Energy Management for Energy Harvesting-Based Embedded Systems: A Systematic Mapping Study

Review Article

Energy Management for Energy Harvesting-Based Embedded Systems: A Systematic Mapping Study

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Energy management for energy harvesting-based embedded systems (EHES) is an emerging field, which aims to collect renewable energy from the environment to power an embedded system. In this work, we use the systematic mapping method to study the relevant literature, with the objective of exploring and analysing the state of the art in energy management for EHES, as well as to provide assistance for subsequent literature reviews. To this end, we conducted extensive searches to find articles related to energy harvesting, embedded systems, energy consumption, and energy management. We searched for papers from January 2005 to July 2019 from three mainstream databases, ACM, IEEE Xplore, and Web of Science, and found more than 3000 papers about EHES. Finally, we selected 142 eligible papers. We have completed the system mapping research from five aspects, namely, (1) research type (validation research, evaluation research, solution proposal, philosophical paper, opinion, and experience), (2) research goals (application or theory), (3) application scenarios, (4) tools or methods, and (5) paper distribution, such as publication year and authors’ nationality. The results showed that the major research type of the EHES papers is validation research, accounting for 65%, which indicated research is still in the theoretical stage and many researchers focus on how to improve the efficiency of harvesting energy, develop a reasonable energy supply plan, and adapt EHES for real-world requirements. Furthermore, this work reviews the tools used for EHES. As the future development direction, it is indispensable to provide tools to EHES for research, testing, development, and so on. The results of our analysis provide significant contributions to understanding the existing knowledge and highlighting potential future research opportunities in the EHES field.

1. Introduction

With an increase of network speed and hardware computing capabilities, many recent studies have focused on IoT and AI. The number of intelligent terminals, which are essential for the Internet of Things and artificial intelligence, has risen rapidly [1, 2]. Most terminal devices are battery-powered. Therefore, the arbitrary use of such devices will reduce battery life which, in turn, decides the terminal life. In this situation, some solutions have been proposed to reduce energy consumption, to a certain extent, such as dynamic voltage and frequency scaling (DVFS) [3–5] and dynamic power management [6–8]. In some cases, it is difficult to recharge or change the battery; for example, in the biomedical field, implants are mainly powered by batteries with capacities limited by physical size constraints. One method to address this issue is to use rechargeable batteries. The most common recharging method used in medical devices utilizes inductive coupling, but this has disadvantages; for example, when the user needs to charge, they must place the external charging device very close to the implanted device [9, 10]. In order to address this issue, researchers have used the renewable energy of the surrounding environment to harvest energy (e.g., a photovoltaic array embedded under the eye’s conjunctiva converts incident solar energy into electrical energy to be stored in a battery [10]). Energy harvesting technologies can be used to power embedded devices and replenish the energy of batteries in embedded devices, thus extending their running time. An embedded system with energy harvesting technology is referred to as EHES. An
EHES converts renewable energy into electricity to power the system. Due to the unpredictability of the environment (e.g., a period of overcast/rain, or solar power not being available during the night), the harvesting of energy is also uncertain. As shown in Figure 1, if the energy available from a renewable source is higher than the required energy of a system, then the system can function without any energy from the battery. If the situation is exactly the opposite, as shown by the shaded regions in Figure 1, additional energy needs to be extracted from the battery to ensure the sustained operation of the embedded system. Moreover, some power strategies, task scheduling strategies, and battery storage strategies are imperfect, resulting in considerable energy consumption of the devices which, then, need frequent charging. This indicates the energy consumption and energy storage of EHES is the main problem in the future development of this domain. Compared with battery-powered embedded devices, energy harvesting embedded devices collect renewable energy from the ambient environment, which can effectively eliminate the demand for battery replacement.

In order to summarize the research status of a special research field and explore the researchable directions within it, a literature review is required. However, researchers in the field of software engineering (SE) usually do not follow a systematic approach when conducting literature research. At present, several guidelines have been proposed to conduct literature research, such as systematic mapping study (SMS) or systematic literature review (SLR) [12–17]. The SMS provides a superficial overview of a certain field, such as the number of research works published in the field and their classification, which is usually done graphically. An SMS helps the reviewer to find research topics in specific fields, as well as contributing to better follow-up research such as SLR. Compared with SMS, SLR can conduct further literature research through an in-depth analysis of selected works. Therefore, SLR is an extension of SMS. In this work, we use SMS with a focus on providing an overview of EHES, identifying research evidence for this topic, and presenting mainly quantitative results [13, 14]. We conducted this work to answer five different research questions about EHES and to collect relevant research by snowballing [18]. We classified the research based on research types, research objectives, application scenarios, tools, methods, and publication venues and collected the required data by reading titles, abstracts, keywords, and full texts. Considering that energy management is significant for EHES, it is necessary to conduct a systematic analysis to develop a comprehensive understanding for this topic’s research and practice. As far as we know, there currently exist no literature reviews which fill this gap. This work, therefore, provides researchers with a study of the practices within this domain over the past fifteen years.

We focus on exploring and analysing the state of the art in energy management for EHES. The remainder of this paper is organized as follows: the SMS is described in Section 2. In Section 3, we present the study results and answer the research questions. And in Section 4, we present the future challenges of the EHES. Finally, we conclude the work in Section 5.

2. The Systematic Mapping Processes

In this section, we follow the systematic mapping process, as defined in the guidelines provided by Petersen et al. [13, 14].

As shown in Figure 2, there are five steps in the SMS. First, the review scope is obtained by the definition of the research question. Second, a search is conducted to find all papers within this scope. Third, relevant papers are found in this field by screening the found papers. Then, by reading the abstracts and looking for keywords and concepts which reflect the contributions of the papers, they are combined to form an understanding of the nature and contributions of the research, thus forming a classification scheme. Finally, with the abovementioned classification scheme, relevant papers are classified in the scheme, and data are extracted. Using the data to analyse each category, the systematic map is presented by means of mapping.

2.1. Research Questions. The overall goal of this SMS is to determine the research type, research objectives, application scenarios, tools, methods, and publications relating to EHES since 2005. This objective led to the following questions:

(i) RQ1: what type of research has been carried out in the research period and how has it developed?
Rationale: popular research types can provide researchers with research trends and future forms of development in the field, as well as which directions provide open areas for research. Our focus is to find the most popular research trends in these years by studying these studies.

(ii) RQ2: what are the research goals?
Rationale: our focus is to group selected studies, according to different research objectives.

(iii) RQ3: what are the application scenarios for the energy management of EHES?
Rationale: our focus is to find popular application scenarios for the energy management of EHES.
(iv) RQ4: how many tool papers and method papers were proposed?
Rationale: our aim is to find out the tool and method papers which can be used by other researchers in their studies.

(v) RQ5: how are the papers distributed?
Rationale: our focus is to find the publication year, type of publication, and author information for the papers.

2.2. Study Collection and Study Screening. In the process of search and selection, we will encounter some problems:

(1) How to search?
First, we needed to select the approximate database range and find the query rules for searching the databases. Then, we determined a query sentence and, finally, conducted the preliminary search. The trial search helped us to find appropriate search databases and search methods. As different databases employ search engines with different search capabilities, we needed a generic query statement, for example, which was expressed as “(embedded systems) AND (energy harvesting)”; however, searching with this method did not allow us to determine whether the papers were what we needed. Therefore, we required further screening.

(2) How to select?
Usually, if reading the title does not indicate the core meaning of the paper, it is necessary to read the abstract of the paper. In some cases (e.g., after reading the title and abstract, we still did not understand the core meaning of the paper), we were required to read the full text or conclusions. In the formal selection, we needed to formulate selection criteria.

2.2.1. Detailed Process. The search and selection process had four steps, as shown in Figure 3.

(i) Step 1: searching for papers in databases. We chose three relatively popular databases for our subject field (see Table 1) and searched for relevant papers using the query statement.

(ii) Step 2: conducting the first round of screening by reading the titles and abstracts of the results of Step 1 search.

(iii) Step 3: if only reading the title and abstract did not indicate the screened paper’s core meaning in Step 2, then we read the full text.

(iv) Step 4: using the method of snowballing [18] to screen the references in the results of Step 3. Then, we repeated Steps 2–4 for the screened papers.

2.2.2. Search Scope. We used three authoritative and well-known databases in our field—IEEE, ACM, and WOS—for this paper collection. Google Scholar was not included in the database search, as its search results may have considerable overlap with other databases and it had insufficient accuracy for our purposes. The research period was set from January 2005 to July 2019. As far as we know, no paper exists which can serve as a milestone in this domain, as this topic is broad and extensive. Therefore, considering that 15 years is a reasonable time for systematic mapping research, we started our search in 2005.

2.2.3. Search Query. To conduct a SMS, building a search string is very important, and thus, we used the PICO
model proposed by Petersen et al. [14] to build the search string, where the population is a specific SE role, type, or application area; interventions are software technologies or methodologies to address specific issues in SE; comparison determines the technologies, techniques, tools, methods, or strategies to be extracted and compared; and outcomes are the influencing factors of the intervention on the practitioners. As shown in Table 2, for each component of the PICO model, we determined many sentences that described the learning topic. We used the guidelines proposed by Petersen et al. [14] to extract keywords. Table 3 shows the keywords extracted with the PICO model.

Boolean "OR" is used to connect synonyms and Boolean "AND" is used to connect terms. The statement of our query was expressed as "(design OR development) AND (embedded systems) AND (energy OR harvesting OR energy harvesting) AND (energy storage) AND (energy efficiency) AND (application OR tool OR method) AND (energy management OR life)."

2.2.4. Search Criteria. In the guidelines of Petersen et al. [13], they pointed out that it is important to determine whether the study meets the necessary characteristics in order to be included or excluded from the SMS. Using this guide as a basis, the following criteria for inclusion and exclusion should be considered when selecting papers:

Inclusion criteria:
(i) The paper offers a new approach or improvements for the energy management of EHES (e.g., energy consumption, use of energy, and collection of energy)
(ii) The paper only has an abstract without full text
(iii) The paper is a poster or book
(iv) The paper only mentions the term energy harvesting
(v) The paper only introduces a new collection method which does not specify its energy management
(vi) The paper only introduces a new energy harvesting embedded system

Exclusion criteria:
(i) The paper only has an abstract without full text
(ii) The paper is a poster or book
(iii) The paper only mentions the term energy harvesting
(iv) The paper is not in English
(v) The paper only introduces a new collection method which does not specify its energy management
(vi) The paper only introduces a new energy harvesting embedded system

2.3. Study Classification. In this section, we followed the guidelines provided by Petersen et al. [13]. We used abstracts and keywords from collection-related research to classify research. In this work, we have classified the research into five different categories depending on the research questions. The taxonomy of the related article is shown in Figure 4.

### 2.3.1. Research Types Classification

We chose an existing classification framework by Wieringa et al. [19] to classify the selected papers. The categories do not require a detailed evaluation of each paper and, thus, are easy to interpret and classify. For example, for research works that were not implemented in practice, evaluation research can be excluded. Moreover, validation research can easily be determined, which only requires checking whether the paper states hypotheses or experimental design is a main component of the paper. In addition, the framework also classifies study into solution proposal paper, philosophical papers, opinion papers, and experience papers:

(i) A validation research paper is a paper which was not implemented in practice, instead of addressing issues through lab experiments, analysis, and design.

(ii) An evaluation research paper evaluates research works that were implemented in practice, indicating the advantages and disadvantages of these research works in the implementation process and the final result. Usually, industrial studies fall into this category.

(iii) A solution proposal paper provides an improvement to an existing solution or proposes a new technology.

(iv) A philosophical paper introduces a new way of looking at existing things or a new conceptual framework.

(v) An opinion paper provides someone's personal opinion on technology, tool, or method.

(vi) An experience paper details an author's personal experience of technology, tool, or method.

### 2.3.2. Research Goals Classification

We identified the overall goals of the research and divided them into the following four categories:

(i) Energy harvesting and conversion strategies for EHES

(ii) Task scheduling strategies for EHES

(iii) Better strategies for battery storage to maintain battery life

(iv) Using EHES independently by the use of energy harvesting technology
2.3.3. Application Scenarios Classification. We identified the following application scenarios, based on all studies:

(i) Building: the EHES provides energy for building or road structure health monitoring systems

(ii) Medical: the energy harvesting embedded system can power some devices which are transplanted in the human body

(iii) Machine: the energy harvesting embedded system can provide energy for machine component health monitoring or power for certain control systems

(iv) Wearable equipment: the collection of vibrational energy, thermal energy, and so on can be converted into electrical energy for monitoring systems of certain wearable equipment or for the life of the equipment

2.3.4. Tool Papers and Method Papers Classification. Papers are divided into energy management tool papers and papers that can effectively improve energy consumption, energy harvesting, and energy storage technologies or improve on existing methods to improve efficiency.

2.3.5. Distribution Classification. We used a general classification scheme for publication venue types, publishers, publication year, and authors’ nationality. Usually, venue categories are divided into international journals, international conferences, seminars, and others.

2.4. Data Extraction and Study Mapping. We answered the research questions presented above and used an Excel table to extract data from each selected study. The form fields included the research type to answer RQ1; research goals to answer RQ2; application scenario details (if any) to answer RQ3; method and tool details (if any) to answer RQ4; and year of publication, publication venue, and publisher to answer RQ5. After reading each research paper, we filled out the data form. The specific extraction results are shown in Table 4. Finally, the research was mapped to the above classification definitions, and the research frequency under each classification was visualized in the form of a graph.

3. Result

3.1. Search Selection and Snowballing Results. As shown in Figure 3, 3584 papers were retrieved from the three databases during the database search. After the first round of screening, 223 papers were retained. After the second round of screening, 124 papers were retained and 18 papers were determined by snowballing [18]. Finally, a total of 142 papers were selected.

3.2. RQ1: What Type of Research Has Been Carried Out in the Research Period and How Has It Developed? Our focus was to discover the popular research types in 2005–2019. As shown in Figure 3, the most frequent research type was validation research, accounting for 65% of papers (92 out of 142), followed by solution proposals, accounting for 22% of papers (31 out of 142); 12% (18 out of 142) of research papers were evaluation research, and 1% (1 out of 142) were experience papers. No opinion or philosophical papers were found.

As shown in Figure 5, the number of validation research studies published since 2009 has increased, and it is important to note that more than 50% of published papers were in this category. This shows the importance of energy management for EHES in lab experiments. Meanwhile, the number of solution proposals, as shown in Figure 6, was not much; this indicates that most technologies have not been implemented in practice. The articles of validation research and solution proposal occupied 87% of the research types and, so, researchers can easily select papers to conduct SLR.
| ID | Ref | Research type       | Research goal | Application scenario | Tool or method | Year | Publish type | Publisher |
|----|-----|---------------------|---------------|----------------------|----------------|------|--------------|-----------|
| 1  | [20]| Validation research | Application    | —                    | Tool           | 2019 | Journal      | Others    |
| 2  | [21]| Evaluation research | Power strategy | —                    | Method         | 2019 | Journal      | Springer  |
| 3  | [22]| Validation research | Energy schedule | —                    | —              | 2019 | Journal      | IEEE      |
| 4  | [23]| Validation research | Energy schedule | —                    | Method         | 2019 | Conferences  | ACM       |
| 5  | [24]| Validation research | Energy schedule | —                    | Method         | 2019 | Journal      | ACM       |
| 6  | [25]| Solution proposal  | Application    | Building            | —              | 2019 | Journal      | Others    |
| 7  | [26]| Solution proposal  | Application    | —                    | —              | 2019 | Journal      | Others    |
| 8  | [27]| Solution proposal  | Application    | Machine             | —              | 2018 | Journal      | Wiley     |
| 9  | [28]| Validation research | Application    | Machine             | —              | 2018 | Conferences  | IEEE      |
| 10 | [29]| Solution proposal  | Harvest strategy| —                    | Method         | 2018 | Conferences  | ACM       |
| 11 | [30]| Validation research | Application    | —                    | Tool           | 2018 | Conferences  | ACM       |
| 12 | [31]| Validation research | Application    | Wearable equipment  | —              | 2018 | Symposium    | IEEE      |
| 13 | [32]| Experience papers  | Application    | —                    | —              | 2018 | Conferences  | IEEE      |
| 14 | [33]| Validation research | Application    | Machine             | —              | 2018 | Journal      | IEEE      |
| 15 | [34]| Validation research | Application    | Building            | —              | 2018 | Conferences  | Springer  |
| 16 | [35]| Validation research | Energy schedule | —                    | Method         | 2018 | Conferences  | IEEE      |
| 17 | [36]| Solution proposal  | Energy schedule | —                    | Method         | 2018 | Conferences  | IEEE      |
| 18 | [37]| Validation research | Application    | Machine             | —              | 2018 | Conferences  | IEEE      |
| 19 | [38]| Evaluation research | Harvest strategy| Machine             | —              | 2018 | Journal      | Others    |
| 20 | [39]| Validation research | Harvest strategy| —                    | —              | 2018 | Journal      | Others    |
| 21 | [40]| Solution proposal  | Application    | Wearable equipment  | Method         | 2017 | Conferences  | ACM       |
| 22 | [41]| Solution proposal  | Application    | Machine             | Method         | 2017 | Conferences  | IEEE      |
| 23 | [42]| Validation research | Power strategy  | —                    | Tool           | 2017 | Conferences  | IEEE      |
| 24 | [43]| Validation research | Energy schedule | —                    | Method         | 2017 | Journal      | Others    |
| 25 | [44]| Validation research | Energy schedule | —                    | Method         | 2017 | Conferences  | IEEE      |
| 26 | [45]| Validation research | Power strategy  | —                    | Method         | 2017 | Journal      | ACM       |
| 27 | [46]| Evaluation research | Energy schedule | —                    | Method         | 2017 | Conferences  | IEEE      |
| 28 | [47]| Solution proposal  | Harvest strategy| —                    | —              | 2017 | Journal      | Others    |
| 29 | [48]| Validation research | Application    | Machine             | —              | 2016 | Journal      | Others    |
| 30 | [49]| Solution proposal  | Application    | Medical             | —              | 2016 | Conferences  | Others    |
| 31 | [50]| Validation research | Application    | Building            | Method         | 2016 | Journal      | Others    |
| 32 | [51]| Validation research | Power strategy  | —                    | Method         | 2016 | Conferences  | IEEE      |
| 33 | [52]| Validation research | Energy schedule | —                    | Method         | 2016 | Journal      | Others    |
| 34 | [53]| Validation research | Energy schedule | —                    | Method         | 2016 | Journal      | Others    |
| 35 | [54]| Validation research | Harvest strategy| —                    | Method         | 2015 | Conferences  | IEEE      |
| 36 | [55]| Validation research | Energy schedule | —                    | Method         | 2015 | Conferences  | IEEE      |
| 37 | [56]| Validation research | Harvest strategy| —                    | Method         | 2015 | Conferences  | ACM       |
| 38 | [57]| Validation research | Application    | Wearable equipment  | Method         | 2015 | Conferences  | IEEE      |
| 39 | [58]| Validation research | Application    | Medical             | —              | 2015 | Conferences  | IEEE      |
| 40 | [59]| Validation research | Energy schedule | —                    | Method         | 2015 | Conferences  | IEEE      |
| 41 | [60]| Solution proposal  | Energy schedule | —                    | Method         | 2015 | Journal      | IEEE      |
| 42 | [61]| Validation research | Application    | Wearable equipment  | —              | 2015 | Journal      | IEEE      |
| 43 | [62]| Validation research | Energy schedule | —                    | Method         | 2014 | Conferences  | ACM       |
| 44 | [63]| Validation research | Energy schedule | —                    | Method         | 2014 | Conferences  | IEEE      |
| 45 | [64]| Validation research | Energy schedule | —                    | Method         | 2014 | Journal      | IEEE      |
| 46 | [65]| Solution proposal  | Energy schedule | —                    | Method         | 2014 | Journal      | IEEE      |
| 47 | [66]| Validation research | Application    | Wearable equipment  | —              | 2014 | Conferences  | IEEE      |
| 48 | [67]| Validation research | Harvest strategy| —                    | Tool           | 2014 | Conferences  | ACM       |
| 49 | [68]| Evaluation research | Harvest strategy| —                    | Method         | 2014 | Journal      | IEEE      |
| 50 | [69]| Validation research | Application    | Building            | —              | 2014 | Conferences  | Others    |
| 51 | [70]| Validation research | Harvest strategy| —                    | Method         | 2014 | Conferences  | IEEE      |
| 52 | [71]| Solution proposal  | Energy schedule | —                    | Method         | 2014 | Symposium    | ACM       |
| 53 | [72]| Solution proposal  | Application    | Wearable equipment  | —              | 2014 | Journal      | Others    |
| 54 | [73]| Evaluation research | Application    | Building            | —              | 2014 | Journal      | Springer  |
| 55 | [74]| Validation research | Energy schedule | —                    | Method         | 2013 | Symposium    | IEEE      |
| 56 | [75]| Solution proposal  | Energy schedule | —                    | Method         | 2013 | Conferences  | IEEE      |
| 57 | [76]| Validation research | Application    | Machine             | —              | 2013 | Conferences  | Others    |
| ID | Ref | RQ1 Research type | RQ2 Research goal | RQ3 Application scenario | RQ4 Tool or method | RQ5 Year | Publish type | Publisher |
|----|-----|------------------|------------------|--------------------------|------------------|----------|-------------|------------|
| 60 | [77] | Evaluation research | Application | Machine | Tool | 2013 | Journal | ACM |
| 61 | [78] | Validation research | Application | Building | — | 2013 | Workshop | IEEE |
| 62 | [79] | Validation research | Harvest strategy | — | Method | 2013 | Journal | Others |
| 63 | [80] | Validation research | Power strategy | — | Method | 2013 | Journal | Others |
| 64 | [81] | Validation research | Energy schedule | — | — | 2013 | Journal | Others |
| 65 | [82] | Validation research | Application | Building | — | 2013 | Journal | Others |
| 66 | [83] | Validation research | Application | Machine | — | 2013 | Journal | Others |
| 67 | [84] | Validation research | Application | Building | — | 2013 | Conferences | IEEE |
| 68 | [85] | Solution proposal | Harvest strategy | — | Method | 2013 | Workshop | ACM |
| 69 | [86] | Validation research | Application | Medical | — | 2013 | Journal | Others |
| 70 | [87] | Evaluation research | Power strategy | — | Method | 2013 | Workshop | ACM |
| 71 | [88] | Validation research | Harvest strategy | — | — | 2013 | Conferences | IEEE |
| 72 | [89] | Evaluation research | Harvest strategy | — | Method | 2013 | Conferences | IEEE |
| 73 | [90] | Validation research | Application | Building | — | 2013 | Journal | Others |
| 74 | [91] | Solution proposal | Harvest strategy | — | Method | 2013 | Journal | ACM |
| 75 | [92] | Validation research | Application | — | Method | 2012 | Journal | IEEE |
| 76 | [93] | Validation research | Energy schedule | — | Method | 2012 | Conferences | IEEE |
| 77 | [94] | Solution proposal | Energy schedule | — | Method | 2012 | Conferences | IEEE |
| 78 | [95] | Validation research | Application | Medical | Tool | 2012 | Conferences | IEEE |
| 79 | [96] | Validation research | Application | Machine | Tool | 2012 | Journal | Others |
| 80 | [97] | Validation research | Energy schedule | — | Method | 2012 | Conferences | IEEE |
| 81 | [98] | Evaluation research | Harvest strategy | — | Method | 2012 | Conferences | IEEE |
| 82 | [99] | Validation research | Harvest strategy | — | Method | 2012 | Journal | Others |
| 83 | [100] | Evaluation research | Harvest strategy | — | Method | 2012 | Journal | IEEE |
| 84 | [101] | Validation research | Application | — | Method | 2012 | Conferences | IEEE |
| 85 | [102] | Validation research | Energy schedule | — | Method | 2012 | Journal | IEEE |
| 86 | [103] | Validation research | Energy schedule | — | Method | 2011 | Conference | IEEE |
| 87 | [104] | Validation research | Energy schedule | — | Method | 2011 | Journal | Others |
| 88 | [105] | Validation research | Energy schedule | — | Method | 2011 | Conference | IEEE |
| 89 | [106] | Validation research | Application | Wearable equipment | — | 2011 | Journal | Others |
| 90 | [107] | Solution proposal | Energy schedule | — | Method | 2011 | Conferences | ACM |
| 91 | [108] | Validation research | Harvest strategy | — | Method | 2011 | Workshop | IEEE |
| 92 | [109] | Validation research | Energy schedule | — | Method | 2011 | Journal | Others |
| 93 | [110] | Validation research | Harvest strategy | — | Method | 2011 | Conference | IEEE |
| 94 | [111] | Solution proposal | Energy schedule | — | Method | 2011 | Conference | IEEE |
| 95 | [112] | Validation research | Application | — | Tool | 2011 | Journal | IEEE |
| 96 | [113] | Solution proposal | Energy schedule | — | Method | 2011 | Conference | Springer |
| 97 | [114] | Evaluation research | Application | Building | — | 2011 | Symposium | IEEE |
| 98 | [115] | Evaluation research | Application | Building | — | 2011 | Journal | Others |
| 99 | [116] | Evaluation research | Harvest strategy | — | — | 2011 | Journal | Springer |
| 100 | [117] | Validation research | Harvest strategy | — | — | 2010 | Conferences | ACM |
| 101 | [118] | Validation research | Harvest strategy | — | Method | 2010 | Journal | Others |
| 102 | [119] | Validation research | Application | Building | — | 2010 | Journal | Others |
| 103 | [120] | Validation research | Application | Wearable equipment | — | 2010 | Conferences | IEEE |
| 104 | [121] | Validation research | Energy schedule | — | Method | 2010 | Conferences | IEEE |
| 105 | [122] | Validation research | Energy schedule | — | Method | 2010 | Journal | ACM |
| 106 | [123] | Validation research | Application | Machine | — | 2010 | Workshop | ACM |
| 107 | [124] | Validation research | Energy schedule | — | Method | 2010 | Journal | ACM |
| 108 | [125] | Validation research | Energy schedule | — | Method | 2010 | Journal | Others |
| 109 | [126] | Solution proposal | Harvest strategy | — | Method | 2010 | Conferences | IEEE |
| 110 | [127] | Validation research | Application | Building | — | 2010 | Journal | ACM |
| 111 | [128] | Validation research | Harvest strategy | — | Method | 2009 | Others | Others |
| 112 | [129] | Validation research | Harvest strategy | — | Method | 2009 | Journal | Others |
| 113 | [130] | Validation research | Harvest strategy | — | Method | 2009 | Journal | IEEE |
| 114 | [131] | Validation research | Harvest strategy | — | Method | 2009 | Conference | IEEE |
| 115 | [132] | Validation research | Application | Machine | — | 2009 | Journal | IEEE |
| 116 | [133] | Solution proposal | Energy schedule | — | Method | 2009 | Symposium | ACM |
| 117 | [134] | Validation research | Application | Machine | — | 2009 | Conference | IEEE |
| 118 | [135] | Validation research | Energy schedule | — | Method | 2009 | Conference | ACM |
| 119 | [136] | Validation research | Harvest strategy | Building | Method | 2008 | Conferences | IEEE |
| 120 | [137] | Solution proposal | Harvest strategy | — | Tool | 2008 | Conferences | IEEE |
fB_herewasonlyonesolutionproposalin2005–2019,which
was published in 2018, and there were no opinion or
philosophicalpapersintheseyears.Inthefuture, researchers
need to provide more opinions, experience, and unique
insights into this field. Future researchers need to apply ideas
in practice to make the field more mature, like other fields.

3.3. RQ2: What Are the Research Goals? We identified four
principal research goals, based on all selected studies. The first
involved the method of collecting energy, which mainly
studied novel methods to enhance the energy conversion rate
or how to improve existing methods to enhance the energy
conversion rate or increase energy harvesting efficiency. The
second was about energy scheduling, involving how to ef-
fectively use the collected energy to supply the system to run
and store power. The third was about battery strategies, which
are important for the efficiency of battery storage. The fourth
was about applications, focusing on using a variety of re-
newable energies to drive some sensors or support autono-
mous supply systems to achieve permanent operations.

There was only one solution proposal in 2005–2019, which
was published in 2018, and there were no opinion or
philosophical papers in these years. In the future, researchers
need to provide more opinions, experience, and unique
insights into this field. Future researchers need to apply ideas
in practice to make the field more mature, like other fields.

As shown in Figure 7, 31% of papers focused on energy
scheduling (see, e.g., [52, 59, 62, 65, 97, 107]), such as
studying how to combine energy-constrained scheduling
algorithms with the introduction of an energy harvesting
unit; 28% of papers focused on energy harvesting methods
(see, e.g., [29]), such as using reinforcement learning (RL) to
automatically configure a device to maximize energy storage
or minimize energy consumption as much as possible (see,
e.g., [23, 29, 36, 45]). Since the energy harvesting by EHES is
affected by geographic location and the surrounding envi-
rionment, the collected data are different. If researchers use
public datasets or publish data, the results may be replicated,
but it is more difficult to replicate if they are not public.
Unfortunately, since the authors in [29, 36, 45] did not have
public data, we could not fully replicate the results. Reference
[23] requires a certain hardware foundation, we cannot
build an experimental environment, and the results also
cannot be replicated; 4% of papers considered power
strategies (see, e.g., El Ghor and Chetto [160]), such as
proposing an energy guarantee dynamic voltage and fre-
quency scaling (EG-DVFS) algorithm which, compared with

| ID | Ref | RQ1 Research type | RQ2 Research goal | Application scenario | RQ3 Year | Publish type | Publisher |
|----|-----|-------------------|------------------|----------------------|--------|--------------|----------|
| 121 | [138] | Solution proposal | Harvest strategy | — | Method | 2008 | Conferences | IEEE |
| 122 | [139] | Solution proposal | Harvest strategy | — | Tool | 2008 | Journal | Others |
| 123 | [140] | Validation research | Energy schedule | — | Method | 2008 | Conferences | IEEE |
| 124 | [141] | Validation research | Application | Building | — | 2008 | Journal | Others |
| 125 | [142] | Evaluation research | Harvest strategy | — | Method | 2008 | Conferences | Others |
| 126 | [143] | Solution proposal | Harvest strategy | — | — | 2008 | Conferences | IEEE |
| 127 | [144] | Validation research | Application | — | Method | 2008 | Conferences | IEEE |
| 128 | [145] | Validation research | Application | Medical | Tool | 2007 | Symposium | IEEE |
| 129 | [146] | Validation research | Application | — | Method | 2007 | Symposium | IEEE |
| 130 | [147] | Solution proposal | Energy schedule | — | Method | 2007 | Journal | ACM |
| 131 | [148] | Validation research | Application | Machine | — | 2007 | Journal | Others |
| 132 | [149] | Validation research | Harvest strategy | — | Method | 2007 | Conferences | IEEE |
| 133 | [150] | Validation research | Harvest strategy | — | Method | 2007 | Symposium | IEEE |
| 134 | [151] | Solution proposal | Harvest strategy | — | Method | 2007 | Symposium | ACM |
| 135 | [152] | Evaluation research | Energy schedule | — | Method | 2006 | Conferences | ACM |
| 136 | [153] | Solution proposal | Harvest strategy | — | — | 2006 | Symposium | ACM |
| 137 | [154] | Solution proposal | Application | Building | Method | 2005 | Conferences | AMC |
| 138 | [155] | Validation research | Application | Wearable equipment | — | 2005 | Journal | IEEE |
| 139 | [156] | Validation research | Energy schedule | — | Method | 2005 | Conferences | ACM |
| 140 | [157] | Validation research | Harvest strategy | — | Method | 2005 | Conferences | ACM |
| 141 | [158] | Evaluation research | Harvest strategy | — | Tool | 2005 | Symposium | ACM |
| 142 | [159] | Evaluation research | Application | — | — | 2005 | Journal | IEEE |

Table 4: Continued.

| RQ5 Publish type | Publisher |
|----------------|-----------|
| Conference... | IEEE |
| Journal... | Others |
| Symposium... | ACM |
| IEEE |

Figure 5: The number of research types per year.
the earliest deadline-harvesting (ED-H) scheduling algorithm, could save up to 33% capacity, while the remaining 37% was applied research. It is worth noting that energy management accounted for a large part of the papers. There has been little research into applications; however, since 2013, the number of research papers concentrated on applications has been increasing. Hence, we believe that applications will become a main focus in this field and, so, energy management still has great potential.

Another important point is to determine the most appropriate method for each research goal, as shown in Figure 8. As the most popular type of research in the four categories was validation research, and as many validation research and solution proposal papers relate to applications, this indicates that the research type most suitable for energy management is validation research, followed by solution proposal research.

### 3.4. RQ3: What Are the Application Scenarios for the Energy Management of EHES?

A total of 32% (45 out of 142) of the 142 papers described application scenarios. As shown in Figure 9, wearable equipment accounted for 20% (9 out of 45), medicine accounted for 11% (5 out of 45), buildings accounted for 36% (16 out of 45), and machines accounted for 33% (15 out of 45).

The theme of wearable equipment mainly included shoes, watches, glasses, and some equipment which pays attention to human health. These devices are powered by the vibrational energy or radiated heat generated by human activity. The theme of medicine is mainly concerned with devices implanted in the human body; for example, Murali et al. [10] proposed a solar energy harvesting power device for use with ocular implants. The theme of buildings mainly considers the monitoring of structural health or collection of information from bridges, buildings, and road, among others; for example, Jasim et al. [25] proposed energy harvesting from piezoelectric modules in asphalt pavement. The machine topic focuses on vehicles, airplanes, and so on, monitoring the health of parts of these machines or providing energy for certain systems in their parts which operate separately; for example, Yaqub and Heidary [38] proposed embedding a piezoelectric material inside of electric vehicle (EV) tyres to mathematically model harvested energy, as well as to collect and process mechanical stress data. The number of research papers in the medicine, building, and machine themes from 2005 to 2019 remained relatively stable, indicating that these three themes have not had much breakthrough research in recent years.

### 3.5. RQ4: How Many Tool Papers and Method Papers Were Proposed?

From 2005 to 2019, a total of 12 tool papers and 81 method papers were published. Our focus was on finding tool papers and method papers which can help other researchers in this field in the future.

In the 12 tool papers found, their purpose was to run an embedded system for a long time and provide energy. Introduced in these papers, most notably, were Heliomote, a plug-and-play solar energy harvesting module [158], and a microscale energy harvesting simulation tool [112]. An important finding here is that most tool papers were designed for energy management or monitoring system status. This demonstrates the importance of health- and energy-related issues when the collection system is running. Of the 81 method papers found, the main purposes were (1) to manage the energy of the system itself, in order to ensure long-time operations and (2) to improve the conversion rate between renewable energy and electric energy. The most notable contributions of these papers included Hibernus [64], a new approach for sustaining computation under intermittent supply; a scheduling algorithm [105, 122, 125]; and dynamic voltage and frequency scaling [5]. An important finding here is that most method papers have been carried out through a large number of simulation experiments, and few algorithms have been implemented in practice. This demonstrates that algorithmic research may encounter some difficulties when attempting to translate...
Figure 7: Research goals classification.

Figure 8: Research goals per research types.

Figure 9: Application scenarios classification.
into practice, which requires further research to be achieved. In the future, researchers need to publish more useful tools to facilitate the research of useful methods their application in practice.

3.6. RQ5: How Are the Papers Distributed?

3.6.1. Distribution by Publication Types. As shown in Figure 10, 46% of authors (65 papers) selected conference publication, 42% (60 papers) selected journal publication, 8% (11 papers) selected symposium publication, and 3% (5 papers) selected workshop publication. Therefore, there were more conference papers than journal papers, which indicates that the technology update in this domain is faster, and conferences can provide researchers with a platform for communication to promote their own research progress.

3.6.2. Distribution of Categories by Publishers. Figure 11 shows that EHES papers were published by different publishers. The review of this work consists of two categories (application and theory). The theory consisted of three tiers as follows: energy schedule, harvest strategy, and power strategy.

ACM published 31 papers in different categories, which were composed of application (6), energy schedule (12), harvest strategy (1), and power strategy (2). IEEE Xplore published 67 papers, which were composed of application (24), energy schedule (24), harvest strategy (17), and power strategy (2). Spring published 6 papers, which were composed of application (3), energy schedule (1), harvest strategy (1), and power strategy (1). Wiley only published 1 paper, which is the application. Other publishers published 37 papers, which were composed of application (19), energy schedule (7), harvest strategy (10), and power strategy (1). About 74% of the papers were published by IEEE, ACM, Springer, and Wiley. This suggests that the research in this field has been recognized and appreciated by popular publishers, thus demonstrating that the field has great future potential.

3.6.3. Distribution by Publication Years. As shown in Figure 12, the number of publications per year from 2005 to 2019 gradually increased from 2005 to 2013. In particular, the number of publications in 2013 was almost three times that of 2007, 2008, and 2009. Although it declined in the three years after 2013, the number of publications then increased again from 2017. This work only selected papers before July 2019, and we believe that the number published in 2019 will exceed those in 2018, as the field has great potential based on recent trends.

3.6.4. Distribution by Nationality of the Author. Figure 13 shows the distribution of EHES research in 23 countries. We noticed that the research was conducted in these countries, or they covered cases in these countries.

The nationality distribution of the 142 EHES papers in numbers shows that the most productive authors are from the USA (44), followed by China (19); France (15); Italy (10); UK (8); Korea and India (5 each); Switzerland and Germany (4 each); Australia, Ireland, Japan, and Pakistan (3 each); Czech, Iraq, Norway, Lebanon, Portugal, and Spain (2 each); and Algeria, Montenegro, the Netherlands, and Turkey (each 1).

We believe that the above data can help new researchers relevant in this field to find suitable publishing venues to publish their future research.

4. Challenges

In this section, two future challenges will be encountered in the processes of EHES energy management.

4.1. Challenge of Energy Management. The most persistent and critical challenges in EHES are related to energy management, such as system scheduling, energy consumption, energy harvesting, and energy distribution. Compared with battery-powered embedded systems, the energy supply of EHES is unpredictable and unreliable. In this case, how to ensure the normal scheduling of system tasks is a significant problem. In this regard, many researchers have proposed various approaches, for example, global controller track the optimal operating point of the photovoltaic panel, state of charge management for the supercapacitor, and energy harvesting real-time task scheduling with DVFS in the embedded device [5]; the time constraints of battery-powered embedded devices are extended to energy constraints [35, 58, 65, 105, 109]; a new strategy was designed in conjunction with traditional battery-powered embedded system scheduling algorithm after considering energy attributes [62, 93, 97, 107]. Energy consumption has always been a long-term problem for embedded systems. Due to the power supply problem of the EHES system, the traditional battery-powered embedded system method cannot be used for EHES. Usually, researchers combine energy harvesting with traditional methods to form new methods [75, 161, 162]. Moreover, energy harvesting needs to consider how to stably and efficiently convert the collected energy [54, 129, 136, 137]. Lastly, how to reasonably supply power to embedded devices distributed in different geographical locations is a challenge currently facing energy distribution. At present, the main method is to use reinforcement learning for configuration [23, 36, 45].

4.2. Challenge of Application. The application of EHES mainly faces the problem of safety. There are two main limiting factors, and they may cause several potential security risks. These problems are mainly caused by environmental factors. Firstly, the energy obtained from the environment is difficult to predict, that is, the amount of electricity generated is random, and when the harvested energy is converted into electric energy, there is a low conversion rate. Under such conditions, it may be difficult to provide equipment continuously sufficient power. If the EHES is transmitting data, data loss may occur. Secondly,
due to differences in physical environment or harvested energy, for example, there are corrosive substances in the environment and energy, which can damage the hardware, the EHES will be damaged and will stop operating [163].

These limiting factors are potential sources of threats to EHES. When devices are powered by energy harvesting sources, they face other threats from attackers who can change the environment. For example, the RF source may be
blocked and the device cannot send their data [164]. There have been researches on attacks and privacy [165–167]. However, the research is still in its infancy and lacks applicability, and many problems remain unsolved.

5. Conclusion

Battery-powered embedded devices have been widely used in various intelligent terminals. At the same time, intelligent terminals that adapt energy harvesting technology have attracted increasing attention. This type of intelligent terminals can solve the situation that intelligent terminals are difficult to charge or to replace batteries. This work contributes to extant published EHES energy management research by a systematic mapping study. We mainly classify papers by answering five questions and comprehensively analysed related papers by highlighting the number of publications, research types, research goals, application scenarios, tools, and methods. Some suggestions for EHES to help researchers find suitable research directions. Furthermore, we also analyse the challenges faced by EHES energy management and the possible implementation plans in the future. Because countries attach importance to sensitive information and privacy issues, researchers need to focus on the security of EHES in the future. At the same time, researchers must continue to deepen the existing research on energy management to ensure the sustainability of EHES.

Our future work will be devoted to the implementation of a systematic literature review (SLR) on the safety of EHES. In addition, we will continue to pay attention to the latest research on EHES energy management.

Data Availability

The data used to support the findings of this paper are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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