Modular Electronics for Broadening Non-Expert Participation in STEM Innovation: An IoT Perspective

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***Abstract*—STEM (Science, Technology, Engineering and Math) initiatives like makerspaces, open-source projects, engineering education etc., influence each other in a larger STEM ecosystem. This ecosystem extends beyond the traditional academic classroom into independent non-expert spaces and large corporate environments, and is critical to the innovative design of novel, efficient, and user-specific Internet of Things (IoT) devices. Although development boards have been commonly used in STEM programs and by engineers for initial design prototyping, these boards are not an ideal solution for non-expert users. Existing development boards lack the flexibility required to enable the rapid development and easy personalization of emerging IoT devices. In this paper, we survey modular electronic technologies used for education and suggest that modular electronics are the sustainable solution for a lightweight, versatile, and easily personalized generation of electronic devices. Modular electronics are application specific circuit pieces that can be combined in different configurations to create many different common devices like mobile phones or tablets. Modular electronics address obvious gaps in the STEM ecosystem, and consequently, the IoT space by allowing rapid prototyping and user-controlled reconfigurability.**

INTRODUCTION

The institution of Science, Technology, Engineering, and Math (STEM) programs in schools is the true turning point for forward development in electronic design. Due to a limited understanding of, and increased interest in, science, technology, and engineering, teachers around the world are including more STEM education in their day-to-day curricula. STEM education has inspired a movement of makers and engineers inside and outside of the classroom, and attracted the attention of even big corporations like Qualcomm, Intel, and Google [1]. These corporations have a vested interest in the bottom-up innovation of makerspaces and STEM programs. This gives rise to a "STEM Ecosystem," in which every member, from non-expert to corporate CEO, affects the other. However, despite this highly consequential relationship, these grassroots innovators do not have the tools that they need to sustain this ecosystem. Existing technologies are heavily based on legacy architectures and offer little to no flexibility for a rapidly changing mobile age. This discrepancy presents an obstacle for non-experts, students, and makers who have become vital for determining the future direction of electronic device design in the Internet of Things space [2]. The landscape for electronics development has shifted from corporations to individual users. Now more than ever, non-experts need a basic understanding of electronics design and optimization techniques.

Self-taught and non-expert STEM enthusiasts of every age need an affordable and practical solution for participation in STEM fields [3]. This need is further exacerbated by the growth of the Internet of Things (IoT), which is poised to transform the way we live, work, and do business [4]. It is expected that key innovations on the IoT will be driven by users and non-expert participants [5].

The IoT refers to an interconnection of uniquely identifiable physical devices spanning a wide variety of applications. The goal of the IoT is to reduce reliance on human beings for data acquisition, visualization, and use, towards creating novel and intuitive solutions and services [6], [7]. The IoT will be driven by devices in several domains, such as smart cities, smart homes, intelligent medical devices, etc. [8]. However, these devices are typically not designed with the individual user in mind. A paradox exists in mass producing a single type of device for a wide variety of users and use cases. As these mobile devices continue to be more integrated into everyday life, they will require the adaptability and reconfigurability to meet the needs of diverse functions and requirements—all with the same hardware. We argue that the required device adaptability and reconfigurability must be achieved through the participation of non-experts in the innovation and design process. Multiple frameworks currently exist to enable large-scale non-expert participation via *crowdsourcing and crowdsensing*, *urban probes*, and *community makerspaces* [9].

This paper suggests and surveys *modular electronics* as an intuitive solution to both learning-targeted and individualized designs for the IoT. Modular electronics are devices with function-specific electronic blocks that can easily be interchanged like LEGO blocks [10]. These modular systems are currently popular in K-8 STEM education [3], and offer high functional flexibility and rapid reconfigurability for creating emerging IoT devices. The latest iterations of modular electronics have a well-established open-source software and hardware online community, reducing cost and complexity for even technological novices [11].

In the context of the IoT, modular electronics serve two purposes: 1) they provide a platform with which students and non-experts can learn about IoT technology, and 2) they give non-experts the opportunity and ability to develop their own IoT electronics. Even if the users are not in the engineering or technology fields, these easy-to-use modules enable amateur users to develop devices that are uniquely suited for the users' needs and can be shared via open-source crowdsourcing or makerspaces. The best people to develop a solution to a problem are those who are directly affected by the problem. Giving non-experts the tools to be self-sufficient can mutually benefit both the users and device manufacturers by solving problems and bringing new perspectives to age-old engineering problems.

In this paper, we explore the emerging non-expert STEM ecosystem and its potential impact on the emergence and growth of the IoT. We also present a survey of the state-of-the-art in modular electronics, and propose that in order for the STEM ecosystem to thrive, and for the success of the IoT, modular electronics must be leveraged for adaptable and easily personalized IoT devices.

BACKGROUND ON MODULAR ELECTRONICS

Currently, most open-source electronics available to non-experts are development boards, such as Arduinos and Raspberry Pis [12]. These boards typically also include programming environments that allow users to program the boards using high-level programming languages, such as Python or C. These boards, however, offer a low level of flexibility—the hardware cannot be reconfigured by users for application-specific functions.

Field Programmable Gate Arrays (FPGAs) [13] allow hardware designs to be reconfigured in the field to suit users' specific requirements. However, to achieve user-specified functionality, FPGAs require a high level of user expertise on hardware design and synthesis tools. FPGAs require a niche hardware description language (HDL), such as VHDL or Verilog, that is unique to electrical engineers[13]. Even though there are several FPGAs available, non-experts have a steep learning curve to understand the board, programming structure, and the programming languages.

Modular electronics eliminate the need for specialized programming languages, and can be leveraged for general-purpose or application-specific electronics with a few quick module interchanges.

A. Modular Electronics

In general, modular electronics are pieces of an entire circuit that can be easily connected, interchanged and updated to make up a more recognizable device such as a mobile phone, microwave, etc. [14].

Modular electronics is an emerging field that was initially popularized in 2013 by the announcement of Google's Project ARA phone [14]. Although the project was subsequently discontinued in 2016, modular technology is gradually expanding from STEM education to general consumer electronics. Despite the project's discontinuation, Googles efforts inspired a movement of developing electronics with non-expert users in mind [11]. For example, in 2015, Motorola released a smartphone with modules that could be attached to the back of the phone. Similarly, companies like LittleBits [3] and Mesh [10] are developing modules that can interface with common development boards, such as Arduino and Raspberry Pi [10], [3].

B. Project ARA

Google's Project ARA was the most popular modular electronics project. This project, which was led by Google's Advanced Technology and Products (ATAP), was an attempt to offer a customizable phone. ATAP's aims were to deliver deep user customization, and to enable a lowered barrier to entry into the mobile hardware ecosystem. The phone exoskeleton and operating system would allow users to swap out malfunctioning or unused modules quickly and efficiently without having to depend on a third-party support specialist [14]. These interchangeable parts would also extend the product lifetime of the phone, as the electronic portion could be easily updated or swapped out at failure. Swapping out individual parts as opposed to an entire phone would also lessen the waste of electronic parts in phones in which the mean-time-to-failure depends on a few parts. Although this project was shelved, it inspired a movement of academics and non-experts to dive deeper into the integration of modular electronics with current offerings.

C. The Importance of Non-Expert Participation

Innovation in consumer products will be driven mainly by consumers rather than from the manufacturers who mass produce the products [15]. These consumers, most of whom are technology non-experts, are directly affected by shortcomings in a technology, and have the urgency to develop simple creative solutions to these gaps. The user-developed solutions may be adopted by other users through platforms like online discussion groups, word of mouth, and other sharing platforms. These solutions can then be honed to perfection by manufacturers who recognize the benefits of the improvements offered by the user-developed solutions. Furthermore, the manufacturers can mass produce the products with the added functionality or better designs. [15].

User innovation can also substantially influence the rate and direction of innovation at the industrial level. With more non-expert participation in the design space of a product, the design space can be explored more exhaustively in the same amount of time. With the rapidly growing IoT market, individual customization is critical for the success of IoT products.

Individual customization of devices can be enabled through the *participatory design* process [16], [17]. In the 1970s, Participatory design (PD)—otherwise known as co-design—was introduced in workspaces as a democratic process to include all the stakeholders, including the end users, in the design and use of workplace computer applications. Nowadays, the focus for PD is on ”infrastructuring,” which allows co-design to become more interwoven with daily life. It is a process that focuses on long-term commitment and is described as ”an open-ended design structure without predefined goals or fixed timelines" [16]. This is a critical feature of the non-expert participation in electronics and enables the stated broader exploration of a design.

It has also been observed that more time is needed for forming meaningful relationships that can enable a long-term participatory design process that involves both experts and non-experts [16]. Thus, it is critical to have hardware that can stand that test of time, instead of quickly becoming obsolete over the development period.

Furthermore, to enable the required relationships needed for enabling non-expert participation, a framework must be in place to support the interactions between the participants. *Public IoT* [18] represents such a framework that was developed as a public initiative for sharing realtime IoT data, distributing knowledge and ideas for IoT projects, and promoting large-scale participation in citizen-led initiatives. Public IoT supports citizen science by making IoT accessible to non-expert users. However, one of the major barriers to public IoT is the absence of easy hardware extensibility. Modular electronics have the potential to eliminate this barrier.

Modular electronics give non-experts confidence in their abilities to solve their own electronic problems using building blocks that they are familiar with, or can quickly learn [19]. Even though efforts are being made to more broadly integrate STEM education into school and pre-college programs, post-college non-expert users are typically not reached by these STEM initiatives. Due to their ease-of-use, modular electronics will be especially useful for educating and involving post-college non-expert users and other neglected demographics that may not be reached by the school-focused STEM activities [20].

Frameworks for Enabling Non-Expert Participation

A. Hackerspaces and Makerspaces

A huge factor in the growth of non-expert participation is the establishment of independent and non-profit *hackerspaces* or *makerspaces*. Hackerspaces are community operated workshop environments where people with common interests collaborate on technical, and sometimes artsy, personal projects [21], [1]. Students come from backgrounds like computer and electrical engineering, machining, science, digital art, and visual arts. While online resource sharing is still popular, these spaces offer an in-person knowledge sharing environment where non-experts can interact with other members of varying expertise levels. Furthermore, hackerspaces allow non-expert users to gain new perspectives on designs, receive hands-on instruction and collaboration, and share their work with large audiences at Maker Fairs.

The users in hackerspaces are united by their motivation to build, learn, and solve everyday problems with creative solutions [22], [23]. Varying ages and backgrounds enable a wider exploration of a solution space for a widespread problem or inconvenience. Users can leverage the idea of modular electronics to decompose a problem into its parts and apply their unique backgrounds to improve a device collaboratively, with everyone improving the part they have prioritized. This collaborative process accomplishes not only an improvement in the overall product, but also allows users to optimize their product for their specific application.

In addition to enabling collaborative design efforts among non-expert innovators, hackerspaces often partner with corporate sponsors. These partnerships make hackerspaces a perfect transition point from consumer innovation to corporate innovation. However, to further support these spaces, corporate partners can enable makers by creating adaptable development boards and tools (i.e modular electronics).

With the model of hackerspaces, rapid scalability also becomes achievable [24]. This trickle up innovation is characteristic of what the STEM ecosystem can achieve. With tools provided by the corporate partners, the design space is much better explored by non-experts and students in STEM education. When the design space is efficiently explored, corporate partners are much better equipped to make design decisions that benefit a larger group of consumers and non-experts starting the cycle again. Modular electronics as a development tool is intuitive enough for even novices to use but complex enough to develop testable prototypes.

Although this crowdsourced IoT development philosophy is established in the software engineering realm [25], hardware is still underdeveloped for this purpose. Most existing context-aware applications do not take the into account the meaning the data has for the person using the application or device. To this end, many papers suggest supporting a wide spectrum of people by creating useful components [25], [26], [3], [1], [27]. Another consequence of providing components instead of inflexible devices is a system that allows both finished and unfinished projects to linger and users to tinker with these projects. Currently the IoT space is at risk of developing into a network in which the people who use it are not in control, thereby defeating the purpose of IoT [25]. Thus, it is critical for hardware and software design processes to support non-experts innovators.

Makerspaces [28], [29], [30], [31] represent the perfect experimental lab for non-experts to develop IoT technologies. Operating in a crowd network of their own, makers pull from open-source websites and word of mouth to develop projects, many of which are IoT related. With every maker that iterates on the project, an improvement is made [30]. At makerspaces' current rate of growth, the limiting factor to their progress is the gap created by the dearth of materials to quickly construct, evaluate, and communicate users' ideas. Modular electronics bridge this gap by enabling makers to continue to grow and learn at a faster rate than otherwise possible. Prior work [32] has shown that modularity is a key to enabling novice prototyping with electronics. Experiments using Amazon's Mechanical Turk (MTurk) [33], [34] showed that modularity increased the quantity of prototypes created by study participants and increased participants' degree of self-efficacy, reported creative feeling, and cognitive flow.

B. Independent Spaces

Independent spaces are spaces that are independently run by volunteers with various engineering and art backgrounds. These independent makerspaces have no hierarchy in terms of leadership, making them the perfect place to collaborate without pressure and get honest feedback. They are available for self-motivated members to run and provide materials, machines, and a space for members to share their unique knowledge and expertise. The understanding within these spaces is that everybody contributes a portion of expertise or a perspective that is unique to them. Independent spaces enable rapid prototyping and give every participant a sense of self-confidence and project ownership critical in product and device development [21].

Rapid prototyping within independent spaces are often achieved using electronics, such as littleBits modules [3] and Arduino boards [35], [36]. Even though development boards like the Arduino are commonly used to prototype simple IoT devices, there is still currently a dearth of modular devices to enable prototyping of more complex IoT devices. Modules are currently very basic and aimed at simple projects that mainly focus on attaching these modules to devices that already exist [12], [37]. Modular electronics have the potential to increase in complexity such that a product can be made entirely of modules while still maintaining the device constraints, such as form factor, energy, performance, etc.

Makerspaces and hackerspaces are also spaces for trial and error. There are typically no deadlines or requirements; thus, users are able to change design directions if necessary. This environment has been proven to produce successful technologies. Companies like Google and 3M have popularized 'tinker time', or 'company time' that allows employees to work on personal projects with no deadlines or requirements. Makerspaces enable this environment on a much larger scale with no timelines, which directly translates to a higher potential for discovering novel IoT technologies and solutions [15].

C. Academic Makerspaces

Because of the success makerspaces have had in communities, some universities have also instituted their own makerspaces specifically for students. These institutions provide materials and tools with the same environment for both students and professors. The professors offer one-on-one expertise and collaborate with students from all backgrounds, making the experience mutually beneficial. Students and members do not necessarily have to be from STEM backgrounds to participate and own the space. A successful example is Georgia Techs Invention Studio [29]. Their mission statement is to foster the demand for creative, self-initiated learning on campus. They have expanded the traditional makerspace to not only include design and prototyping materials but also hold workshops, vendor networking events, experienced guidance, and access to the latest in prototyping machinery. Georgia Tech has improved student engagement by demonstrating the value and sustainability of hands-on design/build to stimulate not only creativity, but also entrepreneurship. Georgia Tech's Invention studio partners with several companies to model the democratization of the practice of engineering.

Similarly, Virginia Tech established a similar studio, called the Maker Lab, which has a structured curriculum. Their makerspace is integrated into a class as the lab portion. The lab teaches entrepreneurship and encourages hands-on learning. Furthermore, the Maker Lab livestreams events and workshops so that the learning material is accessible to students outside of Virginia Tech.

These two learning facilities generate highly successful students and open-minded engineers. Both makerspaces also expand their teaching base to students and non-expert users who might not be as technical. This expanded reach increases the makerspaces' influence on producing highly motivated innovators who can benefit the overall STEM ecosystem.

D. Maker Faires

Makers gather at Maker Faires, coming from makerspaces all over the world. Technology enthusiasts, crafters, educators, tinkerers, hobbyists, engineers, and many others share their work and network with company leadership. These fairs are designed to be forward looking, showcasing makers who are exploring new designs and technologies.

Companies like Mesh, a startup in the IoT space, talk with makers and technologists to get a better sense of what the masses need. Mesh designs blocks that have a sensor or peripheral with built-in functions to easily prototype and build projects for the IoT. These blocks can wirelessly interface with everyday appliances and devices. The programming is also very intuitive, using a graphical interface to connect different blocks together [10]. The modules break down the complexity further so that users can understand an entire system piece-by-piece. Modules allow the user to easily translate their vision from concept to reality: the aim of STEM education and modular electronics.

ACADEMIC WORK

Technology as a STEM teaching tool has been an emerging field of research at many academic institutions, such as the MIT Media Lab, which has focused on using technology such as modular electronics. Although these initiatives have mostly targeted STEM education, the research efforts can affect the direction of the IoT space. In this section, we present a brief overview of modular electronics initiatives that target non-expert education.

A. littleBits

A major contributor to the modular electronics space is *littleBits*, an organization whose mission is to move electronic design from corporate engineers to non-expert users [3]. The organization develops modules containing pre-assembled tiny circuit boards that can interface with each other through magnets. These modules are categorized into sensors, power, peripherals, and interconnects. Open source instructions are provided on the littleBits website, with project ideas from engineers at littleBits and other users of the modules. These modules have enabled hobbyists of all ages to create innovative solutions that solve problems in different domains, such as environment, medicine, and transportation. If these modules were more pervasive and could be leveraged to build more complex electronics, more problems in an even wider space could be solved with the infinite perspectives of the consumers.

B. Novice Tool Kits

Apart from littleBits, many amateur toolkits are being developed to ease entry into the electronics development field. *Blocktopus* through Stanford University [27] and LightUp [38] are two modern examples of such. They identify three guiding insights to build these kits: 1) most ideas are simple interactions, 2) feedback loop is critical, and 3) interfacing should be a one-step process.

Blocktopus demonstrates the feasibility of a system with self-contained plug-and-play USB MIDI modules that allow direct interfacing with a computer or microcontroller and a web-based visual programming model. Although modular electronics like *Phidgets* [39] and *LEGO mindstorms* [40] have been around for several years, Blocktopus features a separation of the sensor/actuator from the main body of the device. Thus, the physical area required to use the electronics is reduced [27]. Researchers at Stanford found that the prototypes that were developed with Blocktopus were flexible enough to try out diverse forms, and making basic functional mappings was sufficient in the web-based tool.

LightUp, much like the popular snap circuits [41], is an augmented learning platform for electronics that consists of electronic components mounted on blocks that connect to each other magnetically to form circuits [38]. The defining factor for this kit is its ability to grow with users as they gain new knowledge and skills. LightUp is low-cost and highly flexible, and represents a step in the right direction for the development of modular electronics.

C. Paper Electronics

Another project involves using paper and conductive and inductive ink to make circuits. The MIT Media Lab has developed pop-up books for children that include LED lights, motors, and switches all made of paper and conductive ink. Their aim is to make electronics accessible by using everyday items like paper [37]. These kinds of devices make the transition to making functional electronics much more intuitive. By using materials that non-experts recognize, and translating it to electronics, a topic that many find as very high level, these hobbyists and consumers have a much easier entry into an otherwise closed off market. Although the current paper electronics are used for K-6 education, paper electronics have started to appear in maker faires and spaces across the country. These electronics are modular, and although they mostly exist in art installations, they can change non-experts' perspective of finding electronic design and development unachievable.

D. Sticker Circuits

In collaboration with Microsoft, the MIT Media Lab also investigated the use of *sticker circuits* for rapid prototyping. Using conductive and insulative materials, the lab developed peel-and-stick construction of interactive electronic prototypes [42]. Their aim was to find a versatile, low-cost method to support quick and easy construction of physically flexible prototypes. The uniqueness of this research was that their stickers could easily interface with off-the-shelf components and other development platforms. Furthermore, the stickers are more targeted towards corporate and research use than STEM education use. Sticker circuits represent the first initiative in modular electronics that targets a direct use of modular electronics to develop consumer electronics. This is a crucial step to integrating modular electronics into modern technology and demonstrates the ease of integration. Old technologies can still be interfaced with these circuits, but they also offer the flexibility to replace those old technologies when an updated device is released.

AN INTUITIVE UNION

A. Gaps in the Internet of Things Consumer Products

Many design issues arise in developing a new generation of devices for the Internet of Things. For example, the wireless protocol must cover the required range while also providing flexible data rates and energy usages. Furthermore, dynamically determined trade-offs must be made between quality of service (QoS) and energy consumption. Benefits and overheads must also be considered for on-board processing [8], [43]—wherein computations are performed directly on the device gathering data—and computational offloading [44], [45]—wherein computations are performed in a remote, high performance system (e.g., on the cloud). In addition, devices must be able to handle the uncertainty and unpredictability of use [46].

IoT devices must also be flexible. Rapidly changing wireless standards and protocols frequently require new hardware (e.g., every year) [8]. However, it is impractical to redesign an entire system when one feature becomes obsolete. Different users will have different use cases and performance requirements. This variability will make dynamic adaptability of hardware critical in the success of IoT devices. Another factor to consider is the wide-reaching influence of IoT devices. These devices will reach a wider range of users, directly and indirectly, than current consumer devices. Despite the differences between these devices, they will have to interface, and these infinite different interactions are more than any current one architecture and design can handle.

There is also the consideration of power budgeting and usage. A wide range of usage means a higher need for flexible power consumption. The efficiency of the devices should be related to the application running on the IoT device and the current system state (e.g., low-battery, connection to a power source, etc.). It is impractical to have multiple different devices that are application specific in an ever-moving and mobile society. Users must be able to decide whether they want to prioritize power or speed of their devices based on the application they are using it for or current availability of power supply. Inherent non-expert participation in IoT innovation and design demands a better architecture and a better model than static hardware.

B. Leveraging the STEM Ecosystem for IoT

A solution to the current gaps in IoT consumer products is to leverage the STEM ecosystem to give students and non-experts the ability to build devices that they need. The users of a device understand their individual needs the best and should be given the tools to meet those needs instead of depending on a device designed by a third party [12]. Due to the fact that industry is at a more removed level than individual users, solutions developed by industry may not be optimally suited for the users.

The potential growth and scale of the IoT will impose concomitant overheads, such as bandwidth bottlenecks, increased latency and energy consumption. To mitigate these overheads, capabilities for *edge computing* [47], [48] will increasingly be more necessary for emerging IoT devices. For several use-cases, edge computing, which enables local computation on the IoT devices, will likely yield faster results for the end-user and relieve pressure on central computing. These local computations also make electronics globally versatile as the local processing can consider the user requirements, system conditions, environment, and computational requirements.

Enabling users to customize their electronics with application specific capabilities at their device rather than trying to do so at a central location increases the amount of active users that can be handled at a compute center. This allows for an even greater number of connected users, increasing non-expert participation, and improving the exploration of the design space.

Enabling consumers to change pieces of hardware based on application instead of having multiple devices can also extend the lifetime of devices. This would also give users the option to guest compute, or process workloads from other users who do not have the modules or are trying to save power. With modular electronics, not only would users connect to their environment, they would be able to interact and help other users, which is one of the ultimate goals of IoT. The foundation for non-expert designed electronics is already in place [1], [9]. Open-source software environments, discussion groups, hackerspaces, and makerspaces provide the support that users would need to build and develop. These user-innovators would not be limited by industry standards or bureaucratic practices. Apart from gaining a better understanding of engineering and technology, these non-expert users will be able to contribute to innovation towards realizing the IoT's full potential.

Conclusions and Future Research Directions

The maker culture, which encourages non-expert participation in innovation, is a perfect foundation for IoT innovation and development. However, the maker culture still currently lacks substantial corporate support and adequate STEM technology programs. Most of the projects and community sharing happens on dedicated websites and blog posts; the makers and non-experts rarely have access to high quality STEM education materials that would further enable them to develop their skills. Although the foundation for software development and sharing is well-established, non-expert needs for hardware development will drastically change with the growth of Internet of Things (IoT). Modular electronics will be instrumental to enabling the involvement of non-expert users in the design and development of highly efficient IoT devices.

Even though modular electronics provide a viable solution to gaps in the IoT design state-of-the-art, there are still several technology challenges that must be addressed in order to exploit the full benefits of modular electronics. For modular electronics to be dynamic and satisfy IoT applications' requirements, new architectures must be developed to enable system adaptation to workload and user requirements. For example, much research focus must be placed on developing IoT-specific memory architectures that can seamlessly interface with modular electronic components. The memory is one of the most important system components—and potential bottleneck—for high performance and energy efficiency in emerging IoT devices. Optimizing the memory for modular electronics would drastically improve non-expert users' ability to design energy-efficient IoT devices that are right-provisioned for the intended functionalities.

Another important research direction is power supplies for modular electronics. Recently, there has been a push to use renewable power sources to supply power to IoT devices. Renewable power sources can scavenge power from human activities or from other limited energy sources, such as ambient heat, light, or vibrations. While these renewable power sources can be leveraged for modular electronics, they are typically unstable and may be unreliable as the sole source of energy for mobile applications. Thus, a future research direction is to explore techniques for exploiting the synergy between these renewable power sources and traditional rechargeable/replaceable batteries in modular electronics.

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