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A Review of Energy Aware Cyber-Physical Systems

Houssam Kanso^a, Adel Nouredine^a and , Ernesto Exposito^a

^aUniversite de Pau et des Pays de l'Adour, E2S UPPA, LIUPPA, Anglet, France

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ABSTRACT

In recent years, the number of connected devices and systems has increased exponentially, along with their use in our daily life. Cyber-Physical Systems (CPS) are complex multi-layered feedback systems that combine computing resources and interaction with the physical environment using sensors and actuators. Energy is considered one of the major concerns driven by the increasing number of connected devices and systems. In this paper, we review current research approaches and directions in energy-aware CPS. We propose a novel architectural methodology to analyze and compare state-of-the-art approaches, on their architectural design and energy-related factors. We finally draw recommendations from our review on how to build energy-aware and energy-efficient CPS solutions.

KEYWORDS

Cyber-Physical Systems (CPS); Power and Energy Management; System Architecture; Heterogeneous Systems

1. Introduction

During the second industrial revolution, electricity was introduced as a practical and easy way of transmitting power to consumers such as buildings and industries. The process of electrification that took place during this period was the main driver of the invention of electrical appliances used in our daily life. The widespread usage of these appliances led to a continuous increase in energy consumption. Since then, researchers have been interested in energy optimizations to maximize the efficiency of devices.

Two industrial revolutions followed: (1) the third revolution characterized by the introduction of automation, information technologies, and electronic revolution, and (2) the ongoing fourth revolution introducing Cyber-Physical Systems (CPS), Internet of Things (IoT), and networks revolution. The Internet is a fundamental technology of these revolutions, providing a networking infrastructure for transmitting data and communicating between people and devices. Moreover, electronic devices' capabilities increased exponentially following Moore's law and allowed the ability to communicate, stay connected, and perform complex tasks. These two factors are the base for the design and development of CPS and IoT.

A significant increase in connected devices is currently observed and will continue in the future, in particular, for IoT and smart home devices [1]. It is estimated that

CONTACT Houssam Kanso. Email: houssam.kanso@univ-pau.fr; Adel Nouredine. Email: adel.nouredine@univ-pau.fr; Ernesto Exposito. Email: ernesto.exposito@univ-pau.fr;

41.2 billion devices will be connected to the internet by 2025 [2]. With this increase, the energy consumption of these devices is growing and may challenge the capacity of energy production. For instance, in 2019, over 25 000 TWh of final energy consumption was electrical, with the majority being consumed by the industrial and residential sectors [3].

The energy impact of CPS goes beyond the use phase, with important energy and resources spent in its entire life cycle (exploitation of natural resources, production, transportation, use, and end-of-life phases) [4]. Our research work focuses on the energy consumption of CPS in the use phase. These devices consume energy directly from the electrical grid (e.g., television) or by storing energy in an internal battery (e.g., mobile phones or laptops). As CPS integrate computing devices (such as sensors and actuators, IoT devices, mobile, and connected devices and appliances), and interact with the physical environment (such as homes and buildings, human end-users, animals, and natural phenomena), the assessment of their energy consumption and its optimization is a challenging task. Reducing the energy consumption of CPS requires a comprehensive study of the various actors and components involved in a CPS. Energy consumption is not only limited to the energy impact of the device itself, but the entire ecosystem impacted by the usage of CPS (such as networking, servers and data centers, database storage, etc.). This complexity is due to additional layers of information that need to be addressed and taken into consideration when applying energy optimization techniques.

The three main contributions of this paper are the following:

- (1) We conduct a systematic review of energy management techniques in CPS and classify these solutions based on seven identified categories. In addition, we present a novel study of the energy-aware CPS based on the layers on which each solution is built. We also compare the state-of-the-art studies based on their domain, studied parameters, monitored layers, and level of autonomy. Therefore, we identify several lacks in the state-of-the-art approaches.
- (2) We present a referential architecture as a potential way for managing energy on different layers of the CPS by collecting data, analyzing them, and executing corresponding actions. This architecture represents a conceptual way to optimize energy on all layers of the CPS in contrast to the current approaches that deal with one CPS layer each.
- (3) We suggest a set of recommendations to be considered in future works in order to reach higher energy saving in CPS and draw new future research directions in this expanding field.

In this paper, we review the state of art approaches in energy management in CPS. Based on this review, we propose a novel architectural classification of energy-aware CPS based on the contextual layers involved. Then we analyze and compare the studied solutions, identifying on which layers energy is optimized, the potential information exchange between layers, and how energy is managed. Finally, we propose recommendations for researchers to address energy consumption in CPS from a holistic point of view. The remainder of this paper is organized as follows: in section 2, we analyze the state-of-the-art energy-aware CPS architectures. We present our research method in section 3. In section 4, the main research trends in CPS energy awareness are presented. We define our comparative methodology, analyze, and discuss the identified approaches in section 5. Finally, we conclude in section 6 with recommendations for energy-efficient CPS.

2. Context and Motivation

In the last few years, there has been an exponentially growing number of connected devices. The main reasons for this growth are: 1) a larger number of people are connected with more than one device (e.g., smartphones, smart watches, computers, cars, etc.). 2) the increasing need to monitor and automate everything from homes to large factories where already existing objects, which were not connected in the past, are now connected to the internet such as light bulbs, heating, surveillance, etc. 3) the introduction of new devices such as robots and smart devices. All these devices need energy to function, and most of this energy comes from fossil fuel sources, therefore raising greenhouse gas emissions (GHGE). Transportation, electrical production, industrial, commercial, and residential sectors are responsible for more than 89% of the GHGE [5]. Nowadays, all these sectors are being automated by CPS, capable of monitoring and optimizing their energy consumption. Therefore, CPS can play an important role in reducing the energy consumption of various industrial and residential sectors. In this study, we survey and analyze the various energy optimization techniques in CPS. Then, we provide recommendations to improve the energy efficiency of CPS and use them to reduce the energy footprint of the industrial and residential sectors.

2.1. Cyber-Physical System Definition

A CPS is defined as a smart system composed of interconnected devices defined by computing and physical processes [6]. These processes run over physical components, and over systems with limited resources in variable temporal and spatial conditions [7]. Computational system's main objective is to control and interact with physical processes via touch points (sensors and actuators). CPS are characterized by the significant interaction between networks of physical and computational components. In addition, human interaction and behavior in such environments have an important impact on the system. It is seen as an intelligent, real time, adaptive, predictive, and distributed feedback system. It is characterized by its interoperability and scalability because it is implemented in heterogeneous environments as seen in figure 1. A CPS can be considered as a system of systems. These systems are usually self-managing and self-optimizing systems [8]. This kind of systems are cross-domain oriented applications, such as in the fields of healthcare, smart homes, autonomous automobiles, industry, and many more [9–12]. An example of this kind of systems could be autonomous vehicles, equipped with sensors and actuators. In order to sense and understand its environment, make its own decisions, and execute these decisions using the actuators. Healthcare robots, medical monitoring devices, industrial robots with monitoring IoT devices in factories, and smart home management systems are all good examples of CPSs. A CPS does not only have great economic and social impacts, but also can have an important energy footprint, and could be optimized in order to reduce the global consumption.

2.2. Cyber-Physical System Architectures

ICT are the different components and infrastructure that make modern computing possible, it includes hardware devices, communication technologies, applications, and systems that shape the digital world [13]. ICT have been modeled and specified with standards to describe their functions such as the OSI model that provides an abstract

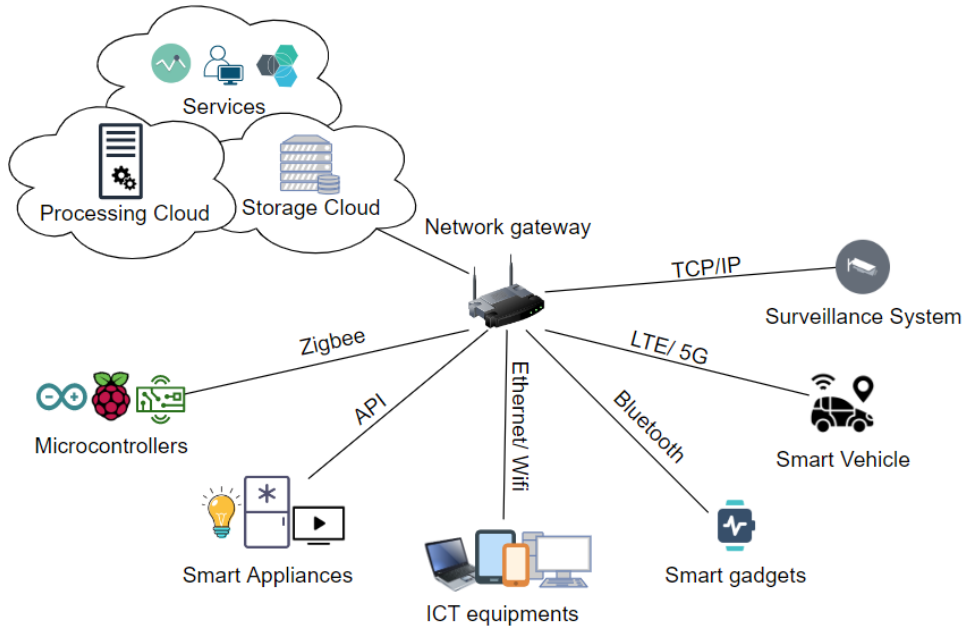


Figure 1.: Example of devices found in a CPS

framework to describe the communication functions of a computer system [14]. However, these standards do not cover all the specificities of heterogeneous physical and logical components of CPS. We believe that there is a need to provide a standardized referential model for CPS, in order to specify their functional and non-functional properties and in particular integrating the energy dimension. In this section, we present previous research work offering architecture proposals for CPS from a structural point of view.

In [15], the authors presented a survey of system integration in the context of Industry 4.0 using the 5 C integration levels (Connection, Communication, Coordination, Cooperation, and Collaboration). They also identified the most common challenges around Industry 4.0 as follows: the complexity of planning, standardization, security, privacy, heterogeneity, and integration. Creating standardized CPS architecture may solve these challenges by allowing all entities to apply the 5 C easily.

The authors in [16] identified challenges facing the CPS. They mentioned the challenges of interoperability, system distribution, real-time concern, component modeling, testing, optimization algorithms, safety concern, and heterogeneous data. One of which is the need to develop standardized architectures while taking into consideration the high dependency between the software and hardware components. Any proposed architecture should respect the three abstract layers of a CPS: Computation, communication, and control (3C). The abstraction of these layers grants the integration and interoperability of heterogeneous systems together. The authors in [17–19] also considered CPS as an integration of computation, communication, and control (3C) technologies. The concept of 3C is considered by some researchers as the backbone architecture of CPS. In [17] a CPS is defined by three main components: a physical, network, and a distributed cyber system, in addition, it operates on perception, transmission, and application layers. [20] proposed a service-based CPS to deal with the challenge of difficult computation capabilities on connected devices with limited re-

sources. Three tiers architecture was essential to build this system. An environmental tier collects the information gathered from the physical world to the control tier that manages the physical components and services. It identifies the appropriate services, and ensures the dynamic composition of new real-time services based on the need. Finally, the service tier provides reusable functionality as cloud computing and micro-services. In [21], the authors presented an environmental monitoring CPS based on a three-layer architecture. The bottom layer is composed of several connected sensor nodes distributed over a wide area. The middle layer of the CPS receives data from the lower layer and stores it, analyzes and takes decisions. The top layer provides web services for clients in the form of Software-as-a-Service to interact with the system. A framework for analyzing cyberattacks against CPS is presented in [22]. Vulnerabilities such as taking complete control, damaging, stopping the functionality, disrupting, and degrading the system are divided into three logical layers. Physical layer (Sensors, actuators, and system dynamics), control layer (Signals from physical layer and control algorithms) and cyber layer (traditional ICT components like buses, processors, memory ...)

The authors in [9] reviewed previous models and proposed a four-layer architecture based on Service Oriented Architecture (SOA) that respects real-time control, security, and integrability characteristics. Perceive tier includes environmental awareness and pre-processing, data tier stores and processes the data to make it homogeneous. Service tier controls the whole system by scheduling tasks, making decisions, and provide API for consumption. Finally, execution tier interacts with the environment directly using physical actuators or with the system itself. Intelligent transportation, agriculture, and medical applications were introduced as potential domains for this architecture. In [23], a distributed public street light adaptation system was proposed to save energy and took into consideration new performance indicators as power reduction, CO_2 emission reduction, and service usefulness. This system was based on the following layers: Capillary networks layer includes heterogeneous wireless sensors and actuators. Network backbone layer assures homogenization, reliability and data transformation. Enabling technologies layer provides data mining and infrastructure management. Services and applications layer exploits the information gathered with an abstraction level to reuse these services. The authors in [24] defined a general architecture of a medical CPS and discussed vulnerabilities regarding secure storage, networking, and computation. Data acquisition layer composed of battery-powered wireless wearable sensors for the collection of patients' data. Data aggregation layer acts as a gateway that collects the data from the previous layer, aggregates them, and sends them to remote locations for further processing. Cloud processing and storage layer achieve storage, processing, and analytics for decision-making and predictions. Action layer executes the decisions actively or passively (With or without physical interaction). The authors in [25] proposed an agricultural management system architecture based on their findings of the four major layers. The physical layer interacts with the environment and collects data. The networking layer ensure the transition of data throw wireless communication. The decision layer stores, and analyzes the data to provide decision-making graphical tools in the application layer. This provides the knowledge to the experts throw dedicated applications and web services. This CPS is not autonomous, its functionality is highly dependent on the farmers' interpretations and interventions.

We identify the distinct layers of a CPS for each of the literature architectures. The main identified layers in CPS are: Sensing, Communication, Actuating, Processing, Services, and Control. In some architectures, sensing and actuating are combined into the same layer. Table 1 summarizes our layer categorization per approach, the domain

Table 1.: Comparative table of distinct CPS layers

Article	Domain	Layers	S	C	A	P	Se	Co	SA
[16]	General	3		x		x		x	
[20]	General	3					x	x	x
[21]	General	3	x			x	x		
[18]	General	3		x		x		x	
[17]	General	3					x	x	x
[22]	Security	3				x		x	x
[9]	General	4	x		x	x	x		
[23]	Smart city	4		x		x	x		x
[24]	Security	4	x	x	x	x			
[25]	Agriculture	4	x	x		x	x		

S:Sensing, C:Communication, A:Actuating, P:Processing, Se:Services, Co:Control, SA:Sensing and Actuating

in which the architecture was proposed, and the number of considered layers.

The previous section showed that many researchers created architectural models of CPSs by dividing them into layers especially in the domain of security and attack protection [22,24,26]. Some adopt the approach of physical architecture separation of layers as in [24] where each layer is identified by one or many components that are physically independent. Most approaches adopt a higher abstraction with the separation of functionalities to identify the layers remarkably found in [16,23] where the function accomplished on each layer makes it identifiable, thus, two tasks operated by the same component can lead to the identification of two layers.

As seen in figure 2, the most common layers of CPS are processing, services, communication, control, sensing, and actuating in most architectures. These layers are not fixed and can be changed or redefined as more granular layers, such as separating the software from the hardware that is running on the processing layer. For example, the sensing layer is referred sometimes to as the perception layer.

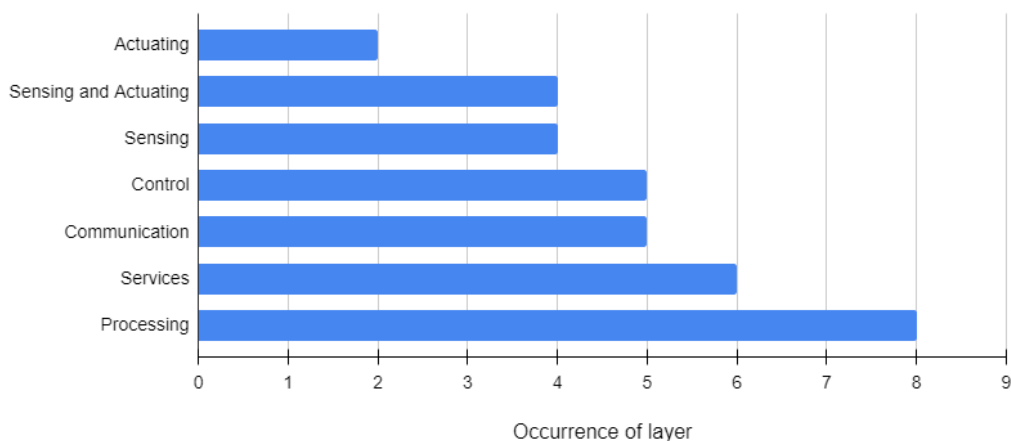


Figure 2.: Identified CPS layers

The analysis of these works allows us to conclude that from a structural point of view, there is no unique architecture to identify a CPS. Moreover, previous research papers do not consider energy as a relevant property to be specified and taken into account. Similar to security concerns, we can identify energy properties by layer. We believe that this kind of non functional property needs to be considered in order to be able to optimize the structure and behavior of CPS in an effort to cope with energy consumption reduction goals.

2.3. Energy in ICT and CPS

Although developers do not usually think about energy while designing a system, energy management has always been a concern in ICT. Power-saving solutions are found on individual devices such as smartphones and laptops notably since they run over batteries. In these devices, energy affects directly user experience but when users are not directly impacted, energy is seen as a non-relevant concern. Most of these solutions are based on making devices more efficient and reducing idle power consumption by using various power plans that make actions such as turning off their screen, CPU frequency modification, and others. They also include different operating modes such as active, sleep, hibernate, and off. Energy management is also found in data centers due to the rapid growth of cloud computing and micro-services, especially with the increasing need for new infrastructure, higher storage, and networking capabilities. For instance, in some countries such as Denmark, data center electricity consumption is expected to increase to 15% of total electricity consumption by 2030 [27].

The increasing number of ICT and CPS devices used by a person in everyday life leads to concerns about saving energy on each system which can lead to better performance and reduce energy on a large scale. At the same time, this could offer an opportunity to gather information and use it for automating energy management. In ICT, energy optimization is limited to certain types of devices, such as computers and smartphones, that usually have a power manager acting locally. Their adaptations are logical and do not directly impact the physical world and are not directly impacted by the physical world. With the integration of the CPS in our daily life, physical activities can be detected and predicted uncovering potentials of energy optimization in CPS. Energy management in CPS could be even more efficient than traditional ICT due to the understanding of the environment where they are implemented. Processing collected data allows them to reduce the consumption of devices that used unnecessary energy. It is important to note that the energy needed for accomplishing a task in the physical world needs usually significant amounts of energy. ICT and CPS can also work accordingly to ensure the best energy optimization. For example, mining the data produced by a user's laptop or phone leads to the knowledge of his geolocation, hence, turning off his home lights when he is away.

2.4. Scope and Limitations

In the previous section, we reviewed the state of the art of different architectures and energy management approaches for CPS. The remainder of this paper presents the research protocol and summarizes different energy optimization approaches in CPS. Some of them optimize the energy consumed by the CPS itself, while others use the CPS to reduce the energy of a wider entity such as buildings. We include both design-time and run-time approaches. We also include some potential software solutions that

are already applied in ICT but not yet widely used in CPS, as we believe they have an impact on its overall energy consumption.

We only analyze the energy impact of the solution without taking into consideration any potential loss of performance or user comfort. Energy optimization can have a positive impact on performance, for example, by minimizing energy drains on a battery-powered device (therefore lasting longer). It could also have negative effects, such as reducing the brightness or the temperature to save energy while sacrificing user comfort.

3. Research method

The research method adopted in this survey follows the process defined in [28]. First, we identify the research questions. Then, we perform a manual and an automated search. Next, we remove the duplicates and apply inclusion and exclusion criteria. After that, we make our analysis and comparison based on the CPS layers and defined comparison criteria. Finally, we discuss the found results. The research method process is presented in figure 3.

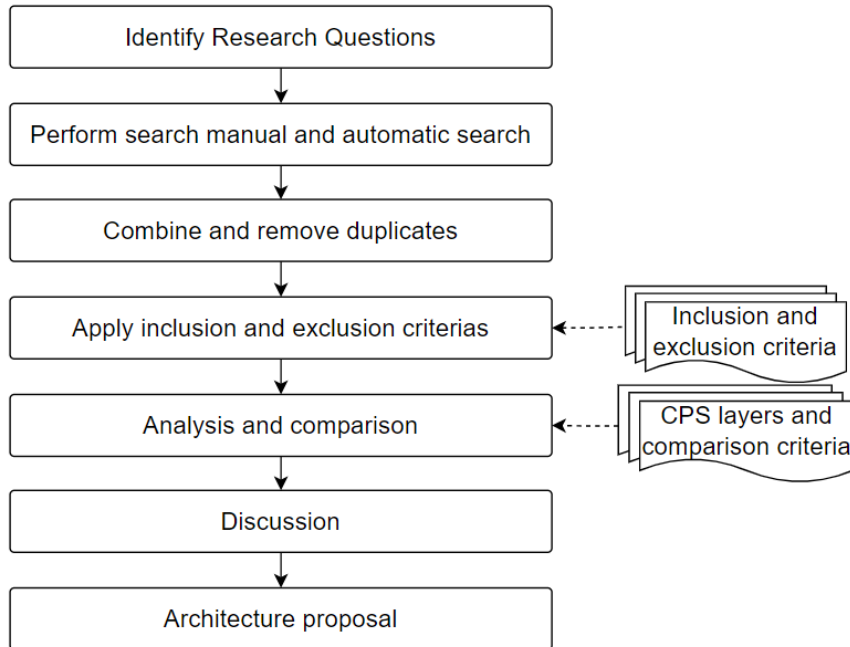


Figure 3.: Research Method Process

Research Questions: The main objective of our review is to identify the existing research approaches dealing with energy concerns in CPS. In order to achieve this goal, we first formulated the following research questions:

- *RQ1: What type of approaches is used to deal with energy in CPS?*
- *RQ2: What are the studied metrics that have an impact on energy consumption?*
- *RQ3: Studied metrics belong to which CPS layers?*

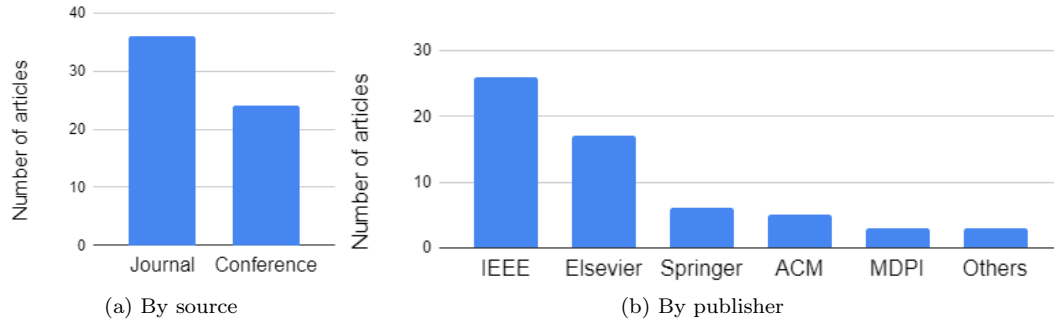


Figure 4.: Article sources and the number of articles found

Search Strategy: The search strategy is based on an automated search using a search string and a manual one in order to include relevant research papers in our survey.

- Automated search: We used SCOPUS, one of the world’s largest and most comprehensive scientific databases, to conduct automated searches using the Harzing Publish or Perish Tool¹. To accomplish that we used the following search string:
(cps OR cyber physical system OR cyber physical systems)
AND (green OR energy OR ((energy OR power) AND (efficient OR consumption OR saving OR management)))

We have limited the number of studied papers to the first 100 found articles while doing the search query².

- Manual search: We manually choose research papers published in relevant journals, conference proceedings, and cited in prior thematic related surveys.
The output of this stage was **140** articles.

Study Selection: A study selection was conducted to ensure that the findings are reliable and informative regarding our research questions. The following describes the selection process:

- Combination and duplicates removal
- Inclusion Criteria: i) studies proposing an approach for reducing energy consumption in CPS, ii) studies published after 2010, iii) studies cited at least one time (except studies published between 2018 and 2021)
- Exclusion Criteria: i) studies that propose the use of CPS without providing an energy reduction approach in the CPS itself (especially in power plants), ii) studies that were not available in full text or we could not access, iii) studies written in language different than English.

Inclusion and exclusion criteria can be formulated in as follows:

```
[(YEAR >= 2010 AND CITATIONS >= 1) OR (YEAR >= 2018 AND
CITATIONS = 0)] AND DUPLICATION = FALSE AND LANGUAGE = "ENGLISH"
AND AVAILABLE_IN_FULL_TEXT = TRUE AND SUITABLE_TITLE = TRUE AND
SUITABLE_ABSTRACT = TRUE
```

The last stage resulted in **60** primary studies, which we have used for our analysis. The

¹Harzing, A.W. (2007) Publish or Perish, available from <https://harzing.com/resources/publish-or-perish>

²The search was executed on October 03, 2022.

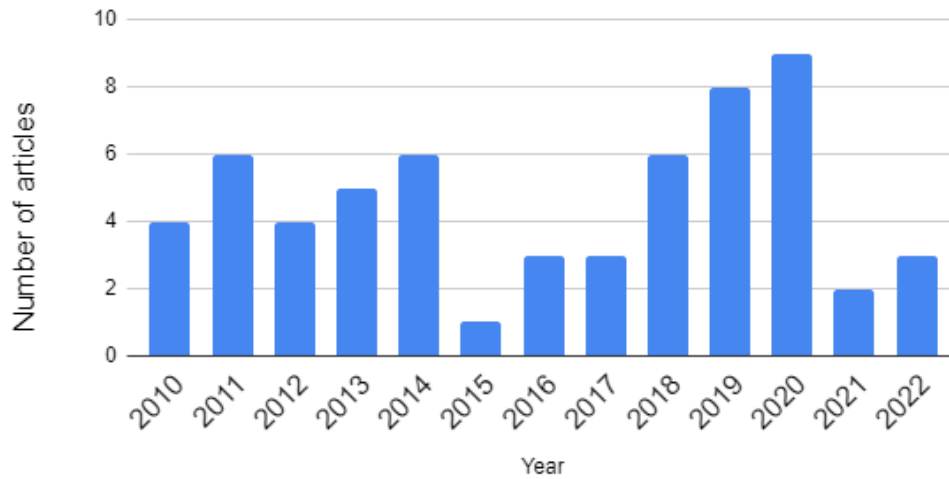


Figure 5.: The number of articles found by year

average number of citations per research paper is higher than 40. This list of studies can be found online³.

Figure 5 shows that in recent years there have been an increasing interest in energy optimization in CPSs.

Figure 4 shows the trend and statistics regarding the sources of the reviewed publications on energy CPS.

Figure 6 shows the papers application domains frequencies. Chosen research papers belong to a variety of domains.

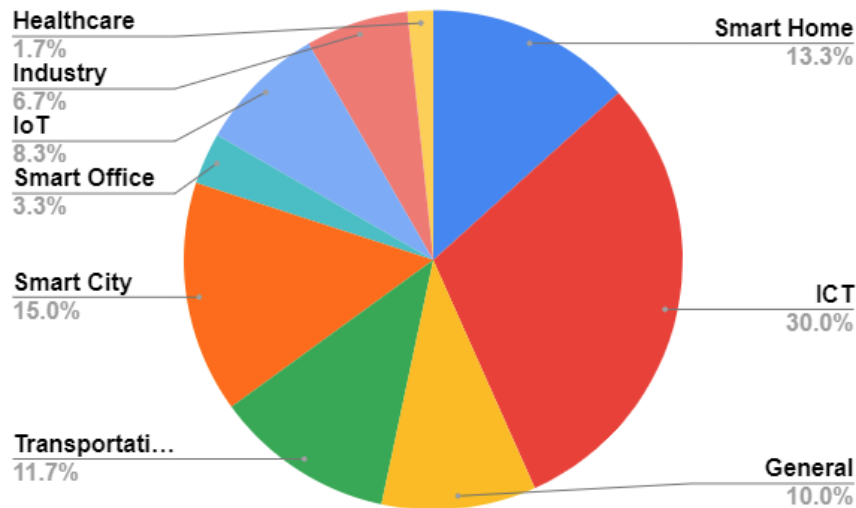


Figure 6.: Studied Papers Application Domains

³The list of the studies: t.ly/rbKe

4. Energy-aware Cyber-Physical System Approaches

In this section, we present a literature review of existing research approaches aiming to optimize and reduce energy consumption in CPS. During our examination, we could identify the most common concepts of energy optimization in CPS. The section is divided into sub-sections based on the behavior of a CPS regarding the energy concern. In each subsection, we define the concept and cite previous efforts based on it. The most common approaches in CPS found in the literature review are scheduling, reconfiguration, contextual awareness, and user recommendation. Some of these solutions are related to the general ICT domain but have potential benefits in the CPS environment, in particular those related to migration, profiling, and software.

4.1. Scheduling

Scheduling is one of the solutions to optimize energy consumption in CPS. It consists of changing the time slot during which a specific task is executed [29]. The change of time is usually done to benefit from the energy when it is greener, for example, solar energy during the day. In addition, scheduling has a target of detecting unused devices and changing their mode between active, idle, sleep, off, and other modes.

IoT devices are usually powered by limited capacity batteries wherefore many ideas were developed to allow these devices to last longer. The authors in [30] propose that activity scheduling can increase energy efficiency while maintaining reliability in addition to the transmission protocol choice and the transmission power in an IoT environment. Each node can choose to switch between standby or active mode as long as it will not affect the efficiency of the whole system and that will inform the other nodes. This solution is based on optimizing energy at the communication layer and at the entire device level while maintaining sensing.

With the increasing number of connected appliances in homes, the evolution of smart homes, and smart cities, Home Energy Management System (HEMS) were introduced. A HEMS using ZigBee communication, smart outlets, and lights is proposed in [31]. The proposed approach minimizes the energy consumed by home appliances during standby mode, where the smart outlet cut-offs the current from a device consuming below a certain threshold. Their solution is simultaneous and the waiting time usually needed before turning off the outlet was eliminated.

The authors in [32] presented an architecture for energy monitoring and saving functions that will encourage users to save electric energy by themselves and also will reduce standby power automatically. The home energy-saving system is divided into clients that measure electrical power and powers-off the devices connected to them if necessary and a server that has the role of monitoring and controlling these clients. This solution operates on the entire device by cutting-off electricity for unused devices.

Scheduling solutions also exist in ICT environments due to the high amount of resources compared to variable demand. They are proposed to solve the problems of efficiency and availability. SleepServers [33] is a software-based solution that creates virtual instances of hosts in a work environment. It allows hosts to run in a low-power sleep mode but still be able to respond on the network and even run some applications. This approach allows to raise the availability and increase usability in sleep states. It is implemented in an ICT environment and acts on the service and communication layers.

The authors in [34,35], proposed three control strategies for data centers depending

on the level of coordination between the cyber (computational) and physical (thermal) components of the environment. They criticize that thermal properties are managed as pure physical, however, they have cyber and physical characteristics. A baseline, uncoordinated (divided into two separate optimizing problems one for the cyber component and one for the physical one), and coordinated (one optimizing problem) strategies are compared. It also introduced a cyber-physical index (CPI) that helps to choose a coordinated or an uncoordinated strategy depending on the amount of workload, servers, and cooling distribution in the data center. The data center was divided into server, zone, and data center levels.

In [36], a QoS-aware virtual machine scheduling method in a cloud environment, named QVMS. The scheduling problem was defined as a multi-objective optimization problem: (1) minimize energy consumption, (2) minimize downtime, and (3) maximize the resource utilization rate. QVMS uses a Non-dominated Sorting Genetic Algorithm III (NSGA-III) is used to find the optimal scheduling policy, however, their optimization resulted in slightly better resource utilization and downtime but the energy was almost not affected compared to other scheduling methods such as: (1) Benchmarking: move the application to the closest physical server using the shortest path algorithm, (2) Energy-aware virtual machine (VM) scheduling method: move the application to a server that has a higher performance or lower energy consumption [37].

The authors in [38] proposed an energy-efficient memory-aware cloud-based scheduling and optimization algorithm. Global scheduling decisions are made by the cloud scheduler based on the information collected by the VMs.

In [39], an energy optimization approach for manufacturing environments was proposed. It was based on collecting real-time data. This data was used by an energy-modeling artificial neural network and a monitoring component. The output of these two modules is compared for scheduling and rescheduling tasks.

The authors in [40] proposed an agent-based routing approach for Wireless Sensor Network (WSN). It achieved data aggregation and processing locally, in addition to the selection of the best routing path for mobile nodes to reduce unnecessary flows between the nodes and optimize energy. [41] also proposed an approach for reducing energy consumption by considering a data cleansing algorithm, an energy-saving scheduling algorithm, and a low-power protocol for communication in a WSN.

In [42], an approach that consists of compromising between the energy efficiency and the reliability of a system in both shutdown and scale-down scheduling techniques was proposed. It was divided into two techniques for reducing the energy consumption of CPUs: (1) make a copy of the scaled-down task as a non-scaled task to recover it if necessary, (2) Specify minimum reliability constant for each task and make sure this value is respected.

Financial cost effectiveness is the main concern in [43]. A problem of controlling a pump and scheduling a dishwasher and a clothes washer to minimize the energy cost, while preserving the desired water level, was solved using Particle Swarm Optimization (PSO). It creates models for water and energy demands, water tanks, energy production, and prices. It takes into consideration different variables (like the water needed in an average household and the energy cost in the USA). Finally, it tuned the parameters using PSO to find the optimal time slot for running each of the appliances.

In [44], an energy management system, that creates profiles for the home residents by taking into consideration factors like their gender and the number of occupants, is presented. It also takes into consideration human behavior, flexibility region for each task in addition to the acceptance for the scheduling of each task. The goals of this research were electricity cost and peak power minimization while satisfying the comfort

of the home residents. In [31,32,43,44] scheduling is done on the entire device as one entity where they are changing the operating mode of each device based on its usage.

In [45], a CPS model based on three states (Idle, Active, and Shutdown). It also proposed a security mechanism that is automatically deactivated to minimize energy consumption.

The authors in [46] proposed an occupancy detection and prediction framework using a WiFi probe-based ensemble classifier in energy-CPS to minimize the energy consumed by the cooling and ventilation demands. This system can detect the presence of individuals in a room or even predict occupancy patterns. Devices schedules followed and were influenced by the schedules predicted for occupants. Their solution acts mainly on the communication layer of a CPS.

Occupancy is an important factor in human interaction with the heating, ventilation, and air conditioning (HVAC) systems because it determines directly the desired mode of the system as real-time scheduling. It could also affect other CPS environments like the city infrastructure as in [23]. IoT devices were implemented to sense the environment and make smarter decisions by detecting the presence of people or cars and controlling an infrastructure of street lighting.

4.2. Reconfiguration

Reconfiguration is the ability of a system to change its initial configuration by tuning some parameters allowing it to adapt to changes that take place during run-time [47]. It is usually based on a finite number of states predefined during design time in contrast to autonomous systems that can accumulate knowledge with time.

The authors in [48] proposed multi-operating modes for each layer of the system to increase energy efficiency (33% energy gain). In this approach, the optimization of each layer is done by the layer itself and there is no interaction with the other layers to share information about their modes. Sensing layer optimization is done by having active mode and sensing mode where sensors are still detecting events but the transceiver that sends data is turned off. They found that the power consumption of the communication layer is high and can be divided into two ranges of transmission speed. For a speed lower than 10 Gbps, active and low-power idle modes (unable to transmit or receive data) are used. If the speed is higher than 10 Gbps, the energy cost of transition between modes is high. A fast wake intermediary mode was introduced to solve this issue (able to transmit but unable to receive data). Computation and control unit changes its frequency to create 4 operating modes: high-performance (highest frequency), low-performance, idle, and napping modes (lowest frequency). Their paper did not include the used frequency values. Actuators are in sleep mode by default, they switch temporarily to active for accomplishing an action. Their proposed solution optimized the energy on the sensing, communication, computation, and actuating layers individually.

The authors in [49] present an energy-efficient reconfiguration tool built on Raspberry Pi in an intelligent transportation scenario. They identified energy-consuming concerns at design time, analyze configurations and variants, create a file containing all the possible configurations and the consumption of each of them, selecting initial configuration, and reconfigure at run-time according to the context. It is based on aspect-oriented programming by using the separation of concerns and adapting the configuration of each concern. For example, the compression algorithm can change during the run-time based on the size of the message that needs to be sent. In this solution, energy can be optimized on many layers by changing parameters based on the

concerns mainly on the sensing layer (monitoring concern) such as sampling frequency. Other parameters also affect the power consumption on the services layer (software concern) such as compression protocols and on the communication layer (networking concern) such as exchange protocols.

The authors in [50] ensured energy optimization while satisfying the user comfort by proposing a smart zoning multiple-mode feedback system in a smart building based on the usage of each room, its orientation, and its occupancy. Each zone can be in normal, pre-cooling, or power-off mode. The HVAC set points are configured dynamically in each room considering the indoor state (temperatures, occupancy schedule, availability of renewable energy) and outdoor state (weather conditions, weather forecasts). Their solution was able to save 15% of the energy while testing it on EnergyPlus [51].

In [52], an energy-efficient large-scale data collection and correlation technique was proposed. Their approach is used in an environment having sinks and correlation regions, it consists of changing the size of the region based on the distance between the latter and the sink based on the residual energy of the node. If the region is close to the sink then the region is increased, on the contrary, if the distance is far, the region is decreased. The authors focused on the energy used by the network layer in large data exchange systems.

The authors in [53] proposed a cloud-terminal-based CPS to reduce energy consumption in machining processes. The proposed architecture contains 4 layers that summarize the functionalities of the approach: machine level (raw data is collected using sensors), data level (data storage/management and prediction analysis is done), decision support level (contains optimization services), and control level (data presentation and on-board physical execution using controllers). The decision-making process was based on the PSO using GPU.

In [54], a machine learning energy manager for hybrid electrical vehicles (which has an internal combustion engine and an electric motor) was proposed. A nested reinforcement learning approach was adopted where an inner loop was responsible for choosing the electric and fuel engines to minimize the fuel usage, while the outer loop was in charge of modulating the battery health degradation. However, the impact of the reinforcement learning technique used was not considered.

In [55], a bidirectional long short-term memory (LSTM) network based on reinforcement learning was proposed. It builds a virtual vehicle of the real physical one and adaptive actions are accomplished.

4.3. Migration

Large distributed data centers also tackled the problem of energy efficiency by the use of VMs alongside migration techniques [56].

The authors in [57] proposed the use of workload consolidation and VM migration as a way to minimize the energy of ICT equipment in a smart building. Migration is usually done for the processing and storage layer. Alongside their solution, they also proposed the necessity to use sustainable equipment like new lighting technologies by using LED lights, and the energy source using Solar PhotoVoltaics.

In [58], VM resource utilization (CPU, memory, and network) are monitored and estimated, overloads and underloads situations are detected, and dynamic VM consolidation through live migration is performed.

In [33], a light image of a computer plays its role on the network and maintains the functionality as if it is awake but consumes as much as if the PC is in sleep mode.

This showed that 60% of the energy used by PCs in enterprise environments could be saved while maintaining user experience and computers' availability. Migration and resource-sharing solutions may have potential in CPS.

[59], proposed a live virtual machine scheduling in data centers in the form of a trade-off between performance and energy. A joint model for energy consumption and performance degradation of VM migrations was formulated. The method can be divided into three steps, (1) Identify the physical machine that has idle space for migration, (2) migration strategy searching to identify which VM to be migrated and to which machine, and (3) identify the global scheduling strategy for all running VMs.

The authors in [60] proposed a relaxation-based algorithm for services replication in different nodes based on the stream flows and their occurrence rate aiming to reduce the communication energy between nodes in a WSN environment. The problem was formulated in the form of mixed-integer linear programming. Their algorithm chose which services should be deployed on which node and scheduled the flow in an optimal way.

4.4. Modeling and Simulation

System modeling is the process of conceptualizing abstract models and designs of a system. It allows respecting several requirements and dimensions of a system. It defines entities and the relations between them that give a comprehensible understanding of the functionality of the whole. System models aim to support analysis, specification, design, verification, and validation of a system [61]. A simulation is a method for implementing a model for validation, integration, verification, and limitations detection purposes [62]. Therefore, some studies aim to raise a device's efficiency while reducing its power consumption by making changes in the design phase by modeling and simulating a system.

[63] showed that software engineers care about energy, however, they are not successful due to a lack of necessary information. It also proposed that energy concern exists during different stages of software development. For instance, during the requirements specification, energy optimization is often seen as a threat to performance. During the design, developers do not consider energy scenarios due to the lack of scenario-aware tools. Ignorance of new energy techniques and the need for fine-grained tools for the whole system are the main reasons energy is forgotten during the construction of the software. Finally, when finding issues and making the maintenance of the application, developers are not concerned by the energy consumption unless it has a big impact, for example, battery drain.

[64] presented an energy-aware model-based approach to the development of a wearable medical device. It is based on the different layers compatible with this CPS. Design decisions were made after evaluating and redesigning different mechanical principles in the mechanical layer, evaluating different regulation algorithms (periodic and event-driven) in the computation layer, and evaluating the energy during different communication scenarios in the communication layer.

Authors in [65] presented a generic co-simulator for ICT and its power consumption. This simulator is distinguished by its architecture, modeling, and time management capabilities. They showed the important impact of ICT on the power consumption of a CPS (especially the networking layer). They also showed that energy-efficient choices of networking could result in lower functional efficiency.

In [66], a model-based design methodology for residential micro-grid was proposed. In

addition to a simulation presenting the structural and behavioral parts of a residential micro-grid system. The model-based design was divided into four parts: (1) modeling the power grid, (2) modeling the grid management algorithms, (3) developing the cyber-physical co-simulator, and (4) verifying and validating. Their simulator made possible the experimentation and comparison of electrical vehicle demand algorithms, residential demand response, and grid reliability.

In [67], energy dimensions were added to CPS and IoT modeling to raise awareness about energy consumption in such systems. It also presented CPS as the key link between energy and information.

The authors in [68] proposed a cyber-physical waste management system solution that provides a cyber-physical model design and description, mathematical modeling, and two cases to investigate the impact on energy consumption and emissions.

In [69], proposed the use of digital twins to raise the capability of improving and enriching knowledge from collected available data. The authors collected data such as temperature and air velocity in different rooms. They used artificial intelligence techniques for predictive analysis.

The authors in [70], proposed a two-stage approach with interpretive structural modeling and structural equation modeling to show the link between the green supply chain and Industry 4.0. Their goal is to prove the correlation between these two concepts and help organizations make decisions for improved sustainability performance.

In [71], an energy management framework used for autonomous electric vehicles in the smart grid was proposed. It is able to collect the real-time power consumption status and demand from autonomous electric vehicles and charging stations. Energy saving in this system was done during design (architecture and communication protocol). For the architecture part, path planning was made with respect to energy saving. For the communication protocol, an event-based control was used to reduce the communication between sensors, controllers, and actuators. This technique acts like the continuous state-feedback controller by establishing communication between components after the occurrence of an event, therefore it reduced CPU and network bandwidth, thus energy reduction is guaranteed.

[72] proposed a domain-specific language for energy-efficient building modeling. It was based on the following elements: location, facility, sensor (including its unit and measured value), and rules. However, their modeling approach was missing actuators, energy feedback, and a more fine-grained description of the system.

In [73], a statistical model for simulating and validating different energy strategies in CPS in the railway CPS domain was presented. It was adopted to choose the most energy-efficient and reliable policies in such stochastic and critical environments.

The authors in [74] presented a framework to monitor, simulate, and analyze data center thermal performance and energy efficiency. It is based on the integration of WSN, building information modeling, and building management systems. However, their proposed framework was not tested or detailed regarding the collected metrics and potential actions.

In [75], a multi-agent architecture for building energy management in CPS was proposed. It is based on 4 main layers: field layer, data acquisition, autonomic computing, and management. Collected data are contextual ones such as temperature, humidity, and light brightness. Actuators include switches, HVAC, and computers.

The authors in [76,77] showed the impact of CPS workloads on its design and optimization. First, they identified the main complex characteristics of CPS workloads (such as self-similarity and nonstationarity), then, they proposed statistical equations for modeling these workloads. They also showed that better design optimization for

some cost functions can be reached using the mathematical description of workloads such as resource allocation and power.

The authors in [78] proposed an energy cyber-physical model for cleaner manufacturing. Their architecture was divided into a physical-energy layer (IoT devices capturing energy-related data during the whole process of production), a cyber-energy layer (that included data cleaning and data mining processes), and a data and knowledge-driven system layer (seen as the top-level layer that monitors, alarm, assess, and optimizes parameters). Their approach ensured not only the monitoring of electrical energy flow but also water and materials.

In [79], contextual collected data and machine learning techniques were used in the context of a cloth dyeing factory. Their goal was to identify and predict the process inefficiency from the functional point of view, therefore, lowering the possibility of repeating the dyeing process and energy waste. The process was adapted, parameters were tuned, and the laboratory pre-production phase was replaced by real-time monitored data.

4.5. User Recommendation and Behavior

The human is a major component in the CPS. On one hand, he has continuous direct and indirect interaction with the environment where the system is implemented [80]. Some researchers [81] include the human in the CPS loop as a service capability description model. They associated properties describing the role of each person, his capabilities, knowledge, availability, reliability, and interaction endpoints with the system for the CPS. On the other hand, user choices can be critical in the energy used by the CPS. For example, different applications performing the same task consume differently because of facts like synchronization with cloud, web-based energy inefficiency, heavy applications on startup before performing the task, continuous events are expensive (Spellchecker), user interface [80]. [44] showed that human behavior has a direct impact on energy consumption in residential CPS.

Encouraging users to change behaviors in a CPS is a new trend. CairnFORM aims at creating and encouraging new socially shared practices by displaying energy data in collective and public spaces in the form of stackable interactive rings, where each ring corresponds to a defined time during the day. It is based on the current consumption of the tested area and the amount of renewable available energy [82].

[83] designed a community-scale energy feedback system having three main features: spatial, energy supply, and energy consumption. It is based on building power meters. It increased the visibility of building energy consumption using augmented reality for real time and for historical data, in addition to the improvement of the power consumption over the years and the energy source for each building. This framework is considered an open urban energy data technique because all this data can be shared from all the buildings to all the citizens of the community. The main drawback of this approach is the total lack of granularity.

A gamification approach that motivates the occupants of an apartment to take action and reduces their energy consumption by rewarding them with points was proposed in [84]. In addition to a framework that learns models based on the players' decisions. An eco-feedback is proposed in [85]. It consists of mapping between the physical and virtual environment to motivate the user to take energy-efficient actions in a smart home. This is done by tracking the user in the house using sensors and knowing what are the activities of the user. Then, by transforming the home into a game form and the

energy-consuming appliances into enemies in this user interface. The authors in [86] presented a virtual pet game by reducing plug loads in mid-size commercial offices. It showed that by using the game the workers reduced their energy consumption by 13% and even after using this game the workers had better energy-saving habits. Besides, findings showed that there was no rebound effect by the users of the game after they stopped playing it but it helped them build energy-oriented habits. This shows that this kind of solution could be useful for raising energy awareness regarding energy-aware behaviors. However, they are not a reliable solution because it takes a lot of effort and time to implement especially regarding graphics and user interfaces.

In the next section, we analyze and compare the reviewed approaches, and draw our observations of the current state of the art in energy-aware CPS.

4.6. Power Supply and Demand

Many approaches deal with the energy efficiency problem in CPS by changing the power supply source to renewable ones or matching demand to the supply in order to use the generated energy more efficiently [87].

In [88], a framework (called SG-CPS) capable of collecting ambient sensors' values in order to predict the user demand and power supplied from renewable energy sources is proposed. It collects temperature, humidity, sunlight, and wind speed. It also includes two optimizers for purchasing energy decision-making (one uses linear programming and the other multi-stage stochastic programming). These two optimizers resulted in lower energy consumption but are computationally intensive. More investigations should be done on more metrics for prediction and lower resource-intensive optimizers.

The authors in [89] presented a framework for energy management in a building by considering different energy resources (especially renewable ones). They also discussed user choice and the use of a decentralized management system. However, their approach was based on production and demand and did not take into consideration a fine-grained view of the systems inside a building and its data.

In [90], an energy balancing system between different houses having solar panels and connected to the grid is proposed. This problem was solved using the minority game algorithm that deals with limited resources and multi-suppliers issues. A multiple-customer model is also proposed where a task that is done by the user can be inactive, active but unassigned to a supplier, active and assigned to the grid, or active and assigned to battery or solar. It reduces the use of the grid and maximizes the use of green sources, however, the high ecological impact of batteries in the long term was not taken into consideration.

The authors in [91] proposed a set of algorithms used to check which set of battery-powered nodes to charge, then charged them with the help of an unmanned aerial vehicle. These algorithms are based on the remaining power, the required power, and the probability of discharge per unit of time for each node.

In the past few years, there has been an increasing interest in the research and development of Electric Vehicles (EVs) that are charged by connecting them to the grid to store energy. The essential advantage of these EVs is that the transition of electricity can be done in both directions, therefore a vehicle can push back electricity to power the grid from its battery. Their storage capabilities enable them to store electricity from renewable energy sources such as wind or solar and discharge when needed. This kind of vehicle is sometimes referred to as Gridable EV (GEV). They are considered distributed energy storage systems. Vehicle-to-everything (V2X) is also

a common research track. V2X covers a wide range of use cases, including vehicle-to-home (V2H), vehicle-to-building (V2B), as well as vehicle-to-grid (V2G) services.

[92] proposed the use of gridable vehicles in cyber-physical energy systems by storing the energy in these vehicles during off-peak and using it when needed. This approach was intended to guarantee the minimization of cost and emissions using the PSO. Three cases were studied: (1) the vehicles charge and discharge randomly, (2) vehicles are charged from the conventional energy generation using load leveling, (3) vehicles are charged from renewable energy sources during off-peak hours and discharged during peak hours. Results showed that the smart grid model (using renewable energy) was the most convenient and resulted in lower costs and emissions.

[93] proposed the use of bidirectional energy exchange between vehicles and the grid in order to fill the gap between demand and supply. Their main contribution is the use of blockchain, contract theory, and edge computing to accomplish this task.

4.7. Software

Without any doubt, software has an impact on the power consumption of any system. Many research articles presented the importance of software development and the main issues faced by developers producing their low interest when it comes to energy [94].

The algorithm and complexity are the main factors that affect the energy drained because of the software. This kind of energy loss is due to the choices made by the developers while writing their code. [95], propose a model to estimate the energy consumption of a JAVA application during execution. The developed tool (TEEC) was tested on an optimized and un-optimized Java code and the results were validated by the Watts Up Pro Portable Power Meter. It found that memory should not always be neglected when compared to the CPU power consumption, whereas power consumption of hard disk could be neglected.

Another important choice while writing code is the choice of programming language. It is not only essential to develop in the most efficient, scalable, and compatible way, research shows that it also affects the power. [96], compare the energy efficiency and performance of the most commonly used approaches to develop applications (Java, JavaScript, C/C++) in Android mobile applications. It found that JavaScript saves more energy and is slower than the other approaches for benchmarks and that application hybridization may be a solution for application optimization, both in performance and energy consumption. For example, the difference between the most energy-consuming (Perl) and the most energy-efficient (C++ with O3) is equal to 25 463 joules which is considered quite high. An identical algorithm can have various energy consumption based on the language used to develop, based on the optimization level and the adopted design (recursive or iterative) [97].

In addition to the algorithms and the languages, it is possible by running the same software on different hardware to get different power consumption results [98]. This shows that the architecture on which the software is implemented also affects energy. For example, running an identical code on a microcontroller like Raspberry Pi consumes remarkably lower energy than on a laptop. [99] measured the power consumption of an application by using different frequencies and changing the number of cores and found that using all the available cores with the highest frequency is the most efficient regarding energy consumption.

5. Analysis and discussions

In this section, we first introduce our comparison methodology, then compare and discuss the reviewed state-of-the-art approaches in two main categories: single-layer and cross-layer approaches. Then, based on our analysis, we propose an energy-oriented referential architecture for CPS.

5.1. Comparison methodology

We define a list of comparative criteria that we use to compare the reviewed CPS approaches:

Applied domain: CPS can be implemented in a variety of domains. It has applications in healthcare, transportation, smart cities, and many others. Most of the domains, where CPS are present, are highly dependent on electric energy to run and are essential to our daily life making us interested to identify in which domains researchers are thinking about energy as a concern.

Studied parameters: A set of energy-consuming related metrics of each solution that researchers found significant and changing them leads to energy optimization. They can be found in all phases of building a system during modeling, developing, or operating phases. These metrics were studied by each of the research papers and it was found that they have an impact on the consumed energy.

Monitored layers: These Are one of the most important comparison criteria because they show the levels of the CPS where these approaches were developed. It allows an understanding of which layers the optimization was done and if it is limited to it. Monitored layers can be any of the CPS layers defined in section 2.2. It can also be the entire device for solutions that take all the layers of a device as one entity, or a contextual layer where the solution monitors only the changes in the environment.

Level of autonomy: Autonomous systems are devices aware of their surroundings and can accomplish their tasks on their own without any intervention from humans. They can perceive, make decisions, and actuate a process in their environment using a control loop. We are also interested to know if the solutions are autonomous or not due to their adaptability in a changing surrounding. To standardize the comparison, four levels of autonomy were defined. They are represented by numerical values ranging from one to four. The first level represents solutions with no actuators or based on changes in the design phase such as architecture or modeling. The second level groups the approaches where user interventions are needed. The third level is with basic automated actions, however, they are limited such as rule-based. The fourth level represents approaches that have a high level of autonomy. For example, non-autonomous solutions are usually predefined rule-based, need the intervention of the user, or are findings that can be implemented on the design time to make more power-efficient CPS.

The following two sections analyze energy-related solutions, first, by identifying what are the solutions proposed to optimize the energy consumption of each layer, as seen in figure 7. Then, by finding cross-layer exchange potential to adapt and holistically optimize the system, in the next section. In both cases, we found that autonomous solutions are rare and that most solutions proposed for CPS are based on scheduling techniques, acting mainly on the entire device or system by changing its mode between active, sleep, and power off to minimize the energy [31,32].

Table 2.: Comparative study of energy CPS (1/2)

Paper ID	Applied domain	Studied parameters	Monitored layers	Level of autonomy
[31]	Smart Home	Stand-by power	Entire device	3 (No reconfiguration)
[44]	Smart Home	Task schedule	Entire device	1
[33]	ICT	Entire system	- Communication - Service	1
[48]	General	- Operating Modes - CPU frequency - Networking speed	- Sensing - Actuating - Communication - Processing	3 (fixed and by layer)
[49]	Transportation	- Sampling frequency - Compression type - Archiving need	Entire Device (per concerns)	3 (defined configurations)
[100]	ICT	Software (Algorithm)	- Processing - Memory	1
[50]	Smart Home	Human presence	Entire System	3
[23]	Smart City	Human presence	Entire Device	3 (Limited to use cases)
[64]	Smart Home	Event-driven communication	- Processing - Communication	1
[83]	Smart City	Human behavior	Entire system	1
[84]	Smart City	Human behavior	Contextual	1
[85]	Smart Home	Human behavior	Contextual	1
[86]	Smart Office	Human behavior	Entire device	1
[30]	IoT	- Transmission protocol - Device state	Communication	4 (local)
[43]	Smart Home	Task schedule	Entire device	3
[46]	Smart Home	Wifi exchange	Communication	1
[57]	Smart Office	Task migration	- Processing - Storage	3
[58]	ICT	Task migration	- Processing - Storage - Communication	3
[76,77]	General	Workload	- Processing - Communication - Control	1
[82]	Smart City	Data visualization	Contextual	1
[92]	Transportation	Energy sources	Entire device	1
[34]	ICT	- CPU - Temperature	- Processing - Contextual	1
[36]	ICT	Task scheduling	Entire device	4
[93]	Transportation	Energy storage	Entire device	N/A
[65]	ICT	- Load - Communication protocol	Communication	1
[39]	Industry	Task schedule	Contextual	3
[71]	Transportation	Communication protocol	Communication	1

Table 3.: Comparative study of energy CPS (2/2)

Paper ID	Applied domain	Studied parameters	Monitored layers	Level of autonomy
[35]	ICT	- Temperature - Workload	- Contextual - Processing	1
[88]	Smart City	- Contextual data - Energy source	Contextual	4
[66]	General	Simulation	Entire system	1
[78]	Industry	Energy sources	Contextual	3
[52]	ICT	- Data correlation - Nodes distance - Residual energy	Communication	4
[59]	ICT	Task migration	Entire device	4
[42]	ICT	- CPU frequency - Task scheduling	Processing	4
[60]	IoT	Location	- Processing - Communication	3
[89]	Smart City	Production/Demand	Entire system	1
[41]	Healthcare	Data cleansing	- Communication - Processing	3
[79]	Industry	Contextual data (not mentioned)	Entire system	2
[74]	ICT	Temperature	Entire device	1
[72]	Smart City	Modeling	Sensing	1
[73]	Transportation	Modeling	Entire device	1
[40]	IoT	- Routing protocol - Task scheduling	Communication	3
[75]	Smart Home	Contextual data	- Sensing - Contextual	N/A
[90]	Smart City	Energy sources	Entire system	3
[53]	ICT	Contextual data (not mentioned)	Entire system	4
[54]	Transportation	Contextual data (not mentioned)	Contextual	4
[95]	ICT	Code Optimization	Service	1
[99]	ICT	- Frequency - CPU cores	Processing	1
[96,97]	ICT	Prog. Language	Processing	1
[98]	ICT	Processor Arch.	Processing	1
[38]	ICT	- Memory access latency - Cache misses	Processing	3
[55]	Transportation	Contextual data	Contextual	4
[45]	IoT	Operating mode	Entire device	2
[67]	General	Modeling	Entire device	1
[68]	General	Modeling	Entire device	1
[91]	IoT	Battery level	Entire device	3
[69]	Smart City	Contextual	Contextual	4
[70]	Industry	Modeling	Entire device	1

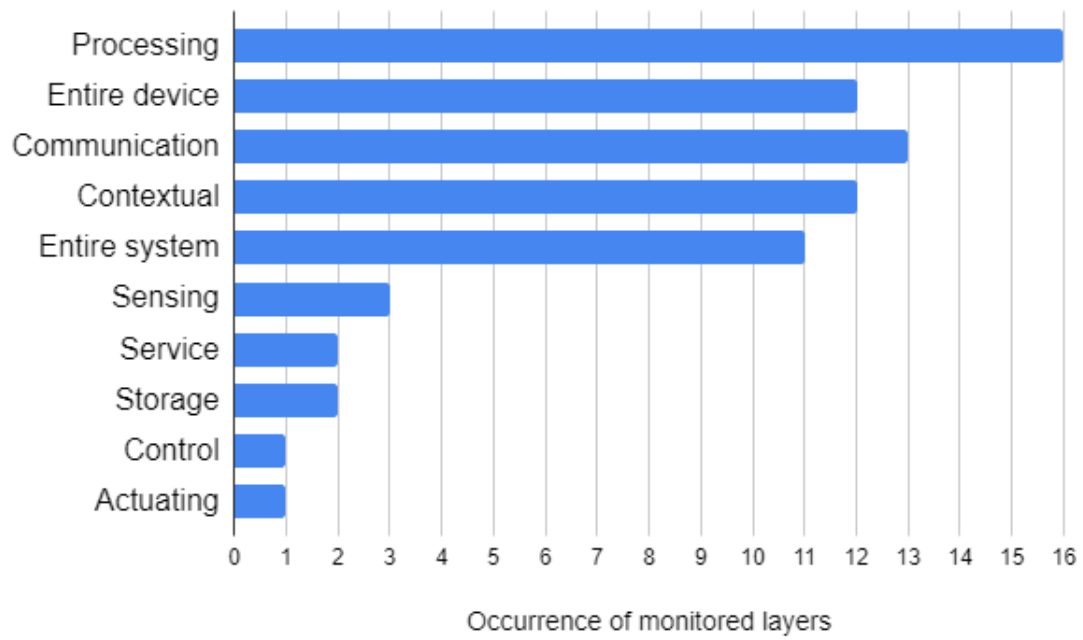


Figure 7.: Quantitative comparison of monitored layers

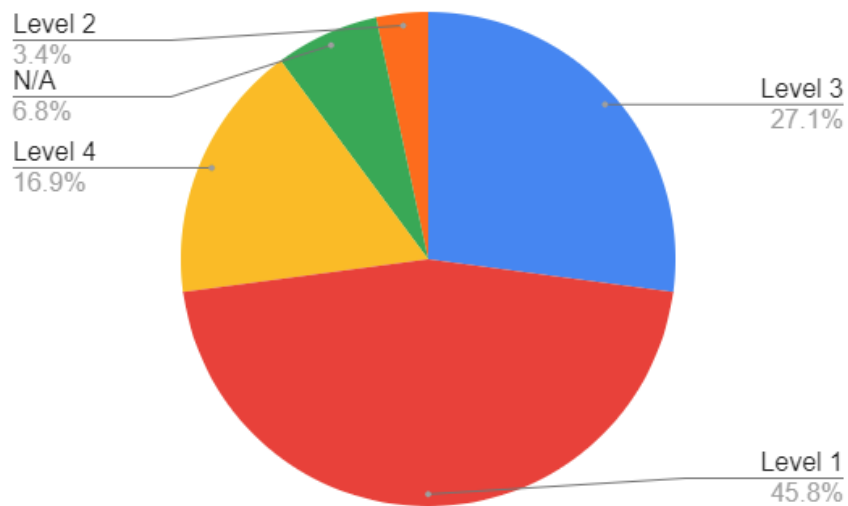


Figure 8.: Quantitative comparison of level of autonomy

5.2. Independent layer approaches

A high number of recent research papers are based on user feedback but they are not autonomous. However, we find that most of the proposed approaches in the literature deal with energy issues on a limited number of layers. We found that some application domains are strongly related to energy concerns in specific layers. I.e., solutions in the IoT domain are related to the communication layer and ICT domain-related solutions are related to the processing layer. For each of these layers, we identify the potential energy hotspots and the applied energy optimization solutions, based on the comparative study in tables 2 and 3. In this section, we discuss the energy management approaches by dividing them based on the previously identified CPS layers.

5.2.1. Entire device

Most solutions propose reducing the energy of an entire device, these solutions are based on scheduling and switching between various operating modes. Even if a high percentage of energy is consumed by devices in idle modes, these solutions optimize energy only when a device is unused. However, no optimizations are applied during its active state, making such approaches less than ideal. In [31,32] no optimizations are being done while a device is running, for example, it is impossible to maintain the sensors of a device running while it is in a low-power mode. A lack of autonomous flexibility is present in the last two solutions, due to the need for the user to change the configuration of the system each time a device gets connected to a different outlet. They also use hardware measurement tools that allow them to measure the whole device with high precision, however, making them more expensive and difficult to deploy. The main drawback in [44] is that not all tasks can be rescheduled automatically due to their diversity and the inconvenience for users to perform the tasks at an involuntary precise schedule. In [89], the entire system is considered as one entity. and it did not take into consideration a fine-grained view of the systems. In other papers such as in [90,92,93], the long-term impact of batteries is not considered.

5.2.2. Services layer

The software can include potential parameters related to the code, for example, the complexity or the number of bugs and violations by the developers. On this layer, many research papers highlight the lack of tools and knowledge of the developers about the impact of their code [63]. Some real-time energy bug scanners exist but are not commonly used across the community. We argue that energy awareness concerns should be introduced to would-be developers in their education curriculum. We also find that another energy concern is the choice of algorithms in software, as some algorithms are more optimized than others (for the same workload), thus leading to energy reductions [95]. The choice of the programming language also has an impact on the power [96,97]. In [97] the same application developed using Perl programming language consumes more energy than developing it using C++. This kind of decision needs to be done during the design and development of the applications running on a CPS but will have an impact during the run-time.

5.2.3. Processing layer

A collection of applications and services usually run over the processing layer. The processing layer is one of the main layers of a CPS, responsible for analyzing data

captured by sensors and running the applications on the system. Many research studies show that running the same application using different processors leads to different energy consumption due to various reasons processor architecture being the main one as in [98]. By changing the frequency [42,48], the number of active cores [99] in a CPU, the algorithm [100], the workload [35,76,77] or the data cleansing [41], energy minimization can be reached. Generally, this is possible due to lower the time needed to accomplish a task, but this is not always the case because this can lead to a power increase even if the time decreased. Another important factor for software is the hardware on which it is running [57,58]. Hence, makes us think about the optimal device to run the analysis, in the case of a system-of-systems most of the processing is either done locally or remotely on a cloud. We believe that running the analysis can also be done on nearby devices in the same CPS if these devices consume less. Most software solutions are done on computers or servers in the domain of ICT. We argue that more research should be done in CPS due to the high potential of using software layer energy optimization for more energy-efficient systems.

5.2.4. Storage layer

The storage layer consists of the equipment responsible for storing the data and keeping them available in order to be processed. Data can be locally stored in SD cards and hard disks or remotely in the cloud. On one hand, storing data on the cloud creates sometimes an illusion of zero energy but it is essential to mention that sending the data to the cloud may result in more significant energy usage. Firstly, by using the networking medium, and secondly, by keeping the data centers that host the cloud servers operational. On the other hand, green data centers use energy-efficient technologies such as low-power servers, modular data centers, free air cooling, renewable energy sources, and other sustainable technologies. Hence, it is essential for each piece of data to choose either to store it locally or on the cloud.

5.2.5. Communication layer

The communication layer is the medium to exchange data and events between devices of the same system, between IoT devices (used as sensors or actuators), or between the system and external sources such as the cloud or web services. Wireless ad-hoc is a form of local area network (LAN) that is built spontaneously by a collection of nodes. It enables two or more wireless nodes to be connected to each other without requiring typical network infrastructure equipment [101]. Delay-tolerant networks operate effectively in extreme conditions and over very large distances [102]. Moreover, wireless ad-hoc and delay-tolerant networks have limited energy resources because they are conceived to operate self-sufficiently in remote locations. Some studies proposed routing algorithms [40,65], other used scheduling techniques [30,59,60], other focused on data collection and cleansing before sharing [41,52]. Reducing energy in the communication layer is also limited to a variety of operating modes based on the used bandwidth. We think scheduling should not only be used to change modes but also to accomplish tasks during the optimal time. For example, if a device needs to download or upload data through the network, it would be more convenient to perform the network transmission when the device is plugged into an outlet, and the electricity produced is from renewable sources. Communication frequency and protocols are also found to have energy impacts. In [46], occupancy detection using the communication layer has one major advantage because there is no need to implement new sensors in

the environment for the system to understand the context.

5.2.6. Sensing and actuating layer

The sensing layer monitors the environment of the CPS using physical and virtual sensors. The actuating layer is the medium used to execute the changes planned by the system. This layer can either be physical (*e.g.*, a hardware sensor) or virtual (*e.g.*, a logical or software sensor). The main concern on these layers is the optimization of idle power consumption. In [48], the authors proposed to have multiple operating modes where the transceiver is turned off because this part of the sensor consumes the most. This approach can be considered efficient if the sensor has a transceiver, but in many cases, the sensor is part of a connected object having one transceiver for its entire operations. Having flexible sampling frequencies is another solution [49]. However, it is trickier to use as it needs to be well understood in order to increase or decrease the frequency, with some situations where a high sampling rate is necessary to obtain reliable information [103].

5.2.7. Contextual layer

The contextual layer is the knowledge and understanding of what is happening in the environment of the system. It is usually built upon the observations of the sensing layer, and also includes human activities and behavior [84,85]. Others use contextual data such as power sources [78,88]. During our literature review, we first found that the main contextual information collected for energy optimization is the detection or prediction of the presence of the user, also called occupancy. However, studying user behavior should not be limited to presence detection. To reach higher energy-saving it is essential to understand all the human actions in the environment (such as the time they use each device, their presence, their sleeping schedules, and many other factors). This leads to an efficient reduction in CPS idle mode power. In [50], one drawback is that their solution takes into consideration occupancy but does not consider users' interactions with the building like opening a door or window. The environment where CPS are implemented is heterogeneous and rich with information that can be collected [53,54,75], however, it only focuses on the functioning loop of the system through its touch points (sensors and actuators). For example, information such as: what is the user doing and what devices are being used. This can be solved by a cognitive system that understands the holistic view of the system and all the aspects of the environment. Second, most solutions that consider the user focus on user recommendations and are not fully autonomous as seen in figure 7 and figure 8. Autonomous systems are needed as these solutions optimize energy automatically and in real time without the need for continuous human intervention. Sharing all this information about user behavior raises a critical concern of security and privacy. Secure and encrypted communication should be used to share this information, with a priority to limit data sharing to local devices.

5.3. Cross-layer approaches

Layered communication has a strong separation in the definition of each layer where the interaction between them is strictly controlled and limited to the necessary data to operate the system. In contrast, cross-layer approaches are protocols or architectures where the information of each layer is highly shareable with others. This way the infor-

mation becomes more valuable and useful to accomplish better performances [104], in our case, lower energy consumption. CPS have a variety of energy-consuming concerns due to their various functionalities. These concerns can be found on an individual layer as seen in section 5.2 as well as on a combination of more than one layer.

First, the review of previously proposed CPS architectures showed a lack of energy concerns while defining the layers of the system. In particular, the optimization of software and contextual layers are not energy-aware. As seen in tables 2 and 3, many layers are used in a CPS and can be energy-consuming. We argue that the way researchers and practitioners model a system, without taking energy into consideration, is a major limitation for sustainable CPS. This might be due to a lack of understanding of energy in CPS. Hence, there is a need for an energy-aware CPS architecture able to identify all potential energy-consuming layers.

Second, as discussed in the previous section, solutions to optimize energy consumption mostly target single layers. We observe a lack of cross-layer energy optimizations. In [48], each layer has its operating modes but no data exchange between the layers to share their modes. The system does not exchange data between layers but optimizes each layer independently regardless of what is happening in the other layers. In [49], a huge amount of effort is needed from developers to specify each of the energy potential consuming concerns, making it complex to implement. Then, they create a file containing a series of configurations and their energy consumption. These approaches are limited because they are not flexible if new functionalities are added to the system or if a new device joins the CPS. They are also limited by the managed or collected metrics and cannot change on run-time.

We observe a lack of holistic solutions at the levels of the device and the entire system, which we argue is needed to build sustainable CPS. For example, each layer on a device can be optimized individually and then exchanging knowledge and information between different devices of the system leads to holistic energy-efficient management and a decrease in energy consumption. This leads to a scalable solution in complex system-of-systems. For example, in the context of a smart home, bulbs can minimize their energy by detecting occupancy and the time of day. They can then share their status with the refrigerator constantly opened by the user. This is done in order to know if the fridge needs to turn its light on or whether the light in the room is enough to illuminate the content of the fridge. In fact, a cross-layer exchange is already present in all CPS, as a CPS includes sensing, actuating, communication, storage, processing, and application/services layers. Most CPS sense information from the environment, analyze the data, then apply actions through actuators to the same environment. This is achieved in one direction and is oriented to satisfy the functionality of devices. Current shared data are limited and are not related to energy. Sharing energy-related data in addition to the operational one leads to a higher understanding of the environment and raises the ability of decision-making. Shared information would include data captured from sensors, in addition to the state of each layer in a device, and contextual information.

5.4. Energy-Oriented Referential Architecture (EORA) for CPS

In this section, we propose a high-level conceptual referential architecture to encourage research on different layers when studying energy consumption in CPS. We present in Figure 9 the Energy-Oriented Referential Architecture (EORA) for CPS. It is inspired by the MAPE-K autonomic computing approach [105]. The adoption of a

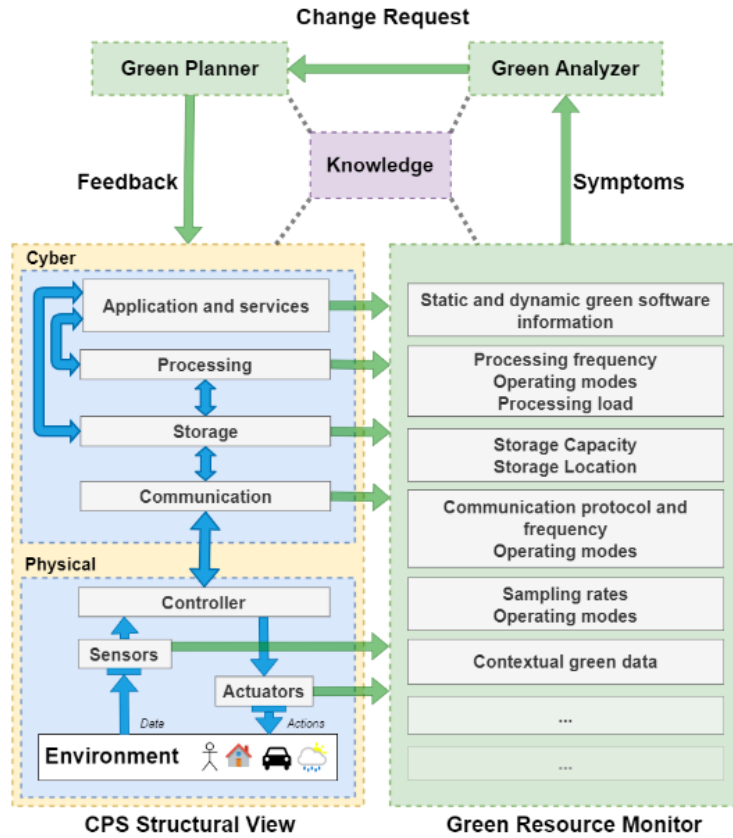


Figure 9.: Energy-Oriented Referential Architecture for CPS

MAPE-K approach guarantees non-functional capabilities including self-management, self-configuration, self-optimizing, self-healing, and self-protection. In addition, it guarantees functional capabilities covering data collection, monitoring, analyzing, planning, executing, and actuating. On the one hand, it is composed of the most widely recognized layers of a CPS as discussed in section 2 from a structural point of view divided into a physical and a cyber part. This architecture is a general one because it contains the commonly found layers of a CPS. We intend to apply it in different domains alongside the particular domain-specific approach already used for energy reduction to guarantee green knowledge acquisition leading to higher energy optimization. On the other hand, an energy-oriented feedback loop is responsible for making the necessary green adaptations, therefore, reducing the energy needed in a CPS. In addition to a common knowledge repository that allows the exchange of information between different components.

CPS Structural View, firstly, in the physical part of the system, we find the contextual environment containing all the actors, objects, and phenomena that produce raw data such as humans, weather, or other factors. This layer interacts with the CPS through touch points (sensors and actuators). On the one hand, sensors collect the data and transform the physical actions into electrical signals. On the other hand, actuators transform electrical commands into physical actions. Both

sensors and actuators need to be mounted on a controller (such as a Raspberry Pi) that has minimal processing, storage, and communication capabilities to be able to communicate with the rest of the CPS. The physical part of the system includes the controller due to its presence in the physical environment. However, it is also considered the gateway to the cyber part. Secondly, in the cyber part of the system, we identified communication capabilities allowing it to interact with a diversity of appliances, microcontrollers, IoT devices, and others to acquire useful data. The collected data is then stored and processed in the same environment or on the cloud. The application and services layer allows users or other systems to access the CPS through specially defined interfaces. It also allows the CPS to provide or consume services.

Green Resource Monitor collects a collection of useful data from each of the previously enumerated layers in the CPS, to identify the energy-related leakage. Data can be captured using APIs, software estimation tools, physical sensors, or other means. In this module, data is cleaned, filtered, and aggregated. Collected data could be related to the context, communication, processing, software, or states of the devices. Some examples of collected data could be contextual, sampling rates, communication protocols, speed, storage information, processing frequency, running software information, operating modes, and states of the devices. It selects the significant features, correlates, and organizes them as symptoms that are sent to the analysis entity.

Green Analyzer is the entity responsible for exploiting and processing the collected data received from the monitor as symptoms. Furthermore, finding what is draining the power of the system and what can be done to reduce this consumption following high-level management strategies. It classifies symptoms and processes them to deduce a diagnosis.

Green Planner proposes a set of actions that need to be achieved to accomplish the high-level goal related to energy consumption. It aims to plan what should be changed to reduce the energy of the system and send this feedback signal back to the CPS to execute it. Short-term and long-term plans are elaborated. They are highly based on the change request sent by the analyzer and the knowledge repository

Knowledge repository is a set of dynamic resources. It is modified in real time with every cycle in the feedback loop. It exchanges with all the previously cited entities with awareness abilities. It can be built using different approaches including predefined rules, machine learning, predictive models, or semantic data models using ontologies. It also includes high-level management policies.

Each device in a CPS is considered a system highly connected to the other ones making the analysis and execution not limited to the device from which the data has been collected but to each available device in the entire system.

We believe that the proposed EORA can be used to minimize the energy used by a CPS from a holistic point of view. It can be implemented in the local environment where devices delegate the role of each of them or with a part being local and the other being on remote devices. However, one main challenge to this architecture is the distribution of its layers on many devices and many locations, in addition to the abstraction level of each of them. For example, different devices can use a variety of protocols that can even be proprietary and not allow us to access the totality of the needed data.

6. Conclusions and recommendations

As CPS are gaining an increasing role in our daily activities, their energy impact is also rising and becoming a major concern for their sustainability. In this paper, we reviewed the state-of-the-art energy-aware CPS approaches and compared them according to several criteria aimed at the studied parameters, monitored layers, and the level of autonomy of each of the approaches. We found that the most common layers of CPS are sensing, communication, actuating, processing, services, and control. We presented a literature review of the previously proposed solutions that deal with the issue of energy optimization in CPS and categorized them. Then, we explored energy approaches for each of the application, processing, storing, communication, contextual, sensing, and actuating layers. We also identified the approaches covering more than one layer and discussed cross-layer solutions and their advantages for building a holistic energy-efficient system.

In short, our findings are the following:

- We have detected a lack of the studied metrics not covering all potential energy drain sources in a system.
- Solutions deal with limited layers of a device mainly due to the challenges of exchanging data in a heterogeneous environment.
- Most solutions are not autonomous. However, some could be considered to have a limited degree of autonomy. Energy optimization in CPS is not yet fully mature, notably due to the lack of holistic and autonomous solutions.

Therefore, we draw the following recommendations for future energy-aware CPS solutions:

- Researchers should address the energy from a holistic point of view by studying the possibility of optimizing energy by collecting various data from different layers in a CPS. They should also investigate if collected data from a layer can help have an impact on reducing the energy of other layers. Therefore, knowledge representations of energy-related metrics in different layers of a system are needed.
- Researchers could improve the energy consumption of idle devices, either by reducing their energy to the minimum or by reusing their unused capabilities to lower the energy costs of other devices. Researchers should also investigate all possible energy-reducing actions.
- Large-scale distributed CPS with tens of processors, in contrast with the simple ones with one processor, have significantly greater complexity and need to be better studied. Research should focus on the heterogeneity of devices, the ease of applying proposed solutions to any domain, and guarantee their efficiency under different circumstances and different devices.
- The energy management in modern CPS needs to be fully automated or autonomous, and be able to adapt to changes in the environment with little or no human intervention. These autonomous adaptations also need to respect users' preferences and comfort levels, to avoid being ignored in favor of more energy-hungry solutions. Autonomous approaches can use artificial intelligence, machine learning techniques, adaptive control systems, or knowledge representations to achieve their goals. Using architectures similar to the proposed conceptual one has the potential to achieve higher levels of autonomy.
- CPS architectures need to take into consideration the contextual data and ac-

tivities in its surrounding environment, in order to efficiently optimize energy consumption. The goal is to build a comprehensive and holistic approach that collects information from multiple layers of the system and applies cross-layer adaptations to reach the lowest possible energy consumption.

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