Exergy: A Toolkit to Simplify Creative Applications of Wind Energy Harvesting

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Energy harvesting reduces the burden of power source maintenance and promises to make computing systems genuinely ubiquitous. Researchers have made inroads in this area, but their novel energy harvesting materials and fabrication techniques remain inaccessible to the general maker communities. Therefore, this paper aims to provide a toolkit that makes energy harvesting accessible to novices. In Study 1, we investigate the challenges and opportunities associated with devising energy harvesting technology with experienced researchers and makers (N=9). Using the lessons learned from this investigation, we design a wind energy harvesting toolkit, Exergy, in Study 2. It consists of a simulator, hardware tools, a software example, and ideation cards. We apply it to vehicle environments, which have yet to be explored despite their potential. In Study 3, we conduct a two-phase workshop: hands-on experience and ideation sessions. The results show that novices (N=23) could use Exergy confidently and invent self-sustainable energy harvesting applications creatively.

CCS Concepts: • **Human-centered computing → User interface toolkits**; **Empirical studies in HCI**; **Ubiquitous and mobile computing systems and tools**; **Empirical studies in ubiquitous and mobile computing**.

Additional Key Words and Phrases: energy harvesting, toolkit, democratization, wind energy, self-sustainable systems, vehicle

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1 INTRODUCTION

In the past decade or so, there have been increasing calls for the democratization of technology innovation [9, 38, 71]. The Do-It-Yourself (DIY) movement has proposed extending the vision of ubiquitous computing (Ubicomp) out of the research labs and into the public sphere [40, 43]. For example, researchers have built DIY

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toolkits for physical user interface [25], data visualization [32], building management [20], and energy-aware operation [38]. Makers have applied energy harvesting to their applications to reduce the burden of power source maintenance, however there are few energy harvesting-related projects documented in Make magazine [49] and online maker communities, such as instructionables.com and hackday.io. These projects employed mature power harvesting techniques, such as solar cells and vibrations. The novel energy harvesting materials and fabrication techniques emerging in academic research labs remain foreign to the general maker communities.

Energy harvesting technology is a domain of sustained interest for the ubiquitous and mobile computing community [2, 36, 54]. However, efforts to democratize it are still very limited [55]. What is missing is a systematic understanding of user-requirements and a toolkit that would leverage these findings. For such energy harvesting tools to be widely adopted, there needs to be a deep understanding of 1) ease of use to novices in an area that leads to confidence in their maker skills and 2) the creativity that can be facilitated. In short, the prototyping tools and fabrication techniques for energy harvesting should be simplified as a "maker technology" to support and empower more creative minds [2]. In this paper, we seek to bridge this gap and invent an energy harvesting toolkit. Unlike the efforts of wearable energy harvesting research in our community [27, 54], such application research for vehicles is sparse. However, vehicles have much higher potential energy that can be harvested. Among various energy harvesting modes, interaction with the wind could be one of the promising sources of harvestable energy, which can be increased in proportion to the cube of the vehicle speed. Therefore, we select wind energy as a case study and apply its toolkit to vehicles.

Numerous researchers in Human–Computer Interaction (HCI) and Ubicomp have tried to transform their knowledge and skills into tools that empower makers, designers, or the general public [23, 35, 56]. In the past, these efforts were often viewed as helping the hobbyists in the DIY community [9]. 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 [71]. It can bring a lot of innovation to our research communities and relevant industries [33]. Successful tools with broad adoption share two characteristics [41]. 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. Collectively, we investigate the following questions (see Figure 1):

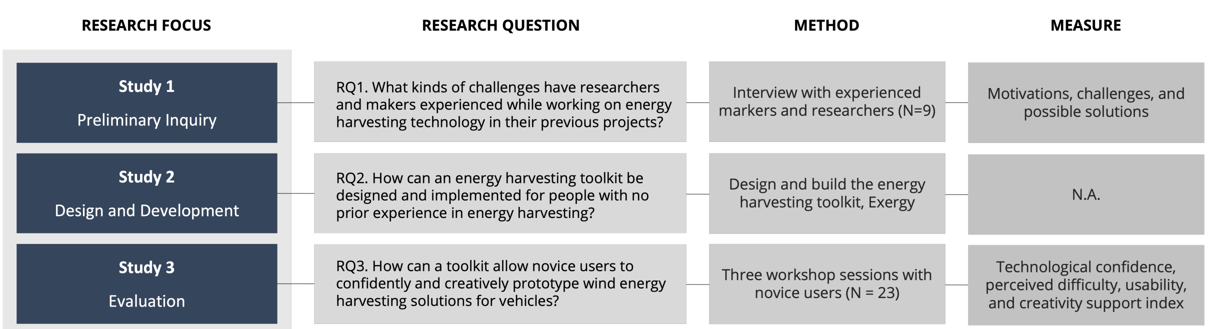


Fig. 1. A schematic figure explaining the research focus, question, method, and measuring factors of each study in this work

This work makes three contributions: First, we characterize the challenges faced by makers and researchers. Second, we take an evidenced-based approach to design and develop a wind energy harvesting toolkit, Exergy, consisting of a simulator, hardware tools, a software example, and ideation cards. Third, we confirm that novices are empowered to design self-sustainable applications using the toolkit that is easy to use and drives their confidence and creativity.

2 RELATED WORK

2.1 Energy Harvesting in Ubiquitous Computing

In ubiquitous computing, power source maintenance has remained a long-standing challenge for the deployment of computing devices. Owing to this challenge, energy harvesting technologies have been studied as a promising solution. For example, various ambient energy sources in everyday environments have been studied as a way to harvest energy and deploy self-sustainable computing devices in different applications, including light [70], temperature [36], vibration [77], wireless communication signals [69], and power lines [26]. Unlike the other types of energy, research on small-scale wind energy harvesting and its applications has yet to be thoroughly explored. We study this untapped potential. In terms of application domains, researchers have explored by taking advantage of everyday environments and/or activities [28, 77]. Vehicles have a great potential for energy harvesting yet research in this mobile environment is sparse. While prior work has demonstrated the potential for creating energy harvesting solutions for an automobile [55], the tools to implement and examine energy harvesting functions in that environment are limited and difficult for end-users to adopt. Therefore, we propose a comprehensive energy harvesting toolkit targeting vehicle environments.

2.2 Democratized Technological Practice

In the field of human-computer interaction (HCI), researchers have attempted to democratize their skills and intellectual findings by turning them into a tool that could empower other researchers, makers, and designers [35, 56]. Democratization in DIY started with fabrication tools for non-functional objects, but it has since expanded to "smart" objects that include electronics [50], soft circuits [51], and battery-free devices [38]. The ideology of the maker culture increased access to the means of creating physical inventions. These efforts later expanded to more intelligent things such as on-skin interface prototyping [39], paper craft for inductive power transmission [78], co-making shared constructions [5], and cardboard machines for prototyping devices [57]. Among various tools proposed in HCI, only a handful of them (e.g., Lilypad[13], Phidgets[25], and the Proximity Toolkit[41]) have been widely embraced by the maker communities because they have improved people's fabrication skills and expanded the scope of their ideation. We incorporate these two aspects in our proposed toolkit.

2.3 Theories of Technology Adoption and Creative Support Tools

Researchers have actively studied how an individual comes to accept a new technology such as a robot and a smartphone [21, 44]. To do that, the technology acceptance model (TAM) has been widely adopted [22, 34]. Initially, TAM considered perceived usefulness and ease of use as primary factors that inform 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 [34]. Thus, we consider the three critical factors of TAM (i.e., technology self-efficacy, perceived ease-of-use, and usability) to examine Exergy's acceptance. Another factor for evaluating Exergy's usefulness is its ability to elicit creativity in the user [24]. Ledo *et al.* extended this concept and claimed that toolkits should "enable creative exploration of design spaces" [41]. This study also evaluates Exergy's ability to support creativity in novice users.

Although energy harvesting has been studied for a long time, the tools to support its practices are very limited [15]. Researchers have found that it is necessary to consider various factors, including which energy source is most suitable, how much energy can be scavenged, and what design parameters of a specific energy harvesting mode should be adjusted to improve performance [15, 54, 76]. Other design variables address the power requirements for the computing solution, as well as how harvesting and computing abilities vary during the typical use [38]. Therefore, energy harvesting tools are needed to enable broader research on energy harvesting and make it more approachable. We do so by conducting three studies as shown in Figure 1.

3 STUDY 1: CHALLENGES AND OPPORTUNITIES ASSOCIATED WITH ENERGY HARVESTING

Prior research has found that energy harvesting applications are hard to develop and hard for experts to use [55]. This problem is compounded for novice end-users. We conduct a qualitative user study to better understand the challenges designers, makers, and researchers have when considering the application of energy harvesting technologies. This step is critical since the problems they have experienced are the ones that novices will face while applying energy harvesting technology. By investigating the issues, we can better understand what possible solutions should be implemented for novices. This section addresses the first research question: *"What kinds of challenges have researchers and makers experienced while working on energy harvesting technology in their previous projects?"* In addition, we 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.

3.1 Data Collection and Analysis

We conducted an IRB-approved semi-structured interviews with makers or researchers (N=9, see Table 1). Participants were recruited by emailing academic researchers and makers across the US and members who actively post energy harvesting projects on online makers communities such as instructables.com and hackday.io. Each participant received a 15 USD gift card as compensation. Since in-person meetings were not feasible due to the COVID-19 pandemic, we hosted and recorded the interview sessions through the university's BlueJeans, a certified conference call system. For each session, we first introduced the scope and objective of the interview to the participant. Second, each participant was asked to review and complete an informed consent form and a demographic survey via Qualtrics. After that, we conducted a semi-structured interview about the motivations, making process, challenges, and possible workarounds that each participant and their maker communities have experienced. Each interview took approximately an hour. Once we completed the interviews, one of the experienced qualitative researchers in our team transcribed the recorded data. She then employed a combination of inductive and deductive thematic analyses to infer a list of themes from the data collected and uncover emergent themes [11, 52]. First, she began with inductive analysis by open coding the themes from the data, followed by deductive analysis to look for themes closely related to our research questions.

Table 1. Demographic and background information of the participants (*EH: Energy Harvesting)

ID	Age	Gender	Highest Degree Awarded	Number of EH Projects	Experienced EH Modes	Difficulty Level of Working on EH
P1	25-34	Male	Advanced	2	Wind, New materials	Moderately difficult
P2	25-34	Male	Advanced	3	Solar, Vibration	Slightly difficult
P3	25-34	Male	Bachelor	2	Solar, RF	Slightly easy
P4	18-24	Male	High School	1	Solar	Neither easy nor difficult
P5	25-34	Female	Advanced	4	Solar, Algae systems	Slightly difficult
P6	25-34	Male	Advanced	3	Solar, Vibration, Heat, RFID	Slightly difficult
P7	55-64	Male	Bachelor	5	Solar, Heat, Bio-diesel	Slightly difficult
P8	25-34	Female	Advanced	2	Solar, Vibration	Slightly difficult
P9	25-34	Male	Advanced	4	Solar, Wind, Vibration	Moderately difficult

3.2 Results

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

3.2.1 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. For example, P1 argued that

> "I was a little bit frustrated about the factor the power generated is not enough to power the actuation, which is critical to implementing the interactive computing devices."

Another 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."

3.2.2 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."

3.2.3 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 a triboelectric nanogenerator 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."

3.2.4 Recommendation-1) Abstract the technical knowledge into "black boxes": Understanding technical concepts and underlying mechanisms 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 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 to implement a target system. P1 mentioned that

> "If the system is more usable or accessible to such beginners, a lot of part can be black box, so that they don't have to understand deep knowledge about electrical components, instead black boxes already do high level functionality, you can just use these black boxes to implement."

3.2.5 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"

3.2.6 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 (to) make that a similar experience in the energy harvesting thing, print (it) out while I am designing and test it out in a 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 am 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."

3.3 Design Implications for Energy Harvesting Tools

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 other researchers' experience 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 [55]. The interview results from this study revealed that researchers and makers who have dealt with energy harvesting experienced similar challenges. Table 2 summarizes the required tools and their functions, which are essential to overcome the challenges discussed above. Although the participants in this study did not articulate basic requirements of energy harvesting tools such as energy conversation and storage, we marked them as *Basics* in Table 2.

Table 2. Components and requirement sources of the required energy harvesting tools

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.			•				•

4 STUDY 2: DESIGNING AND BUILDING AN ENERGY HARVESTING TOOLKIT, EXERGY

This section addresses the second research question: *"How can an energy harvesting toolkit be designed and implemented for people with no prior experience in energy harvesting?"* We describe the design and development of a toolkit, Exergy, to provide a means for novice users to manufacture and ideate self-sustainable systems in mobile environments. Exergy literally means *"the energy that is available to be used"* or *"the portion of energy that can be converted into useful work"* [3]. 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. The needs, pain points, and insights from the study results presented in Section 3 informed the features and specifications of Exergy. It consists of four parts—a simulator, hardware tools, a software example, and ideation cards. In the following sections, we describe each part in more detail. Although we 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.

4.1 Potential Use of Wind Energy Harvesting in Vehicles

Wind energy harvesting in vehicles presents an opportunity to power diverse computing devices. Traditionally, wind energy has been harvested at a large scale using turbine blades whose size is of the order of 100 m because the energy harvested by a wind turbine is directly proportional to the area swept by its blades. However, small wind turbines have also been studied for space-constrained applications, ranging in size from several meters [53] to centimeters [75]. Through this innovation, the emerging sensors attached to the surface of the automobile can be self-powered by wind energy (See Figure 2a). Figures 2b and 2c show two applications—self-sustainable lane detection system and blind spot monitoring system, respectively. The former used a 92mm-diameter turbine and was able to continuously operate the lane sensing at or above 82 km/h (≈ 51 mph), while the latter used a 63mm-diameter turbine and worked in a self-sustainable way at or above 58 km/h (≈ 36 mph). Although we have omitted the details of such applications for the sake of focusing on the toolkit and evaluation, we confirmed that they yield a high potential for self-sustainable operation in typical driving conditions. Appropriate tools are essential to explore such applications for a variety of vehicles, including automobiles, motorcycles, and bikes. We design and develop such tools in the following section.

(a) (b) (c)

Fig. 2. Potential applications on the surface of a vehicle in which wind energy is abundant. (a) an autonomous vehicle has a large number of sensors on their surfaces, which can be potential targets for energy harvesting. (b) a self-sustainable lane detection system, and (c) a self-powered blind spot detector

4.2 Exergy Simulator

4.2.1 Development of Exergy Simulator. One of the first decisions users need to make is where to place the self-sustainable energy harvesting solution. This critical decision will determine how much wind energy can be harvested, so it is important to help them 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 should measure or determine four variables as follows:

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

where ρ is the air density, A is the swept area of blades in a propeller, $\bar{u}$ is the mean of the wind speed, and C_p is an adjustable efficiency factor [72]. Although the air density varies depending on height from ground, ambient temperature, and humidity, many simulation studies assumed the air density of 1.225 kg/m^3, which is the value at sea level and 15°C [4, 48]. The swept area of blades, A, can be adjusted based on the available space and power demand. We assumed the efficiency factor (C_p) of 0.15 due to the expected mechanical efficiency of the motor connected to the propeller.

Unlike these variables, it is challenging to estimate the wind speed at the location in which a wind turbine will be placed since measuring the wind speed of all the points around a vehicle is not practical due to uncontrollable variables (e.g., ambient wind and traffic). Instead, we performed computational fluid dynamics (CFD) simulations to predict the wind speed using Autodesk CFD 2019. We 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.

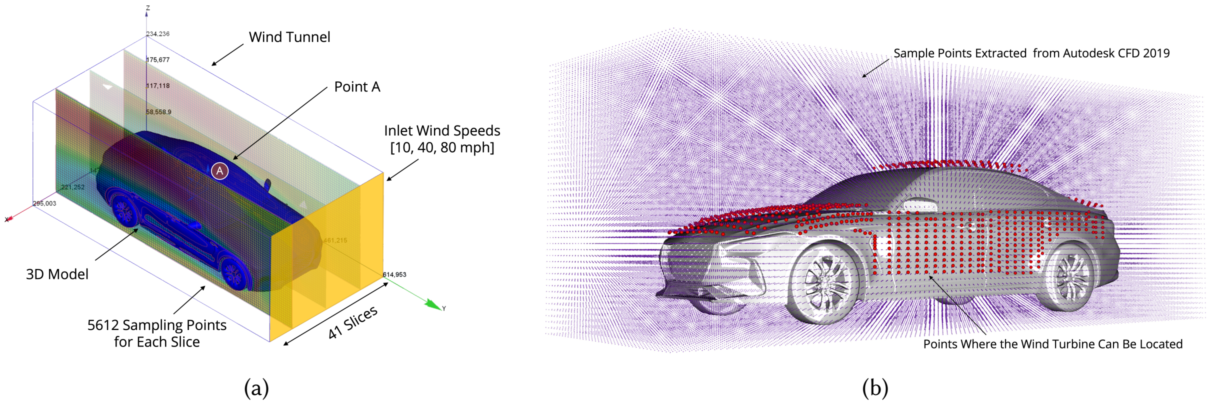


Fig. 3. The data characteristics and results extracted from our computational fluid dynamics simulations. (a) Computational fluid dynamics (CFD) simulations were performed for each transportation model, and the results were exported as described in this figure. (b) Purple dots are the extracted wind sample points from Autodesk CFD 2019. Red dots are the points in which the wind turbine can be located.

As a first step, we 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 3a. 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, we 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 each slice contains 5612 sample points. In total, there are 230,092 wind sample points, the purple dots in Figure 3b, for each inlet wind speed. Second, it was necessary to determine which points on the surface we could use since it would be difficult to attach a wind turbine to certain places such as moving windows or windshield. Thus, we excluded those areas and strategically specified points in which the wind turbine can be located, the red dots in Figure 3b. We applied this rule to other vehicles while integrating the CFD data and 3D models into the simulator.

Table 3. Retrieved wind speed at Point A in Figure 3a by the driving speed from the CFD database

Driving Speed (Inlet Wind Speed) (mph)	10.00	40.00	80.00
Wind Speed at Point A (mph)	14.17	58.01	117.24

Let us assume that a user wants to place a wind turbine at Point A in Figure 3a. 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 3. 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:

$$WindSpeed_{PointA} = DrivingSpeed * 1.47 - 0.68 \tag{2}$$

Note the R^2 value of the linear regression is 1. The coefficient and the constant of this regression may vary, depending on the location of each point. Using this equation, the simulator can compute the wind speed at Point A at any driving speed and estimate the harvested power through Equation (1). 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 1.225 kg/m^3, and the power coefficient is 0.15. All the variables can be modified in the simulator.

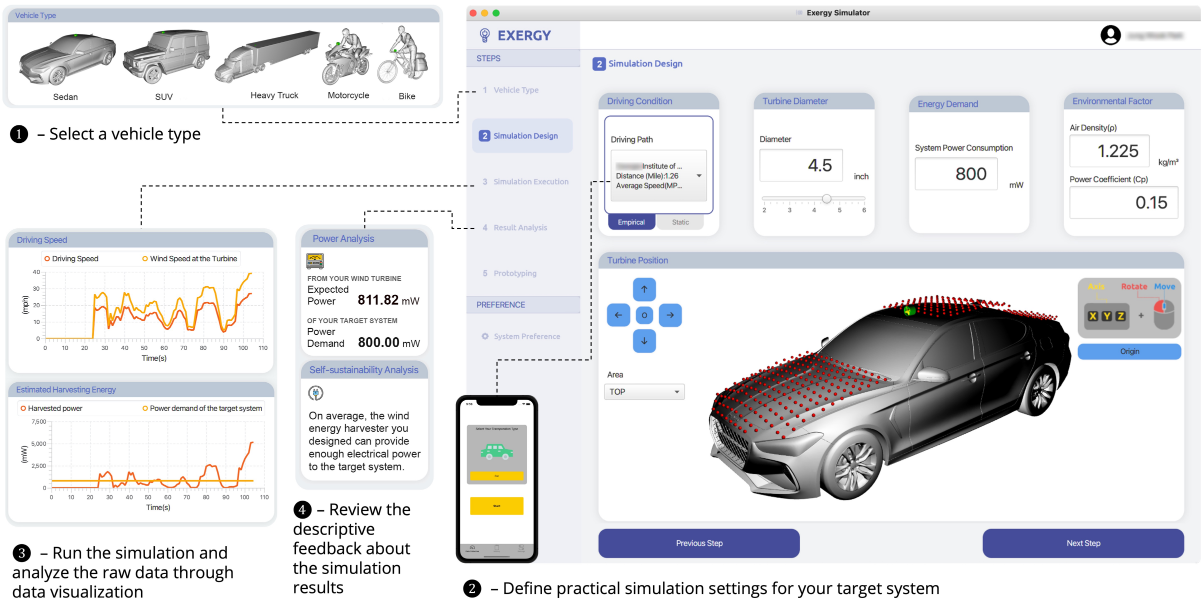


Fig. 4. 1) Exergy supports five vehicle types (i.e., sedan, SUV, heavy truck, motorcycle, and bike). (2) Exergy simulator allows a user to define simulation settings. (3) Exergy visualizes the results of simulation along with the expected power harvested by the wind energy harvester defined in the second step. (4) Finally, Exergy compares the average expected power from the harvester and summarize the final results in a descriptive format.

4.2.2 How to Use the Simulator. First, users can begin to use the Exergy simulator by choosing a vehicle among five options presented in Figure 4-1. As a second step, they can adjust the characteristics of their wind energy harvesting simulation. In this step, Exergy allows to use two driving profile sources—1) Exergy iOS application to collect the real-world driving data and transfer them to the simulator and 2) open-source driving or riding data sets shared in online repositories such as https://www.kaggle.com—for empirical evaluation. If these sources are not available, they can also specify a static driving speed as a driving profile. Other adjustable parameters include the size of wind turbine, the power consumption of target system, the air density in the target environment, and the power coefficient of the energy harvester as shown in Figure 4-2. Once finalizing them, they can move the wind turbine using the four-way buttons and the area drop-down menu. Since Exergy has a 3D viewer feature, they can rotate and zoom in/out the vehicle view and visually confirm how well the wind turbine could be integrated into the target vehicle. Third, once they confirm all the characteristics, Exergy estimates the harvested power and visualizes the results through two line charts—one for wind speed and another one for power—as Figure 4-3. Finally, as shown in Figure 4-4, Exergy presents a simulation summary and provides design guidelines if the average power is below the demand. Exergy could also recommend a battery to store surplus energy for the moments when the harvested power is not enough.

4.3 Energy Harvesting Hardware Tools

After confirming the self-sustainability of the target system through the Exergy simulator, users can start to implement the wind energy harvester. They first can adjust the size of the propeller we designed specifically for small-scale wind turbine and manufacture it through a commodity 3D printer. For the sake of simplicity, this paper does not present how to design and optimize a small-scale high-speed propeller. Since it takes a long time to precisely print the propeller with the 3D printer, we prepared the required one for this study in advance as shown in Figure 5-4. Users then connect the printed propeller to a DC motor for converting wind energy into electric energy. A Buck-Boost DC/DC conversion is essential for a constant, stable power supply because the electrical power from the motor may vary. To do that, we used LTC3119 and built a custom board, as shown in Figure 5-3. In addition to that, we developed another custom board to control the power path between the connected wind turbine and the battery, store surplus power into a rechargeable battery, and measure the remaining power in the battery, see Figure 5-2. We incorporated some off-the-shelf components presented in Figure 5-(5-9) into Exergy. Lastly, we designed a magnet-based bracket to help users to consolidate all the parts into one form factor and easily attach it to any metal surface (e.g., on cars).

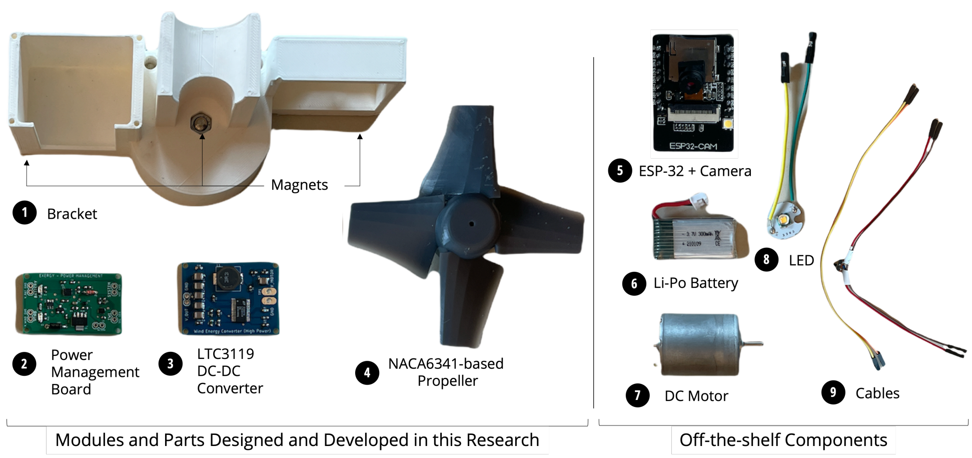


Fig. 5. Hardware of Exergy: (1) bracket with three strong magnets at the bottom, (2) Power management board, (3) Buck-Boost DC/DC converter, (4) Custom-design propeller based on NACA6341, (5) ESP32-CAM module, (6) Li-Po rechargeable battery, (7) DC motor, (8) LED module, and (9) some cables and switches

4.4 Energy Harvesting Software Example

We 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. We expected that many users would recognize the untapped potential of Exergy if we could prove that a wireless camera application can be self-powered with a wind energy harvester. Thus, based on an ESP-32 CAM module, Figure 5-5, we developed a wireless camera application that could interface with the hardware parts of Exergy. Figure 6a describes the system architecture, and Figure 6b presents an example of the software running on a web browser.

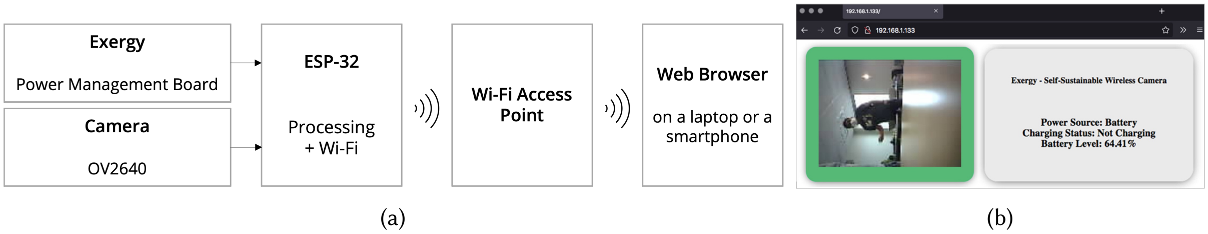


Fig. 6. (a) The system architecture of the software example in Exergy, and (b) the screenshot of the software example

4.5 Energy Harvesting Ideation Cards

In addition to simulation and prototyping features on Exergy, we 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 [1, 30]. 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" [46]. When it comes to the format of the card sets, we 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 [47]. Therefore, we designed a physical card set including two major card types—transportation and system, as shown in Section 4.5. We included power consumption information for each sensor, actuator, processing unit, and communication module for the system cards. By doing so, users could easily estimate the total power consumption of the target system by adding up the numbers on the card.

Fig. 7. Exergy ideation cards, consisting of 21 transportation cards and 26 system cards

5 STUDY 3: EVALUATION OF EXERGY

To answer to the third research question, *"How can a toolkit allow novice users to confidently and creatively prototype wind energy harvesting solutions for vehicles?"*, we conducted a user study that included a tutorial on wind energy harvesting, a hands-on training course, and an ideation session. We anticipated that it would be challenging to manage more than 10 participants in a single user study since our research team needed to help them if they had any issues and observe how they utilized Exergy. Thus, we aimed to recruit 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. The goal of the workshop was to evaluate Exergy on technology self-efficacy, perceived ease of use, usability and creativity elicitation.

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 particular courses at Georgia Tech and wanted the credits instead of monetary compensation. The Office of Research Integrity Assurance at Georgia Tech approved this user study. Before discussing the user study procedure, we present theoretical frameworks that informed the Exergy evaluation.

5.1 Theoretical Framework for Exergy Adoption Evaluation

As discussed in Section 2.3, we investigated three critical factors of TAM—technology self-efficacy, perceived ease-of-use, and usability. Technology self-efficacy can be defined as "an individual's belief in his or her ability to use a *technology* effectively" [67]. We hereafter refer to this concept as *technological confidence* and use it as the first factor to evaluate Exergy. The notion of perceived ease of use is "the degree to which a technology will be free from effort" [18]. We hereafter refer to the perceived ease of use as *perceived difficulty*, the second factor, since the two notions have been used interchangeably [17, 61]. We 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 third factor to discuss is *usability*, "the capability to be used by humans easily and effectively" [65]. To evaluate usability, we chose System Usability Scale (SUS) which has been used to evaluate new hardware platforms and many interface technologies [8, 42]. Additionally, we utilized Single-Ease Question (SEQ) to examine how difficult users perceive the given task [63].

5.2 Assessment of Exergy as a Creativity Support Tool

We consulted two well-known resources to define and operationalize creativity in this study. First, we referred to Plucker and Makel's definition [58], "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 of proper skill(s), process, and environment. Second, Sternberg created the investment theory, which explains six factors affecting creativity [68]. In this study, we consider the role of intellectual skills, knowledge, motivation, and environment as follows:

- **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 we 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.

Remy *et al.* 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 Creative Support Tools (CSTs)[59]. Thus, we employed a well-established evaluation method, Creative Support Index (CSI), that allows us to confirm whether Exergy could support ideation and design work in a creative manner [16].

5.3 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, they evaluated how difficult they thought it would be to build a wind energy harvester and a self-sustainable system and how confident they were. After that, we introduced the fundamental principles of wind energy harvesting and the purpose of Exergy.

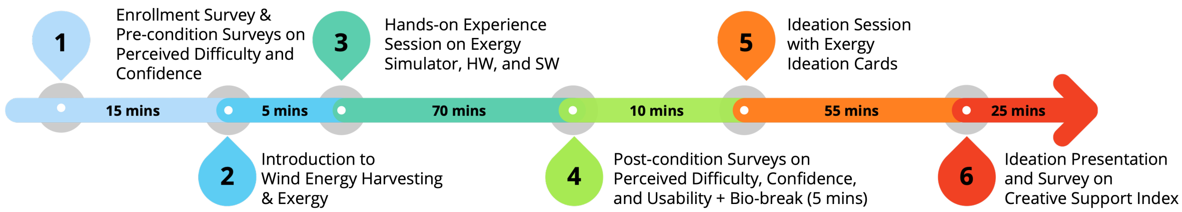


Fig. 8. The flow diagram of Exergy user study, illustrating the different steps of the study and the components of each step (total: 3 hours)

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.

The participants were asked to create a self-sustainable wireless camera system that satisfies three requirements: 1) The power consumption of the target system should be under 800 mW, 2) It should be self-sustainable at 20 mph of driving speed or higher, and 3) its target installation location should be the roof of a sedan. The participants used the requirements in the Exergy simulator (See Figure 4), explored the design specifications of the system (e.g., turbine diameter, installation position, driving speed), and finally were able to ascertain which specifications had to be satisfied for the given design requirements. After that, we explained the required hardware modules to implement the simulated system and educated the participants on how to utilize our pre-built Exergy hardware modules, described in Figure 5. The participants assembled and tested the modules according to the step-by-step guidelines to confirm that the target system could operate self-sustainably. We provided additional explanations for participants that did not understand a specific feature of the software and hardware tools. The Exergy features play a critical role throughout the user study since the participants could freely examine the feasibility of their system design (e.g., size of turbine and location) in a realistic situation (e.g., driving or riding) without actual in-the-wild tests. We also conceptualized each hardware module as a LEGO block and only presented what could be the input and output of the modules. By doing so, the participants did not need to worry about specifications but rather could utilize them to suit their needs. We devised these features and concepts to address the three challenges and incorporate the three recommendations in Section 3.2.

During the steps 1-4 in Figure 8, participants worked by themselves. 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 4.4 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, we 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. 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 Figure 8.

Table 4. 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					

5.4 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 4). 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 5. 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 locations. Thirteen out of 23 participants mentioned that renewable energy supply to the power grids was the only application.

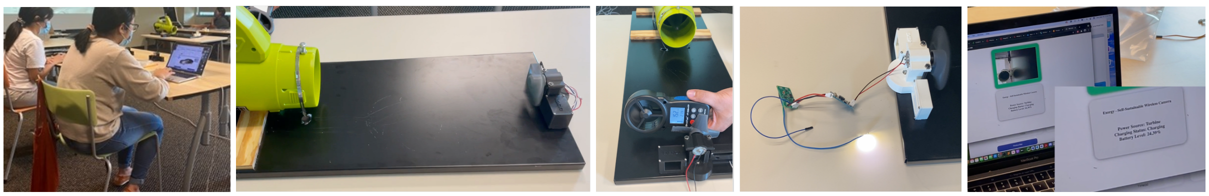
Table 5. Prior knowledge of wind energy harvesting technology. Note that the number in parentheses indicates how many times each item was mentioned in the enrollment survey.

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)

5.5 Results

This section presents the quantitative results of perceived difficulty, technological confidence, usability, and creative support index. We then discuss the qualitative results analyzed by the affinity diagram method.

5.5.1 Manufacturing a Self-sustainable Wireless Camera System. All 23 participants successfully manufactured the self-sustainable wireless camera system. We confirmed this in two ways. First, we 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, we 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 9.



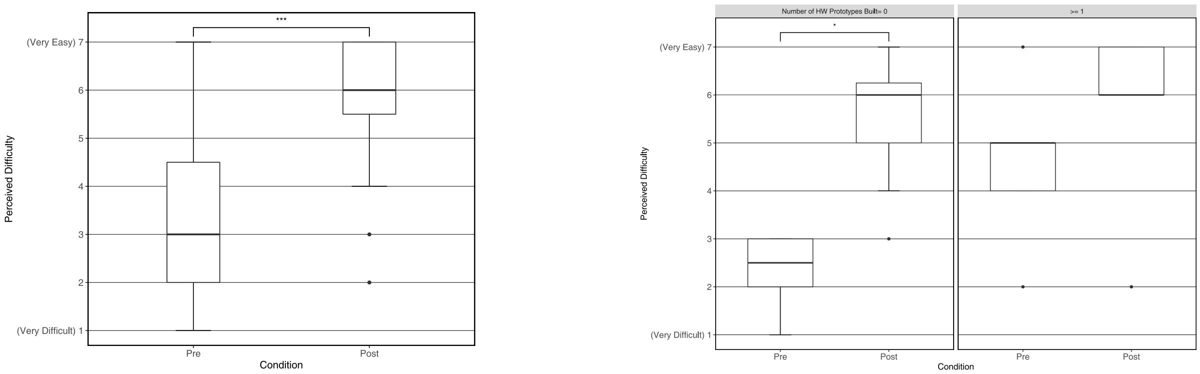
(a) (b) (c) (d) (e)

Fig. 9. Manufacturing and evaluating a self-sustainable wireless camera system. (a) The participants installed the Exergy simulator on their laptops and used it during the use study. (b) The wind generator used in the study. (c) For all the tests with the wind generator, we used an anemometer to inform the wind speed to the participants. (d) To visualize the operation of the wind turbine, we first asked the participants to interconnect the turbine with an LED and check whether they could see the light. (e) 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.

5.5.2 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 the hands-on experience session. Since the data collected for the perceived difficulty was non-parametric, we 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 10a. The ease-of-use that people perceived about the given task significantly increased compared to the pre-condition.

We performed a post-hoc test to confirm whether this result could be different depending on the level of prior hardware experience. We 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, we 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 10b.

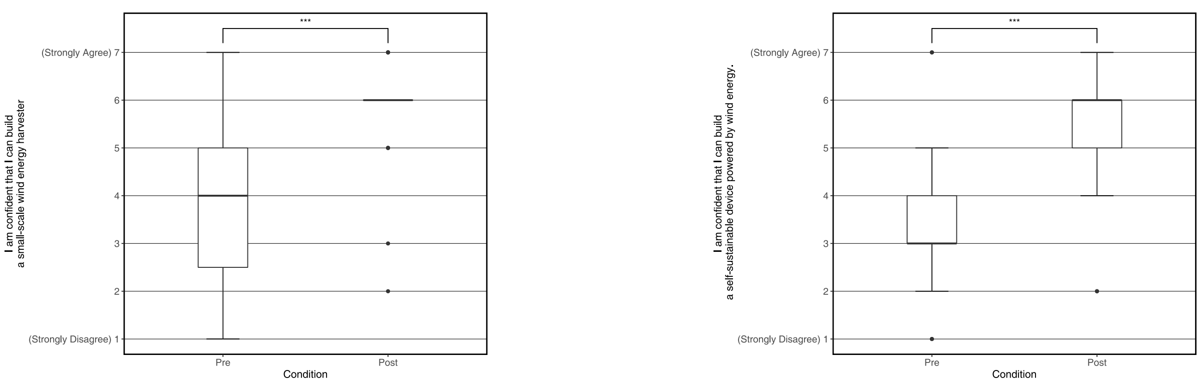
5.5.3 Technological Confidence. The participants were also asked to answer two questions about technological confidence in two tasks—**first task**: building a small-scale wind energy harvester; **second task**: building a self-sustainable system device powered by wind energy. For those who did not know the exact meaning of



(a) (b)

Fig. 10. Changes in perceived difficulty. (a) Overall changes in perceived difficulty between before and after the hands-on experience session, (b) Changes in perceived difficulty between before and after the hands-on experience session by the number of hardware prototypes built before

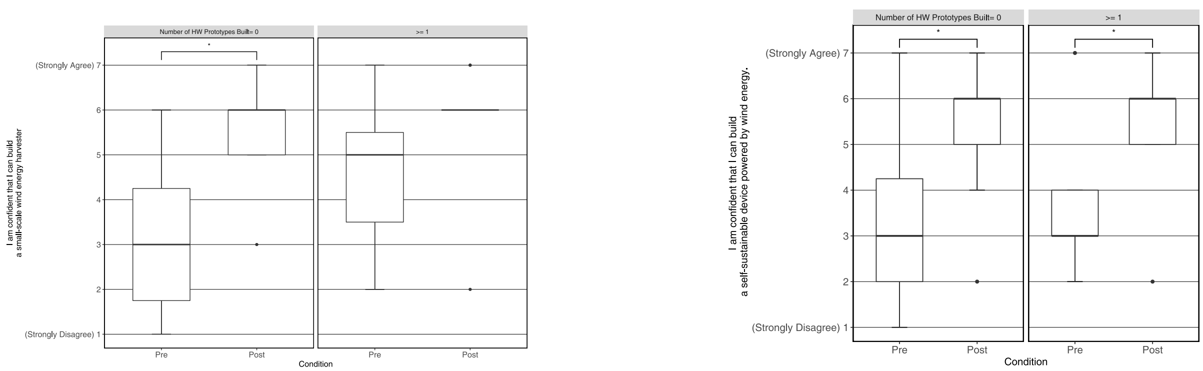
"self-sustainability" in this project, we articulated what it meant and how a device could be self-sustainable before they filled out the enrollment survey. We performed a Wilcoxon signed-ranks test to compare the pre and post conditions. The test result indicated that the hands-on experience of Exergy 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 11a and Figure 11b. People who experienced Exergy felt significantly more confident in those two tasks than the pre-condition.



(a) (b)

Fig. 11. Overall changes in technology confidence before and after the hands-on experience session. (a) Building a small-scale wind turbine and (b) Building a self-sustainable system powered by wind turbine

In addition, we performed a post-hoc test to confirm whether the results 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 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), as shown in Figure 12a and Figure 12b. 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 12b.



(a)

(b)

Fig. 12. Changes in technology confidence before and after the hands-on experience session by the number of hardware prototypes built before. (a) Building a small-scale wind turbine and (b) Building a self-sustainable system powered by wind turbine

5.5.4 Usability: System Usability Scale (SUS) and Single-Ease Question (SEQ). As discussed in Section 5.1, 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. The SUS score of Exergy was 70.8, which is *"Acceptable"* in the acceptability range and *"Good"* in the adjective ranges [8]. 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. 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.

5.5.5 Sketches. In the ideation session, the participants drew 103 sketches by combining various sensors and actuators for different types of vehicles (see Figure 13a). Along with the Exergy ideation cards and sketchpads, we provided blank cards for them to add new sensors or vehicles. The detailed information about the vehicle types and system components used in sketches is presented in Table 6. Figure 13(b-h) are some of the sketch examples they drew.

5.5.6 Creative Support Index (CSI). CSI consists of six core factors: results worth effort, immersion, expressiveness, exploration, enjoyment, and collaboration [16]. 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

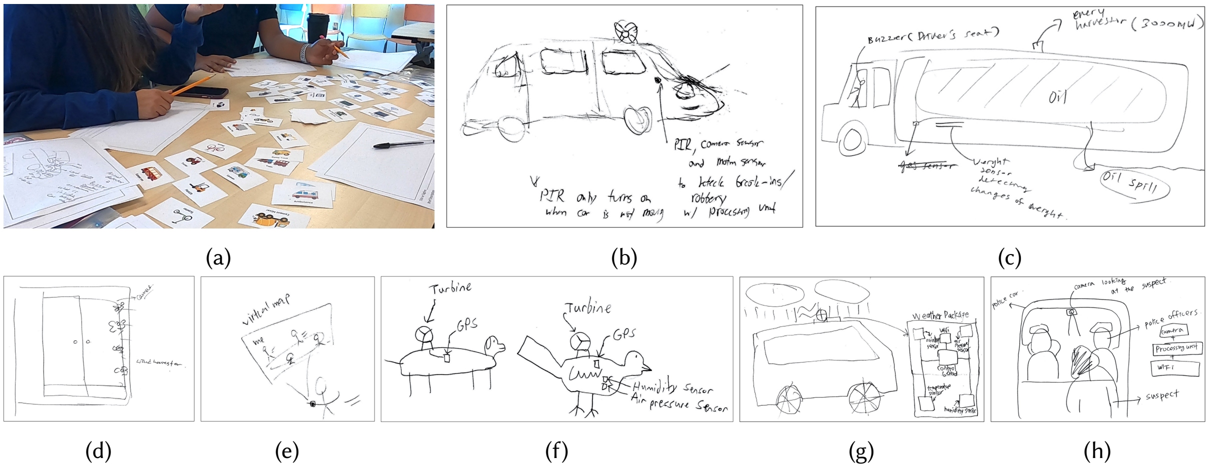


Fig. 13. (a) An example in which a group of participants freely synthesized the Exergy ideation cards during the user study. (b-c) Sketches that present the balance between creativity and practicality. Sketches that lean toward either creativity (d-f) or practicality (g-h).

maximum count for any specific factor was 0 and 5, respectively. We 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** that can be calculated by multiplying the factor score by the factor count.

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 7. The total 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" [16]. 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, we compared Exergy with other creative supports tools in Table 8. Note that, to the best of my knowledge, there were no CSTs to compare with respect to wind energy harvesting or self-sustainable computing. We confirmed that Exergy is in a comparable range to other tools. To interpret the details of each factor, we referred to the analysis examples proposed by Cherry and Latulipe [14, 16].

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

Table 6. Vehicles and system components used in the sketches per each group. Note that the items marked in **blue** 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 display, buzzer, RGB LED, Wi-Fi, processor
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 display, buzzer, speaker, RGB LED, Wi-Fi, Bluetooth, processor
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, processor
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, processor
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 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 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 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, processor

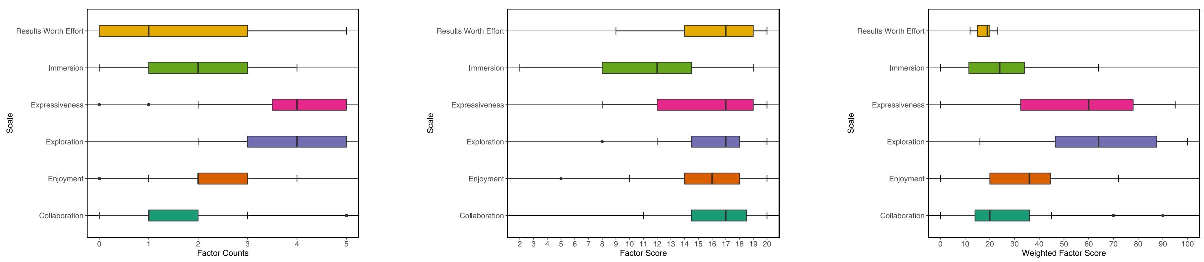
Table 7. CSI Results from our user study using Exergy (N=23). SD = Standard Deviation

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)

Table 8. Comparison of Exergy's CSI score with other CSTs

	Exergy (N=23)	AutoDesk Sketchbook (N=11) [16]	MaxOSX Color Exploration Plugin (N=16) [16]	Multimodal Pen-based Interaction (N=26) [7]
CSI Score	73.54	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 [7].



(a) (b) (c)

Fig. 14. Details of the creative support index (CSI) of Exergy. (a) Factor counts, (b) Factor scores, and (c) Weighted factor scores

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 [47], the ideation cards of Exergy might also be an effective component that supports collaboration.

5.5.7 Qualitative Analysis. Qualitative analysis can allow us to understand the underlying reasons for the quantitative results of Exergy. Three researchers in our team 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 [31, 45]. It has been widely used to understand creative sketches and their related implications [12, 74]. 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 the three researchers during the user study.

The three researchers 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 we were 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 pre-defined categories. Affinity diagrams should be built from the bottom up. Thus, in the first round, the researchers shuffled the individual notes and reviewed them several times. After interpreting the underlying implications of each note, they 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.

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 we 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.

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 [73]. We found great potential for Exergy to support creative work while considering its practical constraints. Our research team observed that nearly half of the participants 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 [37]. For example, in Figure 13b, 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. As shown in Figure 13c, 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. Note that the weight sensor was not an option provided in the ideation cards.

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 we have never imagined before, including (d) the edge of a door, (e) the wrist area of human body, or even (f) animals such as a bird or a dog, see Figure 13. 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 13g. 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 13h. These are meaningful and feasible ideas but not very creative, based on the SAPPhIRE novelty metric [37].

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 DISCUSSION

In this paper, we addressed three questions that are central to democratizing energy harvesting technology. First, "What kinds of challenges do makers and researchers who work with energy harvesting tool experience?" Interviews with 9 participants indicated that the significant issues were the resources (e.g., time, effort, and tool) required to design, develop, and deploy a reliable energy harvesting solution for a target context. Study 1 allowed us to answer the next question, "How can an energy harvesting toolkit be designed and implemented for people with no prior experience in energy harvesting?" We chose wind energy as a case study and designed an energy harvesting toolkit called Exergy, which consists of simulator, hardware tools, a software example, and ideation cards. In contrast to past research that used methods that were beyond the use of novices [6, 26, 76], Exergy encapsulates the complexity of small-scale wind energy harvesting and allow flexibility to explore and evaluate self-sustainable applications.

In the third study, we were able to answer the last research question, "How can a toolkit allow novice users to confidently and creatively prototype wind energy harvesting solutions for vehicles?", through three workshops with a total of 23 novices who had no prior energy harvesting experience. We 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. This is in line with other successful toolkit research [41]. Through in-depth qualitative analysis, we found out why and where the toolkit influenced the participants.

Taken together the results from these studies present a promising horizon for democratizing energy harvesting. This is important because energy harvesting is a critical in creating self-sustainable ubiquitous computing systems. The three studies presented here show that wind energy harvesting in vehicles is an area that can empower participants to design and implement self-sustainable applications. Importantly, using the toolkit is easy and drives novices' confidence and creativity. These results challenge the Ubicomp community to design and implement such toolkits for other emerging energy harvesting modes. Light, vibration, heat, and radio frequency are the modes that are ripe for innovation.

Shneiderman *et al.* and 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 [60, 66]. 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.

6.1 Limitations

Toolkits in HCI and Ubicomp were developed to democratize technological practice. In particular, "democratization" required four iterative stages—learning, building, testing, and analyzing [33]. Although participants in the workshop successfully accomplished all the steps, several limitations may influence their performance in some stages. First, in the learning stage, participants may have been influenced by our researchers' presence, attitude, and rhythm (e.g., Hawthorne effect [64]). Second, as human intermediaries [19, 29], we 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 we could not confirm in the format currently employed. Third, we designed the hardware components of Exergy in a fail-safe manner. For example, each connector shape was unique for each port; thus, it was almost impossible to interconnect the wrong pins while prototyping the example. We also provided only the necessary parts to build the example system. However, in case Exergy includes more hardware components to increase its design flexibility, users will be more likely to take longer than the current exercise or even fail due to the increased complexity. 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 COVID-19 pandemic. In this respect, we need further research in a more independent, self-paced environment.

6.2 Future Work

Our energy harvesting approaches and tools are not exhaustive. They merely begin to highlight the different ways of applying energy harvesting technology to domains that have yet to receive much attention in our research community. More work is needed to better understand the untapped potential of the energy harvesting approach. The first step is to incorporate other energy harvesting modes that Exergy excluded, such as heat, vibration, and solar. Unlike wind, these types of energies could be significantly affected by environmental factors such as ambient temperature, road conditions, 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 factors that affect power output are more beneficial for future research [10, 62]. Even if the energy mode is changed, the core features of Exergy—supporting different moving objects, incorporating empirical motion data, and helping the users change the design of the energy harvester with power estimation—is still 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 considered in the future.

7 CONCLUSION

This work contributes to our understanding of how experienced makers and researchers characterize the challenges they have faced when using established and novel energy harvesting technologies. The problems identified in this work could be the ones that novices will face while applying energy harvesting technology. Thus, we summarized what tool support is needed to address these problems. We chose wind energy as a case study and implemented an energy harvesting toolkit called Exergy that consists of a simulator, hardware tools, a software example, and ideation cards. We confirmed that Exergy significantly improved users' confidence while easing the burden of building a wind energy harvester and its self-sustainable application. The results in the ideation session also showed that Exergy help users elicit creative yet practical designs. Our approaches and examples highlighted the different ways of applying energy harvesting technology to domains (i.e., vehicles) that have not yet received much attention in our research community. It provided a first step toward better understanding the untapped potential of emerging energy harvesting approaches.

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