance costs.

Appendices

APPENDIX A
INTERVIEW GUIDE FOR UNDERSTANDING THE CHALLENGES AND OPPORTUNITIES ASSOCIATED WITH ENERGY HARVESTING TECHNOLOGY

Table A.1: Interview Protocol

Step	Tool	Time	Contents
Introduction	BlueJeans	5 Minutes	Project Explanation
Informed consent	BlueJeans, Qualtrics	5 Minutes	A participant will access the consent form on Qualtrics, and an interviewer will answer any questions from the participant via BlueJeans.
Demographic survey	BlueJeans, Qualtrics	10 Minutes	The demographic survey will be included in the Qualtrics link for the consent document.
Semi-structured Interview	BlueJeans	40-60 Minutes	About the participant and his/her maker community, motivations, making process, and challenges. Possible solutions or workarounds for his/her problems

A.1 Introduction

Hi, My name is Jung Wook. I will be facilitating this interview study. I really appreciate that you are willing to share your experiences of working on energy-harvesting related projects. Feel free to let me know at any time if you feel uncomfortable or if you do not want to answer any specific questions. Those will not affect this interview at all and the most important thing is to make sure you are both stable and comfortable.

A.2 Informed Consent

We will conduct this session with your consent. For that purpose, we have prepared a consent form for you to look over. This is an online document and you can access this via the link just shared via the chat on Bluejeans. Please take as much time as you need to read this document. You can ask questions at any time. If you agree to participate in this project, please click the Yes button at the end of the document.

A.3 Interview Question

About the participant and his/her maker community

- Can you please briefly introduce yourself and your maker community?
- Can you please describe the kind of projects you or your fabrication lab have worked on?
- What factors would drive you or the community to work on a certain kind of project?
- How do you (or the maker community/fab lab you are part of) collaborate with other makers or organizations?

Why, when, and how

- How many energy-harvesting related projects have you done?
- When and how did you get to know about the energy-harvesting technologies? (how)
- Among all the type of projects you or your fabrication lab/maker community have worked on, how do you think of energy-harvesting related projects in general? (why)
- What factors have motivated you (or the lab) choose to work on energy-harvesting related projects in the past?

- What factors have discouraged you (or the lab) from working on more energy-harvesting related projects?
- Would you still want to make more energy-harvesting related projects? Why / why not?
- What do you think of the overall experience that you or the people within the community work on the energy-harvesting related projects?

The process and the challenges

- Can you please describe your most successful and least successful experience of working on energy-harvesting related project?
  - In what context did you choose to do it?
  - Before doing it, did you already have a good knowledge of energy-harvesting technologies?
    - If yes, how did these knowledge help you work through the making process?
    - If no, how did you learn about it?
  - What challenges did you encounter?
  - How did you over come the barriers?
  - Where did you get the help?
  - How is the process different from other projects you have worked on?
  - What do you think makes the difference between these two kinds of the experiences?
- What kinds of challenges you have encountered when you used energy harvesting technologies in your previous projects?

What and how could be better

- What domain knowledge, skills, tools, materials or any resources would you wish to have at that time in order to make the project experience better?
- What successful project experience do you wish to adapt to the energy harvesting projects?
- What factors do you think would lead to a great project experience?
  - In what aspects would you rate energy harvesting projects experiences the lowest? Why?

A.4 Wrap Up

Thank you for sharing your experiences and opinions. Your answers were very helpful. How do you feel? Please use the available resources if you feel uncomfortable after this interview. Do you have anything you wanted to share but have not had a chance to share yet? Do you have any thoughts or ideas other than what we discussed? Do you have any questions? Would you like me to send the gift card to the email address we used to schedule this interview? If not, could you please let me know an alternative email address to send the gift card to? You should receive it within 4 weeks. Feel free to email me if you do not receive it after that time. Thank you again for your help!

End of Interview

APPENDIX B

ENROLLMENT SURVEY FOR THE USER STUDY IN CHAPTER 6

Demographic Information

1. What is your name?

   ____

2. What is your gender?

   - Male
   - Female
   - I prefer not to answer

3. What is your age?

   - 18-24 years old
   - 25-34 years old
   - 35-44 years old
   - 45-54 years old
   - 55-64 years old
   - 65-74 years old
   - 75 years or older

4. What is the highest degree or level of school you have completed? (If currently enrolled, highest degree received.)

   - No schooling completed

- Some high school, no diploma
- High school graduate, diploma or the equivalent (for example: GED)
- Some college credit, no degree
- Bachelor's degree
- Master's degree
- Doctorate degree
- Others

5. Are you currently...?

    - Employed for wages
    - Self-employed
    - Out of work and looking for work
    - Out of work but not currently looking for work
    - A homemaker
    - A student
    - Military
    - Retired
    - Unable to work
    - Others

    Display This Question: If Are you currently... ? = A student

    - If you are a student at Georgia Tech and currently enroll in CS 3790 - Introduction to Cognitive Science, you are eligible to receive extra hourly credits for three hours instead of monetary compensation. Do you want to receive extra course credits for CS 3790?

– Yes, I want to receive the extra hourly credits for CS 3790

– No. I want to receive the monetary compensation

Past Experience on Hardware/Software Prototyping and/or Energy Harvesting

1. How many hardware prototypes have you built so far?

   ____

2. How many software programs have you developed so far?

   ____

3. Do you have any hands-on experience on energy harvesting technologies?

   - Yes
   - No

   Display This Question: If Do you have any hands-on experience on energy harvesting technologies? = Yes

   - Can you elaborate on what kind of experience you had? Here, you can discuss the energy types, tools, or applications

     ____

     ____

     ____

4. Would you please describe everything you know about wind energy harvesting, such as operating conditions, applications, installation locations?

   ____

   ____

   ____

Baseline of Technological Confidence / Perceived Difficulty

1. Overall, making a small-scale wind energy harvester **will be**

Very Difficult 1	2	3	4	5	6	Very Easy 7

2. I am confident that I can build a **small-scale wind energy harvester.**

Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

3. I am confident that I can build a **self-sustainable device powered by wind energy.**

Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

APPENDIX C

POST SURVEY AFTER THE HANDS-ON EXPERIENCE SESSION IN THE USER STUDY IN CHAPTER 6

Demographic Information

1. What is your name?

   ____

Task Completion

1. Do you think you have successfully completed the given task—making a small-scale wind energy harvester?

   - Yes
   - No

Post-analysis of Technological Confidence / Perceived Difficulty

1. Overall, making a small-scale wind energy harvester **was**

Very Difficult 1	2	3	4	5	6	Very Easy 7

2. I am confident that I can build a **small-scale wind energy harvester.**

Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

3. I am confident that I can build a **self-sustainable device powered by wind energy.**

Strongly disagree	Disagree	Slightly disagree	Neutral	Slightly agree	Agree	Strongly agree

4. If you have any concerns or challenges with what you have worked on, would you please articulate them?

    ____

System Usability Scale

1. For each of the following statements, mark one box that best describes your reaction to the tools that you have experienced today.

	Strongly Disagree (1)	(2)	(3)	(4)	Strongly Agree (5)
I think that I would like to use this system frequently.	O	O	O	O	O
I found the system unnecessarily complex.	O	O	O	O	O
I thought the system was easy to use.	O	O	O	O	O
I think that I would need the support of a technical person to be able to use this system.	O	O	O	O	O
I found the various functions in this system were well integrated.	O	O	O	O	O
I thought there was too much inconsistency in this system.	O	O	O	O	O
I would imagine that most people would learn to use this system very quickly.	O	O	O	O	O
I found the system very cumbersome to use.	O	O	O	O	O
I felt very confident using the system.	O	O	O	O	O
I needed to learn a lot of things before I could get going with this system.	O	O	O	O	O

APPENDIX D

POST SURVEY AFTER THE IDEATION SESSION IN THE USER STUDY IN CHAPTER 6

Demographic Information

1. What is your name?

____

Creative Support Index

Please rate your agreement with the following statements:

I was satisfied with what I got out of the system or tool.

Highly Disagree — Highly Agree

It was easy for me to explore many different ideas, options, designs, or outcomes, using this system or tool.

Highly Disagree — Highly Agree

The system or tool allowed other people to work with me easily.

Highly Disagree — Highly Agree

I would be happy to use this system or tool on a regular basis.

Highly Disagree Highly Agree

I was able to be very creative while doing the activity inside this system or tool.

Highly Disagree Highly Agree

My attention was fully tuned to the activity, and I forgot about the system or tool that I was using.

Highly Disagree Highly Agree

I enjoyed using this system or tool

Highly Disagree Highly Agree

The system or tool was helpful in allowing me to track different ideas, outcomes, or possibilities.

Highly Disagree Highly Agree

What I was able to produce was worth the effort I had to exert to produce it.

Highly Disagree Highly Agree

The system or tool allowed me to be very expressive.

Highly Disagree Highly Agree

It was really easy to share ideas and designs with other people inside this system or tool.

Highly Disagree Highly Agree

I became so absorbed in the activity that I forgot about the system or tool that I was using.

Highly Disagree Highly Agree

When doing this task, it's most important that I'm able to...

Explore many different ideas, outcomes, or possibilities	Work with other people
Be creative and expressive	Produce results that are worth the effort I put in
Enjoy using the system or tool	Become immersed in the activity
Become immersed in the activity	Produce results that are worth the effort I put in
Work with other people	Enjoy using the system or tool
Produce results that are worth the effort I put in	Explore many different ideas, outcomes, or possibilities
Be creative and expressive	Become immersed in the activity
Work with other people	Produce results that are worth the effort I put in
Be creative and expressive	Enjoy using the system or tool
Explore many different ideas, outcomes, or possibilities	Become immersed in the activity
Work with other people	Be creative and expressive
Produce results that are worth the effort I put in	Enjoy using the system or tool
Explore many different ideas, outcomes, or possibilities	Be creative and expressive
Work with other people	Become immersed in the activity
Explore many different ideas, outcomes, or possibilities	Enjoy using the system or tool

Please describe any points that Energy needs to be improved, or any other suggestions.

____

____

____

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