From Serendipity to Sustainable Green IoT: Technical, Industrial and Political Perspective

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***Abstract*—Recently, Internet of Things (IoT) has become one of the largest electronics market for hardware production due to its fast evolving application space. However, one of the key challenges for IoT hardware is the energy efficiency as most of IoT devices/objects are expected to run on batteries for months/years without a battery replacement or on harvested energy sources. Widespread use of IoT has also led to a large-scale rise in the carbon footprint. In this regard, academia, industry and policy-makers are constantly working towards new energy-efficient hardware and software solutions paving the way for an emerging area referred to as green-IoT. With the direct integration and the evolution of smart communication between physical world and computer-based systems, IoT devices are also expected to reduce the total amount of energy consumption for the Information and Communication Technologies (ICT) sector. However, in order to increase its chance of success and to help at reducing the overall energy consumption and carbon emissions a comprehensive investigation into how to achieve green-IoT is required. In this context, this paper surveys the green perspective of the IoT paradigm and aims to contribute at establishing a global approach for green-IoT environments. A comprehensive approach is presented that focuses not only on the specific solutions but also on the interaction among them, and highlights the precautions/decisions the policy makers need to take. On one side, the ongoing European projects and standardization efforts as well as industry and academia based solutions are presented and on the other side, the challenges, open issues, lessons learned and the role of policymakers towards green-IoT are discussed. The survey shows that due to many existing open issues (e.g., technical considerations, lack of standardization, security and privacy, governance and legislation, etc.) that still need to be addressed, a realistic implementation of a sustainable green-IoT environment that could be universally accepted and deployed, is still missing.**

***Index Terms*—Energy Efficiency, Internet of Things, IoT, Green Networking.**

I. INTRODUCTION

Internet of Things (IoT) is the network of physical objects that are referred to as *things*. These objects are integrated with particular sensors, software protocols and network adapters to enable intra/inter-connection of objects. With their unique identifiers, these objects are able to associate to each other and collect, transfer and exchange data over the Internet without requiring any human interaction. Therefore, IoT enables remote sensing and controlling of devices/objects over the Internet through existing network infrastructure. Consequently, IoT has a big potential to increase efficiency, accuracy and financial profit in almost every field of life, as it facilitates the direct integration of physical world with computer-based systems [1]. According to Cisco, it is predicted that by 2022, the IoT connections will represent more than half of all global connected devices and connections [2]. While the traffic generated by the IoT-enabled devices is predicted to reach up to 6% of the global IP traffic by 2022 [2].

Although IoT is not a new concept, its popularity has been dramatically increasing nowadays in both industry and academia. The term *Internet of Things* was used first time in 1999 by Kevin Ashton, one of the founders of AutoID Center at Massachusetts Institute of Technology, in a company presentation related to the Radio Frequency Identification (RFID) technology and sensors [3]. According to Ashton, the devices/objects that have RFID tags could communicate with each other via radio frequency as well as they could be linked to the Internet with RFID information. If all the objects and people in daily life were equipped with identifiers and wireless connectivity, computers could actually manage them.

Web Technologies are one of the important parts of the IoT, as devices are directly accessed, monitored, or controlled by them. The combination of Web Technologies and the IoT are referred to as *Physical Web* [4]. Nowadays, people, places, and things have web pages to provide information and mechanisms for user interaction. In this regard, utilizing a unique identifier is the key factor to enable interaction among devices. Internet Protocol Version 6 (IPv6) has extremely large address space, as it uses 128-bit IP addresses and hence, it is capable to assign a unique communication address for a global network consisting of billions of devices. Thus, each object world wide can be supported and easily linked to the Internet. Furthermore, existing web standards and services, such as Uniform Resource Identifiers (URIs) for bridging devices, Uniform Resource Locator (URL) & Distributed Name Service (DNS) for routing and connecting services, and Uniform Resource Names (URNs) are also available and their use and integration into enabling connections for smart devices is increasing.

Nevertheless, a large percentage of the objects in the IoT is not yet suitable for direct wired or wireless connection to the Internet, which makes them fall into the class of passive devices. For these objects, a tag, a smart-phone, and a proxy web service are needed to provide users with the object's web presence [4]. In this context, a variety of technologies for tagging an object that supports the Physical Web, such as RFID, Near-Field Communication (NFC), and Bluetooth Low-Energy (BLE) have became popular for IoT. The increasing popularity of IoT-based applications is leading towards a massive IoT deployment which covers several sectors, such as: agriculture, environment, industrial, consumer, utilities,

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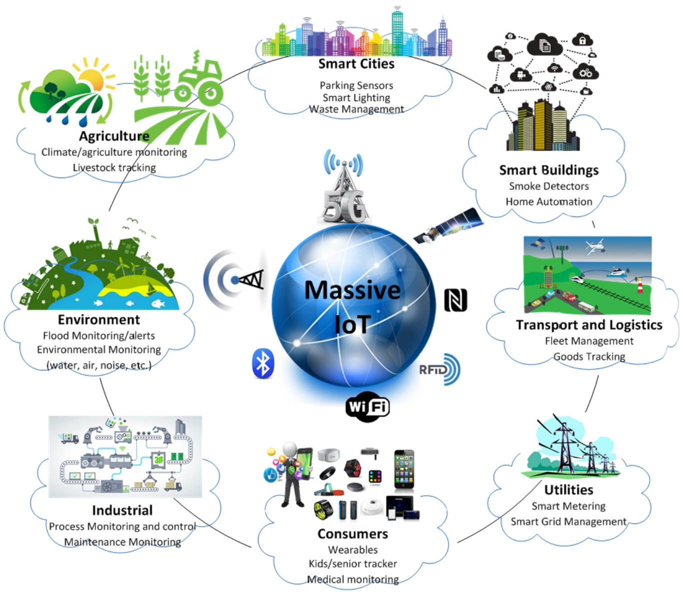

Fig. 1: IoT Solutions

transport and logistics, smart buildings and smart cities as illustrated in Fig. 1. The variety of IoT applications imposes a significant variety of requirements in terms of cost, battery life, Quality of Service (QoS) connectivity performance, security and reliability. For example, some of the critical IoT applications such as, remote health care or traffic safety and control might require high reliability and availability as well as very low latency. Because of the variety of these IoT applications, different underlying technologies (e.g., WiFi, WiMax, LTE, 5G, BLE, etc.) could be used to meet the various requirements of different services. As an example, small cells are already envisioned to be used in 5G-supported IoT communication in various scenarios and use cases to boost the service coverage, capacity and high QoS levels, satisfying mobile users' requests and meeting the requirements of high data traffic [5].

Consequently, IoT is considered to be the next step in the Internet evolution as it opens up new opportunities for players in various industries, such as embedded and control systems, home automation, healthcare, automotive engineering, consumer electronics, education, manufacturing, etc. In this context, the rapid growth of smart devices, sensors, wireless networks, big data and computing power will accelerate the development and deployment of massive IoT. However, in practice, there are substantial issues that need to be addressed with IoT, such as optimization of energy consumption and carbon emission, handling network scaling and complexity, determining device proximity, peer-to-peer connections, low-latency for real-time interaction, integration of devices that have little or no processing capability, etc. Consequently, one of the most defining terms for the next generation of cellular networks (5G) and beyond, is the *green communication* [6].

As stated above, one of the inefficiencies of the current networking technologies is the high amount of energy consumed. In the past, the research scope of Information and Communication Technology (ICT) was mainly based on performance and cost. Consequently, insufficient effort was supplied to the energy consumed by ICTs and its impact on the environment. However, the current trends, such as increasing costs of electricity, reserve limitations, and increasing emissions of carbon dioxide (CO_2) are shifting the focus of ICT towards energy-efficient well-performed solutions [7]. Thus, ICT is expected to have a significant impact in enabling support for global economical, social, and environmental sustainability as well as sustainable industrialization [8]. Even though governments and companies are now aware of the massive carbon emissions and energy requirements, it is obvious that these will continue to increase [9]. According to the SMART 2020 study [10], the ICT-based CO_2 emissions are rising at a rate of 6% per year. With such a growth ratio, it is expected that CO_2 emissions caused by ICTs to reach 12% of the worldwide emissions by 2020. The total amount of energy consumption by ICTs will increase even more with the deployment of IoT, unless it is utilized in a smart way. In this context, significant energy efficiency could be achieved with IoT, by enabling a smart network, where data is dynamically gathered/exchanged among devices, computers and power grids and then processed to build a green environment, smart homes, cities and hence, a smart world.

IoT-based devices are mostly supposed to be autonomous for years and may be equipped with several network interface cards to operate in the existing wireless communication infrastructures in a flexible way. Inter-working of heterogeneous networks may increase network performance and provide mobility support for devices. Nevertheless, this flexibility may cause additional energy consumption on the device.

Most of IoT devices will require batteries and low power consumption states. Although processing power doubles almost every two years according to the Moore's law, the progress in batteries did not even double over the last decade [11]. In this regard, the design concept of protocols, networks and hence devices have started to change in both academia and industry by keeping the energy-efficiency in mind. Therefore, the bottleneck of up-to-date system design is not only the transmission rate, but also the energy limitation as users ask for new energy-hungry services [12], [13].

Theoretically, an efficient integration and the smart communication between physical world and computer-based systems could enable the IoT devices to reduce the total amount of energy consumption. However, it is still ambiguous to tell how well they will really work, or whether people will use them as efficiently as possible. Therefore, energy-centric optimization for IoT is an important challenge that has to be investigated carefully to increase its chance of success and to reduce the overall energy consumption and carbon emissions.

A. Survey Novelty and Contributions

There have been many related works, such as [14]–[19], focusing on the IoT concept. However, these works have no wide spectrum analysis of the energy consumption issues and energy-centric IoT optimization solutions. There have been also several survey studies [20]–[33] that focus solely on energy efficiency in IoT. Yet, these studies generally aim at addressing specific approaches or solutions such as energy harvesting [20], energy-efficient communication and networking technologies [21]–[24], [32], green industrial applications [26], [28], green IoT standardization [29] or power deployment and management in IoT [31]. A summary of the existing surveys focusing on green-IoT is shown in Table I.

Even though some of the ideas covered in the aforementioned studies might overlap with our interest, there is a need for a more comprehensive approach that focuses not only on the specific techniques/solutions but also on the interaction among them, and the precautions/decisions the policy makers need to take to move from serendipity approaches towards a sustainable green-IoT. Consequently, this paper differentiates itself from other survey papers from the literature, through the following aspects:

- it approaches the problem from a wider perspective by presenting not only the work of academia, but also industry and policy-makers.
- discusses not only the specific techniques/solutions, but also possible interactions among various approaches and their impact on energy efficiency for IoT.
- presents the IoT projects and standardization efforts carried out so far by taking into account the technological solutions, industrial applications and legislation.
- demonstrates the importance of a strategic approach from the actors who need to make efforts for an energy-efficient sustainable IoT deployment/management, and their roles.
- identifies the key enabling technologies that assist at facilitating the sustainable green-IoT paradigm.
- gives insights for further research directions towards a sustainable green IoT.

B. Survey Structure

To assist the readers throughout the paper, a list of abbreviations along with their definition is provided in Table II The rest of the paper is organized as follows. Section II presents the IoT technology background information on the definition, classification, procedure, trends and forecasts in IoT. Section III presents IoT undergoing projects and standardization efforts. Section IV and Section V present energy-efficient IoT approaches and applications proposed in various technical/industrial fields, respectively. Section VI examines the challenges and open issues in green IoT. Section VII summarizes the lessons learnt and finally Section VIII concludes the paper presenting a guideline for future research.

II. IoT TECHNOLOGY

In order to become familiar with the IoT paradigm, this section briefly presents the definition, evolution, classification, trends and forecasts of the IoT.

A. IoT Definition

In the last decade, IoT has gained significant attention and become one of the most popular research topics in both academia and industry. Semantically, IoT expression is composed of the words *Internet* and *Thing*, where *Internet* is the global network of interconnected smart devices and *Thing* is any object that is capable, with some modifications if required, to be linked to the Internet, such as a smart-phone, a refrigerator, or even a thermostat. Therefore, IoT can be expressed as a world-wide network of interconnected objects uniquely addressable, based on standard communication protocols [35]. More formally, it can be defined as a dynamic global network infrastructure with self-configuring capabilities and inter-operable communication protocols for physical and virtual *things*, which have identities and attributes and are capable of using intelligent interfaces [14]. Consequently, IoT creates a smart environment making use of the gathered information to make the critical infrastructure components more aware, interactive and well-performed, providing an efficient way of communication among people and things anytime, anywhere, using any path/network and any service [36], [37].

Recently, developing smart objects that are defined as entities or things has become a significant part of the IoT concept. However, to create a smart well-performed communication environment, these objects must have a unique identifier, a name or an address, a minimal set of computing, sensing and communication functionalities to be discovered, and to send/receive messages, which results in new challenges in intelligent sensing and wireless communication techniques.

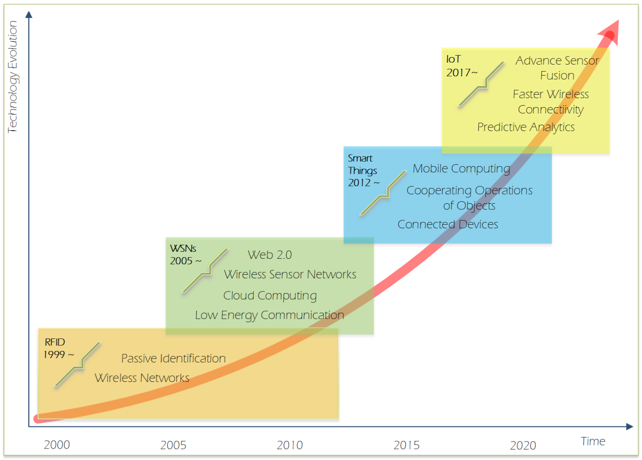

Fig. 2: IoT Evolution

B. IoT Evolution

As it is illustrated in Fig. 2, the evolution of the IoT can simply be expressed as the evolution of existing wireless communication technologies and their enablers, such as RFID, Wireless Sensor Networks (WSNs), NFC, barcodes, low energy wireless communications, Machine-to-Machine (M2M) communications and cloud computing. Since the term IoT was first coined in 1999, it has been widely used in ICT fields. Since millions, even billions of things can be integrated seamlessly and effectively within the IoT, it is expected to be widely used in many fields, such as logistics, industrial, pharmaceutics and manufacturing for the identification and tracking of items with tagging.

C. Classification of IoT

Basically, IoT relies on the integration of several technologies, such as identification, sensing and communication. Like

TABLE I:
Related surveys focusing on green-IoT

Ref	Year	Scope	Observation
[28]	2014	Industrial IoT applications, challenges and research directions for industrial researchers	Key IoT applications in various industries are presented in detail.
[20]	2015	Chipless RFID, energy harvesting and wireless power transfer	A smart-surface application, which utilizes RFID tags and wireless power transfer, is presented for indoor localization systems.
[22]	2015	Access networks, especially, on the central role that cellular networks are considered to play in IoT	Benefits of cellular networks in IoT and potential energy-efficient approaches are presented.
[23]	2015	Energy saving concerns/solutions utilizing various wireless radio access technologies for IoT connectivity	Wireless networking aspects are presented for battery-operated IoT objects/devices.
[26]	2015	Various technologies and issues regarding green-IoT to achieve a sustainable smart world	IoT-centric technologies; RFID, wireless sensor networks, cloud computing, machine-to-machine communication, and data centers, are presented.
[30]	2015	IoT-centric energy efficiency, energy harvesting, and solutions to pollution issues	Energy-centric recent advances for smart cities are presented.
[31]	2016	Designing an energy-centric IoT architecture	Challenges involved in the energy-efficient system design of different classes of IoT edge devices are presented.
[24]	2016	Significance of using low-power wireless techniques/modules in IoT applications	Various wireless technologies that can be used for IoT applications are presented considering their power consumption levels.
[25]	2017	IoT enabling technologies, such as Internet, smart objects and sensors, to achieve a green-IoT environment	Existing green-centric IoT applications, ongoing projects and standardization efforts are presented.
[27]	2017	Strategies, such as green data center and policies, to minimize power consumption in IoT	Smartphone is examined as an IoT-centric case study.
[29]	2017	Standardized layered architecture and protocol suite required for IoT applications	Various consortia, such as government agencies, standards bodies and industry giants, which are working on developing IoT standards, are presented.
[21]	2018	Energy efficient solutions at different layers of the IoT system (e.g., Application, Network, Processing, Transport, and Perception Layers etc.)	Various techniques that can be used for energy optimization at different layers of the IoT system are presented.
[33]	2018	Set of solutions on green RFID, green wireless sensor networks, green machine to machine, green cloud computing, green data center, green Internet and green communication network	Various concepts and techniques that lead towards a green ICT are discussed.
[32]	2019	Hardware, software and policy-based green IoT solutions	Various hardware, software and policy-based approaches for a green IoT are discussed.
[34]	2019	Ambient green energy harvesting, green energy wireless charging and green energy balancing	Free green energy to power IoT devices and revolutionarily enable wireless charging of these devices are discussed.

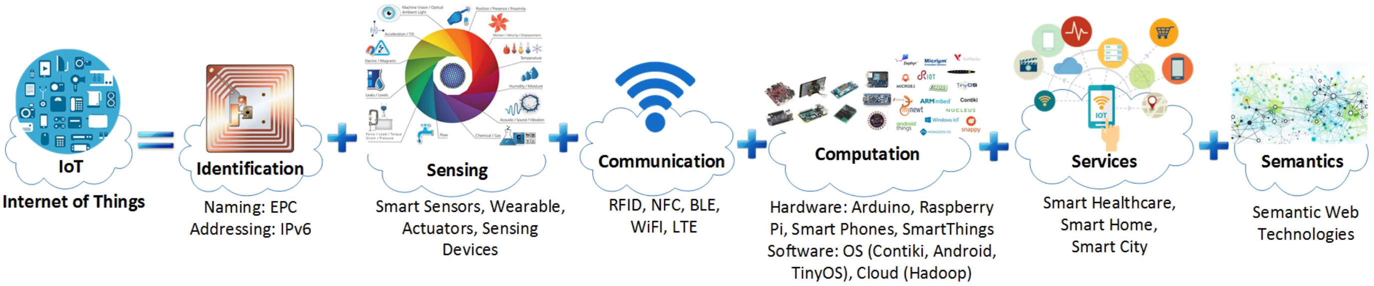

Fig. 3: IoT Elements

any concept in information systems, IoT consists of hardware, software and middleware parts as well. The main elements of IoT are illustrated in Fig. 3.

The *hardware* part may consist of many types of physical components, such as embedded communication hardware, sensors, actuators and nano-electronics devices. Industrial state of the art for the IoT hardware is quite heterogeneous as there are many vendor-specific solutions, such as Arduino, BeagleBoard, TelosB sensor mote, RaspberryPI, pcDuino, Cubieboard, and Libelium waspmote [38]. All of these devices should be well-organized and well-located throughout the network and must be accessible through available communication methods. Critical and mostly-used IoT hardware infrastructure is mainly composed of RFID, NFC and WSNs.

RFID is an identification and wireless communication technology that enables short-range communication via radio-frequency electromagnetic fields. RFID basically consists of a tag and a reader to identify anything automatically. RFID tags can be programmed to get, store and send objects' information, such as Electronic Product Code (EPC), which is a universally unique identifier for an object. A RFID tag consists of a silicon microchip, which allows to receive signal and transmit the

TABLE II:
Abbreviations

Abbreviated	Name	Abbreviated	Name
AHN	Ad-Hoc Network	OIC	Open Interconnect Consortium
BIG IoT	Bridging the Inter-operability Gap of IoT	OMA	Open Mobile Alliance
BLE	Bluetooth Low Energy	PON	Passive Optical Network
CEN	European Committee for Standardization	PPM	Predictive Power Management
CoRE	Constrained RESTful Environments	PV	Photovoltaics
DNS	Distributed Name Service	QoI	Quality of Information
DPWS	Device Profile Web Service	RAT	Radio Access Technologies
EPC	Electronic Product Code	RFID	Radio Frequency Identification
ETSI	European Telecommunications Standards Institute	ROLL	Routing Over Low Power Lossy Networks
EV	Electric Vehicles	S2S	Space to Space
FSC	Food Supply Chain	S2E	Space to Earth
HAN	Home Area Network	SDN	Software Defined Networks
ICT	Information and Communication Technologies	SIoT	Social Internet of Things
IEA	International Energy Agency	SOA	Service Oriented Architecture
IEC	International Electrotechnical Commission	SoC	Systems on Chip
IETF	Internet Engineering Task Force	TSCGCC	Technical Subcommittee on Green Communications and Computing
IIC	Industrial Internet Consortium	UID	Unique Identification
IoT	Internet of Things	URI	Uniform Resource Identifier
IoBT	Internet of Battery-less Things	URL	Uniform Resource Locator
ISO	International Organization for Standardization	URN	Uniform Resource Names
JTC	Joint Technical Committee	VM	Virtual Machine
LTE	Long Term Evolution	W3C	World Wide Web Consortium
M2M	Machine-to-Machine	WBAN	Wireless Body Area Network
MCU	Microcontroller	WEH	Wireless Energy Harvesting
MM	Medium Mathematics	WiMAX	WorldWide Interoperability for Mircowave Access
MWIS	Maximum Weighted Independent Set	WiFi	Wireless Fidelity
NAN	Neighborhood Area Network	WoT	Web of Things
NFV	Network Function Virtualization	WPAN	Wireless Personal Area Network
NFC	Near Field Communication	WPT	Wireless Power Transfer
OASIS	Advancing Open Standards for Information Society	WSAN	Wireless Sensor and Actuator Network
OCF	Open Connectivity Foundation	WSN	Wireless Sensor Networks

tag ID via radio frequency, an antenna and a coating that is formed in a package similar to an adhesive sticker [19]. The microchip stores information about objects using tags. The antenna transmits the object information to the reader using radio frequency. RFID ensures that objects can be identified and tracked with tags in the IoT. Moreover, data can be accessible remotely through the Internet.

NFC is a high-frequency radio communication technology that basically allows close-range communication between electronic devices compliant with NFC standards. NFC ensures to make contactless data exchange over a short distance between two devices by bringing them within close proximity of each other. NFC tags are passive and unpowered and contain an identification data known as Unique Identification (UID). NFC devices, such as a NFC-enabled smart-phones, are able to make connections and transmit data with NFC tags that are attached to objects.

Sensor networks play an essential role in the IoT as well. In particular, WSNs contain a large number of intelligent sensors, which enable to monitor, collect, process, analyze and disseminate valuable information gathered from the environment or the things. Multiple sensor networks are used together and interact through various standards and protocols. Sensors transmit sensed data to actuators, which analyze data before taking any actions. The combination of sensors and actuators enables the objects to be aware of their environment and interact with people and other devices in the network [18].

There have also been many well-known IoT-enabled wireless and cellular Radio Access Technologies (RATs), such as Bluetooth, ZigBee, WiFi, WiMAX, 3/4/5G, deployed worldwide and that are continuously evolving to provide higher bandwidth with lower latency. Furthermore, there are also many network level solutions for encapsulation (e.g. 6LowPAN, 6TiSCH, 6Lo, Thread) and routing (e.g. RPL, CORPL, CARP) of IoT devices/objects. These RATs and networking solutions enable the smart devices/objects to connect over large distances with much fewer nodes while expanding the coverage and increasing the data rate, which it eventually brings new possibilities for the IoT paradigm.

The *middleware*, which lies in between the hardware and software parts, is actually an interface that facilitates the interaction between applications and hardware. It is designed to reduce the software and hardware heterogeneity. It consists of a common platform for aggregating and filtering the data, and provides access control to devices for IoT-enabled applications. The middleware also simplifies developing and deploying new services. Just like the hardware level, the state of the middleware level is also quite heterogeneous due to various vendor-specific solutions (FIWARE, FedNet, Ubicomp, SmartProducts, ACOSO, SkyNet), and cloud computing based infrastructures (Amazon EC2, Google App Engine, Xively, MS Windows Azure).

In addition, the *software* part of the IoT enables processing, storing, computing and monitoring tools for data analytics [39]. In recent years, the Service Oriented Architecture (SOA) approach was adopted to build the middleware architecture for IoT, as it focuses on simple and well-defined services. SOA allows to encapsulate services for hiding the details of service implementations or protocols. Therefore, applications can use heterogeneous objects as compatible services offered by the IoT devices. In this context, data and semantics levels also present high heterogeneity (e.g. WSDL, JSON, UD CAP, uCode Relational Model, RDF, OWL, W3C Semantic Sensor Network XG) and the software realm is even richer including many basic software technologies (e.g. TinyOS, Contiki, FreeRTOS, eCos, Android, Ubuntu, Java, WebRTC, REST, WAMP and, Django).

The integration of sensors and wired/wireless communication technologies empowers the IoT concept and enables additional services in extended applications. Integrating RFID and WSNs also enables IoT to develop new applications across a variety of fields, such as healthcare, decision-making of complex systems, transportation, etc. Fig. 4 shows leading technologies/services that is required to actualize the IoT.

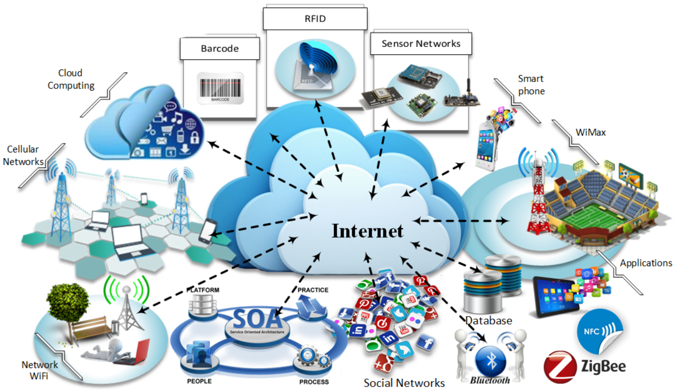

Fig. 4: Technologies/services that are required to actualize IoT

D. Designing IoT

Service-oriented architecture of the IoT needs to be designed to ensure an effective (e.g. fast, energy-efficient, well-performed) communication environment considering various aspects of heterogeneous devices, such as networking, process model and security. It is also necessary to ensure extensible, scalable, and inter-operable services. As shown in Fig. 5, there are four layers in a typical IoT architecture; (i) Sensing, (ii) Network, (iii) Service and (iv) Interface layers. *Sensing* layer consists of hardware infrastructure including embedded systems, sensor networks, RFID tags and other physical entities that are able to sense the status of things. *Network* layer links all the things in the vicinity and enable them to be aware of their surroundings. The things can share related information with other things in their vicinity directly or with any things indirectly through the network layer, utilizing the Internet. This procedure of the IoT is crucial as it enables intelligent event management and smart information processing. Additionally, the *service* layer is responsible to create and manage services required by users or applications. Finally, the *interface* layer provides various interaction methods between users and applications.

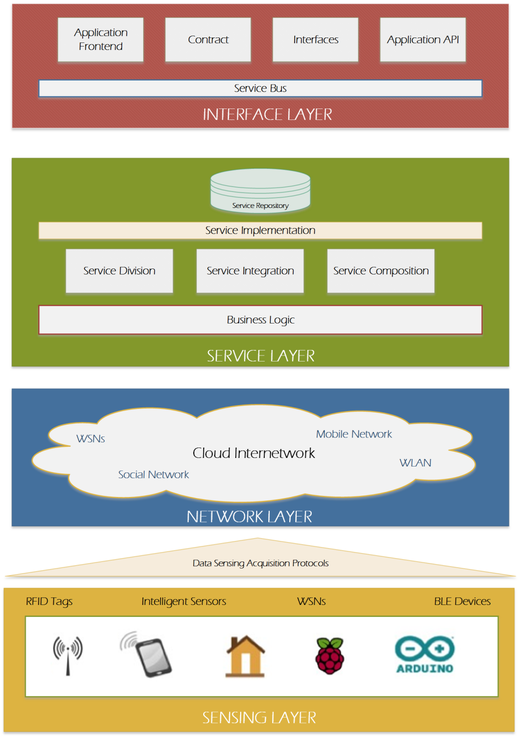

Fig. 5: Service-oriented Architecture for IoT

E. Trends & Forecasts in IoT

Nowadays, IoT researches are mainly centered on investigating new techniques for communicating and exchanging data between networked things to provide smart, flexible and autonomous services that enable interaction between human, machine and the environment. Consequently, it is expected that IoT will bring intelligence into our lives at anytime, anywhere, using any path/network and any service [40].

According to Gartner's Hype Cycle of Emerging Technologies report [41] that helps enterprises to identify which emerging computing technologies, services and disciplines to invest in, IoT is one of the most emerging technologies in the IT sector. Throughout the report, it has also been noted that the trend for the broad IoT is clear and certain; people's demand for technology to play a key role in both basic human needs, work and in various recreational activities, is here to stay. As it is seen in Fig. 6, which is created according to the Gartner's report [41], it has been forecast that IoT will take $5-10$ years for the market adoption, staying at the top of the list of the emerging technologies.

III. UNDERGOING IOT PROJECTS AND STANDARDIZATION EFFORTS

IoT is expected to improve the quality of life by decreasing the environmental impact of mankind on the world which increases the potential of its adoption by users, companies and stakeholders. Nevertheless, the industry has to overcome a number of critical challenges first, out of which possibly the most substantial one is energy efficiency [42].

The general requirements for most of the IoT devices is that they should consume minimal power and provide long

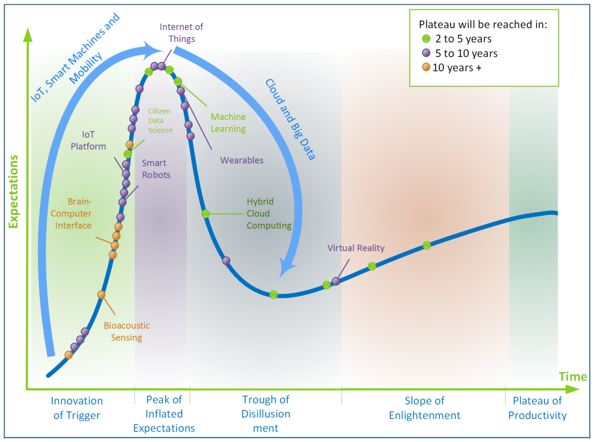

Fig. 6: Gartner Hype Cycle of emerging technologies

battery life in order to operate at least for several years without requiring human intervention, maintenance or replacement. On the other side, some of the IoT devices may be powered by harvesting energy from an external source or the environment. In both cases, energy optimisation is completely vital to take advantage of the full potential of IoT. However, this is not an easy task and requires low-power components, more efficient power systems as well as novel architectural and silicon level changes [43], [44].

At the G20 Summit in 2014, G20 Energy Efficiency Action Plan was reported under the title of *Voluntary Collaboration on Energy Efficiency* [45]. According to this report, the adoption of smart consumer electronics and household appliances that require a network connection is growing exponentially. Although these devices bring more opportunities for an efficient energy management, they also require extra *network standby* power only to remain connected to the network. To be more precise, International Energy Agency (IEA) estimates that networked devices in standby mode currently consume over 600 billion kilowatt-hours per year [46], a figure greater than Canada's annual electricity consumption. Considering that almost 50 billion devices are estimated to be network connected by 2020, the worldwide standby power consumption is expected to double by 2025 [45], [46]. However, the report from IEA [46] also indicates that electricity demand can be cut by more than 60% by enhancing the existing optimized approaches proposed in the literature. That is why G20 initiative encourages governments, researchers, experts and industry for innovative ideas and practical responses in terms of energy optimization of the networked devices, especially by accelerating the development of product standards and policy frameworks.

There have been many projects proposed in the literature, which are funded by academia, industry or policy-makers, focusing on various fields in IoT such as energy efficiency, throughput, service quality, security, etc. However, all these projects have their own architectural designs due to their different aims (energy, performance, security, etc.), or differences in the IoT subdomain (hardware, network, application, etc.). For instance, while the SENSEI [47] project focuses on wireless sensor and actuator networks, the ASPIRE project [48] primarily focuses on the RFID domain, while the SPITFIRE project [49] focuses on the semantic aspects in IoT. The high amount of heterogeneity on the physical, network and application domain of these projects results in different architectural proposals, involving different components and protocols. This eventually leads to a limited inter-operability between the proposed solutions.

Some of the funded projects fundamentally focusing on the green deployment and management of IoT are: EARTH [50], TREND [51], and GREENET [52]. While the project EARTH basically aims at developing energy-efficient component/network deployment and management, through theoretical/practical energy boundaries of existing networks, the project TREND aims at proposing new energy-efficient IoT approaches, gathering power-related data from network components, evaluating existing protocols and solutions. GREENET, on the other hand, focuses on training programs to spread green network awareness for IoT and ICT.

Although rapid and balanced development of IoT and the optimization of energy efficiency will be adversely affected, IoT-based vendor-specific new architectures are still being proposed. In order to avoid this issue, inter-operability oriented projects (IoT-I [53], IoT-A [54], FI-WARE [55], BIG-IoT [56] and inter-IoT [57]) have also been proposed in the literature. In this context, the *IoT-I* project reviews different IoT architectures presented in the literature and examines the arguments to be handled by academia, industry and policy-makers, through International IoT Forums, to provide an IoT-based common architecture. The results of these meetings have been transformed into an academic platform through the *IoT-A* project and a comprehensive IoT architecture reference model has been presented, together with a set of best practices to help system designers with a concrete IoT system design [58]. Similarly, the *FI-WARE* project, funded by industry, focuses on the design of a core IoT architecture, considering the next generation information-centric *Future Internet*.

Although the approaches described above focus on inter-operability by reducing heterogeneity, integration among heterogeneous components is frequently addressed at the physical or network level, which is basically limited to data gathering. In this context, the *inter-IoT* project focuses on a multi-layered methodology combining different IoT devices, networks, platforms, services and applications to provide a global continuum of data, infrastructures and services that will enable different IoT scenarios. Apart from the *inter-IoT* project, The *BIG IoT* (Bridging the Inter-operability Gap of IoT) project also focuses on designing a broadly accepted IoT ecosystem. The *BIG IoT* API, which is a common interface that offers the required functionalities for inter-operability with other platforms, allows developers to create applications that work on top of different platforms by combining data from multiple providers that have their own interfaces. In this way, it is possible for suppliers to promote their assets in the market, and the clients could find those assets and access the preferred suppliers [59].

Due to the multi-layered architecture, vendor-specific products/applications and different hardware and protocols required for each layer, it is difficult to provide inter-operability and homogeneity in IoT. As an example, an IoT environment may have Wi-Fi, Bluetooth, 6LoWPAN or Zigbee RATs for *communication*; EPC, uCode, IPv6, URIs for *identification*; MQTT, CoAP, AMQP, Websocket for *messaging*; Physical Web, mDNS, DNS-SD for *discovery*; JSON-LD, Web Thing Model for *semantics*; TR-069, OMA-DM for *device management*, etc [29].

Although many solutions have been proposed and developed through funds/support from academia, industry and policy-makers, there is still no reference standard related to the IoT. Due to the lack of any standardization, IoT developers simply implement their own vendor-specific protocols/hardware, depending on their needs and proficiency, then design the end-to-end IoT solutions, which mostly result in inefficient and undesirable products within an open market. Therefore, the necessity for a new multi-layer multi-platform IoT standard is tremendous, as lack of an IoT standard may also results in many technological and business-related concerns, such as impossibility to plug non-inter-operable IoT devices into heterogeneous IoT platforms, impossibility to develop IoT applications exploiting multiple platforms in homogeneous and/or cross domains, scarce re-usability of technical solutions, and user dissatisfaction [38]. In this context, several working groups/initiatives have been working on IoT standardization across four layers; *interface*, *service*, *network* and *sensing* layer.

In this sense, consortium such as IETF (Internet Engineering Task Force), OASIS (Advancing open standards for the information society), OMA (Open Mobile Alliance), W3C (World Wide Web Consortium) etc. focus on designing inter-operable multi-platform IoT-based applications/protocols. Other consortium such as oneM2M, OIC (Open Interconnect Consortium), AllSeen Alliance etc. focus on developing frameworks for different IoT-based services. While the consortium such as Thread focus on optimizing the network layer for IoT. Additionally, the consortium such as 3GPP, IEEE 802.11/802.15, LoRa etc. focus on forming communication protocols for different IoT components/objects [29]. Some of the key groups/initiatives working for IoT standardization are as follows:

- *ITU-T Study Group 20* [60]: Established to further develop IoT standardization activities, with a preliminary focus on IoT applications in smart sustainable cities and communities. It is expected to progress between 2017-2020. ITU-T also has a *Recommendation ITU-T Y.4000* [61], which provides an overview for the IoT [62].

- *IEEE P2413 Working Group* [63]: Established to develop new IoT standards, and also to revisit 40 existing standards to re-adapt them to the IoT. IEEE Communication Society has also established a Technical Subcommittee on Green Communications and Computing (TSCGCC) [64], which basically works to develop and standardize energy-sustainable, resource-saving, and eco-friendly green communications and computing technologies.

- *Internet Engineering Task Force (IETF)* [65]: IETF has three different working groups (6LoWPAN [66], ROLL [67] and CoRE [68]) that focus on energy-efficient IoT-centric standardization. While 6LoWPAN (IPv6 over Low power WPAN) group focuses on defining global access for low power devices, ROLL (Routing over Low Power Lossy Networks) group focuses on revising existing routing protocols for IoT adaptation, and CoRE (Constrained RESTful Environments) group focuses on realizing an embedded counterpart for RESTful web services.

- *oneM2M Consortium* [69]: Established in 2012 to develop technical specifications for a common M2M and IoT service layer that can be readily embedded within various hardware and software. It is a global initiative and has more than 200 participants worldwide, including AT&T, Adobe, Ericsson, IBM, Cisco, and Samsung.

- *EPCglobal* [70]: Established to design industry-driven standards for EPC to support the use of RFID. EPCglobal, together with European Telecommunications Standards Institute (ETSI) [71] and European Committee for Standardization (CEN) [72] are making major contributions to standardize the RFID technology.

- *ISO/IEC JTC1/SC41* [73]: Established to develop standards for the IoT and related Sensor Networks and Wearable technologies. It is a Joint Technical Committee (JTC) of the International Organization for Standardization (ISO) [74] and the International Electrotechnical Commission (IEC) [75].

- *Open Connectivity Foundation (OCF)* [76]: Established in 2014 to provide secure inter-operability by delivering a standard communication platform and an open source implementation that allows devices to communicate regardless of form factor, operating system, service provider, transport technology or ecosystem. It is a global initiative and has more than 300 participants worldwide, including Intel, Samsung Electronics, Microsoft and Qualcomm.

- *Industrial Internet Consortium (IIC)* [77]: Established to enable IoT-centric technologies of the Industrial Internet in order to accelerate the market adoption and drive down the entry barriers. It is a global initiative and has more than 300 participants worldwide, including AT&T, General Electric, Cisco Systems, IBM and Intel.

- *Thread Group* [78]: Established in 2014 under the leadership of Alphabet's Nest Labs to develop IoT-centric open standards, especially a low-power wireless mesh networking protocol, through broadly supported IEEE 802.15.4 radio that provides low power consumption and low latency.

- *GreenTouch* [79]: Established by approximately 30 leading ICT companies and research institutes, including Fujitsu, Huawei, China Mobile and Bell Labs to transform communication and data networks, including the Internet, and to reduce carbon footprint of ICT devices, platforms and networks.

- *Celtic-Next* [80]: Celtic-Next is an industry-driven EU research initiative that supports projects that focus on telecommunication and ICT, connecting people and businesses in a secure, eco-friendly and reliable way.

To summarize the works described up until now, brief information of the groups/initiatives working on the standardization of green-IoT is given in Table III.

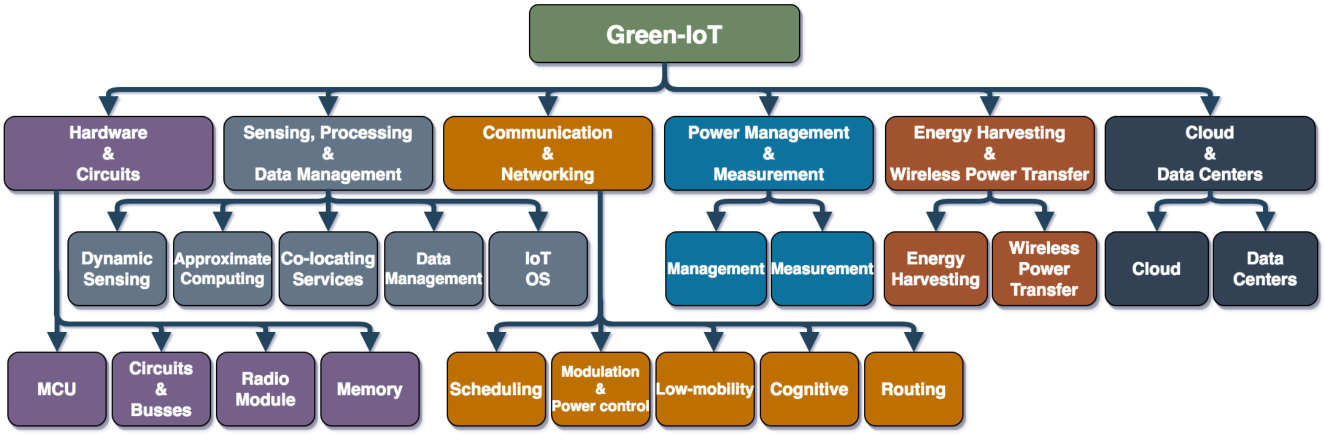

Fig. 7: Taxonomy of technical green-IoT approaches

TABLE III:
Summary of Standardization Activities for a Green-IoT

Standard/Projects	Status	Region	Organizer	Green perspective
ITU-T Study Group 20 [60]	Ongoing	Global	ITU	Develops green IoT applications for smart sustainable cities
IEEE P2413 Working Group [63]	Ongoing	Global	IEEE	Re-visits 40 existing standards to re-adapt them to the IoT
Internet Engineering Task Force (IETF) [65]	Ongoing	Global	IETF	Has 3 working groups: 6LoWPAN, ROLL and CoRE that focus on energy-efficient IoT-centric standardization
oneM2M Consortium [69]	Ongoing	Global	200+ members	Develops technical specifications for a common M2M and IoT service layer
EPCglobal [70]	Ongoing	Europe	ETSI, CEN, ISO	Designs industry-driven standards for Electronic Product Code (EPC) to support the use of RFID
ISO/IEC JTC1/SC41 [73]	Ongoing	Global	ISO, IEC, JTC	Develops standards for the IoT and related Sensor Networks and Wearables technologies
Open Connectivity Foundation (OCF) [76]	Ongoing	Global	300+ members	Provides secure inter-operability by delivering a standard communication platform and an open source implementation
Industrial Internet Consortium (IIC) [77]	Ongoing	Global	300+ members	Enables IoT-centric technologies of the Industrial Internet to accelerate market adoption
Thread Group [78]	Ongoing	Global	100+ members	Develops IoT-centric open standards, especially a low-power wireless mesh networking protocol, through the IEEE 802.15.4 radio
GreenTouch [79]	Ongoing	Global	GreenTouch concorcium	Reduces carbon footprint of ICT devices, platforms and networks
Celtic-Next [80]	Ongoing	Europe	EU research initiative	Supports IoT-centric projects that connect people and businesses in a secure, eco-friendly and reliable way

IV. Energy-efficient IoT Approaches

Over the past 10 years, numerous energy-efficient IoT studies have been presented in various fields in the literature triggered by the possible integration of IoT into our daily life and the high amount of energy savings it is expected to provide. These studies are categorized under six different groups: (i) Low-power Hardware and Circuits, (ii) Low-power Sensing, Processing and Data Management, (iii) Low-power Communication and Networking, (iv) Power Management and Measurement, (v) Energy Harvesting and Wireless Power Transfer, and (vi) IoT-centric Cloud and Data Centers. This way, we aim to gather, evaluate and compare related works in specific categories with texts and tables. In this context, the green-IoT taxonomy examined within the scope of this paper is illustrated in Fig. 7.

It should be noted that energy-efficient IoT-centric approaches/solutions investigated in this section mostly evaluate the performance of their approaches by implementing their own simulation environments. The hardware, architecture, metrics, topology, network scenarios, and the simulation software used are some of the aspects that differ in each of these approaches. Moreover, there is no performance evaluation comparison made between existing approaches. In general, the effectiveness of each proposed approach is compared against the conventional hardware, sensing, processing or networking scenario. Hence, it is extremely tough to compare their effectiveness in terms of energy consumption/harvesting without implementing every existing solution within the same platform. Throughout this section, we evaluate the expected energy efficiency levels of each approach individually. The evaluation criteria are carried out by taking into consideration the specific metrics of each approach, such as the target environment (fixed or mobile), maximum achievable throughput, coverage, number of active links/devices, impact of each parameters used, achieved results, amount of message exchanges required, impact of the operation (chip-level, node-level, network-level), etc. By weight batching the aforementioned metrics, we believe that it will be possible to reach to a general opinion about these proposed solutions. Consequently, the following subsection will summarize the solutions belonging to each category where comparison tables are added to summarize the features, differences and the expected amount of energy gains of the proposed energy-efficient IoT approaches/solutions.

A. Low-power Hardware & Circuit Solutions

Nowadays, IoT has become one of the largest electronics market for hardware production due to its fast evolving application space. IoT hardware greatly requires energy efficiency as most of IoT devices/objects should run either on batteries for months/years without a battery replacement or on harvested energy sources. Hardware-based energy efficiency in IoT can basically be examined under four broad categories: (i) Microcontroller (MCU) design; (ii) Circuit, bus and component design; (iii) Radio module design; and (iv) Memory design. The energy-efficient IoT hardware solutions presented in the literature covering these four categories will be examined below.

- *Green Microcontrollers*: In order to ensure that a MCU provides high amount of energy efficiency, it must have fundamental energy-centric hardware/software features, such as ultra-low power modes with very fast wake-up interval, self-directed peripherals that run in low energy modes and energy profiling software tools [89]. Motivated by these requirements, the authors in [81] propose an energy-efficient heterogeneous dual-core processor, called CoreLH that combines energy-efficient near-threshold coreL (coreL is used most of the time as tasks in IoT mostly do not require high amount of computing ability) and high-performance normal voltage coreH (CoreH is used to process heavier tasks than usual not to miss deadlines). The authors argue that energy efficiency increases up to 2.6 times since energy consumption of the near-threshold core is as low as 7.7pJ/cycle with the usage of CoreLH without any deadline miss. Other industrial vendor-specific MCU and processor solutions that take the above-mentioned energy efficiency requirements into account also exist. For instance, Freescale's Kinetis L series MCUs and i.MX 6 series entry-level applications processors [82] and TM4C129x MCU family from Texas Instruments [90] are two of them that balance high-performance and low-power/low-thermal needs according to the heat generated by the processors.

- *Green Circuits, buses and components*: Considering the impossibility to create a customized-chip for each objects/devices, an extremely modular solution, where systems are constructed by combining pre-existing power and size efficient composable chips, is required for IoT hardware. In this context, Blaauw et al. in [83] investigate the IoT application space and review a low-power bus and a three millimeter sensor system constructed by an 8-die chipset for low-power circuit solutions and low-power inter-die communications, respectively utilizing parameters, such as maximum average power, voltage reference, timers, duty cycle, bandwidth, and standby power. Similarly, the authors in [91] propose an open interface design that aims at making small low-power objects/devices modular, expandable, and cost effective by defining connectors, standard circuit board soldering land-patterns, pads, and recommended module sizes. Additional research on ultra low-voltage circuit design is also required to further reduce the hardware-based power consumption for IoT objects/devices. In this context, Bol et al. [92] investigate the possible impact of ultra-low-power yet high-performance systems-on-a-chip (SoCs) in nanometer CMOS technologies on energy efficiency for IoT-centric objects/devices. Furthermore, an IoT-centric ultra low-voltage circuit design, which simulates a two-input NAND gate in 120nm CMOS technology, is also presented in [84].

- *Green radio modules*: Utilizing low-power wireless modules in IoT is extremely vital to save energy since an important portion of the total energy is consumed through the communication phase. Although there are already many vendor-specific wireless radio modules in the market, they generally fall within two categories: (i) low-power local area networks less than 1000m range (e.g. IEEE 802.15.4, IEEE P802.1ah, Bluetooth/LE, and etc.), and (ii) low-power wide area networks greater than 1000m range (e.g. LPWA, LoRaWAN, LTE-M, EC-GSM and etc.). In this regard, there are several works proposed in the literature that investigate the energy efficiency of various types of wireless radio modules. For instance, Mahmoud et al. in [24] investigate the protocol-based power consumption levels of ZigBee, Low Power WiFi, 6LowPAN, LoRaWAN and LPWA. Similarly, Boulogeorgos et al. in [93] also investigate design specifications of several LPWAN modules, and review their fitness for various IoT applications. Furthermore, energy efficiency of LoRa, which is a long-range, low-power, low-bitrate wireless telecommunication system, is evaluated by Augustin et al. in [85]. The authors state that chirp spread spectrum modulation and high receiver sensitivity of LoRa provides network coverage up to 3km and a high amount of energy efficiency offering good resistance to interference. The results of these studies mostly reveal that BLE and LoRa have high potential to become an important technology for short and long range connectivity, respectively [94].

- *Green memory design*: IoT objects/devices usually work on duty-cycled mode, which leads to these devices to stay mostly in the idle phase. Current MCUs reduce the idle power consumption offering two different sleep modes; (i) shallow sleep that leads to fast wake-up and state retaining, and (ii) deep sleep that leads to longer time to wake-up and no state retaining [31]. An important amount of power is consumed in shallow sleep mode as it keeps some of system components powered to retain state. In contrast, almost no power is consumed in deep sleep mode, yet it requires the MCU to put a checkpoint to the non-volatile memory (typically flash) about the current system state. Therefore, entering/exiting deep sleep mode results in high amount of energy consumption. As seen, there is a trade-off between sleep modes and the energy efficiency. In this context, there are several approaches that aims at reducing the amount of energy consumption caused by sleep-mode based memory

TABLE IV:
Hardware-centric green-IoT solutions - Summary

Ref	Operation	Parameters/Actions	Utility	Network	Energy gain
[81]	Dual-core processor	Task scheduling between processors	It allows devices to stay mostly in low-voltage state without deadline miss	Any network	High
[82]	Kinetis-L MCU	Throughput, power level, heat ratio	It balances high-performance and low-power/low-thermal needs	Any network	High
[83]	Low-power circuitry	Max/Avr/standby power, voltage level, timers, duty cycle, bandwidth	It provides low-power bus and I/O operations	Any network	Low
[84]	NAND-gate CMOS	Voltage levels, power, SoC	It provides an IoT-centric ultra low-voltage circuit design	Any network	Low
[85]	LoRa	Spectrum modulation, sensitivity, coverage	It provides a long-range, low-power, low-bitrate wireless communication system	Wireless long-range	High
[86]	Memory operation	Shallow/deep sleep, MCU supply voltage, data retaining voltage	It combines the state retaining of shallow sleep with a low-power deep sleep	Any network	Medium
[87]	RAM design	Voltage levels, power levels, LVC-MOS	It provides energy-efficient low-voltage complementary metaloxide semiconductor	Any network	Medium
[88]	RAM design	Heat ratio, power levels	It provides IoT-enabled thermal-aware RAM that connects to Internet via IPv6	Any network	Medium

operations. For instance, Jayakumar et al. in [86] suggest a new sleep mode that combines the state retaining of shallow sleep mode with a low-power deep sleep mode that scales the MCU's supply voltage to just above the SRAM's data retaining voltage. Apart from energy-efficient sleep modes, Moudgil et al. in [87] propose an energy-efficient RAM design making use of low-voltage complementary metal oxide semiconductor (LVCMOS) standards. Additionally, Verma et al. in [88] propose an energy-efficient IoT-enabled thermal-aware RAM that connects to the Internet via IPv6 address.

It should also be noted that there are studies in the literature examining the amount of power consumed by different hardware modules that mobile devices have. For instance, Carroll et al. in [95] validates that the radio modules (e.g. GSM and Wi-Fi) when in use can consume up to two times more power than CPUs, up to 10 times more power than RAM, and even much higher power than circuitries. Therefore, assuming an average frequency of communication scenario, it is proper to say that CPUs and radio modules of IoT devices are expected to consume more power than memory and circuitries. In parallel, energy-aware solutions focusing on CPUs and radio modules mostly results in more energy saving considering today's intensive communication and data usage need. In line with the aforementioned explanations and further experiments/measurements conducted by related works, a summary regarding hardware-centric green-IoT solutions is given in Table IV.

B. Low-power Sensing, Processing & Data Management

With the expansion of the IoT application space and the increase in the number of objects/devices deployed, the size of the data to be read from these devices/applications, processing power requirements, and data storage capacities have increased. This increase related to the sensing and processing of the data causes an increase in energy consumption as well. Throughout this section, studies aiming to provide IoT-centric energy efficiency related to sensing and processing in the literature are categorized in five main groups: (i) Dynamic sensing; (ii) Approximate computing; (iii) Co-locating services; (iv) Data management; and (v) IoT-centric operating system. In this context, this section examines specific solutions for each category and evaluates the impact of these proposals on the energy-efficiency.

- *Dynamic sensing*: Since the energy consumed during sensing and data collection from devices in IoT is much higher than the energy consumed by the devices in sleep mode, there are several IoT-centric studies in the literature that aim to perform the sensing and data collection processes dynamically keeping the devices in sleep mode as long as possible. For instance, Kaur et al. in [96] propose a dynamic IoT sensing framework, which has three layers: sensing and control, information processing, and presentation. Here, sleep intervals of sensors are predicted using three parameters, such as remaining battery level, previous usage history, and quality of information required for a particular application. The framework lets sensors switch to the sleep mode under three scenarios: (i) in case sensing the environment in a given time interval is not needed, (ii) in case the coverage area can be compromised for battery life, and (iii) in case the battery-level is very low. In this context, energy-efficient utilization of IoT resources is accomplished by using the predicted value to boost the utilization of cloud resources by re-provisioning the allocated resources when the corresponding sensory nodes are in sleep mode. Additionally, Tang et al. in [97] propose an energy-efficient data sensing and transfer scheme constructing a clustering index tree, which divides the IoT region into grid cells in a hierarchical manner that forms a tree. Here, energy saving is achieved sending the data only when there is a substantial change between currently detected and previously sent value. A group formation and spatial correlation based energy saving scheme is also presented in [98] considering the fact that objects move together when they are carried by a vehicle or a person.

- *Approximate computing*: Energy efficiency in IoT is substantially important especially for battery-powered objects/devices as these devices are now being used to execute computationally heavy processes that are required in different domains/stages, such as recognition, communication, data mining, vision and multimedia [31]. Approximate computing is an evolving method that can influence basic resilience of applications to execute computations approximately, leading to extraordinary amount of energy saving. Techniques regarding the software-based approximate computing include high level transformations, such as loop perforation [99], computation skipping [100], and replacing resilient portions of code with a corresponding simpler neural network that approximates the code's function [101]. It should be noted that approximate computing mainly results in energy vs. quality trade-off in run-time. Therefore, decision on the approximate computing basically varies according to the type of the application being executed, or the inputs of the application. For example, Raha et al. in [102] first reveal that changing the approximation degree for an MPEG encoder causes varying output video quality and then propose a quality-configurable run-time framework that can automatically tune the level of approximation on the basis of internal variables.

- *Co-locating services*: Nowadays, most of IoT devices are equipped with high computing and memory capacities to support real-time multiple services. In this regard, energy saving can also be achieved by co-locating services on one device to reduce computing and communication based energy cost. For example, Huang et al. in [103] propose a service merging framework, in other words a mapping strategy from services to devices, that maps and co-locates different services on one device. Here, authors first model the service co-location problem as a Maximum Weighted Independent Set (MWIS) problem, and then present an algorithm that transforms a service flow to a co-location graph, discovering the maximum independent set, which is used for the service co-location decisions. Another solution, to enable energy efficient data delivery in future green cellular networks is with the integration of Device to Device (D2D) communication [104]–[106].
- *Green data management*: Conventional method of transferring raw-data to a centralized point for data storage and analysis may result in devastating communication and energy cost. Therefore, life cycle of data within the IoT must be discussed and a proper data management approach/policy must be presented for the IoT-centric optimization of communication overhead and storage mechanism [107]. Green data management concept can be basically categorized into two groups: (i) Storage-centric approaches that focus on optimizing the storage space, and (ii) Communication-centric approaches that focus on optimizing data transmission from the lower layer of things to the upper application layer.

Storage-centric green data management mainly has 4 different approaches: (i) efficient indexing schemes; (ii) scalable archiving; (iii) localized data-centric storage; and (iv) migrating data to the cloud. On the other hand, aggregation and query optimization are the most used communication-centric approaches to lower the communication overhead. In this regard, literature has some proposals that specify abstractions to provide combination of data from heterogeneous networks, thus paving the way for the adjustment and smooth integration of other IoT sub-systems. As an example, authors in [108] propose a storage-centric design where sensors are equipped with embedded storage platforms, thus enabling query processing to migrate to the nodes. Here, transmission only takes place to communicate queries to the sensory database and results back to the query initiator. Additionally, Lang et al. in [109] explore energy efficiency of multiple-queries for distributed large scale database systems. Here, batch query-processing leverages the occurrence of common components in multiple-queries within a processing workload. Authors in [110] also examine energy efficiency of query processing in WSNs using multi-query optimization. Here, two-tiers are used to enhance the execution of queries: a base station tier re-writes a set of queries to construct a synthetic set of queries with redundancies removed and common sub-queries merged. Some in-network optimizations, such as time-sharing among temporal queries and aggregation, are then used to enhance the transmission of the query-set results. Finally, Demers et al. in [111] adopt a cross layer approach to save further energy through data management. Here, the communication layer accommodates the needs of the data management layer. The proposed approach treats sensor network as a distributed database, where data gathering is achieved using declarative queries. A central query-optimizer generates efficient query plans aiming at diminishing resource usage within the network for a given query. The sensors sense data and then transfer data matching some criteria to the base station.

In general, for wireless sensor networks the wireless communication process records the highest energy consumption and this is due to the electronic characteristics of the wireless sensor devices. However, to overcome this issue, many approaches make use of data aggregation techniques that aim at reducing the transmission delay and maximizing the lifetime of the wireless sensor networks [112]–[116].

- *Green IoT OS*: IoT objects/devices widely range from lightweight sensors using 8-bit MCUs to powerful devices using 32-bit MCUs. Therefore, it is essential to provide standardized Application Programming Interfaces (APIs) and protocols to ensure interoperability among various vendors as well as compatibility with existing hardware and Internet systems. As a result, several new OSs have been developed to support IoT-centric use case scenarios and provide a unified software platform for heterogeneous devices [117]. Yet, there is currently no IoT-based large-scale specific OS that can be used in a wide perspective on these devices. Related operations are mostly done through non-IoT-centric OSs, such as Contiki, Tiny OS, and Linux. Gaur et al. [118] present a survey of OSs, such as Contiki, TinyOS, LiteOS, FreeRTOS, and Mantis OS that have been designed to assist IoT devices and also outline a generic framework to bring out the key features required in an OS tailored for IoT devices, based on the architecture, programming model, scheduling, networking and portability. Towards closing this gap, Baccelli et al. in [119] re-visit the IoT-based requirements for an OS and then present the RIOT OS, which is an IoT-ready OS that has several networking protocols including 6LoWPAN and RPL. RIOT OS simply reckons objects/devices with minimal resources but eases expansion through a wide range of devices. It provides a multi-threaded programming model including standard ANSI C code and a common POSIX-like API for all supported hardware from 16-bit to 32-bit MCUs. The authors demonstrate the energy efficiency of the proposed OS compared to Contiki, Tiny OS, and Linux. Nevertheless, implementation of most of these OSs in real platforms may also introduce further and unpleasant waste of energy as they are not specifically designed for wide range of IoT devices. As an example, Boccadoro et al. in [120] first presents the Time Slotted Channel Hopping (TSCH), which is standardized by the IETF IPv6 over the TSCH mode of IEEE802.15.4e (6TiSCH) working group [121] and then experimentally measure the energy consumption of TSCH-enabled platforms on two different OSs: OpenWSN and Contiki. The authors demonstrate that OpenWSN, which is an open standard-based implementation of a complete constrained network protocol stack for WSN and IoT [122], always registers a lower energy consumption, compared to the Contiki.

It should be noted that frequency and size of data is crucial to shape how much processing, computation or data management are required to efficiently utilize the IoT. Therefore, green-sensing is the primary concern since it will also let devices to consume less for processing, computation or data management based processes. Indeed, not only processing, computation or data management based processes will be reduced, but also CPU and radio modules will be less utilized, staying in low-voltage states or sleeping mode, through an energy-efficient smart sensing procedure [123], [124]. In this context, energy efficiency levels of approximate computing, data management or middleware solutions highly depend on the CPU and I/O utilization, communication and networking structures. In line with the aforementioned explanations and further experiments/measurements conducted by related works, a summary regarding sensing, processing and data management based green-IoT solutions is given in Table V.

C. Low-Power Communication & Networking Solutions

In terms of wireless communication systems, there are various types of RATs, each of them having different coverage from a few centimeters to tens of kilometers, applicable to IoT deployment. Even though the coverage of any RAT can differ significantly according to the transmit power, receiver sensitivity, modulation techniques and antenna used, in order to provide a general perspective considering the areas where these technologies are widely used, as depicted in Fig. 8, short-to-medium range communications such as BLE, ZigBee, 6LowPAN, and Wi-Fi can be classified under Wireless Personal and Local Area Networking (WPAN and WLAN) technologies, whereas long-range communications such as LPWA LoRa, and cellular 2G/3G/LTE/5G can be classified under Wireless Wide Area Networking (WWAN) technologies [24]. Most of IoT devices are now integrated with various RATs operating on unlicensed spectrum. Depending on the connectivity range or different methods utilized, there are many approaches/solutions proposed in the literature related to communication and networking technologies. Within this section, technical solutions/approaches regarding IoT-centric communications and networking will be evaluated under five broad categories: (i) Scheduling; (ii) Adaptive Modulation and Coding (AMC) and Uplink Power Control (UPC); (iii) Low-mobility; (iv) Cognitive and (v) Routing.

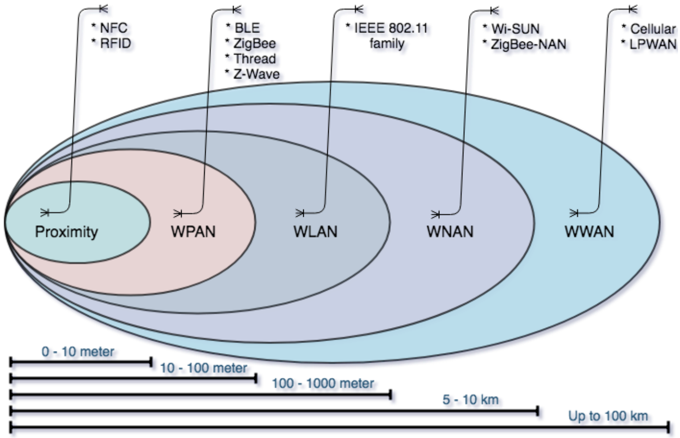

Fig. 8: IoT connectivity technologies

• *Scheduling-based solutions*: IoT objects/devices equipped with wireless networks mostly stay in listening mode not to miss any packets destined for them. Even though this approach lets devices have a high throughput with low latency, it also causes these devices to consume high amount of energy, mostly staying awake. In this regard, the concept of sleep-scheduling, in other words; duty-cycling, is an efficient way to reduce power consumption while keeping the latency and throughput in an acceptable level, especially for data traffic patterns with long silent periods. For instance, authors in [125] propose a generic Discontinuous Reception (DRX) framework for LTE networks, where time is split into DRX cycles containing ON/OFF intervals. While devices monitor the channel in listening mode or transmit their packets in case the state is ON, devices simply enter to sleep state, turning off their receiver circuitries to save energy in case the state is OFF. Similarly, authors in [126] study the power consumption rates of devices equipped with LTE networks, communicating over M2M services with deterministic intervals. Here, authors demonstrate that high amount of energy efficiency can be accomplished increasing the DRX cycle length up to a level where latency increase and throughput decrease does not strictly harm the system performance. In [127] the authors propose an algorithm that dynamically tunes the intervals of both discontinuous reception and transmission (DRX/DTX), ensuring a pre-defined QoS level and taking throughput, packet delay, and packet loss rate into account.

There are numerous studies that focus on energy efficiency through sleep-scheduling. For example, a solution would be to let Access Points (APs) set an offset listen interval between beacon frames to alleviate network contention and delay [128]. Other solution would be to dynamically allow a higher channel access priority for low-power devices through a deep sleep method [129]. Devices could also compute a fixed back-off value (instead of randomly choosing it) and let themselves sleep during the channel access contention through dynamic

TABLE V:
Sensing, processing and data management based green-IoT solutions - Summary

Ref	Operation	Parameters/Actions	Utility	Network	Energy gain
[96]	Dynamic sensing	Remaining battery level, previous usage history, QoS	It lets sensors switch to sleep mode if sensing the environment in an interval is not needed	Any network	High
[97]	Data sensing and transfer	Coefficient of data differentiation	It constructs a clustering index tree dividing region into grid cells in hierarchical manner	Any network	High
[98]	Group-based management	Coverage, power level, spatial correlation	It provides group formation and spatial correlation based energy saving	Any network	Medium
[102]	Approximate computing	Throughput, power consumption, encoder coefficient	It provides a quality-configurable run-time framework to tune level of approximation	Any network	Low
[103]	Service merging	Maximum Weighted Independent Set, co-location graph	It maps and co-locates different services on one device	Any network	Low
[108]	Store-centric design	Query processing, storage platforms, query initiator	It enables query processing to migrate to the nodes	Any network	High
[110]	Multi-query optimization	Time-sharing among temporal queries and aggregation	Two-tiers are used to enhance the execution of queries	WSN	High
[119]	RIOT OS	Reckoning objects/devices with minimal resources	IoT-ready OS that has several networking protocols including 6LoWPAN and RPL	Any network	Medium

computation of channel utilization [130]–[132]. A mobility-supported power saving solution could be used to consider both user mobility and traffic condition to adjust sleep/wake-up schedules [133]. Another solution would be to use a packet-buffering approach that would store the packets at the AP for the devices in sleep mode [134]. Minimizing communication interruptions by scanning channels selectively according to their beacon arrivals obtained with an initial passive scanning was also addressed in [135]. The energy-efficient neighbor discovery, header compression, and fragmentation to enable IPv6 on top of BLE network was discussed in [136], [137].

Other than sleep-scheduling, message scheduling is also used by devices to save energy in IoT. For instance, Abdullah et al. in [138] present an energy-efficient message-scheduling algorithm where objects/devices are gathered into IoT subgroups, each of which has a message-broker that transfer messages originated from the group to the ultimate receiver of the sensed data. Here, message-scheduler works at the broker level to select which message to be transmitted first.

• *AMC & UPC solutions*: One of key principles of RATs today is to increase the amount of data to be transmitted in unit-time as much as possible. Yet, IoT-centric device communications typically consist of small data transmissions, which demonstrate that high amount of throughput will not be required most of the time. Besides, most of todays RATs offer Adaptive Modulation Coding (AMC) and Uplink Power Control (UPC) instruments to manage channel fluctuations and tune the transmission rate according to the channel condition. Aforementioned instruments are also used to decrease communication-based power consumption by IoT applications [139]. In this way, the payload size to be transmitted can be adjusted utilizing the Modulation and Coding Scheme (MCS). Although higher MCS means total energy per bit is lower, it also means that network will be more prone to suffer from errors induced by the wireless medium. In this context, LTE itself runs a dynamic AMC to balance the data rate and the transmission robustness (probability of correctly decoding) through selecting an appropriate MCS [140]. Additionally, UPC is another instrument to challenge channel fluctuations. Here, the aim is to keep the data rate constant, by allowing the sender to adjust at a proper variable amount of power transmitting their packets. Hence, AMC and the UPC instruments must be well-optimized to increase energy efficiency for small data transmissions of IoT applications. For instance, Zhou et al. in [141] propose a dynamic powering algorithm according to packet loss ratios, optimizing power-aware user satisfaction (e.g., in terms of Mean Opinion Score) over a practical IoT.

• *Low-mobility based solutions*: In reality, most of IoT-enabled devices are not expected to move, or rarely to move in vicinity. In such case, mobility management features/protocols that run on IoT devices could be removed, simplified, or optimized to save energy. High amount of signaling can be reduced with low-mobility since devices will have fixed locations (e.g., signaling will be reduced with increasing intervals between Tracking Area Updates (TAUs)) and distance to the associated APs or BSs will be fixed (periodic update for the devices will be avoided as Timing Alignment (TA) parameter is constant) [22]. Low-mobility also results in devices to have reasonably stable path loss. In this sense, devices can also lessen the reporting period of the signal strength measured and further save energy [142].

• *Cognitive-based solutions*: Today, Radio Frequency (RF) spectrum, which is required for devices to transmit/receive data through wireless/cellular networks, is reasonably congested and hard to operate in an energy-efficient way. One of the key solutions is utilizing cognitive radio, as it provides devices to achieve high throughput and continuous connectivity, identifying dependable channels dynamically. In this context, there are some solutions proposed in the literature regarding IoT-centric cognitive radio and interface selection. For instance, Qureshi et al. in [143] propose an energy-efficient cognitive radio communication scheme for IoT devices. The proposed scheme analyzes management frames, such as Availability of Control Channel (ACL), Acknowledgement (ACK), Ready to Sent (RTS) and Clear to Sent (CTS) over dependable and non-dependable channels to let devices switch in between various available channels taking the energy efficiency into account. In addition to the cognitive-based channel hopping approaches, there are also works focusing on dynamic network/interface selection. For example, selecting an operating interface in such multi-radio enabled device, utilizing parameters, such as pre-defined Signal-to-Noise Ratio (SNR) values, channel utilization ratio, and achieved throughput was proposed in [144]. Similarly, energy-aware network selection mechanisms [145]–[147] as well as vertical handover mechanism [148] have been proposed to find the best trade-off between cost, energy, and data rate. Additionally, another solution would be to allow devices/objects to connect to a Point of Attachment (PoA) that is expected to consume the least amount of energy among all PoAs, taking critical parameters into account, such as RSS, channel utilization, collision probability, traffic class of the device and power consumed in each wireless states [12], [149], [150].

- *Routing-based solutions*: Due to its distributed network structure, routing-based energy efficiency of objects/devices is a crucial consideration in IoT. In this sense, IETF ROLL working group standardized an IPv6 Routing Protocol [151] for Low-Power and Lossy Networks (RPL) for resource-constrained devices. There are numerous studies in the literature aiming to obtain routing-based energy efficiency in IoT either using the RPL protocol or other ICT-based routing protocols. For instance, Barbato et al. in [152] present a Resource Oriented Energy Efficient (ROEE) routing protocol, which basically is a resource-oriented optimized version of RPL protocol. Here, two different energy-aware routing metrics (energy consumption rate and battery index) as well as information on resources' availability are used to increase the energy efficiency. Additionally, Alvi et al. in [153] also present an improvement to the RPL considering multimedia devices since RPL implementation for scalar sensor data communication are not feasible for Internet of Multimedia Things (IoMT). Here, energy efficiency is achieved by allowing IoT nodes to choose a preferred parent by considering a set of network metrics, such as delay constraint, battery consumption of potential parent nodes, type of energy sources along the route towards the root node, etc. In addition to the RPL-centric energy-efficient routing solutions, there are also works that focus on gaining energy efficiency utilizing other ICT-based routing protocols. For example, the Shortest Path and Less number of Links (SPLL) based path selection scheme utilizing the location of message sender, and number of processor in specific sensor to develop a longer hops (LH) message scheduling [154]. Another solution would be the use of a path generation scheme with deadline considerations for real-time query processing [155]. Selecting the routes on the basis of a proposed end-to-end link quality estimator mechanism, residual energy and hop count was considered in [156]. The work in [157] regulates the transmission of routing request (RREQ) frames in a stochastic manner by using the residual energy and Expected Transmission Count (ETX) value of a link on the path to facilitate energy-aware routing set-up. Furthermore, energy-efficient IPv6 networking support for Contiki OS was addressed in [158].

Similar to ICT, communication and networking cause high amount of energy consumption in IoT. Depending on the IoT environment and network setup, this rate can be easily more than half of the total energy consumed in the whole IoT process [159]. Therefore, the reduction of communication and networking based high energy consumption will contribute to long-lasting functionality and sustainability for IoT devices. In this context, various techniques and metrics, which are presented in the literature, to reduce energy consumption are explained in this subsection. It should be noted that proposed approaches/solutions utilize a large set of local and network related parameters. Yet, this may also come at the cost of higher network overhead that could lead to increase in processing power and hence the energy consumption. Therefore, utilizing power-critical metrics with less message exchanges would lead to maximizing the energy efficiency. Additionally, it is mostly proper to say that scheduling and cognitive based approaches are expected to save higher amount of energy than those AMC-UPC and Low-mobility based solutions since scheduling and channel/network/interface adaptation continue through the whole communication, while AMC-UPC and Low-mobility based solutions are adapted only in specific circumstances. Furthermore, it is also important to mention that green scheduling, cognitive, low-mobility and AMC-UPC based approaches enable IoT devices to consume less energy and hence provide sustainability. Yet, routing-based approaches mostly enable energy efficiency of networks, not the devices. In line with the aforementioned explanations and further experiments/measurements conducted by related works, a summary regarding communication and networking based green-IoT solutions is given in Table VI.

D. Power Management & Measurement Solutions

The management of the energy consumed by a system is as important as unit energy costs consumed by devices, or cost of energy consumed during sensing, communication or data analysis, since the efficiency of management determines the energy efficiency of the entire system to a large extent. In this regard, the effective achievement of intelligent energy management is based on pervasive and reliable exchange of information between millions of sensors and actuators positioned in the field, with little or no human intervention. This section discusses some practical and theoretical studies regarding IoT-centric green power management and measurement.

- *Green Power Management*: Motivated by achieving low-energy and low-bandwidth consumptions while keeping the performance high enough, Fuhong et al. [160] propose an energy and service management scheme using a cooperative differential game model to discover the optimum point that minimizes the energy consumption, considering bandwidth vs. energy trade-off. Another IoT-centric energy management scheme, which controls the duty-cycles of sensors under Quality of Information (QoI) expectations (e.g. accuracy, latency, and coverage) in a multi-task oriented environment, is proposed in [161]. Here, control choice is set dynamically in view of long-term task usage statistics and service delay of each task that serves as the constraint. Additionally, Pan et al. in [162] presents an energy management model for

TABLE VI:
Communication and networking based green-IoT solutions - Summary

Ref	Operation	Parameters/Actions	Utility	Network	Energy gain
[125]	Discontinuous reception	Throughput ratio, on/off intervals, DRX cycles	Time is split into DRX cycles containing ON/OFF intervals	LTE	High
[127]	Sleep scheduling	QoS-level, throughput, packet delay, packet loss rate	It tunes the intervals of DRX/DTX ensuring a pre-defined QoS level	LTE-A	High
[135]	Green channel scanning	Passive/selective scanning, beacon arrival times, channel utilization	It scans channels selectively after each channel's beacon arrival	Wi-Fi	Medium
[138]	Message scheduling	Message-broker, IoT subgroups	Message-scheduler works at broker level to select which message to be transmitted first	Any network	Medium
[140]	Adaptive modulation	Throughput, frame size, codec	AMC balances data rate and transmission robustness through a proper MCS	LTE	Low
[141]	Dynamic power control	Packet loss rate, mean opinion score	It adjusts the transmitting power according to the signal strength	Any network	High
[142]	Low-mobility	Tracking area updates, timing alignment, coverage	High amount of signaling can be reduced with low-mobility	Any network	Low
[143]	Cognitive radio	RF spectrum, data rate, ACL, ACK, RTS, CTS	It lets devices to switch between available channels considering energy efficiency	Wireless Cellular	High
[144]	Network/interface selection	Signal-to-Noise Ratio, channel utilization, throughput	It lets devices select the network/interface dynamically	Wireless Cellular	Medium
[152]	Resource oriented routing	Energy consumption rate, battery index	It is a resource-oriented optimized version of the RPL protocol	Any network	Medium
[153]	Multimedia based RPL	Delay constraint, battery consumption, type of energy sources	It is an enhanced RPL protocol considering IoT-centric multimedia devices	Any network	Medium
[156]	Route selection	Residual energy, hop count	It selects routes on the basis of a proposed end-to-end link quality estimator mechanism	Any network	Medium

buildings utilizing location-based and human-centric feedback to control energy modes of various appliances and to switch them ON/OFF according to user(s) approaching/leaving buildings. Furthermore, another energy management model, which supports the integration of collected energy-related data into companies' IT tools and platforms, is presented in [163] for industrial corporations. Here, the fundamental aim is to highlight how operational/tactical decision-making processes could leverage on such data to increase energy efficiency and competitiveness. In [164], a joined communication method for intelligent energy management is proposed studying the integration of software-defined networking (SDN) and M2M and focusing on cost reduction, fine granularity resource allocation, and end-to-end QoS guarantee. Ju et al. in [165] present a Predictive Power Management (PPM) method, to accomplish energy-efficient and reliable operation for Internet of Battery-less Things (IoBT). Here, PPM considers three main metrics for IoBTs: system power loss, dynamic energy allocation, and energy-efficient wireless transmission. In this context, optimal working point is derived according to the IoBT system model to minimize the system power loss. The authors test real-life energy harvesting profiles and validate the efficiency of the proposed PPM, obtaining 9.4% to 23.22% improvement of transmission energy efficiency. In addition, Abedin et al. [166] propose another energy management scheme based on the duty-cycle scheduling for various sensors/appliances. The proposed scheme contains three states, such as on-duty, pre-off duty, and off-duty and achieves energy saving switching ON/OFF between these states based on sensing/communication needs. Ventura et al. in [167] embed electronic adapters within appliances, such as a coffee machine, to make them IoT-capable, and then present a cloud-based green power management framework to support Internet-connected appliances to lower their energy consumption through a RESTful infrastructure. Liu et al. [168] propose a routing-based power management scheme which leverages network routing principles to address the optimization model using related metrics, such as energy consumption, link flow balance, and system budget.

- *Green Power Measurement*: There are also a number of measurement-based or predictive power management solutions. For example, Gray et al. in [169] develop a power consumption model to estimate energy consumption for each IoT-gateway. The authors model a few IoT-centric access network technologies (LTE, Wi-Fi and Passive Optical Network (PON)) and demonstrate that Wi-Fi network with PON backhaul is the most energy-efficient choice in case the Wi-Fi background traffic level is modest. Additionally, Deng et al. in [170] study green levels of smart objects/devices as a fuzzy problem and present a novel method to compute energy efficiencies and electromagnetic pollution indexes of those objects/devices, utilizing two dimensional quantification mapping with medium mathematics (MM). In another work, Looga et al. in [171] present a packet-based real-time energy model for IoT objects examining network traffic traces collected at the backend. Furthermore, Pozza et al. in [172] present SmartEye, which is a solar powered observer platform that enables low-energy observation of large-scale WSNs and IoT testbeds.

It should be noted that power management models utilize various approaches to discover an optimum point that minimizes the energy consumption, considering various trade-offs, such as bandwidth vs. energy. In this way, energy efficiency is aimed to be achieved through the whole IoT procedure, from voltage selection, sensing, processing to communication, routing, manipulating, even energy harvesting. In order to evaluate the effectiveness of the proposed solutions, additional mechanisms/test-beds that are able to execute smart and green power measurements are also required. In line with the aforementioned explanations and further experiments/measurements conducted by related works, a summary regarding power management and measurement based green-IoT solutions is given in Table VII.

E. Energy harvesting & Wireless Power Transfer

Self-sustainable energy-independent operations are vital for the long-term IoT development. Due to the possible long distance to energy sources and limited battery capacities, IoT objects/devices must use environmental resources effectively. Energy-aware objects/devices can play a key role to achieve self-sustainability and to extend the device lifetime significantly by either harvesting the required energy from ambient sources, or charging power through wireless power transfer (WPT).

- *Energy Harvesting*: Although there are numerous studies regarding energy harvesting in the literature, solar and kinetic energy-harvesting methods are the most popular study subjects due to the size constraint of small and embedded devices mostly used in IoT. IoT-centric energy harvesting approaches are summarized in detail by Roselli et al. in [173]. One of the proposed solar-based energy harvesting methods is the hybrid solar-rectanna, which is a device used to power small low-power devices in DC form. It contains a solar panel and an antenna that performs like a rectifying circuit, converting an AC signal into a DC signal. In order to test the efficiency of solar energy harvesting, Meng et al. in [174] design a simple wireless IoT terminal that has solar panel, lithium batteries to provide stable power in case is needed, various sensors (e.g. infrared, environmental, multi-channel sensors and RFID readers), communication interfaces (e.g., Ethernet and Zigbee), and a processor to program the energy management. The authors demonstrate that the terminal is able to preserve self-sustainability for a long time throughout the tests, under the scenario of 3 seconds transmissions repeated every 5 minutes. In addition, photovoltaics (PV) to power IoT devices are also analyzed by Haight et al. in [175].

Considerable amount of kinetic energy can also be harvested from moving objects, such as humans when walking, cycling, etc. Gorlatova et al. in [176] construct a motion dataset that has over 200 hours of motion data collected from more than 40 participants. In this regard, authors evaluate performance of various motion-centric energy harvesting adaptive algorithms making use of their own dataset and validate the success of kinetic energy harvesting powering small size low-power body sensor networks.

- *Wireless Power Transfer* or Wireless Energy Harvesting (WEH), is one emerging energy harvesting method getting an excessive success in numerous fields, such as Electric Vehicles (EV), Space to Space (S2S) and Space to Earth (S2E) energy transfer, consumer electronics supply, etc. [20]. The most well-known WPT form is the passive RFID tags as they get the energy to work from the interrogating signal transmitted by the RFID reader [177]. Even though the RF energy is very low (RF power densities up to 300 uW/cm2), it has been validated in [178] that sufficient energy to charge an energy storage device can be provided by WPT. Similarly, Kamalinejad et al. in [179] present a WEH system for IoT that has an antenna able not only to receive the data but also to absorb the electromagnetic radiation to charge the device itself. The authors analyze the lifetime of the WEH-assisted battery-operated IoT systems under two different scenarios: (i) uniform distribution in a ring topology, and (ii) randomly distributed multi-hop topology. To this end, the authors state that further improvements are required at both circuit and system levels to achieve self-sustainability through WEH.

It should be noted that the primary aim of the EH and WPT solutions is to support IoT devices to run longer by collecting the highest possible amount of energy. In this context, even though the amount of energy that can be collected by harvesting is negligible compared to the total amount of energy consumed through the whole IoT procedure, it makes a significant contribution for a sustainable IoT allowing objects/devices to remain in the field. In line with the aforementioned explanations and further experiments/measurements conducted by related works, a summary regarding energy harvesting and power transfer based green-IoT solutions is given in Table VIII.

F. Iot-based Energy-Efficient Cloud and Data Centers

Just like the IoT, cloud computing is also an emerging field that has enormous application space, featuring distinct computing resources and design architectures. The academia and industry, starting with the establishment of Web of Things (WoT) [180], have began to explore the convergence of the cloud and the IoT to take advantage of their essential complementarities. Although there are numerous works surveying cloud and IoT paradigms separately, there are only few works surveying the convergence of these technologies focusing on their key properties, structures, principal technologies, and open issues, as in [181]. First studies regarding the Cloud-IoT were mainly focused on IoT resource management through the cloud rather than service delivery since cloud was viewed as a computing center to enable managing the massive IoT resources. Some examples are: cloud and WSN integration through developing WSN components (e.g. pub/sub broker and resource registry) on the cloud proposed in [182], and the virtualisation of physical sensors as software entities on the cloud proposed in [183]. Later on, to achieve well-performed scalable IoT service delivery, PaaS cloud platforms were proposed in the literature [184].

Apart from offering resource management or service delivery, cloud and IoT convergence can also assist object/devices to provide energy-efficient pervasive data sensing/gathering capabilities and powerful data storage and data processing abilities. In this regard, some of energy-centric cloud-IoT approaches are mentioned below.

Authors in [185] propose a collaborative location-based sleep scheduling (CLSS) scheme for cloud-enabled WSNs.

TABLE VII:
Power management and measurement based green-IoT solutions - Summary

Ref	**Operation**	**Parameters/Actions**	**Utility**	**Network**	**Energy gain**
[160]	Energy/service management	Bandwidth vs. energy tradeoff	A cooperative differential game model to discover the point that minimizes the energy	Any network	High
[161]	Power management	QoI, accuracy, latency, coverage	It controls the duty-cycles of sensors under Quality-of-Information	Any network	High
[162]	Human-centric energy model	Location, energy modes	It uses location-based human-centric feedbacks to control energy modes of appliances	Any network	Medium
[164]	SDN-based energy model	Cost reduction, resource allocation, end-to-end QoS guarantee	It focuses on the integration of SDN with M2M	Any network	High
[165]	Predictive power management	Power loss, dynamic energy allocation, green wireless transmission	Optimal point is derived according to the IoBT system model to minimize power loss	Any network	High
[166]	Duty-cycle scheduling	On-duty, pre-off duty, off-duty states	Achieves energy saving switching states on/ off based on sensing/communication needs	Any network	High
[167]	Cloud-based power model	RESTful infrastructure	It embeds electronic adapters within appliances to make them IoT-capable	Any network	Medium
[169]	Power consumption model	Background traffic, power rates	It estimates energy consumption rates for each IoT-gateway	Wi-Fi, LTE, PON	Medium
[170]	electromagnetic pollution index	Quantification mapping, medium mathematics	It computes energy efficiencies and electromagnetic pollution indexes of objects	Any network	Medium
[171]	Real-time energy model	packet count, throughput, traffic flow	Packet-based energy model that examines network traffic traces collected at backend	Any network	Medium

TABLE VIII:
Energy harvesting and power transfer based green-IoT solutions - Summary

Ref	**Operation**	**Parameters/Actions**	**Utility**	**Network**	**Energy gain**
[173]	Solar-based energy harvesting	Antennas, RFID systems, chipless structures	Solar-rectanna is used to power small low-power devices in DC form	Any network	Medium
[174]	Solar IoT terminal	Preserving self-sustainability for a long time	Solar-powered IoT terminal with sensors, communication interfaces and a CPU to program the energy management	Any network	Medium
[175]	Photovoltaics	Budget estimates, voltage regulation, energy storage	Photovoltaics to power remote sensors and controllers at the edge of the Internet	Any network	Medium
[176]	Kinetic enery harvesting	Motion dataset	Performance of motion-centric energy harvesting adaptive algorithms are evaluated	Any network	Low
[177]	Wireless power transfer	Passive RFID tags	Tags get the energy to work from interrogating signal transmitted by RFID reader	Any network	Low
[178]	WPT validation	Charging a device through WPT	sufficient energy to charge an energy storage device can be provided by WPT	Any network	Low
[179]	Wireless energy harvesting	Uniform and random distribution in a ring/multi-hop topology	It has an antenna to receives data and absorb electromagnetic radiation to charge a device	Any network	Low

Here, WSN's energy consumption is reduced through changing the awake/sleep state of each sensor adaptively according to the mobile users' positions. Another work regarding energy-efficient cloud-IoT is proposed in [186]. Here, the authors propose two novel job-scheduling approaches for cloud-enabled WSNs, which are priority-based two-phase Min-Min (PTMM) and priority-based two-phase Max-Min (PTAM) and validate their energy efficiencies obtaining shorter Expected-Completion-Time (ECT). Additionally, Botta et al. in [187] present two different methods to save further energy through cloud-IoT; (i) compressive-sensing, which consists of decreasing the measurement frequency of the signal and utilizing synchronous-communication to decrease also the transmitting power of each sensor, and (ii) shifting the local computations/manipulations to the cloud to further reduce energy consumed by local deployment. Furthermore, Wan et al. in [188] propose a novel energy-aware para-virtualized hypervisor for delay sensitive applications. Here, the hypervisor executes latency measurements in guest-OS and CPU Power Modulator in host-OS. He et al. in [189] proposes a green resource allocation framework based on deep reinforcement learning in content-centric IoT networks. The framework basically allocates cache capacity among content-centric computing nodes and handles transmission rates under a constrained total network cost and MOS for the whole IoT. There are also a few other energy-centric cloud-IoT solutions proposed in the literature basically addressing issues such as efficient data transmission/compression methods [190], data caching instruments to re-use collected data in time-tolerant applications [191], and middleware design that compresses data in case of continuous/long-term data monitoring [192].

Data centers (DCs) are also an impactful part of the cloud-IoT paradigm as they store/manage the massive digital data, such as social-media updates, web contents and cloud computing processes. Running these datacenters and cooling them requires a high amount of energy. In order to decrease energy consumption ratios of servers, researchers designed OS-centric scheduling methods and increased the overall system performance by virtualization and batching of the computed loads [193]. Datacenter design should also be enhanced for energy efficiency in idle and low utilization conditions. In this regard, routing traffic flows to optimum paths and putting the idle resources in the doze state or turning them completely off can leads to high amount of energy saving [7]. Additional energy saving can also be achieved designing energy-aware DC cooling systems, such as installing DCs in low-temperature zones, deploying efficient ventilation and water-cooling systems, or designing multi-level smart temperature control algorithms as proposed in [194].

It should be noted that IoT platforms has been mostly driven by cloud computing with all the logic in the cloud. In this way, battery-less and battery-dependent IoT devices only sense and transfer related data to the cloud. Storing, analysis and manipulation of the data is carried out in the cloud. Depending on the size and frequency of the data to be transferred, this approach can provide high energy efficiency for many IoT devices. Since some of the processes are carried out by the cloud, not by devices, devices' batteries can last longer. Moreover, taking some part of the logic to the edge might be also suitable for some cases due to cloud-centric issues, such as excessive latency, security weakness, and lagged data transmission [195]. Recently, mobile edge computing (MEC) paradigm is taking the role of mobile cloud computing (MCC) through positioning cloud-based resources, such as storage and computing capability, to the edge within the radio access network (RAN) [196]. Transferring computation-intensive and delay-sensitive tasks to the edge of the network can further reduce energy consumption of IoT-centric objects/devices. In the literature, there are several MEC-centric energy efficient proposals, such as the work that offloads the video encoding task to the MEC server positioned at the eNodeB [197], the work that presents a collaborative and distributed computation offloading method where devices/objects outsource their computation to the edge and/or cloud [198], the work that implements adaptive bit-rate streaming, collaborative caching and processing on a MEC server [199]. However, initial complexity of MEC concept requires further research to completely understand all possible benefits and risks [200]. In line with the aforementioned explanations and further experiments/measurements conducted by related works, a summary regarding cloud and data centers based green-IoT solutions is given in Table IX.

V. ENERGY-EFFICIENT IOT APPLICATIONS

We are in an era where smart objects/devices, such as smartphones, watches, cars, and even buildings serve people by communicating with each other. The increase in the number and variety of objects at incredible speeds makes room for numerous IoT applications in almost every area of our life. Yet, a sustainable smart world can only be achieved through the efficient use of energy resources. Although mass deployment of IoT objects may seem like a burden on energy consumption, as these objects requires additional energy sources to sense, communicate and analyze the environment, high amount of energy saving can be achieved by IoT by diminishing the impact of greenhouse-effect of the IoT itself at first through low-power object deployments and then by diminishing the greenhouse-effect of current applications/services through smart sensing, communication and analysis [26].

In [25], [201], authors examine the IoT application fields, which are frequently studied in the literature, under six main categories: (i) industrial automation, (ii) health and living, (iii) habitat monitoring, (iv) smart cities, (v) energy, and (v) transportation system. Driven by realizing a sustainable smart-world, energy-efficient IoT applications will also be examined under the same categories throughout this section.

A. Industrial Automation

IoT can assist industrial companies to provide energy efficiency and reduce CO_2 emissions during the deployment, installation, monitoring and energy management phases of their factories. In this context, autonomous objects/devices can handle operations and manufacturing tasks faster, more efficiently and hence with less energy consumption without (or with minimal) human intervention through sensing and evaluating the production data, timing and possible issues that may arise. As an example, Shrouf et al. in [163] present an industrial energy management scheme that integrates the energy-related data into the IT-centric tools and platforms of companies and show how operational and tactical decision-making processes could leverage on such data to expand energy-saving.

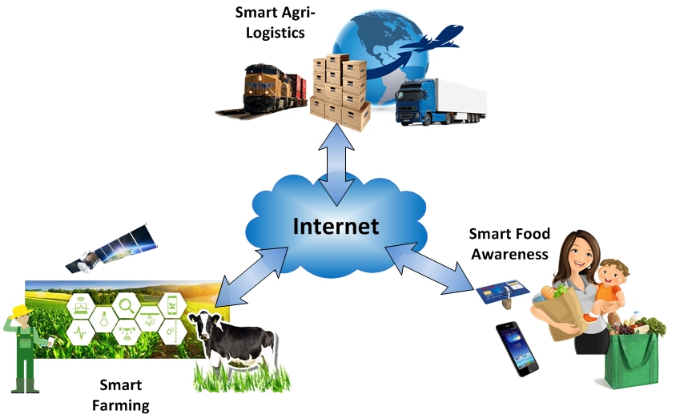

Fig. 9: IoT-based Smart FSC Example - From Farm to Plate

One of the best examples of green IoT-based industrial automation is the Food Supply Chain (FSC). Due to its distributed, complex operation processes, and large number of stakeholders, FSC is facing numerous issues in terms of Quality of Service, productivity, and public food safety. In this context, IoT solutions can assist FSC at all stages from accurate farming, to food production, processing, storage, distribution, and consuming or in other words: from farm to plate [28] as illustrated in Fig. 9. Similarly, Pang et al. in [202] propose a business oriented FSC framework to improve overall energy-efficiency and food security, utilizing IoT's sensing

TABLE IX:
Cloud and data centers based green-IoT solutions - Summary

Ref	Operation	Parameters/Actions	Utility	Network	Energy gain
[182]	Cloud-WSN integration	Pub/sub broker, resource registry	Develops WSN components for the cloud integration	Any network	Medium
[183]	Virtualizing of physical sensors	Network function virtualization	Sensor virtualizing as software entities on the cloud	Any network	Low
[184]	IoT-centric PaaS framework	Virtual verticals, computing resources, middleware services	Provides platform services for IoT providers to efficiently deliver/extend services	Any network	Medium
[185]	Cloud-enabled sleep scheduling	Awake/sleep states, user position	WSN's energy consumption is reduced by changing the awake/sleep state of each sensor according to the mobile users' positions	Any network	Medium
[186]	Cloud-enabled job scheduling	Shorter Expected-Completion-Time	Priority-based two-phase Min-Min (PTMM) and Max-Min (PTAM) schedulers	Any network	Medium
[187]	Compressive-sensing	Shifting the local computations/ manipulations to the cloud	Decreasing frequency of signal measurement and utilizing synchronous-communication	Any network	High
[188]	Para-virtualized hypervisor	Hypervisor for delay sensitive multimedia applications	Hypervisor executes latency measurements in guest OS	Any network	Medium
[191]	Data caching	Delay, QoS	It lets re-using the collected data in time-tolerant applications	Any network	Medium
[193]	OS-centric scheduling	Virtualization, batching, scheduling	Increases overall system performance by virtualization and batching of computed loads	Any network	Medium
[7]	SDN-based data centers	Channel utilization, traffic flow, optimum path	Routing traffic to optimum path and putting idle resources in doze state	Any network	High
[194]	Smart cooling	Low-temperature zones, ventilation, water-cooling	Designing multi-level smart temperature control algorithms	Any network	High

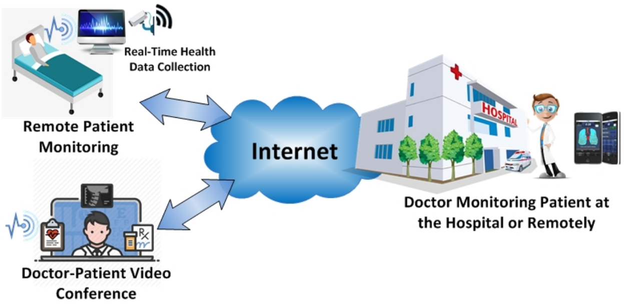

Fig. 10: IoT-based Smart Health Example

equipment, communication technologies, network medium and raw-data manipulation.

Wang et al. [203] propose a layered green Industrial IoT architecture that makes use of a sleep scheduling and wake-up protocol to predict sleep intervals for the sensing entities in order to reduce resource consumption, achieve energy-savings and prolong the lifetime of the entire system. As data collection within Industrial IoT relies on a significant number of sensor nodes and smart devices, energy efficiency can be achieved by optimizing the sensing, processing and communications of these IoT devices [204].

B. Health and Living

As in industrial automation, IoT can improve health and living conditions while also providing energy efficiency, by helping patients through green-hospitals and green-equipment, utilizing natural energy sources, ultra-low power objects/devices, or harvesting the required energy itself. In this context, humans/patients, equipment/devices, hospitals/buildings, etc. can be tracked and monitored in an energy-efficient way through collecting, managing and sharing locations, diagnosis, medications, managements, finances, and even daily activities [205].

Motivated by enhancing healthcare and living condition, together with optimal energy efficiency, Hassanalieragh et al. in [206] present a framework for the integration of remote health monitoring technologies into the clinical practice of medicine, through IoT-based wearable objects, smart observation and data analysis as illustrated in Fig. 10. Furthermore, to show the effectiveness of the low-cost, energy-autonomous and disposable RFID sensors, Amendola et al. in [207] present a survey on state of the art health-related body-centric RFID applications that mainly utilize temperature, humidity, and other gases from patient's living ecosystem.

Apart healthcare, IoT can also provide green participatory sensing, which basically is taking advice or relaying on people for daily activities, such as recommendation for a purchase, car repair, a movie, etc. through the world-wide-web and social-networks [30]. Participatory sensing, together with the Social Internet of Things (SIoT) paradigm, have also been helping to revisit IoT-related issues (e.g. large networks of inter-connected things) and have been carrying suitable implications to a future-world filled by smart things that penetrate people's daily life [208].

C. Habitat Monitoring

Habitat conservation and monitoring is a critical matter to sustain local, nationwide and worldwide environment. It is used to detect spatial/temporal/physical alterations in the ecosystem, and the alterations arising from human-centric or natural events. Within the scope of habitat monitoring, issues such as smart farming, land and sea animal observation, etc. can be addressed by IoT and significant amount of energy savings can be achieved by sensing and analyzing the data gathered.

IoT can assist farmers gathering data on rapidly changing conditions, such as weather, moisture, temperature, fertility of soil, level of water, pest detection, animal intrusion in to the field, crop growth, etc. [209]. Farmers are also assisted through ubiquitous network connections, microcontrollers that manage the decision-making processes, image or video surveillance, and smart applications operated remotely by a smartphone or a computer as illustrated in Fig. 11. Shortly, IoT can enrich the energy efficiency and productivity, while reducing the costs of farming [209].

Fig. 11: IoT-based Smart Farming Example

As another example, Bhanu et al. in [210] propose an IoT-based WSN that aims at increasing the crop yield with low-power sensor deployment. Here, environmental condition, such as water-level, humidity and temperature are gathered, transferred by ZigBee and remotely monitored through a web application. Similarly, Dan et al. in [211], [212] propose frameworks for greenhouse-monitoring of smart agriculture, by performing data gathering, processing and transmission to accomplish energy-efficient low-cost farming.

D. Smart Cities

Due to the ease of access to healthcare services, education and employment/business opportunities, it is projected that 70% of the world population will be living in cities by the middle of this century [213]. In this context, the concept of *Smart Cities*, which fundamentally utilizes IoT-based data collection, communication and analysis, has made a significant progress to be able to confront the expected population growth and to offer citizens a more prosperous, productive and economic future [214]. The concept is basically a mixture of numerous intelligent areas that offer citizens the cutting-edge technological/industrial possibilities under one roof, such as Smart Transportation, Smart Energy Saving, Smart Security, Smart Street Lights, Smart Waste and so on [27] as illustrated in Fig. 12.

There have been numerous solutions regarding smart cities proposed in the literature. For example, Lanthaler et al. in [215] propose a WoT based distributed home automation system that manages appliances according to the power consumption usages monitored. In a similar way, another home automation system, which considers user-preferences, eco-friendly condition, presence and identity of occupants, is proposed in [216]. In addition, to see how green the LEED-gold-certificated green office buildings are, Pan et al. in [162] propose an IoT-based experimental test-bed and monitor/analyze power usages of buildings for one year. Conducted results demonstrate that they are not actually as efficient as promised due to centralized and static building controls. Motivated by the results, the authors also present an IoT-based framework that makes location-based automated/networked energy control possible, through cloud and a smartphone application. Furthermore, various energy-related parameters, which are considered to be integrated in buildings' energy management system, are analyzed in [217]. Aiming at providing adequate amount of lighting required without affecting the visibility, Farahat et al. in [218] propose an application for controlling/monitoring the lights consistent with the nearby environment, making use of automatic subscribes and discoveries of energy-meters by means of Device Profile Web Service (DPWS).

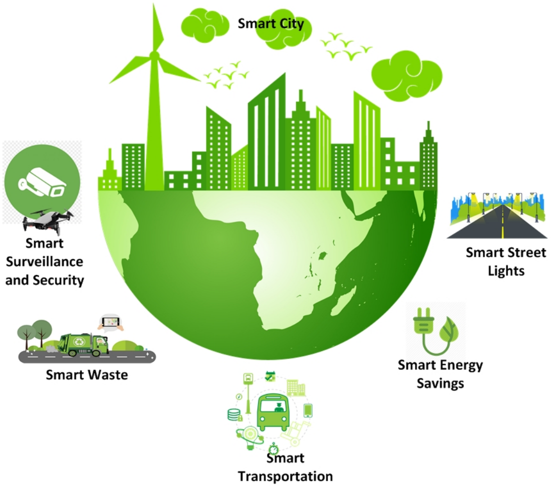

Fig. 12: IoT-based Smart City Example

E. Energy

The large data collected by IoT leads to a valuable information, only together with the ability to realize what this data means. In this context, smart-meters, low-power sensing, remote mass-storing and analysis may result in critical knowledge of waste and how to avoid it for the energy sector. An example is illustrated in Fig. 13. This information enables real time management of the energy, which eventually leads to cost reductions, performance enhancements and expanding operations. This way, both suppliers and consumers can identify, evaluate, assess energy efficiency that may be unobserved and hence, save money.

Smart grid and smart metering paradigms have been developing in parallel with the expansion of IoT and its new solutions, as these paradigms rely on information and communication technologies to sense and react possible variations in usage, rapidly and proficiently. Smart Grid requires gathering various types of data to provide efficient electricity from generators, transporters, providers and consumers, utilizing high amount of smart meters and objects/sensors. In this context, Monnier et al. in [219] evaluate various hardware and software integrated smart grid solutions to address energy-efficient smart grid deployments for buildings. Additionally, through smart metering, it is possible for both consumers and providers

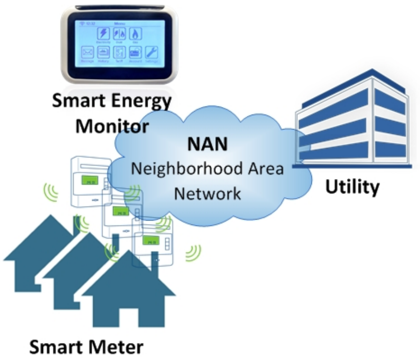

Fig. 13: IoT-based Smart Energy Example

to detect instant utility consumption, such as electricity, water and gas. In this way, both sides will be able to manage either the demand or the generation/distribution/storage plants and hence, will assist diminishing dependency on natural resources [22].

F. Transportation

Problems related to urban life such as traffic congestion, long distance journeys, logistics, shipment and parking cause people to spend a significant portion of their lives on the roads. Yet, massive installation of tags/sensors/actuators on roads and vehicles makes the huge amount of traffic information possible for being stored, processed and managed by centralized or distributed traffic control sites. This type of transportation system not only leads to an energy-efficient transportation, but also assists routing the traffic faster and safer, providing drivers/pedestrians with proper transportation information as illustrated in Fig. 14.

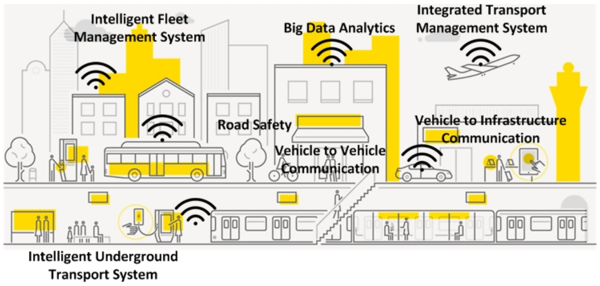

Fig. 14: IoT-based Smart Transport System Example

For example, a smart transportation system that sends vehicles' locations to a web-server, and arriving information, after analysis, to the terminal is proposed in [220]. In this way, pedestrians will be able to know arriving information of vehicles, queried or located in the vicinity. In addition, Da et al. in [28] propose a DNS-based framework to support logistics companies' supply chain management. Here, vehicles/products are tracked source-to-destination by RFID sensors in real time and the data gathered is monitored/analyzed to manage a wide-range of operations in an energy-efficient way. IoT-based cloud-integrated smart parking system is also proposed in [221]. It consists of an on-site IoT module, which is used to monitor/signalize status of parking spaces, and a mobile app that lets users check/book available parking spaces. Furthermore, a cruise control scheme that focuses on assisting drivers with eco-efficient driving recommendations is proposed in [222]. Here, recommendations are achieved through IoT-based data collection and processing.

In line with the aforementioned explanations, operations, parameters, utilities, and energy efficiency levels of the industrial IoT applications evaluated within the scope of this paper are summarized in Table X.

VI. CHALLENGES & OPEN ISSUES IN IOT

Although developments of existing technologies and significant research efforts towards IoT have been made, due to its complex structure and renewal of the problems that the ICT is exposed to with new technologies, there are still some major challenges that must be addressed to achieve a sustainable green-IoT. Throughout this section, we classify green-IoT related challenges into four broad categories: (i) Technical; (ii) Lack of Standardization; (iii) Information Security and Privacy Protection; and (iv) Governance and Legislation. Organizations from different sectors, such as academics, foundations, users and policy-makers, must work together to overcome these problems.

A. Technical Challenges and Open Issues

From the technical viewpoint, design and development of a green-IoT architecture, green infrastructure, green spectrum management, green communication and connectivity, interoperability, adaptation to natural energy sources, complexity and scalability, QoS provisioning, energy management, SoA, middleware coding and big data analysis are some of the major challenges that need to be addressed as listed in Fig. 15.

Fig. 15: Technical Challenges and Open Issues

- *Green IoT Architectures* - in order to allow various object/devices to communicate energy efficiently through different protocols and non-homogeneous networks, a standard architecture such as OSI or TCP/IP is required. In this way, not only the devices, but also protocols and applications will be provided to be energy efficient. Thus, a green-centric IoT

TABLE X:
Comparison of industrial energy-centric IoT applications

Ref	Domain	Interest	Devices	# things	Network	Mobile app	Achieving greenness
[163]	Industrial Automation	Energy management	IT-centric	Medium	LAN	No	Through optimization with production management
[202]	Industrial Automation	Food supply chain	RFID/WSN	Large	WAN	No	Through a value-centric joint design framework
[206]	Healthcare	Remote health monitoring	Wearables	Large	WAN	Yes	Through IoT-based wearable objects, smart observation and data analysis
[207]	Healthcare	Body-centric RFID application	RFID	Small	WLAN	Yes	Through using temperature, humidity, and other data from patient's living ecosystem
[208]	Living	Participatory sensing	Any device	Large	WAN	Yes	Through smart sensing and sharing that penetrate people's daily life
[209]	Habitat monitoring	Agriculture	RFID/WSN	Medium	WAN	Yes	Trough ubiquitous network connection, MCUs, image/video surveillance
[210]	Habitat monitoring	Agriculture	WSN	Low	WLAN	Yes	Through increasing the crop yield with low-power sensor deployment
[215]	Smart cities	Home automation	WSN	Low	WLAN	Yes	Through managing appliances based on the power consumption usages monitored
[218]	Smart cities	Smart lighting	WSN	Low	WLAN	No	Through controlling/monitoring the lights consistent with the nearby environment
[219]	Energy	Smart grid	RFID/WSN	Large	WAN	No	Through making the grid infrastructure, meters and buildings more connected
[22]	Energy	Smart meter	RFID/WSN	Large	WAN	Yes	Through letting both consumers and providers know instant utility consumption
[220]	Transportation	Smart transportation	RFID/WSN	Large	WAN	Yes	Through knowing arriving information of vehicles, queried or located at the vicinity
[28]	Transportation	Logistics	RFID	Large	WAN	Yes	Through tracking vehicles and analyzing the data gathered for various operations
[221]	Transportation	Smart parking	WSN	Low	WLAN	Yes	Through monitoring/signalizing the status of parking slots
[222]	Transportation	Cruise control	WSN	Medium	WAN	Yes	Through assisting drivers with eco-efficient driving recommendations

architecture, which manages connected-objects, their addressing, identification and collaborations among various entities, is a research challenge.

- *Green Infrastructure* - one of the biggest challenges in green-IoT paradigm is to design and deploy an energy-aware low-power infrastructure that consists of various devices (e.g. sensors/objects, routers, clouds and data centers) with a very long life expectancy (or even life-time) without requiring any battery or with low power consumption [223]. Atat et al. [224] make use of stochastic geometry to enable the communication of cyber-physical systems (CPS) over cellular networks as well as to offload their traffic into small cells base stations powered by solar energy in order to provide ubiquitous coverage, global connectivity, reliability and security. Hussain et al. [225] explore the scenario where the underutilized communication and computational resources available in the context of connected vehicles could be actually utilized to enable a fog computing infrastructure for transportation CPS.

- *Green Spectrum Management* - RF spectrum, which is required for objects to transmit/receive data through wireless/cellular networks, is reasonably congested and hard to operate in an energy-efficient way. Although different cognitive radio approaches have been proposed in the literature regarding ICT-centric energy efficiency, new solutions solely focusing on green-IoT are still required. This is because the heterogeneity in IoT is at the maximum level, so that numerous protocols/technologies coexist and interact with one another even in one network domain [226].

- *Green Communication and Connectivity* - the communication of billions of objects and the access of these objects to the Internet has been realized through IoT. Although this communication has enabled numerous solutions with the analysis of the large data collected by these objects, communication of hundreds of objects in a network, or millions of objects in multiple networks has also caused high amount of energy consumption, due to issues such as inter-packet collisions, delay-based retransmissions, and inability of devices to enter sleep mode. In this context, IoT-centric green communication and connectivity approaches that make use of various wired and wireless medium access technologies in a single network is challenging.

- *Interoperability* - since there is no standardization about the IoT yet, solutions presented in the literature focus on their own designs. Nevertheless, high amount of heterogeneity on the physical, network and application domain of these solutions results in different architectural proposals, involving different components and protocols. This eventually leads to a limited interoperability between the proposed solutions/projects. IoT-based vendor-specific new architectures are still being proposed although rapid and balanced development of IoT and the optimization of energy efficiency will be adversely affected. In this context, multi-layered interoperability-oriented green IoT solutions are challenging before any standardization effort/draft has been released.

• *Complexity and Scalability* - IoT-based solutions have enabled a wide-range of things to have communication capabilities, causing an increase in complexity. In this context, simplification of IoT design and deployment is challenging, also considering energy efficiency in mind. In a similar manner, scalability becomes another issue, as there will be many objects, stationary or mobile, connected to the network(s).

• *Adaptation to Natural Energy Sources* - Although maintenance cost of an IoT edge-device/object involves the cost of the device itself, the labor, and the cost faced due to system-downtime, the highest amount of cost comes down to mostly the energy consumed during the lifetime of the device [31]. In this context, effective adaption of natural energy sources into the IoT such as wind, solar, thermal, and vibration is promising yet challenging as it may be difficult or time consuming to integrate the battery system required due to surge in instantaneous energy production into each vendor-specific devices/objects. Additionally, it may not always be possible to supply continuous power to devices using natural energy sources. Consequently, further system-level solutions are required for these devices to be resilient and reliable in case of power loss.

• *Power Management.* In terms of energy efficiency in IoT, energy management is also challenging and critical since IoT devices cannot always generate their own energy or are not always close to the energy sources. Most of IoT devices require energy continuously (or frequently) for data collection, monitoring and analysis. Energy consumption of objects within a network domain depends on a number of factors, such as how often these objects will remain awake, and in which order/interval they will send/receive data. In short, with a proper energy management that considers not only the object itself but also whole network domain, life expectancy of objects can be extended.

• *QoS provisioning.* QoS is expected to cope with network capabilities and resources to deliver a consistent backbone to the IoT connectivity. Nevertheless, IoT is such a complex and mixed network that involves connections among different types of networks through several communication technologies. Considering the IoT's mass data transmission across the network in real-time, providing QoS is challenging due to network and communication related issues, such as bit errors, long delays, collisions, packet droppings and jitter impairments. It is even more challenging to provide QoS taking the energy efficiency into account. However, energy efficient QoS-guaranteed secure services are required in order to ensure the continuity of the IoT paradigm.

• *Middleware Solutions.* As mentioned in Section II, software level in IoT presents high heterogeneity. Therefore, integrating objects/devices with software such as applications and web services requires numerous middleware solutions to be developed. However, developing real-world applications in which heterogeneous IoT-related data are merged with traditional data are challenging for a variety of industries. The high heterogeneity of both hardware and software levels, considering also the energy efficiency in mind, makes it even more challenging to present IoT-centric interoperable middleware solutions.

• *Big Data Analytics.* Since IoT is mostly built on a traditional ICT environment and is influenced by everything connected to the network, high amount of work is required to integrate IoT into existing IT systems or a unified information infrastructure. Additionally, a large number of objects connected to the Internet are expected to produce enormous amount of real-time data flows. This raw data is actually meaningless unless it is comprehended and analyzed in an efficient way. However, deriving valuable information from the vast data collected by the IoT objects through various networks and communication technologies requires robust big data analytics skills, which could be challenging for end-users [39]. Considering the magnitude of energy required due to high amount of processor power and memory usage during large data analysis, IoT-centric green data analysis is expected to be even more challenging. Consequently, the industries are required to exploit green strategies that will enable them to deal with the issues around high energy consumption from big data generation, collection, transmission, storage etc. to avoid energy and resource inefficiencies [227], [228]. A detailed survey on big data for cyber physical systems with the focus on data collection, storage, processing, analytics, energy-efficiency and cybersecurity is presented in [229].

B. Lack of Standardization

Standardization is one of the most critical concerns to be able to further develop and deploy IoT on a large scale. Through standardization, new service providers and users are expected to enter the IoT market easier and faster. Besides, standardization is also expected to advance interoperability among vendors and applications.

Although many solutions have been made through the funds/supports from academia, industry and policy-makers such as scientific communities, European standards organizations, standardization institutions and global alliances, there is still no globally accepted reference standard related to IoT. Due to the lack of any standardization, IoT developers simply implement their own vendor-specific protocols/hardware, depending on their needs and proficiency, then design end-to-end IoT solutions, which mostly result in inefficient and undesirable products in an open market. Although, the necessity for a new multi-layer multi-platform IoT standard is enormous, standardization in IoT is quite challenging as there are numerous device vendors, networking and communication technologies and software platforms competing for a share in the IoT market.

Ongoing works regarding the IoT standardization have focused on numerous parts (see Table III), such as RFID frequency, protocols of communication between readers and tags, and data formats placed on tags and labels [230]. In this context, some of the most important challenges in IoT standardization are energy efficiency, inter-operability, medium access control, semantics, security and privacy [28].

Examining all of the aforementioned issues taking energy efficiency into account, and releasing a green-IoT standard in this context would lead to sustainability.

C. Information Security and Privacy protection

The recognition and pervasive use of various IoT solutions will mainly depend on IoT's credibility in information security and data privacy protection. Security is a major concern for IoT since design and implementation of security processes require a considerable amount of processing power and time from close or distant object/devices. Since security has to be considered early during the design phase and is mostly seemed as an optional extension to the system, establishment of energy-efficient secure IoT framework is a challenging task that has not receive enough attention yet. As IoT includes both resource-constrained objects and high-end data servers, exploiting trade-offs to offer a secure and green IoT platform among heterogeneous objects/devices is crucial.

Tewari et al. [231] investigated the security problems within IoT at different layers, such as perception, transportation and application layer. The authors concluded that a unified vision regarding the insurance of security and privacy requirements within this heterogeneous environment is still missing.

Stergiou et al. [232] propose a new framework that integrates cloud computing with IoT as a base scenario for big data with the aim at improving security and privacy issues while offering a *green* and efficient fog environment for sustainable computing. Blockchain-based distributed ledger technology has been used in [233] to enable a decentralized and secure P2P infrastructure with support from IoT devices. While Gupta et al. [234] make use of elliptic curve cryptography (ECC) to increase the attack resistance and enable a mutual authentication mechanism between the IoT devices and the server.

Additionally, privacy in IoT is also a big concern since numerous data, such as personal and private information, could be collected, monitored and analyzed through multiple associated networks in an IoT system. Here, users' privacy issues mainly arise when collecting (what kind of private data will be collected?), using (what kind of authorized services/providers will be able to access and use the data?), and storing (where and how long the data will be stored?) the related data. It should be noted that while existing ICT-based network security technologies can provide a basis for privacy and security in IoT, some of IoT-centric privacy issues, such as the definition of privacy and legal interpretation are still uncertain and not explicitly defined in IoT.

D. Governance and Legislation

One of the main barriers for the pervasive acceptance of the IoT paradigm is the lack of governance. Since IoT is not just an extension of today's Internet but also a network of independent but inter-operable structures, Internet governance models are not exactly appropriate for the IoT implementation. In this context, having an actual world-wide IoT concept, recognized by states, corporations, and users, would be impossible without an independent governing authority. Yet, governance in IoT is a challenging task that requires transparency, accountability and inclusion of public opinion. In addition, considering the resistances and the failures the RFID, electronic health cards and barcodes have seen during their first releases due to possible public fear for information misuse, the policies must also keep pace with the technology such that the citizens start trusting the new technologies and accept to live within the IoT environment [35].

Consequently, an IoT governance model/authority is required, where the actors and their responsibilities are clearly defined, security and privacy concerns are addressed, through the whole life-cycle of the data (gathering, routing to cloud, storing, analyzing and eventually manipulating) [235]. In addition, IoT must also be protected by legislations as no one wants their home camera security footage to be hacked, digital audio recordings to be listened to, or workplace emails intercepted [236]. In this context, there are some administrations, although not many, that have recently issued IoT-based legislations to protect users, such as UK's release of '*Code of Practice for Consumer IoT Security*', which outlines the basic responsibilities for security and privacy within the value chain [237] and California's new legislation [238] that will force manufacturers to schedule unique default passwords, rather than identical ones, into every device they make starting from January 2020.

VII. FROM SERENDIPITY TO SUSTAINABLE GREEN-IOT: LESSONS LEARNED

Within the scope of this section, the actors, who need to make efforts for an energy-efficient sustainable IoT deployment and management, and their roles are first identified. Key enabling technologies that assist facilitating the green-IoT paradigm and related recommendations to ensure optimal efficiency will be presented afterwards.

A. Actors and Their Roles

Achieving an energy-efficient sustainable IoT environment requires a large-scale united effort, covering both technical and nontechnical actors such as policy-makers, developers and consumers. As all of the actors of this value chain have their own roles to help providing a green-IoT, a global coordination as shown in Fig. 16 becomes vital to fulfill a widespread strategic plan, and to guarantee that all the efforts would benefit optimally.

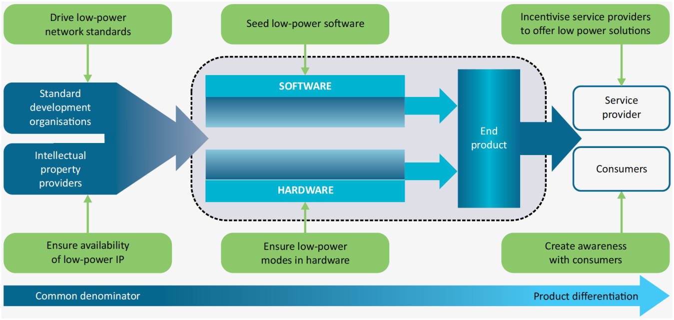

Fig. 16: Energy efficiency along the ICT value chain [46]

TABLE XI:
Actors and actions to be taken for a green-IoT.

Actors	**Actions**	**Stage**	**Impact**
Policy makers	Implementing policy instruments, which motivates other actors to upsurge individual/collective activity towards providing a green-IoT, including R&D, realization/execution of new standards, and development/deployment of energy-efficient IoT objects/devices.	All stages	Communal
Standards development organizations	Shaping official standards by outlining requirements/specifications to enable green-IoT based progress of energy-efficient software/hardware solutions.	Standardization	Communal
Intellectual property providers	Pursuing innovations through R&D within ICT-related areas to empower an energy-efficient IoT environment.	R&D	Corparative
Software and hardware developers	Designing energy-efficient, network-enabled, compatible and inter-operable models/components that can be used by manufacturers of devices.	R&D	Corparative
Device manufacturers	Choosing software and hardware models/components to be used, and integrating energy-efficient features through the entire stages of these components.	Implementation	Corparative
Network designers	Shaping energy-related terms on object/devices to be connected to networks, managing their operations and ensuring an end-to-end energy-efficient communication in all connected devices.	Implementation	Corparative
Service providers	Promoting energy efficiency between manufacturers and consumers by selecting proficient, compatible and inter-operable software and hardware solutions.	Post-implementation	Corparative
Telecommunications industry	Development and implementation of energy-efficient network design by optimizing network architectures, power management, and communication protocols.	Post-implementation	Corparative
Consumers	Making energy-efficient purchases, modifying device settings to save energy and further creating demands for more energy-efficient software and hardware solutions.	Post-implementation	Individual

Nine actors that have been identified as having different roles and that could eventually contribute achieving a green-IoT, namely: (i) policy makers; (ii) standards development organizations; (iii) intellectual property providers; (iv) software and hardware developers; (v) device manufacturers; (vi) network designers; (vii) service providers; (viii) telecommunication industry and (ix) consumers are summarized below:

- *Policy makers* have the leadership role to bring nations together and also to verify that developers, organizations, industry and individuals are enabled to play their roles. They are basically responsible to implement policy instruments, which motivates other actors to upsurge individual/collective activity towards providing a green-IoT, including R&D, realization/execution of new standards, and development/deployment of energy-efficient IoT objects/devices.
- *Standards development organizations* can shape official standards, which indicate how objects/devices or protocols should function by outlining requirements/specifications, to enable green-IoT based progress of energy-efficient software/hardware solutions.
- *Intellectual property developers* pursue innovations through researches and developments within ICT-related areas to empower an energy-efficient IoT environment. In this context, all other parties such as policy makers, funding bodies and industry have to carry out significant roles to enable, support and stimulate the progress of green-IoT based solutions by these researchers and developers.
- *Software and hardware developers* design energy-efficient, network-enabled, compatible and inter-operable models/components that can be used by manufacturers of devices. Since software/hardware components are the key factor in energy efficiency performance, developers have a vital role in enabling the development of more energy-efficient objects/devices.
- *Device manufacturers* basically choose software and hardware models/components to be used, and then integrate energy-efficient features through the entire stages of these components. Awareness on energy demand and power management can also be raised by device manufactures.
- *Network designers* shape energy-related terms on object/devices to be connected to networks, manage their operations as a part of the network and ensure an end-to-end energy-efficient communication in all connected devices in order to increase the lifetime of objects/devices and to reduce the cost for stakeholders.
- *Service providers* promote energy efficiency between manufacturers and consumers by selecting proficient, compatible and inter-operable software and hardware solutions. Further to boost energy efficiency, service providers can also be responsible to deliver software updates on current devices or to provide related device replacement schemes.
- *Telecommunications industry* works on the development and implementation of energy-efficient network design through various approaches such as optimizing network architectures, developing smart power management schemes, improving controller algorithms across networked-systems and motivating the improvement of energy-efficient communication protocols.
- *Consumers* can make energy-efficient purchases, modify device settings to save energy and further create demands for

more energy-efficient software and hardware solutions. Other parties, such as organizations, manufacturers, retailers and service providers, can also increase the awareness of energy waste and guide consumers about the efficient ways of using their devices.

In line with the above-mentioned explanations, to provide an energy-efficient sustainable IoT deployment and management, the actors, actions to be taken, action stages and their impacts are summarized in Table XI.

B. Energy-centric Key Recommendations

Just like the ICT, IoT is also a broad term that involves information and communication related various facilities, technologies and applications, aiming at enabling suppliers/consumers to access, transfer and manipulate information. In this section, we classify key enabling requirements/technologies of green-IoT into seven categories: (i) Green Policies and Standardization; (ii) Green Infrastructure; (iii) Green Communication; (iv) Green Networking; (v) Green Service Management; (vi) Green Clouds and Data Centers; and (vii) Green ICT. Energy-centric recommendations that would help us facilitate a green-IoT are also disscussed.

- *Green Policies and Standardization* - The first and probably the most important step that should be taken urgently for an energy-efficient inter-operable IoT environment is the standardization and related green policies. In this regard, energy-centric IoT standards and protocols for various IoT subdomains are required through the collaboration among different parties as depicted in Section III, such as policy-makers, standards bodies and industry consortia.

With the standardization of IoT, higher reliability, safety and environmental care will be ensured. Cost of ownership and maintenance will be down. Inter-operability issues will be reduced since systems will not be tightly-coupled to specific solutions, or will not be bounded to a specific vendor.

In addition to the standardization for energy efficiency optimization, well-defined policies with quantifiable energy efficiency objectives have to be developed by the policy-makers as well. In this context, short or long-term benefits both for suppliers and consumers can be delivered by evaluating the existing policies, analyzing their efficiencies and enhancing alignments. Furthermore, close interaction (e.g. encouragement, rewards, launching/promoting events or initiatives, and etc.) between policy-makers and industry is needed to facilitate technology and policy development to be mutually supportive.

- *Green Infrastructure* - IoT infrastructure basically includes identification and tracking related objects/devices, such as sensors, barcodes, RFID tags, readers and various wired/wireless communication networks. These objects/devices have power consuming components, such as microcontrollers, memories and wireless communication equipment. In this context, energy efficiency in IoT infrastructure can be gained by various methods, such as: (i) reducing the sizes of RFID tags to cut the amount of non-degradable material used in manufacturing [239], (ii) designing energy-efficient approaches/protocols to optimize tag estimation/collision, transmission power, overhearing, (iii) avoiding resource restrictions with the development of ultra low-power MCUs, cheaper memories, high performance batteries, optimized networking protocols, (iv) keeping objects/devices awake only when necessary, and (v) utilizing energy harvesting.

- *Green Communication* - Although different objects/devices have different communication protocols and transmission power requirements in IoT, all these objects/devices can be connected through gateways that have abilities to facilitate communication or interaction of various objects/devices over the Internet. This communication provides devices with the mobility and ubiquitous coverage. Yet, billions of devices are expected to connect to Internet and exchange information. This information exchange will obviously result in very high, if not the highest among IoT's key enabling technologies, amount of energy consumption. Nevertheless, energy consumption rates caused by communication technologies could be decreased dramatically utilizing efficient ways, such as: (i) identifying empty channels through cognitive radio, (ii) adjusting sleep and message scheduling, (iii) utilizing various low-power communication equipment efficiently according to the coverage and transmission rate requirements, (iv) managing devices that require handover with power-aware mobility management techniques, and (v) utilizing already deployed communication channels/protocols that can be leveraged to enable new services.

- *Green Networking* - There are many IoT-capable wireless networking technologies, such as Wireless Sensor and Actuator Networks (WSANs), Wireless Personal Area networks (WPAN), Wireless Body Area networks (WBAN), Home Area Networks (HAN), Neighborhood Area Networks (NAN), Ad Hoc Networks (AHNs), etc. Nevertheless, since objects/devices in IoT are mostly different hardware, and require diverse communication and computation capabilities and changing QoS requirements for the information exchange through the Internet, these networks must be re-adjusted before they can be applied to IoT. By making the necessary adjustments, as in IoT-centric communication technologies, energy consumption rates caused by networking technologies could also be decreased dramatically utilizing efficient ways, such as: (i) using low-power state of the art networking equipment, (ii) leveraging energy-efficient routing techniques (e.g., cluster architectures, multi-path routing, relay node placement, node mobility, etc.), and (iii) making use of data reduction instruments (e.g., aggregation, adaptive sampling, compression, network coding).

- *Green Service Management* - Service-oriented and context-aware IoT architecture, where each virtual and physical object can communicate with each other, enables objects/devices to have variety of functionalities as standard services, which could let both devices and networks escalate their energy efficiencies. Implementations and managements of IoT services are handled according to the needs of users and applications. SOA approach is adopted to build the middleware architecture for the IoT, as it focuses on simple and well-defined services. SOA allows encapsulating services for hiding the details of service implementations or protocols. Therefore, applications can use energy-aware low power heterogonous objects as compatible services offered by the IoT devices and save energy. Additionally, further energy savings could

TABLE XII:
Key recommendations to enable a green-IoT.

Subject	Action required by	Technologies/Parameters	Approaches/Recommendations
Policies/ Standardization	Policy-makers and Standards development organizations	Inter-operability, sustainability, reliability, safety, environmental care	Well-defined policies with quantifiable energy efficiency objectives have to be developed by the policy-makers. Close interaction between policy-makers and industry is needed to facilitate technology and policy development to be mutually supportive.
Infrastructure	Intellectual property providers, hardware developers, device manufacturers, network designers, telecommunication industry	Identification, tracking, sensors, barcodes, RFID tags, readers, microcontrollers, memories	Reducing the sizes of RFID tags, designing energy-efficient approaches/protocols to optimize tag estimation/collision, transmission power, overhearing, avoiding resource restrictions with the development of ultra low-power microcontrollers, cheaper memories, high performance batteries, optimized networking protocols, keeping objects/devices awake only when necessary, and utilizing energy harvesting.
Communication	Intellectual property providers, software and hardware developers, network designers, telecommunication industry	Mobility, coverage, transmission rate, sleep/message scheduling, cognitive radio	Identifying empty channels through cognitive radio, adjusting sleep and message scheduling, utilizing various low-power communication equipment efficiently according to the coverage and transmission rate requirements, managing devices that require handover with power-aware mobility management techniques, and utilizing already deployed communication channels/protocols that can be leveraged to enable new services.
Networking	Intellectual property providers, software and hardware developers, network designers, telecommunication industry	RATs, QoS requirements, cluster architectures, multi-path routing, relay node placement, node mobility, network coding	Using low-power state of the art networking equipment, leveraging energy-efficient routing techniques, making use of data reduction instruments.
Service Management	Intellectual property providers, software developers, service providers, consumers	SOA, context-awareness, middleware, service layer architecture	Service-oriented and context-aware IoT architecture enables objects/devices to have variety of functionalities as standard services, which could let both devices and networks escalate their energy efficiencies. Energy savings could be achieved through energy-centric development of gateways, middleware and service layer that acts as a bridge between a typical sensor network deployment and rest of the Internet.
Clouds and Data Centers	Intellectual property providers, software and hardware developers, device manufacturers, network designers, service providers, telecommunication industry	Voltage/frequency scaling, VM consolidation, VM migration, VM placement, VM allocation, resource allocation	Using low-power hardware and software solutions, deploying energy-efficient VM techniques, utilizing energy-efficient resource allocation methods, power management techniques, using renewable or green sources of energy.
ICT	Policy-makers, standards development organizations, intellectual property providers, software and hardware developers, device manufacturers, network designers, service providers, telecommunications industry, consumers	Path length, data length, hop counter, switching devices on/off	Turning off devices/services that are not needed, transmitting/receiving only the data required, minimizing the hop count and the length of data path, making use of advanced energy-aware communication and networking technologies, supplying renewable energy sources through energy harvesting.

be achieved through energy-centric development of gateways, middleware and service layer that acts as a bridge between a typical sensor network deployment and rest of the Internet.

- *Green Clouds and Data Centers* - In order to decrease device costs, and increase data manipulation speeds, data collected by objects/devices in IoT is transmitted, stored and manipulated mostly in the cloud utilizing data centers. The rapid rise in the number and size of data stored and processed on the cloud leads to an increase in the energy costs on the cloud and data centers as well. In this context, various solutions could be adapted to save energy on clouds and data centers, such as: (i) using low-power hardware and software solutions (e.g. dynamic voltage and frequency scaling), (ii) deploying energy-efficient virtual machine (VM) methods (e.g. VM consolidation, VM migration, VM placement, VM allocation), (iii) utilizing energy-efficient resource allocation methods (e.g. auction-based or gossip-based resource allocation) and power management techniques (e.g. Turboboost, vSphere), (iv) using renewable or green sources of energy (e.g. wind, water, solar energy, heat pumps).

- *Green ICT* - Considering that the IoT is a part of the ICT, it would be appropriate to mention other possible energy saving approaches currently available with the ICT, such as: (i) turning off devices/services that are not needed, (ii) transmitting/receiving only the data required, (iii) minimizing the hop count and the length of data path, (iii) making use of advanced energy-aware communication and networking technologies, and (iv) supplying renewable energy sources through energy harvesting.

In addition to the seven categories mentioned above, further energy efficiency could also be gained by several approaches, such as (i) designing/deploying and managing IoT environment as simple as possible (simplicity of installation and ease of use could result in less energy consumption), (ii) through smart sensing (nonstop sensing by objects often drains energy quickly), (iii) preserving the context of the data produced (in this way processing of the data could lead to consequential results), (iv) utilizing mobile applications (e.g. smartphones already have various RATs integrated, fast processors and cheap memories), (v) observing the existing behavior, auditing energy usage and understanding the energy profile, (vi) designing specific services/application for each user type, (vii) developing a general data collection and data management plan, (viii) giving consumers access to data, and (ix) emphasizing overall system efficiency, rather than device or user based efficiency.

In line with the above-mentioned explanations, to provide an energy-efficient sustainable IoT deployment and management, energy-centric key recommendations regarding seven categories are summarized in Table XII.

VIII. CONCLUSIONS AND FUTURE RESEARCH DIRECTIONS

This paper aims to familiarize the readers with the green perspective of the IoT paradigm by presenting various energy-efficient state-of-the-art IoT approaches from academia and industry. Trending topics, technologies and protocols for the green-IoT are discussed along with standardization efforts, governance and legislations. Moreover, a comprehensive evaluation of the actors, and their roles to enable a sustainable green-IoT environment is provided. Key enabling technologies are summarized, remaining challenges and open issues are discussed and related recommendations to ensure optimal efficiency are provided.

Despite the excessive amount of research done in this area, there are still many open issues (e.g., technical considerations, lack of standardization, security and privacy, governance and legislation, etc.) to be addressed before a realistic implementation of a green-IoT sustainable environment will be universally accepted and deployed especially while ensuring users' Always Best Experience [240], [241]. In this context, a few prospective technologies that have the potential to satisfy a sustainable green-IoT environment and that are worth further standardization are summarized below as future research directions.

User expectations and demands increase dramatically in parallel with the advances in technology. People are now expecting high-performed, green and personalized services on their mobile devices, with access from anywhere at anytime and from any device. In this sense, 5G-centric green-IoT is a robust research direction as relay techniques utilized by 5G can benefit wireless/RF energy harvesting, making smartphones act as gateways/sink nodes [242]. SDN and Network Function Virtualization (NFV) represent other essential research directions. Deploying IoT infrastructure with SDN and NFV can enable providers and consumers to share the same infrastructure, consisting of data servers, network switches, and communication links. In addition, information-centric network softwarization (which allows data-plane capabilities such as protocols/resources to be adaptively set by software applications to meet service requirements), mobile edge computing (which is a networking model to transport computing and storage facilities, as well as services from the centralized cloud servers to the edge of the network), and ID-based communication (which assists achieving location-independent communication in heterogeneous networks, and automatic/remote configuration) are also future research directions that have the potential to satisfy a sustainable green-IoT environment [62].

More recently, with the support of Internet of Things, Big Data, Artificial Intelligence and Machine Learning, the development of digital transformation through the notion of *Digital Twin (DT)* [243] has been taking off in many industries such as smart manufacturing [244], oil and gas industry, constructions, bio-engineering, as well as automotive [245]. The DT creates a high-fidelity digital replica of the physical object where the former evolves synchronously with the latter throughout their entire life cycle. Apart from the obvious potential of DT in helping with the development, deployment and management of complex environments and systems, a DT could also improve ongoing operations by continuously monitoring the real physical systems through the use of IoT, Big Data analytics and machine learning and enable the prediction of any issues before they would happen in the real world. Consequently, this shows that the potential of the DT technology and beyond is limitless and could open new research horizons, new business models as well as specialized techno-economic models for the future cooperative intelligent communication systems. For example, Orkney in Scotland is currently working towards a carbon-neutral future by developing a 5G-powered digital twin system[1] that creates a 3D model of Orkney with overlaid data from the energy system (e.g., electric vehicles, domestic batteries, generators, turbines etc.). The 5G-powered digital twinning systems aims to bring a positive impact on the society and the economy.

Other than the aforementioned research directions, in order to make the IoT trustable, reliable, and globally identifiable, and also to legally protect providers and consumers, additional R&D and standardization efforts on emerging concerns, such as security and privacy protection and unique naming and identification, are also required not only by researchers but also by policy-makers and device manufacturers.

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