Designing Energy Partnership Between Users and Intermittently Powered Device

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Master Thesis

Designing Energy Partnership Between Users and Intermittently Powered Devices

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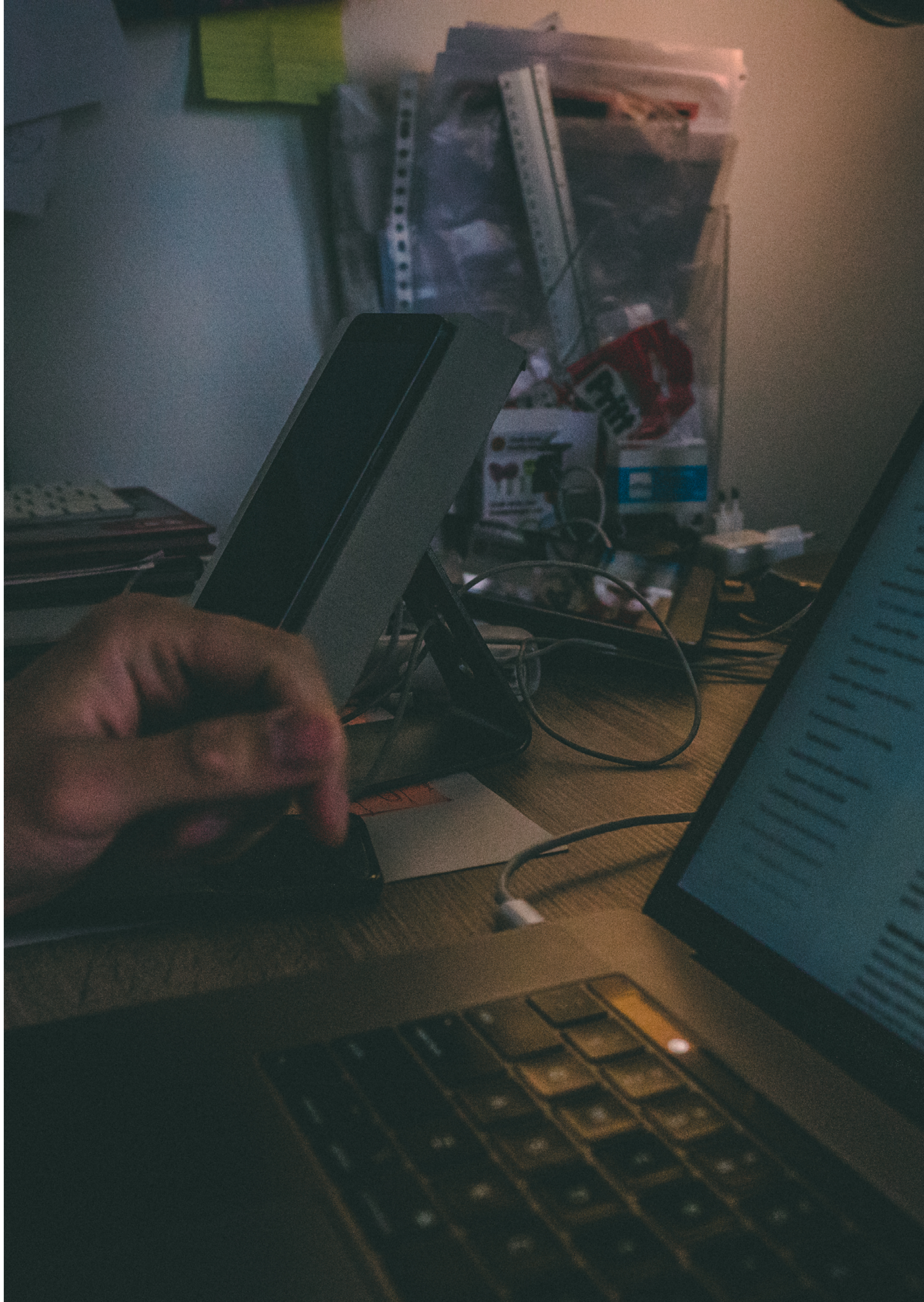
Preface

This work was carried out at TU Delft. It is my great pleasure to thank all the people who supported me during the past five months.

It's an extremely different and challenging experience to explore the project in the quarantine of Covid-19. Special thanks to the Chair and Mentor of my project: Prof. Gerd Kortuem and Prof. Elisa Giaccardi who gave me a lot of suggestions on refining the model, inspired me with resources and papers, and guided me with the excellent help for the research method, prototype testing, and model building. It's their kind help and enthusiasm towards the project that motivated me and led me to conclude the satisfactory work in such a stressful and conflict-filled moment.

Thanks to all my friends: Zhu Heming, Chu Yuxin, Yuan Jian, Ding Yiqi, Gu Shengfeng, Guo Cheng for their valuable comments, advice and encouragement. They also actively took part in the testing of this project, providing feedbacks and suggestions.

Finally, I would love to thank my girlfriend: Fang Ying who's pursuing a master degree in PoliMi. It's through numerous discussions and communication with her that I could beat the loneliness and keep up in the most difficult period.



Content

Abstract

Today's mobile devices powered by batteries have kept feeding users endless entertainment and convenience, whereas always accompanied by some unfavorable experiences that is 'Always have to recharge'. The puzzle of battery life has been an inevitable limitation that could probably degrade user experience, even though smartphones, smart homes, and smart wearables are growing ever more advanced. A new technology named 'Energy Harvesting' emerge. As an enabler of battery-less devices, it has exceptional potential in replacing the battery as the power source for future mobile devices. On the other hand, however, accompanied by enormous potential, energy harvesting will also bring tremendous concerns. Current mobile device users have equipped the knowledge of handling the limited battery life and formulated a cognition towards energy in battery-based devices. In other words, the Current Energy partnership, meaning the interactive and cognitive relations between users and energy in battery-based devices, is built on the battery capacity limitation. However, such a partnership will not be compatible with the non-battery devices in which battery life is no longer a limitation.

The central aim of this research has been to explore the current and future Energy Partnership between users and future intermittently powered devices. The Research-through-Design methodology has been employed, embracing online surveys, user interviews, prototypes design, and user tests to launch a collaborative discussion with interviewees about the possibilities of the future Energy Partnership.

From a set of user studies and a systematic integration of previous research, the current EP Model is proposed to demonstrating the interactive and cognition process between users and the energy in battery-based mobile devices. The research found that the current energy partnership can be conceptualized as a balance between user and appropriate usage time. Building on the current EP Model and insights distilled from expert interviews, a hypothetical EP Model has been developed, articulating the transformation of Energy Partnership brought by energy harvesting technology. The hypothesis was then iterated twice through designing and testing the prototype simulating the energy behavior of intermittently powered devices.

Abbreviation

Energy Partnership	**EP**
Energy Harvesting Technology	**EHT**
Battery Interface	**BI**
Energy Interface	**EI**
Human-battery Interaction	**HBI**
Human-energy Interaction	**HEI**
Internet of Things	**IoT**

Figure 1.1 - Photo took during prototype test

01

The Project

Overview

This chapter introduces the overview of the project, the research context, the project assignment, and the approach.

1.1 Introduction

Today's mobile devices provide infinite features with a pleasing experience for users that are powered by batteries. Smartphones, smart homes, and smart wearables are growing ever more advanced. However, they're still limited by power.

The battery industry hasn't advanced in decades. But we are on the verge of a battery revolution. Big tech and car companies are all too aware of the limitation of Li-ion batteries. Even if chips and operating systems are striving to be more powerful and energy-efficient, users are still dreaming of a day when they use a smartphone without having to recharge.

Energy Harvesting, as an enabler of battery-less devices, has exceptional potential in replacing the battery as the power source for future mobile devices. While the roots of Energy Harvesting technology date back over a hundred year, the growing need for innovations to power the tidal wave of IoT devices on the horizon has given it a new urgency(Smith, 2017). Armed with this energy-transferring technology, future mobile powered by ambient energy can be of any size and weight as they want without being constraint by battery capacity.

Keven Smith (2017, August 23). The Surprising Energy Set to Power the Future of Smart Devices. Jame Software. https://www.jamasoftware.com/blog/surprising-energy-set-power-future-smart-devices/

However, accompanied by its enormous potential, energy harvesting will also bring tremendous UX challenges. Current mobile device users have already equipped with the experience to tackle with battery percentage, low-power notification, and other energy-related user interfaces to their usages because battery-based devices are limited by battery life. But seldom of these user experience and knowledge would be compatible with future battery-less devices.

Given this tremendous transformation of the energy system from battery to non-battery, designers must be aware of this change and be acknowledged of how to design energy-related interactions on mobile devices accordingly. Hence, to conceive the future energy-related interactions, the whole process of Human-Energy Interactions must be explored and redescribed so that it can be utilized as background knowledge

Hi-Silicon and Nowi Energy B.V. (2020, July 2nd) NB-IoT Module Uses Energy Harvesting for Power-Free Operation. Source: https://www.everythingrf.com/News/details/10456-nb-iot-module-uses-energy-harvesting-to-provide-power-free-operation

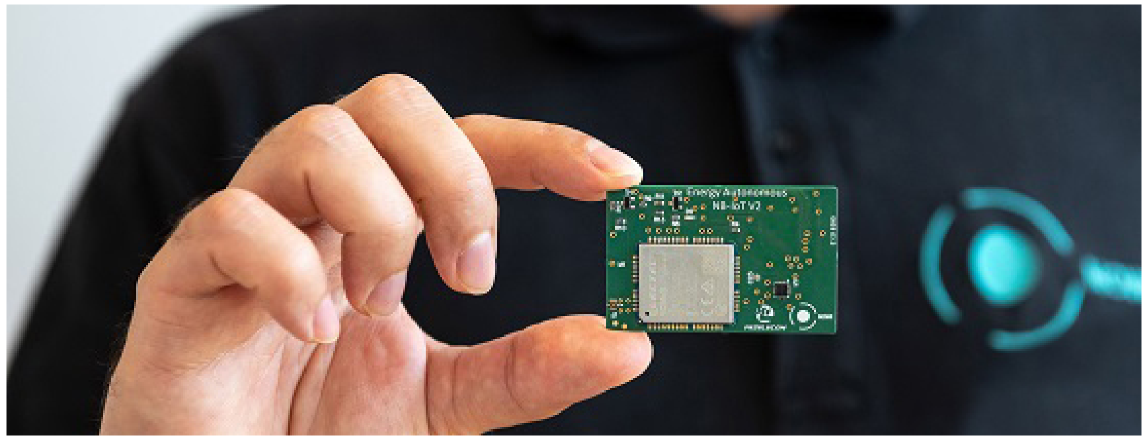


Figure 1.2 - Energy Autonomous NB-IoT platform (Hi-Silicon., 2020)

for designers.

Therefore the central aim of this project is to explore the future Energy Partnership (abbr. EP) **between users and future mobile devices powered by ambient energy.** To reach the goal, the method of "Research Through Design" has been chosen as the primary approach of this project. Through a series of user studies, a current EP for battery devices and the hypothetical EP model for the battery-less devices will be proposed. The hypothetical one will then be iterated twice by designing and testing the prototypes that simulate the energy behavior of future devices.

This thesis is built up of six chapters. Chapter 1 provides an overview of the research, setting the research objectives and approach. In Chapter 2, the context of this research is established through an exploration of theoretical underpinnings from which the framework of the EP model is drawn. From this position, the current EP Model describing user's interactions with battery behaviorally and conceptually is framed and filled in Chapter 3, with the conduction of a series of user studies.

Together with insights distilled from expert interviews, a hypothetical EP model conceiving the future relationship between users and battery-less devices is proposed in Chapter 4. With the goal of refining the assumed model, a prototype simulating the energy behavior of future mobile devices has been designed and tested, which is described in Chapter 5. Finally, Chapter 6 provides the conclusion of this research and Chapter 7 discusses the answer for the research questions and defines the contribution to new knowledge that this thesis has developed. Moreover, the limitations and implications of the research are discussed, and recommendations for further research are suggested.

1.2 Background

Harb, A. (2011). Energy harvesting: State-of-the-art. Renewable Energy, 36(10), 2641-2654.

Guilar, N. J., Kleeburg, T. J., Chen, A., Yankelevich, D. R., & Amirtharajah, R. (2009). Integrated solar energy harvesting and storage. IEEE Transactions on Very Large Scale Integration (VLSI) Systems, 17(5), 627-637.

Goudar, V., Ren, Z., Brochu, P., Potkonjak, M., & Pei, Q. (2013). Optimizing the output of a human-powered energy harvesting system with miniaturization and integrated control. IEEE Sensors Journal, 14(7), 2084-2091.

Kim, S., Vyas, R., Bito, J., Niotaki, K., Collado, A., Georgiadis, A., & Tentzeris, M. M. (2014). Ambient RF energy-harvesting technologies for self-sustainable standalone wireless sensor platforms. Proceedings of the IEEE, 102(11), 1649-1666.

Yu, H., Zhou, J., Deng, L., & Wen, Z. (2014). A vibration-based MEMS piezoelectric energy harvester and power conditioning circuit. Sensors, 14(2), 3323-3341.

For the purpose of setting the context of this project, several terms regarding energy harvesting, energy harvesting technology and energy partnership are discussed in this section.

Energy Harvesting

Energy harvesting, also known as energy scavenging or power harvesting, is the process by which energy is derived from external sources. The energy source for energy harvesters is called "ambient energy," which is present as ambient background and freely available. The main task of an energy harvesting device is converting the captured ambient energy into electrical energy and, in the next step, power consumer electronics, wireless sensor nodes, implantable biosensors, military equipment, and many more (Harb, 2011). Many different energy sources can be used for the conversion, such as:

• Light energy (solar energy from sunlight or lamps) (Guilar, 2009)
• Thermal energy (human body, industry) (Goudar, 2014)
• Radiofrequency energy (electromagnetic spectrum, antennas) (Kim, 2014)
• Kinetic energy (motion, vibration, rotation, linear movement) (Yu, 2014)
• Chemical/biological energy (osmose, diffusion, radioisotopes, redox reactions)
• Atmospheric energy (gravity changes, pressure changes, etc.)
• Hydro energy (kinetic energy from water)

Rao, Y., McEachern, K. M., & Arnold, D. P. (2013). A compact human-powered energy harvesting system. In Journal of Physics: Conference Series (Vol. 476, No. 1, p. 012011). IOP Publishing.

Vullers, R. J. M., van Schaijk, R., Doms, I., Van Hoof, C., & Mertens, R. (2009). Micropower energy harvesting. Solid-State Electronics, 53(7), 684-693.

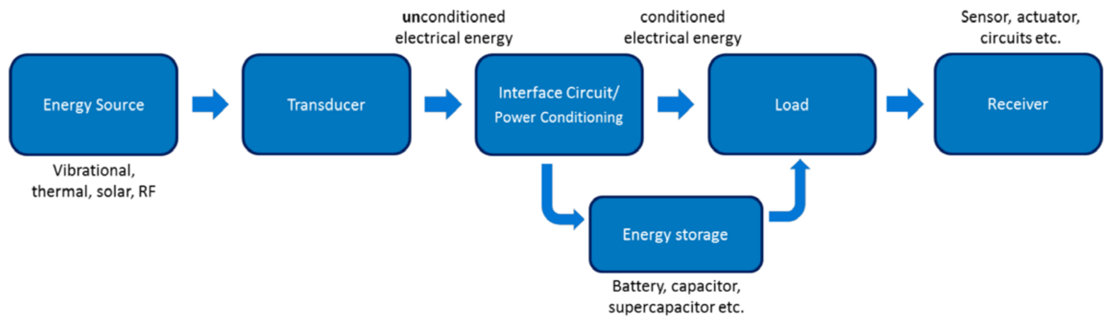


Figure 1.3 - Block diagram of an energy harvesting system. (Rao, 2014)

Energy Harvesting Technology

Energy Harvesting Technologies (abbr. EHT) can convert ambient energy, such as solar energy, thermal, vibrational, or RF energy into usable electrical energy. As illustrated in Figure X, a complete energy harvesting system comprises in its simplest form three main components:

1. A transducer,
2. An interface circuit (architecture with or without energy storage)
3. A load

The transducer is responsible for converting the energy harvested from the ambient source listed above to the electrical domain. Conventionally, the transducer is often called "energy harvester." Furthermore, the interface circuit serves to extract a maximum amount of energy from the transducer (Harb, 2011). It also makes the energy available to the load by various adjustments such as voltage rectification, voltage regulation, and other power management functions (Vullers, 2009). The load may comprise power consuming electronic devices and energy storage elements (usually capacitors and supercapacitors), as depicted in Figure 1.3.

Potentials and Challenges

EHT has exceptional potentials of powering tiny sensors in the built environment, IoT devices, and wearables. And current Research on EHT focusing on improving the size and efficiency of harvester that provide power ranging from 10 microWatt to 1 Watt, in which most sensors and IoT devices are predominantly found (Figure 1.4).

Figure 1.5 shows the many applications for batteryless sensors in the built environment, specifically homes. These invisible, cheap sensors, can harvest indoor light, RF signals, vibrations or heat from appliances, or even energy from footsteps to power their tasks.

Another example shown in Figure 1.6 are the potential sensors and their purpose deployed in a batteryless body-area network. These tiny devices unobtrusively monitor the health and wellness of a worker or patient. They can provide interventions from medical care providers, managers, or automatically—while assisting and interacting with the wearer from a smartwatch hub.

Ünlü, F., Wawrla, L., & Diaz, A. (2018). Energy harvesting technologies for IoT edge devices. 4E, Int. Energy Agency, Paris, France.

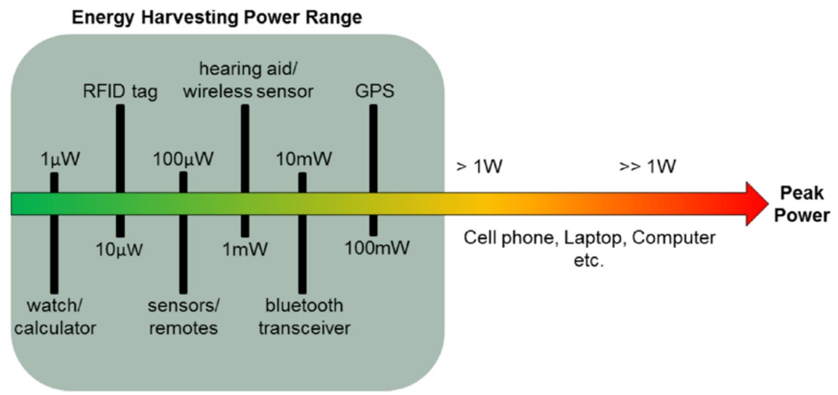


Figure 1.4 - Power consumption overview of devices incl. energy harvesting power range (Ünlü, 2018).

To implementing energy harvester on these applications, several technological requirements on EHT must be considered.

• **Power**

First of all, the energy harvester should supply at least milliwatts of power from the device's environment. In Figure 1.7, an overview of different EHT with their available power range. On the other hand, the suitable range for IoT devices and sensors is from 0.1 microWatt to 1 Watt. As illustrated in Figure 1.7, the feasible power generation range of an energy harvesting device (with photovoltaic cell) with a manageable size should be up to 500 microWatt. Addtionally, since energy supply and demand may come at different times, in practice, a temporary energy buffer (e.g., supercapacitor) and power management electronics are necessary to effectively deliver the energy from the harvester to the IoT edge device.

• **Size**

With the progress in integrated circuit design, integrating more electrical components into one microchip, the size of the device is no longer the bottleneck of the system. The battery, which powers such devices, often dominates the size and weight of the system. Energy harvester, as the alternative to the battery, suppose to ideally not take up more space than the previous source.

Hester, J., & Sorber, J. (2017, November). The future of sensing is batteryless, intermittent, and awesome. In Proceedings of the 15th ACM Conference on Embedded Network Sensor Systems (pp. 1-6).

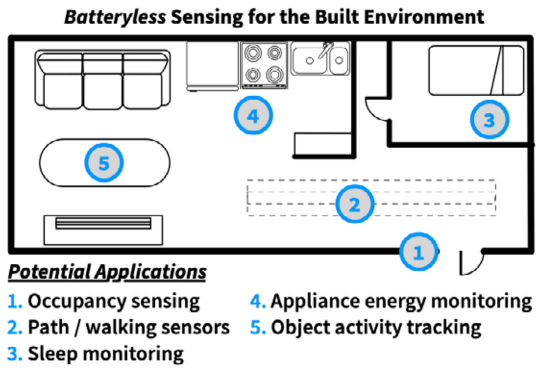


Figure 1.5 - This figure shows the many applications for batteryless sensors in the built environment, specifically a home (Hester, 2017).

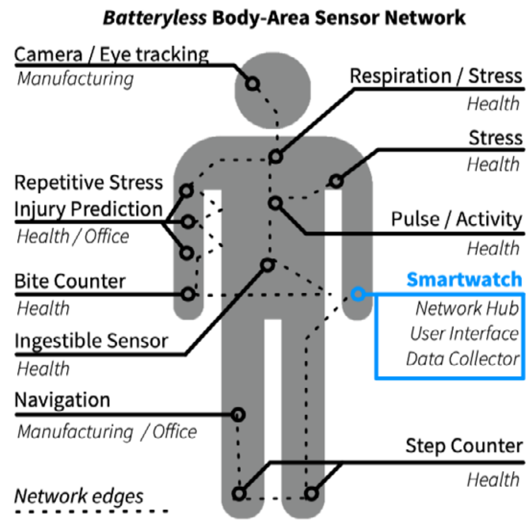


Figure 1.6 - This figure shows the many applications for batteryless sensors in the built environment, specifically a home (Hester, 2017).

Besides the technology requirement, EHT will also bring a significant challenge for battery-less devices that execute specific tasks and users who interact with it-Intermittent Operation.

P. Harrop,(2017) Introduction to Energy Harvesting & Off-Grid Renewable Energy,» in IDTechEx Show! Emerging Technologies Unleashed, Berlin

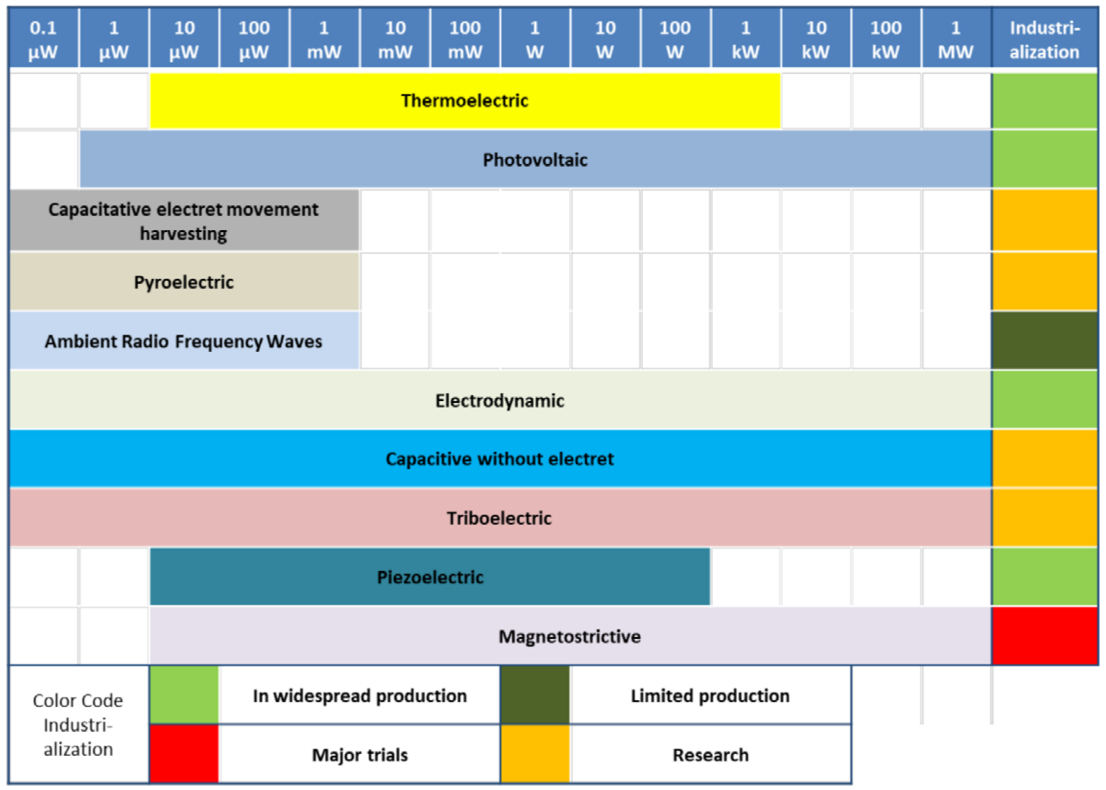


Figure 1.7 - State of EH technologies and their generated intermittent power (Harrop, 2017).

Intermittent Operation

Battery-less devices harvest and buffer energy as it is available and operate when sufficient power is banked. However, operations like harvesting and buffer energy in these devices are intermittent because energy is not always possible to harvest. Even when electricity is available, buffering enough power to do a useful amount of work takes time. Therefore, battery-less devices will behave like "a few seconds on and a few seconds off," also termed as Intermittent Operation (Hester, 2017), which is a tremendous challenge faced by both developers and users. Battery-less devices, therefore, violate one of the most basic computing assumptions—a stable power supply. Energy harvesting is inconsistent, energy storage is scarce, power failures are inevitable, and execution is intermittent. As shown in Figure 1.8, the energy level harvested by EHT will drop unexpectedly and then gradually accumulate to reach the device's threshold to execute tasks, resulting in the battery-less device being powered intermittently.

For developers who develop applications on intermittently powered devices, fragmented variable-length execution needs to combine into useful work; For users, it would bring extreme confusion and anxiety if devices were behaving unexpectedly on and off considering users have deal with battery-based devices for a long time. More Details of EHT can be found in Appendix B.

Hester, J., & Sorber, J. (2017, November). The future of sensing is batteryless, intermittent, and awesome. In Proceedings of the 15th ACM Conference on Embedded Network Sensor Systems (pp. 1-6).

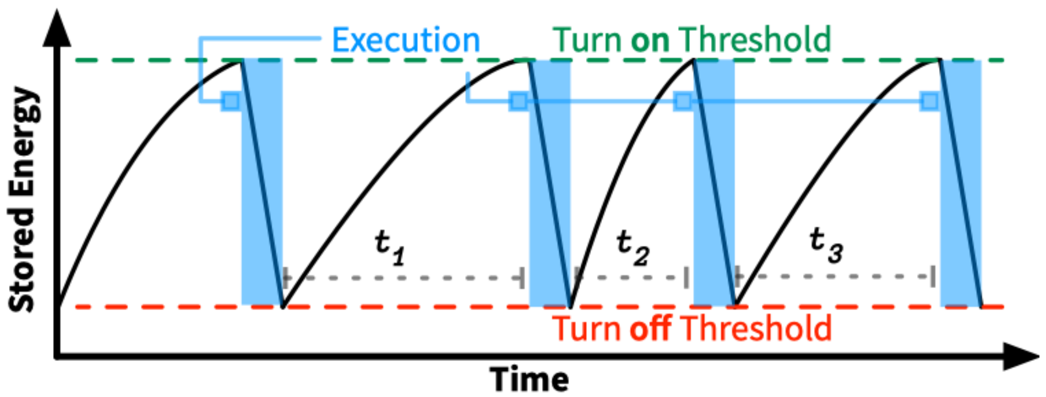


Figure 1.8 - A typical intermittent execution pattern for a batteryless sensor. Energy availability depends on environmental conditions and sensor behavior (Hester, 2017).

Human-Energy partnership

Rahmati, A., Qian, A., & Zhong, L. (2007, September). Understanding human-battery interaction on mobile phones. In Proceedings of the 9th international conference on Human computer interaction with mobile devices and services (pp. 265-272).

Smart devices have been using batteries as the only measure to recharge and dissipate energy recurrently. Consequently, users have been accustomed to deal with limited battery life through a reciprocal process that can be conceptualized as Human-Battery Interaction Model (Rahmati, 2007) (More on Page 37). Nevertheless, concerning the transformation from battery to energy harvesting, every energy-related interactions and interfaces that users have experienced for decades will no longer be applicable, resulting in the radical change of users on the interactive and conceptual level. Thus a future Human-Energy Partnership needs to be conceived behaviorally and conceptually so as to provide a profound understanding of energy interactive process on energy harvesting devices for designers.

1.3 Assignment

Problem Definition

• Design Aspect
Firstly, The current human-battery interaction model is not suitable for describing the energy partnership between users and battery-less devices. Users have been accustomed to perceive energy level through numeric percentage indicator, charge through cable or wireless charger, and trading off an extension of usage time against usability. However, part of the battery interfaces such as battery percentage indicator and low-battery notification will no longer be applicable for future battery-less devices. What's more, the intermittent operation brought by the EHT violates assumptions of most established UX and interaction models.

• Technical Aspect
Ideally, the user may no longer need to pay attention to energy since the ambient energy is adequate enough to support the use. However, in practical life, the energy supply of energy harvesters will be intermittent, dynamic, and unpredictable, contrary to what users have been experienced using battery-based devices. Therefore, the technical aspect of EHT will have an impact on how users interact with and see energy, resulting in the formulation of a new energy partnership.

Concluding, the problem statement of the thesis is:

1. The current battery-based energy partnership is no longer suitable for battery-less devices because of the incompatibility of the current interaction model and the lack of experience for users dealing with battery-less devices.

2. The intermittent, context-sensitive, and dynamic energy supply of energy harvesters will1 have a significant impact on the current energy partnership

Objectives

The project aims to formulate the future human-energy partnership between users and intermittently powered devices. In order to reach the goal, two research themes will be covered: the current battery-based EP and future battery-less EP. Therefore, two main research questions are formed:

1. How to depict the current human-energy partnership between users and battery-based devices?

2. How will the future human-energy partnership between users and battery-less devices be?

Assignment

With the goal of solving the problem mentioned before, the project focuses on building the future EP Model, demonstrating the relationship between users and future intermittently powered devices interactively and conceptually. The model should exhibit the external and internal procedures of users interacting with future mobile devices, reveal the transformation of user reacting to two different energy systems, thus serve as a guide for designers to understand the change so as to design proper applications and energy interactions on intermittently powered devices.

Outcomes

The report includes a review on the previous literature and a set of user studies, including an online survey, user and expert interviews, which was the fundament for the conceptual model summarizing the future EP. The model is dedicated to the exploration of future EP on both levels of behavior and perception.

• The model should clearly indicate the conceptualized process of human energy interactions between users and intermittently powered devices.

• The report forms a stepping stone for the model development by sensing and seizing insights around future contexts.

• The model should provide a profound understanding of the human-energy interactive process and thus serve as fundamental knowledge for designers who create energy-related designs on mobile devices.

1.4 Approach

Research through Design

This thesis has employed an RtD research methodology. RtD stands for the research methodology in which design activities that play a formative role in the generation of knowledge. Any typical actions could be recognized as design activities from one of the design professions, that depends on the professional skills of designers such as gaining actionable understanding of a complex context, framing and reframing it, and iteratively developing prototypes that address it (Stappers, 2017).

Stappers, P. J., & Giaccardi, E. (2017). The Encyclopedia of Human-Computer Interaction.

The most commonly-used design activities involved in an RtD process is the development of a prototype (or artifact), which means an object created during a design process that can realize the action that is studied. Either a sketch on the paper, a diagram summarizing the interaction flow, or a prototype that enables someone to interact and experience could be called an artifact. In this thesis, the development of prototypes that simulates the energy behavior of intermittently powered devices is regarded as the design activities to generate knowledge of how users will react to the new energy system and iterate on the hypothetical future EP.

RtD approach was chosen because this is a future-oriented thesis requiring knowledge and insights from a product that does not exist and needs to be realized in some form. Therefore, the prototype created in RtD provides the possibility of reflection and iteration of unproven knowledge and theory that is hard to get in other approaches.

Research Structure

Figure 1.9 shows the research structure of this whole project. The current EP model is formulated through user studies and literature review. Then two pivotal roles of EHT is extracted, and a hypothetical EP model is proposed. The hypothesis is iterated twice with prototype designing and testing. Finally, the final EP model depicting the relationship between users and battery-less devices concludes this project.

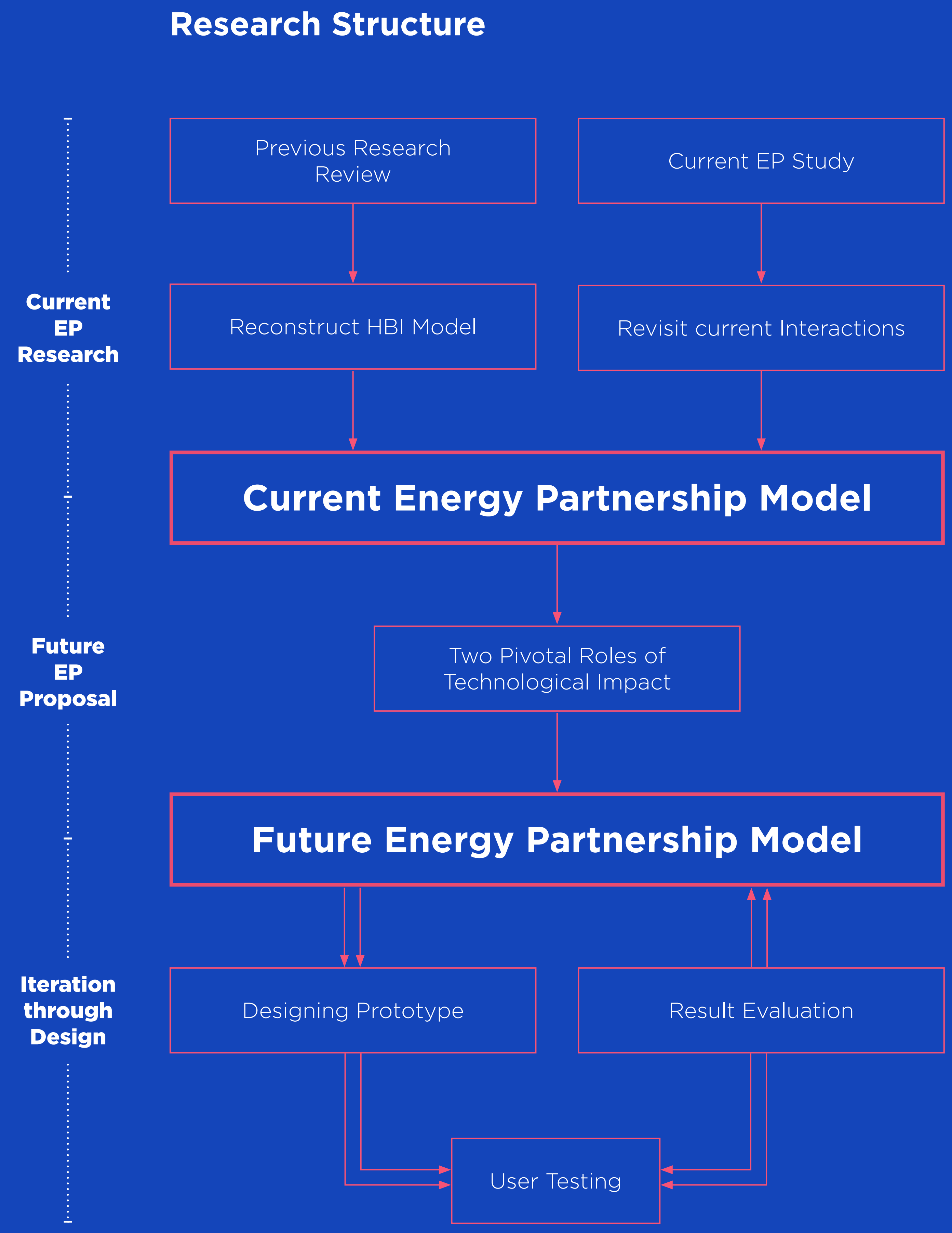


Figure 1.9 - A diagram showing the research structure of the whole thesis.

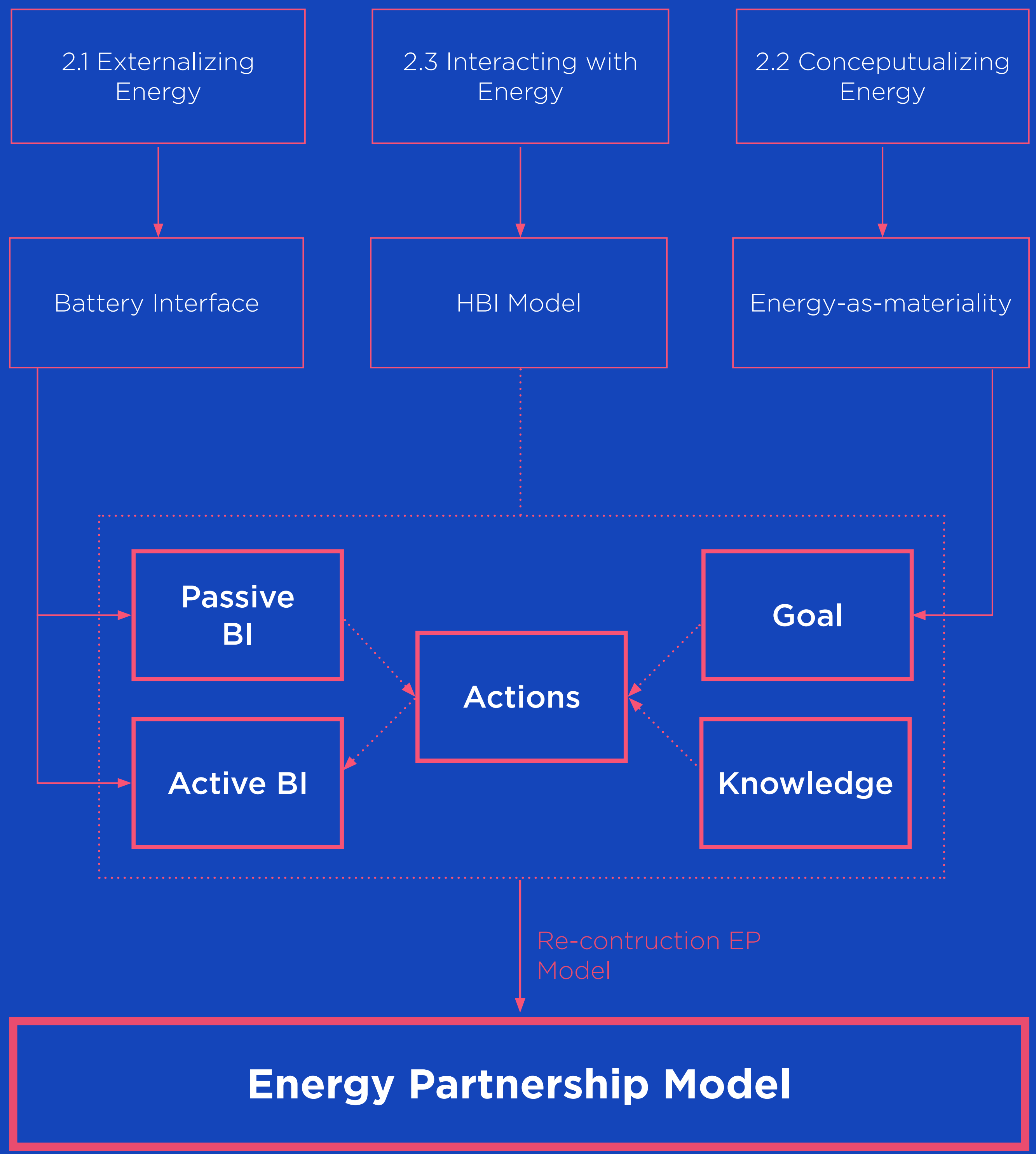


Figure 2.1 - A diagram showing the research structure of Chapter 2.

02

Literature Review

Overview

In this chapter, two perspectives of energy study: energy as manifestation and energy as ideology, together with a model explaining HBI are covered. Firstly, concepts of battery interfaces are outlined, and a broader, theoretical view of articulating energy as materiality is spread. Additionally, a conceptual model describing the process of HBI is provided. Finally, the research context, scope, and method of this project are set based on the HBI Model as well as two perspectives that have been undertaken.

2.1 Externalizing Energy

Energy-as-manifestation

One of the main views of understanding EP is to look at its manifestation, energy interface, or specifically, battery interface(abbr. BI). The main research approach of such perspective is through conducting user studies on existing BI or designed BI to validate its efficiency, usefulness, and to see if they match the user's needs for battery management. Previous research has mostly focused on extending battery life or optimizing its use through creating new applications that provide new ways of managing batteries, including Task-Centered Battery Interface(Truong, 2010), Carat (Oliner, 2012), PowerBooter (Zhang, 2010), and Powerlet (Jung, 2014). Since this project is focused on the energy partnership rather than its manifestation, valuable insights will be extracted from their research methods, process, and conclusions in order to set the scope and context of this project.

Truong, K. N., Kientz, J. A., Sohn, T., Rosenzweig, A., Fonville, A., & Smith, T. (2010, September). The design and evaluation of a task-centered battery interface. In Proceedings of the 12th ACM international conference on Ubiquitous computing (pp. 341-350).

Oliner, A. J., Iyer, A., Lagerspetz, E., & Tarkoma, S. (2012). Collaborative energy debugging for mobile devices. In Presented as part of the Eighth Workshop on Hot Topics in System Dependability.

Zhang, L., Tiwana, B., Qian, Z., Wang, Z., Dick, R. P., Mao, Z. M., & Yang, L. (2010, October). Accurate online power estimation and automatic battery behavior based power model generation for smartphones. In Proceedings of the eighth IEEE/ACM/IFIP international conference on Hardware/software codesign and system synthesis (pp. 105-114).

Jung, W., Chon, Y., Kim, D., & Cha, H. (2014, September). Powerlet: an active battery interface for smartphones. In Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing (pp. 45-56).

Two Types of BI

BI, according to Jung, is "a function intended to help ease energy-related problems via user intervention."(Jung, 2014) The BI includes an indicator of the device's power status and interfaces to adjust the power-related variables. Users may take adequate actions with regard to power consumption based on the energy usage information provided by their BI. Therefore, BI is defined by its functions. The purpose of BI is to help users address the battery issues. However, as is claimed by a variety of researchers, the BI that mobile operating systems provided had not kept pace with user interest in battery issues, which means system native BI failed to help users taking actions to address energy issues.

With the goal of solving such a problem, Jung, the same as other BI researchers, conducted a survey evaluating the usability and usefulness of system BI in 2014. He found that many users do not utilize BI features(battery indicator excluded) even though the function is provided. Respondents expressed dissatisfaction with the accuracy or types of information, but were highly satisfied with the alarm and power-saving features.

Therefore, based on the implications derived from the survey, Jung categorized two types of BI triggering different interactions: passive BI and active BI, defined as follows:

• With a **passive BI**, the user triggers a set of interactions with the device. The user decides when to interact with the interface and when energy-related information is viewed, and accesses to the information in a "pull" manner.

• With an **active BI**, the device initiates a chain of interactions. The device alerts the user at appropriate moments and displays a range of information that the user needs to be aware of; that is, the information is delivered to (or notified to) the user in a "push" manner.

Jung argued that users greatly preferred the active BI compared to passive BI, and proposed Powerlet, an improved BI that emphasizing more on active interaction type. Further research and test revealed that users behaved more energy-efficient while using Powerlet. (More on Page 36)

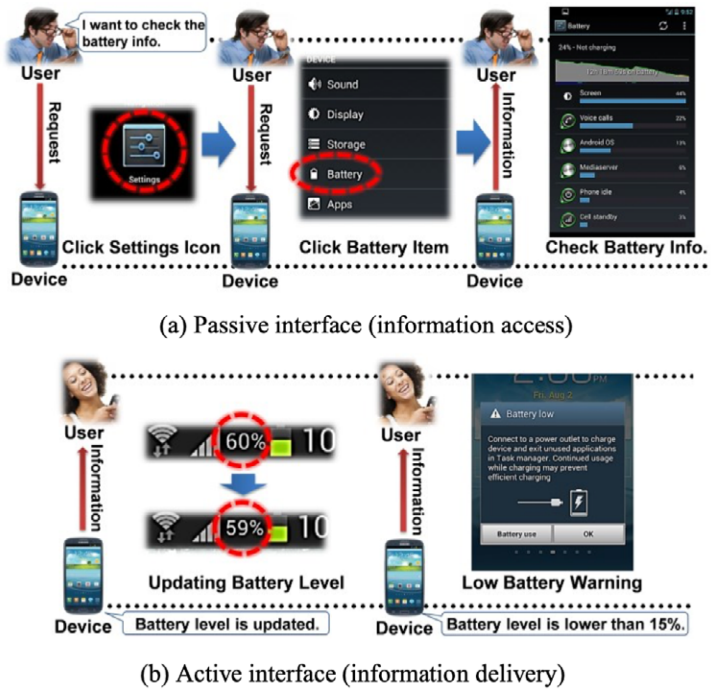


Figure 2.1 - Types of interaction between BI and user (Jung, 2014).

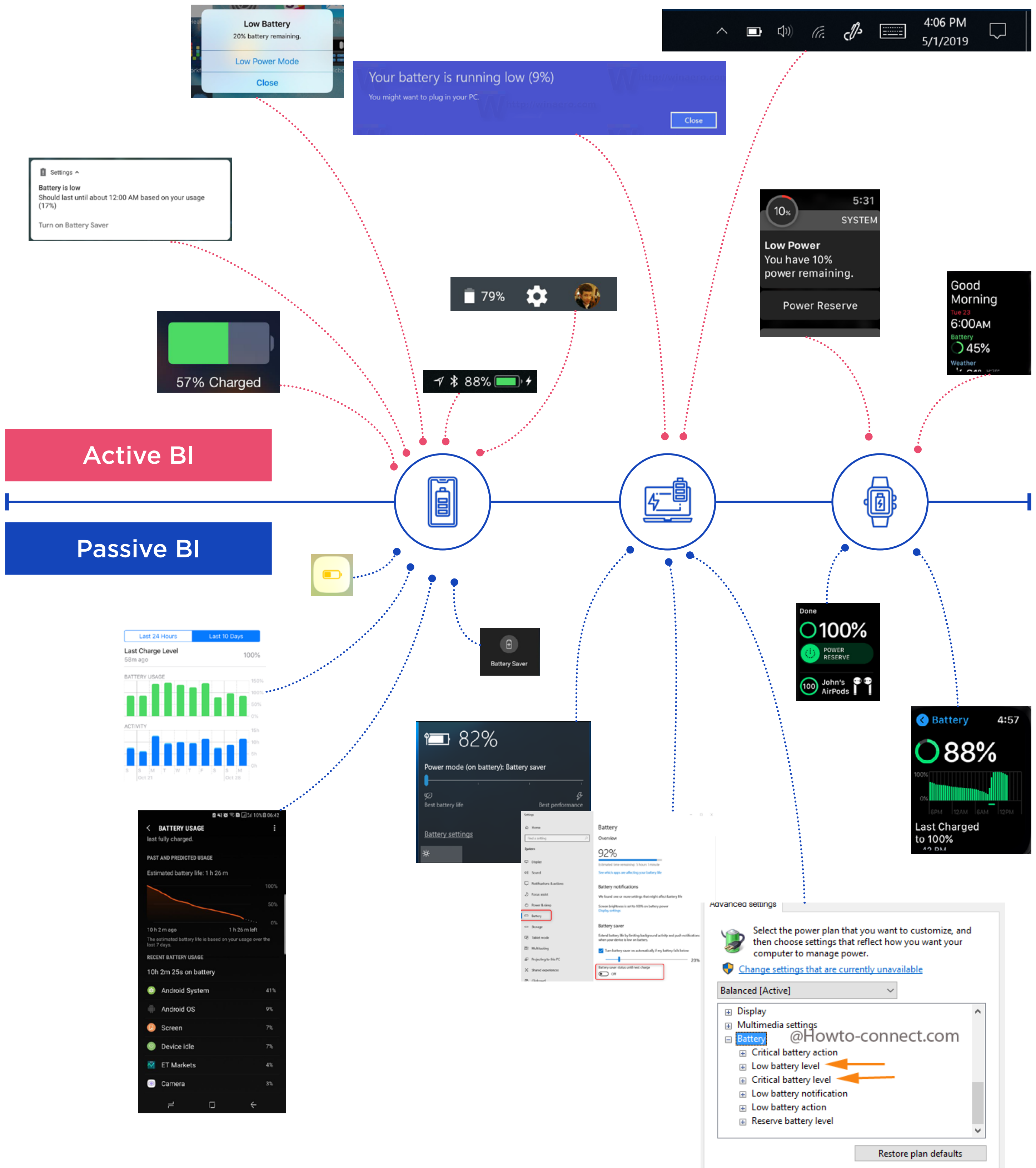


Figure 2.2 - Matrix of Two Types of BI on different devices.

Applying to current BI

Verify Jung's theory of categorizing BI, an application on the current BI is developed. As is shown on the left, this diagram presents basically every energy-related interface of different mobile devices, including mobile phones, tablets, watches and laptops. The top side shows a group of BI that can be categorized as Active BI, and the bottom side shows the opposite. It can be concluded that most of the modern BI still fall into the category of Active and Passive, confirming that this categorizing theory is still effective and viable now.

A Different Context

It should be underlined that the BI research had been limited in a battery life shortage context. Researchers focusing on proposing new BI from 2010 to 2015 were all based on the precondition that users were facing the issue of battery life shortage and willing to play a proactive role in lengthening battery life.

However, it appears to no longer be the case. A piece of clear evidence is the evolution of battery life in a decade (Figure 2.3). While Apple's 2013 flagship phone, iPhone 5s, lasted around 5 hours and 46 minutes under normal usage (Prospero, 2014), the 2020 iPhone 11 Pro Max has 20 hours of video playback (SPoonauer, 2020). Mobile phone users in 2020 no longer face the same issue as 2013 users who still need to charge their phones within a day's usage. BI on mobile devices, on the other hand, has not changed a lot. Mobile operating systems still offer users with active BI as battery percentage indicator and Low Power Mode, and passive BI as Battery Usage. Therefore the BI on mobile devices and its relation with energy interactions needs to be revisited in this project.

Additionally, mobile devices are also bringing countless applications with exceptional experience, amplifying its significance in the user's daily life. Computational chips and software have also evolved multiple times, becoming more powerful and energy-efficient (Wikipedia contributors, 2020). Users also charge their devices differently. Those transformations on the mobile device itself and the way users utilize their devices should also be taken into consideration in this project.

Mike Prospero. (2014, September) iPhone 6 and 6 Plus Battery Life: How Long They Last. https://www.tomsguide.com/us/iphone-6-battery-life,news-19591.html

Mark Spoonauer. (2019, September) iPhone 11 Pro Max Review. https://www.tomsguide.com/reviews/iphone-11-pro-max

Wikipedia contributors. (2020, August). Apple-designed processors. Wikipedia. https://en.wikipedia.org/wiki/Apple-designed_processors#Apple_A10_Fusion

Benjamin Mayo. (2020, April). iPhone battery life compared: How does the new iPhone SE stack up? https://9to5mac.com/2020/04/16/iphone-battery-life-compared/

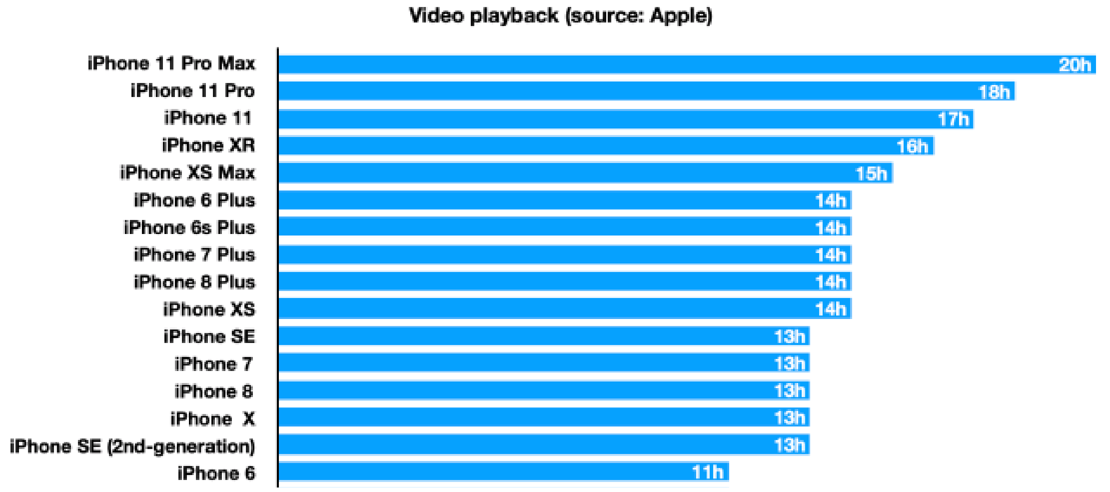


Figure 2.3 - iPhone's Battery life Evolution From 2014 to 2020 (Source: 9to5Mac)

2.2 Conceptualizing Energy

Energy-as-ideology

Another perspective to articulate EP between the user and mobile device, yet was rarely mentioned, is energy as ideology. This is a point of view normally motivated and informed by perspectives on sustainability and design, discussing the conceptualization of energy in people's mindset.

Verbeek, P. P. (2006). Materializing morality: Design ethics and technological mediation. Science, Technology, & Human Values, 31(3), 361-380.

Philosopher of technology Peter-Paul Verbeek elaborated that interactive technologies play the role of mediator of user's perceptions of and then relationships with and within the world (Peter-Paul Verbeek, 2006). Interactive products or systems can be designed to mediate user's actions and perceptions in the way designers demand, sustainability for instance. As for this project, therefore, it is essential to explore the conceptual aspect of energy through investigating the energy technology itself so as to reach the current EP as well as envision the future one.

Pierce, J., & Paulos, E. (2010, August). Materializing energy. In Proceedings of the 8th ACM Conference on Designing Interactive Systems (pp. 113-122).

James Pierce draws on a diverse body of scholarly works related to energy and materiality to articulate a perspective on energy-as-materiality. Three critical themes of energy technology were developed through the combination of critical investigation and design exploration, which will be discussed next.

The Intangibility of Energy & Background Relationship

A common sense among designers and researchers interested in sustainability and energy is that energy is "invisible." However, the energy that people consume every day for powering devices, homes, and cities is not simply perceptually invisible but indeed **intangible** (Pierce, 2010). Energy consumers are unaware of energy with the reason that it does not have (and

Pierce, J., & Paulos, E. (2010, August). Materializing energy. In Proceedings of the 8th ACM Conference on Designing Interactive Systems (pp. 113-122).

Figure 2.4 - Energy Memento Prototype. Crank-Sound Box. Turning the crank on one face records sound using energy collected from cranking; turning the crank the opposite direction plays the recorded sounds through the speaker on the opposing face (Pierce, 2010).

Figure 2.5 - Energy Memento Prototype. Light Jar. The jar collects solar or other light energy; opening the jar activates the energy as a glowing light (Pierce, 2010).

Figure 2.6 - Energy Memento Prototype. Shake-Light Bottle. Shaking the bottle collects energy; removing the cap activates the light energy (Pierce, 2010).

Ihde, D. (2004). Philosophy of technology. In Philosophical problems today (pp. 91-108). Springer, Dordrecht.

is not designed to have) a strong tangible presence in daily lives. The interactions people can take with electricity, for example, is limited primarily to plugging a cord into an outlet. Consequently, the user's relationship with energy, as well as most infrastructural technologies supporting it, may be said to be constituted in what philosopher of technology Don Ihde describes as a **background relation** (Ihde, 1998). Through background relations, energy technology is present to users only to the extent that it helps shape the context of experience; users do not directly and consciously perceive them. Example of design concepts are shown on Figure 2.4, 2.5, and 2.6.

Drawing Energy

At SuslabNWE's research 'Drawing Energy,' 180 images were collected, presenting a diverse, multi-faceted, and highly personalized picture of 'energy.' The abstractions way of drawing together with a diverse of objects involved in these images proofs the intangibility of energy as a concept in people's mind.

Bowden, F., Lockton, D., Gheerawo, R., & Brass, C. (2015). Drawing energy: Exploring perceptions of the invisible. London: Royal College of Art.

A group discussion was held for the students to explore the themes that emerged

The ArtScience Prize students displayed their drawings on the wall

The drawing materials used by participants at the V&A

Figure 2.7 - Energy-as-materializy design example (Bowden, 2015).

The Undifferentiatedness & Availability of Energy

Pierce, J., & Paulos, E. (2010, August). Materializing energy. In Proceedings of the 8th ACM Conference on Designing Interactive Systems (pp. 113-122).

Current, centralized energy management employing large-scale power plants and distribution networks tend to position all energy as the same, differentiated only by quantity (e.g., kilowatt-hour) and other metrics related to power (e.g., voltage, amperage). **Users' experiences of energy-consuming do not exhibit significant differences, types, or qualities of energy.** Once user's devices are connected, energy does not matter that much as long as it continuously power users' devices. Hence Pierce claimed that from the perspective of energy usage, all energy is essentially the same—and it is this way by design.

Furthermore, it is underpinned by Pierce that electrical or other forms of consumable energy are becoming more and more accessible. The occasional event in which energy becomes unavailable when gasoline prices surge, a power line is down, or users forget to bring a power bank when traveling—are often the only hints at the otherwise unremarkable availability of energy(Pierce, 2010).

Energy-as-materiality

Finally, as a challenge to the intangibility, undifferentiatedness, and availability of energy as it is discussed before, Pierce proposed a perspective of energy-as-materiality and a design approach aimed at materializing energy, which is an approach that takes the design of energy-related interactions as something tangible as a starting point. **The notion of energy-as-materiality allows sustainable-oriented interaction designers to re-conceptualize and re-design how users will think about and interact with energy and energy-related technologies.**

Discussion

Put aside the stand of sustainability and design, energy, just as Pierce articulated, has been taken by people as a steady image because of the limited way of interactions exposed to its user. And such a conceptual image is inherited and influenced on how users interact with the energy in their mobile devices, mediated via BI. Therefore, it is crucial to reflect on the battery-based energy system (and energy harvesting system later on) in devices with the above three themes elaborated above in this project(More in page 73).

2.3 Interacting with Energy

Energy-as-reciprocity

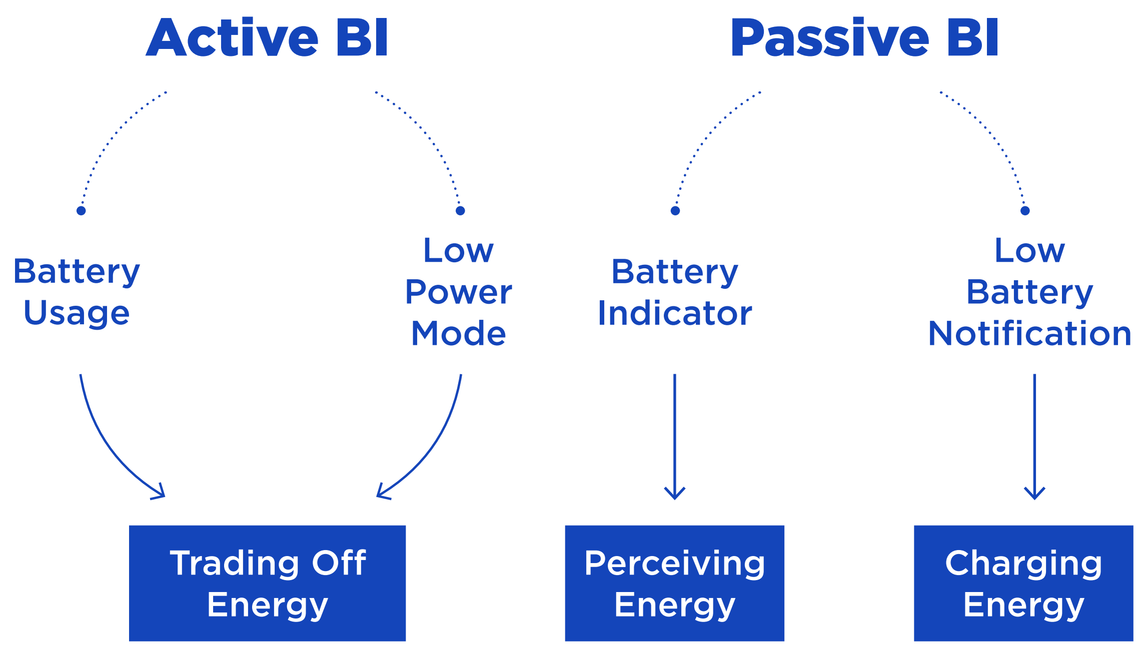


Figure 2.8 - From BI to Three Energy-related Actions

Three Energy-related Actions

As mentioned before, Jung's categorization towards BI(passive and active BI) not only serves as a way of categorizing the BI, but also indicates the relations between different BI with their capacity for interactivity. Passive interfaces, such as Low Power Mode and Battery Usage, enable users to take control of the energy in devices to their usage, and thus actively trade off part of the usability even functionality for an extension of battery life. Active interfaces, such as Battery Indicator, display energy information that the user needs to be aware of and notify users when the battery needs to be recharged. Therefore, based on the classification of BI, three energy-related actions can be drawn (Figure 2.8).

- **Perceiving Energy**: Users perceive the energy level of their devices passively(Low Battery Notification) or actively(Battery Indicator), which was the process of interacting with active BI.

- **Trading Off Energy**: Users actively sacrifice part of the usability, such as background mail fetch, screen brightness, or even functionalities, to exchange for an extension of battery life. This type of behavior is enabled by passive BI, including Low Power Mode, Battery Usage, and possibly other settings like screen brightness, which are manually operated by users based on their knowledge.

- **Charging Energy**: Users recharge their devices in order to maintain their follow-up usage, which is notified through active BI.

Rahmati, A., Qian, A., & Zhong, L. (2007, September). Understanding human-battery interaction on mobile phones. In Proceedings of the 9th international conference on Human computer interaction with mobile devices and services (pp. 265-272).

While the perspective of Energy-as-manifestation focusing on BI and its usefulness, Rahmati presented a comprehensive view of understanding how users deal with limited battery life and interact with energy and illustrated it as Human-Battery Interaction(abbr. HBI) Model in 2007, which will be discussed next.

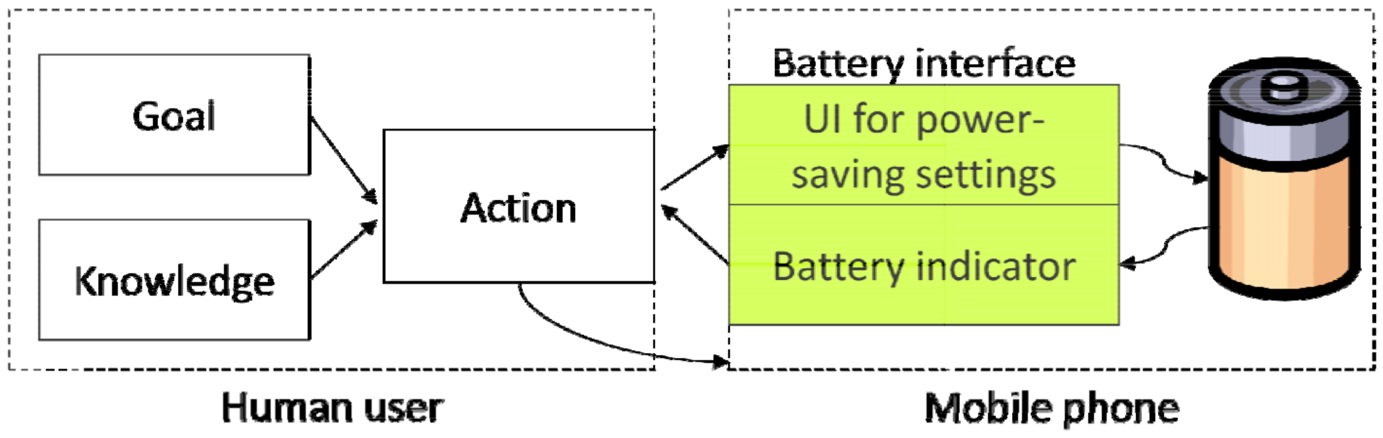


Figure 2.9 - Proposed conceptual model for HBI (Rahmati, 2007).

Rahmati, A., Qian, A., & Zhong, L. (2007, September). Understanding human-battery interaction on mobile phones. In Proceedings of the 9th international conference on Human computer interaction with mobile devices and services (pp. 265-272).

The Contribution & Limitation of HBI Model

Rahmati proposed an HBI model and elaborated it as "The user reads the battery indication and evaluates the situation with their knowledge of system power characteristics and their goal in using the phone. The user then changes their usage pattern and the phone's power-saving settings in the hope of meeting the goal. (Rahmati, 2007) "From the description above, it can be seen that Rahmati recognized his model as a conceptualization of the whole HBI interactive process, involving passive & active BI performing as the energy mediator, actions as the user's interactions towards BI, and goal & knowledge as the cognitive process.

One of the notable contributions of HBI Model is that it indicates that the study of HBI should include the investigation of user knowledge and cognitive process, of how mobile users set goals in battery lifetimes and prioritize different aspects of usability, the design of BI, and how users employ it (Rahmati, 2007). However, considering the limitation of context plus the antiquated data, **the accuracy and integrality of the HBI model is questionable.**

Although the classification BI has not changed that much, the evolution of the user's knowledge and experience about energy and BI has been considerably progressing on account of the spread of smart devices. Hence the "actions" in the HBI model also become more and more diverse, corresponding to the adaptation of different types of devices and use scenarios. The rest of the thesis will demonstrate using Rahimate's HBI Model as the base framework to develop the Current and future EP Model.

Figure 2.10 - The base framework for EP Model(refined from Rahimati's HBI Model)

Summary for Literature Review

To sum up this chapter, a summary of the literature review is delivered below to extract the key points. The diagram on the next page visualized the mind process of summarizing and the plan for the next step. More details on the other papers not mentioned in this thesis on be found in Appendix C.

Pierce, J., & Paulos, E. (2010, August). Materializing energy. In Proceedings of the 8th ACM Conference on Designing Interactive Systems (pp. 113-122).

Rahmati, A., Qian, A., & Zhong, L. (2007, September). Understanding human-battery interaction on mobile phones. In Proceedings of the 9th international conference on Human computer interaction with mobile devices and services (pp. 265-272).

Jung, W., Chon, Y., Kim, D., & Cha, H. (2014, September). Powerlet: an active battery interface for smartphones. In Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing (pp. 45-56).

• Energy-as-manifestation

Jung categorized two types of BI triggering different interactions: Passive BI, which is triggered by the user and provide information in a "pull" manner, and Active BI, which is initiated by the operating system alerting users at appropriate moments and displays energy-related data that the user needs to know (Jung, 2014). Such classification is still viable in the current BI on diverse devices. This theory's significance is that it indicates the relations between different BI with their capacity for interactivity.

• Energy-as-ideology

James Pierce articulated three critical themes of energy in his research: Intangibility, Undifferentiatedness, and Availability, discussing the relations between the energy technology and people's conceptual attitude towards energy. For the intangibility of energy, Pierce brought out the point that the energy that people consume every day for powering devices, homes, and cities is not simply perceptually invisible but indeed intangible (Pierce, 2010). Undifferentiatedness, on the other hand, referred to users' experiences of energy-consuming do not exhibit significant differences, types, or qualities of energy. Finally, the Availability of energy represents the trend of consumable energy are becoming more and more accessible.

• Energy-as-reciprocity

Rahmati presented a comprehensive model called HBI Model (Rahmati, 2007), illustrating how users deal with limited battery life and interact with energy. He outlined the relationship between human and in-device energy into five characters: UI for power-saving settings (Passive BI), Battery indicator (Active BI), Action, Goal, and Knowledge.

The Next Step

The literature review serves as a recap of different perspectives that previous researchers viewed the user-energy partnership and points out the next step that this project needs to accomplish to resolve the research questions.

• Revisit User Action

First, to understand the partnership between the current user and mobile devices, how users are interacting with the energy should be revisited. Since most of the studies on BI were conducted five years ago, it is necessary to revisit the actions that current users take towards in-device energy.

• Reconstruct the EP Model

As mentioned before, one of the notable contributions of HBI Model is that it indicates the study of HBI should include the investigation of user knowledge and cognitive process. However, considering the limitations of context and outdated data, a new EP Model must be reconstructed to summarize the relationship between current users and energy in devices.

• Rebuild Conceptualization

The conceptual image in people's mind is inherited and influenced on how users interact with the energy in their mobile devices. Therefore, another aspect that needs to be included in the new EP Model is the conceptualization of energy. A vizualization of the summary and the next step can be found on the next page.

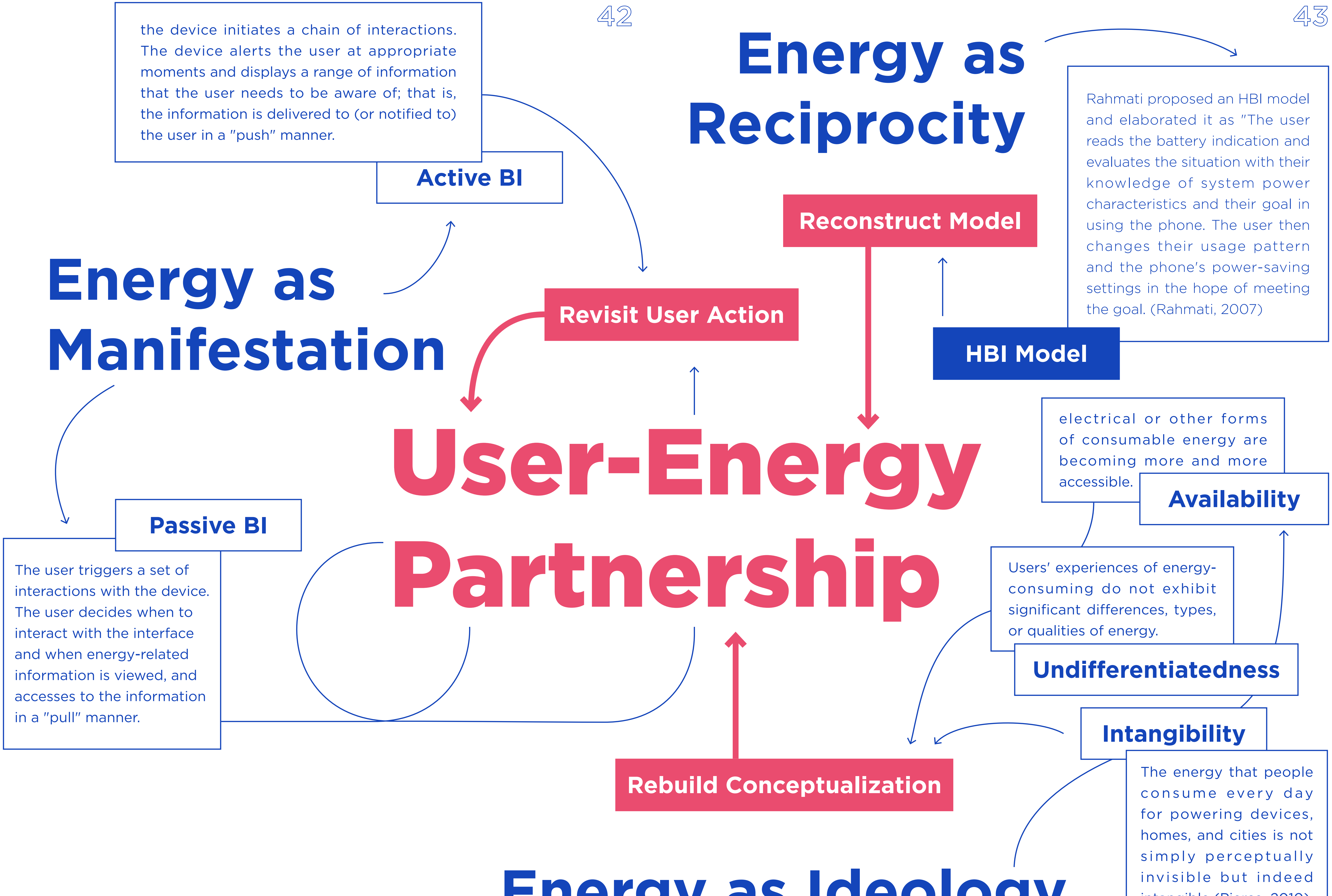


Figure 2.11 - A vizualization for the summary of literature review and the next step.

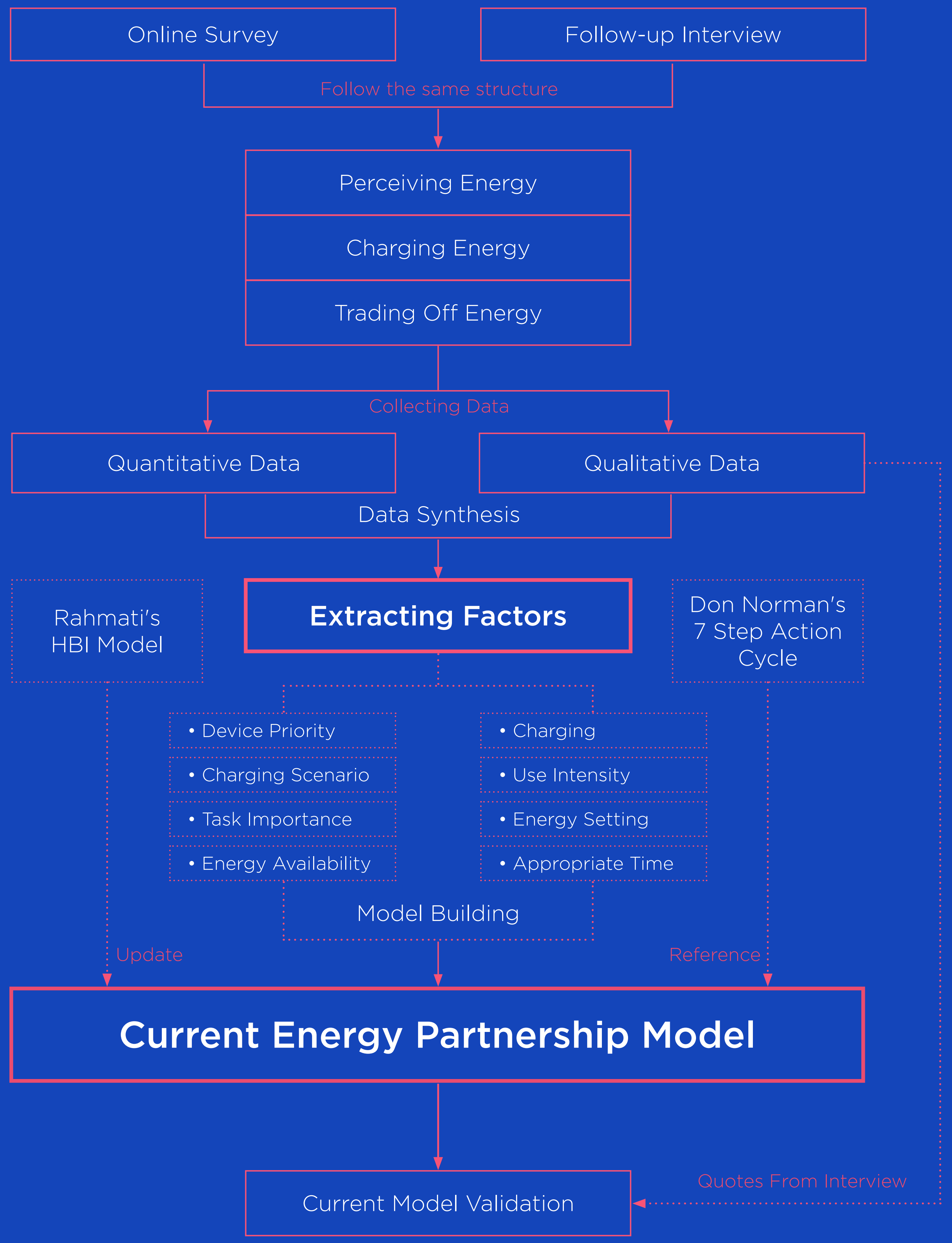


Figure 3.1 - The research sturcture of Chapter 3.

03

Research & Model of EP

Overview

This chapter describes two user studies and the data synthesis undertaken to understand the current EP and the generation of the Current EP Model. This includes an investigation of diverse aspects of the HBI cycle and cognition cycle. Furthermore, data gathered from quantitative and qualitative research are synthesized to gain several recapitulative factors of different aspects of the HBI & Cognition Cycle. Such factors are then mapped to the framework of the EP Model, which is deduced from Rahmati's HBI Model and Don Norman's 7 step Action Cycle, and thus the Current EP Model is proposed and further explained. Finally, the Current EP Model is validated using quotes from previous user interviews and consolidated.

3.1 Quantitative & Qualitative Research

Inspired by the methodology of previous BI researchers, an online survey and follow-up user interviews were conducted with the purpose of dive into all aspects of the HBI process. Two pieces of research mainly covered the same three fields of HBI yet providing different types of data for further analysis. The raw data of each two research can be found in Appendix D.

Quantitative Research

• Goal

an online survey was conducted to explore how users of different contexts and knowledge currently interact with energy in their devices. This study sees HBI from a broad view to get the overall trends and manners of how people are interacting with energy in their smartphones nowadays.

• Method

The online survey was distributed through the social network and a total of 200 valid responses were collected. Three aspects of HBI were mainly covered, including perceiving, charging, and trading off, with corresponding question types. The full question list and the format of the survey is provided in Appendix D.

Qualitative Research

• Goal

Six follow-up interviews were then conducted to gain more specific, in-depth personalized HBI experience. This study serves as a micro perspective of collecting detailed HBI processes with particular contexts as well as multiple devices.

• Method

Three participants were chosen from the online survey, and another three were recruited from social media. The interviews were semi-structured and all of the interviews were operated with online video-conference

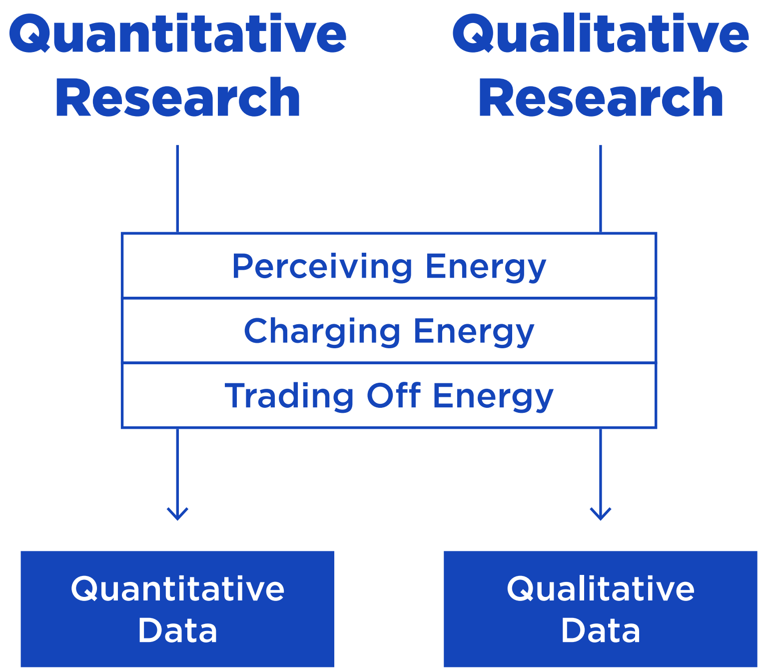


Figure 3.2 - The base framework for EP Model(refined from Rahimati's HBI Model)

platforms like Zoom or Skype due to the quarantine. Topics covered in these interviews included perceiving, charging, and trading off energy in their devices.

• Procedure

This research was explorative in nature, and whilst a set of questions was utilized, participants were asked to respond in whatever ways they felt appropriate. This allowed for more personal responses, including charging habits and context-wise trading off experience, to be captured. As described by Kvale, the main task in interviewing for qualitative research is to understand the meanings (both explicit and implicit) of what the interviewees say(Kvale, 1996). The question list is included in Appendix D.

Flinders, D. J. (1997). InterViews: An introduction to qualitative research interviewing: Steinar Kvale. Thousand Oaks, CA: Sage Publications, 1996.

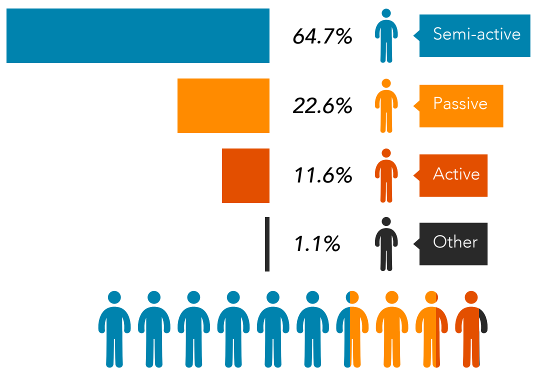
List of Participants

Figure 3.3 - Hand drawing protrait of six participants involving in follow-up interviews

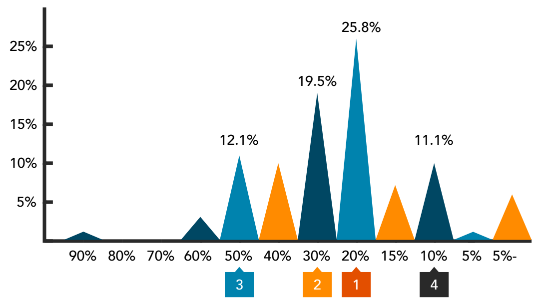
3.2 Data Synthesis

Energy Perception - Quantitative Data

How do people perceive energy level of their phones?



What energy level would trigger people to charge their phones?



How do people feel about different energy level of their phones?

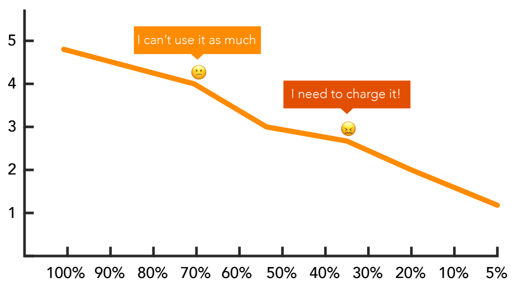


Figure 3.4 - The vizualization of data on Energy Perception

From the result of the online survey, it can be seen that more half of the participants perceive the energy level of their phones in a "semi-active" manner (through glancing at the energy indicator while playing with their phones on other applications) and more than 20% of the participants get to know the battery level of their phones passively (completely rely on active BI like low power notification to know the battery level). Such a result can indicate that **current mobile device users no longer need to pay as much attention to the energy level as the situation five years ago.** As mentioned before, the battery life under normal usage intensity of today's mobile phones exceeds two times more compared to the one seven years ago due to the evolution of mobile chips and the optimization of the mobile operating system.

Furthermore, it can be corroborated with another result, which is the energy level that motivates users to charge their phones. As shown in the diagram, users are mostly triggered to charge their phones when the battery is at 20% or 30% through Low battery notification. However, the reason why 50% also motivates users to charge is unsure. Probably because users treat 50% as a threshold of "need to charge" status and would get their phones charged once had the chance.

Energy Perception - Qualitative Data

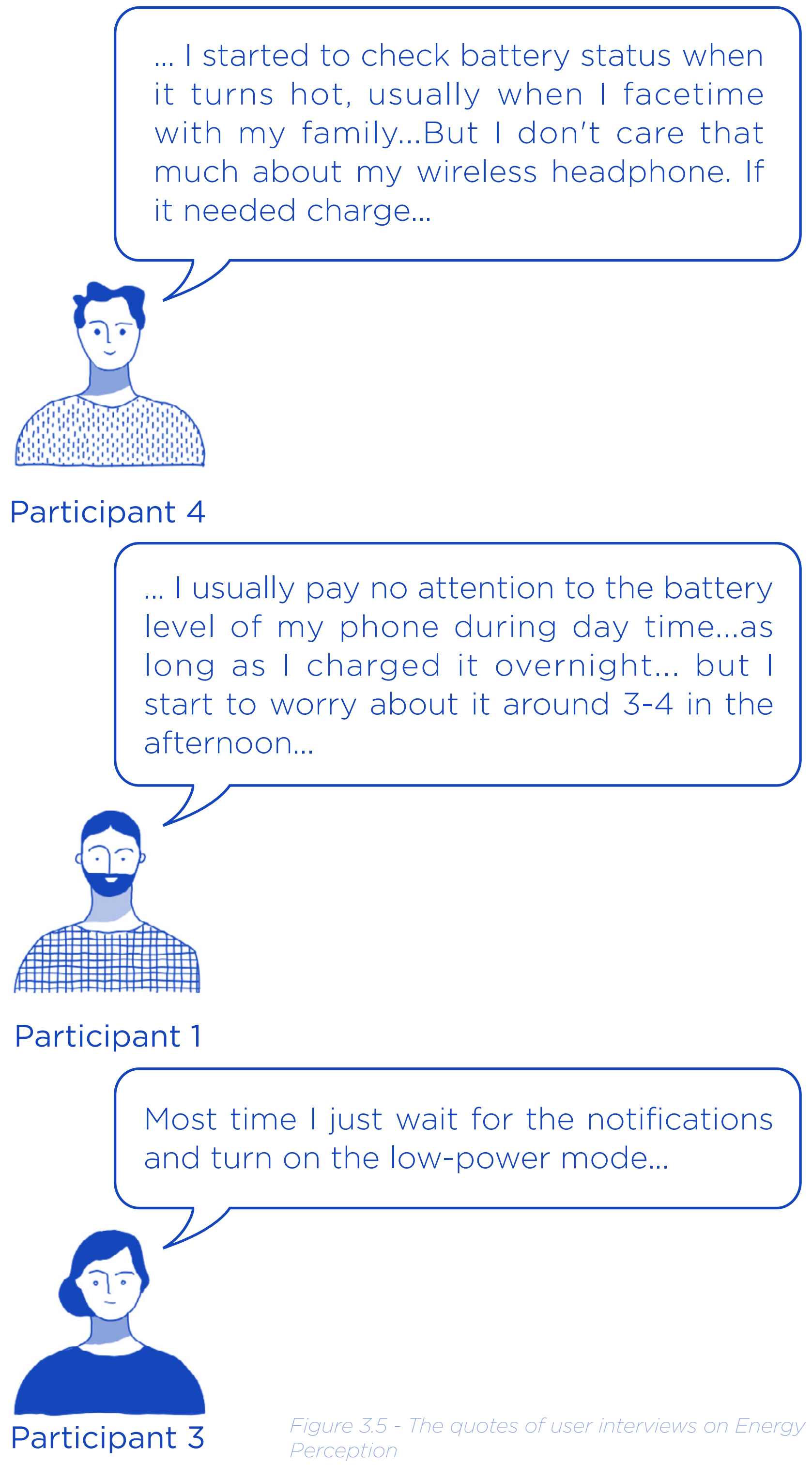


Figure 3.5 - The quotes of user interviews on Energy Perception

The data from interviews also confirmed the opinion that nowadays users do not need to pay as much attention to the battery level as it was before. Notifications and low-power mode are mainly relied upon to perceive the energy. But for some participants who have been using their phones for several years, it is not the case. They start to check the battery actively when using energy-hungry applications like Facetime and games because it cannot last as long as they want.

Another insight from interviews is **user holds varying attitudes to different type of devices.** For example, for wireless headphones and Kindle, most participants will not charge it unless the battery is dead. For entertainment devices like iPad or Kindle, the battery level seems not to be noticed until the battery reaches 5%.

Energy Charging - Quantitative Data

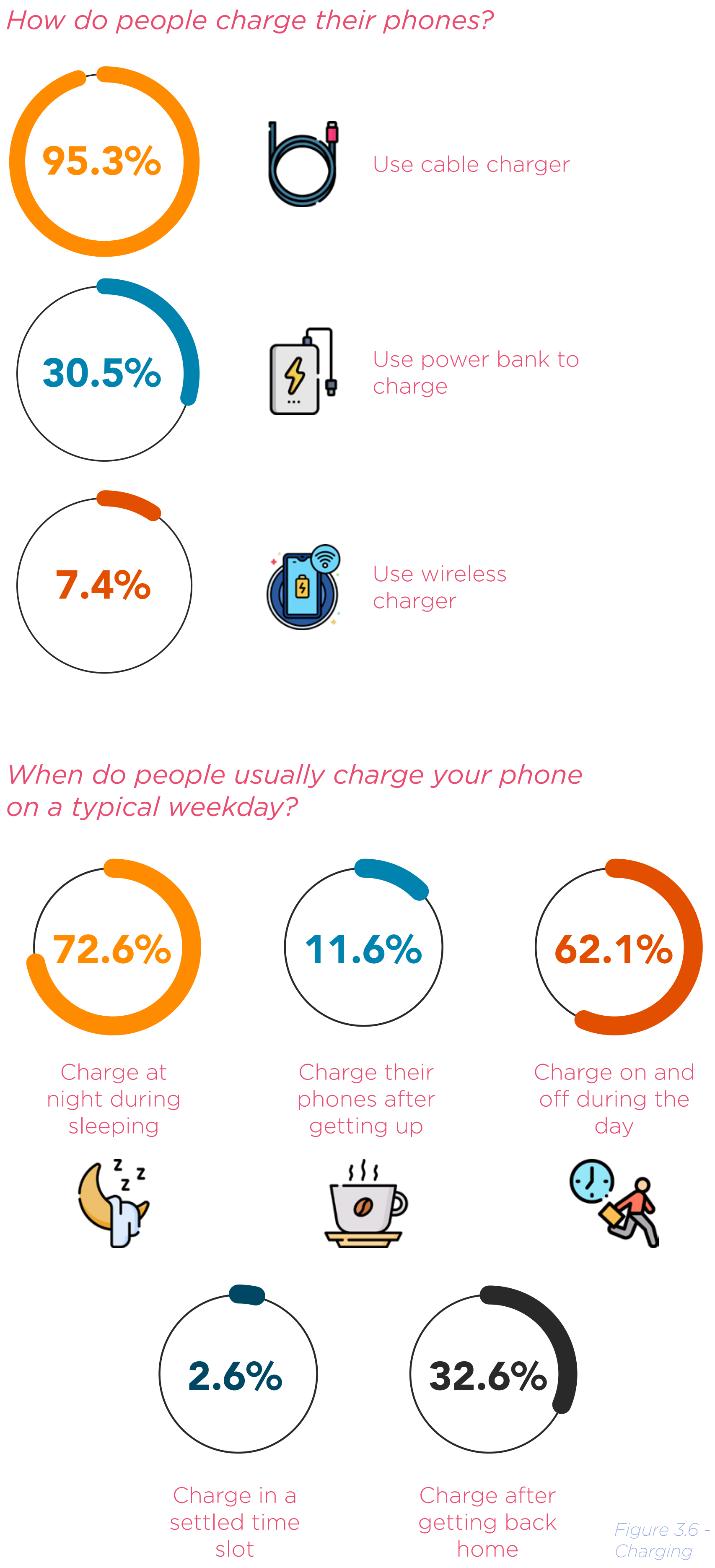


Figure 3.6 - The vizualization of data on Energy Charging

As for the way of charging, the majority of the participants still use cable charger, the most traditional way of charging smartphones. It is worth noting that almost one-third of the users choose to carry a power bank so as to be able to charge on the way.

The time of charging, on the other hand, has a rather routinized trend. Most people charge their phones during the night (72.6%) so that they can have a fully functional phone to start the day. Also, more than half of the participants charge on and off during the day considering the energy accessibility of their working context. Along with the rising importance of mobile phones, current mobile phone users have extended their **charging scenarios**, forming a routinized charging manner, and arranging multiple charging opportunities according to their context of charging phones.

Energy Charging - Qualitative Data

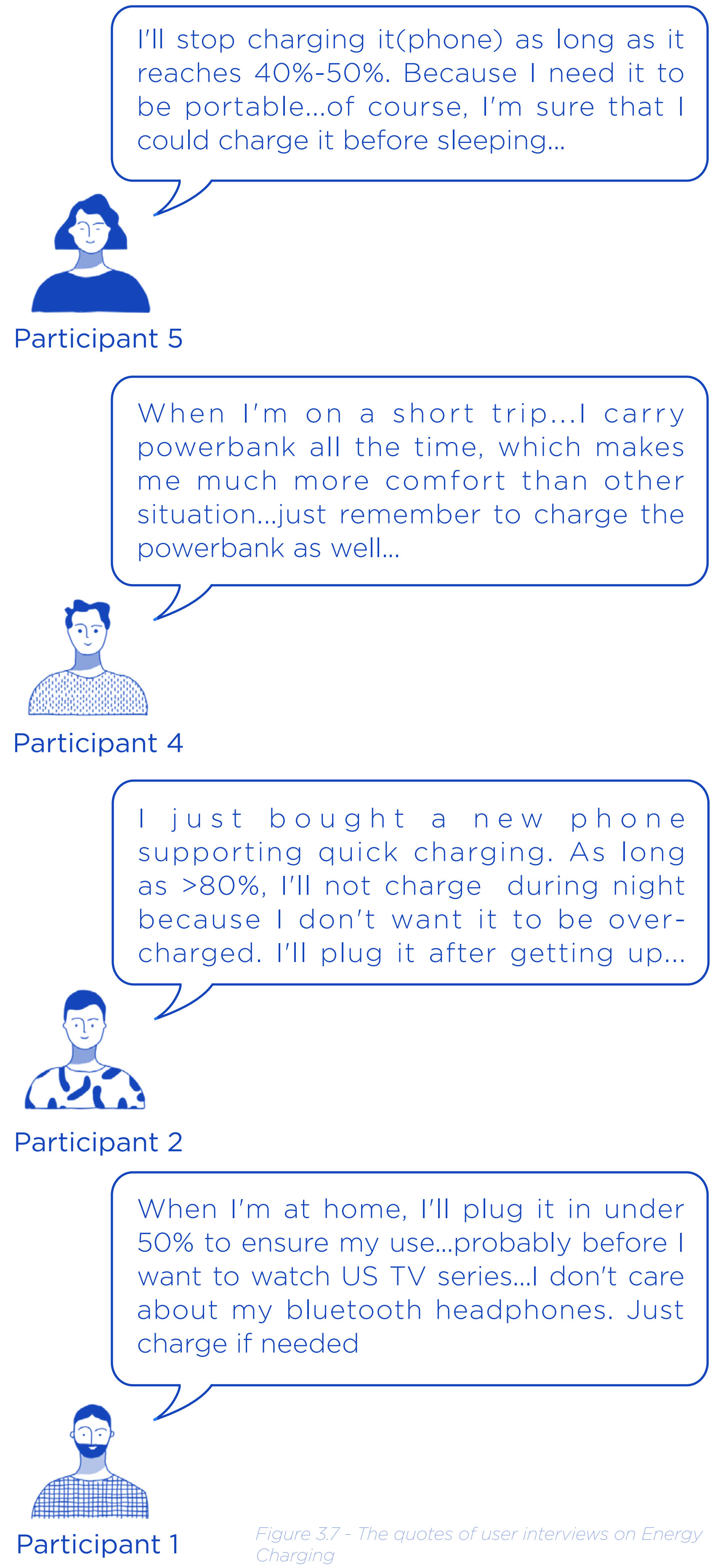


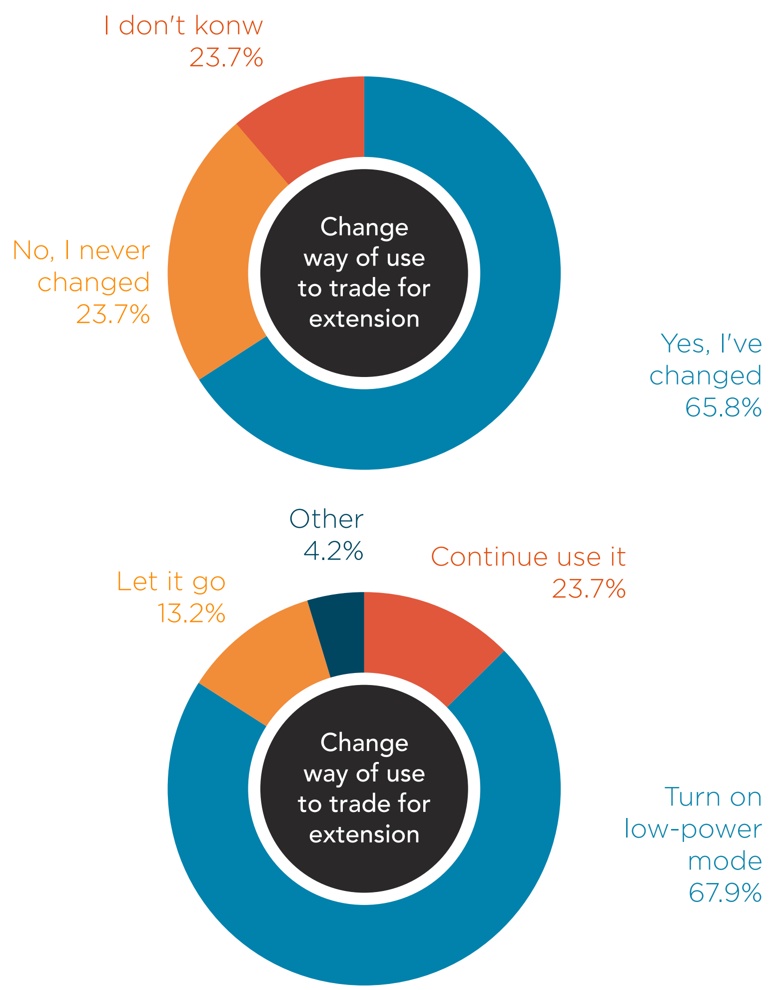
Figure 3.7 - The quotes of user interviews on Energy Charging

After digging into the quotes from interviews, several in-depth, hidden insights are exposed in terms of charging. Participant 5, who holds an iPhone 7 and has used for several years, mentioned he has to plug in the phone after getting back home because of limited battery life. However, he will unplug it when the battery regains at about 40%-50% because he "doesn't want to lose the portability of phones even at home." P4 also reported that the reason he chooses to carry a power bank with him on short trips is "more comfort, don't need to worry about the battery."

Such responses show that charging can also be seen as a sacrifice for portability and thus smartphone users would rather charge as short as possible at home so that it can be "mobile" again. Along with the opened up opportunities and manners of charging, aside from over-night charging, more users charge it on and off during the day in several short periods of time to just keep it alive. This can also come to the conclusion that **current users are getting way more experience around in-device energy than years ago, and thus can take control of energy more advanced and play with it.**

Energy Trading Off - Quantitative Data

Do people change their way of using the phone to trade for extension of life?



Trading off part of the usability for an extension of battery life has always been one of the main HBI that users have to learn about. According to the quantitative data, 65.8% of the participants have experienced trading off and one of the main ways users choose is the **Low Power Mode**, sacrificing the background mail push, screen maximum brightness, and transitional animations for extending the battery life. This is the simplest and most accessible way of achieving that effect provided by mobile operating systems.

How do people do that? How do they feel?

Figure 3.8 - The vizualization of data on Energy Trading Off

Energy Trading Off - Qualitative Data

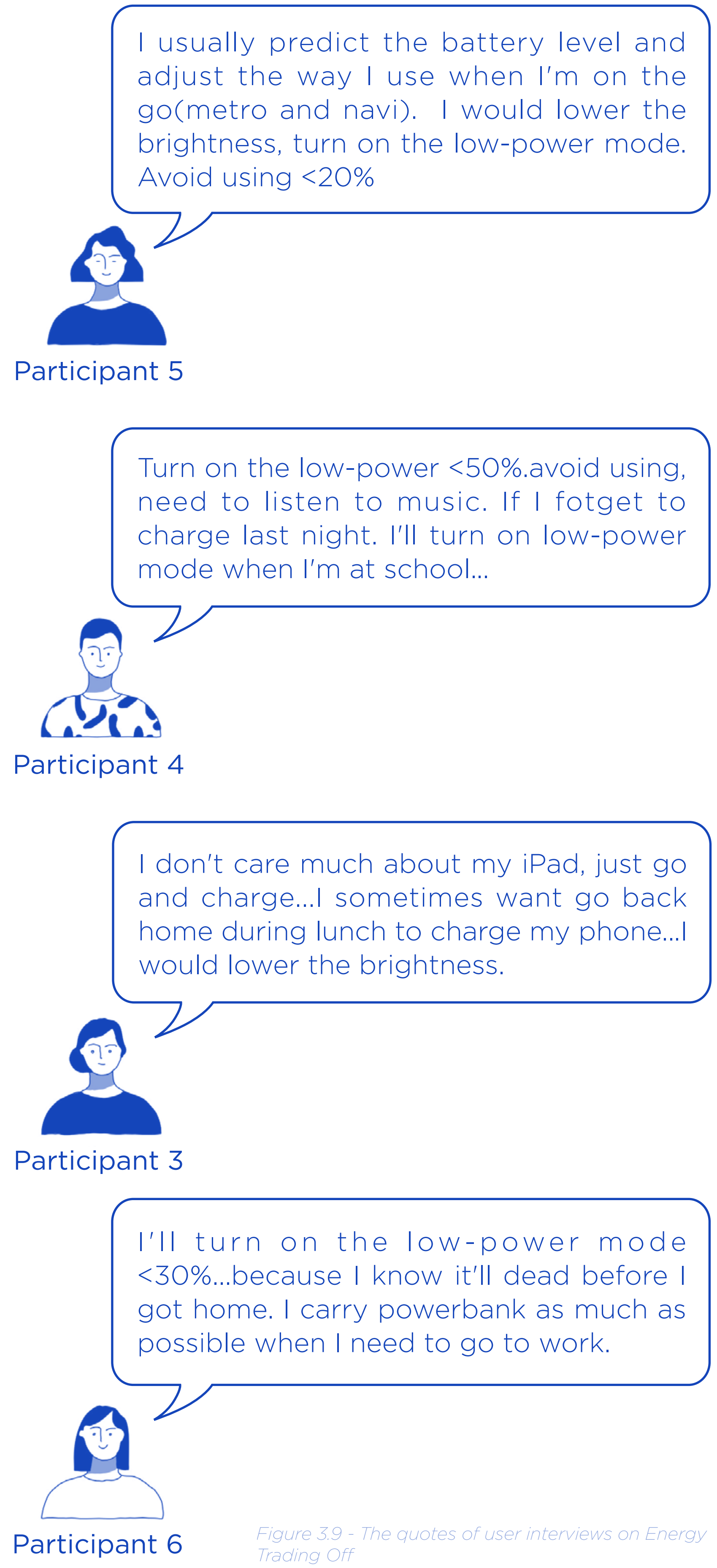


Figure 3.9 - The quotes of user interviews on Energy Trading Off

Further interviews support the result of quantitative research. Most mobile users know Low Power Mode and will switch it on when facing power shortages. The situation usually happens when the user fails to charge it the night before or break the charging scenario (forget to bring power bank). Most of the interviewees also reported that they will lower their **usage intensity** manually, such as lower the frequency of checking social media and choose to send SMS instead of IM. Besides, some of them also reported that they will decrease the screen brightness since they believe that it matters a lot to energy consumption. From such results, it can be concluded that Low Power mode and manually sacrificing the usage intensity are the two principal ways of trading off energy, together with the adjustment of the adjunctive energy setting.

Summary for the User Study

Summing up the data from quantitative and qualitative research, the following insights are presented, demonstrating how users are dealing with energy currently.

• Perceiving Energy
Current mobile device users perceive energy in a semi-active manner, which means they just glance at the indicator while performing other tasks. More and more users rely on the notifications from the mobile operating system to tell them their devices' energy level.

On the other hand, current users usually hold more than one device. But their attitudes towards different types of devices are different. Most users care about their mobile phones' battery level. As for other devices like smartwatches, tablets, and laptops, users do not care that much.

• Charging Energy
Current mobile device users have extended their charging scenarios, forming a routinized charging manner, and arranging multiple charging opportunities according to their usage context. They are getting way more experience around in-device energy than years ago. They can take control of energy more advanced and play with it.

• Trading Off Energy
Most users have reported trying to trade off part of the usability for extension of battery life, and the primary way users take is Low Power Mode, which is the simplest and most accessible way of achieving that effect provided by mobile operating systems. Moreover, users will also manually lower their usage intensity to keep their devices alive.

Discussion

From what has been discovered through user studies, it can be seen that the current mobile device user take different manners and attitudes towards the energy in devices. Firstly, modern devices have way more capabilities and performance than five years ago, while those devices' battery life also increases twice as much. At the same time, users are also getting more experience in dealing with limited battery life; their Knowledge(in Rahmati's HBI Model) towards energy and battery is also way more advanced.

This project aims to uncover the EP between users and mobile devices, and how users deal with energy is just the surface of it. These user behaviors that can be observed and recorded are just the externalization of a bigger picture. To outline the EP, besides the external user actions, the cognition process between user and energy should also be uncovered.

3.3 Factor Extraction

Explaining Factors

After synthesizing the data collected quantitative and qualitative research, these insights are then conceptualized into several factors with the basis of Rahmati's HBI Model by means of card sorting. The figure at left shows the eight factors extracted from insights and data of the two research. Compared to mobile users seven years ago, current mobile users take Device Priority into consideration since most of them own more than one mobile device with different purposes of use. Also, current mobile device users are more experienced and thus have the ability to take control of and play with energy in their devices by adjusting the Use Intensity and Energy Setting. What's more, current users have also formed their personal Charging Scenario to maximize their Appropriate Time of using mobile devices because of the energy accessibility for today's users.

HBI Factors

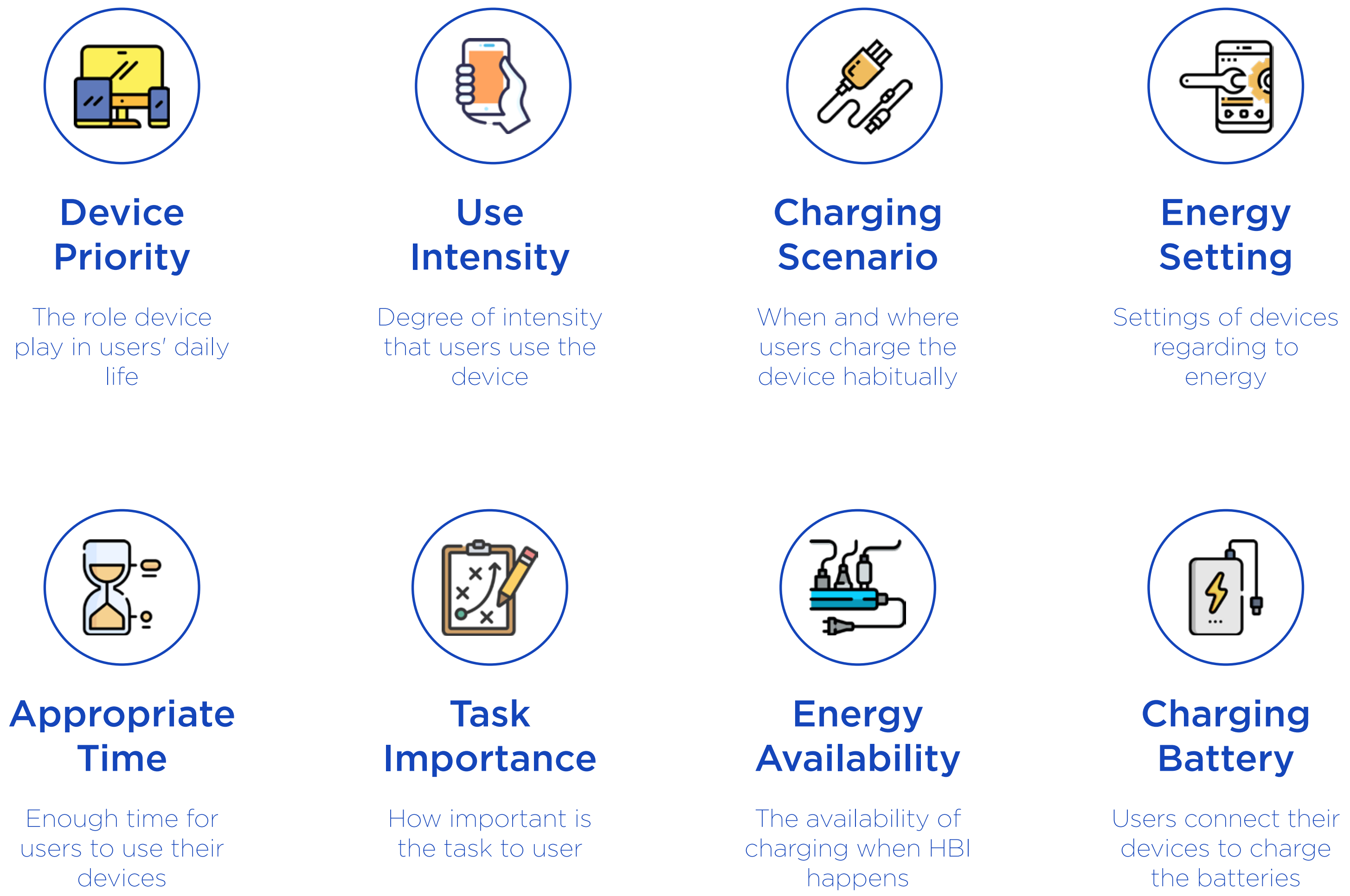


Figure 3.10 - The showcase of eight HBI Factors

3.4 Current EP Model Generation

Rahmati, A., Qian, A., & Zhong, L. (2007, September). Understanding human-battery interaction on mobile phones. In Proceedings of the 9th international conference on Human computer interaction with mobile devices and services (pp. 265-272).

Norman, D. A. (1988). The psychology of everyday things. Basic books.

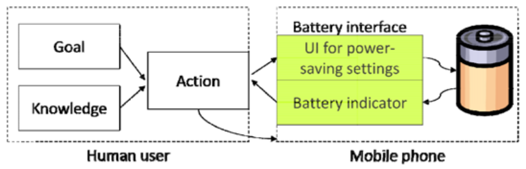


Figure 3.11 - Rahmati's HBI Model

HBI Model's limitation

As mentioned before, the evolution of the user's knowledge and experience towards energy and devices has been considerably progressing, which was solved through a set of research of HBI before.

Additionally, even though Rahmati's HBI Model covered the HBI aspect and the Human Factor, the Human side has not been fully discussed and developed. With the aim of building the EP model, the cognition cycle part of the HBI model will be discussed and reshaped next.

Don Norman's 7 Step Action Cycle

In "The Design of Everyday

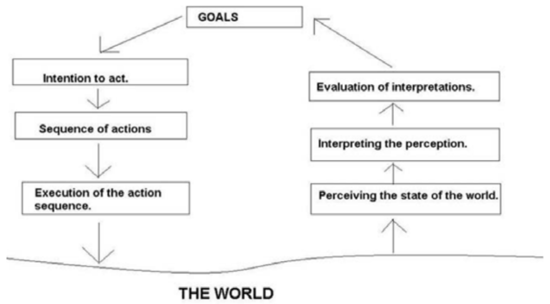


Figure 3.12 - Don Norman's 7 Step Action Cycle

Things" (Norman, 1988), Don Norman elaborates the steps of a specific interaction process as a seven-step "action cycle". This is a model conceptualizing interaction as a "Cognitive processor" in the human mind, and describe every step that takes place in the human's head when an interaction between human and interactive products and services. In this model, the center of it is the generation of "Goal", a conceptualized term representing the meaning of the interactive product perceived by users and the purpose of the following sequence of actions.

Integrating Two Models

Just as discussed before, the human side of Rahmati's HBI Model was not fully developed. At the same time, Don Norman's 7 Step Action Cycle successfully conceptualized the interaction at the cognition dimension. Therefore, this project will try to integrate the above two models to propose a new EP Model demonstrating both the HEI and Cognition process.

Looking back at Rahmati's HBI Model, Actions act as the central character bridging the energy and human sides. The energy side clearly outlined the relationship between two BI and user's Action: user perceiving the energy through **Active BI** and manipulate the battery with **Passive BI**. The human side, on the other hand, simply described the **Action** was triggered by the **Goal** and user's **Knowledge** of in-device energy.

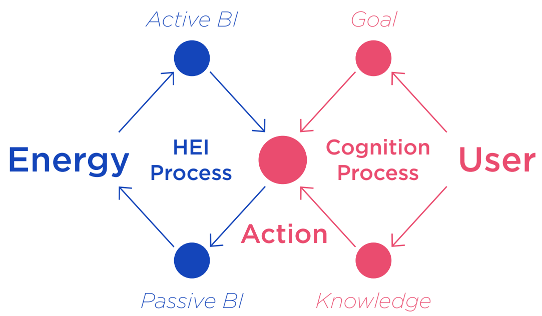


Figure 3.13 - A revised version of Rahmati's HBI Model

Don Norman's 7 Step Action Cycle broke down the universal interaction process, breaking it down into seven cognitive steps. After **Perceiving** the information from the external world, humans will try to **Interpret** and then **Evaluate** it using the knowledge accumulated in their mind beforehand. The **Goal** for the upcoming Actions will then formulate. Finally, the **Actions** will be performed by humans motivated by the **Intension**.

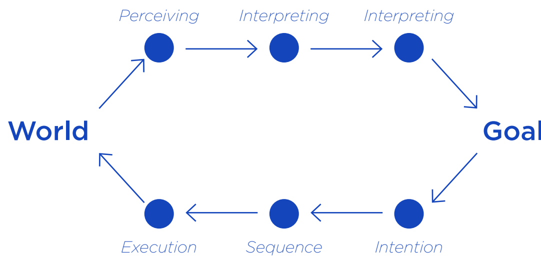


Figure 3.14 - A revised version of Don Norman's 7 Step Action Cycle

The EP Model will apply the interaction side of Rahmati's HBI model and reconstructing the human side by appending two more steps before the formulation of the Goal, merging the Knowledge into the Evaluating step, and adding the Intension before the Action. Therefore, a new EP Model is proposed.

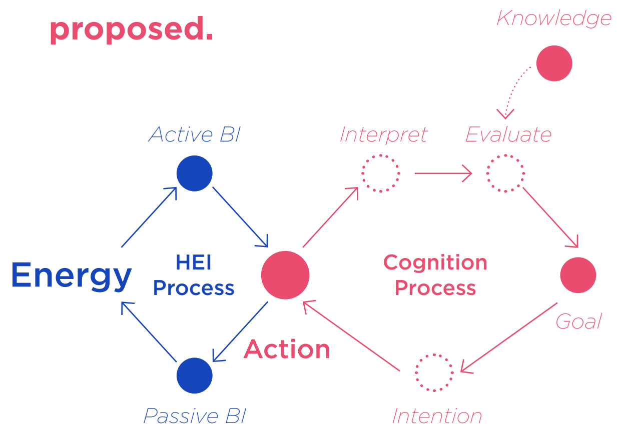


Figure 3.15 - The process of integration

Proposing the EP Model Framework

Based on what has been discussed on the previous page, this project proposes a new EP Model framework conceptualizing the relationship between users and energy in mobile devices. Two main processes are involved in the EP Model: **HEI process**, which describes the relationship between the user's actions and the Energy Interface, and the **Cognition process**, which articulate the procedure of information processing in the user's mind. **Action** serves as the connectors of two processes, indicating the energy-related actions that users take.

The disgram on the right vizualizing the formulation procedure of the EP Model and how Rahmati's HBI Model and Don Norman's 7 Step Action Cycle are integrated. The EP Model is presented at the bottom of the diagram.

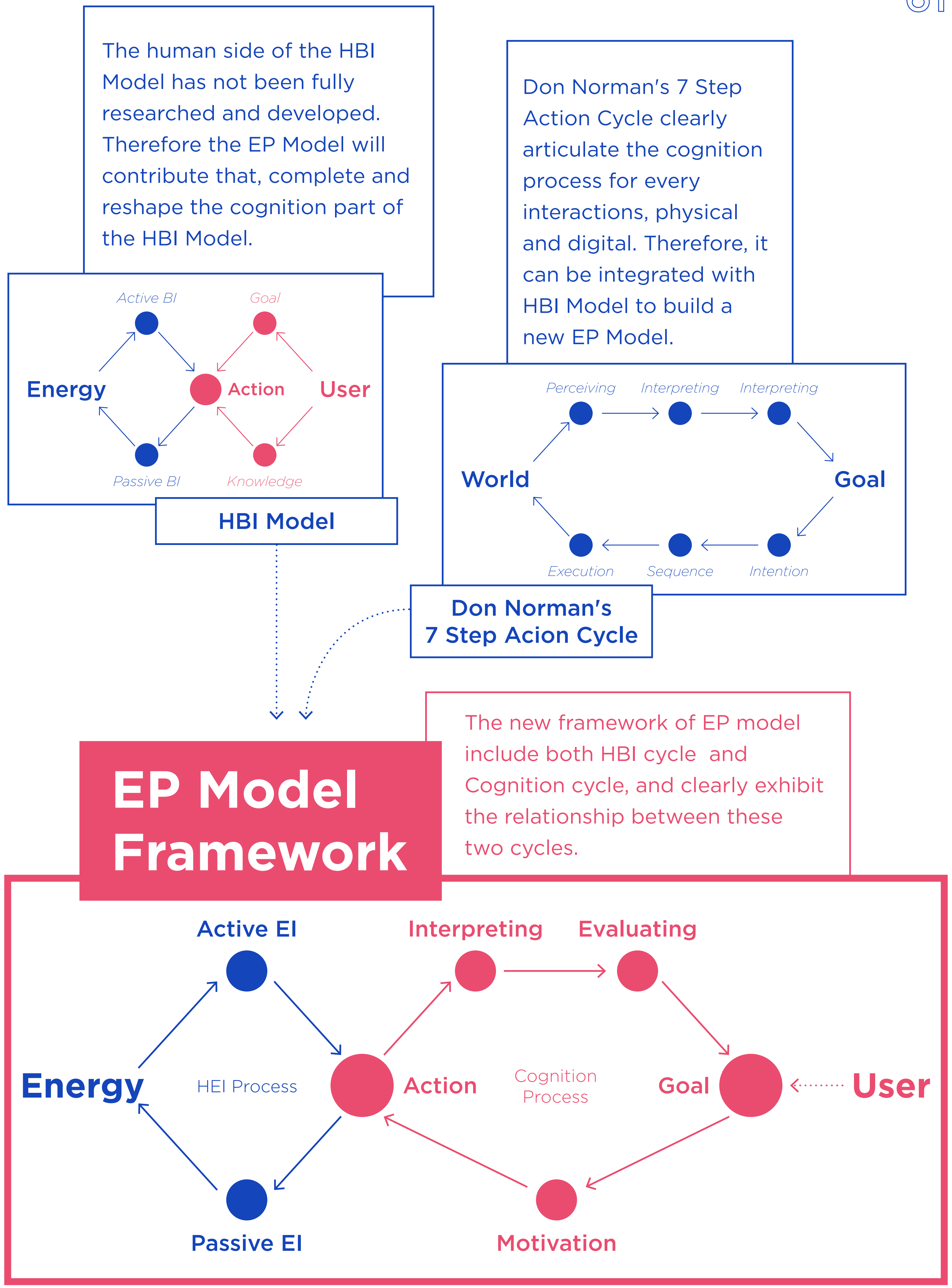


Figure 3.16 - The Process of formulating EP Model framework.

Categorizing Factors

To get to the Current EP Model, all factors extracted from user study will be categorized and mapped to the EP Model.

• Active BI
According to Jung (Page 23), Active BI alerts the user at appropriate moments and displays a range of information that the user needs to be aware. Based on the previous user study, Battery Indicator and Low Battery Notification are two main Active BI that has been used mostly for mobile devices.

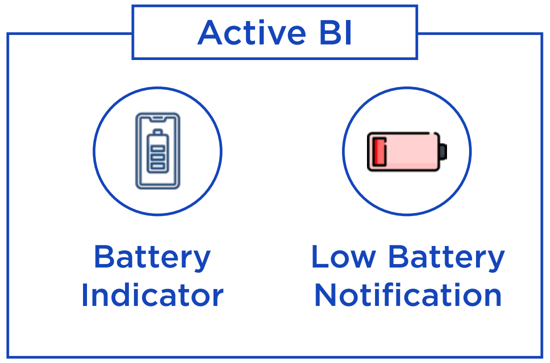


Figure 3.17 - Category of Active BI

• Passive BI
Current users mainly use the Passive BI device to conduct the action of Trading Off Energy. Previous user study shows that Use Intensity and Energy setting like Low-Power Mode are mainly utilized by users to manipulate the battery in devices.

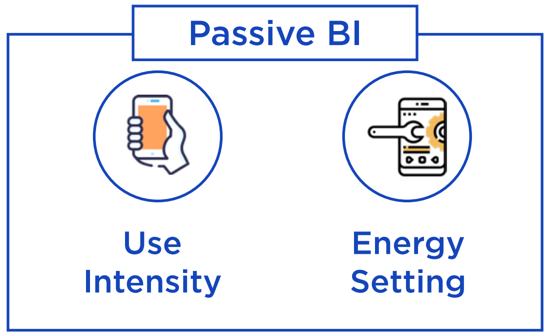


Figure 3.18 - Category of Passive BI

• Actions
Actions are external user behaviors towards energy that can be observed and recorded. Perceiving, charging, and trading off are the three main actions that current mobile device users will take.

• Evaluating
In the Cognition process, Evaluating is a step that users evaluate the perceived information with experience and knowledge accumulated through a long period of usage time. From the extracted factors, it can be categorized that Device Priority, Task Importance, Charging Scenario, and Energy Availability falls into Evaluating. Moreover, Charging Scenario and Device Priority are relatively long-lasting factors that users form over a longer period while the other two factors are evaluated every time on a case-by-case basis. The evaluating category can therefore

be sub-categorized into Long-term Evaluating Factors, which Device Priority and Charging Scenario pertain to, and SHort-term Evaluating Factors which the rest two belong.

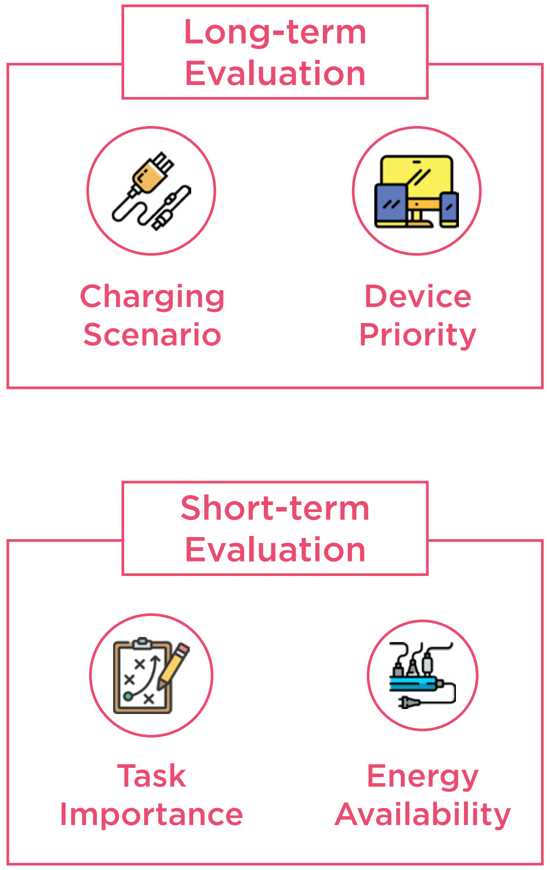


Figure 3.19 - Category of Evaluation

• Goal
Goal plays the central role in Cognition Process because it's the result of Interpreting and Evaluating and the guidance of Action. For the EP, Goal stands for users' interest and manifests the conceptualization of energy that users hold in their minds. Appropriate Time, from the result of user study, is the Goal factor in the Current EP Model.

Mapping to the Framework

With all factors summarized from the previous user study map into every character in the EP Model, the Current EP Model can be concluded.

The diagram on the right elaborates how these factors are categorized into each character, and integrate into the EP Model.

Current EP Model shows the current mechanism of how energy and users are mutually related, the interaction and cognition process between battery-based devices and users, and the factors that current users concern in each character of the EP Model

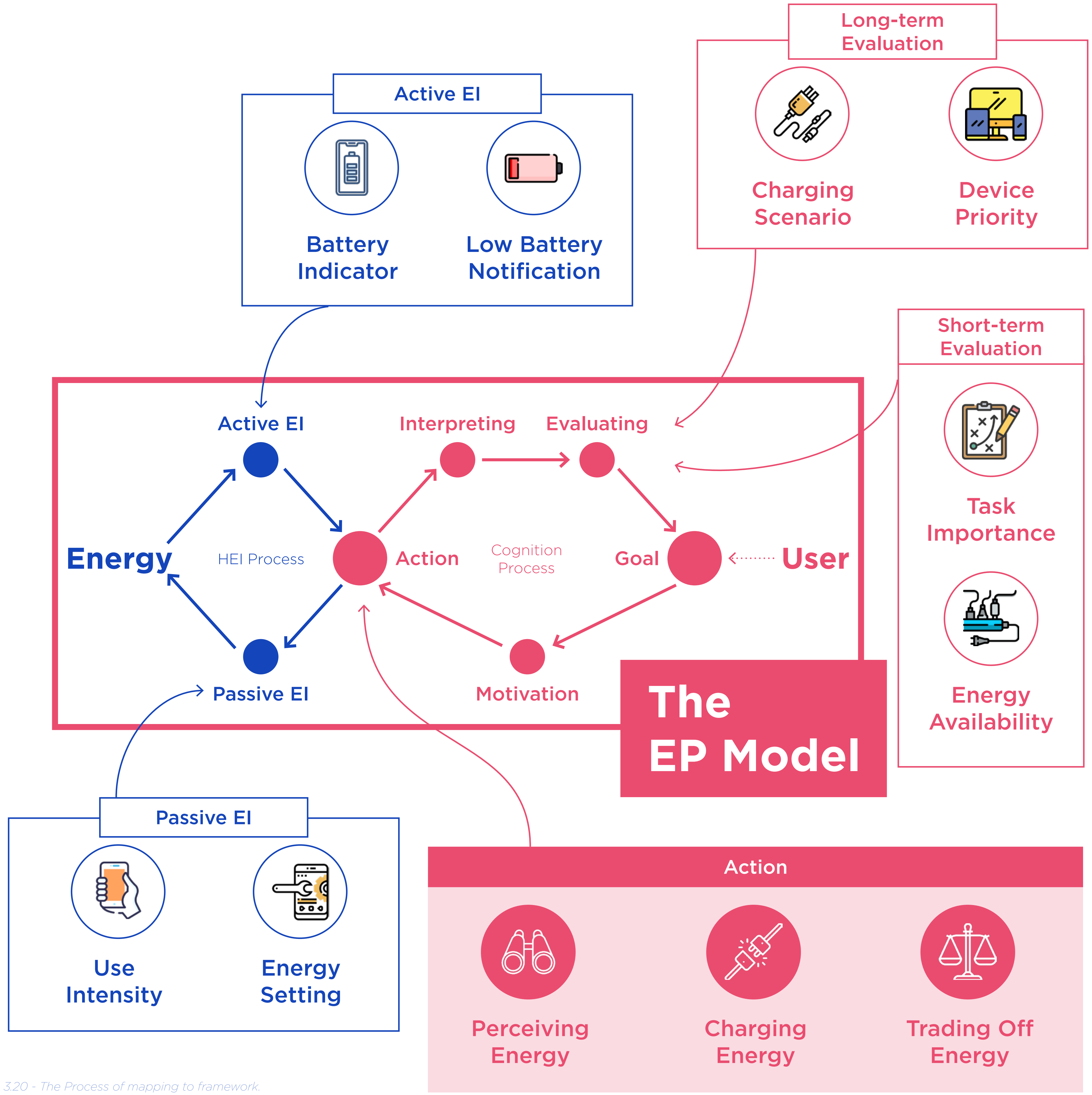


Figure 3.20 - The Process of mapping to framework.

Current EP Model

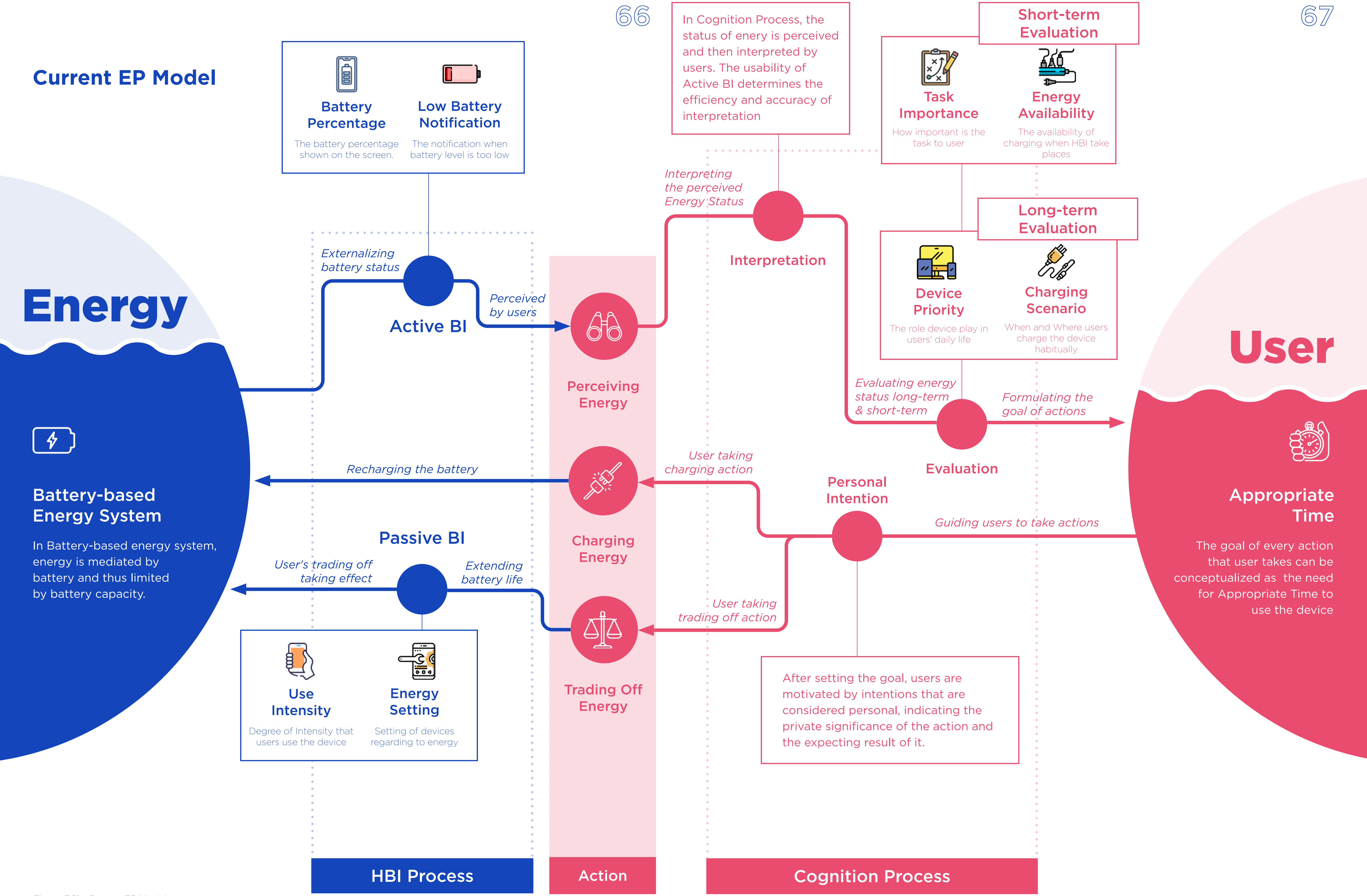


Figure 3.21 - Current EP Model

Explaining Model

The previous page model demonstrates the current relationship between energy in battery-based mobile devices and users. It consists of two processes: the **HBI process**, which describes how users will interact with the manifestation of energy externally, and the **Cognition process**, which describes how users will internally process the perceived energy-related information in their minds before taking actions. Two process are connected with each other through **Action**. In order to efficiently explain the current model, the operation of the model break down into several steps, with a diagram indicating the position and a description for each step.

Step 1: Energy System (HBI)
For mobile devices that are powered by battery, energy manifest itself continuously. It is also the starting point of HBI process.

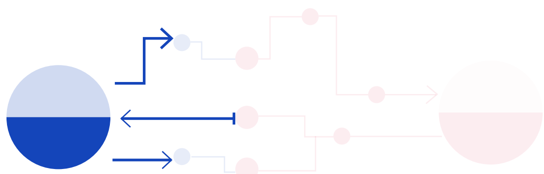


Figure 3.22 - Energy in Current EP Model

Step 2: Perceiving through Active BI (HBI)
Users perceive the battery level through the Active BI, which is the battery indicaor and low battery notifications informing a status of energy insufficiency.

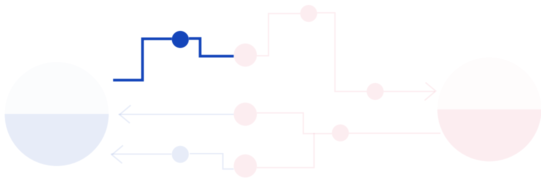


Figure 3.23 - Perceiving Energy in Current EP Model

Step 3: Evaluating (Cognition)
After perceiving and interpreting, the cognition process begins. Users will evaluate battery-related information with long-term factors, including checking how important the device is to them and if the charging scenarios that formed through prolonged use can be utilized. Short-term factors, such as how important the current performing task is for them, and if there is any chance of charging in the surroundings, will also be considered.

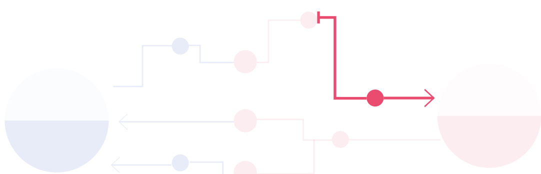


Figure 3.24 - Evaluating in Current EP Model

Step 4: Forming Goal (Cognition)
Based on the information perceived and evaluated, users will form their goals for the actions that they will take in practice, which is to get an appropriate remaining time of using devices.

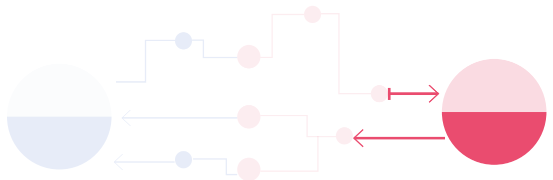


Figure 3.25 - Goal in Current EP Model

Step 5: Taking Actions (Action)
Then different types of actions, motivated by Personal Intention, will be taken by users to gain the appropriate time of use. Users will try to recharge the device, or trading off the usability for a better experience.

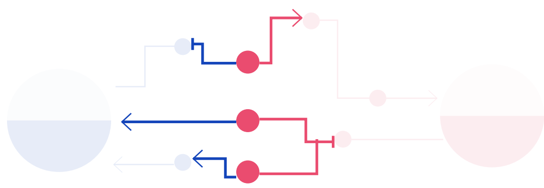


Figure 3.26 - Action in Current EP Model

Step 6: Actions taking effect (HBI)
The receptor of those actions, the battery itself and the Passive EI, will be changed accordingly, and finally passed the effectiveness to the energy. Users will perceive the feedback through Active EI, and the whole model will operate again.

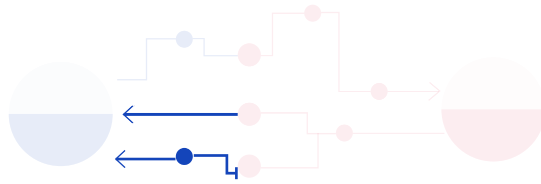
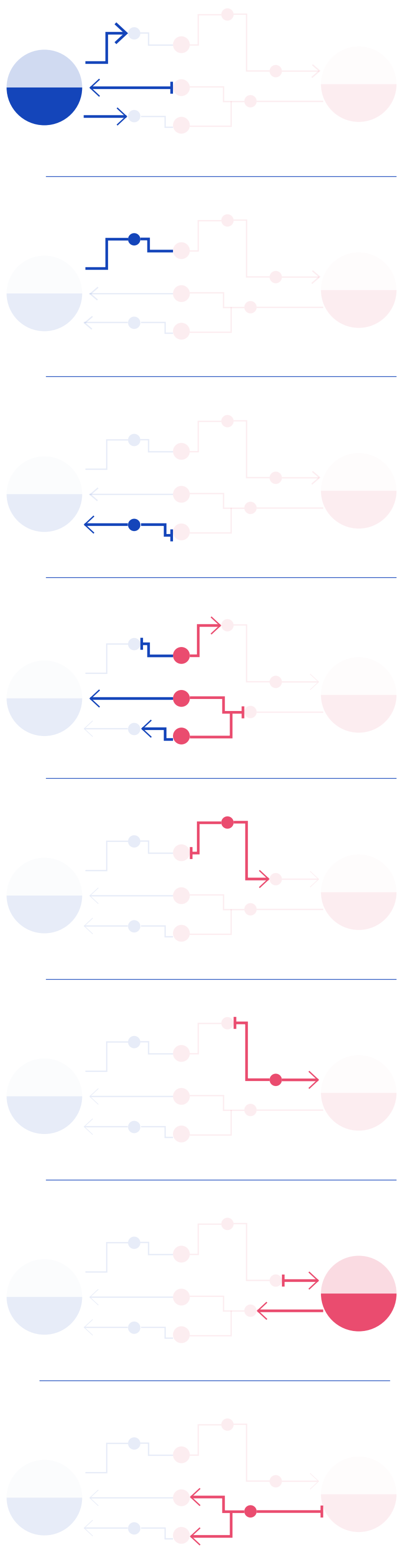


Figure 3.27 - Passive BI in Current EP Model

Therefore, it can be noticed that the Current EP Model is a loop of perceiving, interpreting, and interacting, which users will continue performing. Users learn to interpret the manifestation of energy, forming customized long-term and short-term evaluating factors and finally, manipulating the battery-based energy system for their use.

Current EP Model Matrix



CHARACTER	DESCRIPTION	PARADIGM OF CURRENT EP	
Energy	The upholder for every interactions on mobile devices. It manifests itself and interacts with the user with Active and Passive BI.	Battery-based Energy System	HBI process
Active BI	The device alerts the user with Active BI and displays a range of energy information that the user needs to be aware of.	Battery Percentage; Low Battery Notification	HBI process
Passive BI	The user decides when to interact with the interface and when energy-related information is viewed.	Use Intensity; Energy Setting	HBI process
Action	The bahaviors that can be recorded as interactions between users and the manifestation of energy	Perceiving Energy; Charging Energy; Trading Off Energy	
Interpretation	The translation process from visual signal to the data type that our mind can recognize and handle.	In Cognition Process, the status of enery is perceived and then interpreted by users. The usability of Active BI determines the efficiency and accuracy of interpretation	Cognition process
Evaluation	**Short-term**: The factors evaluated as appropriate	Task Importance; Energy Availability	Cognition process
	Long-term: The factors formed from long-term usage	Device Priority; Charging Scenario	Cognition process
Goal	The conceptualized goal that the users hold for every interactions with energy.	Appropriate Time	Cognition process
Intention	The motivation of actions and the expected consequences of actions that can be considered as private to users.	After setting the goal, users are motivated by intentions that are considered personal, indicating the private significance of the action and the expecting result of it.	Cognition process

Figure 3.28 - The matrix of current EP Model

The matrix on the left elaborates every character of the current EP Modell. It serves as a 'dictionary' of each character in the current EP Model aiming at understanding how does the current model work.

The far left column indicates the position of each part and how it is connected in the model. The Description column explains the meaning of each part and its relationship with each other. Finally, the far right column lists the factors of every part in current EP Model.

To distinguish the HBI and Cognition process, Characters of HBI process are in blue while characters involving in Cognition process are in red. Action, the connector of these two process, is also marked red.

The Conceptualization of Battery Energy

As articulated before, energy, as an ideology, is conceptualized under the impact of massive power supply network technology since it hides the generation and transmission of energy and exposed only the endpoint of it to the user. Therefore as a conceptualization, energy presents three attributes, intangibility, undifferentiatedness, and availability in regard to Human Energy Interactions. User's interactions with in-device energy, on the other hand, share these three attributes in general yet have some differentnesses of each thread.

• **Intangibility:** Energy in mobile devices is considered intangible to users. Battery, as the technological mediator which stores and releases energy to power the electronic components, does not announce its tangible presence besides using active BI as the manifestation and passive BI as the receptor of interaction.

• **Undifferentiatedness:** In-device energy means no difference to mobile devices users because it brings no difference to experience the device itself and the applications in it, as long as it's adequate.

• **Availability:** Even though in-device energy brings no difference to the user experience of each application on devices, it did affect the user's expectations of how long it can be used. Although the accessibility of charging is already developed, which means users can charge their devices almost everywhere with a power bank or a cable charger and a nearby power

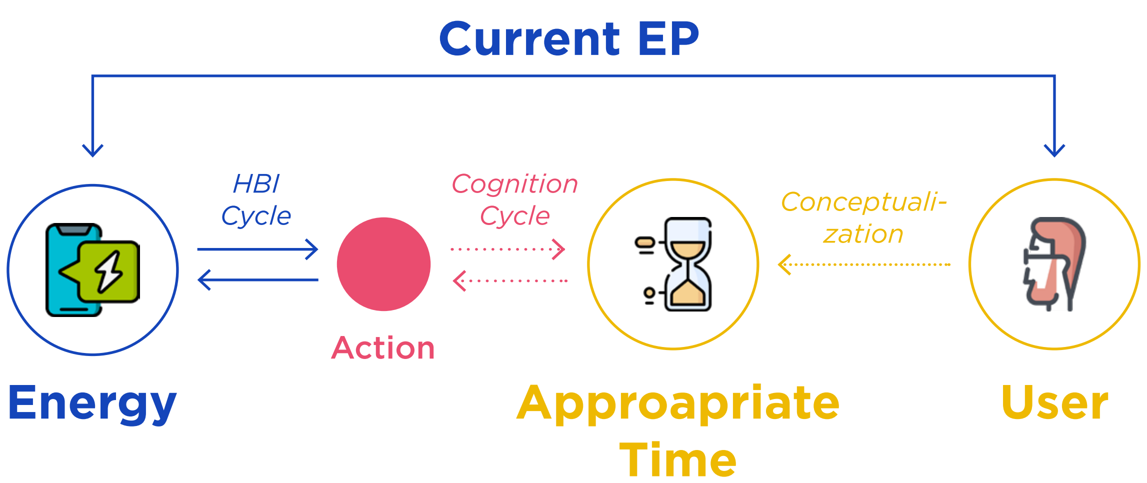


Figure 3.29 - The matrix of current EP Model

outlet, the charging action itself always means a sacrifice to the mobility of the device for the user. The capacity of the battery also limits the continuous usage time without charging.

Therefore, the conceptualized goal of each HBI Model for the user is to get appropriate time to use. Users are aware of the limitation of battery and they're not expecting infinity usage time. Instead, they interact with Passive BI like Low Power Mode, or adjusting the use intensity and energy setting in exchange for appropriate usage time. The current energy partnership between user and energy in devices, therefore, can be conceptualized as **a balance between user and appropriate usage time.**

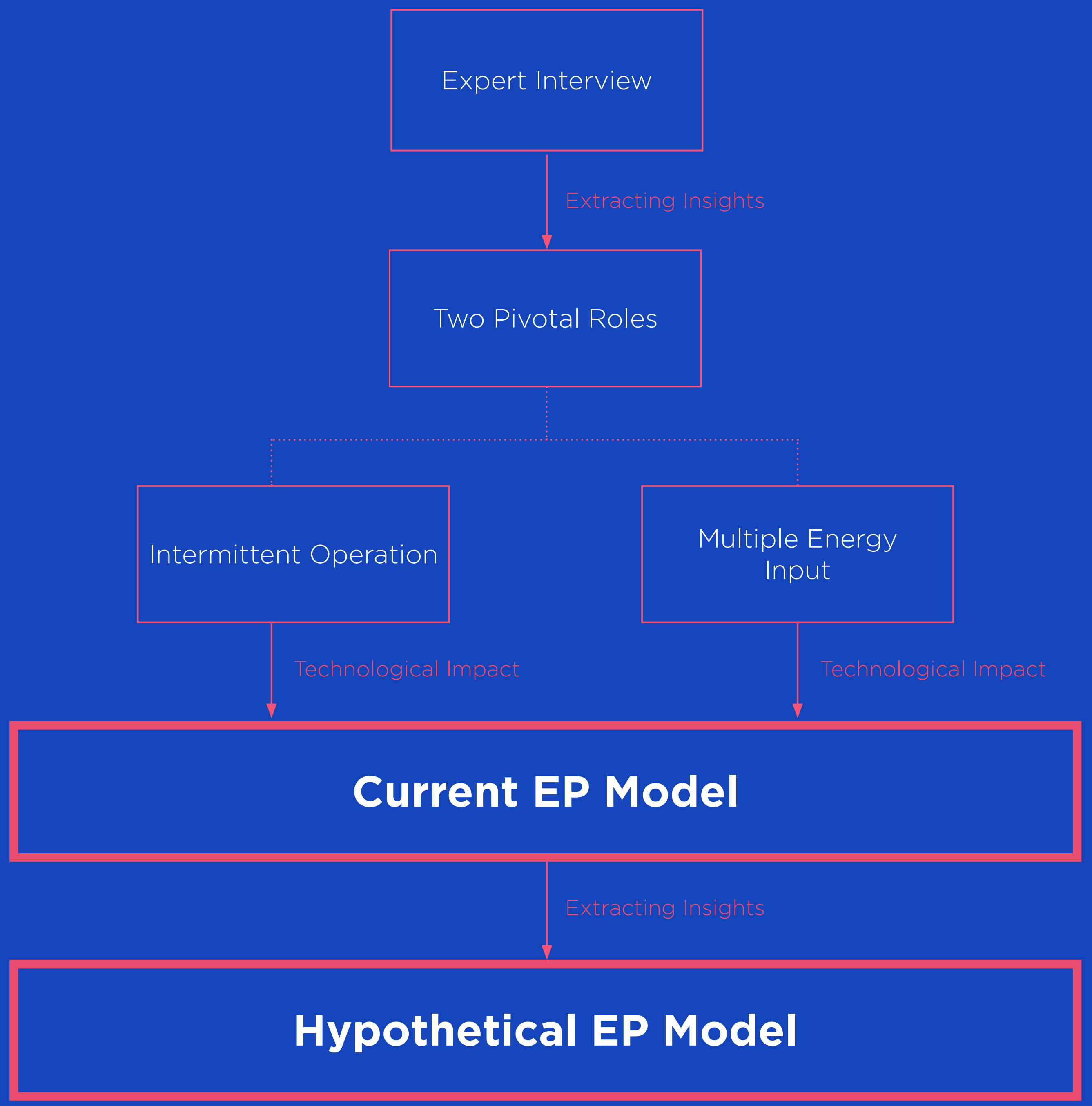


Figure 41 - The research structure of Chapter 4

Envisioning Future EP

04

Overview

This chapter describes the formation process of a hypothetical future EP Model. Firstly, the topics of intermittent operation, the capacity of energy harvesting, and multiple energy sources are discussed through several times of expert interviews. Furthermore, derived from the interviews, two pivotal roles that energy harvesting technology will bring to the Current EP are presented. Finally, the Hypothetical EP Model envisioning between future intermittently powered device and the user is proposed.

4.1 Expert Interview

This section elaborates the process of expert interviews and answers for four key questions.

• Goal
The goal of the expert interview was to delve into the energy harvesting technology and the side-effect it brings along-Intermittent Operation

• Participants
Przemysław Pawełczak, Embedded Software Lab, Assistant Professor of TU Delft
Prof. Przemek has been Iucubrating energy harvesting technology and its application for years and contributed to the method of intermittent computing technique and energy harvesting prototyping.

• Procedure
Two interviews were conducted, and the content is shown next. The interviews were semi-structured; each has specific themes with regard to different aspects of energy harvesting. Through interviews, the current situation of energy harvesting research and development, the future vision, and aspects that affect the current EP were covered (see Appendix E).

Q1: How will people experience intermittent operation in reality?

A: Intermittent operation is the phenomenon of sudden on and off because the harvester fails to get enough energy to continue powering the device. It can be as short as barely visible or can be as long as several seconds that make users think the product is broken. Take current research prototypes for example, if the prototype is mainly powered by sunlight and a cloudy condition may result in several seconds of suspend due to the lack of energy. Even if the prototype is tested under an ideal condition, participants will still feel it now and then.

In the future, as the progressing of research, the frequency and duration of intermittent operation will be significantly reduced. Thus the application of energy harvesting will be opened up for future mobile devices.

Q2: What does the intermittent operation have relation with?

A: Intermittent operation mainly related to two variables: environmental availability and the intensity of interactivity. Simply speaking, if you locate in an environment that can provide much more energy for harvester, the intermittent operation will happen much less frequently and short compared to the environment that can not. But energy harvesting devices can gain power not only through absorbing ambient energy, but also through manual energy input, which means users can manually "powering" the device by pressing buttons or other solutions.

As for the intensity of interactivity, let's say we have a GameBoy that is powered by ambient energy. Under identical environmental conditions, users will be interrupted more frequently when playing Super Mario other than Tetris, because Super Mario is a much more interactive game. Users will interact with Gameboy more often, requiring faster feedbacks than Tetris.

Q3: What's the difference between different energy sources?

A: Nowadays, the research prototypes all use solar energy as their main harvesting target because it is the only source that has sophisticated technology and stability. Other sources like heat, vibrant, or RF, the harvesting technology is still immature. Another source is the manual energy input, such as collecting the mechanical energy of pressing buttons or squeezing new textures that enables harvesting energy, but the efficiency is not as good as a solar panel. Such as the GameBoy prototype that we're working on, the energy of pressing buttons provide only 15% percent of the energy in all. But it can be felt that when the user is intentionally pressing buttons during the interruptions, the task can be resumed for a short period of time.

Q4: What are the pros and cons of energy harvesting applying to mobile devices?

A: In probably three to five years, we can expect small IoT devices like smart home devices that have a fairly stable working context applying energy harvesting. Then through iterations and feedbacks on the market, it can gradually be introduced into smartphones or tablets, replacing some of the component's power supply.

4.2 Two Pivotal Roles

Aiming at envisioning the Future EP, the technological impact of energy harvesting should be exploited. In this section, two pivotal roles of influencing current EP are summarized from the outcome of interviews.

Intermittent Operation

One of the main changes for mobile device users is the perceiving action. The battery-based energy system developed the Passive/Active BI as its manifestation. The user perceives the battery level, starts the cognition cycle, and takes actions accordingly. Therefore, the shift of perceiving action, as the starting point of every HBI, will entirely change the game. And the incentive of such transformation, is intermittent operation.

It is obvious that for the ambient energy system, either passive or active BI will not be capable of the externalization of energy. **Users will have to adapt to a more dynamic, low-predictable energy system as well as the manifestation of it.** Besides, users will also feel abruptions now and then because of the lack of environmental energy availability. **Intermittent operation, together with the future energy indicator,**

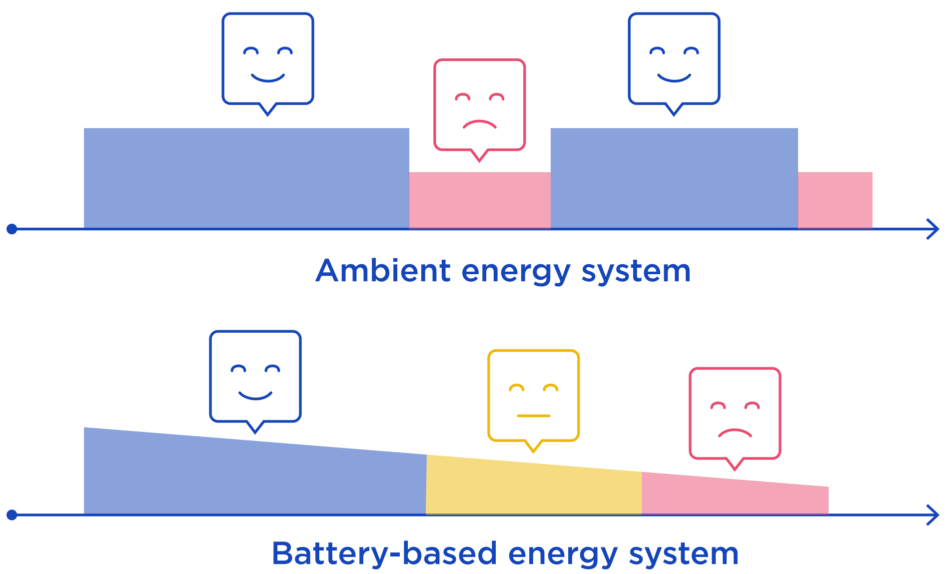


Figure 4.2 - Comparison of two different energy system

will be the starting point of future HBI.

Furthermore, the previous percentage indicator enables users to predict the remaining time and adjust their usage intensity accordingly, which will no longer be the case in the energy harvesting devices. Intermittent operation will show up unexpectedly and thus force users to face (and probably solve) the issue of energy shortage.

Multiple Energy Input

Multiple energy input, on the other hand, enables future users to take actions on the sudden interruptions, especially the manual energy input. As discussed in expert interviews, manually pressing buttons or new form of textures can compensate for the abrupt energy shortage issue that user encounters. Hence, **the manual energy input will act as a new type of Actions in EP Model and provide opportunities for users to self-generating energy as emergency measures.**

Moreover, other ambient sources like heat, kinetic, or RF will also be utilized in mobile devices of specific use scenarios. For example, the kinetic energy will be rather accessible when the user is jogging. Such future devices with specific use cases and energy input might open up the possibilities for future designers to explore.

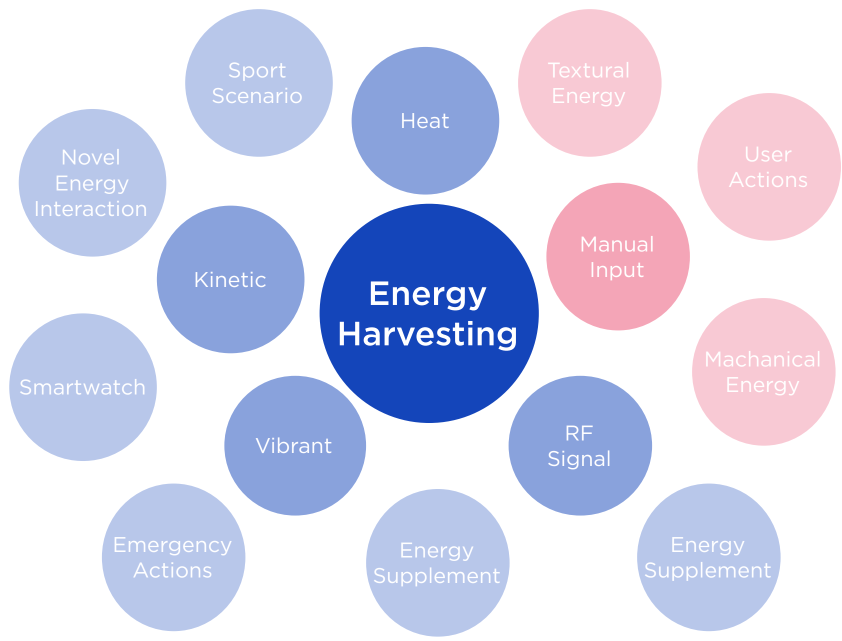


Figure 4.3 - Diagram of diverse energy input

4.3 Hypothesis of Future EP Model

After setting the two pivotal roles as impact factors of the current EP Model, a hypothetical Model is created representing how energy harvesting will influence the current model. Then prototypes will be designed and test subsequently so as to iterate on the hypothesis. The diagram below represents how these two pivotal roles influence the Current EP Model and guide the rest of this project.

Factors Transformation

• Interactivity Intensity
Since the intermittent operation is related to the degree of interactivity, interactivity intensity can play as the main trading off action receptor. However, due to the limited time of this project as well as the difficulties of defining the intensity of interactivity, the rest of the project will not cover this factor.

• Energy Awareness
Intermittently powered devices will mainly be powered by ambient energy, it can be derived that future users will build a sense of environmental energy and roughly judge the environment energy availability based on long-term usage.

• Spacial Changing
Since intermittently powered devices will rely on environmental energy, one of the main options for users facing interruptions is just find another space with more energy supply. Therefore, a new type of action, spacial changing should be taken into consideration.

• Intermittent Operation
intermittent operation will play as one of the Active BI and users will perceive it as soon as the energy shortage takes place in the device.

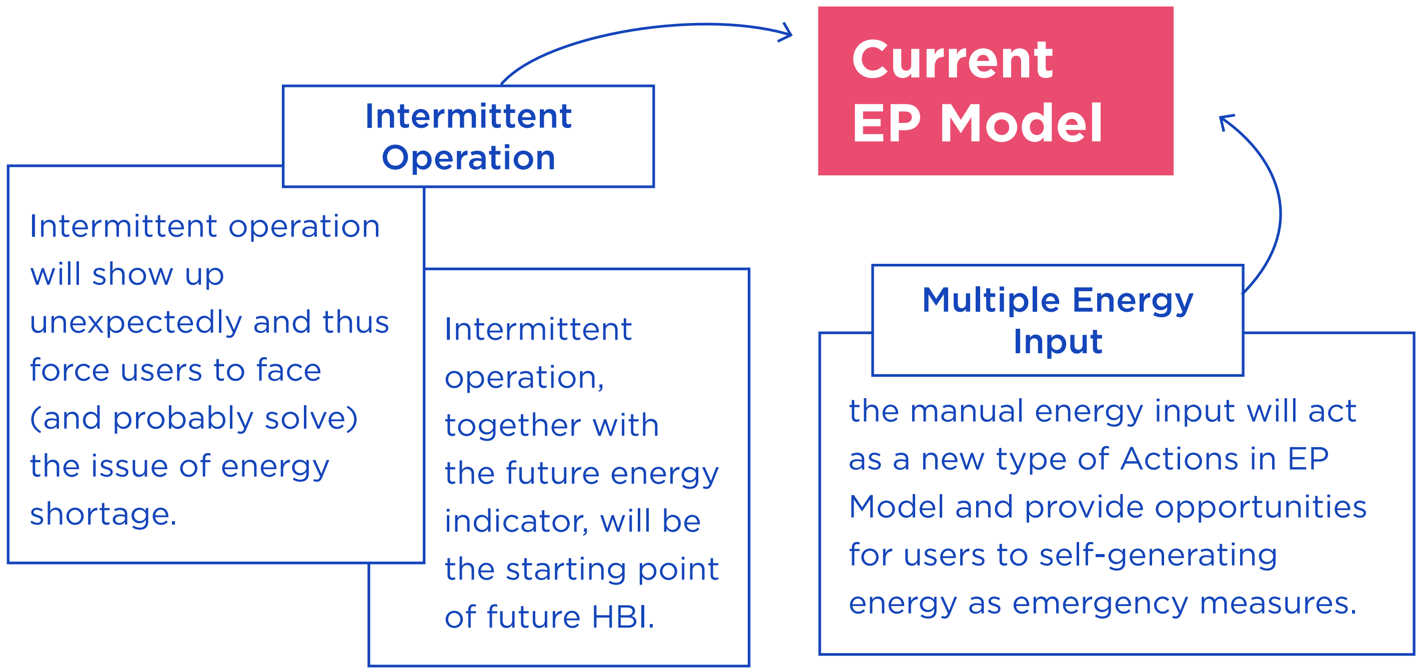


Figure 4.4 - Diagram expressing the relationship between two pivotal roles and the current EP Model

Assumptive Factors

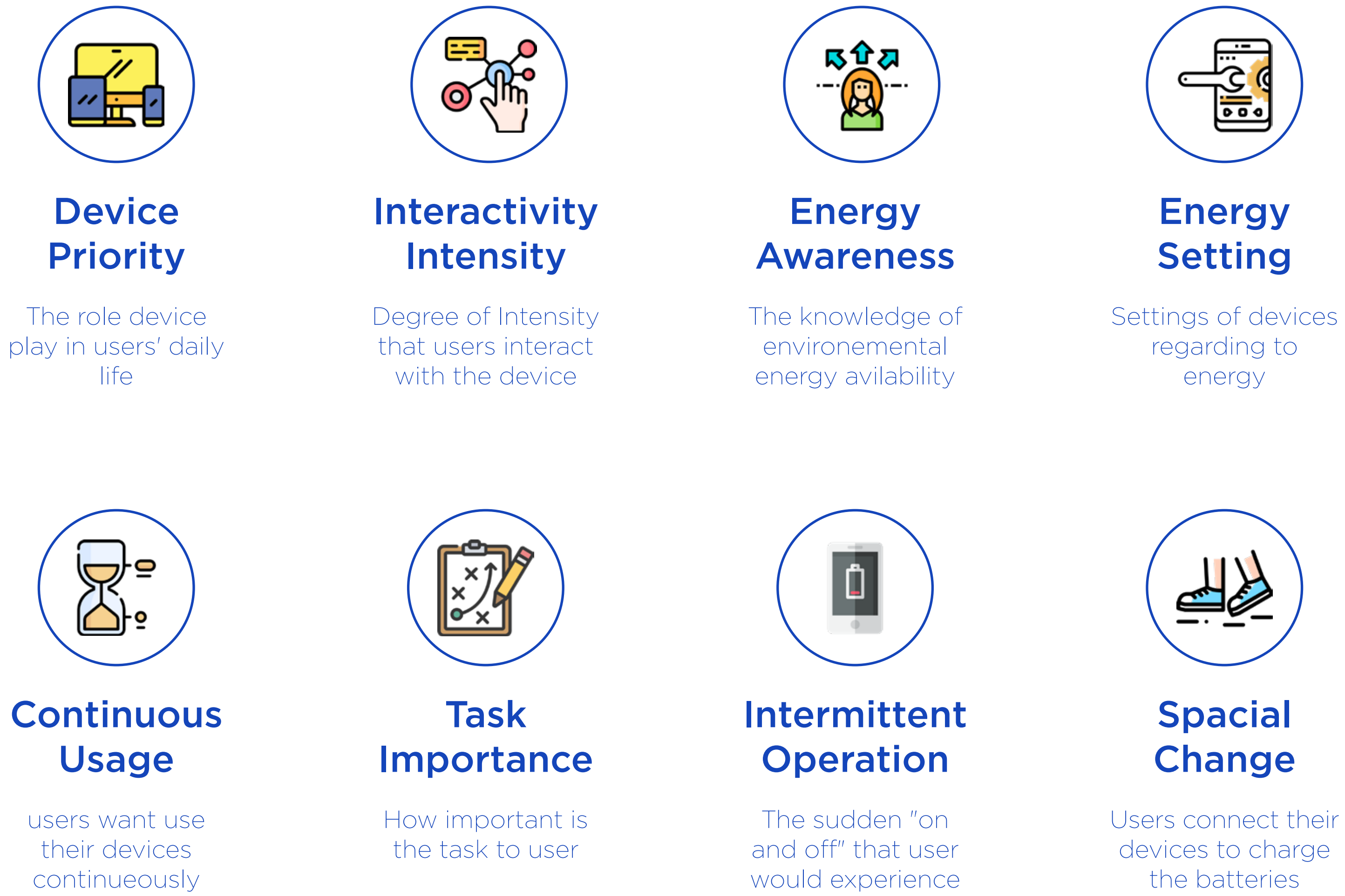


Figure 4.5 - The hypothetical factors

Hypothetic EP Model

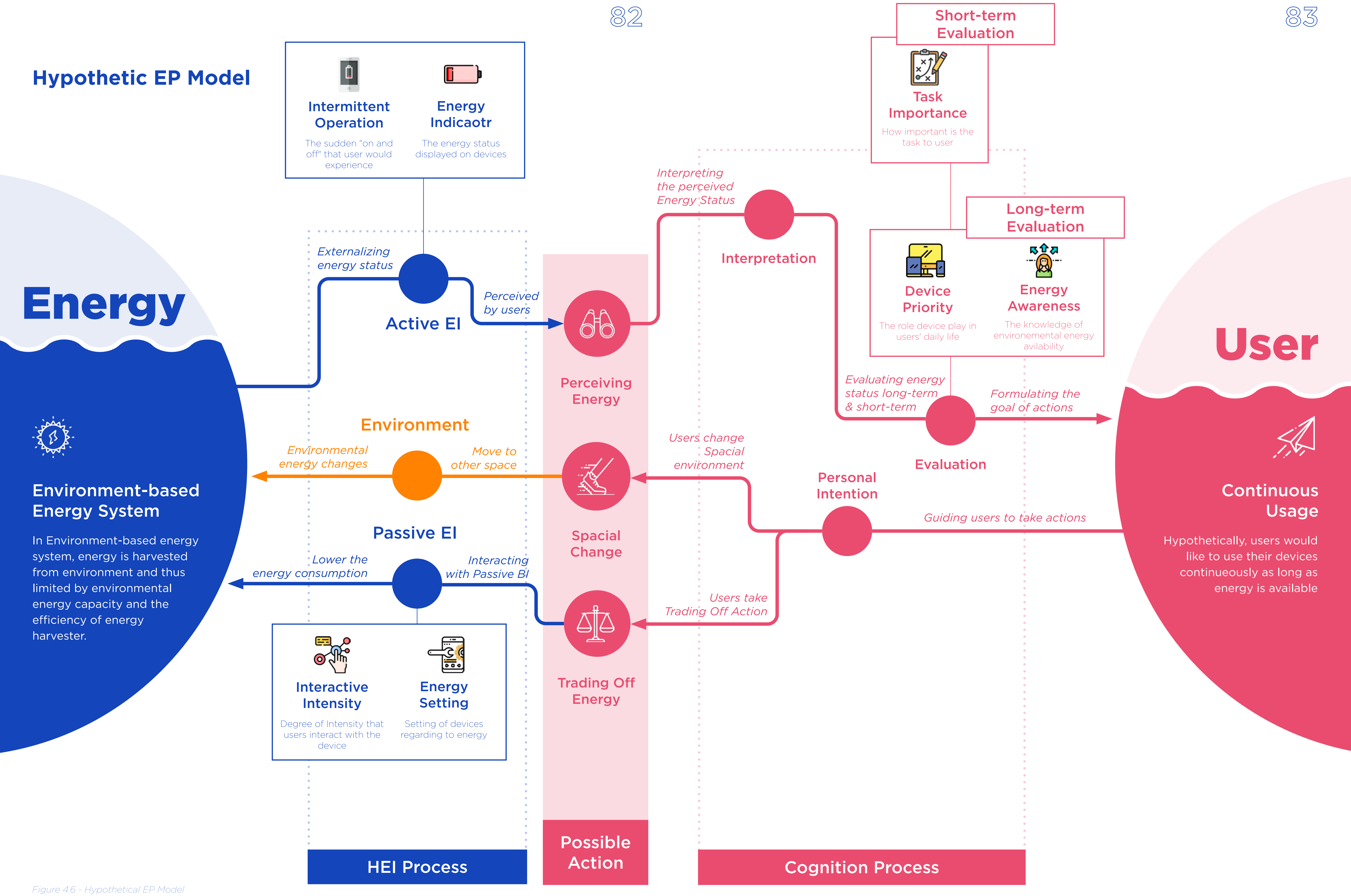


Figure 4.6 - Hypothetical EP Model

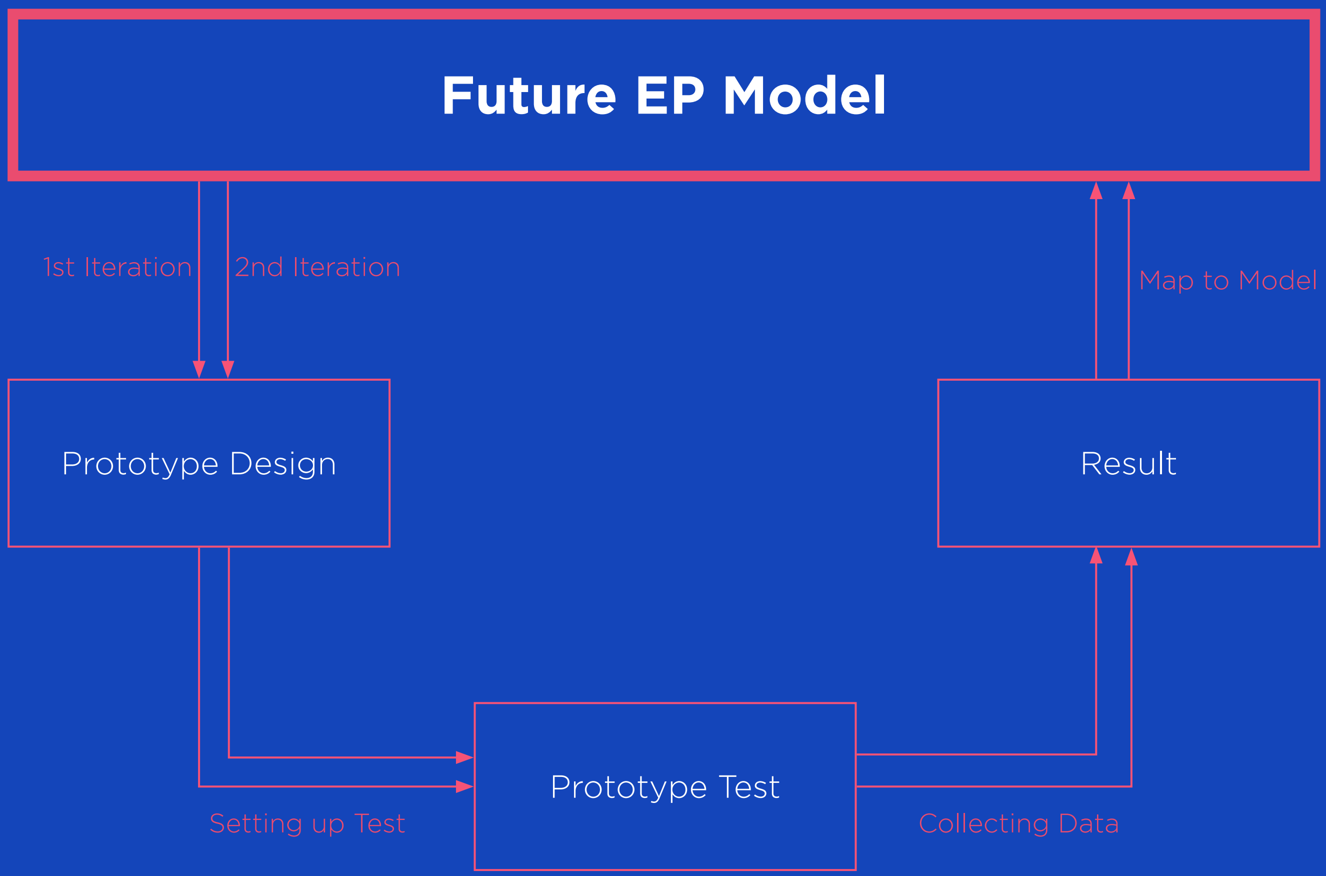


Figure 5.1 - The research structure of Chapter 5

05

Reseach through Design

Overview

This chapter describes the iteration process of the Future EP Model through the design and test of prototypes simulating the energy behavior of intermittently powered devices. After setting up the test, a reusable prototype framework was designed and applied to the following iteration process. Furthermore, the future model is iterated twice according to insights gained from testing.

5.1 First Iteration

Reaction on Intermittent Operation

In order to find out how users will react to intermittent operation as well as iterating on the hypothesis, a prototype design and user tests were conducted.

Test Setup

• Objectives
The objectives of user test are:
a. User Action
To get the knowledge of how will user react and feel facing intermittent operation under critical and relaxation situation.
b. Conceptualized Goal
To learn the goal of the user's energy interactions towards intermittent operation.
c. Evaluation Factor
To understand the long-term and short-term factors that user taking into consideration before taking actions

• Participants
Eight participants were invited with different backgrounds and customs towards energy in their devices. The minimum requirement for participation is to have experience in using battery-based devices.

• Context
As the prototype simulated the harvesting process of intermittently powered devices, the context of the test needs to provide a diverse light environment for participants to react to the intermittent operation. Therefore, the tests will be conducted at participants' homes so that participants could react to the intermittent operation based on the familiar conditions.

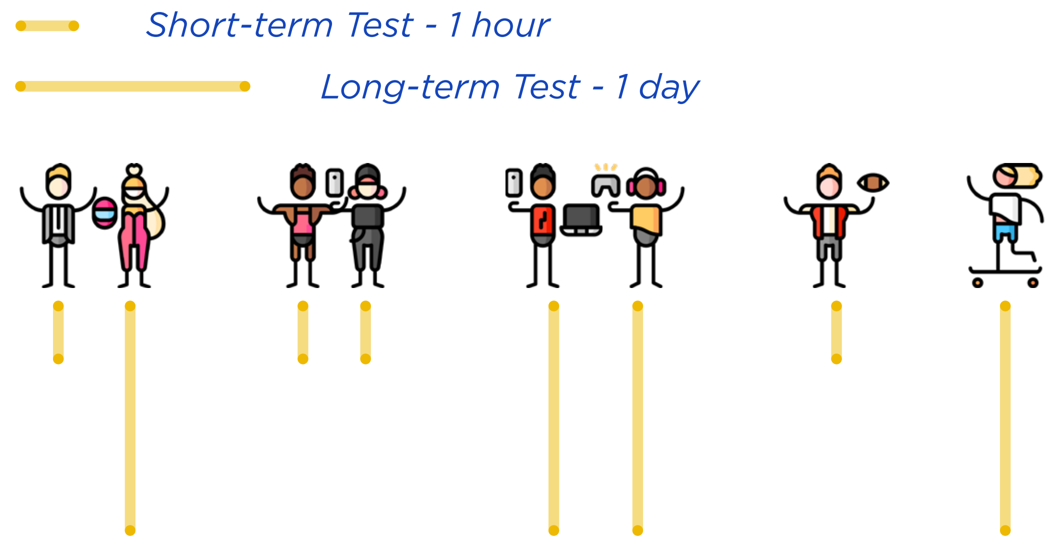


Figure 5.2 - Testing setup

• Measurement
The user test used observation and follow-up interviews as the main ways of getting insights. As the goal is to gaining knowledge instead of measuring the design itself, the key value for this user test is to observe participants' reactions towards the intermittently powered device and find out their conceptualized goal and evaluation factors.

• Task
Participants were asked to use the provided prototype to listen to music for one hour or one day. Again, because of the unstable power supply, the music will be fitful. Participants may react to that and may try to solve it.

• Follow-up Interview
After the participants complete the task, a semi-structured discussion will be held about the reactions, feelings, and thoughts when using intermittently powered devices. A list of questions was delivered in Appendix F to guide the discussion. The question sample is presented below.
- I saw you were doing ..., what did you think when you reacted like that?
- How did you feel when you faced the sudden on and off?

• Instruments
During the test, the participants were free to move around or even go outside, depending on the context of their home. Photos and audio recordings will be taken during the tests as well as interviews.

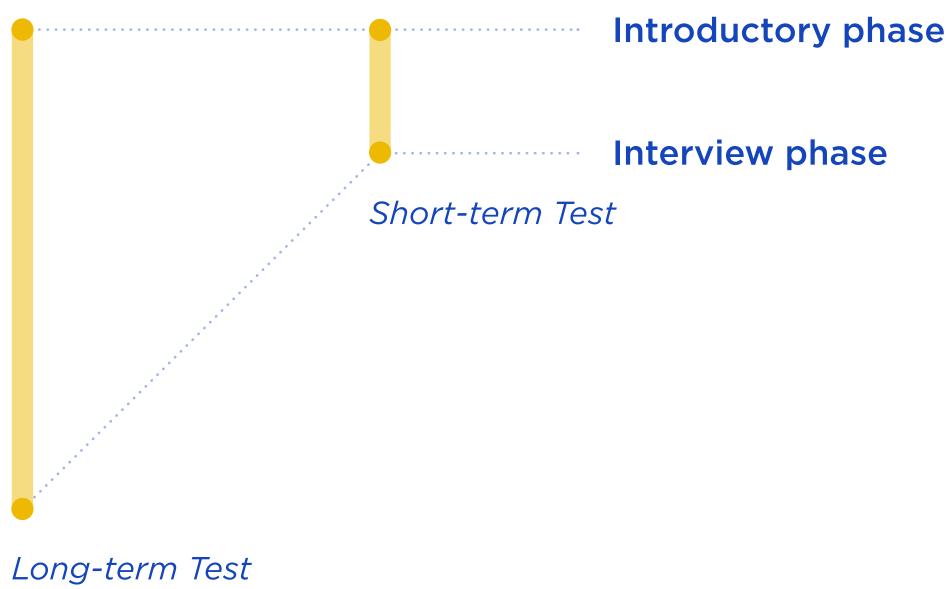


Figure 5.3 - Testing Procedure

Idea Generation

With the aim of designing a prototype that can play the music while performing the intermittent operation, two types of prototype structures were conceived and evaluated. Considered the limitation of time and prototyping technique, the light will be the only energy input that is simulated as an energy source harvested from the surrounding environment. The prototype should enable participants to play and pause, go to the next or previous tracks, and control the volume.

Option1: Arduino-MP3 Shield System

The first scheme using the Arduino board as the control center, the energy harvesting part reads the analog signal from a light sensor, estimates the energy state with preset thresholds, and expresses with three LEDs. The energy state will then be transmitted to the task performer part, which is the actual part performing the task of music playing to the participants. The pre-stored MP3 files in a TF card were read by the MP3 shield, an Arduino-compatible component that can decode and play mp3 files. Arduino board, according to the energy status, interrupts the MP3 shield to simulate the sudden stops.

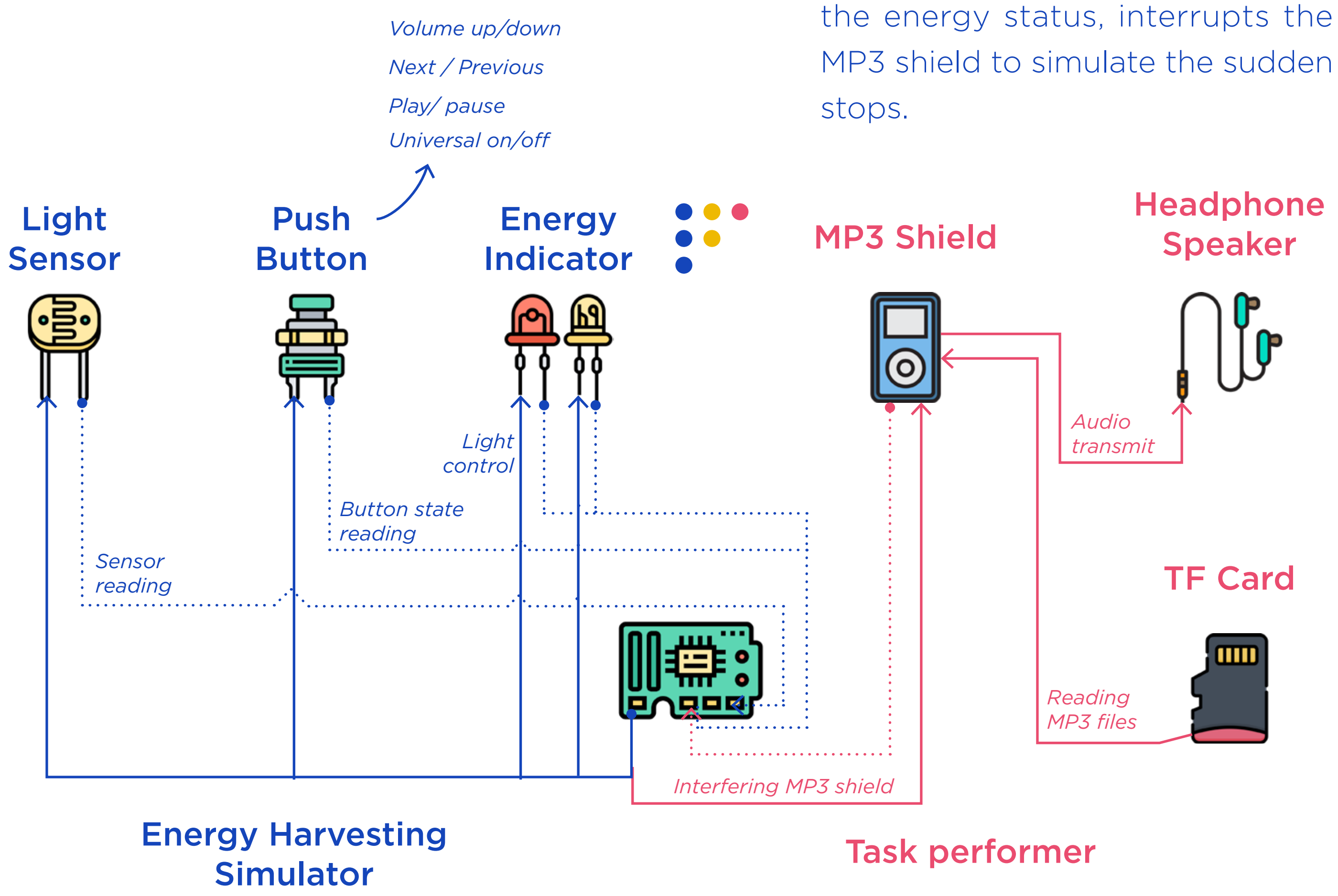


Figure 5.4 - Option 1: Arduino-Shield System

Option2: Arduino-Phone System

The second scheme using digital prototypes as the central controller of the whole prototype. The energy harvesting simulator, the same as the first one, consists of a light sensor and 3 LEDs as an energy indicator. The main task is conducted by a UI prototype that is designed with Protopie, a popular prototyping tool that can receive Arduino signals and respond. Music will be played and controlled on the phone, together with intermittent operation. After receiving the energy state sent from the Arduino board, the digital prototype respond with interruptions of sound and display.

The frequency and duration of interruptions are related to the energy states. Through this, participants will experience an intermittent music experience

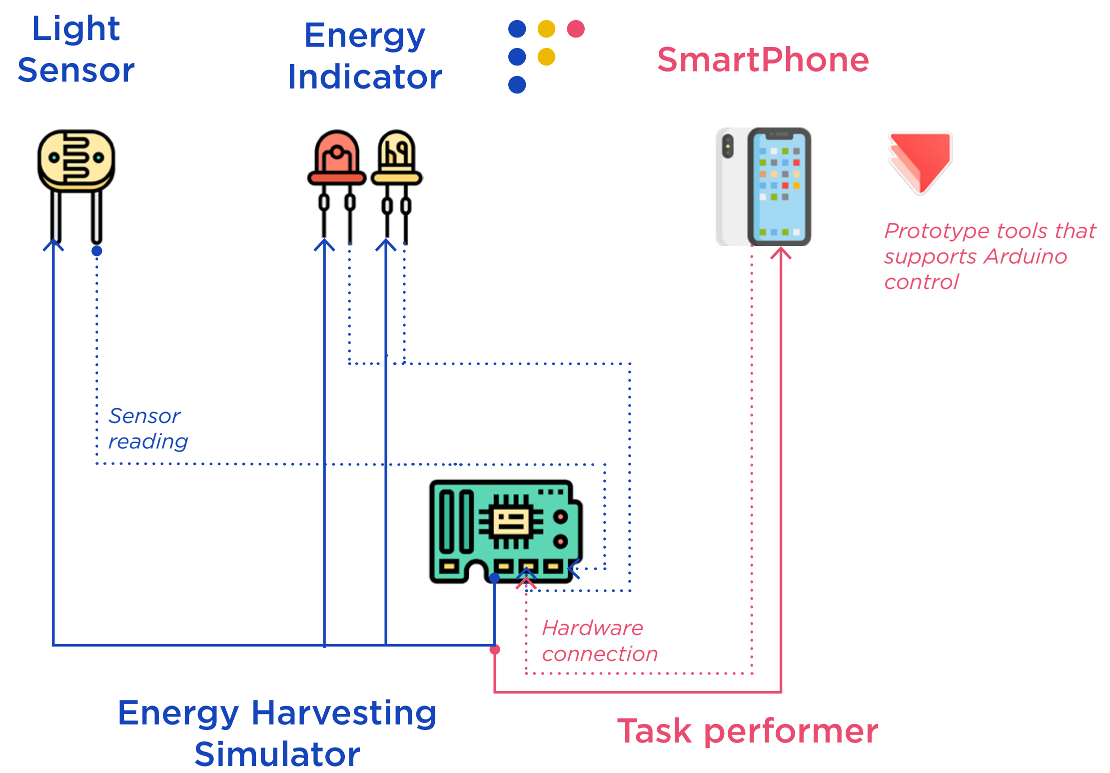


Figure 5.5 - Option 2: Arduino-Phone Framework

Prototype Design

Scheme Evaluation

Compared to the second option, the first one is more hardcore and thus difficult to fulfill. What's more, the result of it will be a screen-less, pure mp3 player like iPod Shuffle. The looking of it would be obsolete, and the interactions with it will also bring the feeling of antique. The feeling of "different product" will be hard for participants to map their normal way of using current mobile devices to the prototype, resulting in the increase of learning cost and adaptation time.

Figure 5.6 - The Spotify UI used in test

The second option, focusing on building the digital prototype, is easier to build, iterate, and modify. It triggers users to use it as a normal mobile phone and start reacting to the intermittent operation at once. The rest of the project will follow the second option as the structure of prototype building.

Digital Prototype

In order to avoid the influence of designed UI to the result, an original Spotify user interface was utilized as the main task performer. The original Spotify interactions like sliding album cover to switch to the next track, are also included in the prototype. The tracks are tailored for each participant by inquiring every participant three of their favorite songs beforehand.

Assembly

The physical construction of the prototype is shown right. The energy harvesting part is hidden in a box, connected with an Android Phone with an OTG cable. The only exposed part of the energy harvesting simulator is the light sensor.

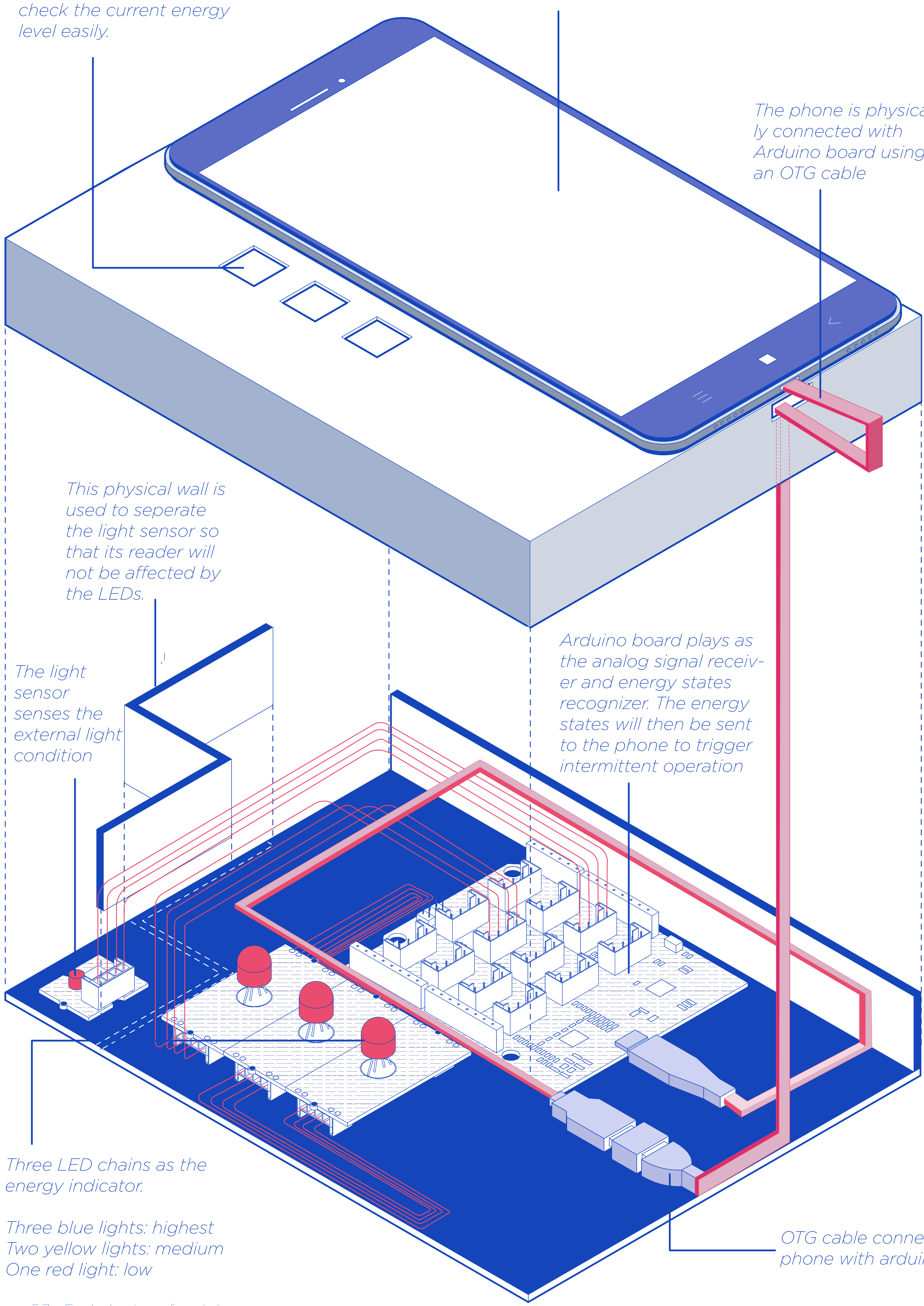


Figure 5.7 - Explode view of prototype

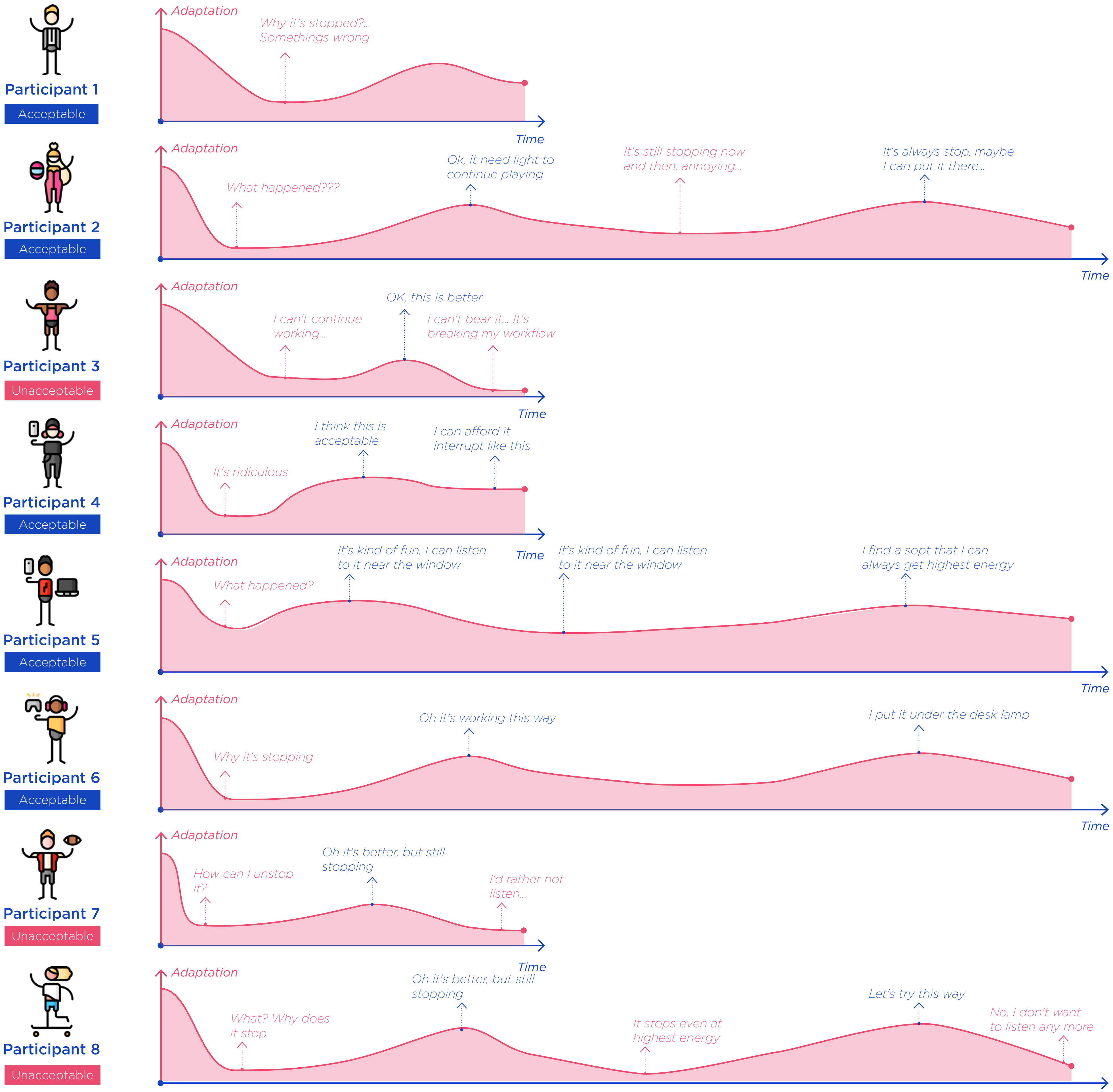


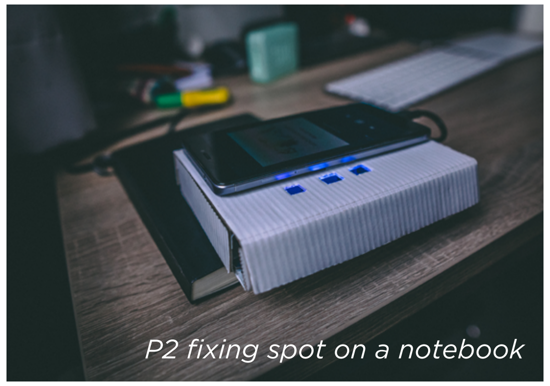
Figure 5.8 - Result Matrix

Result Matrix

The left diagram shows the change of participant's adaptation in each test. All of the participants showed maladaptation at the starting of the user test and recovered gradually through exploration, while the final result shows a diverse range of degrees of adaptation.

- **Task Importance**

Three of eight participants (P3, P7, and P8) reported that they believed that the interruptions for music listening experience is unacceptable, since those sudden stops break their flow when using music as background music for working at homes. However, there were also three participants who played music as a background reported that the interruptions were acceptable because they were not actually listening to it. They just need some sound to help them focus, and the intermittent music had little harm to that effect. The rest two participants were purely enjoying the music during tests, one reported unacceptable, and one did not. From the result presented before, it is clear that even for the same task, users hold diverse attitudes towards it. Task Importance is taken into consideration for every cognition cycle in EP.


P2 fixing spot on a notebook


P4 finding enjoying music while working at home


P6 finding highest spot near window


P3 finding solutions for annoying interruptions


P5 fixing spot under a desk lamp


P1 finding highest spot besides window


P6 putting prototype on a fridge near window


P3 exploring energy level pointing window


P8 setting "stage" for the prototype


P7 finding highest spot on his desk

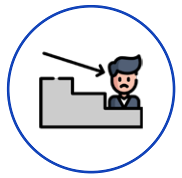
Figure 5.9 - Collection of photos during tests

Appropriate Experience

users want use their devices continueously

Fixed Scenario

The role device play in users' daily life



Lower Requirement

Settings of devices regarding to energy

Energy Accessibility

The knowledge of environemental energy availability

Outcomes

• Fixed Answers

One of the key findings from observing and interviewing participants' reactions is they all tried to find a "fixed spot" for this prototype so that they do not have to worry about where is the highest the spot. Such a phenomenon is remarkably noticeable on the long-term participants who experienced the prototype for one day. Additionally, several participants also envisioned this technology being applied to devices that have specific functions, such as Kindle. One of them even mentioned bringing a battery-less Kindle to the balcony and read books on a sunny afternoon. Therefore, it can be concluded that as users gaining more experience of interacting with energy in intermittently powered devices, a fixed scenario of using such devices that tend to high environmental energy levels will be formed by future users.

• Access high energy spot

As for the instant actions, participants all tried to find a higher energy spot when being interrupted by intermittent operation. The process of continuously evaluating the surrounding ambient energy level based on previous knowledge and real-time perceptions took place in every test. This process can be served as a new form of evaluation in the future EP Model.

• Lower Requirement

Another novel insight from post-interviews is that all of the participants were lower the requirement for the intermittent music listening experience. For battery-based mobile devices, the experience is always non-interfered as long as the battery is not dead. When participants experience the interfered experience on battery-less devices, however, they lowed their basic requirement for an experience to match the imperfect experience in tests.

• Appropriate Experience

From what has been discussed before, it can be concluded that in the future EP model users will look for Appropriate Experience for every energy future energy interaction. In other words, Appropriate Experience is the conceptualized goal in the future EP model. As users getting used to the setting that devices are powered by ambient energy, time is no longer the burden for using devices. Instead, every experience on future devices might be interrupted and imperfect because of energy shortage. Therefore, the seek for appropriate experience will be the goal of energy interactions.

First Future EP Model Deduction

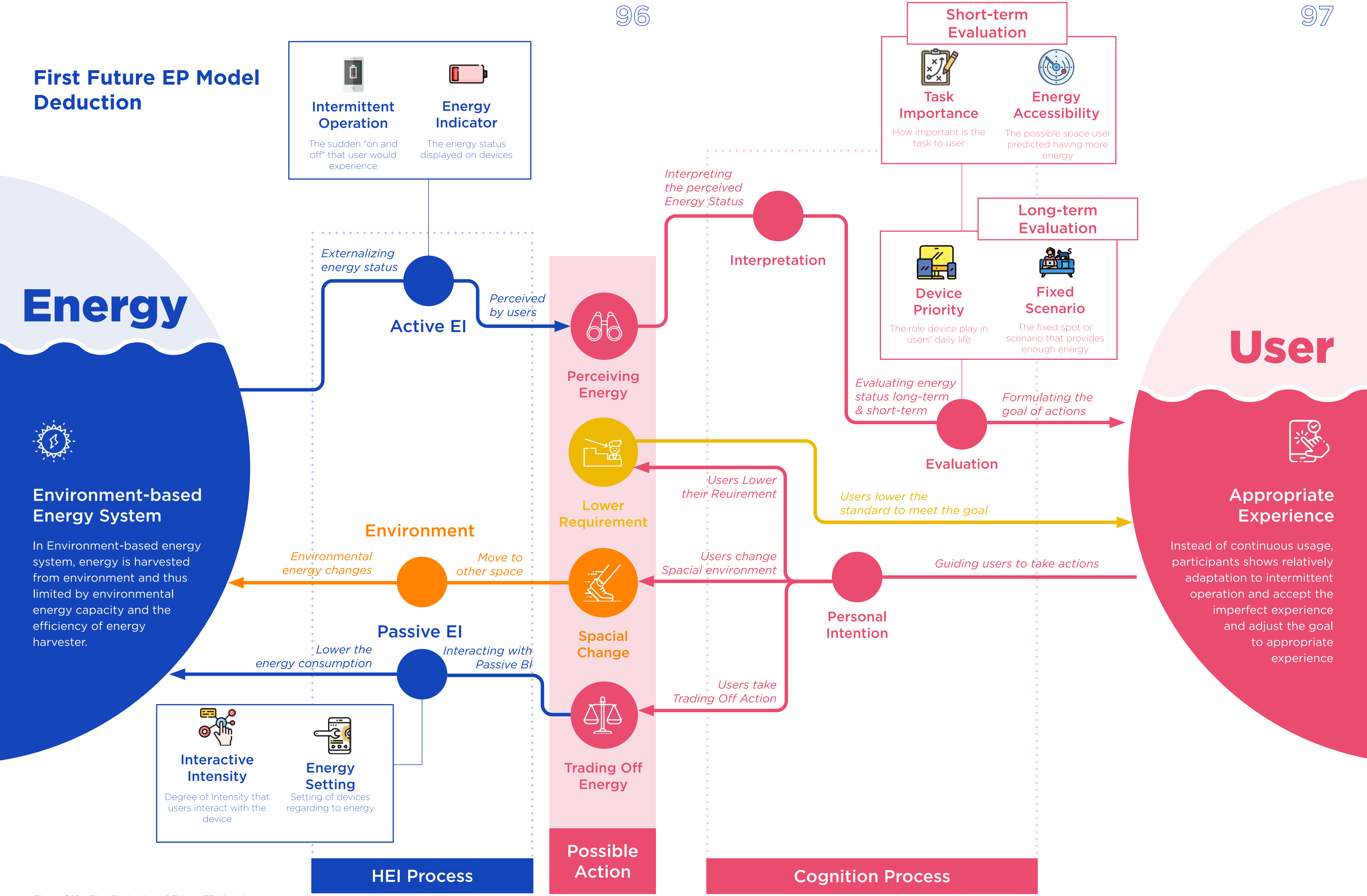


Figure 5.10 - First Deduction of Future EP Model

5.2 Second Iteration

Multiple Energy Input

Another pivotal role, multiple energy inputs, will enable users to take actions on sudden interruptions, especially on urgent usage(Page 59). Aiming at iterating on the future EP model and discover how the second role will change the way users engage with intermittently powered devices, a second design and test were conducted.

Test Setup

Since the second test follows the setup of the first test in most aspects so as to get a consistent result. Only the difference will be discussed next.

- **Objectives**

The objectives of the second test are

a. User Action

To get the knowledge of how the user will use the option of multiple energy inputs and what they will envision multiple energy inputs in future use scenarios.

b. Conceptualized Goal

To see if the goal of the user's energy interactions towards intermittent operation will transform because of a new way of interacting with energy.

c. Evaluation Factor

To verify if multiple energy inputs will change the long-term and short-term factors that users are taking into consideration before taking action.

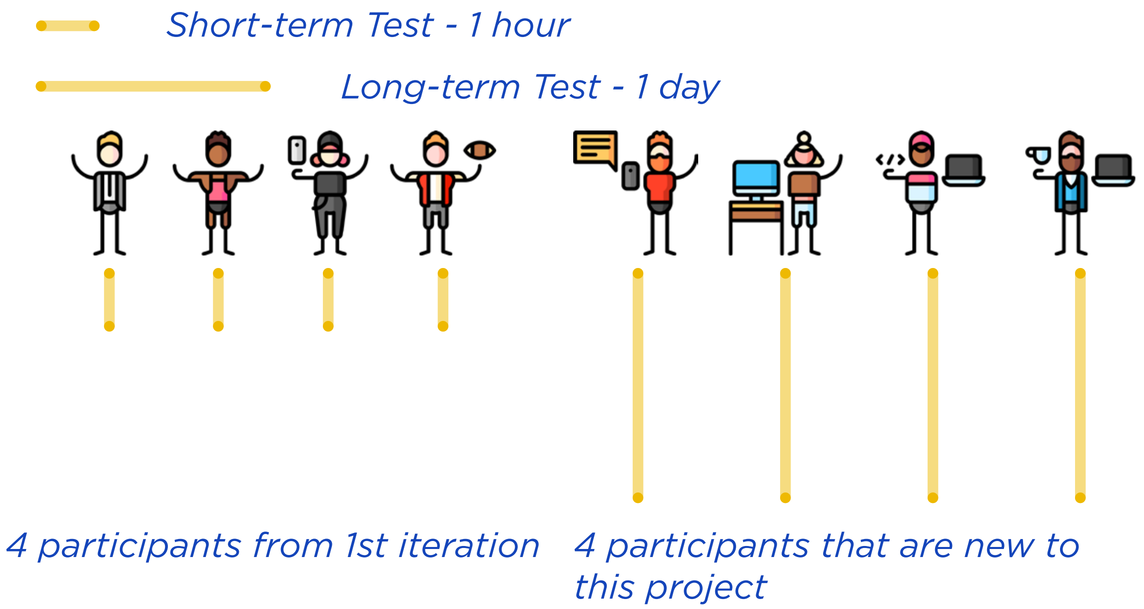


Figure 5.11 - Testing setup

- **Participants**

Eight participants were invited with different backgrounds and customs towards energy in their devices. Four of them were from the first iteration, while the other four are new to this project.

- **Context**

The tests will be conducted at participants' homes and public spaces of the apartment (if they want), just as the first iteration.

- **Measurement**

The user test used observation and follow-up interviews as the main ways of getting insights. What is different from the first iteration is that the interviews will ask the participants to envision their possible usage of the multiple energy inputs in future scenarios.

- **Tasks**

With the goal of variable control, participants were asked to perform the same task as the first iteration: listen to music with the provided prototype for one hour or one day. But the second prototype provided a manual button simulating the manual energy input.

- **Follow-up Interview**

After the participants complete the task, a semi-structured discussion will be held about the reactions, feelings, and thoughts when experiencing intermittently powered devices with the manual energy button.

- **Instruments**

During the test, the participants were free to move around or even go outside, depending on the context of their home. Photos and audio recordings will be taken during the tests as well as interviews.

Prototype Design

The second prototype followed the same basic structure as the first one, which consisted of an energy harvesting simulator and a mobile phone performing the task. The main difference between the first prototype and the second is the manual energy input in the energy harvesting simulator.

Simulation of Manual Energy Input

Based on what has been discussed in chapter 4, the multiple energy input serves as a measure that enables users to manually power the intermittently powered devices through mechanical or textual structure. Manual Energy Input is extremely helpful when users face urgent use cases, like making an important phone call. Therefore it is essential to be covered in this project. Since mechanical energy input is more practical to simulator and easily adapted by the partcipants, the second prototype will focus on simulating the mechanical energy.

According to quotes from previous expert interviews, the mechanical button can provide 15% of the whole energy harvested from diverse sources. Considered the credibility of hardware and the condition of tests, a button was added to the first prototype serves as the simulator of manual energy input. Additionally, to simplify the interactions during tests, the button was designed to bring the device back for one second when participants click it once during intermittent operation.

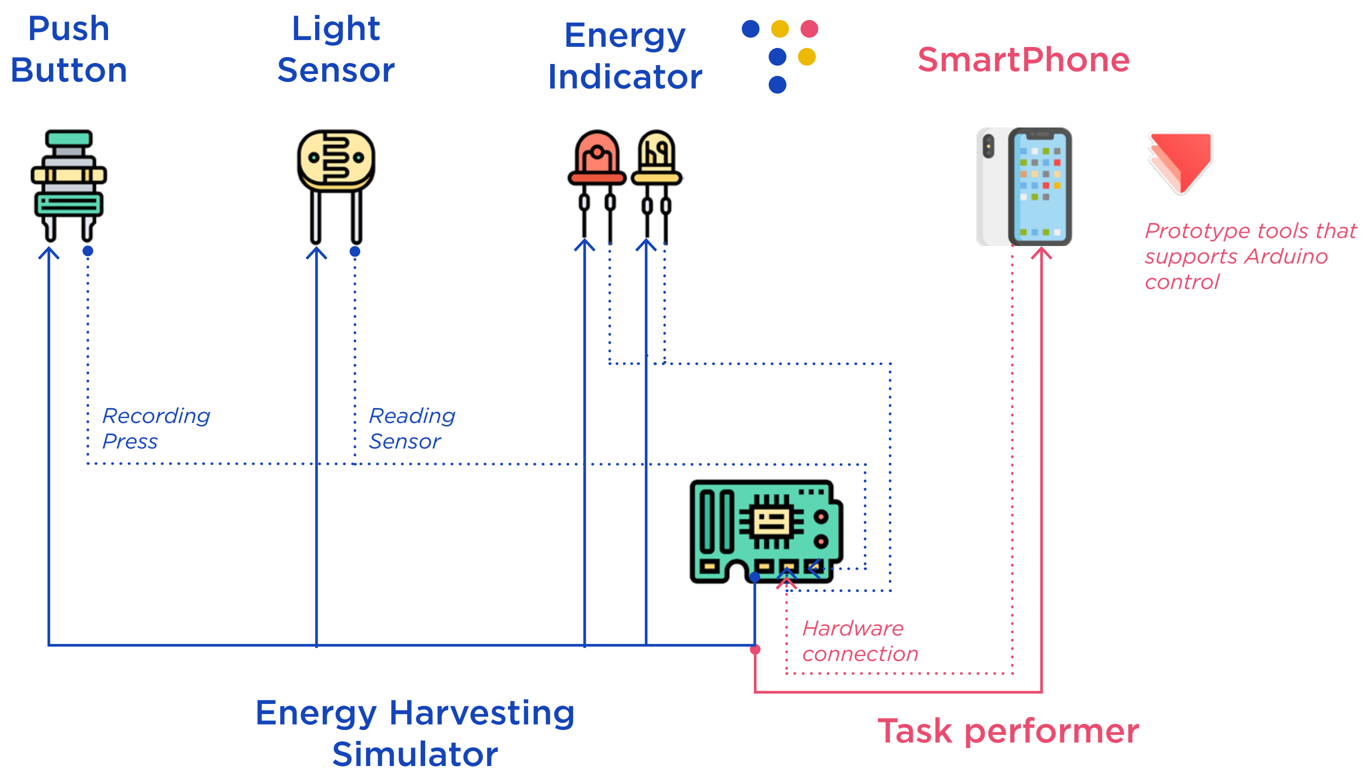


Figure 5.12 - Arduino-Phone Framework for manual energy input

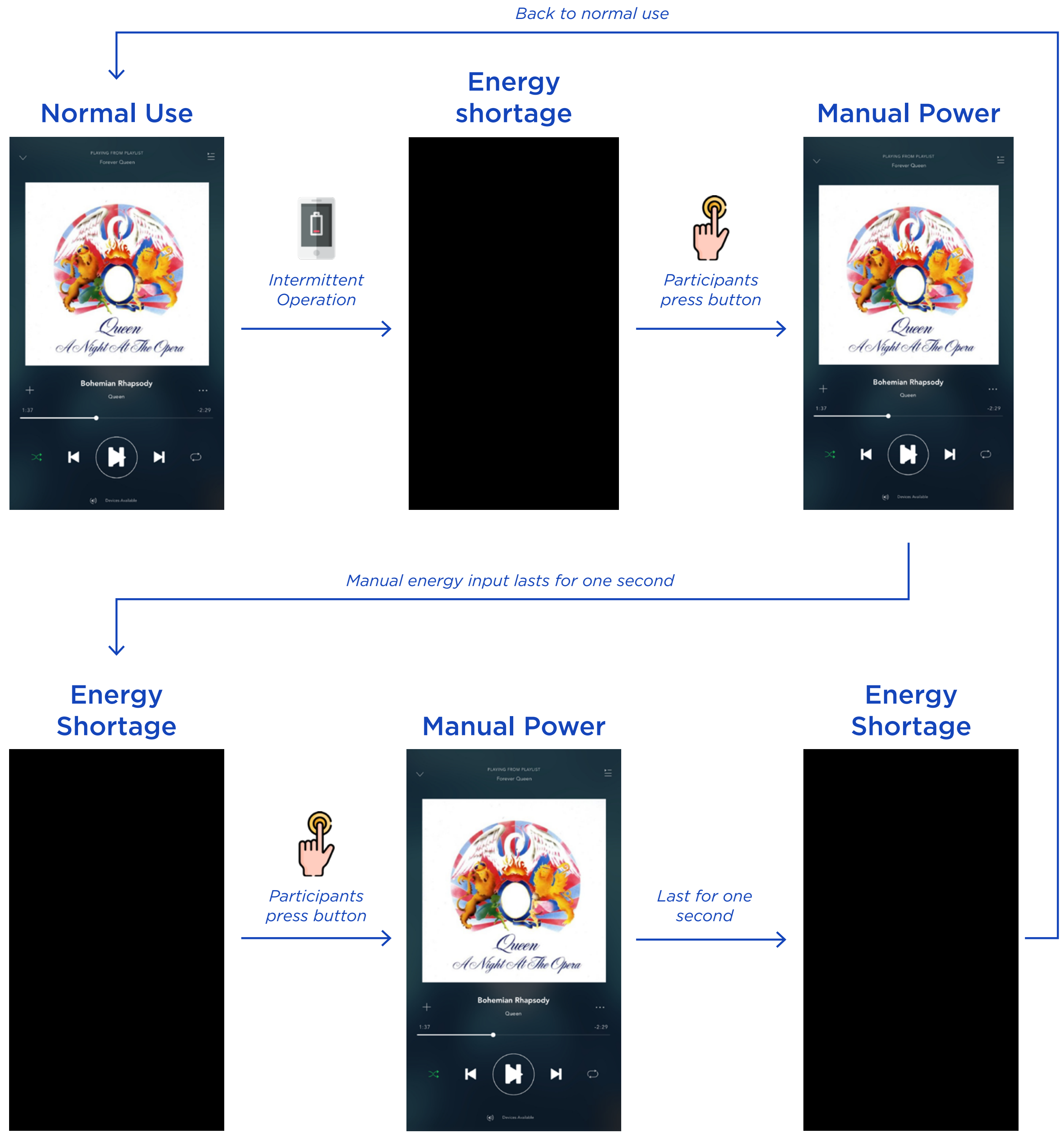


Figure 5.13 - Demonstration of the button interaction

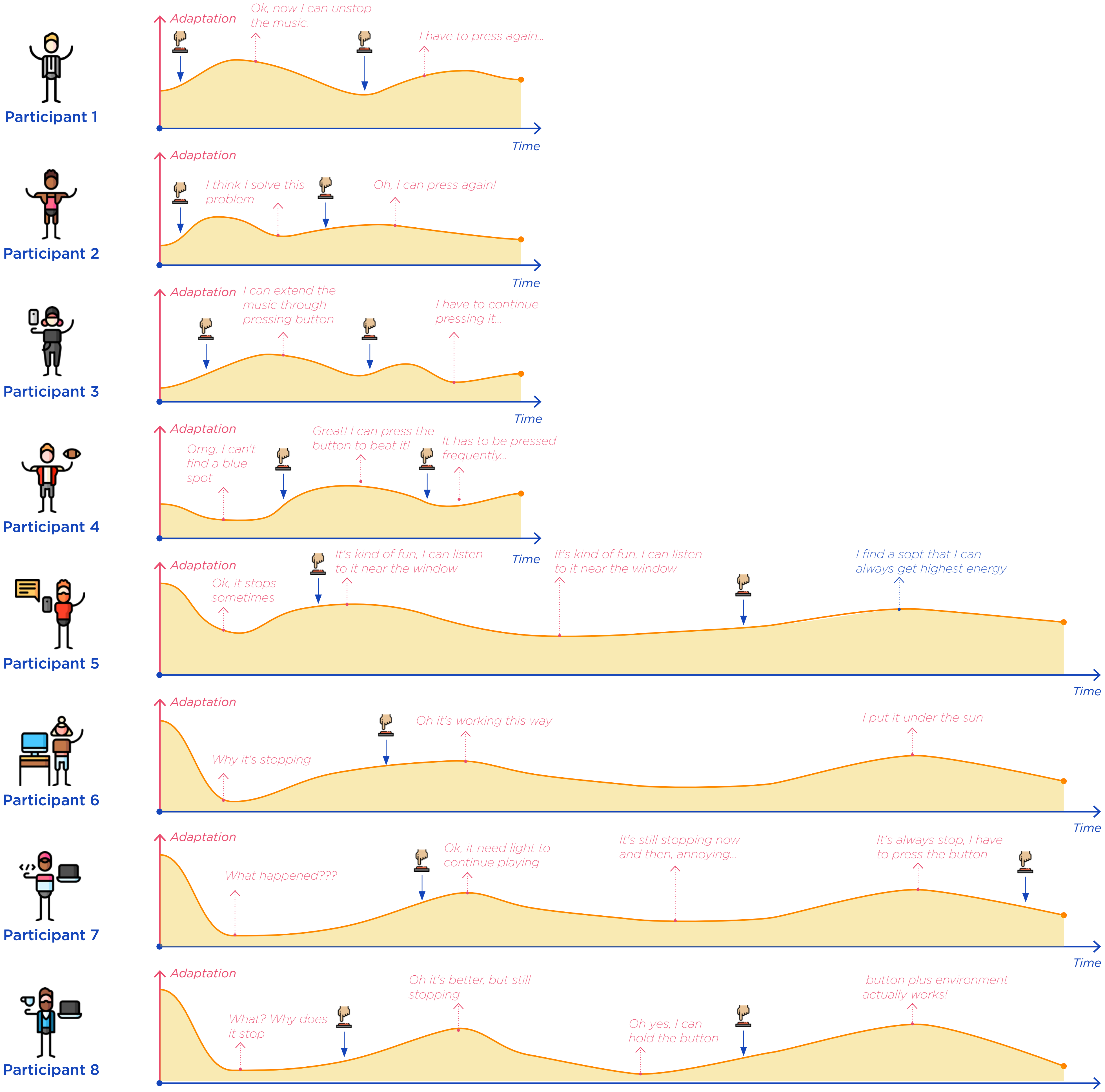


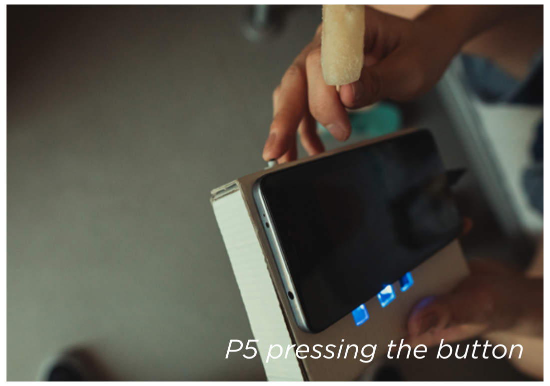
Figure 5.14 - Result Matrix

Result Matrix

The diagram on the left side shows how eight participants adapted manual energy input and intermittently powered devices. The first four participants who experienced the intermittent operation get used to the energy button quickly. In comparison, the other four participants who were new to this project took some time to digest the behavior of those two pivotal roles.

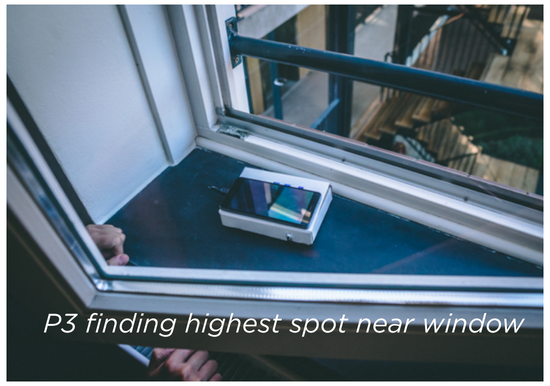
• A new type of action

All of the participants have been observed trying to press the button when encountered energy shortage. The feedback of pressing the button, which brings the device back from suspension for one second, has also been perceived well by all eight participants. Several participants reported that such a new energy action make the intermittent music not that annoying and uncomfortable. The button ease their minds when facing the side-effect of energy harvesting.



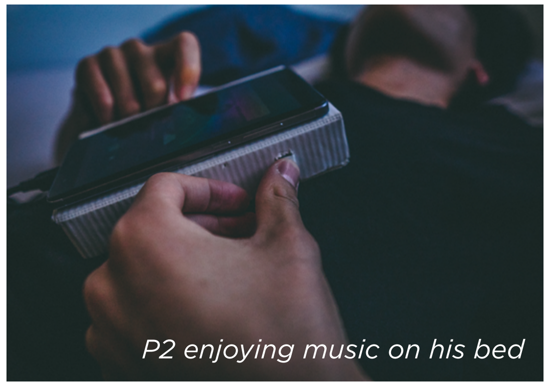
P5 pressing the button

P6 enjoying the music beside the bed



P3 finding highest spot near window

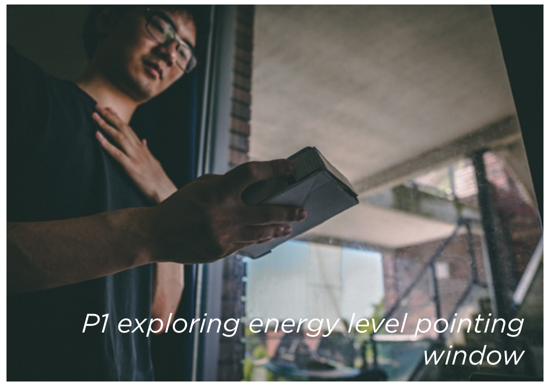
P8 reform his environment condition



P2 enjoying music on his bed

P2 pressing button

P7 putting prototype on a fridge near window



P1 exploring energy level pointing window

P4 setting fixed scenario for the prototype

P4 finding highest spot on his desk

Figure 5.15 - Collection of photos during tests

Outcomes

• Lack of motivation

Although the button itself has been responded positively, participants also mentioned that during the follow-up interviews, they didn't have the motivation to press the button every time facing energy shortage, especially when they found the highest energy spot at home. Just as one of the participants mentioned, 'I'd rather put it near the window and let it do the work.' The proper explanation for such a phenomenon is that users still need to continuously check the prototype's energy status when they try to press the button to take action to intermittent operation, which will bring a lot more cognitive burden.

• Emergency button

What's more, when participants were asked to envision their future use case of powering the device manually when using intermittently powered mobile phones, the majority of them responded that they would press the button for essential tasks, such as making a phone call or video conferencing. Therefore, in the future EP, multiple energy inputs will mainly serve as the urgent energy source when users react to intermittent operation in essential tasks.

Concluding, manual energy inputs will be indispensable in future mobile devices powered by ambient energy. It will be the compensation of annoying abruptions not only functionally, but also emotionally. Users will have the ability to power the device manually during ambient energy shortage. They will also be more confident to use the device because they know that they have a reliable energy source. The button in the prototype performs more as a simplified simulation than a designed interaction since this project focuses on the relationship, not the design itself.

Figure 6.1 - Photo took during prototype test

06

Final EP Design

Overview

Chapter 6 aims to synthesize the outcomes from iterations and deliver a finalized design of future EP model conceptualizing the EP between users and intermittently powered devices.

6.1 Finalizing Future EP Model

As articulated in chapter 5, the hypothetical model brought up in chapter 4 were iterated twice through prototype design and testing activity. Future Actions and Evaluation factors were extracted from participants' reactions towards the prototypes and response of follow-up interviews. Synthesized all those insights into the hypothesis, the final model of the future EP model is shown on page 112.

Categorizing Factors

• Active EI

For intermittently powered devices, battery capacity and battery life will no longer be the limitation for user experience. With the advancement of efficiency and adaptability of energy harvesting, future devices will likely be able to operate in most environments. Users will no longer need to worry about charging their devices and dealing with battery life in almost every use scenario. However, active EI will still be provided to users since not every piece of space is ideal in practical life, and users will experience intermittent operation. Therefore, the Active EI for intermittently powered devices will be the intermittent operation in which users face energy shortage in the environment and future energy indicator that monitors the real-time energy level status of the environment that users are located.

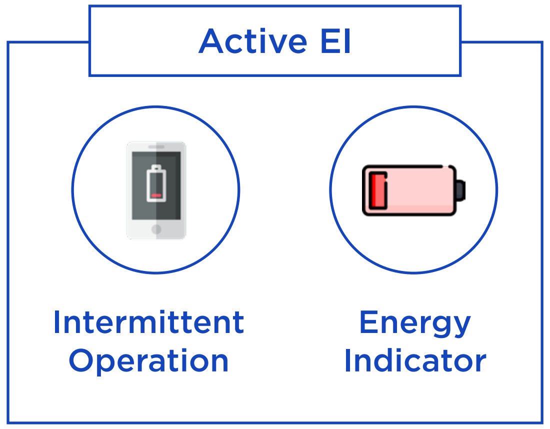


Figure 6.2 - Category of Active EI

• Passive EI

In the Current EP Model between users and battery-powered mobile devices, passive EI is the receptor of trading off action that enables users to trade-off usability for an extension of battery life. As discussed in chapter 3, current mobile device users have acquired much more knowledge and experience in using mobile devices and limited battery life. According to the current EP research in chapter 3, modern mobile users mainly adjust their use intensity and the Low-Power Mode provided by the mobile operating system as the Passive BI, other than battery management interfaces because of its limited and complicated options. In the relationship between energy and future users, based on the insights distilled from expert interviews, the Passive EI should be the interactive intensity and energy setting. Considering its alignment with the current EP and the restriction of this project, the future factors of Passive EI is not validated in this project.

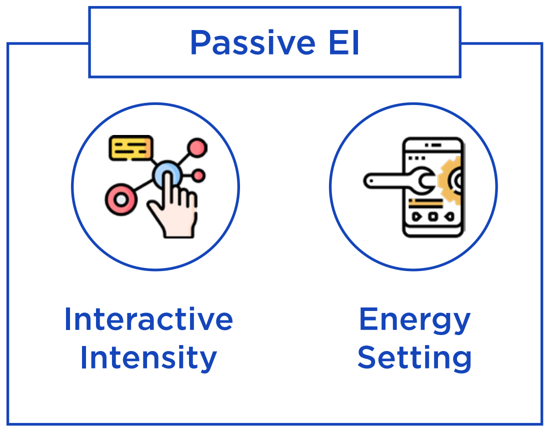


Figure 6.3 - Category of Passive EI

• Long-term Evaluation

Long-term Evaluation factors are formed through a long-term usage, articulating the relationship between devices and the diverse context of users. It can be seen as the knowledge that is accumulated through countless energy-related actions and feedbacks. Modern mobile users have adapted to the situation of multiple devices of different purposes, various ways of charging, and different battery capacities. Thus, the Device Priority describes how modern users recognize multiple devices differently, and Charging Scenario outlines how users distribute their chargers to context according to their use intensity. In the future scenario, users will gradually build their Fixed Scenario, which means the fixed spots, or scenarios such as on the balcony or under a desk lamp where users acknowledge them will provide enough power for their devices. Device Priority will stay the way it is since the trend of multiple devices with different performance and forms does not seem to change soon.

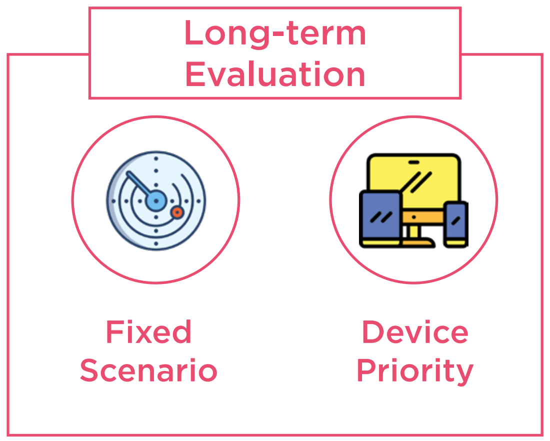


Figure 6.3 - Category of Long-term Evaluation

• Short-term Evaluation

On the other hand, short-term evaluation factors are a group of factors that users take them into account on a case-by-case basis when they try to take action on in-device energy. The current EP Model summarizes it into two categories: Task Importance outlines the current importance of the task that users want to operate on the device and Energy Availability outlines if users can get the chance to charge the device in the current environment. For intermittently powered devices, based on the two iteration process, Task Importance will play the same role while Energy Availability will perform as a new type of short-term evaluation factor describing the ability to roughly estimating the energy level of the surrounding environment.

• Actions

Those can be recorded as interactions between the user and energy interfaces are defined as energy-related Actions. As discussed in chapter 3, current actions include perceiving, charging, and trading off energy. From participants' reactions towards the prototypes, Spatial Change, Lower Requirement, and Manual Energy Input will be taken between users and intermittently powered devices.

Mapping to the Framework

Therefore, those factors mentioned before should map to the EP model structure, whose process is shown as the diagram on the right. And the result of mapping that defined as the Final Future EP Model, is demonstrated on the next page.

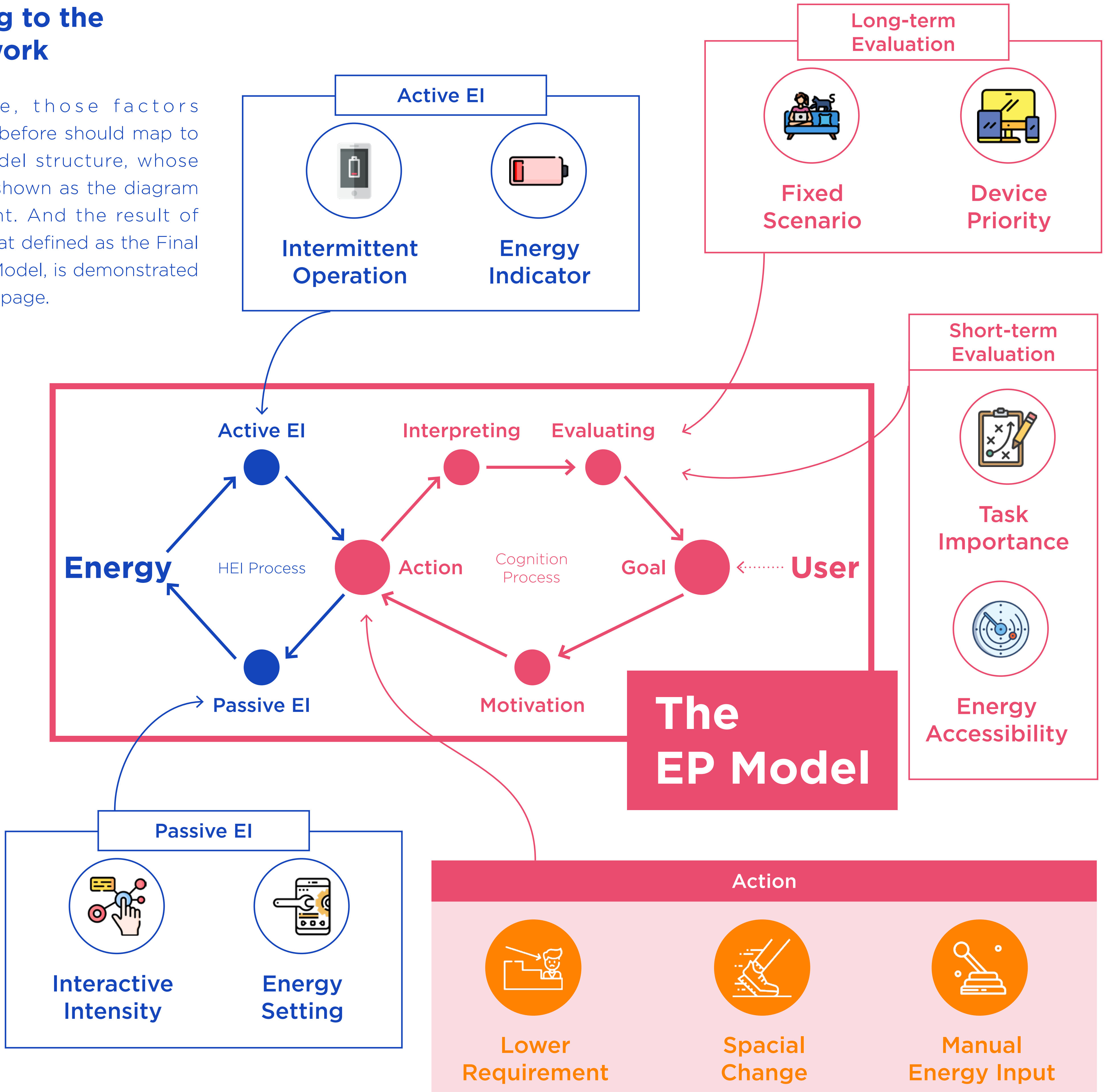


Figure 6.4 - The process of mapping to framework

Future EP Model Conclusion

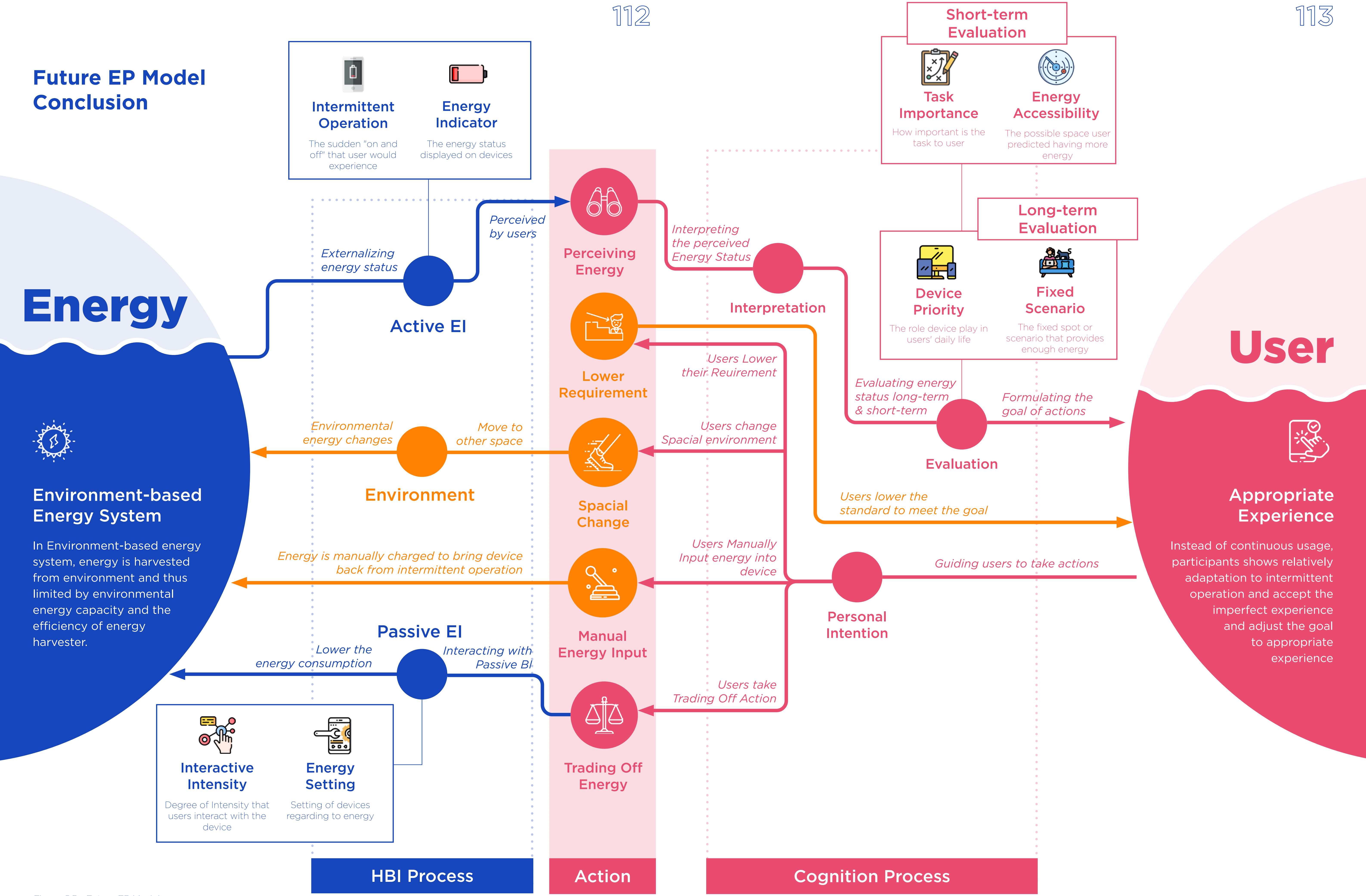


Figure 6.5 - Future EP Model

Explaining Model

The previous page model demonstrates the future relationship between energy in intermittently powered devices and users. It consists of two processes: the HEI process, which describes how users will interact with the manifestation of energy externally, and the Cognition process, which describes how users will internally process the perceived energy-related information in their minds before taking actions. Two process are connected with each other through Action. In order to efficiently explain the future model, the whole model will break down into several steps, with a diagram indicating the position and a description for each step.

Step 1: Energy (HEI)
For mobile devices that are powered by energy harvester, energy will not manifest itself until the environmental energy is insufficient. It is also the starting point of HEI process

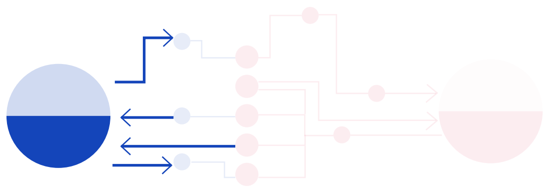


Figure 6.6 - Energy in Future EP Model

Step 2: Perceiving through Active BI (HEI)
Users will perceive the energy shortage through the Active BI, which is an Intermittent Operation and Energy Indicator that has not been designed yet.

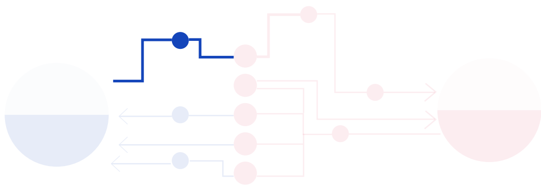


Figure 6.7 - Active EI in Future EP Model

Step 3: Evaluating (Cognition)
After perceiving and interpreting, the cognition process begins. Users will evaluate this information with long-term factors, including checking how important the device is to them and whether they have fixed scenarios formed through prolonged use. Short-term factors, such as how important the current performing task is for them, and if the surrounding space can provide more energy, will also be considered.

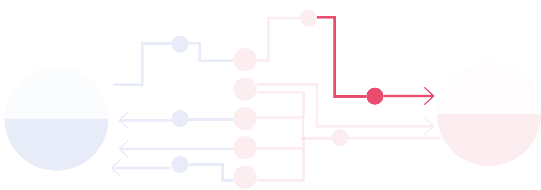


Figure 6.8 - Evaluating in Future EP Model

Step 4: Forming Goal (Cognition)
Based on the information perceived and evaluated, users will form their goals for the actions that they will take in practice, which is to get an appropriate experience of using devices.

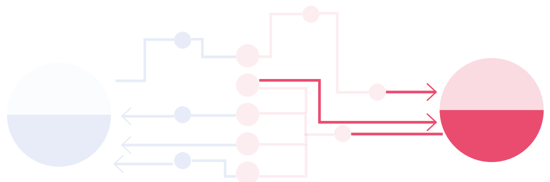


Figure 6.9 - Goal in Future EP Model

Step 5: Taking Actions (Action)
Then different types of actions, motivated by Personal Intention, will be taken by users to gain the appropriate experience. Users will try to Lower their Requirement for experience, Change the Space to reshape the relationship between environment and energy, trading off the usability for a better experience, or manual power the devices for urgent tasks.

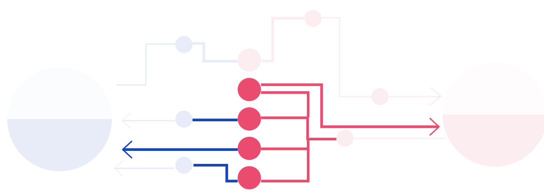


Figure 6.10 - Action in Future EP Model

Step 6: Actions taking effect (HEI)
The receptor of those actions, the Environment and the Passive EI, will be changed accordingly, and finally passed the effectiveness to the energy itself. Users will perceive the feedback through Active EI, and the whole model will operate again.

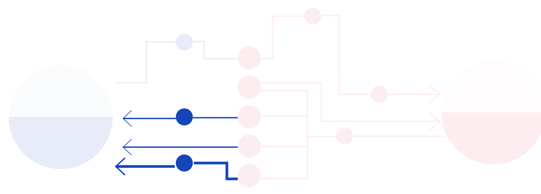
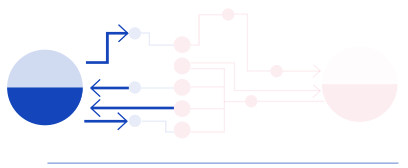
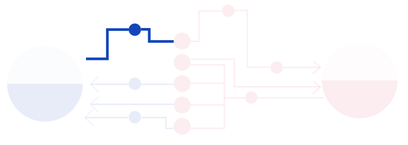
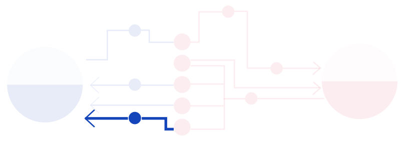
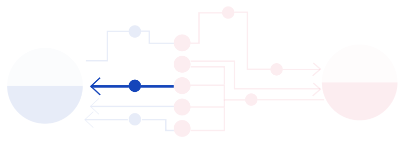
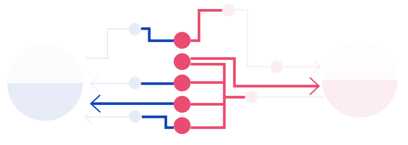
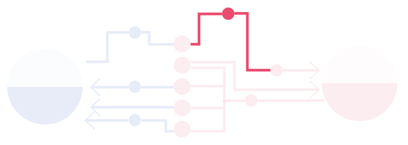
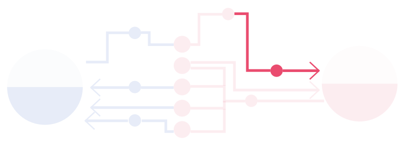
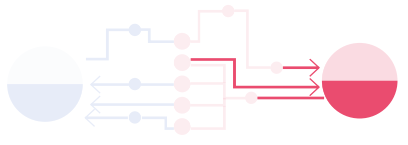
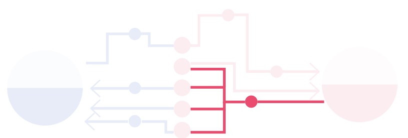


Figure 6.11 - Passive EI & Environment in Future EP Model

Through this model, it can be noticed that the Future EP Model is also a loop of perceiving, interpreting, and interacting, which users will continue performing when facing energy shortage. Users will learn to interpret the manifestation of energy, forming customized long-term and short-term evaluating factors and finally get better at manipulating energy.

Future EP Model Matrix

POSITION	CHARACTER	DESCRIPTION	PARADIGM OF FUTURE EP	TRANSFORMATION FROM CURRENT TO FUTURE
	**Energy**	The upholder for every interactions on mobile devices. It manifests itself and interacts with the user with Active and Passive EI.	Ambient-Powered Energy System	From battery-based to ambient-powered, energy will be harvested on-demand instead of being stored beforehand. Therefore the HEI process will be more dynamic, real-time, and unpredicatble for users
	**Active EI**	The device alerts the user with Active EI and displays a range of energy information that the user needs to be aware of.	Intermittent Operation; Energy Indicator	Instead of predicting and planning ahead with battery percentage indicator, users will have to face the sudden energy shortage and take actions at once.
	**Passive EI**	The user decides when to interact with the interface and when energy-related information is viewed.	Interactive Intensity; Energy Setting	When the abruption is perceived, trading off usability for a smoother experience is still accepted through Passive EI. But instead of use intensity, which is a more flexible and customizable option, user will have to reduce to interactive intensity.
	**Environment**	A new receptor of future HEI. Users either shift to a new environment or reform the current one so as to reshape the environment-energy relationship.	In the future HEI process, environment will accept user's actions with the goal of reduce the intermittent operation.	As a new recpetor of environmental-related HEI and energy source for intermittently powered devices, users enjoy its tremendous accessibility while take its dynamic and unpredicability.
	**Action**	The bahaviors that can be recorded as interactions between users and the manifestation of energy.	Perceiving Energy; Lower Requirement; Spatial Change; Manual Energy Input; Trading Off Energy	Besides perceiving and trading off, new types of actions will be taken by users, including environment-related actions, manually powering and simply lower the requirement.
	**Interpretation**	The translation process from visual signal to the data type that our mind can recognize and handle.	In Cognition Process, the status of enery is perceived and then interpreted by users. The usability of Active BI determines the efficiency and accuracy of interpretation	Users are satisfied to the current Active BI because it is easy to interpreted and mapped to estimated usage time. The new form of Active EI is not exist yet, but the knowledge from current BI can be utilized.
	**Evaluation**	**Short-term**: The factors evaluated as appropriate **Long-term**: The factors formed from long-term usage	Task Importance; Energy Accessibility; Device Priority; Fixed Scenario	Aside from Device Priority and Task Importance, the evaluation factors, either in Current or Future EP are describing the 'distance' between energy and device.
	**Goal**	The conceptualized goal that the users hold for their interactions with energy.	Appropriate Experience	Both Battery-based and Ambient-powered energy system has its restrictions. And users will have to adapt it and finally, control it.
	**Intention**	The motivation of actions and the expected consequences of actions that can be considered as private to users.	After setting the goal, users are motivated by intentions that are considered personal, indicating the private significance of the action and the expecting result of it.	Personal Intention will always been considered and evaluated in cognition process.

HEI process (Energy – Environment)

Cognition process (Interpretation – Intention)

The matrix on the left elaborates every character of the future EP Model for a better understanding of the future EP model. Here the explanation of vocabulary that are created for EP study can be found, with paradigms in future EP model and how will it shift from the current model to the future one.

The far left column indicates the position of each character in the model. The Description column explains the meaning of each character. The Paradigm of Future EP elaborates the factors for each part in future EP Model. Finally, the far right column describes the differences and transformations from Current EP to Future EP for every character.

Same as the Current Model's matrix, the characters involving in HEI process are blue, and the Action and Characters of Cognition process are marked red.

Figure 6.12 - The matrix of future EP Model

6.2 Transformation from Current to Future EP

Compared with the current mobile devices, energy harvesting technology, casting off the battery-based energy system, will empower future mobile devices with significant accessibility and diverse form without charging and limiting battery capacity. But its side-effect, intermittent operation, will also be annoying and unpredictable. Intending to uncovering how energy harvesting will affect the current EP, this research revisits battery-based EP, builds a model conceptualizing every step of interaction and cognition process, and finally brings out the future EP model through design activities. The transformation from battery to energy harvesting, is not only a technology evolution, but also a transformation of interactions and cognitions. The diagram on the next page uncovers the essence of this transformation.

Transformation of interactions

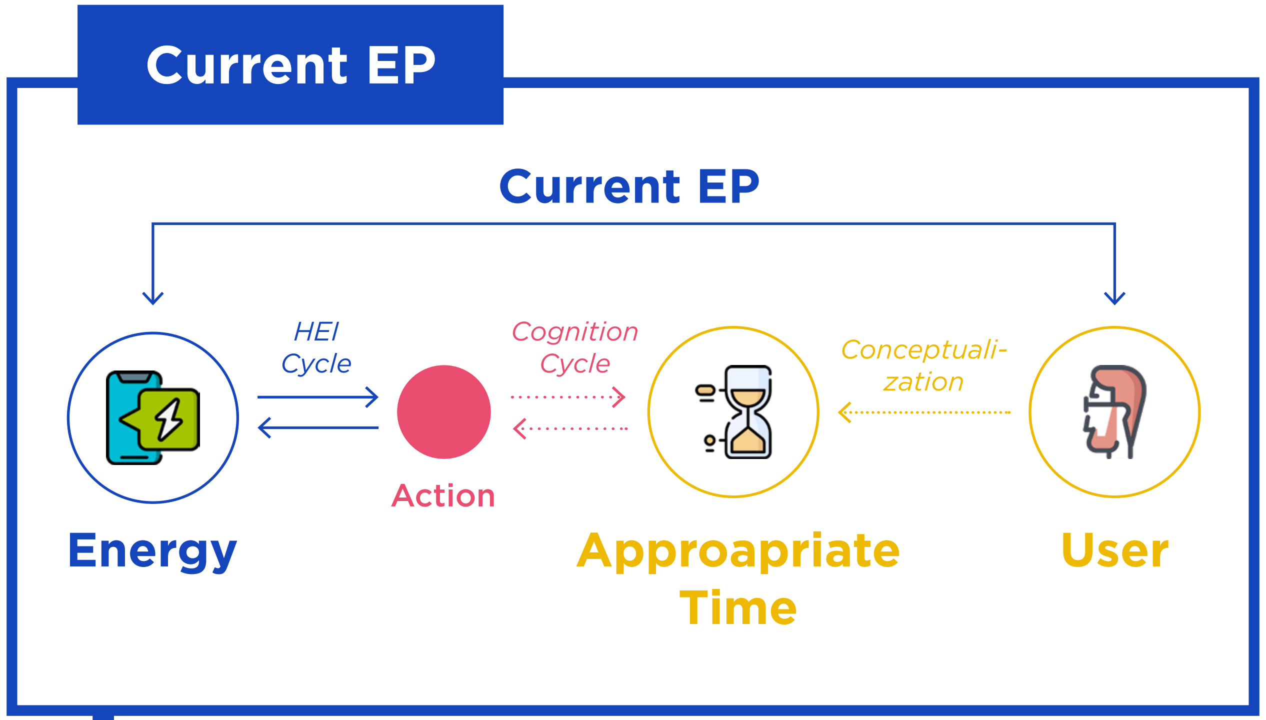
Limited battery capacity leads to prescribed usage time and frequent charging. Current mobile devices enable users to perceive energy level to know how much time remains that the device can hold; charge to keep it alive; trading off usability with the extension of battery life. On the other hand, users learn to deal with limited battery capacity through years of use to perceive battery level through indicators and notifications, adjust usage intensity, and build charging scenarios. Energy harvesting frees users from the burden of dealing with battery life but brings new troubles to them-the intermittent, fast changing, context-sensitive energy supply. Therefore, users are forced to reshape the relation between environment and energy.

New interactions between users and energy emerge, including Spatial Change, meaning reshape the relationship between the user and energy; manual energy input describing the actions of manually power the device shortly; lower requirement articulating users lower their standards to avoid the mental load. **Energy harvesting technology transforms the typical, linear, predictable interactions into novel, dynamic, context-sensitive human-environment interactions.**

Transformation of cognition

One of the main contributions of this research is that it adds another dimension of understanding the EP-cognition process. Every interaction is the externalization of the cognition, and its feedback feeds for the next cycle of the cognition process. The energy-related interactions can be various, but they are all triggered by a universal goal-to gain the Appropriate Time. After all, all of the current interactions are the manifestation of users dealing with limited battery life that causes limited usage time. This uncertainty forces users to interact with battery interfaces to make sure there is enough usage time for their current and planned tasks.

Energy harvesting offers users with unlimited usage time, but bring sudden interruptions to them at the same time. Users then evolve new interactions to handle the sudden energy shortage with another unified purpose- to gain the appropriate experience. The technology revolution will make users adapt to the unlimited time, yet flaw use experience of using devices. Users will reform their actions and evaluation factors, reshape their knowledge between environment and energy, and finally, re-conceptualize their goal as appropriate experience. **The conceptual transformation from current to future EP, is the transformation from time to experience.**



The cognitive transformation from current to future EP, is the transformation from time to experience.

Transformation of Cognition

Transformation From Current To Future

Transformation of Interactions

Energy harvesting technology transforms the typical, linear, predictable human-battery interactions into novel, dynamic, unpredictable human-energy interactions.

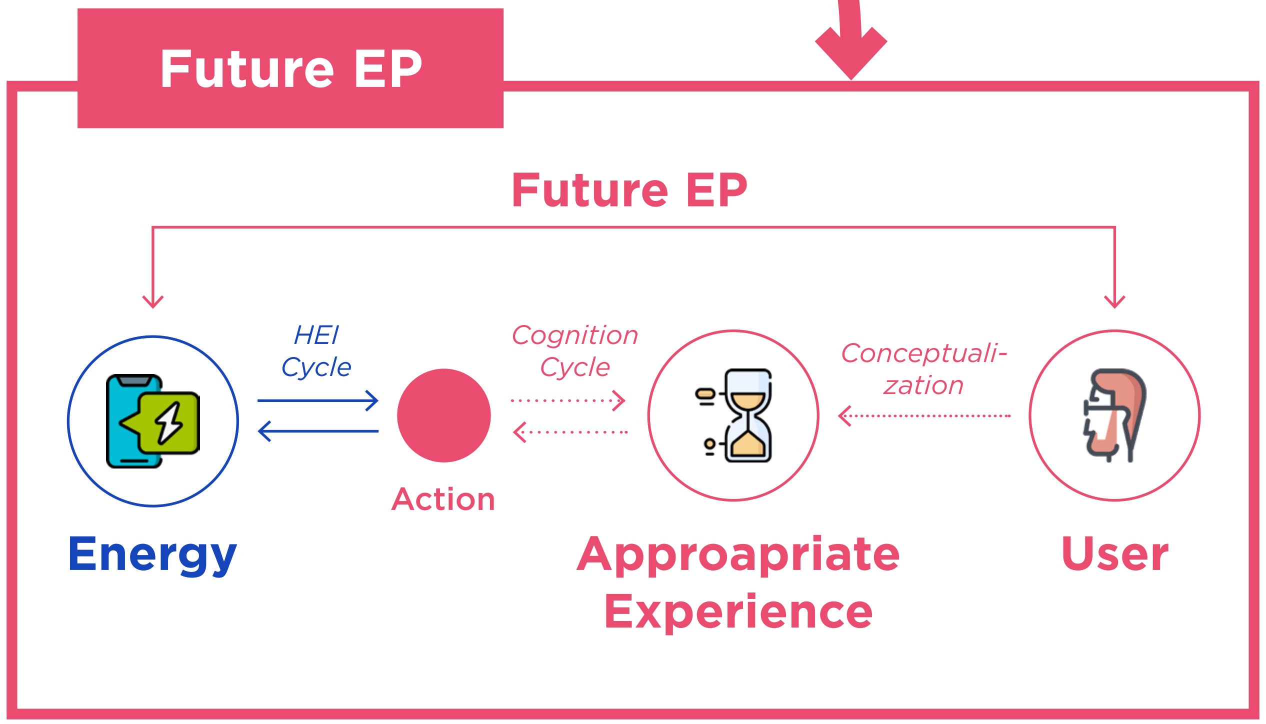


Figure 6.13 - The transformation from Current to Future EP.


Figure 71 - Photo took during prototype test

07

Conclusion & Reflection

Overview

This chapter concludes the whole project and reflects on the applied methodologies, the proposed EP Model, and the limitations. The thesis will be concluded with recommendations and personal reflections on the project.

7.1 Addressing Research Questions

The aim of this research has been to formulate the future human-energy partnership between users and intermittently powered devices. The EP model framework and the current EP model outlined in Chapter 3.4 frame the first objective of depicting the battery-based energy partnership. The future EP model is finalized in Chapter 6.1.

Overview

Chapter 1 of this thesis provided an overview of the research, setting the background, objectives, and approach. Chapter 2 sets the research context in which this work is framed by exploring the previous research perspectives and approaches. The framework of the current battery-based energy partnership was then defined and depicted with factors extracted from a set of user studies in Chapter 3.

Throughout several expert interviews, a hypothetical model envisioning the future EP of battery-less devices was proposed in Chapter 4. This hypothesis was iterated through design activities in Chapter 5 and finalized in Chapter 6.

This final chapter provides the conclusions of the research and how it has addressed the research question and defines the contribution to new knowledge that this master thesis has developed.

1. How to depict the current human-energy partnership between users and battery-based devices?

In answering the first research question of how to depict the current human-energy partnership, a series of user studies and theoretical deduction have been carried out to proposed a model describing the current human-energy partnership. This closed-loop model conceptualizes interactive and cognitive characters that users go through. For the interaction process, the current model elaborates it as a rhetorical process between interfaces and user's actions intending to interact with energy. The cognition process demonstrates how users interpret, evaluate and set the goal for their actions. Goal, as the central character of the cognition process in this model, represents how users conceptualize the energy when they are dealing with limited battery life. And in the current model, it is the appropriate time.

2. How will the future human-energy partnership between users and battery-less devices be?

The second research question in this research was concerned with envisioning future human-energy partnership. A hypothetical model was conceived built on the current EP model and the expert interviews towards energy harvesting technology. Prototypes were designed and tested to iterate and validate the hypothesis of energy partnership. Following the framework of the EP model, the future EP model articulates the change of interaction, cognition, and corresponding user action brought by the shift from battery to battery-less. The intermittent, dynamic, and context-sensitive energy supply forces users to reform their actions and evaluation factors, reshape their knowledge between environment and energy, and finally, re-conceptualize their goal as appropriate experience.

7.2 Contributions

Contribution to new knowledge

This research set out to investigate the energy partnership in mobile devices, and to illustrate the current battery-based and future battery-less energy partnership. The following are the main research contributions of this study.

Firstly, this thesis's findings can be used to help understand the current energy partnership between users and battery-based devices. Specifically, the EP model framework provides another dimension for understanding energy partnership - cognition. It reveals how users internally evaluate and conceptualize in-device energy in their minds during the interaction with BI. Therefore, the EP model can be considered as a designerly way of manifesting the relationship between users and energy.

Moreover, the future EP model envisions the relationship between users and energy in battery-less devices. It will help designers and researchers understand how energy harvesting technology will impact the current battery-based EP. The future model provides new findings of how users will react to the drastic shift of energy system, externally and internally.

Finally, this research uncovers the user's conceptualization of in-device energy and its shift due to the energy harvesting technology. It can be used to understand the essence of energy interactions and interfaces from the user perspective.

Contribution to design practice

This research, intended to understand the EP of battery-less devices, takes the first step in designing experience and energy-related interactions on battery-less devices. It shows how the intermittent, fast-changing energy supply impacts the interaction and cognition process of users who get used to dealing with limited battery life. The evaluation factors and user actions in the future EP model can be served as principles and key points for designers intending to design experience on battery-less devices. For designers who are going to design energy-related interactions on battery-less devices, the EP Model can help understand the reactions and expectations of users towards energy in battery-less devices and perform as the starting point of developing design concepts.

7.3 Limitations, Recommendations & Personal Reflections

Limitation

• Research on Energy Harvesting
Due to the limited time frame of this project, the energy harvesting technology was only researched through reviewing papers and expert interviews, which might lead to an incomplete acknowledgment and biased envision on its future applications.

• The Prototype
This research was conducted through the RtD approach, resulting in a battery-less EP model iterated by testing the prototype, simulating battery-less devices' energy behavior. Considering the capacity of harvesting different types of ambient energy, the designed prototype only simulated light energy harvester without covering other ambient energy sources. Also, because of the limitation of time and prototyping skills, the prototype only shows the side-effect of EHT, its intermittent, context-sensitive, and dynamic attributes. The mobility, accessibility of battery-less devices did not show together with its side-effect, which may lead to biased user reactions.

• The Current Model
Although the current model was developed with data gathered from user studies, the effectiveness of the current EP model sill needs validation.

Recommendation

The proposal provides visions for understanding the relationship between users and energy in battery-less devices with limited knowledge of energy harvesting technology. Therefore, the future model could be continually

developed and iterated by diving deeper into the technology, designing prototypes that are truly powered by ambient energy.

Moreover, another recommended direction to continue this research is using the insights and conclusions of this project to design experience or energy-related interactions on battery-less devices. The new knowledge provided by this project has already paved the way towards a successful design for battery-less devices.

Personal Reflections

As a designer, this graduation project has been challenging because it is future-oriented, researching a technology that has not been applied to the reality. I got to practice the RtD approach, involving design activities into the research process. It was a challenging but enjoyable experience along the way.

My key personal outcome from this project is to learn how to conduct research as a designer and how to combine the skill of design into a research process.

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