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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 coverts 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.

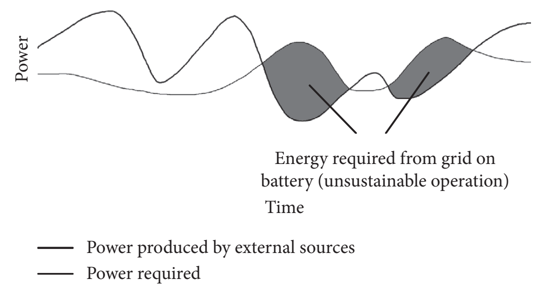

Figure 1: Profile of energy required and energy available from external sources. The unsustainable operation can be caused by the imbalance of available and required power, in which case additional energy needs to be extracted from the battery [11].

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.

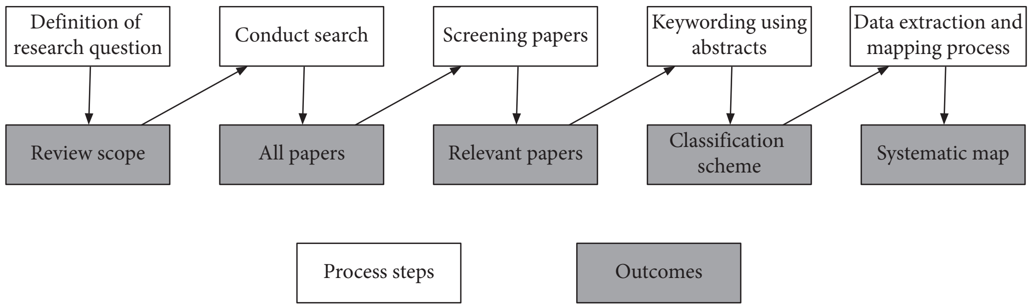

FIGURE 2: The systematic mapping study.

(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.

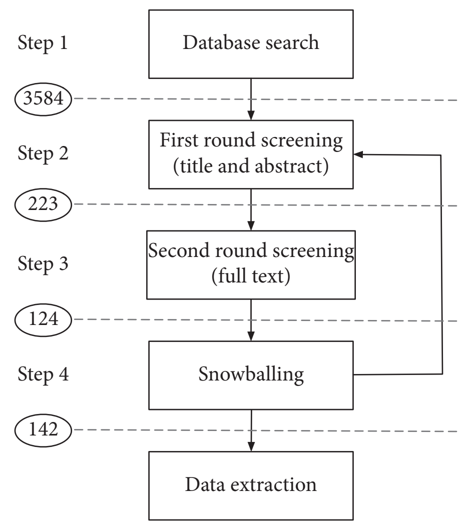

FIGURE 3: Formal search and selection process.

(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

Table 1: Database.

Database	Link	Matched scope in database
IEEE Xplore	https://ieeexplore.ieee.org/Xplore/guesthome.jsp	Title, abstract
ACM Digital Library	https://libraries.acm.org	Title, abstract, keywords
Web of Science	http://login.webofknowledge.com	Title, abstract, keywords

(Population, Interventions, Comparison, and Outcomes) 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)

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

Table 2: Description of our PICO model which matches the EHES.

Component	Description
Population	Energy harvesting embedded system energy management studies
Interventions	Method design and development of energy storage efficiency; design and development of methods to reduce energy consumption
Comparison	We identify different applications and tools of EHES, analyse different methods and technologies for energy management, and compare research on EHES
Outcomes	Maximize EHES life through energy management methods

Table 3: Extracted keywords from the PICO model.

Component	Keywords
Population	Energy harvesting, embedded system, energy management
Interventions	Method, design, development, energy storage, efficiency, consumption
Comparison	Applications, tools, analysis, methods, technologies, energy management
Outcomes	Life, energy management, methods

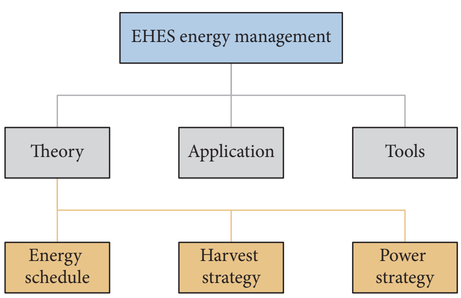

Figure 4: Taxonomy of research literature on EHES energy management.

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.

Table 4: Data extracted from the selected papers.

ID	Ref	RQ1 Research type	RQ2 Research goal	RQ3 Application scenario	RQ4 Tool or method	RQ5 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]	Evaluation 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	[10]	Validation research	Application	Medical	—	2015	Conferences	IEEE
40	[58]	Validation research	Energy schedule	—	Method	2015	Conferences	IEEE
41	[59]	Validation research	Energy schedule	—	Method	2015	Conferences	IEEE
42	[60]	Solution proposal	Energy schedule	—	Method	2015	Journal	IEEE
43	[61]	Validation research	Application	Wearable equipment	—	2015	Journal	IEEE
44	[62]	Validation research	Energy schedule	—	Method	2014	Conferences	ACM
45	[63]	Validation research	Energy schedule	—	Method	2014	Conferences	IEEE
46	[64]	Validation research	Energy schedule	—	Method	2014	Journal	IEEE
47	[65]	Solution proposal	Energy schedule	—	Method	2014	Journal	IEEE
48	[66]	Validation research	Application	Wearable equipment	—	2014	Conferences	IEEE
49	[67]	Validation research	Harvest strategy	—	Tool	2014	Conferences	ACM
50	[68]	Evaluation research	Harvest strategy	—	Method	2014	Journal	IEEE
51	[69]	Validation research	Application	Building	—	2014	Conferences	Others
52	[70]	Validation research	Harvest strategy	—	Method	2014	Conferences	IEEE
53	[71]	Solution proposal	Energy schedule	—	Method	2014	Symposium	ACM
54	[72]	Solution proposal	Application	Wearable equipment	—	2014	Journal	Others
55	[73]	Evaluation research	Application	Building	—	2014	Journal	Springer
56	[74]	Validation research	Energy schedule	—	—	2014	Journal	IEEE
57	[5]	Validation research	Energy schedule	—	Method	2013	Symposium	IEEE
58	[75]	Solution proposal	Energy schedule	—	Method	2013	Conferences	IEEE
59	[76]	Validation research	Application	Machine	—	2013	Conferences	Others

Table 4: Continued.

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]	Evaluation 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	Springer
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	ACM
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	—	—	2012	Conferences	IEEE
85	[102]	Validation research	Energy schedule	—	Method	2012	Journal	IEEE
86	[103]	Validation research	Energy schedule	—	Method	2011	Conferences	IEEE
87	[104]	Validation research	Energy schedule	—	Method	2011	Journal	Others
88	[105]	Validation research	Energy schedule	—	Method	2011	Conferences	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	Conferences	IEEE
94	[111]	Solution proposal	Energy schedule	—	Method	2011	Conferences	IEEE
95	[112]	Validation research	Application	—	Tool	2011	Journal	IEEE
96	[113]	Solution proposal	Energy schedule	—	Method	2011	Conferences	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	Conferences	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	Conferences	IEEE
118	[135]	Validation research	Energy schedule	—	Method	2009	Conferences	ACM
119	[136]	Validation research	Harvest strategy	Building	Method	2008	Conferences	IEEE
120	[137]	Solution proposal	Harvest strategy	—	Tool	2008	Conferences	IEEE

Table 4: Continued.

ID	Ref	RQ1 Research type	RQ2 Research goal	RQ3 Application scenario	RQ4 Tool or method	RQ5 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	Application	—	—	2005	Journal	IEEE

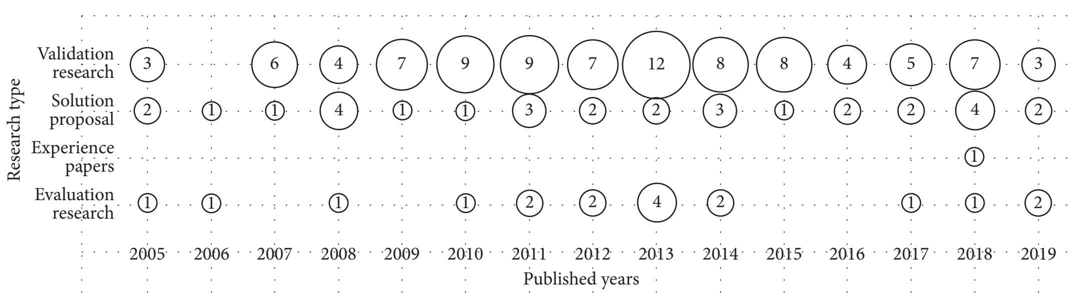

Figure 5: The number of research types per year.

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.

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 effectively 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 renewable energies to drive some sensors or support autonomous supply systems to achieve permanent operations.

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 environment, 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 frequency scaling (EG-DVFS) algorithm which, compared with

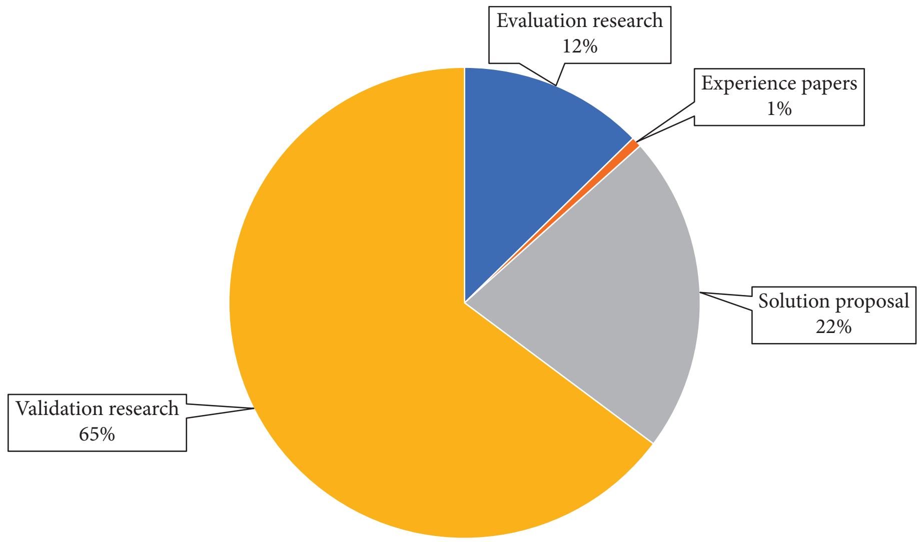

Figure 6: Research type classification.

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

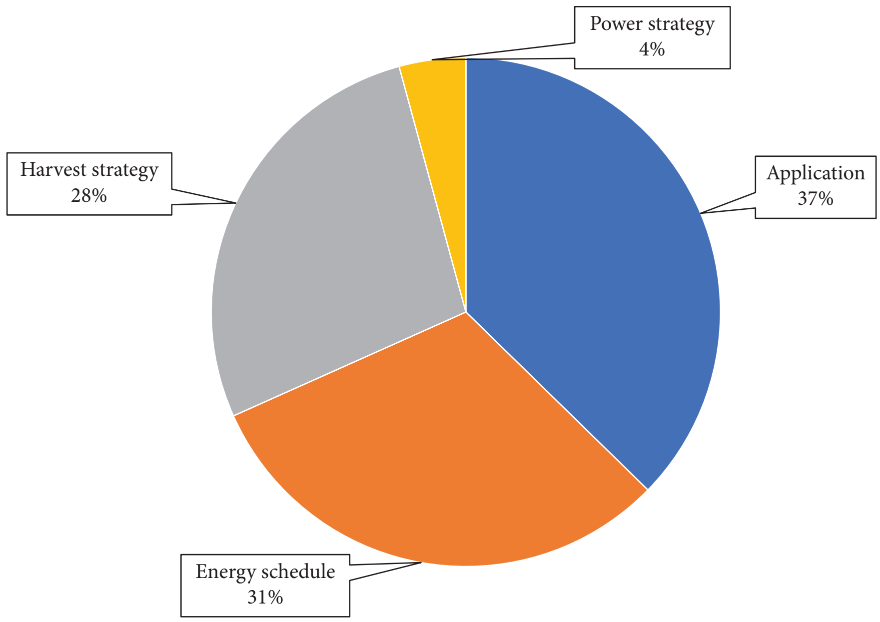

Figure 7: Research goals classification.

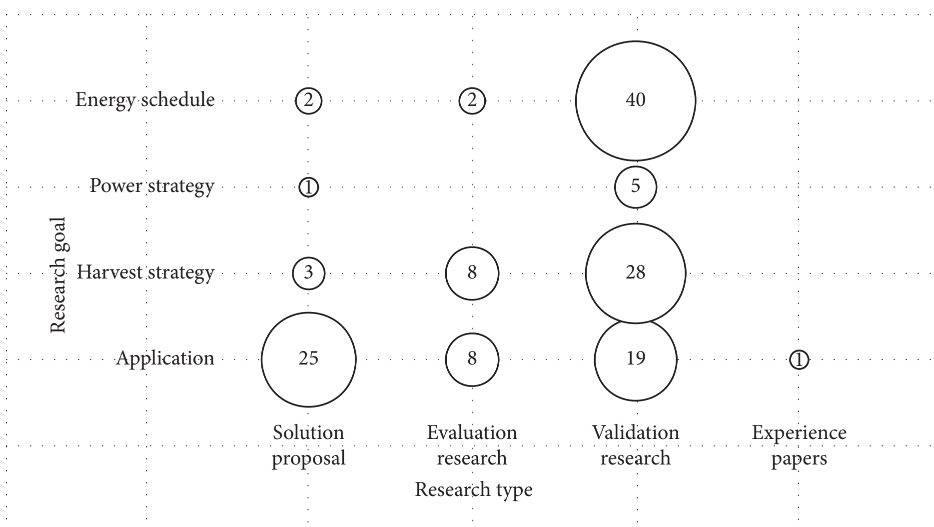

Figure 8: Research goals per research types.

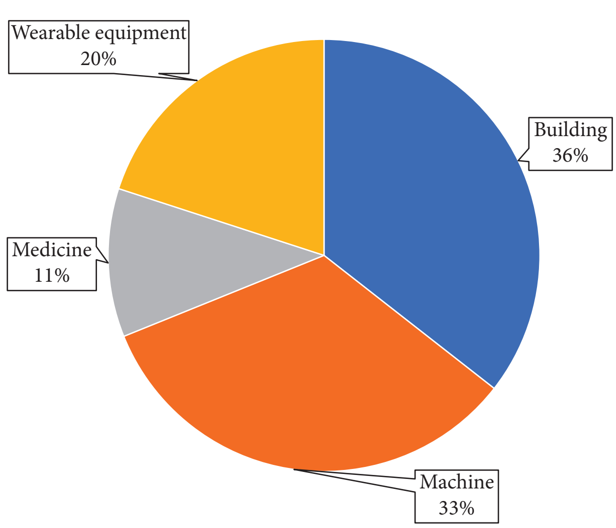

Figure 9: Application scenarios classification.

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 ties 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 (11), 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 signification 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,

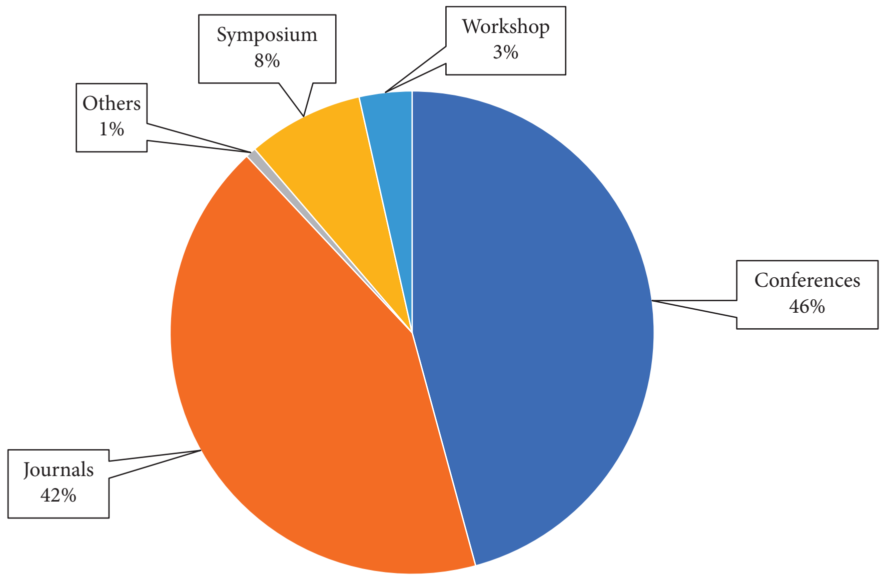

Figure 10: Publication types classification.

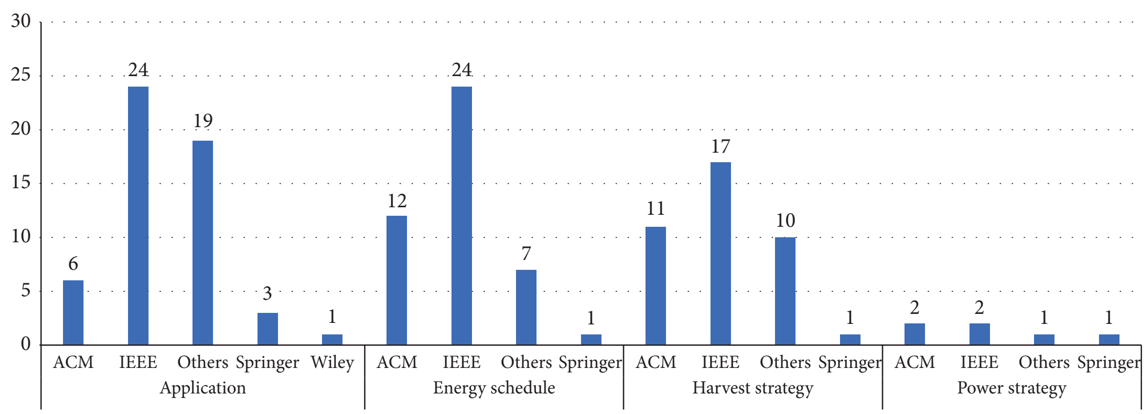

Figure 11: Statistics of the included papers in four different categories by publishers.

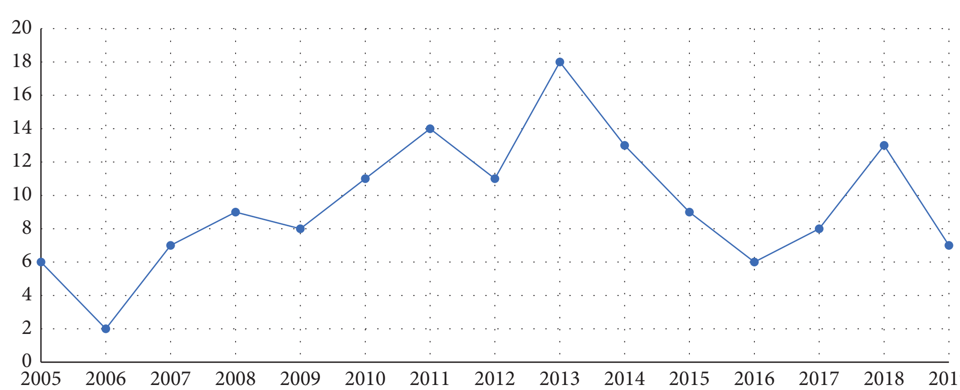

Figure 12: Statistics of the included papers by publication year.

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

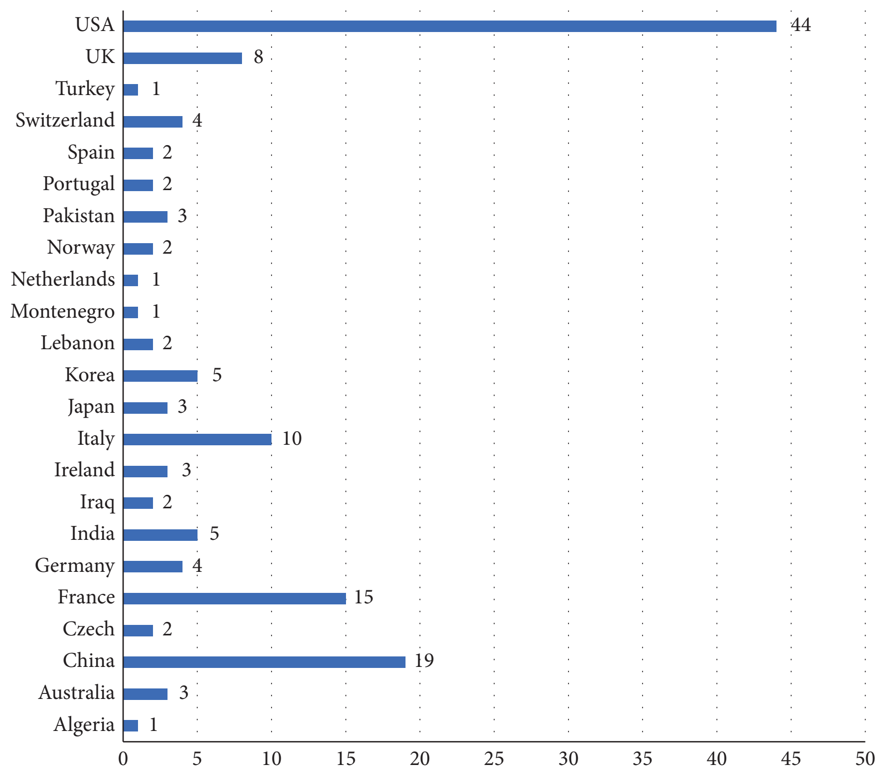

Figure 13: Distribution by authors' nationality.

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.

Acknowledgments

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