Empirical Studies on Energy Consumption Issues Based on Stack Overflow and Google Chrome Extensions

By

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Abstract

The advancement of technology has driven a rise in energy consumption, while energy-related issues prospectively influence every avenue in the software life cycle from design and implementation to maintenance. To conserve energy, prolong battery life, and enhance user experience, the energy consumption of software applications has been becoming a critical issue for practitioners to consider in their daily development processes. To address this issue, researchers and practitioners have been exploring various approaches to optimize energy consumption in computing systems. In this thesis, we present empirical studies to garner insights into developing energy-efficient software from two perspectives: (1) understanding practitioners' perception of energy consumption; and (2) evaluating the impact of extensions on Google Chrome browser performance.

In the first part of this thesis, we investigate practitioners' concerns about energy consumption on Stack Overflow (SO). Our findings reveal that the practitioners' intent to initiate discussions in the energy domain is intimately related to the usage of concepts. We also identify six common topics regarding energy consumption questions. Questions related to computing resources are the most concerning topic, while monitoring is the most challenging topic, taking the longest time to receive an accepted answer. We also notice that practitioners consider energy consumption at different levels during application development.

In the second part, we delve into the impact of browser extensions on energy consumption and page load time. We conduct experiments to study the performance implications of 61 extensions across 11 categories on Google Chrome, the most popular browser. Our observations indicate that browser performance can be negatively affected by the use of extensions, even when they are not active or used in unexpected circumstances. We also find that highly-rated extensions and those with larger code sizes tend to be more energy-efficient.

In summary, this thesis provides insights into the practical issues related to energy consumption in software development. We believe our findings can raise practitioners' awareness about the energy impact on software from various perspectives and can aid in the development of energy-efficient software.

Acknowledgments

Eight years ago, in 2015, I came to Canada with no idea that I would reach this point in my academic journey and achieve such great results. Although I constantly strategize for my next move, the future often disrupts my plans. Nevertheless, I am cheerful about the positive outcomes that have resulted from my arduous labor and dedication. As I embark on a new chapter, I would like to express my genuine appreciation to the many people who have supported me throughout my voyage.

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Chapter 1

Introduction

Technological advancement has led to an increase in energy consumption [33]. Various services, such as information search, video streaming, online shopping, or social networking services, rely on software, such as web browsers (e.g. Google Chrome) and Chrome extensions. However, energy-related issues can prospectively influence every avenue in the software life cycle, from high-level design, code implementation and testing to maintenance [15]. If the software is designed to perform its functions in a more energy-efficient manner, energy might be saved from the annual growth trend of electricity used by the software. In particular, energy usage is recognized as a non-trivial quality attribute of software products to save more energy, extend battery life, and even improve the user experience [44]. This chapter discusses the research challenges (Section 1.1), followed by the thesis statement (Section 1.2), objectives (Section 1.3), contributions (Section 1.4), and organization (Section 1.5).

1.1 Research Challenges

Software development faces various challenges related to energy consumption, performance monitoring, and intention analysis. Various studies [12, 21, 32, 39, 40, 44, 46, 48, 53, 61] are dedicated to developing effective strategies and solutions for energy-related issues in software development. Despite the existing approaches to perceiving energy consumption from practitioners and software, the development and research teams face the following challenges:

- **Challenge 1:** ***Lack of understanding of practitioners' concerns on energy consumption.***

  Existing studies [39, 44, 48] explore practitioners' perceptions of energy consumption. However, these studies investigate practitioners' perspectives of energy consumption only, without studying practitioners' intentions and concerns in reducing energy consumption in their daily development activities. Without a clear understanding of practitioners' intentions and concerns, the ones directly involved in software development cannot obtain practical help in making decisions about energy use in their work. Although the issue of energy consumption in software development has gained attention, there is still a lack of clear understanding of how practitioners perceive the problem and what specific concerns in regard to energy consumption they have. Therefore, providing an in-depth understanding of practitioners' concerns regarding energy issues in practice is crucial in developing effective strategies and solutions to address energy challenges in software development.

- **Challenge 2:** ***Lack of comprehensive understanding of the impact of browser extensions on browser performance.***

  While there are various studies [12, 40, 46] that investigate the effect of privacy-focused browser extensions, such as ad blockers, on browser performance, little is known about the performance implications of installing such extensions and potential factors that contribute to their performance implications. Prior work [12, 40, 46] predominately focuses on the examination of a single type of extensions, particularly those associated with activity blocking, and has limited scope in terms of the factors considered. Such limitations cause potential side effects, such as inadequate evaluation of extension impact on browser performance, and a lack of understanding of the trade-offs involved in using different types of extensions. Under extension performance evaluation, researchers investigate energy consumption in sources of energy (e.g., page load time, RAM energy consumption, and CPU energy consumption). Nonetheless, there has been no proposed approach to identify potential factors that contribute to the performance impact of browser extensions, which is imperative for helping developers and users make informed decisions on optimizing and selecting extensions. Hence, it is essential to provide a comprehensive understanding of the impact of browser extensions on browser performance to inform users about the potential costs and benefits of using these extensions.

1.2 Thesis Statement

Energy consumption affects software performance, cost, and environmental sustainability. Failure to be aware of or consider energy consumption in software can lead to higher costs for software development and maintenance, inefficient system performance, and environmental impacts, as well as negative user experience. Despite various studies on perceiving energy consumption from practitioners and software, there are limited studies on understanding the specific barriers (e.g., the intentions of practitioners to raise questions and how software performance is influenced) that contribute to energy issues in practice. Considering conceptual perceptions may be abstract and esoteric to practitioners, we further provide a deeper understanding of software energy efficiency by investigating the impact of extensions on browser performance. Prior work predominantly focuses on a singular type of extensions, particularly those associated with activity blocking, and has limited scope in terms of analyzing the performance-affected factors. To help practitioners and researchers understand energy-efficient software, we propose to conduct comprehensive studies of the specific barriers that contribute to energy issues in software development practices. To this end, we perform our research along two objectives: (1) understand practitioners' perception of energy consumption; and (2) evaluate the impact of extensions on Google Chrome browser performance. The results of this thesis identify the popularity and trends in different topics regarding energy consumption for the design and development of energy-efficient systems and help practitioners select performance-efficient extensions and optimize their development decisions at the development phase.

1.3 Thesis Objectives

This thesis aims to achieve in addressing the aforementioned challenges. Figure 1.1 presents a high-level overview of this thesis, illustrating the alignment of the objectives outlined below with the subsequent chapters.

Objective I: Studying the characteristics of energy-related questions. Various characteristics of questions, such as intention types, popularity, and difficulty, offer valuable insights into the challenging aspects of energy-related software development problems. This study aims to gain a deeper understanding of energy-related software development patterns and challenges in software development and energy use by examining various characteristics behind the questions asked on SO. This study

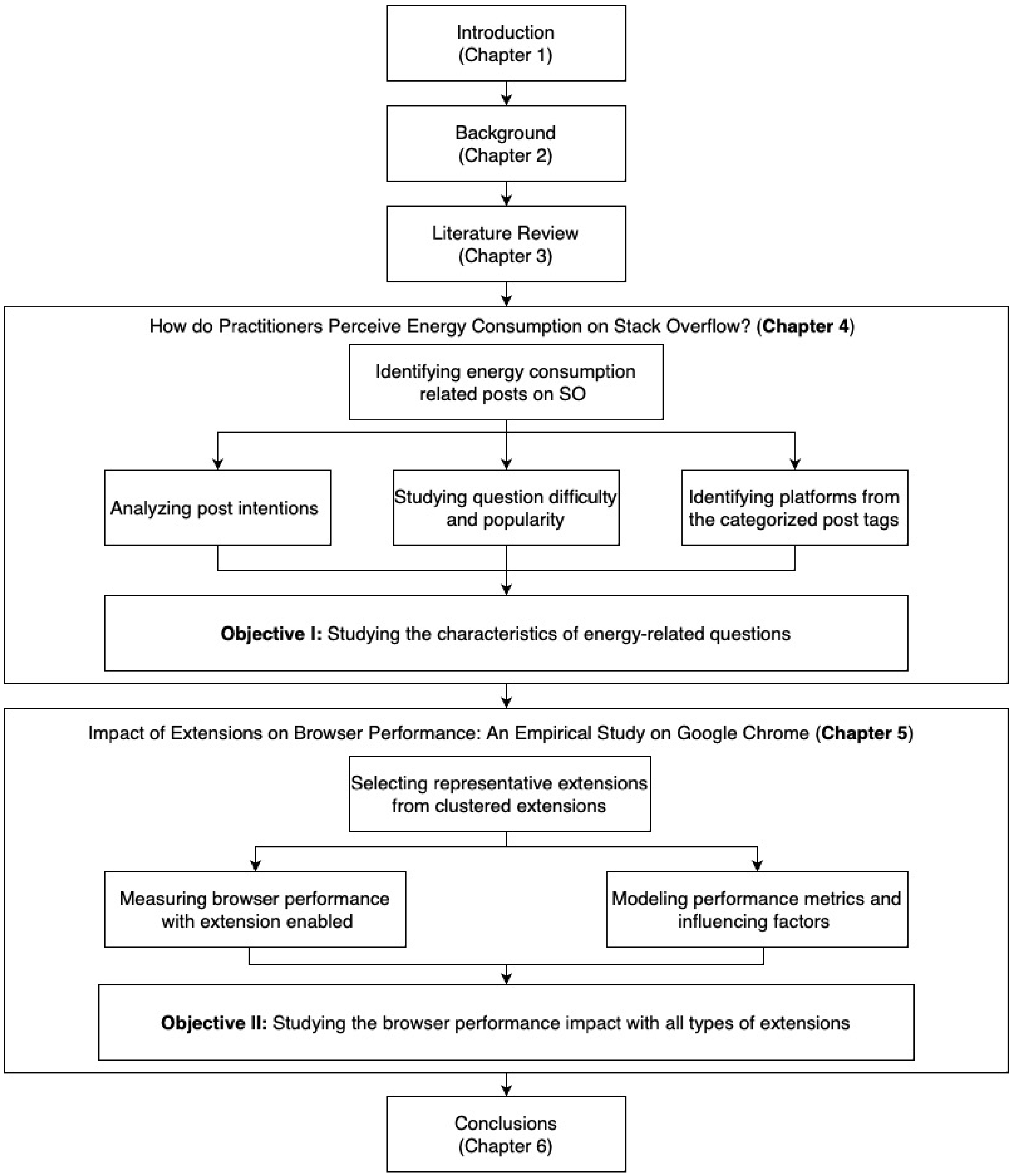


Figure 1.1: Thesis overview.

provides three types of categorization of questions, i.e., a question intention-based categorization, a question topic-based categorization, and a question tag-based categorization, to help the researchers, practitioners, and energy professionals understand the characteristics of energy-related questions raised by practitioners. We categorize the question intention types and analyze question popularity and difficulty regarding topics of the energy-related questions to investigate the most concerned aspects in software development and energy use problems. We identify concerned platforms of energy-related questions to reveal what major platforms practitioners are the most concerned about energy consumption. This study reports a set of recommendations to practitioners and researchers to help resolve barriers related to energy issues in practice.

Objective II: Studying the browser performance impact with all types of extensions. Extensions are small software programs and are known to impact browser performance. However, the impact of the extensions on the performance of browsers remains unclear. Underlying factors that influence performance remain unexplored. With the insights gained from Objective I, we conduct a practical experiment to investigate the influence of extensions on browser performance, which provides another crucial aspect that can affect software efficiency. This study investigates all types of extensions, aiming to uncover how the use of extensions affects browser performance in three aspects (i.e., page loading time, page load energy consumption, and stabilized energy consumption). We monitor performance changes with and without the extension enabled to reveal the overall impact of extensions on browser performance. We assess extensions in different extension activation modes to determine how different activation modes affect browser performance, providing insights for users to optimize their extension configurations. Moreover, we propose an approach to help extension developers determine which factors have significant associations with performance changes. We build machine-learning models to verify the correlation and significance between performance metrics and underlying factors. This study reports a set of recommendations to arouse awareness among users about the energy consumption of extensions and provide guidance on the proper use of extensions and reports actionable findings of the use-level and build-level factors and side effects of these factors.

1.4 Contributions

The main contributions of this thesis are presented as follows:

- Provide three types of categorization of intentions of questions posted on SO, i.e., an intention-based categorization, a topic-based categorization, and a tag-based categorization. Such categorizations help the research community, software developers, and energy professionals understand the characteristics of energy-related questions raised by practitioners (Chapter 4).

- Provide a customized dataset of 985 manually verified energy-related SO posts in Tables A.1 and B.1 from Appendices A and B and make it publicly available. The dataset contains 277 posts that are manually labeled with question intentions and topics (as listed in Table A.1 from Appendix A). Our dataset can be used as a benchmark for future work that aims to study the energy aspect of software or system development (Chapter 4).

- Conduct an empirical study on understanding energy consumption issues faced by practitioners. The findings of this chapter work can be used to support practitioners to build or optimize SO-based recommending systems related to energy in practice (Chapter 4).

- Present the impact of extensions on browser performance across different activation modes of extensions and identify the factors that contribute to this performance impact (Chapter 5).

1.5 Organization of Thesis

We present an overview of this thesis in the following:

Chapter 2: Background. We discuss the significance of energy consumption in software and provide background information regarding the characteristics of the Stack Overflow (SO) posts, as well as the properties of browser extensions. This chapter aims to provide a better understanding of the content explored in Chapters 4 and 5.

Chapter 3: Literature Review. We give a literature review of the thesis to differentiate our work from the related research.

Chapter 4: How do Practitioners Perceive Energy Consumption on Stack Overflow? We identify the intentions of questioners to post questions and the common topics for the energy-related questions. In addition, we evaluate questions in two dimensions (i.e., difficulty and popularity) with respect to the question topics. We present different development platforms for the energy-related questions on which practitioners raise more questions or are more concerned.

Chapter 5: Impact of Extensions on Browser Performance: An Empirical Study on Google Chrome. We describe how extensions and the way extensions are executed affect browser performance and identify the performance-influencing factors of extensions.

Chapter 6: Conclusions and Future Work. We conclude the thesis and discuss the promising extensions of the thesis for future work.

Chapter 2

Background

This chapter presents an overview of software energy consumption, encompassing its impacts, types, and measurement methods. Furthermore, we discuss the attributes of the energy-related post on Stack Overflow (SO), as well as the properties of browser extensions.

2.1 Impact on Software Energy Consumption

The increasing use of technology and digital devices in our daily lives has led to a significant increase in the energy consumption of software. The total energy consumption of Information and Communication Technology (ICT) surges by 822.79% over 30 years, from 2182.72 TWh per year in 2001 to 17959.11 TWh per year in 2030 [65]. For example, in 2020 alone, ICT accounts for up to 7% of global electricity use [3] and 2.1%–3.9% of the global greenhouse gas emission [25]. By 2030, data centers alone will consume 10% of the world's electricity [49]. This trend has raised concerns about the impact of software on the environment, as well as the need to develop more energy-efficient computing systems. Software developers play a critical role in determining the energy consumption of ICT as they make decisions that affect the efficiency of the software they run on. In particular, energy-related issues can prospectively influence every avenue in the software life cycle, from high-level design, code implementation, and testing to maintenance [15]. If the software is designed to perform its functions in a more energy-efficient manner, energy might be saved from the annual growth trend of electricity used by the software. In fact, energy usage is recognized as a non-trivial quality attribute of software products to save more energy, extend battery life, and even improve the user experience [44]. Practitioners have demonstrated their willingness to learn about energy issues in software development [39]. Therefore, it is essential to measure and optimize the energy consumption of software to minimize its environmental impact.

2.2 Types of Software Energy Consumption

Measured in joules or watts, software energy consumption is influenced by multiple factors, including the type of the application, device employed, code complexity, hardware usage frequency, and operating temperature. Software energy consumption is categorized into three primary types: processing, data storage, and communication.

- Processing energy refers to the energy consumed by the processor and other components of the device, such as graphics processing units (GPUs), when executing software instructions.

- Data storage energy denotes the energy consumed by devices, such as random access memory (RAM) and solid-state drives, when storing data.

- Communication energy refers to the energy consumed by network components when transferring data between devices.

2.3 Energy Measurement

The general process for measuring energy consumption involves using specialized tools, such as Perf[1], and APIs, such as Running Average Power Limit (RAPL) [19], to gather data on the power consumption of hardware and software components. Energy consumption can be collected at various levels, such as the system level or the application level, and analyzed to identify energy-efficient solutions and optimize power consumption. In this thesis, we use RAPL to obtain the energy measurements from the CPU (Central Processing Unit) and the memory. RAPL offers a fine-grained approach to leverage hardware performance counters to provide a detailed and precise reading on the system energy consumption of the CPUs and memory usage [26, 35]. RAPL is a well-established and widely used utility that has been employed in the related work, such as [18, 41, 47], and the accuracy of the measurement has been validated by various studies, such as [22, 34, 36, 45]. RAPL offers a high sampling interval, with one reading taken per 1 millisecond. The results acquired from RAPL provide a measurement of the total energy consumption in millijoules.

Figure 2.1: Energy reading code examples.

```
# Measurement.py
# Paths to RAPL interfaces
path_core =
    "/sys/class/powercap/intel-rapl/intel-rapl:0/intel-rapl:0:0/energy_uj"
path_ram =
    "/sys/class/powercap/intel-rapl/intel-rapl:0/intel-rapl:0:1/energy_uj"
# read energy consumption from the CPU
reading_core = open(path_core).readline()
# read energy consumption from the memory
reading_ram = open(path_ram).readline()
```

[1] https://perf.wiki.kernel.org/index.php/Main_Page

Figure 2.1 presents code examples for measuring energy measurement from the CPU usage and memory usage in the Linux system. The RAPL interfaces, introduced in Linux 3.13, are defined in the powercap interface (intel-rapl) and are directly provided by the manufacturer in the in-built system files. As a result, we can access the files located at "/sys/class/powercap/intel-rapl/intel-rapl:0", and it does not require any special permissions.

2.4 Practitioners' Perceptions about Energy Efficiency

Stack Overflow (SO) is a question-and-answer website for programmers, developers, and other technical professionals, so allows users to post questions, answer questions, and vote on the quality of both questions and answers. The site covers a wide range of programming topics and is a popular resource for developers to share knowledge, troubleshoot issues, and learn from others in the community. The community of Stack Overflow serves more than 100 million developers[2] with approximately 16 million registered users around the world and has received around 22 million questions and 32 million answers[3]. The practitioners post questions on SO and seek answers from SO, as Stack Overflow features critical and essential online resources that practitioners can share and learn programming-related knowledge, make discussions on their design of software, troubleshoot code issues, and get feedback on the best practices. Stack Overflow allows practitioners to connect with others in the industry and learn from their experiences, making it a valuable resource for professional development and problem-solving in software development. Moreover, as the most well-known community-driven Q&A website, SO affects a diversity of users. Specifically, the SO

[2] `https://stackexchange.com/about`

[3] `https://stackexchange.com/sites?view=list#users`

users range from programming to development, and from novices to professionals. The enormous amount of users increases the diversity of the problems for analysis.

A screenshot of the Stack Overflow page illustrates a sample post[4] shown in Figure 2.2. The sample post aims to ask for help on whether using Streaming SIMD (Single Instruction/Multiple Data) Extensions (SSE) instructions for parallel operations consumes more power than other types of instructions. We predominantly focus on nine pieces of information from the post, namely: the post title, the number of views (i.e., View Count), the question body, the post tags, the score of the question (i.e., Question Score) and the adopted answer (i.e., Answer Score), the number of favor (i.e., Favorization), and the first creation dates of the question (i.e., Question Creation Time) and the answer (i.e., Answer Creation Time).

- The post title gives a brief summary of the question being asked or the topic being discussed.
- The view count is the number of times the post has been viewed by users on SO.
- The question body is the main content of the post and includes the details of the question and the discussion topic.
- The post tags are labels that have been assigned to the post according to the areas of the question. A post tag is used to categorize a post and make it easier to find.
- The question score is the score assigned to the question by other users based on the usefulness, clarity of the problem statement, and relevance to the topic being discussed.

[4] `https://stackoverflow.com/questions/19722950`

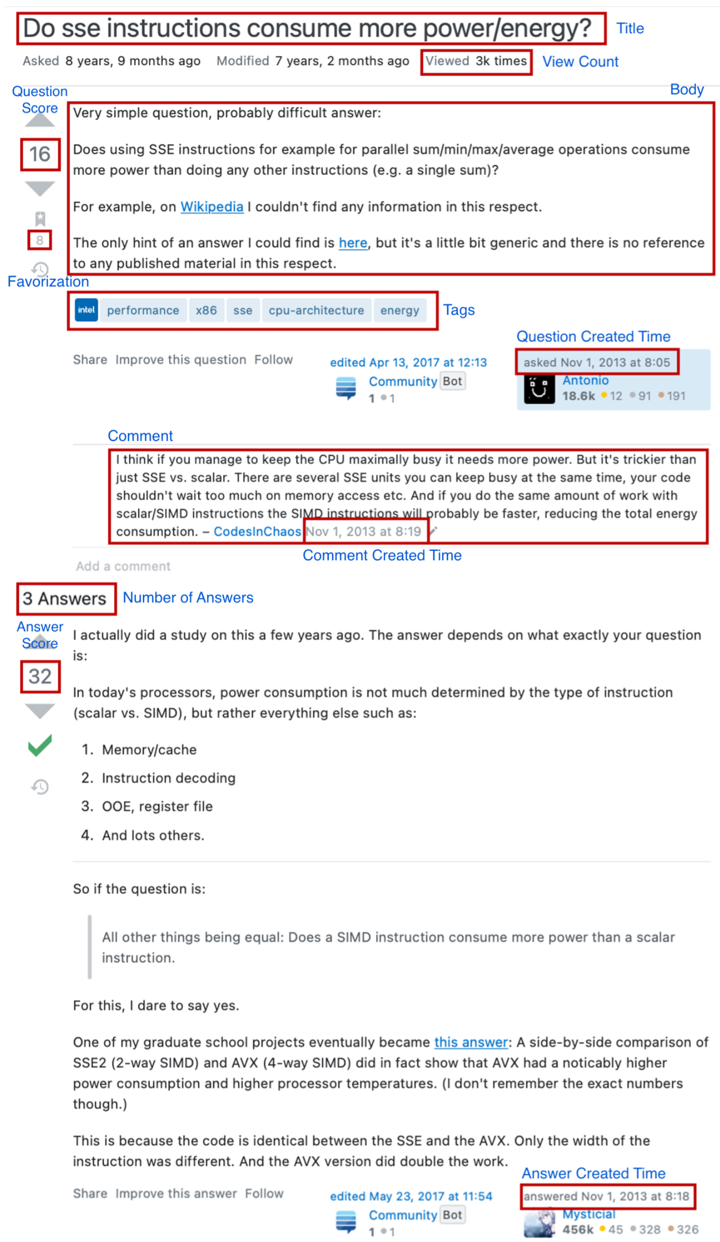


Figure 2.2: An annotated screenshot of a Stack Overflow post.

- The answer score is the score assigned to the chosen answers for the question based on correctness, completeness, and relevance to the question being asked.

- The favorization is the number of users who have marked the post as a favor, indicating that they find it useful or relevant.

- The question creation time is the date and time when the question is first posted on SO.
- The answer creation time refers to the date and time when the first accepted answer is posted in response to the question.

2.5 Browser Extensions

Extensions are small software programs that can be added to a web browser to provide additional features or services that are not built-in to the browser itself. A screenshot of an example extension is shown in Figure 2.3. Six components of an extension are annotated in the figure, including the extension name, rating score, extension category, the number of users, the size of the extension, and privacy practices used by the extension.

In the rest of this subsection, we introduce the extension types, activation, activation modes of extensions, and privacy policies.

Extension type. Google Chrome is one of the most popular web browsers[5] with its own extension marketplace called the Chrome Web Store, which categorizes extensions into 11 different categories, including accessibility, blogging, developer tools, fun, news & weather, photos, productivity, search tools, shopping, social & communication, and sports. However, not all extensions are trustworthy (e.g., from third-party resources), and we only consider extensions from the Chrome Web Store in this thesis, collecting extension information subsuming extension name, category,

[5] `https://analytics.wikimedia.org/dashboards/browsers/#desktop-site-by-browser/browser-family-timeseries`

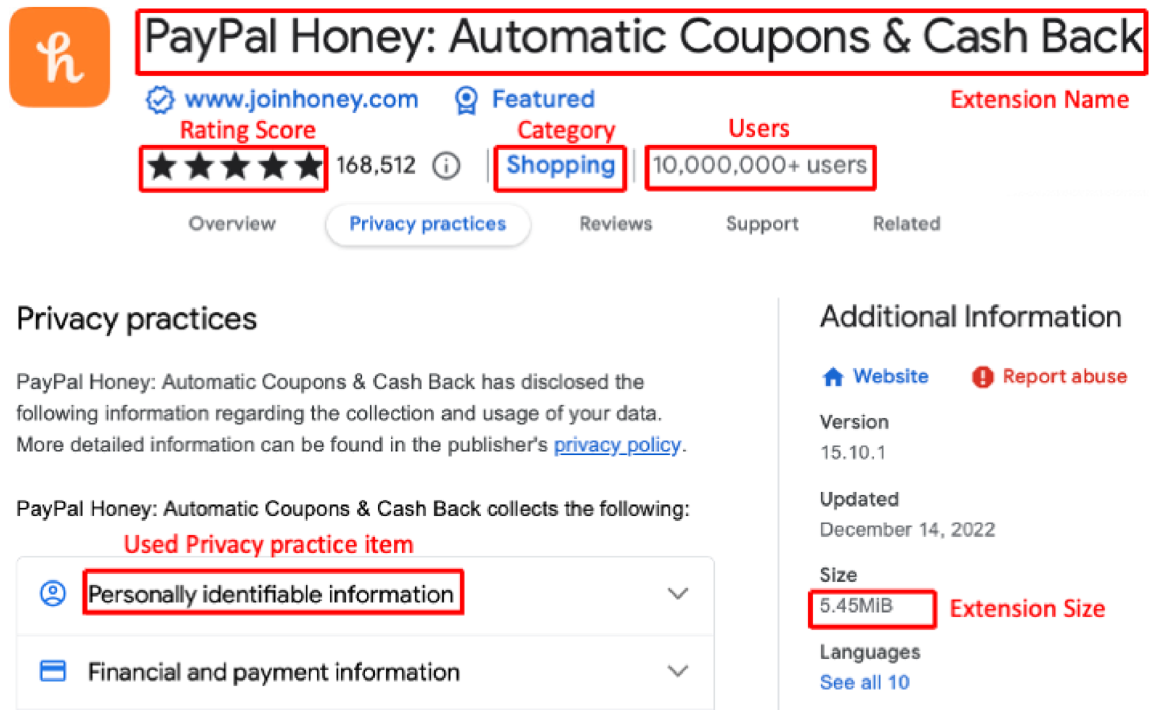


Figure 2.3: An annotated screenshot of an extension from the Chrome Web Store.

rating, privacy practices, size, and the number of downloads, as shown in Figure 2.3.

Inactive extension. Some extensions are designed to work on designated websites (i.e., target websites). These extensions are considered to be active, as they are able to access and interact with the website, providing the intended functionality to the user. If an extension is not compatible with a website, it implies that it is not designed to work on that particular website and does not function properly. The incompatible extensions are considered to be inactive, as they are not being used on the website. The user may have the extension installed on their browser but cannot access its features. The inactive extensions may consume energy. Thus, we investigate the energy consumption and running time changes of the inactive extensions compared to extension-free measurements.

Table 2.1: Activation modes of extensions.

Mode name	Login	Grant	Target webpage	Extension used	Description
Extension-free	0	0	0	0	No extensions are used on the browser. (**Baseline**)
Fully loaded	1	1	1	1	Access to an extension and access permission to a webpage are granted and used for the designated websites
No login	0	1	1	1	Access to an extension is not granted
No grant	1	0	1	1	Extension's access permission to a webpage is not granted
Inactive	1	1	0	1	An extension is not used for the designated websites
Fully inactive	0	0	0	1	Access to an extension and access permission to a webpage are not granted and not used for the designated websites

* 1 represents True (i.e., performed), and 0 represents False (i.e., not performed).

Activation modes of extensions. Extensions may have different performance impacts depending on different activation modes (e.g., not logging in to the extension or using the extension on a website that it is not designed for). There are six activation modes of extensions, as demonstrated in Table 2.1.

Extension-free mode: no extensions are used on the browser. This mode serves as a baseline for comparison with the other extensions' activation modes.

Fully Loaded mode: extensions require login or access permission are given the necessary authentication and access, and then tested on the targeted webpage (i.e., the webpage that the extension is designed to work on). This mode allows for the full functionality of the extension to be tested.

No Login mode: extensions require login or access permission are given access but not logged in, and then the extensions are tested on the targeted webpage. This mode enables testing the performance of the extension when not logging in.

No Grant mode: extensions that require login or access permission are logged in but not given access, and then tested on the targeted webpage. This mode enables testing the performance of the extension when access is not granted.

Inactive mode: extensions require login or access permission are logged in and given access but not tested on the targeted webpage. This mode enables testing the performance of the extension when not used on the targeted webpage.

Fully Inactive mode: extensions are not logged in, not given access, and not tested on the targeted webpage. This mode enables testing the performance of the extension when not in use.

Privacy practices. Extensions can be useful tools that enhance the functionality of a web browser, but they can also pose a threat to user privacy and data security. It is important for users to be aware of the privacy implications of the extensions they install. Thus, Chrome Web Store allows developers to be transparent about their data collection and use practices. To build an extension, developers may use one or many of the nine privacy practice items, such as Location, User Activity, Website Content, Personally Identifiable Information, Authentication Information, Web History, Personal Communications, Financial and Payment Information, and Health Information, as shown in Figure 2.3. Each of the privacy practice items has a different level of impact on energy consumption and running time performance of the browser, as it consumes more resources to process and store data. For example, tracking a user's location using GPS can consume more energy, as the GPS receiver of a device needs to be activated to obtain the location data. This can lead to a decrease in battery life if the extension is used frequently or for prolonged periods of time.

In this chapter, we discuss the pressing issue of burgeoning software energy consumption caused by the pervasive use of technology and digital devices. With different types of software energy consumption, we introduce RAPL, a tool for quantifying software energy consumption, and describe its interfaces used for sensing energy consumption. Moreover, we provide background information regarding the SO Q&A web forum, outlining nine key features of the SO posts. We also elucidate the properties of browser extensions, such as their types, activation modes, and privacy practices. Such information is indispensable for comprehending the concepts presented in Chapters 4 and 5.

Chapter 3

Literature Review

This chapter gives an overview of the prior research related to the work conducted in this thesis across five categories: (1) energy consumption consideration; (2) classification of forum posts; (3) mobile energy consumption; (4) browser performance; and (5) extension performance.

3.1 Energy Consumption Consideration

Pinto et al. [48] mine Stack Overflow for software energy consumption-related questions and answers. They study the perspectives of practitioners on software energy consumption-related problems. They find that questions and answers have been increasing year by year, and energy consumption for mobile development accounts for 25% of the tags. Our dataset contains 985 SO questions, collected from 2008 to 2021. *Pinto et al.*'s dataset contains 325 SO questions, collected from 2008 to 2013. Our dataset provides an updated view of the issues faced by the practitioners. To retrieve a wider range of relevant topics from the dataset, we use more wildcards in our search query. We analyze the intentions behind the questions. We categorize tags associated with the posts and merge synonymous tags into tag categories, which gains more comprehensive insights into the challenging aspects of the energy-aware software development. In contrast, *Pinto et al.* focus on the popularity of the questions, while we analyze the posts based on their popularity and difficulty.

Pang et al. [44] conduct a survey of over 100 practitioners to investigate if practitioners are knowledgeable enough about software energy consumption. The authors present that most practitioners (86%) lack awareness of energy consumption and find that most practitioners cannot identify the main source of high energy consumption. Their findings demonstrate that practitioners have limited knowledge about energy efficiency, lack knowledge about the best practices to reduce software energy consumption, and are concerned about energy consumption when building applications but are not successful due to a lack of necessary information, practices, tools, and supported infrastructure.

Manotas et al. [39] quantitatively analyze a survey responded by 464 experienced practitioners from ABB, Google, IBM, and Microsoft in terms of writing requirements, designing, constructing, testing, and maintaining their software. They find that practitioners have shown a willingness to sacrifice other requirements to reduce energy usage. Practitioners are unsure how often energy issues occur but believe that energy problems are more difficult to detect and diagnose than other performance problems. Chapter 4 complements these studies by providing different perspectives on practitioners' perception of energy consumption from the real-world energy-related issues encountered in their development activities.

3.2 Classification of Forum Posts

Beyer et al. [8] manually investigate 1,052 Android-related SO posts and classified 1,000 of them into seven categories, namely: `API Usage`, `Conceptual`, `Discrepancy`, `Errors`, `Review`, `API change`, `Learning`. The most frequently assigned intention category, according to the author's finding, is `API Usage`, followed by `Discrepancy` and `Conceptual`.

The study by *Venkatesh et al.* [62] presents their understanding of the challenges that are encountered by client developers on SO and analyzes the trend of how topics change over time. They perform an empirical study and an exploratory analysis on 32 Web APIs with a total of 92,471 discussions from developer forums and SO. As a result of their study, they identify five dominant (i.e., the most discussed) patterns (e.g., persistent topics with the number of discussions declining quickly) from the trends of all 40 extracted topics, which covers at least 50% of discussions for each Web API.

Wang et al. [64] use Latent Dirichlet Allocation (LDA) to cluster Stack Exchange posts to discover topics related to blockchain discussions. *Wang et al.* investigate the popularity and impact of discussion topics across the Stack Exchange communities. Alike, *Rosen and Shihab* [53] use LDA to summarize the mobile-related questions on SO. *Yang et al.* [67] use an advanced topic model (Latent Dirichlet Allocation tuned using Genetic Algorithm), LDA-GA, to cluster different security-related questions on SO. *Barua et al.* [6] utilize LDA models to investigate SO posts' primary discussion topics and trends over time.

Different from prior studies, chapter 4 focuses on Stack Overflow posts that are related to energy consumption. In chapter 4, we also follow the work by Beyer et al. [8] to derive the categories of energy-related posts on Stack Overflow. Similar to prior works [6, 53, 64], we use LDA to extract topics from the energy-related posts. We also perform manual analysis to verify the reliability of the resulting topics.

3.3 Mobile Energy Consumption

The previous work, such as [14, 30, 43, 59], investigates the impact of code smells (a set of bad programming practices in Android mobile applications) and other factors on the energy consumption of Android mobile applications on the Android platform.

Palomba et al. [43] investigate the impact of specific code smells in 60 Android applications on energy consumption and find that refactoring these code smells is important for improving energy efficiency. *Hao et al.* [30] introduce a technique called eLens to estimate energy consumption without the usage of power measurement hardware and find that eLens is a useful technique for estimating energy usage in Android mobile apps. *Tawalbeh et al.* [59] study the energy consumption of two Android smartphone brands, i.e., Galaxy Note3 and Sony Xperia Z2, and find that the major energy consumption occurs in the 3G unit and the OLED with a considerable amount of power also consumed by the WiFi unit. *Chan-Jong-Chu et al.* [14] investigate the correlation between performance scores and the energy consumption of 21 mobile web applications and find a significant negative correlation. *Chan-Jong-Chu et al.* recommend developers to use the Lighthouse to improve performance and lower the energy consumption of their web apps.

Chapter 5 complements prior studies such as [14, 30, 43, 59] because this chapter mainly focuses on the performance impact of browser extensions on the desktop end. Unlike the desktop-based Chrome, the mobile version of Chrome does not support extensions, as mobile devices have limited processing power and storage capacity compared to desktops, making mobile devices difficult to sustain energy-intensive extensions.

3.4 Browser Performance

Studies, such as [21, 32, 61], investigate the run-time performance and the energy consumption of mobile web applications.

Macedo et al. [21] compare the energy consumption of Google Chrome and Mozilla's Firefox when browsing webpages and find that Google Chrome is more energy-efficient when navigating web pages, but uses more energy for RAM, particularly when interacting with YouTube. *Janssen et al.* [32] conduct a study to investigate the effect of the Critical CSS technique on the run-time performance and the energy consumption of Android mobile web applications in Google Chrome and Mozilla Firefox. *Janssen et al.* find that while the technique can positively improve the run-time performance of Android mobile web apps slightly, it has no significant impact on energy consumption. *Tian et al.* [61] analyze the quality of user experiences across three mobile browsers - Chrome, Firefox, and Opera - by collecting data from 337 webpages and analyzing the loading time and cache performance. *Tian et al.* show that a significant proportion of webpages exhibit notable variations in terms of loading time and cache performance across different browsers.

Prior work [21, 32, 61] primarily focuses on examining the browsing quality across various browsers but does not explore the impact of browser extensions on browser performance. Chapter 5, in contrast, studies the impact of extensions on browser performance.

3.5 Extension Performance

In comparison to the studies in the previous subsections 3.3 and 3.4, studies, such as [12, 40, 46], delve deeper into the effect of privacy-focused browser extensions on the browser performance.

Pearce [46] explores the potential of open source advertisement (ad) blockers to reduce the page loading time by eliminating ads from internet browsing and video streaming. The evidence indicates that ad blockers are effective in saving energy due to their ability to shorten page loading time. *Pearce*'s work is complementary to chapter 5, where we encompass a broader range of extension types and provide an in-depth analysis with various factors, e.g., the stabilized energy consumption and activation modes. While *Pearce* focuses solely on the browsing quality of experience for ad-blocking extensions, chapter 5 encompasses a broader scope.

Merzdovnik et al. [40] evaluate the effectiveness and the system performance impact of 5 anti-tracking extensions (e.g., Ad-Block Plus) across 100,000 websites. The results show that these anti-tracking extensions do not increase CPU time, however, they consume more memory. The metrics used in the study, such as memory consumption, are comparable to the performance metrics used in chapter 5. Chapter 5 places a greater emphasis on the impact of the extensions on browser performance and delves deeper into the underlying factors that cause these changes.

Borgolte et al. [12] analyze the impact of eight privacy-focused browser extensions (e.g., Ad-Block Plus and Privacy Badger) on user experience and system performance in both Google Chrome and Mozilla Firefox. Overall, the results indicate that these privacy-conscious extensions do not impede the system performance and even improve the user's browsing experience.

Prior studies [12, 40, 46] predominately focus on the examination of a single type of extensions, particularly those associated with activity blocking. Chapter 5, however, stands out by encompassing extensions from 11 diverse categories, which cover all functional types of extensions. These extensions are categorized based on their characteristics, such as the use of privacy practices, and we assess the performance impact of various activation modes of extensions utilizing more comprehensive metrics that concentrate specifically on browser performance. Furthermore, we go beyond simply measuring and comparing energy consumption and delve into the underlying factors that lead to spikes in energy and page load time.

Chapter 4

How do Practitioners Perceive Energy Consumption on Stack Overflow?

4.1 Introduction

Technological advancement has propelled an increase in energy consumption [33]. The total energy consumption of Information and Communication Technology (ICT) has surged by 822.79% over the last three decades, from 2182.72 TWh per year in 2001 to 17959.11 TWh per year in 2030 [65]. Notably, in 2020 alone, ICT accounts for up to 7% of the global electricity use [3] and 2.1% to 3.9% of global greenhouse gas emissions [25]. By 2030, data centers alone are projected to consume 10% of the world's electricity [49]. The role of Software in the energy consumption of ICT is crucial [63]. In particular, energy-related issues can prospectively influence every avenue in the software life cycle, from high-level design, code implementation, and testing to maintenance [15]. If the software is designed to perform its functions in a more energy-efficient manner, energy could be saved from the annual growth trend of electricity used by the software. In fact, energy usage is regarded as a non-trivial quality attribute of software products, enabling the software to save more energy, extend battery life, and even enhance the user experience [44]. Practitioners have also demonstrated their willingness to learn about energy issues in the software development [39].

A few existing empirical studies that are conducted to understand practitioners' perceptions of energy consumption. For instance, prior studies [39, 44] perform online user surveys with 122 and 464 self-identified practitioners, respectively. The targeted subjects are experienced practitioners (e.g., developers and testers) across various application domains [39]. The studies report that 65% of the practitioners on Reddit are aware of that energy usage is a crucial factor in evaluating the quality of software products [44], and practitioners are willing to sacrifice other requirements to reduce energy consumption [39]. However, both surveys investigate practitioners' opinions on energy consumption solely, without studying the specific barriers that contribute to energy issues in practice. Moreover, *Pinto et al.* [48] study 325 Stack Overflow (SO) questions posted over a five-year period from 2008 to 2013 and derive five primary themes of energy-related questions (e.g., measurement). With the rapid shift in technologies and focus (e.g., the fast-growing IoT devices), practitioners may face different challenges in recent years. Therefore, *Pinto et al.*'s work needs to be extended to subsume more recent posts on SO.

In short, prior work has two major limitations: (1) a limited number of participants involved in the studies and (2) a lack of investigation into more recent energy consumption issues in the software development. In this paper, we are interested in investigating practitioners' experiences in developing energy-efficient software in order to provide new perspectives on practitioners' perceptions of energy consumption.

To increase the number of practitioners in this chapter, we aim to study the questions posted on SO in which the questions reflect the concerns of a broad range of practitioners. Different from *Pinto et al.*'s work, this chapter studies a large dataset of 985 SO questions, covering a longer period from 2008 to 2021. In addition, this chapter is different from *Pinto et al.* in research questions and methodology, leading to different results.

We combine qualitative and quantitative analyses to comprehend the question categories and uncover the intent behind the questions, the topics of the questions and their popularity, and the tag categories (e.g., hardware devices or OS) regarding which practitioners ask their energy-related questions. The intentions behind the energy-related SO questions and the tag categories of the questions are not studied by *Pinto et al.* Specifically, the following research questions are formulated to guide this chapter:

- **RQ1: What are the intentions behind the energy-related questions asked by practitioners?**

  Questioners have diverse intentions for posting their questions on SO, such as having difficulties in understanding the causes of the rising energy consumption. Understanding the intentions behind the questioners can provide insights into the challenges associated with energy consumption problems [2] in the realm of the software development. We observe that nearly half of the questions in the energy-sphere are mainly `CONCEPTUAL`, subsuming questions about the background knowledge of an API, and understanding programming concepts, such as design patterns. Such questions are frequently accompanied by questions related to `API USAGE`, e.g., inquiring about how to use an API. As the third most concerning intention, i.e., `DISCREPANCY`, it is found that practitioners face difficulties in resolving discrepancies between their observed execution results and their expectations regarding energy consumption.

- **RQ2: What are the topics of the energy-related questions and their popularity?**

  Practitioners can ask a question with the same intention (e.g., concept). However, the same intention may involve distinct topics. For example, both resource consumption and coding are under the concept-related intention. To further understand the characteristics of energy-related questions on SO, we analyze the titles and bodies of the energy-related posts using topic modeling. We uncover six recurring topics (i.e., main concerns) related to energy issues in the software development, namely: `Coding`, `Energy (general)`, `Device`, `Monitoring`, `Computing Resource`, and `Data Transmission`. Questions related to `computing resources` (e.g., CPU and memory) are the most concerned questions, while questions related to general `Energy` efficiency in the software development and `Monitoring` are the two most challenging issues, often requiring the longest time to receive responses in the posts.

- **RQ3: What are the concerned development categories in practitioners' energy-related questions?**

  Questions in the energy-sphere may pertain to various development categories. To acquire information regarding the categories of posts expressing energy-related concerns, we use the tags attached to each post. The tags signify the scope of questions and provide us with useful information regarding the categories of posts.

By studying the tag categories, we provide suggestions for the allocation of technical support to help practitioners solve energy-related problems. We notice that practitioners consider energy consumption at different levels, i.e., `OS`, `Hardware`, and `Programming Language`.

4.2 Experiment Design

To investigate our research questions, we analyze the energy-related posts on Stack Overflow (SO). In this section, we outline our data collection, pre-processing, and analysis steps. Figure 4.1 gives an overview of our approach for collecting, pre-processing and analyzing the collected data used in this chapter.

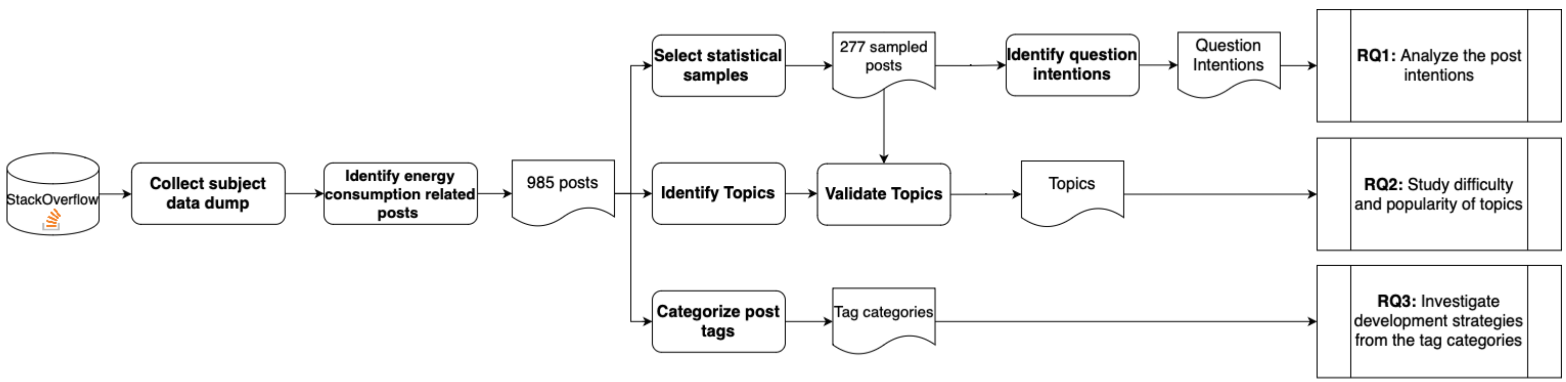


Figure 4.1: An overview of our approach to collecting, filtering, and processing SO posts.

4.2.1 Subject Dataset

In this chapter, we study energy consumption-related forum posts extracted from SO. We download the SO dataset from the official Data Dump in October 2021[1] which consists of 21,641,802 posts over a 13-year period from January 1, 2008 to October 7, 2021.

A snapshot of the Stack Overflow page illustrates a sample post[2] shown in Figure 2.2. We mainly focus on the following nine pieces of information from the post:

- The post title gives a brief summary of the question being asked or the topic being discussed.
- The view count is the number of times the post has been viewed by users on SO.
- The question body is the main content of the post and includes the details of the question and the discussion topic.
- The post tags are labels that have been assigned to the post according to the areas of the question. A post tag is used to categorize a post and make it easier to find.
- The question score is the score assigned to the question by other users based on the usefulness, clarity of the problem statement, and relevance to the topic being discussed.
- The answer score is the score assigned to the chosen answers for the question based on correctness, completeness, and relevance to the question being asked.

[1] `https://archive.org/details/stackexchange`
[2] `https://stackoverflow.com/questions/19722950`

- The favorization is the number of users who have marked the post as a favor, indicating that they find it useful or relevant.
- The question creation time is the date and time when the question is first posted on SO.
- The answer creation time refers to the date and time when the first accepted answer is posted in response to the question.

4.2.2 Identifying SO Posts related to Energy Consumption

A two-phase approach is used to filter out the posts in which neither the question title nor body contains keywords related to energy consumption. The post questioners sometimes provide code snippets in the question body, which may contain comments, strings, or code method names that match with wildcards. Even though comments may potentially contain energy consumption-related descriptions, the intent of the questioner does not aim to discern energy consumption. Thus, we exclude the code snippets from our keyword search using a regular expression to remove the content surrounded by the anchor tags of <code></code>.

To identify posts related to energy consumption, we match the text of a post with wildcards. More specifically, we adopt eight wildcards from prior work [48] and four new wildcards based on our own observations. The resulting 12 (i.e., 8 + 4) wildcards are applied to our dataset of 21,641,802 records to distil posts that contain the keywords in either the title or the body. The wildcards used include %energy consum%, %power consum%, %energy efficien%, %power efficien%, %energy sav%, %power sav%, %energy us%, %power us%, %energy econ%, %power econ%, %sav% energy%, %sav% power%. The character '%' at the beginning and the end of each term makes the string (e.g., %energy consum%) work as a wildcard, which allows for fuzzy matching of key terms in the post content. As a result, we filter out 1,930 posts based on wildcards. Each post in the dataset is manually reviewed to eliminate false positives. For example, the question[3] is a false positive. The questioner mentions the keyword "Energy Consumption" in the post but does not intend to investigate reasons or explore efficient solutions.

The manual labelling is conducted following an open coding procedure [58] by two annotators: The first author of the paper and a master's student majoring in Software Engineering. The energy-related posts are discerned in regard to the intention of the questioner and the theme of the post. A post is considered energy-related if the questioner describes a problem related to energy consumption or seeks for a solution to resolve an energy-related issue. Cohen's Kappa statistic [17] is used to assess the inter-rater agreement between the two annotators. There is a moderate level of agreement (i.e., 0.55) between two annotators in terms of identifying 1,930 SO posts at the end of labeling. In cases of conflict between the two annotators, a third specialist, a post-doctoral researcher with 7 years of experience in investigating energy conserving-related topics, is consulted to label the issue. If a further disagreement arises between the three annotators, the conflict is discussed and resolved among all participants. We follow this procedure until all issues are agreed upon.

After the manual labeling phase, 1,240 posts are recognized as false positives, leaving a final dataset of 985 questions and 1,255 answers.

[3] `https://stackoverflow.com/questions/43459393`

4.2.3 Pre-processing the Posts

We perform preliminary data processing to transform the raw data into a refined dataset, which we then employ for topic modeling purposes. This facilitates the model training process, enabling us to obtain high-quality outcomes. To this end, we conduct the following steps to prepare the posts.

- **Title and Body Composition.** The title of a question generally provides a succinct description that conveys the intention of the question, while the body of the question elaborates the narrative of the entire post. The combination of the title and textual body of the post helps understand the contexts of the post.

- **Tokenization.** The content of a post is broken down into a list of tokens through the function `simple_preprocess` within the package `Gensim` [52] The tokens can consist of words, phrases, or sentences. Statistical analysis of the frequency and co-occurrence of the tokens is then employed to identify the most relevant and meaningful keywords within the posts. Through the use of topic modeling techniques, a cluster of related keywords is subsequently identified as representatives of distinct topics within the corpus.

- **Stop Words Removal.** Stop words refer to frequently occurring words in written text, such as "the", "of", "an", "by", "is", and "what", which do not contribute significantly to the overall meaning of the sentence. To eliminate such stop words, we leverage the package `STOPWORDS` (a well-defined corpus of stop words) in the package `Gensim` to check whether a given word is present in the corpus `STOPWORDS`.

- **Stemming and Lemmatization.** Stemming is a technique used to reduce words to their basic form, while lemmatization is a linguistic process that transforms words from the third person from to the first person from and changes verbs from the past and future tenses to the present tense. For example, after lemmatizing, the words, such as “using”, “used”, and “uses”, are transformed to the root form “use”. Similarly, stemming removes the suffix “s” from “apples” to acquire the root form. To ensure obtaining the most unique words, we use the `SnowballStemmer` [50] stemming function and `WordNetLemmatizer` [24] Lemmatization function from the `NLTK` [9] library.

- **Bag of Word (BOW).** We create a BOW representation for each sentence, which maps each token to a unique numerical number in the form of a dictionary. This process disregards the syntax and the word order in the text while preserving multiplicity of the tokens. We adopt the function `doc2bow` from the package `Gensim`.

4.2.4 Topic Modeling

To study the most significant concerns regarding energy consumption, we utilize topic modeling to group the related posts into a topic. More specifically, we implement Latent Dirichlet Allocation (LDA) [10] from the `Gensim` package on the titles and bodies of the energy-related posts (as discussed in Section 4.2.3) to identify recurring topics. LDA is a generative statistical model that automatically generates common topics based on the probability of the generative distribution of discrete words in a corpus, without the need for labels or predefined taxonomies [11, 28].

However, since the LDA model cannot yield the number of topics on its own, we train the model for 100 iterations with a varying number of topics (1 – 14 topics) and determine the optimal number of topics using both topic coherence and Jaccard similarity. We derive the Jaccard similarity of each pair of two adjacent topics (i.e., Topic 1 and Topic 2) via Equation (4.1) to maximize the coverage of the different keywords and optimize the stability of the LDA model [1, 27].

$$J(w_i, w_j) = \frac{(w_i \cap w_j)}{(w_i \cup w_j)} \tag{4.1}$$

where i and j stand for two different topics; and w_i and w_j are sets of words. When two topics share all the words in the word sets, the Jaccard similarity results in 1. When all words are distinct, it would result in a Jaccard similarity of 0. We utilize Jaccard similarity to maximize the topic divergence so as to obtain the degree of the topic overlapping, defined by Equation (4.2).

$$Sim(i) = \{mean(J(w_j,\ w_k)) \ \mid \ w_j \in T_i, w_k \in T_{i+1})\} \tag{4.2}$$

where i is the number of topics; w_j and w_k represent one of the words in the topic j and k, respectively; and $T_i = \{w_1,w_2,...,w_i\}$ represents the set of words in the i th-topic.

To evaluate the coherence of the generated topics with the original text [42], the `CoherenceModel` model [55] (i.e., Coh in Equation (4.3)) from the `Gensim` package is used. Coherence measures the degree of the semantic similarity of the words within each topic by analyzing the co-occurrence patterns in the pre-processed texts. To determine the optimal number of topics, we aim to maximize the topic coherence within each topic while minimizing the similarity (i.e., maximizing topic divergence) between topics. Equation (4.3) computes the optimal number of topics, which subtracts the degree of the topic overlapping from the coherence score.

$$\arg\max_{i} f(i) = Coh(LDA(i),\ text) - \overline{Sim(i)} \tag{4.3}$$

where i is the number of topics; Coh measures the coherence score between the LDA model with the topic i (i.e., $LDA(i)$) and the preprocessed original $text$; $Sim(i)$, defined in Equation (4.2), stands for the degree of the topic overlapping; and $f(i)$ represents the score of the differences between the coherence and Jaccard similarity with the topic i.

After performing 100 iterations of tuning with each topic number, ranging from 1 to 14, we determine that the optimal number of topics is 6.

The LDA model generates a topic as a collection of keywords, along with the percentage of the significance of each keyword. For instance, a set of keywords (0.029*"devic" + 0.026*"android" + 0.024*"connect" + 0.019*"sleep" + 0.019*"mode" + 0.015*"work" + 0.015*"phone" + 0.013*"save" + 0.012*"turn" + 0.011*"screen") indicates that `devic` is a high frequent keyword. A keyword can appear in multiple topics with varying percentages of the significance assigned to each topic. We merge the identical words that appear in different sets of keywords into the set of keywords with the highest significance for the keyword. Lastly, we manually analyze each set of keywords for each topic to derive a high-level description of the topic that encompasses the meaning of its constituent keywords. Table 4.1 displays the labeled topics and the corresponding keywords, as discovered after post-processing the topics.

Table 4.1: The LDA dominant topics in SO energy-related posts.

Topic	Keywords
Coding	“code”, “time”, “run”, “file”, “try”, “write”, “efficiency”, “calculate”, “read”
Energy (general)	“energy”, “battery”, “usage”, “sensor”,“impact”, “high”, “start”
Device	“device”, “android”, “connect”, “mode”,“sleep”, “phone”, “work”, “save”, “turn”, “screen”
Monitoring	“locate”, “application”, “measure”, “want”, “update”, “network”, “know”, “current”
Computing Resource	“core”, “program”, “process”, “perform”, “memory”
Data Transmission	“data”, “message”, “send”, “server”, “like”, “need”, “node”, “user”

4.3 Experiment Results

In this section, we describe the motivation, the approach, and our findings for each of our three research questions.

4.3.1 RQ1: What are the intentions behind the energy-related questions asked by practitioners?

Motivation: Questioners pose questions on SO due to a variety of reasons, such as seeking assistance in comprehending a concept and using an API. Despite a SO post having up to five tags that define the domain of the question, the tags are insufficient in classifying questions and expressing the intentions of the questioner (i.e., why a question is asked). In RQ1, we aim to categorize the intentions of the questioners, which aids in understanding the distribution of the most troublesome issue types concerning the energy efficiency of the software and provides insights into the difficulties encountered in the energy-aware software development.

Approach: *Bayer et al.* [8] propose categories of intentions, including `API USAGE`,

`CONCEPTUAL`, `DISCREPANCY`, `ERRORS`, `REVIEW`, `API CHANGE`, and `LEARNING`. We aim to categorize the intentions behind the questioners based on *Bayer et al.*'s work. We randomly draw a statistically representative sample of 277 questions from the 985 questions to ensure a 95% confidence level with a 5% margin error. Two annotators, who happen to be the first and second authors of this paper, manually derive the intention category of each question, such as `CONCEPTUAL` and `REVIEW`, based on the existing taxonomy proposed by *Bayer et al.*.

Each annotator is provided with the sampled 277 posts and labels the intention categories independently based on the content of each post, including the question title and question body. A post can include multiple questions about different intentions, and hence, is not associated with only one intention category. Any disagreement between the two annotators is resolved until a consensus is reached. To validate the agreement between two annotators, we employ Krippendorff's Alpha provided by the package `simpledorff` in Python [31, 38]. Krippendorff's Alpha measures the degree of agreement between the labels. The details of computing Krippendorff's α are described in prior work [37]. Krippendorff's α indicates a highly reliable (i.e., $\alpha \geq 0.80$) [38] inter-rater agreement (i.e., 0.99) between two annotators in regard to categorizing the intentions of the questions. Using the result set of 277 posts, we then compute the number of occurrences of each intention category among all the sampled posts.

Table 4.2: Number of posts per respective intention category.

Intention Category	Definition	Example	#Posts	Percentage
Conceptual	Questions that understand concepts and ask the limitations of an API and API behavior	https://stackoverflow.com/questions/30027148	138	49.64%
API Usage	Questions about how to implement certain functionality or how to use an API	https://stackoverflow.com/questions/3412026	86	30.94%
Discrepancy	Questions related to exception problems that the observed result is different from the expectation	https://stackoverflow.com/questions/22339063	44	15.83%
Review	Questions that ask for the best practice approaches or ask for help to make decisions	https://stackoverflow.com/questions/6866236	33	11.87%
Errors	Questions about problems of exceptions with or without code snippets, as well as requiring help in fixing the error or understanding the meaning of the exception	https://stackoverflow.com/questions/60771095	11	3.96%
Learning	Questions that ask for documentation or tutorials to learn a tool or language by their own, without asking for a specific instruction or solution	https://stackoverflow.com/questions/63105570	7	2.52%

* Based on 277 manually labelled posts related to Energy Consumption.

Findings: **Understanding the concepts related to energy consumption is the most common intention of developers, occuring nearly half of their energy-related questions.** Our manual analysis results are listed in Table 4.2, showing the number of posts for each intention category. Upon analyzing the energy-related SO posts, we observe that understanding concepts (i.e.,`CONCEPTUAL`) is the most frequently asked intention category, accounting for 49.64%. `API USAGE` (30.94%) is the second most frequently inquired intention category, which is nearly twice as frequent as `DISCREPANCY` (15.83%). The categories, `API USAGE` and `CONCEPTUAL`, are the two intention categories that often appear together. Furthermore, 11.87% of the posts are for decision-making or asking for the best solution (i.e., `REVIEW`). Troubleshooting related questions, such as understanding the meaning of the exception (i.e., `ERRORS` at 3.96%), and self-learning materials (i.e., `LEARNING` at 2.52%) are the least frequent.

Our results indicate that nearly half of the energy-related questions are related to `CONCEPTUAL` matters. This is in stark contrast to prior work [8] that studies SO questions on Android development, where only 26.80% of the questions pertain to `CONCEPTUAL`. Through in-depth analyses, we identify two reasons for this discrepancy: (1) energy consumption is a vast domain that involves various hardware and software platforms. For instance, the post[4] demonstrates that measuring the energy consumption of a Python script necessitates different hardware and software platforms, as well as specific APIs and tools, depending on the platform being used; and (2) as noted in prior work [39, 44], practitioners are concerned about energy consumption but face challenging in understanding the concepts of energy consumption, the API limitations, and the API behavior. An example post[5] illustrates that practitioners

[4]https://stackoverflow.com/questions/66697291
[5]https://stackoverflow.com/questions/66697291

who develop applications for battery-powered ARM-based embedded Linux systems have trouble optimizing power consumption and choosing appropriate kernel APIs. Consequently, a high frequency of conceptual questions may be attributable to the intricate and diverse nature of energy consumption issues.

Approximately one-third of the energy-related questions are concerned about how to use an API. We observe that `API USAGE` is the second most frequent intention, taking 30.94% of questions. In contrast, prior work [8] on Android development shows that 38.80% of questions are related to `API USAGE`. The post[6], for instance, raises questions about the best practices for making location requests using the LocationRequest API in Android. The post also conveys concerns regarding the impact of APIs on power consumption, as the asker seeks advice on the most suitable API to receive real-time updates without consuming a lot of power. With the increasing number of applications developed for mobile devices and energy-constrained platforms, there is a growing need to optimize the usage of system resources, such as CPU, memory, and battery, to ensure optimal performance and user experience. As the number of devices and platforms continues to grow, it becomes increasingly challenging to ensure compatibility and interoperability across different APIs, making API usage a critical aspect of energy-efficient software. Therefore, it is not surprising that `API USAGE` is the second most popular intention among energy consumption-related questions on SO. Practitioners need to have a comprehensive understanding of the rationale of APIs to optimize power consumption during the software development.

Practitioners face challenges in resolving discrepancies in the energy-aware development. Being the third most frequent intention (i.e., 15.83%) after `CONCEPTUAL` and `API USAGE`, the prevalence of `DISCREPANCY`-related questions could

[6] `https://stackoverflow.com/questions/38158828`

be due to the fact that energy consumption is a more specialized and technical domain that requires a higher level of expertise and experience to troubleshoot and debug. In an example question[7], the asker seeks guidance on how to resolve the discrepancy in power consumption and reduce the energy usage of an app. The asker mentions the use of the components in the app but is uncertain about what to check in the app to reduce energy usage. To optimize energy consumption, practitioners need to understand how different system components interact and identify areas of inefficiency in their app code, which requires expertise and specialized tools. Practitioners, who are not familiar with the hardware and software configurations of energy-constrained platforms, may find it challenging to identify discrepancies between the observed result and the expectation and resolve the unexpected behavior in code snippets related to energy consumption. Given the abstract nature of energy consumption-related issues, there may be fewer resources and solutions available for practitioners to turn to for guidance, compared to more general-purpose topics, such as API usage and conceptual questions.

[7] https://stackoverflow.com/questions/42850419

Summary: We observe that nearly half of the questions are related to the concepts of energy consumption rather than implementation details. This suggests that energy consumption is still a high-level abstract concept for practitioners, as it can be linked to various components (e.g., devices and operating systems). Questions related to `API USAGE` are the second most frequent intention, followed by questions related to `DISCREPANCY`. In comparison to *Breyer et al.*'s work, our findings demonstrate that practitioners exhibit more concern toward the concept of energy consumption instead of `API USAGE`. The proportion of `DISCREPANCY`-related questions is halved compared to *Breyer et al.*'s work. Nonetheless, practitioners still encounter difficulties in resolving discrepancies between the execution results and their expectations related to energy consumption, which is a specialized and technical domain requiring expertise and experience for troubleshooting and debugging.

4.3.2 RQ2: What are the topics of the energy-related questions and their popularity?

Motivation: In RQ1, we have analyzed the intentions of posts expressed by practitioners. From another perspective, practitioners may raise a question on the same intention, whereas the question with the same intention may be shared by different topics (e.g., device and coding). Understanding the topics of the energy-related questions helps us delve into the predominant concerns of energy-related issues among practitioners in the SO community. Hence, in this RQ, we cluster the energy-related SO posts using topic modelling in order to identify similar energy-related concerns and group them under a topic. Some topics may be raised more often than others, or some may be less likely to receive prompt responses. Thereby, we are interested in studying the popularity of the questions associated with each topic and their likelihood of receiving effective community support by answering the questions. By studying this research question, we make the practitioners aware of the popular topics, which can help identify the concerned topics and advise researchers and practitioners to work toward addressing the raised concerns.

Approach: Topic modeling yields topic memberships ranging from 0 to 1 for each topic in a post, which represents the likelihood of a particular topic belonging to the post. For instance, the post[8] has topic memberships of 0.40 in topic 1, 0.25 in topic 2, 0.02 in topic 3, 0.15 in topic 4, 0.06 in topic 5, and 0.12 in topic 6, as determined by the LDA model. In this case, the membership of Topic 1 in the example post is 0.40, indicating a 40% probability that Topic 1 represents the example post. Therefore, any topic with a non-zero membership can partially represent a post, such as Topic 3 in the example above, which has a 2% chance of representing the example post. The higher the membership, the more likely the topic represents the post. Consequently, it is necessary to validate the relevance of the identified topics to a post to ensure the validity of the topics.

To further understand energy consumption-related posts, we conduct a detailed analysis of the posts in each LDA topic according to the LDA results. Our approach consists of the following steps: (1) manually validating topic modeling results; (2) computing popularity; and (3) calculating the median response time.

Validating topic modeling results. Regarding the topic modeling results, LDA generates six common topics, as listed in Table 4.1. A post can be associated

[8] `https://stackoverflow.com/questions/10246188`

with multiple topics. The two annotators, who have previously labeled the categories of the intention of the questions in RQ1, manually label the topics of posts using the LDA-generated six topics as references (as discussed in Section 4.2.4). We check if topics that we conclude from the topic modeling results are truly associated with a post. For example, our topic modeling extracts 6 sets of keywords, and we manually conclude the 6 keyword sets into 6 topics (as discussed in Section 4.2.4), i.e., Topics 1 *Coding*, 2 *Energy (general)*, 3 *Device*, 4 *Monitoring*, 5 *Computer Resource*, and 6 *data Transmission*. We use the 6 topics to label what topics belong to each of the sampled 277 posts. For example, we manually label *Device* and *Monitoring* to Post 1, *Energy (general)*, *Computer Resource*, and *Device* to Post 2, and *Monitoring* to Post 3 until Post 277 (as shown in Table A.1). We check all 277 posts and identify the possible topics by the two annotators based on the output of LDA. The output from the annotators is a set of manually labeled topics of the questions that can be compared to the topics generated by the topic modeling results. After completing the manual labeling of topics, the quality of manual work conducted by the two annotators is then assessed by Krippendorff's Alpha. Krippendorff's Alpha indicates a highly reliable inter-rater agreement (i.e., 0.92) of the manual results between the two annotators.

During the manual analysis, the two annotators eliminate the noise from the topic modeling results. We use the manual labels to validate the LDA results. Since any topic with a non-zero membership in the LDA results can partially represent the post, it is unclear if a topic is truly associated with a post. To ensure consistency between the manual results and the results from the topic modelling, we use Krippendorff's Alpha to obtain the best match of the LDA results with the manual labels. We want to ensure that specific topic(s) is representative of a post, as all topics can be associated with the post before validation.

We then set a threshold and filter out any topics whose memberships are below the threshold. Following this, both the manual results and the filtered LDA results are used as inputs of Krippendorff's Alpha to evaluate the degree of the agreement. Although the result of Krippendorff's Alpha may improve, it still may fall short of our expectations. We experiment with different thresholds until the processed LDA results attain a highly reliable agreement (i.e., 0.80) with the human-labelled results. A threshold of 0.32 is ultimately found to be the minimum membership of all topics that are present in a post to achieve an 0.80 agreement rate between the manual labels and the topic modeling results. However, if no memberships in a post are above 0.32, then the topic with the highest membership in the post is selected.

Computing popularity. To understand the relative popularity of different topics, the topics are compared to the average popularity of questions on SO. We use Equation (4.4) proposed by *Pinto et al.* [48] to measure the popularity of questions associated with each topic.

$$\mathbb{P} = \mathbb{S} + \mathbb{A} + \mathbb{C} + \mathbb{F} + \mathbb{V} \tag{4.4}$$

where $\mathbb{S}$ is the score of the question; $\mathbb{A}$ denotes the adopted answer score of the question; and $\mathbb{C}$, $\mathbb{F}$, and $\mathbb{V}$ stand for comments, favorizations of the question, and the normalized number of views, defined in Equation (4.5), respectively.

$$\mathbb{V} = \frac{QuestionViews}{StackOverflowViews} \tag{4.5}$$

where $QuestionViews$ refers to the view count shown in Figure 2.2; and $StackOverflowViews$ stands for the total number of view counts of all 985 filtered posts used in the study.

The score of a question is derived from the satisfaction level of the user. If a question solves the practitioner's concern, the practitioner can "up-vote" that question, or "down-vote" it, otherwise. Practitioners can also mark a question as favorite to indicate their interest in knowing more or keeping track of this question. In addition, all variables are subjected to normalization to prevent distortions and avoid situations where the outcomes are skewed by certain large absolute values. Values are normalized by min-max normalization, as shown in Equation 4.6.

$$X_{norm} = \frac{x - min(x)}{max(x) - min(x)} \tag{4.6}$$

where x denotes values in the value set awaiting normalization; X_{norm} is the normalized x; and $min(x)$ and $max(x)$ represent the minimum and maximum values of the value set x, respectively.

Calculating difficulty-related metrics. We calculate a set of metrics to characterize the level of difficulty of the questions related to each topic. The metrics comprise the proportion of questions that remain unanswered and the median response time for receiving an accepted answer in hours.

Table 4.3: Definitions of the derived energy consumption related topics.

Topics	Definition (D) - Quote (Q)	Freq
Computing Resource	**D**: Questions that concern about perceiving the use of computing resources. **Q**: "*Is there a way to use processors/[...] more effectively?*"[5]	272 (27.61%)
Device	**D**: Questions that concern about devices or systems that run on devices. **Q**: "*How to [...] with iOS/Android/etc.?*"[3]	221 (22.44%)
Monitoring	**D**: Questions related to measuring energy utilization by techniques or tools. **Q**: "*How to measure [...] power consumption?*"[4]	207 (21.02%)
Energy in general	**D**: General questions that are related to reducing energy consumption or impact. **Q**: "*How much does power draw [...]?*"[2]	201 (20.41%)
Coding	**D**: Questions that seek to save energy in programming techniques. **Q**: "*Are there any design architectures [...] to make code energy efficient?*"[1]	171 (17.36%)
Data Transmission	**D**: Questions are related to data sending virtually. **Q**: "*Is it optimized in terms of data consuming and power efficiency to receive new messages on the server/[...] and send notifications to the user's app?*"[6]	125 (12.69%)

1 `https://stackoverflow.com/questions/47000639` 2 `https://stackoverflow.com/questions/23981664`

3 `https://stackoverflow.com/questions/26329993` 4 `https://stackoverflow.com/questions/53494820`

5 `https://stackoverflow.com/questions/61660649` 6 `https://stackoverflow.com/questions/60244674`

Findings: Table 4.3 presents the common energy consumption topics generalized from the topic modelling results in Table 4.1, accompanied by definitions and illustrative examples. We describe the topics from two aspects: (1) topic popularity, which is appraised based on the popularity score (i.e., $\mathbb{P}$) and the number of views (i.e., $\mathbb{V}$); and (2) difficulty levels of each topic, calculated through the percentage of questions without an accepted answer, percentage of unanswered questions, and the median response time for receiving an accepted answer, as displayed in Tables 4.4 and 4.6.

We discover six topics from the energy-related questions, including topics related to *Computing Resource*, *Device*, *Monitoring*, *Energy in general*, *Coding*, and *Data Transmission*. Among the six topics, questions related to *Computing Resources* are discussed the most frequently, accounting for 27.61% of the questions. The second most discussed topic is *Device*, with 22.44% of the questions, followed by *Monitoring* with a similar frequency, accounting for 21.02% of the questions. *General Energy* efficiency in the software development is the fourth most discussed topic, with 20.41% of the questions, while *Coding*-related questions account for 17.36%. Data Transmission, the least discussed topic, is comprised of 12.69% of the questions.

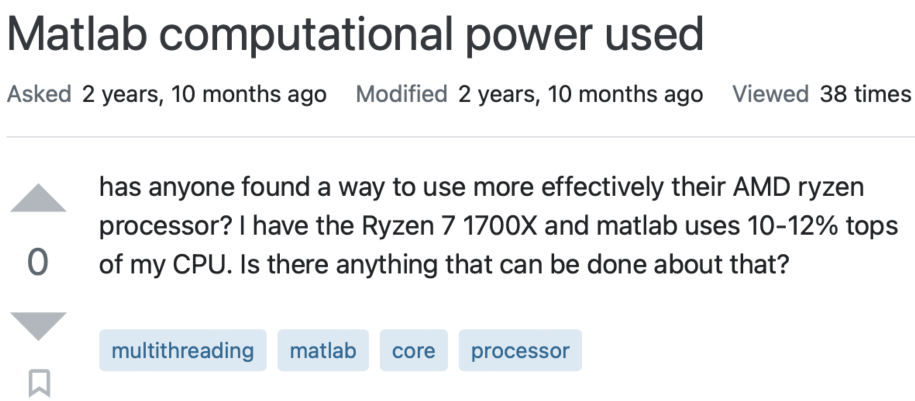
Questions related to computer resources receive the most attention from the SO community, followed by questions related to monitoring. According to Table 4.4, questions related to *Computing Resource* rank the highest in most popularity metrics. Such questions are of interest to practitioners due to the critical role that computing resources play in the performance and efficiency of computer systems. The increasing complexity of managing and optimizing computing resources,

Table 4.4: Common energy-consumption topics with cumulative normalized popularity score metric. The **bold** numbers highlight the most popular topic in terms of each metric.

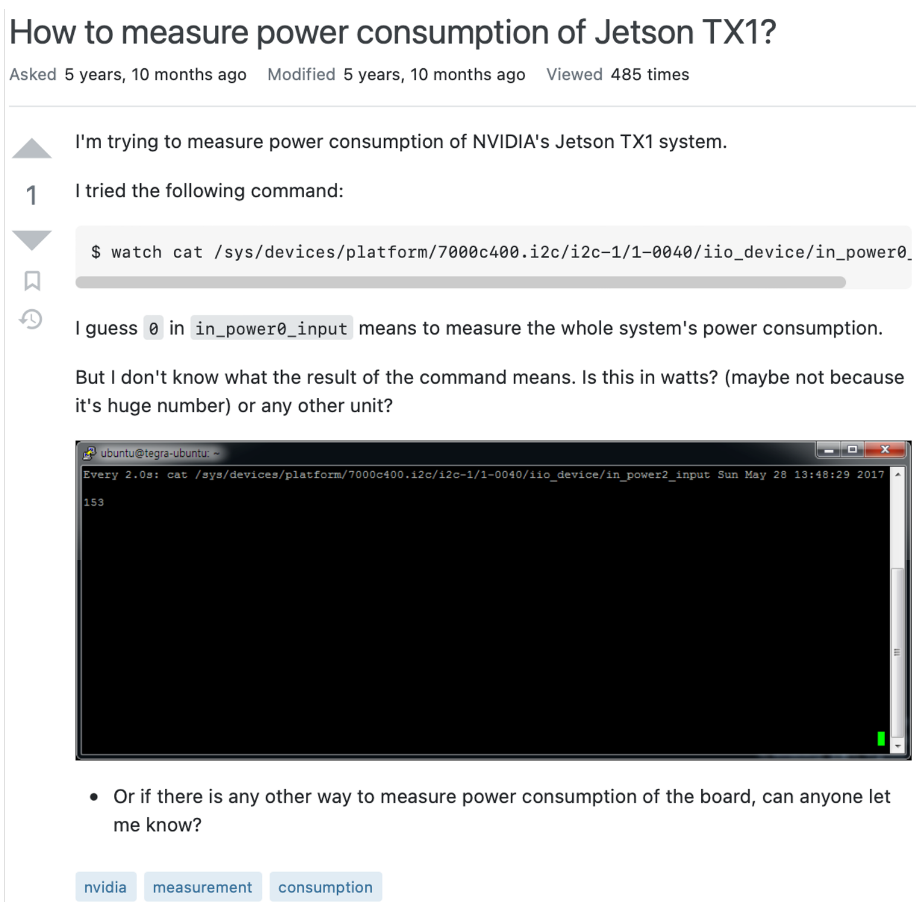
Topics	P	S	A	C	F	V
Computing Resource	**73.72**	**25.68**	**11.10**	**27.74**	**4.00**	5.20
Device	46.27	18.46	6.92	14.26	2.11	4.52
Monitoring	47.71	18.58	7.33	12.35	3.14	**6.31**
Energy (general)	42.19	17.65	6.70	12.39	2.06	3.39
Coding	44.16	14.00	5.58	21.78	0.95	1.84
Data Transmission	27.29	11.44	4.99	6.48	1.60	2.78

* P represents the popularity of the question, S is the score of the question, A denotes the adopted answer score of the question, and C, F, and V stand for comments, favorizations of the question, and the normalized number of views, respectively.

particularly in the context of cloud computing and virtualization technologies, may lead to a greater interest in *Computer Resources*. The need to stay up-to-date with the latest trends and development in computing resources may further drive interest in questions related to *Computer Resources*. Therefore, practitioners are likely to have concerns about the optimization and utilization of computing resources to improve overall performance and efficiency. Example posts in Figure 4.2 show the importance of understanding and optimizing computing resources to improve the performance and efficiency of software, which can be a single application or a larger infrastructure (e.g., a virtualized environment and cloud computing platform). *Monitoring* is a frequently viewed topic (i.e., the highest number of views per question $\mathbb{V}$) as it is essential for identifying energy-hungry components, inefficient algorithms, and other areas where energy consumption can be reduced. Such observation implies that monitoring-related questions are of greater interest to users to verify the answer due to the complexity of analyzing large amounts of data and interpreting complex metrics. Monitoring is also a critical aspect of modern technologies, such as cloud computing and DevOps, which are rapidly evolving and becoming more complex. As a result, there may be a greater need for practitioners to stay up-to-date with the latest monitoring tools or techniques, which could contribute to the high level of interest in monitoring-related questions. For instance, the questions shown in Figure 4.3 demonstrate the importance of monitoring in the software development and its relevance to energy consumption. Table 4.5 lists the resource of each figure shown in Figures 4.2 and 4.3. By monitoring the performance of a system or an application, practitioners can identify areas where energy consumption can be reduced and optimized for efficiency.

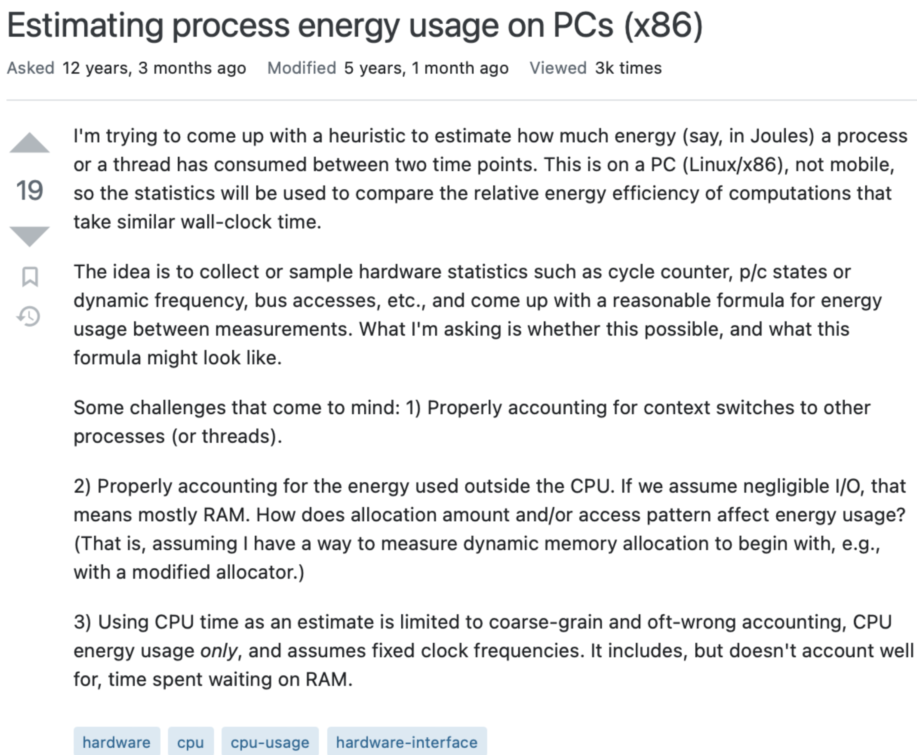


((a))



((b))

Figure 4.2: Example SO posts related to optimization and utilization of computing resources.



Estimating process energy usage on PCs (x86)

Asked 12 years, 3 months ago Modified 5 years, 1 month ago Viewed 3k times

19

I'm trying to come up with a heuristic to estimate how much energy (say, in Joules) a process or a thread has consumed between two time points. This is on a PC (Linux/x86), not mobile, so the statistics will be used to compare the relative energy efficiency of computations that take similar wall-clock time.

The idea is to collect or sample hardware statistics such as cycle counter, p/c states or dynamic frequency, bus accesses, etc., and come up with a reasonable formula for energy usage between measurements. What I'm asking is whether this possible, and what this formula might look like.

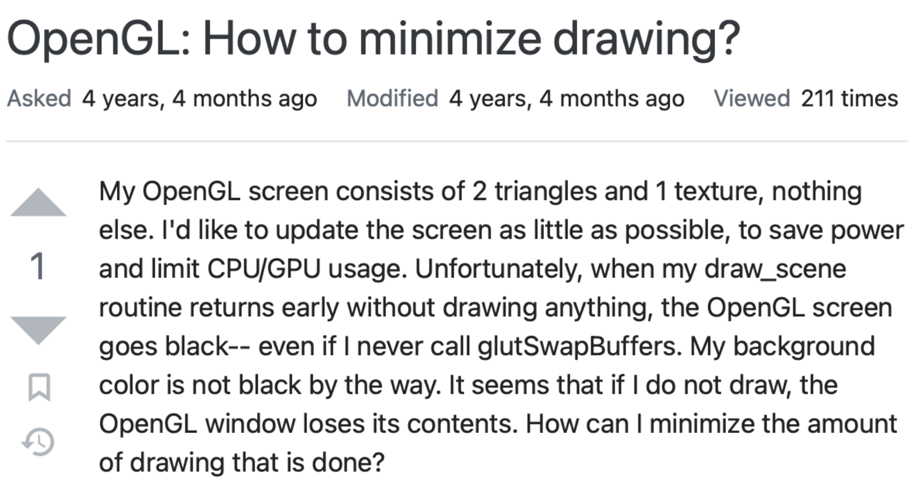
Some challenges that come to mind: 1) Properly accounting for context switches to other processes (or threads).

2) Properly accounting for the energy used outside the CPU. If we assume negligible I/O, that means mostly RAM. How does allocation amount and/or access pattern affect energy usage? (That is, assuming I have a way to measure dynamic memory allocation to begin with, e.g., with a modified allocator.)

3) Using CPU time as an estimate is limited to coarse-grain and oft-wrong accounting, CPU energy usage *only*, and assumes fixed clock frequencies. It includes, but doesn't account well for, time spent waiting on RAM.

hardware cpu cpu-usage hardware-interface

((c))



OpenGL: How to minimize drawing?

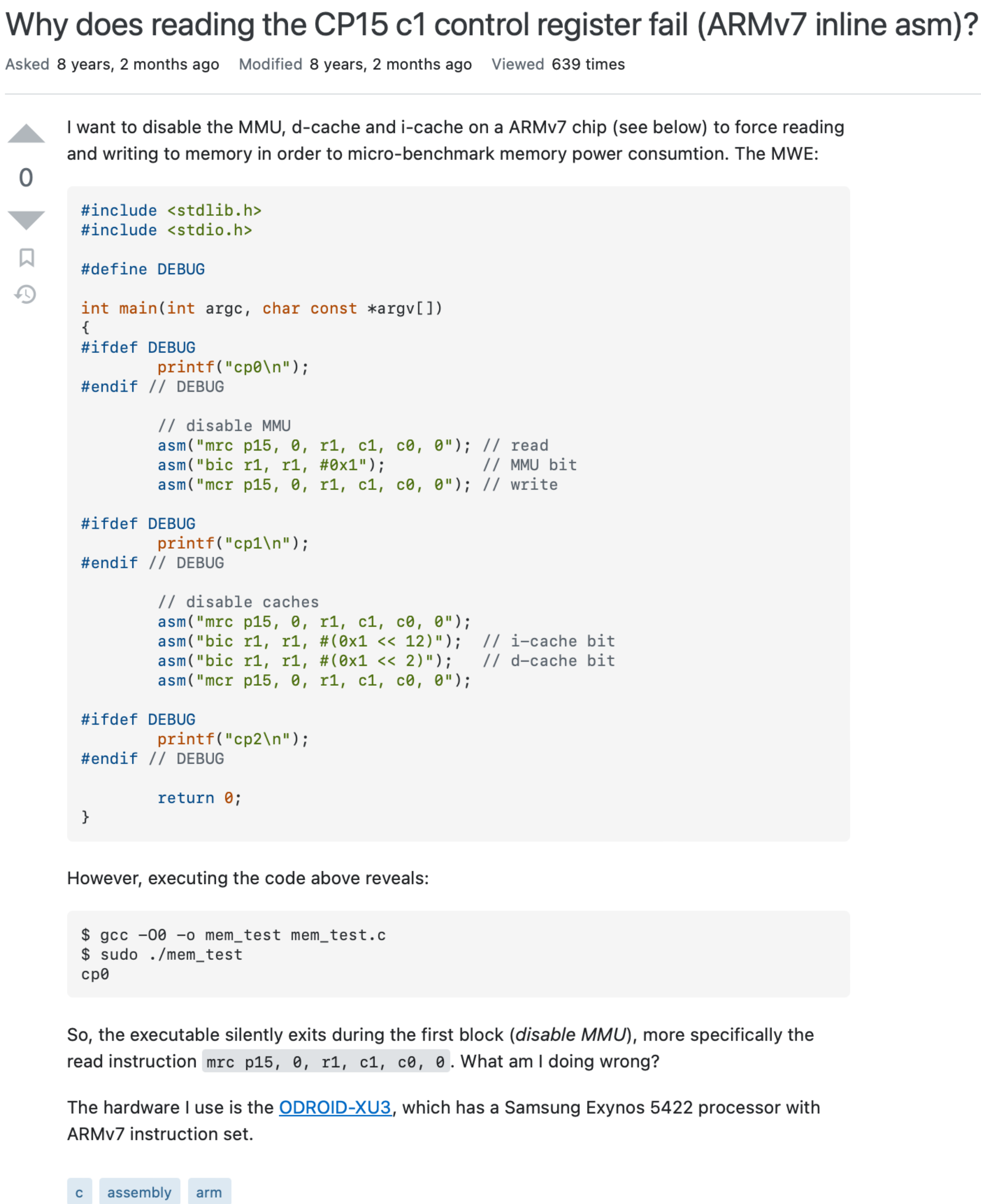
Asked 4 years, 4 months ago Modified 4 years, 4 months ago Viewed 211 times

1

My OpenGL screen consists of 2 triangles and 1 texture, nothing else. I'd like to update the screen as little as possible, to save power and limit CPU/GPU usage. Unfortunately, when my draw_scene routine returns early without drawing anything, the OpenGL screen goes black-- even if I never call glutSwapBuffers. My background color is not black by the way. It seems that if I do not draw, the OpenGL window loses its contents. How can I minimize the amount of drawing that is done?

((d))

Figure 4.2: Example SO posts related to optimization and utilization of computing resources (cont.).



Why does reading the CP15 c1 control register fail (ARMv7 inline asm)?

Asked 8 years, 2 months ago Modified 8 years, 2 months ago Viewed 639 times

0

I want to disable the MMU, d-cache and i-cache on a ARMv7 chip (see below) to force reading and writing to memory in order to micro-benchmark memory power consumtion. The MWE:

```
#include <stdlib.h>
#include <stdio.h>

#define DEBUG

int main(int argc, char const *argv[])
{
#ifdef DEBUG
        printf("cp0\n");
#endif // DEBUG

        // disable MMU
        asm("mrc p15, 0, r1, c1, c0, 0"); // read
        asm("bic r1, r1, #0x1");          // MMU bit
        asm("mcr p15, 0, r1, c1, c0, 0"); // write

#ifdef DEBUG
        printf("cp1\n");
#endif // DEBUG

        // disable caches
        asm("mrc p15, 0, r1, c1, c0, 0");
        asm("bic r1, r1, #(0x1 << 12)");  // i-cache bit
        asm("bic r1, r1, #(0x1 << 2)");   // d-cache bit
        asm("mcr p15, 0, r1, c1, c0, 0");

#ifdef DEBUG
        printf("cp2\n");
#endif // DEBUG

        return 0;
}
```

However, executing the code above reveals:

```
$ gcc -O0 -o mem_test mem_test.c
$ sudo ./mem_test
cp0
```

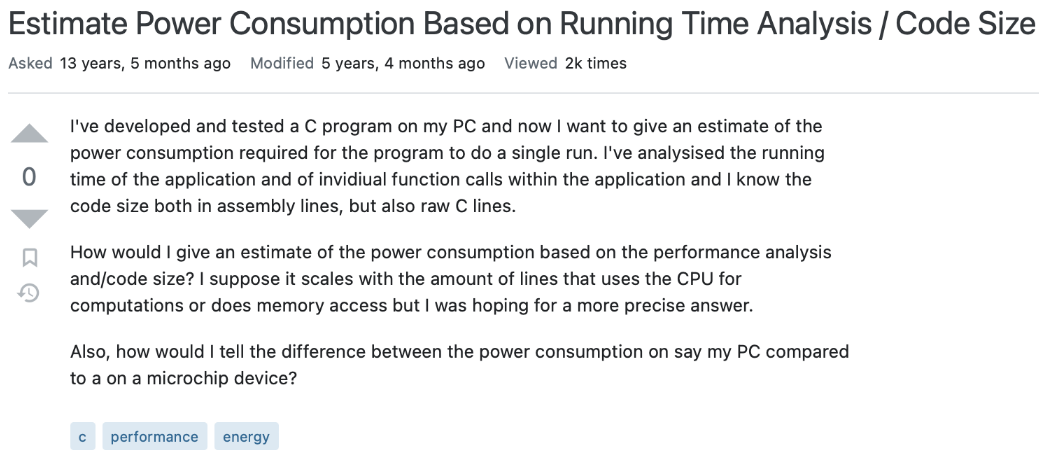
So, the executable silently exits during the first block (*disable MMU*), more specifically the read instruction `mrc p15, 0, r1, c1, c0, 0`. What am I doing wrong?

The hardware I use is the ODROID-XU3, which has a Samsung Exynos 5422 processor with ARMv7 instruction set.

c assembly arm

((e))

Figure 4.2: Example SO posts related to optimization and utilization of computing resources (cont.).



Estimate Power Consumption Based on Running Time Analysis / Code Size

Asked 13 years, 5 months ago Modified 5 years, 4 months ago Viewed 2k times

0

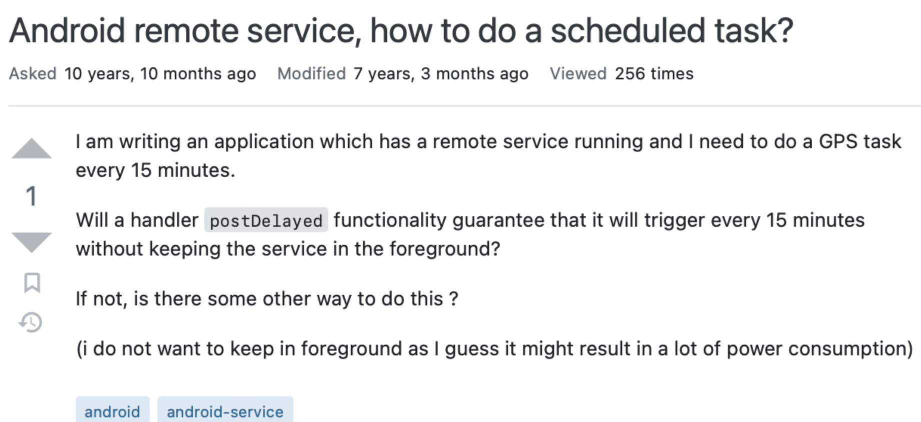
I've developed and tested a C program on my PC and now I want to give an estimate of the power consumption required for the program to do a single run. I've analysised the running time of the application and of invidiual function calls within the application and I know the code size both in assembly lines, but also raw C lines.

How would I give an estimate of the power consumption based on the performance analysis and/code size? I suppose it scales with the amount of lines that uses the CPU for computations or does memory access but I was hoping for a more precise answer.

Also, how would I tell the difference between the power consumption on say my PC compared to a on a microchip device?

c performance energy

((a))



Android remote service, how to do a scheduled task?

Asked 10 years, 10 months ago Modified 7 years, 3 months ago Viewed 256 times

1

I am writing an application which has a remote service running and I need to do a GPS task every 15 minutes.

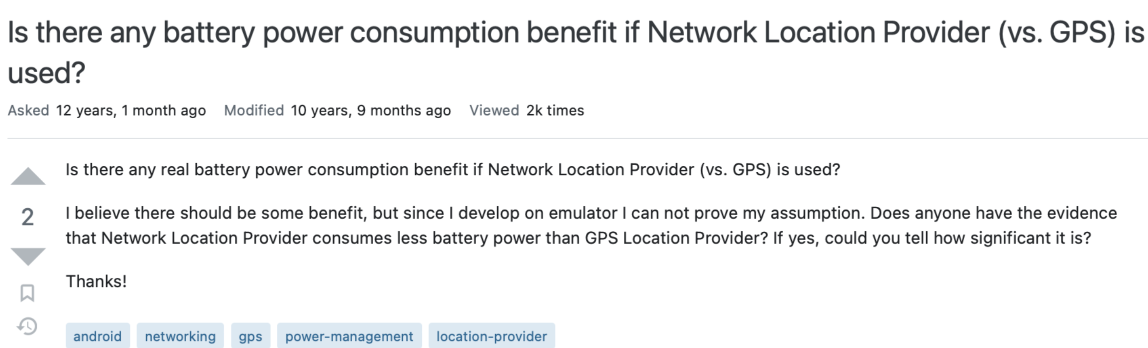
Will a handler `postDelayed` functionality guarantee that it will trigger every 15 minutes without keeping the service in the foreground?

If not, is there some other way to do this ?

(i do not want to keep in foreground as I guess it might result in a lot of power consumption)

android android-service

((b))



Is there any battery power consumption benefit if Network Location Provider (vs. GPS) is used?

Asked 12 years, 1 month ago Modified 10 years, 9 months ago Viewed 2k times

2

Is there any real battery power consumption benefit if Network Location Provider (vs. GPS) is used?

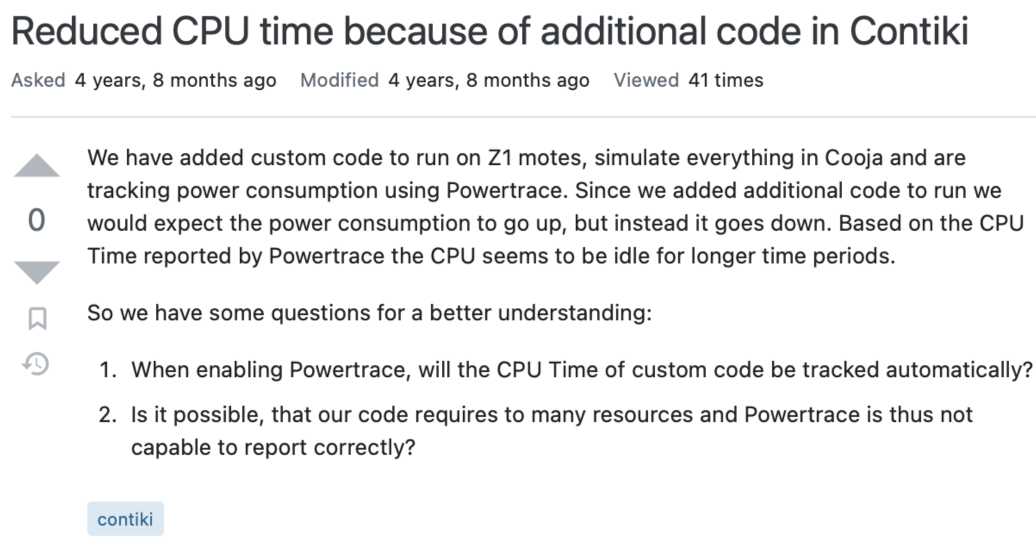
I believe there should be some benefit, but since I develop on emulator I can not prove my assumption. Does anyone have the evidence that Network Location Provider consumes less battery power than GPS Location Provider? If yes, could you tell how significant it is?

Thanks!

android networking gps power-management location-provider

((c))

Figure 4.3: Example SO posts related to monitoring energy consumption.



Reduced CPU time because of additional code in Contiki

Asked 4 years, 8 months ago Modified 4 years, 8 months ago Viewed 41 times

0

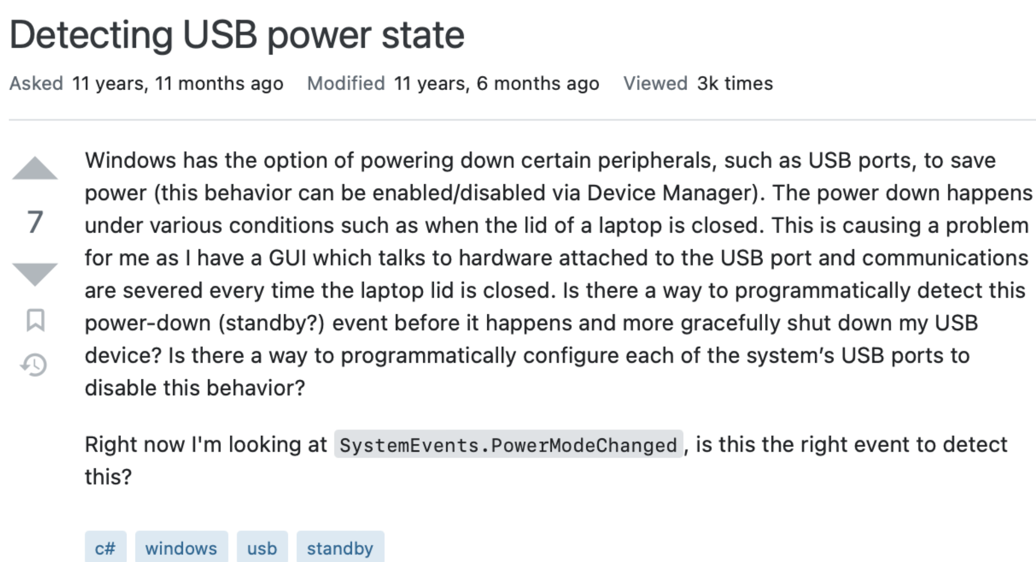
We have added custom code to run on Z1 motes, simulate everything in Cooja and are tracking power consumption using Powertrace. Since we added additional code to run we would expect the power consumption to go up, but instead it goes down. Based on the CPU Time reported by Powertrace the CPU seems to be idle for longer time periods.

So we have some questions for a better understanding:

1. When enabling Powertrace, will the CPU Time of custom code be tracked automatically?
2. Is it possible, that our code requires to many resources and Powertrace is thus not capable to report correctly?

contiki

((d))



Detecting USB power state

Asked 11 years, 11 months ago Modified 11 years, 6 months ago Viewed 3k times

7

Windows has the option of powering down certain peripherals, such as USB ports, to save power (this behavior can be enabled/disabled via Device Manager). The power down happens under various conditions such as when the lid of a laptop is closed. This is causing a problem for me as I have a GUI which talks to hardware attached to the USB port and communications are severed every time the laptop lid is closed. Is there a way to programmatically detect this power-down (standby?) event before it happens and more gracefully shut down my USB device? Is there a way to programmatically configure each of the system's USB ports to disable this behavior?

Right now I'm looking at `SystemEvents.PowerModeChanged`, is this the right event to detect this?

c# windows usb standby

((e))

Figure 4.3: Example SO posts related to monitoring energy consumption (cont.)

As for the difficulties of the questions posted on each topic, **energy-related questions appear to be more challenging than general programming questions**. Table 4.6 shows that questions related to general energy efficiency in the software

Table 4.5: Resources of example SO posts.

Figure	Description	Post Title	Example
Figure 4.2	SO posts related to optimization and utilization of computing resources	Matlab computational [...]	https://stackoverflow.com/questions/61660649
		OpenGL: How to [...]	https://stackoverflow.com/questions/53577434
		Why does reading [...]	https://stackoverflow.com/questions/28003660
		How to measure [...]	https://stackoverflow.com/questions/44228005
		Estimating process [...]	https://stackoverflow.com/questions/4485153
Figure 4.3	SO posts related to monitoring energy consumption	Estimate Power [...]	https://stackoverflow.com/questions/1596252
		Android remote service, [...]	https://stackoverflow.com/questions/10908666
		Reduced CPU time [...]	https://stackoverflow.com/questions/51406465
		Detecting USB power state	https://stackoverflow.com/questions/5884820
		Is there any battery power [...]	https://stackoverflow.com/questions/4926963

Table 4.6: Common energy-consumption topics with their metrics representing difficulties. The **bold** numbers highlight the most difficult topic in terms of each metric.

Topics	Percentage of questions without an accepted answer	Percentage of questions without an answer	Median time for receiving an accepted answer (Hr)
Computing Resource	59.93%	22.79%	5.47
Device	65.16%	22.62%	4.53
Monitoring	63.29%	16.91%	**5.74**
Energy (general)	**68.66%**	**25.87%**	5.14
Coding	57.89%	23.98%	3.55
Data Transmission	56.80%	21.60%	2.43
Average	61.96%	22.30%	4.48

development have the highest unaccepted answer ratio of 68.66% on average and take a median of 5.14 hours to receive an accepted response. In contrast, *Rosen and Shihab* [53] highlight a lower average nonacceptance ratio (i.e., 30.00%) and a shorter median response time of 21 minutes to obtain an accepted answer for mobile development-related questions on SO. *Bagherzadeh et al.* [5] report an unaccepted answer ratio of 60.50% for big data-related questions, with an average median response time of 3.30 hours to receive an accepted answer. The higher nonacceptance ratio and longer response time of energy-related questions may be due to the complex nature of energy consumption in computing systems. Energy consumption involves multiple layers, including hardware, systems, and applications, and addressing energy-related challenges may require specialized expertise or resources. Consequently, it is not surprising that practitioners may need to seek out more specialized help to effectively address these challenges. Similarly, researchers may need to investigate the underlying reasons for the lower acceptance ratio and longer response time of energy-related questions to identify potential areas for improvement in energy-efficient computing practices.

***Monitoring* is the most difficult topic in energy consumption for practitioners.** Table 4.4 shows that the topic *Monitoring* has the highest ratio of questions with failed answers (i.e., 63.29%-16.91%=46.38%) and the highest accepted-answer response time (i.e., 5.74 hours on median), implying that *Monitoring* is the most challenging topic. For example, the post[9] asks for a way to monitor the power consumption of specific processes on an Android device, but it takes 1.77 years to receive an accepted answer. The high ratio of questions with failed answers and the longest median answer response time mean that practitioners are struggling to get accurate and reliable answers related to monitoring energy consumption, which may lead to increased energy costs, reduced energy efficiency, and missed opportunities for energy savings. The lack of specialized monitoring tools may further aggravate the issue, making it even more challenging for practitioners to measure energy consumption at various levels of detail or resolution. To address this challenge, more attention should be given to developing specialized monitoring tools and providing training and support for practitioners to use these tools effectively. Additionally, collaborative efforts between practitioners, researchers, and technology developers can help advance the field of energy monitoring and facilitate more effective and efficient energy use.

Questions related to *general Energy* efficiency in the software development lack contexts thus making them difficult to get a good answer. For

[9] `https://stackoverflow.com/questions/6051807`

example, the question[10] "Xcode Energy impact very high - Display on iPhone X" is too broad and lacks a specific context. The question is unclear what specific app or task causes the high energy impact on the iPhone X, and whether the issue is related to the hardware or software. The lack of contexts has implications for practitioners who want to ask questions related to energy consumption during the software development. To increase the likelihood of receiving more targeted and relevant responses, practitioners should ask questions in a specific context. In the case of the example question, more contexts could include the specific app being developed, any graphics-intensive features, any relevant code, and configurations. Without additional information, it can be challenging to determine the root cause of the high energy impact and provide precise and effective solutions. Thus, practitioners should strive to provide a specific context when asking questions about general energy efficiency in the software development, which can help potential respondents to understand the problem and suggest more precise and relevant solutions.

[10] `https://stackoverflow.com/questions/56699763`

Summary: We derive six common topics using LDA: *Computing Resource*, *Device*, *Monitoring*, *Energy in general*, *Coding*, and *Data Transmission*. Our results indicate that understanding *Computing Resources* used by their programs is of particular interest to practitioners due to the critical role of computing resources in computer system performance and efficiency. Questions related to *general Energy* efficiency in the software development and *Monitoring* are the two most difficult topics to receive community support. Our results suggest that understanding *Computing Resources* can have implications for the design and development of energy-efficient systems and suggest a need for more specialized monitoring tools and training to effectively measure energy consumption. Our results also suggest that practitioners should ask energy-related questions in a specific context to get better community support rather than being too general.

4.3.3 RQ3: What are the concerned development categories in practitioners' energy-related questions?

Motivation: In practice, a SO post typically contains one to five tags that succinctly identify the subject of the questions. Assigning relevant tags to a post facilitates its searchability and attracts the attention of practitioners who specialize in the respective area. From a high-level interpretation perspective, energy-related questions can be further classified into different categories based on the tags attached to the questions, such as different computing devices (e.g., mobile devices or servers), operation systems (e.g., Linux or Windows), and programming languages (e.g., Java or C). We are interested in identifying the prevalent tag categories and those that garner more attention or raise more questions with regard to energy consumption. Understanding the tag categories that practitioners have more questions about sheds light on directing technical support toward addressing energy-related challenges faced by practitioners.

Approach: We identify the tag categories that practitioners post their concerns about in the following three steps.

Table 4.7: Tag category specification.

Tag Category			Tag List
OS (485)			android, ios (ios, ios7, and ios8), linux, windows, macos, ubuntu, wear-os
Programming Language (686)			java, c, python, c++, swift (swift and swift3), c#, objective-c, sql, php, .net, verilog, node.js, assembly, shell, vhdl, matlab, bash, kotlin, json, jquery, css
Hardware (452)	Mobile (70)		apple, ipad, mobile, phone, tablet
	Accessory (156)		accelerometer, beacon, bluetooth, gps, ibeacon, usb, wifi, sensors
	Server (16)		server, computer
	Embedded (128)		embedded, stm32, esp8266, esp32, arduino, pi, raspberry, fpga, xilinx, iot
	Processing Unit (149)	Central (117)	microchip, microcontroller, amd, arm, core, cpu, intel, x86, msr
		Graphics (24)	gpgpu, gpu, nvidia
		Storage (15)	memory

* The number of posts for each tag category or sub-category is listed in parentheses (e.g., OS (485)).

** Since a post may span tag categories (e.g., both Central and Embedded), the sum of subcategories does not add up directly (e.g., the number of posts in Processing Unit does not equal to the sum of Central, Graphics, Storage, and Embedded).

Step 1: Counting the tag frequencies. We merge the synonymous tags that have similar meanings into a single tag category, and the posts for each of the synonymous tags are grouped under the tag with the most frequent occurrences. For example, the post[11] is assigned with two tags, i.e., Bluetooth and bluetooth-lowenergy. As the two tags are semantically similar and Bluetooth has a higher frequency of occurrences than bluetooth-lowenergy, we merge posts under the tag with the highest frequency, i.e., Bluetooth. Then, we replace the synonym tags in all posts with one tag that has the highest frequency. For instance, the post[12] is assigned with a tag of Bluetooth, and post[13] is assigned with a tag of bluetooth-lowenergy. We associate all the post tags with a higher frequency, i.e., Bluetooth. Finally, the number of occurrences of all synonymous tags is counted.

Step 2: Selecting the tags. We find 628 tags in total in our dataset. The tags occur a total of 3,150 times in the posts. We consider the most frequently occurring tags (i.e., roughly 20% of the tags) that account for 80% of the total occurrences based on the Pareto principle (i.e., 80/20 rule). The selection process results in 142 tags. To include the tags with the same occurrence frequency, a final total of 173 tags (i.e., covering 82.95% of all tag occurrences in the final) is determined.

Step 3: Grouping the tags. We manually categorize the selected tags into categories based on their functionalities. We mainly focus on development platforms, including operating systems (e.g., Windows, Linux, Android, and iOS), integrated development environments (e.g., Eclipse, Visual Studio, and IntelliJ IDEA), version control systems (e.g., Git, SVN, and Mercurial), testing and debugging tools (e.g., Selenium, JUnit, and Xdebug), and cloud platforms (e.g., Amazon Web Services,

[11] `https://stackoverflow.com/questions/23190179`
[12] `https://stackoverflow.com/questions/10777741`
[13] `https://stackoverflow.com/questions/21636511`

Microsoft Azure, and Google Cloud Platform). We filter out the tags that are not related to development platforms. As a result, we select 69 tags out of 173 tags. These 69 tags are further grouped into three tag categories in our manual analysis, including Operating System (9 tags), Programming Language (22 tags), and Hardware (38 tags). The tags in each tag category with the occurrences greater than or equal to 1% of the total occurrences of the tags are considered, as the tags $\leq$ 1% are not informative due to their infrequent usage in the total posts. Including the infrequent tags could introduce noises to the analysis and potentially skew the results, which is the reason we exclude the infrequent tags from consideration.

Step 4: Categorizing results and counting the number of the posts for each tag. We investigate the posts associated with each tag. The number of the posts related to each tag is then counted. By observing the frequency of occurrences of the tags, we identify different tag categories based on the similarity of the semantic meanings of the tags.

Findings: Practitioners are concerned about energy consumption from different aspects: programming languages, operating systems (OS)s, and hardware. Three tag categories, as shown in Table 4.7, are identified as follows:

- The **OS** category contains tags related to device operation systems, such as Linux, Android, and MacOS.
- The **Programming Language** category subsumes tags related to programming techniques, such as Java, and PHP.
- The **Hardware** category includes tags related to hardware components for mobiles, accessories, CPUs, GPUs, memory, and embedded.

Table 4.8: Distribution of posts related to operating systems (the tag category OS).

	Operating System				
Tag	**Android**	iOS	Linux	Windows	MacOs
Freq	27.82%*	12.18%	5.28%	3.35%	1.02%

* The figure indicates the percentage of tag category-related posts (e.g., Android) among all posts.

Table 4.9: Distribution of posts related to hardware (the tag category Hardware).

	Hardware						
					Processing Unit		
Tag	**Accessory**	Embedded	Mobile	Server	Central	Graphics	Storage
Freq	15.03%	14.42%	6.90%	1.12%	10.56%	3.05%	1.22%

Table 4.10: Distribution of posts related to programming languages (the tag category Programming Language).

	Programming Language							
Tag	**Java**	C	Python	C++	Swift	C#	Objective-C	SQL
Freq	6.80%	5.08%	4.06%	3.65%	3.65%	2.13%	1.73%	1.52%

***Programming Language* is the most discussed and mentioned subject by practitioners on SO when talking about energy consumption.** Table 4.7 lists tag categories with the numbers of posts and a set of tags for each tag category. A total of 686 posts are related to *Programming Language*, while the categories *OS* and *Hardware* appear 485 times and 452 times in the posts, respectively.

Tables 4.8, 4.9, and 4.10 introduce the percentage of the posts on *OS*, *Hardware*, and *Programming Language* with respect to each tag, respectively. As a post is not only limited to one tag, the sum of the three tag categories is not 100%, e.g., a post can be related to both embedded and Object-C[14]. The number corresponding to each tag category represents the percentage of all the specific computing tag category-related posts (e.g., Android) out of all posts. For example, 27.82% at the bottom of

[14] `https://stackoverflow.com/questions/17134522`

Table 4.8, corresponds to the frequency of *Android* in the total posts.

Practitioners raise more questions related to mobile operating systems than PC/server-related operating systems. In particular, `Android` and `Linux` are the most discussed subjects among the mobile and PC/server operating systems, respectively. As shown in Table 4.8, questions associated with `Android` and `iOS` account for 27.82% and 12.18% of the total questions, while questions related to PC/server-based operating systems are 5.28% (`Linux`), 3.35% (`Windows`), and 1.02% (`MacOS`), respectively. Such an observation implies that mobile-based operating systems get more attention than PC/server-based operating systems. Mobile operating systems have a higher number of questions, in particular Android and iOS, than PC/server-based operating systems. This could be due to the limited battery life of mobile devices. PC/server-based systems are frequently connected to a dependable power source, energy consumption is generally not as much of a concern. Moreover, mobile operating systems are more complicated than PC/server-based systems as mobile operating systems require to handle several hardware components and sensors and frequently execute apps in the background. To optimize the apps and devices for better energy efficiency, practitioners are more likely to have energy-related questions pertaining to mobile operating systems.

In terms of hardware, practitioners are most concerned about the energy consumption of accessories (e.g., Bluetooth or GPS), followed by processing units (e.g., CPU, GPU, or microchip). Table 4.9 illustrates the concerned subjects in *Hardware*. We find that most questions (15.03%) are concerned with energy consumption in `Accessory`, while `Embedded` (14.42%) and `Central`

`Processing Unit` (10.56%) are the next most concerned. Accessories, such as Bluetooth and GPS, consume a significant amount of energy, as they continuously send and receive signals. The processing units, including CPU, GPU, and microchips, consume a lot of energy because they are responsible for executing the source code and performing calculations. Thus, these hardware components are the most power-hungry and frequently used in software applications.

Although `Java` is the most concerned subject (6.80%) for a single programming language, the C family still holds the majority (i.e., 12.59%) of the practitioners' concerns from a macro perspective. Concerned subjects in *Programming Language* are listed in Table 4.10. Since Java is used in the development of Android, and Android is the most discussed subject in *OS*, there is an active discussion list on the Java forums about `Java` energy use and seeking programming efficiency. In particular, `Java` development occupies the largest concern among all programming languages (6.80%). However, in a broader sense, the C language family, including `C` (5.08%), `C++` (3.65%), `C#` (2.13%), and `objective-C` (1.73%), takes a total of 12.59% of discussions on *Programming Languages*. This is because many of the hardware, software, and OS developments, such as the kernel of Linux, integrated devices, and IoT devices in accessories, are based on the family of C languages.

Summary: Our results suggest that practitioners consider energy consumption from different levels when developing applications, namely: *OS*, *Hardware*, and *Programming Language*. *Programming Language* is the most concerned by practitioners, with the C language family being the most frequently discussed topic. We also observe that practitioners are more concerned about the energy consumption of mobile operating systems (e.g., Android) and accessories (e.g., Bluetooth) than PC/server-related operating systems (e.g., Linux) and processing units (e.g., CPU), respectively. Our findings shed light on future work to aid practitioners in their energy-aware development from the perspectives of OSes, hardware, and programming languages.

4.4 Implication

In this section, we discuss the implications of our findings for knowledge-sharing communities, practitioners, and future researchers.

4.4.1 Implication for Knowledge Sharing Communities

We propose that our community centrally build enhanced knowledge-sharing, resources, documentation, and tutorials to aid practitioners in understanding the *concepts* of energy-related aspects of the software development. As noted in Section 4.3.1, the majority of posts in the community pertain to seeking `CONCEPTUAL` knowledge regarding energy consumption, such as the constraints of using a certain API to discern energy usage. Such an observation implies that practitioners may lack familiarity with handling APIs or may have conceptually vulnerable. Knowledge-sharing web forums, such as Stack Overflow, can integrate and centrally manage the repeatedly shared knowledge and index problems to facilitate easier searches for solutions. Once the commonly asked knowledge is indexed by the intention categories, the posts that share such knowledge are expected to be indexed.

Energy-related questions are more challenging than general programming questions. In particular, questions about monitoring and general energy efficiency in the software development are the two most difficult topics regarding energy consumption. This might be due to a lack of awareness about the energy efficiency in the software development within the community. Questions related to the energy efficiency in the software development are complex and abstract, requiring answerers to have a solid knowledge of various areas, such as software systems, hardware components, and software development, and to be proficient in using tools to profile energy consumption. Such expectations may deter potential respondents from answering questions. Thus, the community can help promote the importance of the energy efficiency in the software development, share the energy-efficient programming knowledge, and encourage practitioners to engage in online discussions on the energy-efficient software development.

4.4.2 Implication for Practitioners

Practitioners seeking guidance on the implementation of certain functionality and the use of an API associated with discerning energy usage are encouraged to describe their problem in more succinct language and assign relevant tags that best match their problems to aid in their search. In Section 4.3.2, our findings suggest that practitioners are more likely to receive better community support while asking energy-related questions in a specific context rather than being too general. Vague or generic questions could make it challenging for others to identify the root causes and provide relevant advice, leading to delays in receiving an accepted answer or receive irrelevant responses. To increase the probability of receiving timely and relevant feedback from the community, practitioners are encouraged to provide specific details about their problem (e.g., the hardware and software configurations, use cases, code snippets, and specific energy efficiency metrics) and use appropriate tags to further clarify their problems and help others better understand the contexts of the questions.

Practitioners are encouraged to pay attention to the energy impact of hardware accessories, e.g., GPS and Bluetooth, on mobile devices. As discussed in Section 4.3.3, mobile operating systems, particularly Android, have significant energy concerns. The majority of questions posed by practitioners are related to the energy consumption of hardware accessories, such as Bluetooth and GPS. Efficient utilization of hardware is crucial for developing energy-efficient software. Practitioners need to be aware of the hardware components and their energy consumption patterns to optimize the software accordingly. For example, a software application that frequently makes use of Bluetooth or GPS can be tuned to activate the hardware accessories only when necessary rather than keeping them on continuously. Similarly, optimizing the code to reduce the processing time of the CPU and GPU and the use of RAM may help in reducing energy consumption.

4.4.3 Implication for Future Research

Tool researchers could provide more tooling support for evaluating and monitoring energy consumption. As highlighted in Section 4.3.1, we observe that monitoring energy usage of computing resources is a top consideration for practitioners, but assistance is also a challenging issue. One major limitation of current energy monitoring tools is that they predominately concentrate on the entire system or application, rather than a specific layer or a specific software stack component, such as GPUs, RAMs, and CUPs. As a result, it is challenging to acquire a comprehensive view of the energy consumption of a specific element. Practitioners are keen to know how to profile energy consumption using the available tools. To address this limitation, we recommend that tool researchers could develop supporting tools that offer an atomic view of energy consumption on specific layers of the software stack. Moreover, techniques can be devised to automatically identify energy hotspots in software by analyzing energy consumption data to detect patterns and anomalies that indicate areas of high energy consumption.

4.5 Threats to Validity

The goal of this study is to investigate energy consumption-related topics. In this section, we present the threats to the validity of the study.

Construct Validity refers to the extent to which an experimental design can accurately assess the theoretical construct or concept it is intended to measure. Our construct threads to validity are mainly related to (i) post retrieval and (ii) manual annotation. Even though our data cover as a wide range of characteristics as possible, our selection of posts may not be exhaustive. We have not fully examined all relevant posts in the data dump. The size of the data and the linguistic freedom of presentation - different words present the same meaning - can have a significant impact on the results. Furthermore, we conduct manual inspection twice: one is to filter out the posts related to energy consumption from the retrieved posts, and another is to validate the LDA result as well as intention categories. With the involvement of the specialist (a post-doctoral researcher in Software Engineering with 7 years of experience) in the manual labeling process (as discussed in Section 4.2.2), we attempt to mitigate this threat. To ensure the normality of the rule set, we follow *Seaman*'s open coding procedures [58].

Internal Validity pertains to factors that undermine the accuracy and credibility of research findings by introducing bias or distorting the relationship between the variables under investigation. The LDA modeling is a main factor that challenges internal validity. We choose the LDA model as our research method, but the results are further validated by Krippendorff's α from the manual labels. In addition, we select the tags of posts to summarize tag categories with regard to the occurrences of the tags. The occurrence may not indicate the true relationship between the theme of a post and the tag categories. However, we cover the most development category-related tags, which increases our relevance to the study.

External Validity refers to factors that challenge the generalizability of the findings of a research study to settings or circumstances beyond the study sample and context. Our results apply only to questions interested in energy usage on Stack-Overflow. It does not include other Q&A websites, such as Ask Ubuntu, nor does it include the posts asked in other languages (e.g., French). Although Stack Overflow is the most popular development Q&A website, further investigation could be conducted to subsume additional sources.

4.6 Summary

In this chapter, we conduct an empirical study to investigate how practitioners on SO are concerned about energy consumption. We study 985 energy-related questions retrieved from 1,641,802 posts on SO. This chapter provides three types of categorization for questions posted on SO, including a question intention-based categorization, a question topic-based categorization, and a question tag-based categorization. Our findings can help researchers, practitioners, and energy professionals facilitate the comprehension of the characteristics of energy-related questions raised by practitioners. In this chapter, we observe the following:

- Energy consumption is an abstract concept for practitioners in that it can be attributed to numerous components (e.g., devices, operating systems, and hardware peripherals).

- The intentions of practitioners to initiate posts in the energy realm are intimately linked with the usage of concepts, followed by the questions concerning `API USAGE`.

- There are six common topics identified regarding energy consumption questions, namely: *Computing Resource*, *Device*, *Monitoring*, *Energy*, *Coding*, and *Data Transmission.*

- *Computing Resources* used by the programs is of particular interest to practitioners due to the critical role of computing resources in the performance of computer systems and efficiency.

- *Monitoring* and the *general Energy* efficiency in the software development are two of the most difficult topics to receive community support.
- Practitioners consider energy consumption at different levels while developing applications, namely: *OS*, *Hardware*, and *Programming Language*.
- *Programming Language* is of the most concern to practitioners, and the C language family is the most frequently discussed topic.
- Practitioners are more concerned about the energy consumption of mobile operating systems (e.g., Android) and hardware accessories (e.g., Bluetooth) than PC/server-related operating systems (e.g., Linux) and processing units (e.g., CPU).

Based on our findings, we provide actionable suggestions for knowledge-sharing communities, practitioners, and future researchers. For example, we call for better documentation and training from our knowledge-sharing communities to help practitioners in understanding the energy aspect of their development tasks. Practitioners are encouraged to pay special attention to the energy impact of their mobile application development, especially when they access the hardware accessories, such as Bluetooth and GPS. When practitioners have energy-related questions, they are suggested to ask in a specific context to get better community support instead of being too general.

Our findings shed light on future work to assist practitioners in their energy-aware development from various perspectives (i.e., OSs, hardware, and programming languages), in particular, to improve tooling support for the measurement and monitoring of energy consumption.

Chapter 5

Impact of Extensions on Browser Performance: An Empirical Study on Google Chrome

5.1 Introduction

Various online services, such as information seeking, video streaming, online shopping, or social networking services, rely on web browsers (e.g., Google Chrome) as the user interfaces to allow the users to interact with the provided services. The performance of web browsers (e.g., energy consumption or page load time) can significantly impact user experience and sustainability. In particular, web browsers running on personal devices, such as desktops and mobile phones, drain a substantial amount of power to keep the webpage alive, update the content of webpages, or retain multiple tabs [20]. In addition, the page load time of web browsers is crucial, as a web browser that takes longer to load or runs slower can be frustrating for users, leading to decreased productivity or even customer attrition [51].

Web browsers, such as Google Chrome, typically support a variety of extensions that allow users to customize or extend the browsers' functionalities. Although extensions provide additional functionality and features to the Chrome browser, such as advertisement (ad) blocking, password management, and language translation, they can consume additional resources, such as processing power, memory, and network bandwidth, which may potentially affect the performance of browsers. However, the impact of the extensions on the performance of browsers remains unclear. Pearce [46] studies the energy effect of ad blockers in the Chrome browser during page loading and finds that open-source ad blockers reduce waiting time for ads to load and decrease power consumption. However, the study by Pearce estimates the energy impact without actually monitoring the energy consumption and is limited to the functional types of extensions. Borgolte and Feamster study the impact of privacy-focused extensions on browser performance in terms of page load time and CPU time. They observe that a browser with privacy-focused extensions performs similarly or better than a browser without extensions. However, their results may not generalize to other types of extensions.

In Chapter 4, we study the general concerns raised from the software development community by analyzing energy-related questions posted on SO. We find that (1) Energy consumption presents itself as a high-level abstract concept for practitioners; (2) Computing Resource used by the programs sparks great interest among practitioners, as the computing resources have the most attention from the SO community; (3) Monitoring emerges as one of the most difficult topics, demanding the longest wait time to receive a response from the community; and (4) Practitioners consider energy consumption at different levels (i.e., Programming Language, OS, and Hardware) during the development of applications, with mobile operating systems being the subject of greater inquiry as opposed to PC server-related operating systems. In particular, Android and Linux are the most heavily discussed subjects in the mobile and PC domains, respectively.

In this chapter, we focus on studying the energy consumption issues in one application domain. In particular, we perform an empirical study at the OS level to gauge the performance impact of extensions. We focus on Google Chrome due to its lopsided domination of the user market (As of April 2023, Chrome has approximately 53% of the user base, while Firefox only has around 10% of users)[1]. Despite Android being the most prevalent subject in mobile operating systems, mobile Chrome does not support extensions as extensions have high power consumption when compared to desktops. Therefore, our study focuses on desktop-based Chrome in this chapter. To address the most concerned issue of monitoring the energy usage of computing resources, we measure the energy consumption of the CPU and memory as well as page load time, as these aspects are critical for user experience [12, 46]. To surmount the challenge of inadequate monitoring techniques, we propose an approach to aid extension developers in identifying the significant factors that are significantly correlated with performance changes. By using our approach, extension developers can optimize their extension development decisions, while extension users can select the most performance-effective extensions for their specific needs. Investigating performance-affected factors and activation modes of extension (e.g., not logging into the extension) not only helps in monitoring but also enables practitioners to gain a better understanding of energy consumption concepts.

In this chapter, we study the performance impact of 61 Chrome extensions selected from 11 categories (e.g., shopping, blogging, or accessibility). We design experiments to study the effects of these extensions on energy consumption and the page load time

[1] `https://analytics.wikimedia.org/dashboards/browsers/#desktop-site-by-browser/browser-family-timeseries`

of the Chrome browser, the impact of the different configurations of the extensions (e.g., active or inactive), as well as the factors (e.g., privacy policies) that influence the performance impact of these extensions. We organize our paper along the following three research questions:

RQ1: How do extensions impact browser performance? Practitioners may not be aware that extensions can impair the performance of browsers and degrade the user experience. We observe that the use of extensions can lead to a statistically significant impact on the browser performance, with the largest negative impact on the load time energy consumption.

RQ2: How do the activation modes of extensions affect browser performance? Extensions may have different performance impacts depending on different activation modes (e.g., not logging in to the extension). We find that browser performance can be negatively impacted by extensions even when they are used in unexpected circumstances or are not active. The improper use of the extension (e.g., ignoring requests for login and page access permission) negatively affects the performance the most.

RQ3: What factors of the extensions influence browser performance? Developers create extensions using various decisions that may potentially affect browser performance, such as privacy practices (e.g., tracking location, and user activity). By investigating the relationship between the various factors of extensions and browser performance, we observe that highly-rated extensions or those with larger code sizes tend to be more energy efficient. We also observe the significant impact of the activation modes and the privacy practices of extensions on browser performance.

5.2 Experiment Design

Figure 5.1 presents an overview of our approach. We first collect a dataset of extensions from the Google Web Store, then we cluster the extensions based on their similarities and select representative extensions from each cluster as our final studied extensions. With the selected extensions, we design experiments to understand how they impact the browser performance in terms of energy consumption and page load time (RQ1), how the different activation modes impact the performance (RQ2), and what factors of the extensions impact the performance (RQ3). Below, we discuss the details of our experiment design that prepare for answering our research questions, including our data collection, extension selection, testing scenario design, testbed, and measurement and evaluation criterion.

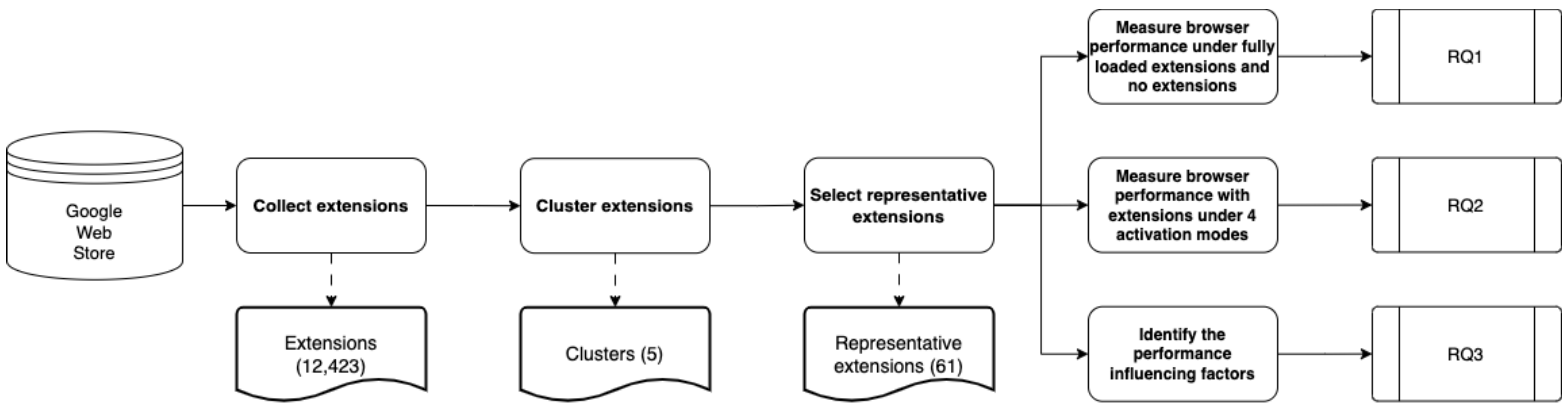


Figure 5.1: An overview of the general approach of our quantitative study.

5.2.1 Collecting Extensions

Unlike desktop-based Chrome, mobile Chrome does not support extensions because mobile devices have limited processing power and storage capacity to support resource-demanding extensions. Therefore, this chapter targets desktop-based Chrome. We collect a total of 110,240 extensions across 11 different categories from the Chrome Web Store. To consider the impact of the privacy practices on Chrome's performance (in RQ3), we exclude the extensions without providing privacy practices where the property for privacy practices is marked as "not provided" or "none". In the end, 12,423 extensions are gathered. We collect the information on the 12,423 extensions including extension name, category, rating, privacy practices, size, and the number of downloads. A screenshot of an example extension is shown in Figure 2.3. The different components of an extension are annotated in the figure.

5.2.2 Selecting Representative Extensions

Popularity could be an intuitive factor in choosing extensions, as popular extensions may have a larger user base and more contributors. In this chapter, however, we are interested in investigating the performance impact of all types of extensions instead of focusing on popular extensions. To eliminate the bias towards popular extensions and ensures the inclusion of lesser-known extensions, we apply the K-medoids clustering algorithm [56, 57] to cluster the 12,423 extensions based on the uses of privacy practices. Privacy practices of extensions refer to the actions and policies that extensions take to collect the personal information and data of users. Developers use privacy practices to inform users how they collect, use, store, and share their data. One or many of the nine privacy practice properties, including Location, User Activity, Website Content, Personally Identifiable Information, Authentication Information, Web History, Personal Communications, Financial and Payment Information, and Health Information, may be used during the development of extensions. We use the K-medoids clustering algorithm as it outperforms k-means in handling outliers, noise, and non-convex shapes of clusters, leading to more accurate clustering results [4, 23].

Since properties in the privacy practices are categorical values, we use one-hot encoding [29] to convert the privacy practices of each extension into numerical variables (i.e., 1 means True, and 0 means False). For example, suppose an extension (EXT) is a set with three distinct and discrete categorical variables $p1$, $p2$, and $p3$. With the extension using privacy practices $p1$ and $p3$, the set is encoded as (1, 0, 1) using one-hot encoding.

By using both Silhouette [54] and Elbow methods [60], we select the best K value, i.e., the best number of clusters, to be 5. Each cluster is characterized by the center of the cluster, also known as the medoid. Privacy practices of the medoid are most similar to the other extensions in the cluster, as it is calculated by minimizing the sum of dissimilarities of privacy practices between the medoid and the other extensions in the cluster.

To include all 11 categories of extensions in the Chrome Web Store, we select one representative extension from each category in each cluster. The representative extension chosen has the minimum Manhattan distance to the medoid of each cluster. The Manhattan distance is calculated using Equation (5.1):

$$d(EXT_1, EXT_2) = \sum_{i=1}^{9} |p_i - p_i^{'}| \tag{5.1}$$

where $|\mathbf{p}| = (p_1, ..., p_9)$ and $|\mathbf{p}\text{'}| = (p_1^{'}, ..., p_9^{'})$ are two feature vectors of extensions

EXT_1 and EXT_2, respectively. p_i corresponds to the use of a privacy practice i in the extension EXT. $d(EXT_1, EXT_2)$ denotes the Manhattan distance from EXT_2 to EXT_1. More specifically, the Manhattan distance is computed using a 9-dimensional vector representing privacy practices. Each dimension corresponds to a specific privacy practice. Consequently, 55 extensions are chosen, i.e., 11 extensions representing each category from a cluster multiplied by 5 clusters.

However, not every extension is suitable for performance measurement. For instance, MyJDownloader[2] is evoked without using web resources in the web browser. As we focus on the changes in the browser performance rather than resources outside of browser usage, we do not consider these extension types. We evaluate each representative extension and filter out the extensions that are not suitable for measurement. Moreover, there are 6 extensions which are not targeted for browsing a website, such as Weather[3]. In order to ensure that this chapter covers all types of extensions, we retain these 6 extensions and complement additional 6 extensions that are closest in proximity to the medoid within the same cluster. As a result, a total of 61 representative extensions are selected, i.e., 55 extensions + 6 compensating extensions.

5.2.3 Designing Testing Scenarios

To design testing scenarios for measuring the performance of extensions, we first check the conditions that an extension can execute on a website. Based on the conditions, we group the extensions requiring similar execution conditions together and create a

[2] `https://chrome.google.com/webstore/detail/myjdownloader-browser-ext/fbcohnmimjicjdomonkcbcpbpnhggkip?hl=en`

[3] `https://chrome.google.com/webstore/detail/weather/iolcbmjhmpdheggkocibajddahbeiglb?hl=en`

Table 5.1: Classification of testing scenarios and the corresponding number of extensions.

Scenario	# Ext.	Overview
Generic	34	10 most visited websites selected from Semrush[1]
Video	8	10 videos of 720P quality and approximately 10 minutes for YouTube or approximately 8.5 hours for Twitch
Shopping	6	10 best-selling products selected from each of Amazon's top 10 categories
GitHub	2	10 projects with around 20 lines of code selected by ranking from GitHub
News	2	10 press articles: 5 from Naver[2]and 5 from Daum[3]
Targeted	9	90 websites: 10 target websites of each extension

[1] `https://www.semrush.com/blog/most-visited-websites`
[2] `https://news.naver.com`
[3] `https://news.daum.net`

testing scenario for such extensions. In total, we find 6 types of testing scenarios based on the execution conditions of extensions, as listed in Table 5.1. More specifically, 34 extensions are universally compatible (i.e., active) with all types of websites on the internet. The testing scenario for these extensions is named the `Generic` type. The `Video` type tests extensions for video sites, while the `Shopping` type is designed to test extensions that enhance the shopping experience. The `GitHub` type tests extensions that improve the user experience on the GitHub website. We select only code development projects based on repository ranking. We classify testing scenario that is designed to test extensions for news resource websites as the `News` type. Finally, for 9 extensions that cannot be grouped, we classify their testing scenarios as the `Targeted` type, comprising of nine individual testing scenarios for nine extensions.

5.2.4 Performance Measurement

We measure the performance of a browser using three metrics: page load time, page load energy consumption, and stabilized energy consumption.

The page load time is the time period in seconds that it takes for the webpage to load completely. A slow response time can result in a poor user experience.

The page load energy consumption calculates the amount of energy in joules (a unit of energy) consumed by the CPU and RAM during the page load time. As energy consumption is a concern for many devices, it is important to consider page load energy consumption.

The stabilized energy consumption refers to the energy consumption of the CPU and memory in joules after a webpage finishes loading. This metric differs from the page load performance, which focuses on the energy consumption during the loading process. Stabilized performance provides insight into the energy consumption of a webpage once it has been fully loaded, which can help identify any issues with the webpage that may cause excessive energy consumption.

To collect energy measurements, we employ Running Average Power Limit (RAPL) [19]. RAPL[4] leverages hardware performance counters to provide detailed and precise reading on system energy consumption of the CPUs and memory usage [26, 35]. RAPL is a well-established and widely used utility that has been employed in related work, such as [18, 41, 47], and its accuracy has been validated by various studies, including [22, 34, 36, 45]. RAPL offers a high sampling interval, with one reading taken per 1 millisecond. The results obtained from RAPL provide a measurement of

[4] https://www.intel.com/content/www/us/en/developer/articles/technical/software-security-guidance/advisory-guidance/running-average-power-limit-energy-reporting.html

the total energy consumption in millijoules, as well as the running time of loading a webpage in seconds.

5.2.5 Testing Procedure

To conduct our experiment, a desktop equipped with an Intel i7-4770 @3.4GHz processor, 32 GB of RAM, running Ubuntu (kernel version: 5.4.0-91-generic) with both WiFi and Bluetooth disabled is utilized. We use Selenium[5], a tool that generates simulation scripts, to automatically execute a web browser. Specifically, we use Chrome of Version 104.0.5112.79 (Official Build 64-bit) in our experiment. The script opens and navigates to the designated web pages, simulating the users' activity in reality.

To conduct measurements for each testing scenario, we design and perform the experiment in the following steps:

- **Step 1:** Utilizing Selenium to launch the Google Chrome browser.
- **Step 2:** Repeating each testing scenario 10 times to avoid system disturbation. For each run of a testing scenario, the local storage and caches of the browser are cleaned.
- **Step 3:** Collecting performance measurements of energy and running time while the testing scenario is running, as illustrated in Figure 5.2.
- **Step 4:** Sleeping for a minute to avoid tail power states [13], allowing the system to reach a stable condition again (idle energy consumption) before executing the next testing scenario.

[5] `https://www.selenium.dev`

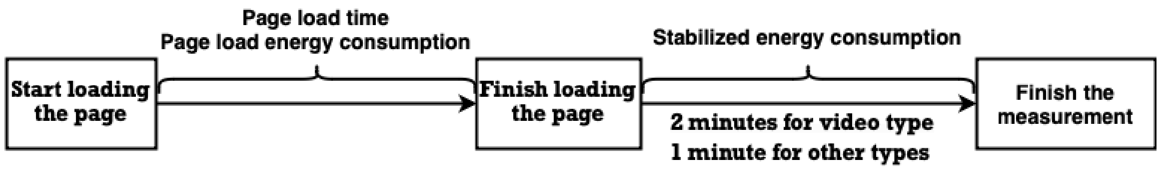


Figure 5.2: Measurement timeline.

- **Step 5:** Terminating Google Chrome browser for each finished task by closing all windows and pages, thereby ending the browser session that is opened during measurement.

- **Step 6:** Repeating steps 1 to 5 for another extension.

- **Step 7:** Collecting the energy consumption of the CPU and memory, and the page running time on each website without any extension.

We execute the testing scenario for each extension 10 times (i.e., 100 measurements in total for 10 websites) to obtain stable measurements in that testing scenario, as specific energy measurements may vary across executions of the same testing scenario. The page load time and the page load energy consumption are recorded in order to measure the page loading time and the energy consumption of the CPU and memory usage during the loading of a webpage, respectively. Both measurements are monitored from the time the user starts loading the webpage until the webpage completes the loading. Once the page finishes loading, the energy consumption of CPU and memory usage is measured for two minutes in the `video` type of testing scenarios and one minute for other testing scenario types. The measurement duration of two minutes in the `video` type is intended to include the ad time in videos and measure the energy usage of the video content. To obtain stable measurements in other testing scenario types, we monitor the energy usage of the website for one minute.

5.2.6 Normalization

To ensure consistency and comparability of all measurements collected during the testing of extensions, regardless of the testing scenario and the website, we normalize the measurements obtained with and without the use of an extension. The normalization process is guided by Equation (5.2) and is calculated based on the testing scenarios and the websites.

$$Norm = \frac{x(site_i)}{median(free_i))} \tag{5.2}$$

where $site$ indicates the website in the testing scenario, and $i \in 1, 2, .., 10$ represents the i-th site in the testing scenario. $Norm$ represents the normalized values in the testing scenario. $x(site_i)$ is the measurements for the i-th website in the testing scenario. $free_i$ represents the measurements in extension-free mode for the i-th website within the same testing scenario.

Extension-free mode: the 10 measurements for each website in each testing scenario are divided by the median value of the website's measurements.

All other modes: the measurements are normalized according to the results obtained in the extension-free mode. Specifically, for each extension under each test scenario, the measurements of each website are divided by the median value of the measurements of the website in the extension-free mode. The normalization is performed on the measurements with the same type of testing scenario.

5.3 Experiment Results

The objective of this chapter is to investigate the impact of extensions on the energy consumption and page load time of browsers through a case study on Google Chrome. This section describes our research questions, our approaches and answers to each of the research questions.

5.3.1 RQ1: How do extensions impact browser performance?

Motivation: Extensions are developed for various purposes, such as easy dictionary searching or blocking advertisements. However, practitioners may not be aware that extensions may cause significant performance impact to browsers, such as extra CPU computation and memory usage, and increased page loading time, resulting in degraded user experience and impaired performance of other applications running on the same computer. In this RQ, we investigate the effect of extensions on the overall browser performance. We strive for understanding the extent to which extensions affect browser performance and provide insights into the adoption of energy-efficient extensions.

Approach: We conduct performance evaluations of 61 representative extensions through the execution of testing scenarios outlined in Section 5.2.3. For each extension, we execute the target websites 10 times with and without the extension enabled, as described in Section 5.2.5. Subsequently, we perform statistical analysis to understand the performance impact of the extensions.

Configuring activation modes of extensions. Extensions may have different performance impacts depending on different activation modes (e.g., not logged in to the extension or using the extension on a website that it is not designed for).

We consider six activation modes of extensions, listed in Table 2.1[6]. In this RQ, we primarily focus on the changes that occur when the extensions are used in the fully loaded mode. The fully loaded mode is the most common activation mode for extensions. For websites and extensions that require access and login, we perform the "agree" operation, which grants the extension access and logs the extension in. Measurements are then collected and normalized in accordance with the normalization method described in Section 5.2.6. The comparison baseline for the two modes (i.e., extension-free and fully loaded modes) is the measurements taken with the extension disabled.

Statistical analysis. To evaluate the significance of the differences in measurements in the two modes, we apply the Wilcoxon signed-rank test [66] at a 5% confidence level to determine if there is a statistical difference between the paired performance energy metrics (e.g., the page load time under the extension free and the fully loaded mode, respectively).

The Cliff's δ test [16] is used to quantify the differences between the measured performance energy metrics (of the extension-free and fully loaded modes) as effect sizes. The resulting effect sizes are then classified into several qualitative degrees of differences [7]: negligible ($|\delta| < 0.147$), small ($0.147 \leq |\delta| < 0.33$), medium ($0.33 \leq |\delta| < 0.474$), and large ($|\delta| \geq 0.474$). We only perform the Cliff's δ test for a performance energy metric of an extension when the Wilcoxon signed-rank test indicates that an extension leads to a statistically significant performance difference between the performance energy metrics of the two tested modes.

[6] The details of the activation modes are discussed in RQ2 where we discuss the impact of the activation modes of extensions on browser performance.

Performance change ratio. When an extension leads to a statistically significant performance difference between the performance energy metrics of the two tested modes, we calculate the change ratio of the performance energy metric.

The change ratio is determined by comparing the normalized measurements obtained with and without the extension enabled, using the same type of testing scenarios for both measurements. To eliminate the effect of outliers in website measurements, the median value is used. Specifically, Equation (5.3) computes the change ratio of an extension in terms of its performance energy metrics:

$$Ratio(metric) = \frac{1}{10}\sum_{i=1}^{10}\frac{median(ext_i) - median(free_i)}{median(free_i)} \tag{5.3}$$

where $Ratio(metric)$ is the change ratio of the corresponding performance energy metric (i.e., the page load time, the page load energy consumption, or the stabilized energy consumption), ext_i is the measured performance energy metric (normalized) under the fully loaded mode of an extension, $free_i$ is the measured performance energy metric (normalized) under the extension-free mode, $median(ext_i)$ and $median(free_i)$ indicate the median of the 10 extension measurements for the i-th website, under the fully loaded mode and the extension-free mode, respectively. Finally, $i \in 1, 2, .., 10$ indicates the i-th tested website.

Table 5.2: Statistical performance changes caused by the extensions in their fully-loaded mode.

Statistical analysis		Wilcoxon		Cliff's δ					
		Sig.		Small		Medium		Large	
Performance energy metrics	Tendency	Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio
Page load time	Increase	16	18.07%	7	17.30%	3	29.34%	6	18.70%
	Decrease	16	-7.16%	9	-4.16%	5	-9.02%	2	-43.39%
	Overall	32	1.00%	16	-2.92%	8	-4.59%	8	18.07%
Page load energy consumption	Increase	36	17.12%	10	8.69%	7	18.51%	19	34.58%
	Decrease	4	-6.61%	1	-1.39%	2	-6.61%	1	-60.92%
	Overall	40	15.57%	11	7.93%	9	12.99%	20	31.29%
Stabilized energy consumption	Increase	38	1.73%	9	0.87%	9	1.35%	20	2.23%
	Decrease	6	-1.58%	4	-0.95%	2	-2.96%	0	-
	Overall	44	1.44%	13	0.34%	11	1.18%	20	2.23%
# of extensions being tested		61							

* The table reports three performance energy metrics (e.g., the page load time), showing the number of extensions that have a statistically significant effect on the energy metric, including an increase, decrease, and overall change (increase and decrease) and the respective change ratio.

** The results of the extent of the effect size, as determined by Cliff's δ, are categorized as Small, Medium, and Large. The effect sizes are statistically significant, i.e., p-value less than or equal to 0.05 in the Wilcoxon signed-rank test and categorical effect sizes.

*** The Sig. category encompasses extensions with a p-value less than or equal to 0.05 and at least a small effect size.

Findings: **Using an extension can either deteriorate or improve browser performance, while performance deterioration is more common.** Table 5.2 presents the statistically significant changes in the performance energy metrics when an extension is used in its fully loaded mode. A total of 61 extensions are tested, and at least 52.46% of the extensions (i.e., 32) exhibit a statistically significant performance impact on performance energy metrics. We observe that the extensions can either improve or deteriorate the browser performance in terms of each performance energy metric. In particular, 32 extensions (i.e., 52.46%) exhibit statistically significant changes in the page load time, among which 16 increase the metric while the other 16 decrease the metric. 40 extensions (i.e., 65.57%) exhibit statistically significant changes in the page load energy consumption, among which 36 and 4 lead to an increase and a decrease in the metric, respectively. 44 extensions (i.e., 72.13%) exhibit statistically significant changes in the stabilized energy consumption, with 38 and 4 of them increasing and decreasing in the metric, respectively.

The deterioration in browser performance may be attributed to the extra resources required to run the extensions, the automatic backend search capabilities of certain extensions, such as potential coupon detection (e.g. SimplyCodes) and tracking of product price history (e.g., Keepa), web content adjustments (e.g. Octotree), monitoring of website content (e.g. Dynatrace), and site analysis (e.g. Wappalyzer) during page load. On the other hand, the improvement in the browser performance may be due to the blocking of web content (i.e., Naver/Daum Media Filter and ad blocker: Informess), simplification of web content (e.g., Better Tab), and preventing information trackers (e.g., Neeva).

16 (26.23%) extensions statistically significantly increase the page load

time, with an average increase of 18.07%, while another 16 (26.23%) extensions statistically significantly reduce the page load time by 7.16% on average. Over half (32/61) of the extensions lead to statistically significant changes in the page load time, with an average increase of 1.00%. In particular, six extensions lead to an increase in the page load time by a large effect size, while two extensions lead to a decrease by a large effect size.

36 (59.02%) extensions statistically significantly increase the energy consumption during the page load, with an average increase of 17.12%. 40 out of 61 extensions demonstrate statistically significant differences in the page load energy consumption, with an average increase of 15.57%. An increase in energy consumption is observed in 59.02% of the extensions (i.e. 36), with an extra 17.12% of energy consumed. Conversely, only 6.56% of the extensions (i.e., 4) reduce energy consumption, by 6.61% on average. In particular, 19 (31.15%) extensions exhibit a large effect size in the increase of the page load energy consumption, by an average increase of 34.58%, while only one extension decreases the page load energy consumption by a large effect size. Compared to other performance metrics, using extensions leads to the largest negative impact on the load time energy consumption.

Even after the web page has been loaded, 38 (62.30%) extensions still lead to a statistically significant increase in energy consumption. A significant proportion of extensions, 72.13% (i.e., 44 extensions), demonstrate a statistically significant difference in the stabilized energy consumption. 62.30% of the extensions (i.e., 38) consume an extra 1.73% of the stabilized energy on average, while 9.84% of the extensions (i.e., 6) reduce the stabilized energy consumption by an average of

1.58%. Compared to the impact on the load time energy consumption, the extensions' impact on the stabilized energy consumption is relatively small. This may be explained by the fact that the extensions are less active after the pages have been loaded.

> **Summary:** Our results indicate that the use of extensions under their typical activation mode (i.e., fully loaded) can lead to a statistically significant impact on the browser performance, with the largest negative impact on the load time energy consumption. Our observations suggest that browser and extension developers should pay attention to the performance impact of browser extensions, particularly in regard to energy efficiency.

5.3.2 RQ2: How do the activation modes of extensions affect browser performance?

Motivation: The activation modes of extensions (i.e., different modes of using extensions) can be classified based on the conditions for accessing and executing an extension, including whether login to an extension is required, whether permission to access the website is granted, whether an extension is required to run on the targeted website and the usage of an extension on the browser. It is possible that different activation modes of extensions may result in various performance impacts. Thus, this RQ aims to investigate the influence of various activation modes of extensions on browser performance. Our results may provide insights for browser users to optimize their configuration of extensions.

Approach: **Classifying activation modes of extensions.** Our classification of the activation modes of extensions is based on the criteria for accessing and executing the extensions. The details of the classification and the description of each activation model are listed in Table 2.1. We evaluate the performance changes compared to the extension-free mode across five distinct activation modes of extensions: "fully loaded", "no grant", "no login", "inactive", and "fully inactive", respectively. As described in RQ1, all 61 extensions can be selected for testing under the fully loaded mode (i.e., logged in and access permission granted when required, used for designated websites when needed). However, for the other four partial activation modes, we need to select the extensions that satisfy the corresponding requirements. In particular, the extensions that require access permission to the webpage are selected for testing in the "no grant" mode. Similarly, the extensions requiring login are chosen for the "no login" mode. The "inactive" mode involves testing the inactive extensions within the context of generic testing scenario websites rather than the target websites. The "fully inactive" mode assesses the performance of the inactive extensions in conjunction with the generic testing scenario, without logging in or granting access to the webpage. We measure a total of 40 extensions across these modes, with the distribution of the number of extensions tested in each activation mode presented in Table 5.3. For comparing the impact of the fully loaded mode and other partial activation modes, we report the results of the fully loaded model for the corresponding extensions used for each partial activation mode. The measurement procedures are conducted, as outlined in Section 5.2.5. The measurements are recorded and then normalized using the procedure outlined in Section 5.2.6. The normalization is performed relative to the measurements in the "extension-free" mode.

Statistical analysis of the experiment results. We use the same statistical methods (i.e., the Wilcoxon signed-rank test and the Cliff's Delta test) as in RQ1 to determine the degree of difference of the measurements between running an activation mode of an extension and running in the extension-free mode. Only the measurements that pass the statistical tests are considered to have a statistically significant difference and be practically meaningful.

Performance change ratio. When an extension leads to a statistically significant performance difference between the performance energy metrics under an activation mode and the extension-free mode, we calculate the change ratio of the performance energy metric, following the same method described in RQ1.

Findings: **We observe that the browser performance is impacted by the use of extensions, regardless of a specific activation mode of extensions.** Tables 5.3 presents the performance changes caused by the extensions in the four partial activation modes, namely: no access permission, no login, inactive, and fully inactive. Table 5.3 shows that each activation model of the extensions can statistically significantly impact the browser performance in terms of all performance energy metrics. In particular, the fully inactive mode has the most significant impact on the browser performance, especially on the page load time and page load energy consumption.

Table 5.3: Statistical performance changes of the Extensions in different activation modes of extensions

Activation mode of extensions		No Grant								No Login							
Cliff's Delta		Signif.		Small		Medium		Large		Signif.		Small		Medium		Large	
Performance energy metric	Tendency	Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio
Page load time	Increase	1	13.37%	1	13.37%					1 (1)	33.16% (29.34%)	1	33.16%				
	Decrease	4 (3)	-6.92% (-3.07%)	3	-6.51%	1	-8.86%			1	-7.08%	1	-7.08%				
	Overall	5 (3)	-6.51% (-3.07%)	4	-6.35%	1	-8.86%			2 (1)	13.04% (29.34%)	2	13.04%				
Page load energy consumption	Increase	4	14.82%	3	10.68%	1	18.95%			7 (6)	11.53% (19.48%)	4	7.06%			3	46.06%
	Decrease																
	Overall	4	14.82%	3	10.68%	1	18.95%			7 (6)	11.53%(19.48%)	4	7.06%			3	46.06%
Stabilized energy consumption	Increase	9 (6)	2.81% (2.76%)			3	2.79%	6	4.29%	8 (6)	2.72% (1.42%)			1	2.47%	7	2.98%
	Decrease									(1)	(-0.83%)						
	Overall	9 (6)	2.81% (2.76%)			3	2.79%	6	4.29%	8 (7)	2.72% (1.12%)			1	2.47%	7	2.98%
# of extensions being tested		10								8							

* The bracketed figures indicate the change ratio of corresponding extensions in each activation mode found in the fully loaded mode.

Table 5.3: Statistical performance changes of the extensions in different activation modes of extensions (continued).

Activation mode of extensions		Inactive								Fully Inactive							
Cliff's δ		Signif.		Small		Medium		Large		Signif.		Small		Medium		Large	
Performance energy metric	Tendency	Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio	Count	Ratio
Page load time	Increase	1	335.48%					1	335.48%	4 (4)	231.28% (21.25%)	2	109.07%	1	324.68%	1	716.16%
	Decrease									3 (2)	-36.26% (-40.87%)			2	-34.07%	1	-60.11%
	Overall	1	335.48%					1	335.48%	7 (6)	80.27% (11.06%)	2	109.07%	3	-31.89%	2	328.02%
Page load energy consumption	Increase	5 (3)	14.46% (10.68%)	3	10.19%	1	14.98%	1	728.47%	4 (6)	577.49% (13.54%)	1	11.69%	1	283.53%	2	1376.72%
	Decrease	(1)	(-60.92%)							3 (1)	-28.89% (-5.88%)	1	-4.10%	2	-38.41%		
	Overall	5 (4)	14.46% (7.95%)	3	10.19%	1	14.98%	1	728.47%	7 (7)	11.69% (10.68%)	2	3.80%	3	-28.89%	2	1376.72%
Stabilized energy consumption	Increase	3 (7)	1.56% (1.33%)			2	1.06%	1	43.16%	8 (9)	13.04% (1.35%)	2	6.66%	3	14.18%	3	19.28%
	Decrease	5	-0.79%	5	-0.79%					3 (1)	-27.75% (-3.84%)					3	-27.75%
	Overall	8 (7)	-0.47% (1.33%)	5	-0.79%	2	1.06%	1	43.16%	11 (10)	8.79% (1.34%)	2	6.66%	3	14.18%	6	-7.23%
# of extensions being tested		11								11							

* The bracketed figures indicate the change ratio of corresponding extensions in each activation mode found in the fully loaded mode.

Using extensions in unexpected circumstances (i.e., when access to the extension is not granted or a user is not logged in) still leads to substantial energy consumption. 40.00% of the extensions (i.e., 4) running without a granted permission (i.e., no grant mode) and 87.50% of the extensions (i.e., 7) running without the required login (i.e., no login mode) lead to an average of 14.82% and 11.53% increase in the page load energy consumption, respectively. 100.00% of extensions (i.e., 8) in the "no login" mode and 90.00% of extensions (i.e., 9) in the "no grant" mode result in a slight increase in the stabilized energy consumption, leading to an average of 2.72% and 2.81% increase, respectively. However, denying access permission to the website may decrease the response time while leading to an increase in energy consumption during the page load and the stabilized periods. In particular, 50.00% of the extensions (i.e., 5) result in a 6.51% decrease in the page load time.

Even when extensions are inactive (i.e., not used for target websites or fully deactivated), they can still lead to significant energy consumption and increase the page load time. In particular, the fully inactive mode results in statistically significant changes in all the performance energy metrics, leading to an 80.27% increase in the page load time, an 11.69% increase in the page load energy consumption, and an 8.79% increase in the stabilized energy consumption, all on average. The inactive mode results in statistically significant changes in the page load energy consumption by 14.46% on average. The negative performance impact of the inactive modes may be because the extensions make attempts to gain access when a webpage is loading, which may cause significant extra overhead.

The partial activation modes or inactive modes of extensions can lead to even worse performance impact than the fully loaded mode. For the 10 extensions tested in the "no grant" mode, 4 extensions demonstrate a statistically significant increase in the page load energy consumption, with an average increase of 14.82%. In comparison, the fully loaded mode does not lead to a statistically significant increase in the metric. In the "no login" mode, 8 of the 8 tested extensions result in a statistically significant increase in the stabilized energy consumption, with an average increase of 2.72%, while the fully loaded extensions result in a 1.12% statistically significant increase in the metric. The activation mode of extensions only affects the performance of the extension itself. The explanations of additional resources required to run the extensions on the deterioration of browser performance, as outlined in RQ1, still apply to activation modes such as "no login" and "no grant". Among the 11 extensions tested in the "inactive" and "fully inactive" modes, all performance energy metrics are generally higher compared to the fully loaded mode, with 7 extensions showing a significant increase of 80.27% in the page load time and 11 extensions showing an 8.79% increase in the stabilized energy consumption in the "fully inactive" mode. In comparison, 6 fully loaded extensions exhibit an average of 11.06% statistically significant increase in the page load time in the "fully inactive" mode. For extensions that are not active, such as "inactive" and "fully inactive" modes, even though the extensions are not deployed on the target website, they continue to run, which aligns with our observation that most extensions have a negative impact on browser performance. Furthermore, this deterioration is exacerbated when extensions are used improperly, specifically in the "fully inactive" mode.

Summary: We observe that browser performance can be negatively impacted by the use of extensions, even when the extensions are used in unexpected circumstances (e.g., not logged in or access to a webpage not granted) or are not active (e.g., not used for target websites or fully deactivated). Extension users should be aware of such performance impact to optimize their configurations of the extensions. Our findings also suggest that browser developers should take action to reduce the performance impact of extensions when they are not providing proper functionalities (e.g., when in an inactive mode) to users.

5.3.3 RQ3: What factors of the extensions influence browser performance?

Motivation: Browser extensions are designed with various decisions, such as privacy practices and the source code size of the extension, to suit development demands. Nevertheless, some design decisions may have a hidden impact on the browser performance. We are interested in gaining insights into the underlying factors that influence browser performance in terms of page loading time and energy consumption. Such an analysis may provide guidance for extension developers to optimize their extensions or for extension users to select extensions for their needs.

Approach: In this RQ, we construct a statistical model to understand the factors of the extensions that influence the browser performance.

Model Construction. To study the correlation between performance energy metrics (e.g., the page load time) and the underlying factors of the extensions, a linear mixed effects model is built. A mixed-effect model is a statistical model that accommodates both fixed and random effects. Fixed effects represent systematic influences that are constant across all observations. Random effects represent variations specific to groups of observations. We identify 16 potential factors that may impact the browser performance, as listed in Table 5.4. We use `lme4` function provided in R to construct a linear mixed-effects model. We identify the testing websites as random effects (i.e., the performance impact of different websites is considered random), while the potential performance-affecting factors as fixed effects (i.e., the performance impact of the extensions' factors is considered fixed), as listed in Table 5.4. We employ a stepwise elimination process, implemented in `buildmer` function in R, to eliminate variables in the model. The stepwise elimination removes variables one by one based on their statistical significance and effect on the model fit, to improve the interpretability and accuracy of the model. Moreover, we normalize the number of users, rating score, and the number of raters by dividing each value by the largest value in the dataset, which facilitates the convergence of coefficients.

Correlation and redundancy analysis. To maintain the stability and reduce the complexity of the model, we first identify the correlated variables using the Spearman correlation test. We utilize the `Hmisc` function in R and employ variable clustering analysis to create a hierarchical representation of the relationships among the explanatory variables. The results of this hierarchical clustering are displayed in Figure 5.3, where variables below the red horizontal line are considered highly correlated with each other (i.e., $|\rho| > 0.7$) and are removed. Specifically, the factors, *the number of users* and *the number of raters*, as well as *cluster label* and *user activity*, are highly correlated to each other, with a correlation $|\rho|$ greater than 0.70. Only one factor from the sub-hierarchy with $|\rho|$ greater than 0.70 is selected for inclusion in our model. As the factor *cluster label* is computed using privacy practices, we remove the

Table 5.4: Studied factors that may influence the performance impact of browser extensions.

Variable type	Potential influential factors	Description
Fixed variables	Cluster label	The cluster label categorized by K-medoid clustering algorithm
	Number of privacy practices	The number of privacy practice properties used in building the extension
	Location User Activity Website Content Personally Identifiable Information Authentication Information Web History Personal Communications	Seven privacy practice items that practitioners use to develop the extensions
	Extension size	The package size of the extension
	The number of users	The number of users installing the extension
	The number of raters	The number of users rate the extension
	Rate score	The rate score of the extension in Chrome Web Store
	No Login No Grant Inactive Fully inactive	Four interactive modes of extensions
Random variable	150 websites	Websites used in each test case

factor *cluster label*. Moreover, the number of users better represents popularity than the number of raters, we remove the number of raters. Furthermore, the redundancy analysis provided by `Hmisc` function in R is performed to evaluate the redundancy correlation between the remaining 15 factors. Factors with R^2 cutoff larger than 0.90 are deemed highly redundant and thus eliminated from the result set. As a result, only *the number of privacy practices* used by the extension is redundant and not considered in our model, as it is unlikely to provide additional explanatory power.

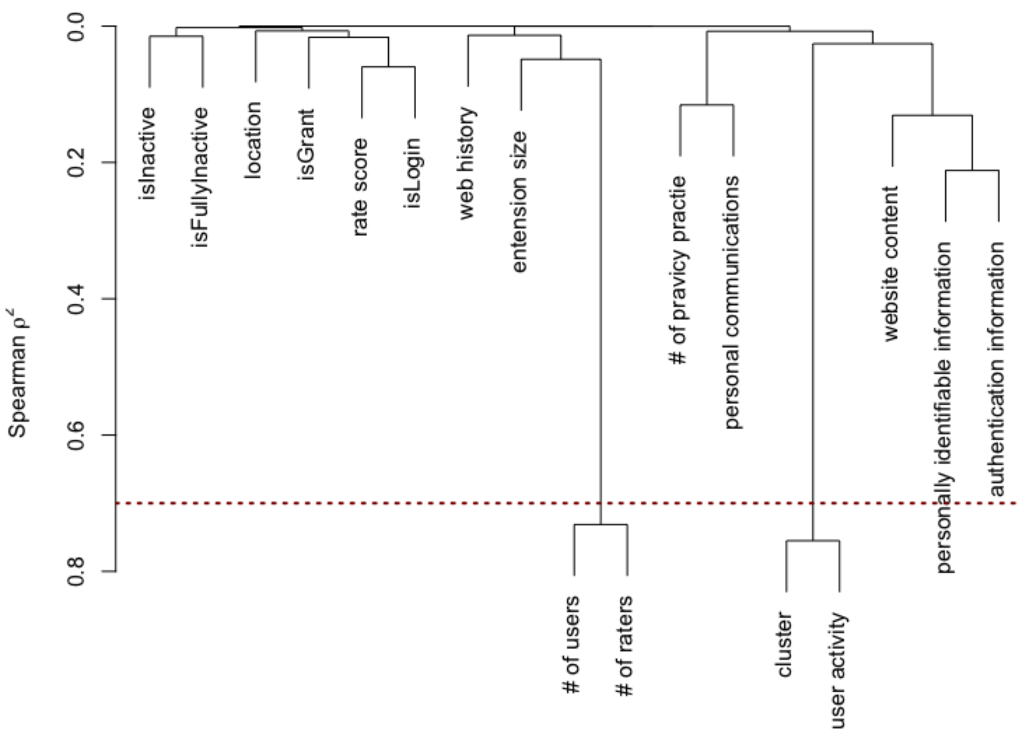


Figure 5.3: Hierarchical clustering of extension variables according to Spearman's $|\rho|$

Table 5.5: Linear mixed-effects model results of the page load time based on extension performance energy metrics.

Measurement	Chi-Squared	Pr(Chisq)	Signif.	Estimate	Effect
Location	0.0642	0.7999		-0.0510 ± 0.2014	$\searrow$
User Activity	12.58	0.0004	***	0.4156 ± 0.1172	$\nearrow$
Website Content	6.026	0.0141	*	0.2670 ± 0.1088	$\nearrow$
Web History	2.738	0.0980	.	-0.3970 ± 0.2400	$\searrow$
Personally Identifiable Information	0.9458	0.3308		1.724 ± 1.773	$\nearrow$
Authentication Information	5.212	0.0224	*	0.2634 ± 0.1154	$\nearrow$
Personal Communications	12.41	0.0004	***	-1.000 ± 0.2839	$\searrow$
Extension Size	1.317	0.2512		-0.2307 ± 0.2011	$\searrow$
# of Users	0.5913	0.4419		-0.1779 ± 0.2313	$\searrow$
Rating Score	0.3352	0.5626		-0.0933 ± 0.1612	$\searrow$
isLogin	0.3829	0.5361		0.0646 ± 0.1044	$\nearrow$
isGrant	2.722	0.0990	.	-0.2072 ± 0.1256	$\searrow$
isInactive	18.24	1.952e-05	***	0.5110 ± 0.1197	$\nearrow$
isFullyInactive	62.70	2.405e-15	***	0.9529 ± 0.1203	$\nearrow$

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Table 5.6: Linear mixed-effects model results of the page load energy consumption based on extension performance energy metrics.

Measurement	Chi-Squared	Pr(Chisq)	Signif.	Estimate	Effect
Location	1.369	0.2420		0.2042 ± 0.1745	$\nearrow$
User Activity	0.0114	0.9148		-0.3361 ± 3.142	$\searrow$
Website Content	65.31	6.404e-16	***	0.7617 ± 0.0943	$\nearrow$
Web History	8.701	0.0032	**	-0.6142 ± 0.2082	$\searrow$
Personally Identifiable Information	5.218	0.0224	*	0.2654 ± 0.1162	$\nearrow$
Authentication Information	86.05	<2.2e-16	***	0.9274 ± 0.1000	$\nearrow$
Personal Communications	94.49	<2.2e-16	***	-2.415 ± 0.2484	$\searrow$
Extension Size	35.41	2.673e-09	***	-1.036 ± 0.1741	$\searrow$
# of Users	0.4884	0.4846		0.1400 ± 0.2004	$\nearrow$
Rating Score	0.0551	0.8143		-0.0327 ± 0.1391	$\searrow$
isLogin	0.1493	0.6992		-0.0349 ± 0.0903	$\searrow$
isGrant	4.725	0.0297	*	-0.2367 ± 0.1089	$\searrow$
isInactive	48.39	3.488e-12	***	0.7230 ± 0.1039	$\nearrow$
isFullyInactive	573.8	2.2e-16	***	2.504 ± 0.1045	$\nearrow$

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Table 5.7: Linear mixed-effects model results of the stabilized energy consumption based on extension performance energy metrics.

Measurement	Chi-Squared	Pr(Chisq)	Signif.	Estimate	Effect
Location	30.87	2.757e-08	***	-0.0367 ± 0.0066	$\searrow$
User Activity	26.05	3.333e-07	***	-0.0196 ± 0.0038	$\searrow$
Website Content	3.557	0.0593	.	0.0067 ± 0.0036	$\nearrow$
Web History	1.668	0.1965		0.0103 ± 0.0080	$\nearrow$
Personally Identifiable Information	5.343	0.0208	*	-0.0102 ± 0.0044	$\searrow$
Authentication Information	36.76	1.338e-09	***	0.0229 ± 0.0038	$\nearrow$
Personal Communications	23.22	1.441e-06	***	0.0449 ± 0.0093	$\nearrow$
Extension Size	38.94	4.377e-10	***	-0.0411 ± 0.0066	$\searrow$
# of Users	0.8919	0.3450		0.0072 ± 0.0076	$\nearrow$
Rating Score	11.73	0.0006	***	-0.0180 ± 0.0053	$\searrow$
isLogin	2.178	0.1400		-0.0050 ± 0.0034	$\searrow$
isGrant	11.67	0.0006	***	-0.0141 ± 0.0041	$\searrow$
isInactive	16.26	5.510e-05	***	0.0158 ± 0.0039	$\nearrow$
isFullyInactive	0.0464	0.8294		-0.0009 ± 0.0040	$\searrow$

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Findings: **Our model analysis confirms that the activation modes of extensions significantly impact the browser performance. Logged-in extensions tend to have a faster page load time and lower energy consumption.** The negative relationships between *isLogin* and the performance energy metrics suggest that logging in to the extension can improve the browser performance. Recalling the observations in RQ2, we can see that the page load energy consumption of the extensions without login is lower than it is in the fully loaded mode. Therefore, it is recommended that users log in to the extension when prompted to do so. **The significance of the factor *isInactive* implies that improper use of extensions, i.e., not using them on designated websites, negatively impacts browser performance.** In particular, the inactive mode refers to the scenario where the extension is not being used or is inactive on the designated website. For example, an extension, designed to function only on a press website A, is used on a shopping website B. **It is observed that the fully inactive practice significantly impacts the browser performance.** When the use of the extension is ignored, only the page load time and the page load energy consumption are affected, without notable impact on the stabilized energy consumption. Adhering to proper usage practices, i.e., logging in to the extension, granting access, as well as utilizing the extension on the target website, benefit the overall browser performance.

Surprisingly, a larger extension size results in lower energy consumption. Our analysis of Table 5.7 reveals a negative correlation between the code size of an extension and energy consumption. This suggests that an increase in the size of code or components that make up the extension does not necessarily lead to a negative impact on energy consumption. The larger size of the installation package for an extension indicates a larger amount of code, providing more comprehensive and robust functionality. This results in fewer resources being required during the execution of an extension and improved compatibility with the underlying hardware and software.

Highly-rated extensions are not only well-maintained in terms of code but may also be optimized for energy costs. This can be inferred from the negative relationship between the rating score of the extension and the stabilized energy consumption. The negative relationship suggests that popular extensions that have a higher rating score may not only be better maintained in terms of code but also better optimized for energy consumption. Improving code or components that build up the extension may lead to lower energy consumption.

The implementation of privacy practices within extensions can have varying impacts on browser performance. Specifically, utilizing *location* within an extension only has an effect on the stabilized energy consumption. While *personal communications* may not significantly increase energy consumption during loading the page, it is highly correlated with the increased stabilized energy consumption. This may be due to the fact that the extension only monitors user location and personal communications once the page has completed loading.

The use of *web history* does not burden the page load performance, but the use of *personally identifiable information* negatively affects the page load energy. However, both *web history* and *personally identifiable information* do not have a significant impact on energy consumption during page stabilization. Furthermore, *user activity* has no significant effect on the page load energy consumption but negatively affects the stabilized energy and the page load time. The use of *web content* or *authentication* *information* negatively impacts overall performance, regardless of the loading stage of the page.

Summary: Our analysis confirms the impact of the activation modes on energy consumption: adhering to proper usage practices, i.e., logging in to the extension, granting access, as well as utilizing the extension on the target website, benefit the overall browser performance. Besides, we observe that highly-rated extensions or those with larger code sizes tend to be more energy efficient. We also observe the significant impact of the privacy practices of extensions on browser performance. Our findings provide insights for users to select performance-efficient extensions and for developers to optimize their development decisions.

5.4 Implication

In this section, we discuss the implications of our findings for extension users, extension developers, and future researchers.

5.4.1 Implication for Extension Users

Extension users should be aware of the performance ramifications associated with different activation modes of extensions to optimize their configurations of the extensions. As noted in Sections 5.3.1 and 5.3.2, browser performance is negatively impacted by the use of extensions, irrespective of the specific activation mode of extensions. Such an observation implies that even when extensions are not activated, they can still adversely impact the browser performance. Extension users should carefully consider the activation mode of extensions while using the extension and only activate the extension that is indispensable. Moreover, they should also periodically scrutinize their extensions and remove any that are no longer needed. By optimizing the configurations of the using extensions, users can improve the overall performance and refine the user browsing experience by reducing page load time and minimizing energy consumption.

Extension users could select fungible extensions that have minimal impact on browser performance. As highlighted in Section 5.3.3, we discuss the factors that have a correlation with performance changes. Extension users can select a substitute that offers similar functionality with less impact on the browser performance based on the affecting trend of these factors (e.g., privacy practices or extension size) that we find in Section 5.3.3. By selecting extensions that have less performance-impacted factors, users can mitigate the negative impact on browser performance while still enjoying the functionality they need.

5.4.2 Implication for Browser and Extension Developers

Browser and extension developers should pay attention to the performance impact of browser extensions, particularly in regard to energy efficiency. In Section 5.3.2, we find that using extensions can cause performance deterioration to the browser, which may lead to a poor user experience. Therefore, it is crucial that browser and extension developers prioritize optimizing the performance of their extensions to ensure that their extensions consume minimal resources while still providing the intended functionalities to the users. To enhance user satisfaction and decrease the negative impact on the browser performance, we recommend browser and extension developers to take heed of the performance impact of browser extensions by improving the code quality, reducing the size of the extension, and utilizing proper privacy practices for the extension. Furthermore, they should regularly maintain their extensions to ensure that extensions are up-to-date and compatible with the latest browser versions.

5.4.3 Implication for Future Research

Researchers focused on performance and energy profiling could provide mechanisms to mitigate the adverse performance impact of extensions that fail to provide proper functionalities (e.g., when in an inactive mode) to users, particularly when they are in a fully inactive mode. As discussed in Section 5.3.3, highly-rated extensions and extensions with a larger extension size tend to lower energy consumption. Privacy practices used within extensions can also have varying impacts on the browser performance. Future researchers could verify that whether poorly optimized extensions can consume significant amounts of energy and slow down the browser. Such effects can be particularly troublesome for users who have multiple extensions installed, as the cumulative effect of extensions can lead to significant performance degradation. Hence, it is recommended that performance and energy profiling researchers could use our proposed approach in Section 5.3.3 to develop mechanisms that can detect when an extension is not being used or not providing useful functionalities to users and automatically deactivate such extension to reduce the performance impact of extensions.

5.5 Threats to Validity

The goal of this chapter is to discern the performance impact of browser extensions. In this section, we present the threats to the validity of the study.

Internal Validity. In RQ3, we used a mixed-effect model to study the relationship between the various factors of an extension and its performance impact. However, the correlation may not suggest causation. Threats to the internal validity of our study may also involve running background processes and daemons while we collect the measurements. It is challenging to fully control all background processes or daemons of a system. However, we try to reduce the impact of background processes and daemons as much as possible by stopping them while we collect the measurements.

External Validity. In this chapter, we only studied the Google Chrome browser. Our results may not generalize to other browsers. Nevertheless, as Chrome is the most popular browser, our findings can benefit a large number of browser users and extension developers. In addition, popular browsers such as Chrome and Safari are using similar structures. Our findings may provide similar insights to other browsers. Future work may extend the work conducted in this chapter by evaluating the performance impact of extensions on other browsers. Furthermore, we exclusively test and measure one extension per execution. When assessing and analyzing energy consumption, using multiple extensions concurrently on Chrome may introduce confounding or extraneous variables that could have adverse impacts on the precision and validity of the results. Specifically, when multiple extensions are functioning simultaneously, they may interfere with each other, leading to inaccurate or inconsistent measurements. For example, some extensions may prevent content or scripts that other extensions depend on, causing conflicts that affect the browser performance. Moreover, running multiple extensions at once can amplify the resources required by the browser, resulting in higher energy consumption or longer page load time. Analyzing data from multiple extensions can be more complicated than analyzing data from a single extension. The additional variables introduced by multiple extensions can make it more challenging to identify and interpret patterns in the data. Thus, we carry out experiments that examine performance using one extension at a time in order to obtain precise and reliable results.

5.6 Summary

In this chapter, we conduct an experiment to investigate the impact of extensions on browser performance, specifically in terms of page load time and energy consumption. We present how extensions and the way extensions are executed affect browser performance. We utilize mix-effect models to assess the correlation and significance between performance energy metrics and underlying factors. Finally, our findings provide insights for users to select performance-efficient extensions and for developers to optimize their development decisions. Our results suggest:

- Browser performance can be negatively impacted by the use of extensions, even when the extensions are used in unexpected circumstances (e.g., not logged in or access to a webpage not granted) or are not active (e.g., not used for target websites or fully deactivated).
- Privacy practices of an extension are significantly correlated with its performance impact and that highly-rated extensions or those with larger code sizes tend to be more energy efficient.

Based on our findings, we provide several recommendations for browser users, extension developers, and future researchers. For instance, we call for mechanisms to discern when extensions are not used or fail to offer useful functionalities to users. Such mechanisms should be able to automatically deactivate such extensions to reduce the performance impact of extensions. Furthermore, browser and extension developers are encouraged to pay special attention to the energy impact of extensions on the browser performance. Extension users are urged to explore alternative extensions and select ones that have less performance-impacted factors but the same functionality based on the factors we determined.

Our findings shed light on future work to assist browser and extension developers in identifying the significant factors that have correlations with performance changes. The results of this chapter will also guide extension users in making informed decisions about the use of extensions and their impact on browser performance.

Chapter 6

Conclusions and Future Work

Energy efficiency is key to achieving and maintaining the success of energy-efficient software systems. Neglecting to take into account energy effects in software development can result in increased expenses for software creation and upkeep, poor system performance, negative user satisfaction, and environmental consequences. This thesis addresses the development of energy-efficient and performance-effective software from two perspectives (i.e., practitioners' perception and practical software performance), benefiting development and research teams by providing effective strategies and solutions for energy-related issues in software development. To achieve this, we conduct two empirical studies to gain insight into the energy-related challenges in software development: (1) a study of the practitioners' perception of Energy Consumption, and (2) a study of the impact of extensions on browser performance and associated factors influencing performance.

The subsequent sections provide a summary of the contributions made by this thesis and suggest potential research opportunities that could enhance our work.

6.1 Contributions

The main contributions of the thesis are listed below:

Understanding the practical energy challenges in software development (Chapter 4). We apply six categories to identify the intentions of questioners to post energy-related questions. We model the energy-related posts to identify common topics associated with them. We propose two criteria to prioritize concerned topics, including difficulty and popularity. We present different development platforms where practitioners raise more energy-related questions or are more concerned. Our approach can provide insights to the developer and research community to develop effective strategies and solutions to address energy challenges in software development.

Summary 1

Our results suggest that 1) nearly half of the questions are related to the concepts of energy consumption instead of implementation details; 2) practitioners are particularly interested in comprehending *computing resources* utilized by their programs, while questions related to *energy (general)* and *monitoring* pose the greatest difficulty in garnering community support; and 3) practitioners are more concerned about the energy consumption of mobile operating systems (e.g., Android) and accessories (e.g., Bluetooth).

Revealing the impact of browser extensions on browser performance (Chapter 5). We select a variety of extensions that represent all functional types and are distinguished by their use of privacy practices. We apply three performance metrics (i.e., page load time, page load energy consumption, and stabilized energy consumption) to evaluate the representative extensions across different activation modes while comparing results with and without the extension enabled. Extension users may use our approach to be aware of the potential costs and be benefited from using these extensions. Moreover, we propose an approach to assist extension developers in identifying the significant factors that have correlations with performance changes. We select potential user-level and build-level factors and develop mixed-effect modules to determine the significance and correlations between performance metrics and underlying factors, as well as the side effects of influential factors. By using our approach, extension developers can optimize their extension development decisions to improve performance, and extension users can select the most performance-effective extensions for their specific needs.

Summary 2

The results of our case study suggest that 1) the use of extensions under their typical activation mode (i.e., fully loaded) can cause a statistically significant impact on the browser performance, particularly in terms of load time energy consumption, resulting in negative consequences; 2) browser performance can be negatively impacted by the use of extensions, even when extensions are not active or used in unexpected circumstances, such as not being logged in or having access to a webpage not granted; (3) highly-rated extensions or those with larger code sizes tend to be more energy efficient; and 4) the privacy practices of extensions negatively impact browser performance.

6.2 Future Work

The research work presented in this thesis highlights the significance of considering energy consumption in software development and the potential impact of extensions on browser performance, as well as provides insights and recommendations for improving energy efficiency and performance in software development. The arguments, nevertheless, can be expanded upon from multiple perspectives. In this section, we outline promising research opportunities that may advance this line of work in the future.

- **Learning trends in practitioners' concerns in energy-efficient software.** This thesis only provides a general snapshot of practitioners' perceptions and concerns regarding energy consumption in software development over 13 years, without analyzing how they have changed over time or identifying any patterns in their concerns. However, as the demand for energy-efficient software continues to grow, it is valuable to investigate emerging trends and popular areas in practitioners' perceptions regarding energy consumption, such as energy issues in the development of Apple products. Future research could conduct a longitudinal study to track changes in practitioners' perceptions of energy consumption over time. To conduct a longitudinal study, researchers could use various methods, such as collecting data on SO, conducting surveys or interviews, or other appropriate methods. The collected data could be analyzed using statistical methods to identify trends and patterns in practitioners' concerns about energy consumption.

- **Perceiving concerns of energy-efficient software.** Despite the growing awareness of the energy impact of software, there is still a lack of understanding of how to effectively promote energy-efficient practices in software development. Our approaches only focus on practitioners' perceptions of energy consumption and do not address the effectiveness of different approaches to promoting energy efficiency in software development, which is a crucial aspect that needs to be explored. Investigating the effectiveness of different approaches to promoting energy efficiency in software development, such as the use of energy consumption metrics in software development tools, is potential for research, which can lead to the development of new tools and methods that can help developers to reduce the energy consumption of software applications. Researchers can compare the energy consumption of different software development tools and methods and use case studies to explore how energy-efficient practices are implemented in real-world software development applications.

- **Conducting cross-base performance analysis.** This thesis demonstrates the enormous potential for the extensions to impact browser performance, in particular, Google Chrome deployed in Linux. Future studies could consider different operation systems, browsers, and other versions of Google Chrome to validate the impact of the extensions on browser performance. The advantage of conducting cross-base performance analysis is that it can help validate and complement the results of the current study and provide a more comprehensive understanding of the impact of extensions on browser performance. By examining the impact of extensions in different configurations, researchers can identify whether the results are generalizable, systematic, or specific to certain configurations. Researchers can utilize the same approaches to collect data and analyze the results. By comparing the results across different configurations, researchers can identify any differences or similarities in the impact of extensions on browser performance.

- **Detecting the effect of the increasing use of extensions on Web browsers.** With the increasing popularity of web browser extensions, there is a need to understand the potential impact of using extensions on the energy consumption and performance of web browsers. Our approaches only study the impact of a single extension on the web browser. It could be valuable for future studies to investigate whether the usage of the number of extensions has a scaling effect on energy consumption and on performance. Investigating the effect of the increasing use of extensions on web browsers could benefit developers, as they could make more informed decisions about which extensions they install and how many they use. Researchers could conduct studies to measure the energy consumption and performance of different web browsers with varying numbers of extensions installed. Additionally, future studies could investigate the impact of using different types of extensions (e.g., ad-blockers, password managers, etc.) together on energy consumption and performance.

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Appendix A

Chapter 4: 277 customized SO posts related to energy consumption with question intentions and topics labeled

Table A.1: 277 SO posts with question intentions and topics labeled.

Index	Example	Post Title	Topic	Intention
1	https://stackoverflow.com/questions/9062404	Monitoring per Application [...]	Device;Monitoring	api usage
2	https://stackoverflow.com/questions/53580298	How to significantly [...]	Energy (general);Computing resource; Device	review; api usage
3	https://stackoverflow.com/questions/39017765	SQL query getting [...]	Monitoring	api usage
4	https://stackoverflow.com/questions/61660649	Matlab computational [...]	Computing resource	conceptual
5	https://stackoverflow.com/questions/58772263	Measure the battery [...]	Monitoring;Data Transmission; Energy (general)	conceptual
6	https://stackoverflow.com/questions/6573925	Android Live Wallpaper [...]	Coding;Device	api usage
7	https://stackoverflow.com/questions/30822622	Android touch screen [...]	Device;Monitoring;Energy (general)	conceptual
8	https://stackoverflow.com/questions/42548761	iOS: Tracking User [...]	Device;Monitoring;Energy (general)	discrepancy; review
9	https://stackoverflow.com/questions/6829909	Bluetooth + Android [...]	Device;Energy (general)	conceptual
10	https://stackoverflow.com/questions/40685084	nvidia-smi shows GPU [...]	Computing resource;Device	discrepancy
11	https://stackoverflow.com/questions/67378114	what should be [...]	Device;Energy (general)	conceptual
12	https://stackoverflow.com/questions/53577434	OpenGL: How to [...]	Computing resource;Device; Energy (general)	api usage; discrepancy
13	https://stackoverflow.com/questions/55956287	perf power consumption [...]	Monitoring	conceptual
14	https://stackoverflow.com/questions/34081364	Measure energy [...]	Monitoring;Device;Coding	api usage
15	https://stackoverflow.com/questions/33476817	How would you [...]	Monitoring;Device	api usage
16	https://stackoverflow.com/questions/6925572	How would a [...]	Computing resource;Energy (general)	conceptual
17	https://stackoverflow.com/questions/63447643	Why does my [...]	Device;Monitoring	discrepancy

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Table A.1 – continued from previous page

Index	Example	Post Title	Topic	Intention
18	https://stackoverflow.com/questions/66989354	how to access [...]	Monitoring;Computing resource;Device	api usage
19	https://stackoverflow.com/questions/27114493	Arduino: how to [...]	Device;Energy (general)	errors
20	https://stackoverflow.com/questions/9918177	mobile application and [...]	Data Transmission;Energy (general); Device	review
21	https://stackoverflow.com/questions/30027148	Fuel gauge to [...]	Device;Monitoring	conceptual
22	https://stackoverflow.com/questions/11917617	Dim screen on [...]	Device;Monitoring	api usage
23	https://stackoverflow.com/questions/44769502	Does every simple [...]	Coding;Energy (general)	review; conceptual
24	https://stackoverflow.com/questions/44451983	How does idle(halt) [...]	Device;Computing resource; Energy (general)	conceptual
25	https://stackoverflow.com/questions/20046908	How can I [...]	Coding	api usage
26	https://stackoverflow.com/questions/21253621	Perlin noise shader [...]	Coding	errors
27	https://stackoverflow.com/questions/15375053	Does Google cloud [...]	Data Transmission	conceptual
28	https://stackoverflow.com/questions/15951974	Best practice to [...]	Monitoring;Device;Energy (general)	conceptual
29	https://stackoverflow.com/questions/7900386	Manually pairing [...]	Device;Energy (general)	api usage
30	https://stackoverflow.com/questions/38901527	Power consumption [...]	Device;Monitoring	conceptual
31	https://stackoverflow.com/questions/40413091	How do I [...]	Computing resource;Coding	api usage
32	https://stackoverflow.com/questions/5151872	How can I [...]	Device;Coding	api usage
33	https://stackoverflow.com/questions/25464441	iOS: How can [...]	Device;Energy (general);Monitoring	conceptual
34	https://stackoverflow.com/questions/68366204	Passing pointers of [...]	Computing resource;Coding	api usage
35	https://stackoverflow.com/questions/5490707	Does CLLocationManager [...]	Energy (general);Monitoring;Coding	api usage
36	https://stackoverflow.com/questions/55167792	Sending sensor info [...]	Device;Data Transmission; Energy (general)	api usage; errors
37	https://stackoverflow.com/questions/19519	Do you use [...]	Device;Energy (general)	conceptual
38	https://stackoverflow.com/questions/44296990	iOS what is [...]	Device;Energy (general);Coding	api usage
39	https://stackoverflow.com/questions/29099232	execute periodic network [...]	Device;Energy (general)	api usage
40	https://stackoverflow.com/questions/42955973	background bluetooth [...]	Device;Energy (general)	conceptual
41	https://stackoverflow.com/questions/10663479	AddProximityAlert power [...]	Device;Monitoring;Energy (general)	conceptual
42	https://stackoverflow.com/questions/42850419	My app keep [...]	Device;Monitoring;Energy (general)	discrepancy
43	https://stackoverflow.com/questions/55816530	How does the [...]	Device;Energy (general)	conceptual
44	https://stackoverflow.com/questions/43955006	Set BLE connection [...]	Device;Energy (general)	conceptual
45	https://stackoverflow.com/questions/9863131	Android accelerometer, [...]	Device;Energy (general)	conceptual
46	https://stackoverflow.com/questions/31318297	Which camera to [...]	Device;Energy (general)	review
47	https://stackoverflow.com/questions/45251839	How to reduce [...]	Device;Energy (general);Coding	review; conceptual
48	https://stackoverflow.com/questions/56448709	Does the Linux [...]	Device;Energy (general);Monitoring	conceptual
49	https://stackoverflow.com/questions/38198369	Measure Power [...]	Device;Monitoring	conceptual
50	https://stackoverflow.com/questions/68426962	What kind of [...]	Device;Coding	api usage; conceptual
51	https://stackoverflow.com/questions/7765152	Android GPS tracking [...]	Device;Monitoring;Energy (general)	review; conceptual
52	https://stackoverflow.com/questions/68446745	How to estimate [...]	Device;Monitoring;Computing resource	api usage
53	https://stackoverflow.com/questions/33124994	How often do [...]	Device;Data Transmission; Energy (general)	conceptual
54	https://stackoverflow.com/questions/12766763	Do reading of [...]	Device;Energy (general)	conceptual
55	https://stackoverflow.com/questions/14719418	Power Usage of [...]	Device;Energy (general)	conceptual
56	https://stackoverflow.com/questions/43688086	disadvatages of local [...]	Device;Computing resource;Coding	conceptual

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Table A.1 – continued from previous page

Index	Example	Post Title	Topic	Intention
57	https://stackoverflow.com/questions/66366935	Wemos modem sleep [...]	Data Transmission;Device; Energy (general)	api usage
58	https://stackoverflow.com/questions/27383269	Why dynamic power [...]	Device;Monitoring	discrepancy
59	https://stackoverflow.com/questions/10766587	Measuring power usage [...]	Coding;Monitoring	errors
60	https://stackoverflow.com/questions/64880421	nRF52 DK BLE [...]	Device;Coding	discrepancy
61	https://stackoverflow.com/questions/38516968	Realtime update of [...]	Computing resource;Monitoring	api usage; conceptual
62	https://stackoverflow.com/questions/41576572	What are the [...]	Device;Computing resource; Energy (general)	conceptual
63	https://stackoverflow.com/questions/56699763	Xcode Energy impact [...]	Device;Energy (general)	discrepancy
64	https://stackoverflow.com/questions/20651601	Building Time and [...]	Device;Energy (general);Coding	api usage
65	https://stackoverflow.com/questions/19298451	Is there any [...]	Device;Energy (general);Monitoring	api usage
66	https://stackoverflow.com/questions/28003660	Why does reading [...]	Device;Computing resource	discrepancy
67	https://stackoverflow.com/questions/48379717	Omnet++- Energy [...]	Monitoring	conceptual
68	https://stackoverflow.com/questions/12124752	Google Cloud Messaging [...]	Data Transmission;Energy (general)	conceptual
69	https://stackoverflow.com/questions/27176300	Extracting power [...]	Device;Monitoring;Coding	api usage
70	https://stackoverflow.com/questions/43981309	Energy savings with [...]	Data Transmission;Monitoring	api usage
71	https://stackoverflow.com/questions/63920933	How to programmatically [...]	Monitoring;Device	api usage
72	https://stackoverflow.com/questions/15413932	MonkeyTalk for recording [...]	Data Transmission;Monitoring;Device	conceptual
73	https://stackoverflow.com/questions/59472665	Castalia 3.2 energy [...]	Monitoring	discrepancy
74	https://stackoverflow.com/questions/38158828	Android Google Play [...]	Device;Monitoring	api usage; conceptual
75	https://stackoverflow.com/questions/67029189	How to dim [...]	Device;Data Transmission	api usage
76	https://stackoverflow.com/questions/44228005	How to measure [...]	Computing resource;Device;Monitoring	conceptual; api usage
77	https://stackoverflow.com/questions/36808568	SimpleSclar Error as: [...]	Monitoring	errors
78	https://stackoverflow.com/questions/46853680	Beacon size vs [...]	Data Transmission	conceptual
79	https://stackoverflow.com/questions/28024898	How can two [...]	Device;Energy (general)	api usage
80	https://stackoverflow.com/questions/62935821	Firebase Energy Impact [...]	Energy (general);Device; Data Transmission	conceptual; discrepancy
81	https://stackoverflow.com/questions/45042071	Fabric on iOS [...]	Device;Energy (general)	discrepancy
82	https://stackoverflow.com/questions/64116583	how can I [...]	Monitoring;Computing resource	api usage
83	https://stackoverflow.com/questions/33097914	Power consumption using [...]	Device;Data Transmission; Energy (general)	api usage
84	https://stackoverflow.com/questions/4485153	Estimating process energy [...]	Device;Monitoring;Computing resource	conceptual
85	https://stackoverflow.com/questions/8600731	android turn GPS [...]	Coding;Device;Energy (general)	api usage
86	https://stackoverflow.com/questions/66010775	disable HDMI in [...]	Device;Energy (general)	conceptual
87	https://stackoverflow.com/questions/26329993	iOS wake up/interrupt [...]	Device	api usage
88	https://stackoverflow.com/questions/22215344	Remove update when [...]	Device;Monitoring;Energy (general)	api usage
89	https://stackoverflow.com/questions/27672560	Making sense of [...]	Monitoring;Energy (general)	api usage
90	https://stackoverflow.com/questions/45993142	Frequency scaling and [...]	Computing resource;Monitoring	discrepancy
91	https://stackoverflow.com/questions/53106613	How to determine [...]	Device	api usage
92	https://stackoverflow.com/questions/7312597	Is using hardware [...]	Energy (general);Computing resource	conceptual
93	https://stackoverflow.com/questions/27896877	How to detect [...]	Energy (general);Coding	api usage
94	https://stackoverflow.com/questions/10293713	How to calculate [...]	Device;Monitoring;Energy (general)	conceptual; api usage
95	https://stackoverflow.com/questions/44472730	Defining a variable [...]	Energy (general);Coding	api usage

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Index	Example	Post Title	Topic	Intention
96	https://stackoverflow.com/questions/3655806	How to measure [...]	Device;Monitoring	api usage
97	https://stackoverflow.com/questions/55164804	Linux on Arm [...]	Device;Computing resource; Energy (general)	conceptual
98	https://stackoverflow.com/questions/51406465	Reduced CPU time [...]	Computing resource;Energy (general); Monitoring	conceptual
99	https://stackoverflow.com/questions/28123415	Timer, TimerTask and [...]	Energy (general);Coding;Device	review
100	https://stackoverflow.com/questions/10911825	Automatically Wake NAS [...]	Device	api usage
101	https://stackoverflow.com/questions/50188960	FPGA Will pausing [...]	Device;Coding	review
102	https://stackoverflow.com/questions/1998778	How to measure [...]	Monitoring;Coding	conceptual
103	https://stackoverflow.com/questions/20060628	Implementing Deferred [...]	Monitoring	discrepancy; api usage
104	https://stackoverflow.com/questions/2236041	Tracking power use [...]	Monitoring;Energy (general)	conceptual
105	https://stackoverflow.com/questions/63180936	Power consumption on [...]	Monitoring	review
106	https://stackoverflow.com/questions/57299265	Using consumer cellphones [...]	Data Transmission;Device	conceptual
107	https://stackoverflow.com/questions/34932727	Intentionally high CPU [...]	Computing resource	discrepancy
108	https://stackoverflow.com/questions/47564756	Is there a [...]		conceptual
109	https://stackoverflow.com/questions/44490679	Energy efficient detection [...]	Monitoring;Energy (general)	conceptual
110	https://stackoverflow.com/questions/23467778	Android - App [...]	Monitoring;Device	api usage
111	https://stackoverflow.com/questions/13286662	Any tool/software [...]	Monitoring	api usage
112	https://stackoverflow.com/questions/8782922	Decentralized Clustering [...]	Coding;Energy (general); Data Transmission	api usage
113	https://stackoverflow.com/questions/32256305	Refresh Text / [...]	Coding;Energy (general)	review
114	https://stackoverflow.com/questions/41248566	Energy Level data [...]	Monitoring;Device	discrepancy
115	https://stackoverflow.com/questions/32195298	Create dispatch table [...]	Coding;Device	api usage
116	https://stackoverflow.com/questions/57522269	iPhone restarts after [...]	Device;Energy (general); Computing resource	discrepancy
117	https://stackoverflow.com/questions/25847846	Taxonomy of battery [...]	Device;Energy (general)	conceptual
118	https://stackoverflow.com/questions/21373913	How to measure [...]	Monitoring	api usage
119	https://stackoverflow.com/questions/28495166	Arduino voltage regulator [...]	Device;Energy (general)	conceptual
120	https://stackoverflow.com/questions/17893849	QML causing switch [...]	Computing resource;Device; Energy (general)	conceptual
121	https://stackoverflow.com/questions/10074254	How to calculate [...]	Monitoring;Device	api usage
122	https://stackoverflow.com/questions/39687731	Low GPU usage [...]	Computing resource;Device	discrepancy
123	https://stackoverflow.com/questions/30460012	How to Autoconnect [...]	Device;Energy (general)	api usage
124	https://stackoverflow.com/questions/66592256	Performance Counter for [...]	Computing resource;Monitoring	api usage; conceptual
125	https://stackoverflow.com/questions/680684	What are the [...]	Computing resource;Energy (general)	conceptual
126	https://stackoverflow.com/questions/66698308	Does Google not [...]	Computing resource	api usage
127	https://stackoverflow.com/questions/36055657	Energy economy: BLE [...]	Device;Energy (general)	review
128	https://stackoverflow.com/questions/36140321	Measurement of energy [...]	Device;Monitoring	conceptual
129	https://stackoverflow.com/questions/66718036	What is an [...]	Energy (general)	learning; conceptual
130	https://stackoverflow.com/questions/14650973	Does the amount [...]	Computing resource;Energy (general)	conceptual
131	https://stackoverflow.com/questions/68576876	Calculate node energy [...]	Monitoring	conceptual
132	https://stackoverflow.com/questions/4788132	How to get [...]	Monitoring	conceptual
133	https://stackoverflow.com/questions/40008200	Angular 2 Ahead-of-Time [...]	Computing resource;Energy (general)	discrepancy
134	https://stackoverflow.com/questions/60242296	CP-SAT Optimizing [...]	Coding	api usage

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Table A.1 – continued from previous page

Index	Example	Post Title	Topic	Intention
135	https://stackoverflow.com/questions/11366329	Implementing an event [...]	Coding	conceptual
136	https://stackoverflow.com/questions/29938401	android how to [...]	Device;Data Transmission	conceptual
137	https://stackoverflow.com/questions/63105570	How to turn [...]	Device;Energy (general)	learning
138	https://stackoverflow.com/questions/50641205	Low energy consumption [...]	Energy (general)	conceptual
139	https://stackoverflow.com/questions/60244674	Best way to [...]	Data Transmission	review
140	https://stackoverflow.com/questions/45751387	How do I [...]	Monitoring;Energy (general);Device	conceptual
141	https://stackoverflow.com/questions/60771095	I can't see [...]	Computing resource;Monitoring;Device	errors
142	https://stackoverflow.com/questions/1596252	Estimate Power [...]	Monitoring;Coding;Energy (general)	conceptual
143	https://stackoverflow.com/questions/3589086	Best Practice - [...]	Energy (general);Device;Monitoring	review
144	https://stackoverflow.com/questions/68206910	power consumption of [...]	Computing resource;Monitoring; Energy (general)	conceptual
145	https://stackoverflow.com/questions/53359800	Java TCP server [...]	Device;Data Transmission; Energy (general)	conceptual
146	https://stackoverflow.com/questions/68003904	How can I [...]	Device;Monitoring	api usage
147	https://stackoverflow.com/questions/4419909	Finding cyclic function [...]	Energy (general)	conceptual
148	https://stackoverflow.com/questions/8102396	How do I [...]	Monitoring;Device	conceptual
149	https://stackoverflow.com/questions/32061776	Best practices to [...]	Energy (general);Coding	learning
150	https://stackoverflow.com/questions/23207209	Which Google OAuth [...]	Device;Energy (general)	review
151	https://stackoverflow.com/questions/34558115	powertop shows 40 [...]	Energy (general);Device	conceptual
152	https://stackoverflow.com/questions/39001087	Android How to [...]	Monitoring;Device	conceptual
153	https://stackoverflow.com/questions/2657766	How can I [...]	Device;Energy (general); Coding;Monitoring	api usage
154	https://stackoverflow.com/questions/4926963	Is there any [...]	Monitoring;Device;Energy (general)	conceptual
155	https://stackoverflow.com/questions/32926438	Reduce Bluetooth Classic [...]	Device;Energy (general)	conceptual
156	https://stackoverflow.com/questions/9823026	Bluetooth power [...]	Device;Energy (general)	conceptual
157	https://stackoverflow.com/questions/1761611	Hard disk drive [...]	Computing resource;Energy (general); Device	conceptual
158	https://stackoverflow.com/questions/35623051	Does SSL affect [...]	Data Transmission	review
159	https://stackoverflow.com/questions/50645463	Dispatch Main Queue [...]	Energy (general);Coding	review
160	https://stackoverflow.com/questions/62352570	Tips on getting [...]	Computing resource;Device; Energy (general);Monitoring	review; conceptual
161	https://stackoverflow.com/questions/11560011	Dual optimization with [...]	Energy (general)	conceptual
162	https://stackoverflow.com/questions/40884596	Less Battery consumption [...]	Monitoring;Device;Energy (general)	api usage
163	https://stackoverflow.com/questions/25369708	Can I use [...]	Data Transmission;Device	conceptual; learning
164	https://stackoverflow.com/questions/35267365	Standby and sleep [...]	Device	conceptual
165	https://stackoverflow.com/questions/5884820	Detecting USB power [...]	Device;Data Transmission; Coding;Monitoring	api usage
166	https://stackoverflow.com/questions/33159696	nodejs api for [...]	Monitoring;Device	api usage
167	https://stackoverflow.com/questions/32998040	CLGeocoder [...]	Energy (general);Coding	discrepancy
168	https://stackoverflow.com/questions/25525817	Is there any [...]	Device;Monitoring	api usage
169	https://stackoverflow.com/questions/23660322	Are there any [...]	Energy (general)	conceptual
170	https://stackoverflow.com/questions/15419583	Sorting content from [...]	Coding;Energy (general)	review
171	https://stackoverflow.com/questions/10908666	Android remote service, [...]	Device;Energy (general);Monitoring	conceptual; api usage
172	https://stackoverflow.com/questions/65293303	UnitDiskRadioMedium no [...]	Energy (general)	conceptual

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Table A.1 – continued from previous page

Index	Example	Post Title	Topic	Intention
173	https://stackoverflow.com/questions/34284649	How to get [...]	Monitoring;Energy (general); Device;Coding	api usage
174	https://stackoverflow.com/questions/14947130	Comparing Time by [...]	Coding;Monitoring	conceptual; learning
175	https://stackoverflow.com/questions/16716443	How to disable [...]	Computing resource;Device; Energy (general)	conceptual
176	https://stackoverflow.com/questions/5134257	What is the [...]	Device;Energy (general)	review
177	https://stackoverflow.com/questions/12860734	Booting an embedded [...]	Energy (general);Device	discrepancy; conceptual; learning
178	https://stackoverflow.com/questions/43734649	NRF51 - iOS [...]	Device	discrepancy; conceptual
179	https://stackoverflow.com/questions/39014791	Battery Historian Error [...]	Device;Energy (general);Coding	errors
180	https://stackoverflow.com/questions/38325958	android service logging [...]	Device;Energy (general);Monitoring	api usage; discrepancy
181	https://stackoverflow.com/questions/48528517	Why is this [...]	Computing resource;Coding	discrepancy
182	https://stackoverflow.com/questions/44748275	Setting modem sleep [...]	Device;Energy (general)	discrepancy
183	https://stackoverflow.com/questions/62536146	Comparison between USB [...]	Device;Energy (general)	review
184	https://stackoverflow.com/questions/20863314	Arduino: Incoming USB [...]	Device;Energy (general);Coding	discrepancy
185	https://stackoverflow.com/questions/35247106	Low-Power Video [...]	Data Transmission;Energy (general)	conceptual
186	https://stackoverflow.com/questions/51529023	ARKit ARSession [...]	Energy (general);Computing resource; Device	errors
187	https://stackoverflow.com/questions/41031060	macOS/ OS X [...]	Device;Monitoring; Coding;Energy (general)	review
188	https://stackoverflow.com/questions/22258112	Metrics to compare [...]	Device;Computing resource; Energy (general);Monitoring	conceptual
189	https://stackoverflow.com/questions/59502937	will geofence reduce [...]	Monitoring;Energy (general)	conceptual
190	https://stackoverflow.com/questions/9250121	Android: Improve sensor [...]	Device;Coding;Energy (general)	conceptual
191	https://stackoverflow.com/questions/53494820	How do you [...]	Monitoring	conceptual
192	https://stackoverflow.com/questions/19937920	Bluetooth peripheral v. [...]	Device;Energy (general)	conceptual
193	https://stackoverflow.com/questions/506452	Software performance [...]	Device;Coding;Energy (general)	conceptual
194	https://stackoverflow.com/questions/38194821	Is there a [...]	Device;Energy (general); Coding;Monitoring	review; conceptual
195	https://stackoverflow.com/questions/62338496	Is there a [...]	Device;Energy (general);Monitoring	api usage
196	https://stackoverflow.com/questions/43977571	calculate app uptime [...]	Device;Energy (general);Monitoring	api usage
197	https://stackoverflow.com/questions/8558964	Power measurement for [...]	Device;Monitoring	conceptual
198	https://stackoverflow.com/questions/56363631	Get CVPixelBuffer (camera [...]	Computing resource;Energy (general); Device	review; api usage
199	https://stackoverflow.com/questions/39503891	Disabling allowance of [...]	Device;Energy (general);Coding	discrepancy
200	https://stackoverflow.com/questions/58424276	Why can $_{m}m_{p}ause()$[...]	Coding;Energy (general)	api usage
201	https://stackoverflow.com/questions/22860890	How does Android's [...]	Device;Energy (general)	conceptual
202	https://stackoverflow.com/questions/19104549	How to read [...]	Monitoring	api usage
203	https://stackoverflow.com/questions/8380906	Power consumption [...]	Monitoring;Energy (general);Device	api usage
204	https://stackoverflow.com/questions/10171400	Is Energy Usage [...]	Device;Monitoring	conceptual
205	https://stackoverflow.com/questions/32179106	CLLocationManager running [...]	Device;Coding;Energy (general)	api usage
206	https://stackoverflow.com/questions/14586233	Explanation of GPGPU [...]		conceptual

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Table A.1 – continued from previous page

Index	Example	Post Title	Topic	Intention
207	`https://stackoverflow.com/questions/43588220`	Simplifying multiple OR [...]	Coding;Energy (general)	errors; review; discrepancy
208	`https://stackoverflow.com/questions/1996524`	Optimizing performance on [...]	Computing resource;Device	conceptual; review
209	`https://stackoverflow.com/questions/37984425`	Clarifying the use [...]	Coding;Energy (general);Device	api usage
210	`https://stackoverflow.com/questions/21581328`	Problems using CoreLocation [...]	Device;Energy (general);Coding	discrepancy; conceptual
211	`https://stackoverflow.com/questions/20907535`	Is it possible/easy [...]	Monitoring;Computing resource;Device	conceptual
212	`https://stackoverflow.com/questions/20448647`	Questions on Measuring [...]	Computing resource;Energy (general); Monitoring	conceptual
213	`https://stackoverflow.com/questions/6866236`	Calculating values from [...]	Coding;Monitoring;Energy (general)	review
214	`https://stackoverflow.com/questions/25090606`	Using setImmediate() over [...]	Coding;Energy (general)	conceptual
215	`https://stackoverflow.com/questions/9653480`	Profiling Power consumption [...]	Computing resource;Energy (general); Monitoring	conceptual
216	`https://stackoverflow.com/questions/48697024`	Time measurements, CPU [...]	Computing resource;Monitoring	conceptual
217	`https://stackoverflow.com/questions/47693264`	How to reduce [...]	Energy (general);Monitoring	discrepancy; conceptual
218	`https://stackoverflow.com/questions/7488196`	what is the [...]	Coding	conceptual
219	`https://stackoverflow.com/questions/26751607`	Using GMail system [...]	Coding;Energy (general)	conceptual
220	`https://stackoverflow.com/questions/12352325`	How to implement [...]	Coding;Energy (general);Device	api usage
221	`https://stackoverflow.com/questions/51390641`	Is it possible [...]	Monitoring	conceptual
222	`https://stackoverflow.com/questions/12277651`	Does Reach-ability class [...]	Data Transmission;Device;Monitoring	conceptual
223	`https://stackoverflow.com/questions/24811191`	Parallel lookup in [...]	Computing resource;Energy (general)	conceptual
224	`https://stackoverflow.com/questions/45577258`	Gauge acceptable CPU/GPU [...]	Computing resource;Device; Energy (general)	discrepancy; conceptual
225	`https://stackoverflow.com/questions/3092498`	How to do [...]	Device;Energy (general)	api usage; conceptual
226	`https://stackoverflow.com/questions/63137042`	Image detection optimization [...]	Energy (general);Coding	review; discrepancy
227	`https://stackoverflow.com/questions/43356814`	How to get [...]	Device;Monitoring; Computing resource;Data Transmission	conceptual; api usage
228	`https://stackoverflow.com/questions/61490802`	Programmatically get process [...]	Device;Coding;Monitoring	conceptual
229	`https://stackoverflow.com/questions/29282070`	WebSockets Energy [...]	Device;Energy (general); Data Transmission	conceptual
230	`https://stackoverflow.com/questions/52847403`	I have a [...]	Energy (general)	conceptual
231	`https://stackoverflow.com/questions/40086495`	battery consumption check [...]	Device;Monitoring	conceptual
232	`https://stackoverflow.com/questions/8738269`	Is there any [...]	Device;Energy (general)	conceptual
233	`https://stackoverflow.com/questions/33903458`	C/C++ Control CPU [...]	Computing resource;Coding;Monitoring	api usage
234	`https://stackoverflow.com/questions/14905560`	Mono for Android [...]	Device;Coding;Energy (general)	conceptual
235	`https://stackoverflow.com/questions/56925813`	AVR wakeup for [...]	Device;Energy (general)	discrepancy; review
236	`https://stackoverflow.com/questions/11949778`	Getting power consumption [...]	Monitoring;Coding	api usage
237	`https://stackoverflow.com/questions/11271758`	iOS chat APNS, [...]	Device;Data Transmission; Energy (general)	review
238	`https://stackoverflow.com/questions/6602241`	Explicitly Managing WiFi [...]	Device;Energy (general)	conceptual
239	`https://stackoverflow.com/questions/20926665`	Self-modifying code in [...]	Coding;Energy (general)	api usage

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Table A.1 – continued from previous page

Index	Example	Post Title	Topic	Intention
240	https://stackoverflow.com/questions/22339063	Infinite for loop [...]	Coding;Computing resource; Energy (general)	discrepancy
241	https://stackoverflow.com/questions/46928100	energy consumption for [...]	Data Transmission;Monitoring	conceptual
242	https://stackoverflow.com/questions/60030854	Deal with low [...]	Coding;Device;Monitoring	api usage
243	https://stackoverflow.com/questions/51940896	CLion 2018.2 using [...]	Computing resource	discrepancy
244	https://stackoverflow.com/questions/67925368	How does Intel's [...]	Computing resource;Monitoring	conceptual
245	https://stackoverflow.com/questions/21946881	Any disadvantages to [...]	Device;Computing resource;Coding	conceptual
246	https://stackoverflow.com/questions/54031708	requestLocation() fails to [...]	Energy (general);Monitoring	discrepancy
247	https://stackoverflow.com/questions/54519991	App uses a [...]	Energy (general);Device	conceptual
248	https://stackoverflow.com/questions/14151152	iPhone battery drain [...]	Energy (general);Monitoring	discrepancy; conceptual
249	https://stackoverflow.com/questions/37715638	Is Thread.sleep() a [...]	Coding	review
250	https://stackoverflow.com/questions/65250145	How can I [...]	Coding;Monitoring	api usage
251	https://stackoverflow.com/questions/68053529	Contiki-NG RE-Mote [...]	Monitoring;Device;Data Transmission	conceptual
252	https://stackoverflow.com/questions/36725225	How can I [...]	Device;Monitoring	conceptual
253	https://stackoverflow.com/questions/20787507	How to check [...]	Device;Monitoring;Coding	api usage; conceptual
254	https://stackoverflow.com/questions/17143661	Most power efficient [...]	Device;Energy (general); Data Transmission	conceptual
255	https://stackoverflow.com/questions/19393904	Android vs Linux [...]	Device;Energy (general)	discrepancy
256	https://stackoverflow.com/questions/48818676	python syntax error [...]	Coding;Energy (general)	errors
257	https://stackoverflow.com/questions/16621947	Save energy previewcam, [...]	Device;Energy (general);Coding	review
258	https://stackoverflow.com/questions/37940689	Slow contact fetching [...]	Device;Coding; Computing resource;Energy (general)	discrepancy
259	https://stackoverflow.com/questions/3412026	hybrid algorithms in [...]	Coding;Energy (general)	api usage
260	https://stackoverflow.com/questions/46383050	STM32L0 Stop Mode [...]	Coding;Computing resource; Energy (general)	discrepancy
261	https://stackoverflow.com/questions/55794496	which ML algorithm [...]	Energy (general)	conceptual
262	https://stackoverflow.com/questions/49755046	Switch off a [...]	Coding;Device;Energy (general)	api usage
263	https://stackoverflow.com/questions/16001080	Creating a single [...]	Coding;Monitoring	api usage
264	https://stackoverflow.com/questions/7590475	Why does increasing [...]	Energy (general)	discrepancy
265	https://stackoverflow.com/questions/30692203	Power and timing [...]	Coding;Energy (general)	conceptual; learning
266	https://stackoverflow.com/questions/46355479	Advanced home network [...]	Device;Energy (general)	conceptual
267	https://stackoverflow.com/questions/60185954	Stm32 Power consumption [...]	Coding;Device	discrepancy
268	https://stackoverflow.com/questions/36276883	Wi-Fi vs Bluetooth [...]	Device;Data Transmission; Energy (general)	conceptual
269	https://stackoverflow.com/questions/24552715	Implementing custom [...]	Device;Data Transmission	conceptual
270	https://stackoverflow.com/questions/58156084	Is there a [...]	Computing resource;Energy (general); Device;Coding	discrepancy
271	https://stackoverflow.com/questions/6908168	How to determine [...]	Monitoring;Device	conceptual
272	https://stackoverflow.com/questions/49043925	Responsiveness of [...]	Device;Coding;Monitoring	discrepancy; conceptual; api usage
273	https://stackoverflow.com/questions/23981664	Why hardware [...]	Energy (general)	conceptual
274	https://stackoverflow.com/questions/31497164	Error: primef not [...]	Coding;Energy (general)	errors; conceptual

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Table A.1 – continued from previous page

Index	Example	Post Title	Topic	Intention
275	`https://stackoverflow.com/questions/10929875`	Interupts Vs Poling [...]	Device;Energy (general); Data Transmission	review
276	`https://stackoverflow.com/questions/21173596`	How can I [...]	Energy (general);Device	api usage
277	`https://stackoverflow.com/questions/21609673`	are we able [...]	Device;Monitoring	api usage

Appendix B

Chapter 4: Remaining of 708 manually verified energy-related SO posts

Table B.1: 708 manually verified energy-related SO posts.

Index	Example	Post Title
1	https://stackoverflow.com/questions/61882	Power Efficient Software Coding [...]
2	https://stackoverflow.com/questions/410122	Reducing power consumption on [...]
3	https://stackoverflow.com/questions/724349	How can I measure [...]
4	https://stackoverflow.com/questions/726596	Continual wake and sleep [...]
5	https://stackoverflow.com/questions/734104	Why does the Main [...]
6	https://stackoverflow.com/questions/742892	Build a small code-hosting [...]
7	https://stackoverflow.com/questions/764439	Why binary and not [...]
8	https://stackoverflow.com/questions/955209	Developing power consumption aware [...]
9	https://stackoverflow.com/questions/1123156	Calculate Energy Used on [...]
10	https://stackoverflow.com/questions/1215016	Does keeping a file [...]
11	https://stackoverflow.com/questions/1268112	What is relation between [...]
12	https://stackoverflow.com/questions/1298600	Bluetooth UUID discovery [...]
13	https://stackoverflow.com/questions/1318851	PHP vs. Java are [...]
14	https://stackoverflow.com/questions/1738515	RAM memory reallocation - [...]
15	https://stackoverflow.com/questions/1831952	Server socket programming in [...]
16	https://stackoverflow.com/questions/2208595	c# How to get [...]
17	https://stackoverflow.com/questions/2378519	Algorithm to calculate the [...]
18	https://stackoverflow.com/questions/2439619	Getting the battery current [...]
19	https://stackoverflow.com/questions/2594550	How to achieve a [...]
20	https://stackoverflow.com/questions/2902382	Android Nexus One - [...]
21	https://stackoverflow.com/questions/2905958	Can we optimize code [...]
22	https://stackoverflow.com/questions/2960319	how to calculate power [...]
23	https://stackoverflow.com/questions/3034890	Determine Android phone's proximity [...]
24	https://stackoverflow.com/questions/3239490	Find out which apps [...]
25	https://stackoverflow.com/questions/3625568	Power efficient and Speed [...]

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Table B.1 – continued from previous page

Index	Example	Post Title
26	https://stackoverflow.com/questions/3632521	Collection with 10 elements [...]
27	https://stackoverflow.com/questions/3752347	GPS LocationListener and phone [...]
28	https://stackoverflow.com/questions/3862990	How to find out [...]
29	https://stackoverflow.com/questions/3866746	Writing "Power" Efficient Code [...]
30	https://stackoverflow.com/questions/3971494	ALSA: Power Saving Guidelines [...]
31	https://stackoverflow.com/questions/4117465	Can I completely disable [...]
32	https://stackoverflow.com/questions/4361967	What kind of bugs [...]
33	https://stackoverflow.com/questions/4435585	Battery drain of iPhone [...]
34	https://stackoverflow.com/questions/4602828	How to get power [...]
35	https://stackoverflow.com/questions/4635611	How do I easily [...]
36	https://stackoverflow.com/questions/4746410	Does anyone know any [...]
37	https://stackoverflow.com/questions/4847651	Powering down an ethernet [...]
38	https://stackoverflow.com/questions/4946600	get instant energy consumption [...]
39	https://stackoverflow.com/questions/5598995	DeactivateDevice vs. IOCTL_BUS_DEACTIVATE_CHILD [...]
40	https://stackoverflow.com/questions/5612352	When using CSS transitions/animations/etc., [...]
41	https://stackoverflow.com/questions/5680384	Manually controlling framerate of [...]
42	https://stackoverflow.com/questions/5765212	Is it ok to [...]
43	https://stackoverflow.com/questions/6019996	Monitor apps power usage [...]
44	https://stackoverflow.com/questions/6030750	Control access to files [...]
45	https://stackoverflow.com/questions/6036632	Android Power Profiler [...]
46	https://stackoverflow.com/questions/6051807	per process power consumption [...]
47	https://stackoverflow.com/questions/6128960	What is the relation [...]
48	https://stackoverflow.com/questions/6253187	Possibilities to reduce power [...]
49	https://stackoverflow.com/questions/6503385	How to measure memory [...]
50	https://stackoverflow.com/questions/6527345	Simulating Poisson Waiting Times [...]
51	https://stackoverflow.com/questions/6552637	Hardware clock signals implementation [...]
52	https://stackoverflow.com/questions/6553595	Sending a String array [...]
53	https://stackoverflow.com/questions/6567346	Save battery power consumed [...]
54	https://stackoverflow.com/questions/6586356	Turning "Discoverable" on [...]
55	https://stackoverflow.com/questions/6649664	Cocoa message loop? (vs. [...]
56	https://stackoverflow.com/questions/6722184	Calculate reverse percentage amount [...]
57	https://stackoverflow.com/questions/6738600	Combined XY realtime plots [...]
58	https://stackoverflow.com/questions/6912859	Power optimization in Linux [...]
59	https://stackoverflow.com/questions/6941251	powerTutor, Android application battery [...]
60	https://stackoverflow.com/questions/6955782	OpenGL-ES Puzzle game - [...]
61	https://stackoverflow.com/questions/7028671	USB port current value [...]
62	https://stackoverflow.com/questions/7098813	Disable Linux Scheduler to [...]
63	https://stackoverflow.com/questions/7262546	Rails Minimizing Database Load [...]
64	https://stackoverflow.com/questions/7327632	Android webkit and battery [...]
65	https://stackoverflow.com/questions/7420970	Raspberry Pi cluster, neuron [...]
66	https://stackoverflow.com/questions/7715148	iPhone 4 profile power [...]
67	https://stackoverflow.com/questions/7784585	Power Consumption of an [...]
68	https://stackoverflow.com/questions/7832314	How to calculate the [...]
69	https://stackoverflow.com/questions/7835843	how much battery power [...]
70	https://stackoverflow.com/questions/8074811	How to estimate power [...]
71	https://stackoverflow.com/questions/8100506	How do I use [...]
72	https://stackoverflow.com/questions/8302508	UserIdleDetectionMode versus ApplicationIdleDetectionMode [...]

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Table B.1 – continued from previous page

Index	Example	Post Title
73	https://stackoverflow.com/questions/8377163	In need of a [...]
74	https://stackoverflow.com/questions/8397268	what is the battery [...]
75	https://stackoverflow.com/questions/8434633	Print an OpenGL Texture [...]
76	https://stackoverflow.com/questions/8552417	C2DM Push chat application [...]
77	https://stackoverflow.com/questions/8737612	Energy Usage Instruments - [...]
78	https://stackoverflow.com/questions/8757001	Testing checklist for a [...]
79	https://stackoverflow.com/questions/8937162	Power consumption for various [...]
80	https://stackoverflow.com/questions/8981462	Is it possible to [...]
81	https://stackoverflow.com/questions/9029709	Does Handler.sendMessageDelayed() work when [...]
82	https://stackoverflow.com/questions/9121591	Need help in debugging [...]
83	https://stackoverflow.com/questions/9187303	Android Battery Application [...]
84	https://stackoverflow.com/questions/9332516	Notification when modified file [...]
85	https://stackoverflow.com/questions/9335276	Constantly monitor accelerometer sensor [...]
86	https://stackoverflow.com/questions/9341414	Excel to make sense [...]
87	https://stackoverflow.com/questions/9551938	What is the ratio [...]
88	https://stackoverflow.com/questions/9646238	Instruments doesn't show Energy [...]
89	https://stackoverflow.com/questions/9711458	Determine power usage programmatically [...]
90	https://stackoverflow.com/questions/9917221	What units of power/energy [...]
91	https://stackoverflow.com/questions/9924255	AIR for iOS: Power [...]
92	https://stackoverflow.com/questions/10138087	Measure power consumption related [...]
93	https://stackoverflow.com/questions/10173029	Most power efficient location [...]
94	https://stackoverflow.com/questions/10241426	How quickly will Android [...]
95	https://stackoverflow.com/questions/10246188	iOS Testing with Instruments [...]
96	https://stackoverflow.com/questions/10372334	Pure C Code For [...]
97	https://stackoverflow.com/questions/10420586	Perfmon - Refresh rate [...]
98	https://stackoverflow.com/questions/10468305	Reducing power consumption [...]
99	https://stackoverflow.com/questions/10528334	Simulation in energy efficiency [...]
100	https://stackoverflow.com/questions/10777741	Reducing power consumption of [...]
101	https://stackoverflow.com/questions/10804829	AVCaptureSession video preview without [...]
102	https://stackoverflow.com/questions/10825162	Energy consumption of smartphone [...]
103	https://stackoverflow.com/questions/10920904	Energy efficient GPS tracking [...]
104	https://stackoverflow.com/questions/10981518	Changing brightness of display [...]
105	https://stackoverflow.com/questions/11011260	which code is consuming [...]
106	https://stackoverflow.com/questions/11016779	Can Android be woken [...]
107	https://stackoverflow.com/questions/11067070	Java Socket Connection is [...]
108	https://stackoverflow.com/questions/11122662	Instruments Energy Diagnostics -¿ [...]
109	https://stackoverflow.com/questions/11234335	How can we reduce [...]
110	https://stackoverflow.com/questions/11334109	Running cpu intensive task [...]
111	https://stackoverflow.com/questions/11381543	Constant FPS Android OpenGLES [...]
112	https://stackoverflow.com/questions/11398732	How do I receive [...]
113	https://stackoverflow.com/questions/11401458	Is it possible to [...]
114	https://stackoverflow.com/questions/11486036	Prevent iPhone to sleep [...]
115	https://stackoverflow.com/questions/11790833	How to measure ARM [...]
116	https://stackoverflow.com/questions/11805041	How much power consume [...]
117	https://stackoverflow.com/questions/11833557	How to programatically detect [...]
118	https://stackoverflow.com/questions/11867052	Q-learning value update [...]
119	https://stackoverflow.com/questions/11943099	How to get the [...]

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Index	Example	Post Title
120	https://stackoverflow.com/questions/11977497	android monitoring apps [...]
121	https://stackoverflow.com/questions/11987643	Storing local Cell-id to [...]
122	https://stackoverflow.com/questions/12037649	Does usage of black [...]
123	https://stackoverflow.com/questions/12120629	What is the power [...]
124	https://stackoverflow.com/questions/12128056	minimum power required algorithm [...]
125	https://stackoverflow.com/questions/12165519	Power efficient video streaming [...]
126	https://stackoverflow.com/questions/12175067	What is the difference [...]
127	https://stackoverflow.com/questions/12296082	How to reduce the [...]
128	https://stackoverflow.com/questions/12332609	OpenCL for GPU vs. [...]
129	https://stackoverflow.com/questions/12424973	How to put the [...]
130	https://stackoverflow.com/questions/12510902	efficient gps service in [...]
131	https://stackoverflow.com/questions/12514078	How to measure the [...]
132	https://stackoverflow.com/questions/12561920	Interpretation of results of [...]
133	https://stackoverflow.com/questions/12581333	Android App power consumption [...]
134	https://stackoverflow.com/questions/12584365	Read power input from [...]
135	https://stackoverflow.com/questions/12764175	Android WebView consumes lots [...]
136	https://stackoverflow.com/questions/12997971	Access to Power consumption [...]
137	https://stackoverflow.com/questions/13007925	Setting On windows' High [...]
138	https://stackoverflow.com/questions/13064468	Explain the statistics of [...]
139	https://stackoverflow.com/questions/13140989	UIViewController persistence - save [...]
140	https://stackoverflow.com/questions/13205453	PubNub long polling vs [...]
141	https://stackoverflow.com/questions/13450388	Best practice for sending [...]
142	https://stackoverflow.com/questions/13558510	image/video processing options [...]
143	https://stackoverflow.com/questions/13574168	Android Power modeling like [...]
144	https://stackoverflow.com/questions/13583357	Reduce power conssumption while [...]
145	https://stackoverflow.com/questions/13584367	Bluetooth Low energy best [...]
146	https://stackoverflow.com/questions/13650503	How to monitor the [...]
147	https://stackoverflow.com/questions/13710725	Can a low-end ARM [...]
148	https://stackoverflow.com/questions/13847229	User's location and battery's [...]
149	https://stackoverflow.com/questions/13873570	Correct way to implement [...]
150	https://stackoverflow.com/questions/14069885	Process or Thread level [...]
151	https://stackoverflow.com/questions/14288772	Measuring and Exporting System [...]
152	https://stackoverflow.com/questions/14473773	Statistics on Location Settings [...]
153	https://stackoverflow.com/questions/14484719	Source code power profiling [...]
154	https://stackoverflow.com/questions/14568453	When to call [clLocationManager [...]
155	https://stackoverflow.com/questions/14573752	windows 8 desktop: bluetooth [...]
156	https://stackoverflow.com/questions/14689214	My Energy Usage Test [...]
157	https://stackoverflow.com/questions/14726783	Simulink - electrical appliances [...]
158	https://stackoverflow.com/questions/14731293	Optimising Firebase's power consumption [...]
159	https://stackoverflow.com/questions/14744506	CLLocationManager Precision and Power [...]
160	https://stackoverflow.com/questions/14771654	Energy Consumed by my [...]
161	https://stackoverflow.com/questions/14930772	How to walk the [...]
162	https://stackoverflow.com/questions/14944110	Working around Windows Store [...]
163	https://stackoverflow.com/questions/14970411	Leading zeros counter [...]
164	https://stackoverflow.com/questions/14997997	Syncronizing Android client with [...]
165	https://stackoverflow.com/questions/15290374	Update information on other [...]
166	https://stackoverflow.com/questions/15373809	Reliable, lightweight communication protocol [...]

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Index	Example	Post Title
167	https://stackoverflow.com/questions/15376135	CoreLocation design best practice [...]
168	https://stackoverflow.com/questions/15627328	CUDA Matrix Multiplication Locks [...]
169	https://stackoverflow.com/questions/15688887	What happens in the [...]
170	https://stackoverflow.com/questions/15698999	Implementing a battery widget [...]
171	https://stackoverflow.com/questions/15731420	Calculating seconds in MATLAB [...]
172	https://stackoverflow.com/questions/15800816	DRAM instrumentation [...]
173	https://stackoverflow.com/questions/15904785	Energy consumption parameter on [...]
174	https://stackoverflow.com/questions/15965885	Is it possible to [...]
175	https://stackoverflow.com/questions/16001625	Running Node and Apache [...]
176	https://stackoverflow.com/questions/16211199	Which motion sensor would [...]
177	https://stackoverflow.com/questions/16225653	ultra low power adders [...]
178	https://stackoverflow.com/questions/16264488	Interface or API to [...]
179	https://stackoverflow.com/questions/16284838	How turning off animation [...]
180	https://stackoverflow.com/questions/16325940	Does Android's requestLocationUpdate() with [...]
181	https://stackoverflow.com/questions/16379458	Android wifi geofence/background location [...]
182	https://stackoverflow.com/questions/16417773	Too much power consumption [...]
183	https://stackoverflow.com/questions/16454066	turn off or stop [...]
184	https://stackoverflow.com/questions/16500703	Execution time issue in [...]
185	https://stackoverflow.com/questions/16618232	Android with GPS and [...]
186	https://stackoverflow.com/questions/16899978	nexus 7 set to [...]
187	https://stackoverflow.com/questions/17257244	Java socket - lost [...]
188	https://stackoverflow.com/questions/17391387	Battery consumption needed for [...]
189	https://stackoverflow.com/questions/17602253	Android app that kills [...]
190	https://stackoverflow.com/questions/17707361	fine granularity nanosleep not [...]
191	https://stackoverflow.com/questions/17722096	what is the low [...]
192	https://stackoverflow.com/questions/17782512	android event for current [...]
193	https://stackoverflow.com/questions/18006071	Any benefits from implementing [...]
194	https://stackoverflow.com/questions/18009420	Exclude WIFI from NETWORK$_PROVIDER$[...]
195	https://stackoverflow.com/questions/18100141	Implications of using GLSurfaceView [...]
196	https://stackoverflow.com/questions/18218698	Processing Power In Python [...]
197	https://stackoverflow.com/questions/18467425	PhoneGap Website Ping [...]
198	https://stackoverflow.com/questions/18538180	Viewing power consumption of [...]
199	https://stackoverflow.com/questions/18730922	How can I prove [...]
200	https://stackoverflow.com/questions/18800599	design pattern for participant [...]
201	https://stackoverflow.com/questions/18909185	Batching requests to minimize [...]
202	https://stackoverflow.com/questions/19033390	NodeJS + SocketIO android [...]
203	https://stackoverflow.com/questions/19061578	PAPI with CUDA power [...]
204	https://stackoverflow.com/questions/19080139	Something Similar to RAPL [...]
205	https://stackoverflow.com/questions/19698124	What is consuming power [...]
206	https://stackoverflow.com/questions/19832346	Save energy while app [...]
207	https://stackoverflow.com/questions/19921104	Best Java IDE for [...]
208	https://stackoverflow.com/questions/19955232	Black out screen like [...]
209	https://stackoverflow.com/questions/20012518	How does Android determine [...]
210	https://stackoverflow.com/questions/20030805	Compute the power consumption(mW) [...]
211	https://stackoverflow.com/questions/20034182	Analyzing Energy in NS-2 [...]
212	https://stackoverflow.com/questions/20059223	Tracking app battery consumption [...]
213	https://stackoverflow.com/questions/20098165	Programmatically get power consumption [...]

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Index	Example	Post Title
214	https://stackoverflow.com/questions/20298991	Does generally RISC processors [...]
215	https://stackoverflow.com/questions/20446113	iOS7: Is it more [...]
216	https://stackoverflow.com/questions/20851818	Why is there a [...]
217	https://stackoverflow.com/questions/21166153	Energy efficient spin loop [...]
218	https://stackoverflow.com/questions/21298965	How to get location [...]
219	https://stackoverflow.com/questions/21428105	Energy-efficient cpu usage in [...]
220	https://stackoverflow.com/questions/21448654	PIC wakeup on ADC [...]
221	https://stackoverflow.com/questions/21636511	what is the difference [...]
222	https://stackoverflow.com/questions/21645992	How to compute the [...]
223	https://stackoverflow.com/questions/21735714	How does CPU frequency [...]
224	https://stackoverflow.com/questions/21917250	Any way to launch [...]
225	https://stackoverflow.com/questions/22065865	Which Wireless communication system [...]
226	https://stackoverflow.com/questions/22211656	CUDA timing kernels - [...]
227	https://stackoverflow.com/questions/22387251	Alternatives to C and [...]
228	https://stackoverflow.com/questions/22535654	How do Android and [...]
229	https://stackoverflow.com/questions/22542713	Calculating energy consumption of [...]
230	https://stackoverflow.com/questions/22626498	Energy efficiency of Android [...]
231	https://stackoverflow.com/questions/22794251	Measure Nexus 4 power [...]
232	https://stackoverflow.com/questions/22816089	SensorManager: One SensorEventListener VS [...]
233	https://stackoverflow.com/questions/22827907	How to use Powertop [...]
234	https://stackoverflow.com/questions/22914385	Creating reusable widgets with [...]
235	https://stackoverflow.com/questions/22963253	Using gpsctl to put [...]
236	https://stackoverflow.com/questions/23190179	Will Bluetooth 4.0 actually [...]
237	https://stackoverflow.com/questions/23306543	Can the C preprocessor [...]
238	https://stackoverflow.com/questions/23385052	Application doesn't work properly [...]
239	https://stackoverflow.com/questions/23487728	Ethernet disabling in raspberry [...]
240	https://stackoverflow.com/questions/23524878	How to make Virtual [...]
241	https://stackoverflow.com/questions/23530846	Power consumed by GUI [...]
242	https://stackoverflow.com/questions/23560949	Android LocationListener for a [...]
243	https://stackoverflow.com/questions/23617388	How to select element [...]
244	https://stackoverflow.com/questions/23689510	Timer Coalescing before Windows [...]
245	https://stackoverflow.com/questions/24046742	OS X: Energy Efficient [...]
246	https://stackoverflow.com/questions/24156162	Android App power consumption [...]
247	https://stackoverflow.com/questions/24205021	Most efficient way to [...]
248	https://stackoverflow.com/questions/24270679	Microcontroller for EEG data [...]
249	https://stackoverflow.com/questions/24341874	Line size in LibGDX [...]
250	https://stackoverflow.com/questions/24411859	Does the Nest API [...]
251	https://stackoverflow.com/questions/24450144	Battery Power Consumption between [...]
252	https://stackoverflow.com/questions/24507714	How to ues "dumpsys [...]
253	https://stackoverflow.com/questions/24555572	Is there a way [...]
254	https://stackoverflow.com/questions/24626501	Correct way to implement [...]
255	https://stackoverflow.com/questions/24759633	Bluetooth Low Energy Alert [...]
256	https://stackoverflow.com/questions/24817646	Whether using mipmap technique [...]
257	https://stackoverflow.com/questions/24831813	Detailed battery usage - [...]
258	https://stackoverflow.com/questions/24918101	Understanding cpu frequency, thread [...]
259	https://stackoverflow.com/questions/24935152	Bluetooth Low Energy (BLE) [...]
260	https://stackoverflow.com/questions/25025151	How to make UIImageView [...]

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Index	Example	Post Title
261	https://stackoverflow.com/questions/25245270	calculate process mean with [...]
262	https://stackoverflow.com/questions/25302011	Does OpenGL ES drain [...]
263	https://stackoverflow.com/questions/25304441	Android ”Polling” Bluetooth vs [...]
264	https://stackoverflow.com/questions/25315661	iOS: How to discover [...]
265	https://stackoverflow.com/questions/25337479	Energy efficiency in unity3d [...]
266	https://stackoverflow.com/questions/25419489	cudaGetDevice function what does [...]
267	https://stackoverflow.com/questions/25467037	Java Operations that will [...]
268	https://stackoverflow.com/questions/25566166	Will it be a [...]
269	https://stackoverflow.com/questions/25680367	How is generating PWM [...]
270	https://stackoverflow.com/questions/25693408	Time1 Interrupt wakes up [...]
271	https://stackoverflow.com/questions/25797756	What is the difference [...]
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