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NFV/SDN Enabled Architecture for Efficient Adaptive Management of Renewable and Non-Renewable Energy

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ABSTRACT Ever-increasing energy consumption, the depletion of non-renewable resources, the climate impact associated with energy generation, and finite energy-production capacity are important concerns that drive the urgent creation of new solutions for energy management. In this regard, by leveraging the massive connectivity provided by emerging 5G communications, this paper proposes a long-term sustainable Demand-Response (DR) architecture for the efficient management of available energy consumption for Internet of Things (IoT) infrastructures. The proposal uses Network Functions Virtualization (NFV) and Software Defined Networking (SDN) technologies as enablers and promotes the primary use of energy from renewable sources. Associated with architecture, this paper presents a novel consumption model conditioned on availability and in which the consumers are part of the management process. To efficiently use the energy from renewable and non-renewable sources, several management strategies are herein proposed, such as prioritization of the energy supply and workload scheduling using time-shifting capabilities. The complexity of the proposal is analyzed in order to present an appropriate architectural framework. The energy management solution is modeled as an Integer Linear Programming (ILP) and, to verify the improvements in energy utilization, an algorithmic solution and its evaluation are presented. Finally, open research problems and application scenarios are discussed.

INDEX TERMS Energy efficiency, energy management, demand response, IoT, green energy, NFV, renewable energy, SDN.

I. INTRODUCTION

THE CONTINUOUS increase in energy consumption, the depletion of non-renewable resources, the CO_2 emissions caused by energy production, and the associated global warming have become critical concerns worldwide, that drive the creation of new solutions for energy management and consumption. To ensure the long-term development of human society, measures such as energy saving and energy efficiency have been promoted in recent decades, but above all, the need for low or zero-carbon emission sources, like renewable energy sources, has been reinforced [1]. Thus, the integration of the so-called green or clean energy from renewable sources, such as solar and wind, into power grids, has emerged as an important, environmentally friendly, sustainable alternative to meet current and future energy demands. However, the fluctuating nature of renewable sources due to environmental and geographical conditions may cause instability or imbalance when integrated in the generation-consumption ecosystem [2]. This factor, as well as the inefficient use of the limited energy generated, has led to the development of mechanisms and schemes, such as Demand-Response (DR) systems [3], that are aimed at the efficient use of what energy is available.

DR schemes consist of a set of requests and actions exchanged between the Energy Supplier (ES) and the Energy Consumers (ECs) that are carried out on the basis of agreements or contracts, with the aim of promoting consumer participation in energy management by allowing the modification of consumption according to availability [3]. The main incentives for engaging users in DR initiatives are free-use periods or reduced electricity bills [4], [5]. DR programs can be implemented using Information and Communication Technology (ICT) infrastructures, such as Data Centers (DCs) [6]. Then, DCs, as part of DR and acting as an Energy Manager (EM) can execute strategies such as workload scheduling to coordinate and adjust energy provisioning and consumption. Moreover, DCs can be enabled by sophisticated communications technologies, such as Network Functions Virtualization (NFV) [7] and then offer smarter programmable energy management solutions. Based on all the aforementioned characteristics, the DR approach has been used as the basis for the development of our proposal.

On the other hand, one of the motivators for the research into energy-efficient systems is the growing energy demand from the deployment and operation of ICT systems, first, due to the emergence of Internet and cloud computing services, and recently, because of the proliferation of the concept of the Internet of Things (IoT). Although, in the first instance, the development and continuous evolution of communication systems can represent a great challenge in energy terms, the technologies and infrastructure deployed can also be used for energy management. For example, the massive connectivity of devices with low latency and higher capacity, offered by the new generation of communications systems based on 5G enabling technologies such as NFV and Software Defined Networking (SDN) [8], [9], [10], can be leveraged not only for the deployment of different services with varied requirements, but also to deploy robust management systems, in this particular case focused on the efficient use of energy. Furthermore, since communication systems play an increasingly important role in the operation of power grids (e.g., in smart grids), in tasks such as monitoring generation and consumption, the integration of sophisticated ICT technologies such as 5G, NFV, and SDN represents a feasible and very promising move towards efficient and intelligent energy management, which is the objective of this paper.

A. CONTRIBUTION

Considering the structure of a DR system [4], the management capability of customers enabled by the massive connectivity that is supported by modern technologies like 5G networks (NFV and SDN) [10], and finite energy-production capacity, this paper proposes an NFV/SDN enabled DR energy management solution for IoT devices, services, and applications, which aims to optimize the use of available energy. The proposal involves three main areas: (i) a DR architecture enabled by NFV and SDN technologies; (ii) management strategies that are implemented in the context of the proposal and focus on the efficient use of available energy, whether 100% renewable or not; and (iii) a novel consumption model in which the ECs actively participate in the management process.

Unlike traditional schemes that promote additional energy generation to meet demand (which may cause expenses for the supplier and customers, as well as environmental impacts) or that encourage the sometimes unjustified reduction of consumption, our proposal focuses on efficient consumption of available energy, whether deterministic or not (the latter when the energy comes from renewable sources). This is because indiscriminate generation to meet all existing demand is an unfeasible option. In fact, the design and operation of current energy systems does not guarantee universal energy access. A study carried out in 2016 [11] reported that nearly one-fifth of the world population (7.2 billion in 2016) is deprived of electricity. This situation will be of even more critical concern in the near future due to the increasing number of users, devices, and services. Just in regard to the ICT sector, a study carried out by Cisco [12] estimates that there will be 28.5 billion networked devices by 2022, up from 18 billion in 2017 (i.e., more than 10 billion new energy consumers). The limited energy resource, which is often misused or wasted, is therefore essential for the development of current and future energy systems. Likewise, efficient energy distribution avoids rationalizations or unplanned power outages and offers economic benefits to both suppliers and consumers—the former can meet energy demands without adding new plants, whereas the latter can benefit from reduced rates or free-use periods.

Regarding the use of renewable energy, the adaptive consumption capacity of the proposed DR architecture allows for managing the dynamic and intermittent nature of renewable sources and optimally exploiting their generation capacity. Motivated by environmental (reduction of CO_2 emissions) and economic benefits (free use energy), as well as by potential participation by consumers (photovoltaic or wind installations) [13], and considering that an energy sector that is truly sustainable in the long term requires a very high penetration level of renewable sources in the world energy matrix, our architecture encourages primarily using green energy and transitioning to energy systems powered by 100% renewable sources.

To efficiently use the available energy, the proposed architecture establishes a collaborative energy management environment between the ECs and the ES that is carried out using advanced 5G technologies (NFV and SDN) and aims to adapt consumption according to generation. Unlike existing management approaches, in our proposal, the ECs (devices or services with connectivity capacity and manageable), traditionally seen as an inactive entity, actively participate in negotiating their consumption with the ES. For this, a new consumption model is proposed, in which, before using energy, a two-way handshake is established between the parties. During this process, the ECs send the parameters of services or power demands (e.g., duration, power demanded, priority and initial time) to the ES. Then, this latter using management strategies such as prioritization in energy supply or time-shifting applied to the service execution, send the consumption conditions to the ECs (i.e., the service(s) to be processed and the corresponding execution time). The collaboration between the ES and the ECs is laid out in agreements established in contracts that involve technical (parameters of services and management strategies to be used) and economical (bonuses or penalties schemes) aspects. The contractual terms are beyond the scope of this paper, but the technical aspects of the DR system are covered.

In the proposed architecture, a reliable and scalable communications infrastructure between the ES and the ECs is an essential requirement for efficient energy management. This is vital for realizing the proposal; otherwise, the management of IoT devices (from the view of their activation and consumption) could not be carried out. In addition, the architecture requires robust computational resources on the ES side (specifically deployed in the EM) for the execution of the different management strategies, algorithms, and calculations involved in the optimal utilization of the energy resource. In this context, our proposal uses sophisticated communications technologies such as NFV, SDN and 5G as enablers. Specifically, SDN [14] provides the reliable, dynamic and programmable connectivity necessary for the exchange of information (parameters and consumption conditions) between the ES and the ECs, whereas NFV, deployed in cloud computing infrastructures (i.e., at the DC level), is responsible for the execution of workload scheduling strategies for the adaptation of consumption according to the available energy. In addition, NFV also provides the management entities (management and orchestration functionalities), so all the components of the energy generation and consumption ecosystem (actions and resources between ES and ECs) work in an orchestrated manner [7]. Thus, SDN and NFV are indispensable technologies in the proposed architecture that offer a flexible and scalable ICT infrastructure that can grow proportionally (increase in computing, storage and networking resources) according to the varied requirements of the ECs. These technologies enable efficient, automated, agile, dynamically reconfigurable, and programmable energy management for varied IoT devices, services, and applications.

This paper also presents the Integer Linear Programming (ILP) formulation associated with the energy management proposal, and to solve the problem optimally, an exact algorithmic solution is implemented. Evaluating the optimal solution for a case study allows us to verify the operation of the proposed solution and the improvements in energy consumption achieved.

In summary, our proposal analyzes from scratch the architecture, stakeholders, consumption model, and management strategies to develop the best possible energy management system, taking into consideration the capabilities of current consumers (massive connectivity), the most advanced existing communications technologies, that are already in the deployment phase (SDN and NFV enablers of 5G), and a finite capacity for energy production. The proposed management solution can evolve as the energy market and technological developments evolve and can be applied to perform efficient energy management in varied scenarios (from residential users to companies, populations, smart cities, or even countries). In addition, the information provided in this paper can be used by energy suppliers and operators to design current and future energy-efficient systems, as well as faster and more scalable energy management algorithmic solutions. The major contributions of this paper are summarized as follows:

- An architecture that, based on modern communications technologies such as 5G, NFV, and SDN, is able to perform an efficient and adaptive management of available energy, whether 100% renewable or not, for IoT devices, services and applications.
- A novel energy consumption model subject to availability where the consumer is part of the management process.
- Several management strategies for the efficient consumption of energy produced by a combination of renewable and non-renewable sources. These include the prioritization of energy supply and the time-shifting capability of energy demands.
- The computational complexity estimation of proposal in order to present a robust architectural framework for the efficient management of energy consumption.
- An ILP formulation for the proposed energy management solution.
- An exact algorithmic solution (OptTs) and performance metrics to verify the improvements in energy utilization achieved with the proposal.
- Discussion of open research challenges and possible applications scenarios in the context of the proposal.

A list of acronyms used throughout the paper is presented in Table 1. The rest of the paper is organized as follows. Section II discusses the related work. Section III formally presents the architecture proposal. The ILP formulation is addressed in Section IV. An example of evaluation of the most relevant management strategies is presented in Section V. The open research challenges and potential application fields are discussed in Section VI and Section VII, respectively. Finally, the conclusions and future work are drawn in Section VIII.

II. RELATED WORK

This section reviews the related work. Section II-A describes the ICT participation in energy systems. Then, Section II-B discusses the DR approaches enabled by IoT and DCs. Finally, Section II-C presents a summary of the contributions of the proposal compared to existing approaches.

A. ICT-BASED ENERGY SYSTEMS

In the last decades, with the deployment of smart grids, several proposals have analyzed the impact on energy

TABLE 1. List of acronyms and corresponding definitions.

Acronym	Definition	Acronym	Definition
$AllCombserv$	Total number of combinations	P_d^k	Power demanded by a service k, if $l = 1\ \forall k$
AR	Acceptance ratio	$P_d^{k,l}$	Power demanded by a service k, with priority l
$Combserv$	Combination of services	$P_d^{k,cs}$	Power demanded by critical services
CS	Critical Services	$P_d^{k,ncs}$	Power demanded by non-critical services
DC	Data Center	P_{ES}	Power provided by the energy supplier
DR	Demand Response	PLC	Power Line Communications
EC	Energy Consumer	P_{NR}	Power from Non-Renewable Energy Sources
EM	Energy Manager	P_R	Power from Renewable Energy Sources
ES	Energy Supplier	P_{RES}	Residual power
FC	Fog Computing	$SCADA$	Supervisory Control And Data Acquisition
$GreenSDAs$	Green Supply Demand Agreements	SDN	Software Defined Network
$GreenSLAs$	Green Service Level Agreements	SFC	Service Function Chain
ICT	Information and Communications Technologies	S_k	Service identifier
IoE	Internet of Energy	T_d^k	Lifetime of the service k
IoT	Internet of Things	T_{init}^k	Starting time of the service k
ITU	International Telecommunications Union	$T_{init}^{P_{ES}}$	Starting time of P_{ES}
l	Priority level identifier	Ts	Time-shifting value if $T_{s_{bw}}^k = T_{s_{fw}}^k\ \forall k$
L	Maximum number of priority levels	$T_{s_{bw}}^k$	Backward time-shifting of service k
m	Time interval of P_{ES}	$T_{s_{fw}}^k$	Forward time-shifting of service k
$MANO$	Management and Orchestration	U^k	Priority information of a service k
N	Number of services	VIM	Virtual Infrastructure Manager
NCS	Non-Critical Services	VNF	Virtual Network Function
NFV	Network Function Virtualization	$VNFM$	VNF Manager
$NFVO$	NFV Orchestrator	W	Maximum time horizon of analysis
NS	Network Service	w_R	Weight associated with renewable energy
$OptTs$	Optimal or exact workload scheduling algorithm	$\sigma_{P_{RES}}$	Standard deviation of P_{RES}
P_D	Aggregated power demanded	σ_{Ts}	Standard deviation of T_s^k

use and consumption when communications systems work together with energy systems [15]. From this perspective, the technological term of the Internet of Energy (IoE) has been introduced to refer to a complex and sophisticated Internet-type network for the next generation of power grids [16], [17]. The IoE paradigm promises robustness and reliability in energy systems and is the result of the integration of advanced ICT infrastructures (e.g., IoT) into the power grids to carry out automation, monitoring, and management tasks, taking in to account generation, distribution, storage, and consumption factors [16]. Unfortunately, the existing energy infrastructure is not immediately ready to offer an IoE, and several operational changes and functionalities must be introduced in current energy systems. The most relevant requirements for the deployment of IoE solutions are presented in what follows [15], [16], [17].

- *ICT infrastructures between the ES and the ECs:* A robust and scalable communications infrastructure to support the bidirectional information flow between the ES and the ECs for energy management is an essential requirement for implementing the IoE. In this regard, the ICT infrastructure deployed must allow a hierarchical and scalable operation if necessary, in order to guarantee optimum performance of the energy system and use of resources (communications and energy). From the consumer side, the deployed IoT infrastructures are seen as key participants in future energy management systems. In addition, because future energy systems will consist of a tremendous amount of interconnected components in generation (distributed power plants, substations, energy storage components, and metering systems) and consumption (ECs with different requirements), it is necessary that the ICT infrastructure used for the IoE have high-performance computing capacity/resources to carry out all monitoring and management processes for the stakeholders (specially for ECs). Then, with the information of P_{ES} and P_D different analytics can be performed, as well as planning or forecasting actions [16].
- *Demand side management and efficient use of produced energy:* Traditionally, all energy management actions are carried out only on the ES premises. Modern power grids require the participation of the ECs in the energy management process. Enabled by ICT infrastructures (e.g., IoT deployments), the ECs can, for example take part in DR programs through an intermediary or directly with the energy utility, with the objective of effectively managing load peaks, load reduction, and the fluctuation of energy generation from renewable sources [17]. The interoperability between the ES and the ECs and the actions carried out by the latter can lead to efficient energy utilization, with reduced or minimal waste, which is of paramount importance for future energy systems [18].
- *Use of renewable energy sources and transition to systems powered entirely with green energy:* A important requirement for a sustainable energy ecosystem is the continuous penetration of renewable energy. Future energy systems will aim to operate primarily with renewable energy sources and with the capability of managing distributed energy production from ECs (e.g., energy generated by photovoltaic installations in

household) [15], [19]. Thus, IoE architectures must be designed to operate partially or completely with green energy sources [17].
- *Flexibility and adaptability in energy management:* Future energy systems will demand flexibility and adaptability in operation and pricing. Regarding the operation, IoE architectures require that modifications of functionalities or incorporation of new features be quickly introduced and deployed throughout the entire power grid. As for tariff systems, the active participation of ECs and adaptive consumption leads to new dynamic and variable payment schemes for energy use (e.g., payment incentives, or penalties), which can be modified in time, even in real-time, according to generation conditions and agreements/negotiations established between parties [16].
- *Regulation and standardization:* The progression towards smart and efficient energy systems involves a discussion on regulation and standardization of operational and economic aspects of both the energy and ICT sectors, to guarantee a consistent evolution of the energy ecosystem and the correct interoperability of the involved stakeholders. For the successful development of future energy systems, a standardization of protocols and interfaces is needed, which can be based on existing standards, or might require the creation of new platforms or procedures [15].

In the literature there exist several architectural candidates for the IoE. An example is shown in [20], where Huang *et al.* propose an architecture for using distributed renewable energy and distributed energy storage devices at the residential and industrial levels. In this approach, produced green energy is integrated into the power grid to meet power demands. The proposed system considers the integration and participation of consumers (devices) through a simplified communication network, that is composed of energy routers integrated into the power grid to manage the energy flows. The proposal promotes the need for a communications infrastructure, but it does not provide detailed information about communication protocols/technologies nor energy management strategies, and the analysis is mostly done from the supplier side.

Regarding the use of advanced ICT technologies, some research works analyze the potential of NFV and SDN integrated into energy systems. For example, in [21], the authors present a substation network architecture enabled by SDN that provides simplified management and reliable communication between the intelligent electronic devices used to monitor the state of the electricity infrastructure. The authors also analyze the virtualization of some components of the power grid and the incorporation of ICT infrastructure to deploy improved management mechanisms. Instead, in [22], the authors propose an NFV-enabled virtual advanced metering infrastructure network to transmit energy-related information about power consumption and distributed power production from customers. The evaluation results show that NFV is a reliable and cost-effective alternative for exchanging information about consumption and generation and, in turn, improving the performance of the energy system.

B. DEMAND-RESPONSE APPROACHES AND ARCHITECTURES

Several studies have demonstrated that ICT infrastructures, such as IoT and DCs, can be considered as potential enablers for the development of DR programs. For example, in [23], Wei *et al.* propose an IoT-based common information model and communication framework with existing ICT protocols (e.g., Ethernet, IP, and IoT protocols), to deploy an DR energy management system for industrial consumers. The proposal mostly analyzes the operation from the facility side (i.e., from the ECs side), and experimental results demonstrate that the interoperability of entities in industrial facilities, enabled by ICT systems, allows for the rapid and low-cost implementation of an integrated management system for controlling electrical loads depending on the generation sources, which not only produces improvements in energy efficiency, but also a reduction in the energy cost for the consumer side.

Because demand-side management is an important concern in energy systems and because IoT infrastructures and technologies are already deployed in homes as part of automated systems, DR schemes have been proposed for these kinds of environments [19]. In [18], the authors present an intelligent home energy management system, which uses sensors, actuators, smart meters, and devices connected through a wireless local area network using standard communications protocols, *e.g., Ethernet, IP, TCP*. The system integrates local renewable-energy production (from photovoltaic panels) and includes a central hub for monitoring energy consumption and executing the DR strategies (there is no details about the implementation) for controlling of loads. The results show that the integration of IoT technologies and renewable energy in the housing sector optimizes energy performance but is also a sustainable practice to reduce carbon emission.

Several studies reveal that DCs can be key participants in DR programs due to their intense power consumption, operational characteristics, the great influence on the operation of power grids, the amount of data they handle and their highly automated infrastructure [6]. DCs in DR strategies can be enabled by communications standards such as the OpenADR Communication Specification [24], or NFV to offer intelligent and flexible energy management ecosystems. As part of DR schemes, DCs can coordinate requests and/or actions among the supplier and consumers in order to autonomously and continuously adapt energy generation to the changing loads over time [5]. For instance, DCs can encourage or stimulate consumption caused by an excess of power generated from renewable energy sources, or they can coordinate a demand reduction/redistribution in emergency situations [25]. In some research works, complete DR systems have been described, examples include the projects DC4Cities [26] and ALL4Green [4]. In [26] for instance

Klingert *et al.* analyze the technical aspects of power management between DCs and smart cities when renewable energy sources are incorporated to the DR system. Instead, in [4], [5] the ALL4Green project describes the technical and business relations between energy providers, DCs and end users or ICT customers. In this project the authors proposed a collaborative environment that, based on service level agreements, is able to foster the power adaptation (increase/decrease) between energy providers and consumers. The ALL4Green architecture divides the DR system into two subsystems: the first subsystem, Energy Provider–Data center, governed by Green Supply Demand Agreements (Green SDAs) [27], [28], meanwhile the second subsystem, Data center - ICT consumer, is based on agreements defined as Green Service Level Agreements (Green SLAs) [5].

C. DIFFERENTIATORS OF OUR PROPOSAL

Our proposal is aligned with the main requirements for future energy systems [15], [16], [17], because it considers the use of renewable sources [16], communications systems in energy management processes [16], customer-side participation [18], and the adaptive consumption of the available supply [17]. Even our proposal could be considered as an architecture on the road to the IoE. Unlike other works in literature, our proposal presents several differences: (i) management strategies, such as prioritization in energy supply, individual time-shifting for service execution, and service rejection; (ii) a consumption model in which there is a two-way negotiation between the ES and the EC before energy consumption to ensure the optimal use of energy; and (iii) a unified NFV/SDN architecture for energy management, built from scratch, considering that most of the proposed approaches seek to adapt technological advances to the operational features of current energy systems, which limits the improvements that can be obtained.

Most research works address energy efficiency through the minimization of consumption or encouraging energy savings, whereas our proposal instead seeks to maximize the utilization of available power at all times, by means of the minimization of power waste. The design of the architecture is not solely approached from the supplier side, as described in [21], nor solely from the customer side, as discussed in [23], nor is it exclusively focused on the development of algorithmic solutions, as shown in [29]. On the contrary, our proposal presents a complete system for the efficient management of energy consumption. This paper presents a complete vision of the architecture, stakeholders, mathematical models related to generation and consumption, and it discusses the complexity associated with the optimal management of the available supply for later present an appropriate architectural framework. In addition, the mathematical model associated with optimal energy use is presented, performance metrics are defined, and an algorithmic solution and its numerical evaluation is introduced. The works reviewed in the literature lack the description of any or several of these elements.

III. NFV-ENABLED POWER MANAGEMENT ARCHITECTURE PROPOSAL

An overview of the proposed architecture is presented in Section III-A. The description of its components and the strategies for energy management are discussed in Section III-B. Section III-C presents the energy consumption model and the complexity of the proposal is analyzed in Section III-D. Then, the architectural framework is described in Section III-E. Finally, a use case is summarized in Section III-F.

A. ARCHITECTURE PROPOSAL DESCRIPTION

The proposed architecture follows the general structure of a DR system [4] and is composed of three stakeholders:(i) an ES, that provides energy from renewable and non-renewable sources, (ii) an NFV-enabled EM, that is part of the ES and disposes of all ICT infrastructures (e.g., DC or cloud computing infrastructures) for executing management strategies and algorithms and for making the calculations (e.g., prioritization of energy supply and workload scheduling using time-shifting capabilities) to adapt the aggregated consumption (consumption of all services or power demands) to available generation, and (iii) ECs, that represent the end users (i.e., IoT devices, services and application) that demand energy.

The ES and ECs are coordinated by the instructions/actions/requests performed by the EM. Thus, the ES-EM-ECs ecosystem works in a dynamic and collaborative environment to offer an efficient energy management solution, the aim of which is to use the available energy efficiently/optimally, by means of the minimization of energy waste. All the connectivity requirements to enable the interaction between the stakeholders are provided by SDN and 5G. These technologies meet the massive connectivity and latency requirements for providing efficient, flexible, and scalable energy management for IoT. In this regard, and as defined in the objectives of the standards of international organizations such as the International Telecommunications Union (ITU) [8], [9], 5G guarantees reduced latency and connectivity capacity for millions of devices per square kilometer in our architecture. A pictorial representation of the architecture is shown in Fig. 1.

From an operational point of view, the proposal may involve technology providers (e.g., ICT and telecom providers, manufacturers of appliances, smart control/home systems providers), energy services providers and operators (aggregators and/or suppliers), and customer representatives. In addition, taking as a reference the work done in [4] and [5], the proposed DR architecture can be analyzed in terms of two subsystems, ES-EM and EM-ECs, which are governed by cooperation agreements, specifically, the GreenSDAs to identify the set of requests/actions carried out in the ES-EM subsystem, and the GreenSLAs to distinguish the requests/actions executed in the EM-ECs subsystem.

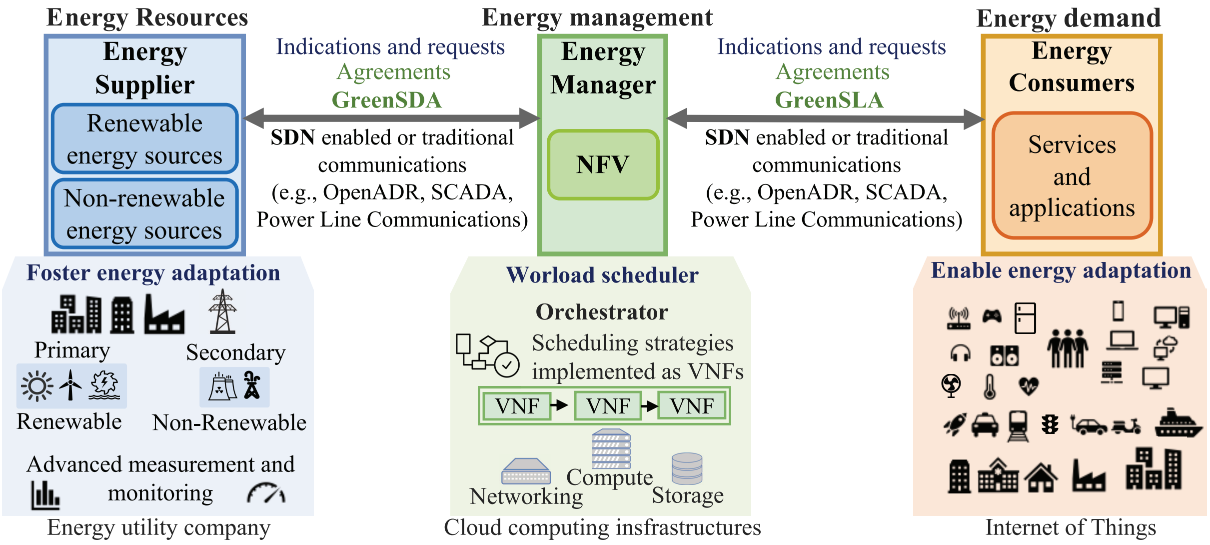

FIGURE 1. High-level architectural framework of the proposal.

B. COMPONENTS OF THE ARCHITECTURE

1) ENERGY SUPPLIER (ES)

The ES provides power to the architecture and performs energy-mixing process.[1] The ES has communications systems to interact with the EM, and it makes use of advanced control and monitoring systems, the former to handle the power from different energy sources and the latter to monitor the amount or level of the generated power, at every moment. This entity may be composed of more than one energy supplier or sub-supplier, however, for analytical simplicity, the ES within the ecosystem is regarded as a single entity. The architecture considers the use of energy from renewable sources (hydroelectric, solar, wind, etc.) and non-renewable sources (coal, natural gas, etc.). The mathematical model of the total power supplied by the ES (P_{ES}) is given by:

$$P_{ES} = P_R + P_{NR} \tag{1}$$

where, P_R denotes the power generated from renewable energy sources, while P_{NR} stands for the power from non-renewable energy sources. These parameters can be expressed as:

$$P_R = P_{Es} \times w_R \tag{2}$$

$$P_{NR} = P_{Es} \times (1 - w_R) \tag{3}$$

where, the factor $w_R \in [0, 1]$, represents the weight associated with the contribution of the renewable energy in the total generated power P_{Es}. In this regard, our architecture is able to manage the complete provisioning of green energy if $w_R = 1$ (100% renewable energy), as shown in Eq. (2) and in Eq. (3). The proposed architecture aims to allow a transition to an energy system powered entirely by renewable energy, where the contribution of energy from fossil sources is minimal (e.g., to meet certain demands if P_R is not sufficient to meet all the demand) or zero. With the changing of global climate, the world energy shortage, the pollution and CO_2 emissions produced by energy generation, and the depletion on resources, the integration of renewable energy into the power grids is presented as an effective, sustainable and environmentally friendly solution [15], [19], [31]. In addition, it has been demonstrated that the renewable energy sources, subject to climatic or geographical conditions, can be successfully integrated to DR systems [26], as the solution presented in the proposal.

According to the amount of power supplied (P_{ES}) and power demanded (P_D), three different operation states are presented on a periodic basis: normal, shortage and surplus. The *normal operation state* or the regular state refers to a power level in which all the generated power is consumed; i.e., in this state, the power demanded by the ECs is equal to the power supplied by the ES, $P_{ES} = P_D$. In this condition, there is no wasted energy and all services are processed. The *normal operation state* is an ideal scenario; however, the behavior of the ES and the ECs is not flat but it changes over time, which causes shortage or surplus periods. These power levels within the ecosystem are called *shortage operation state* and *surplus operation state*. Thus, a *shortage operation state* represents a scarcity of available power [5], and it can originate from a low supply level (low or zero power generation) or a high demand (demand increase). The ratio between P_{ES} and P_D in a *shortage operation state* can be defined as:

$$0 \leq \frac{P_{ES}}{P_D} < 1 \tag{4}$$

During a *shortage operation state* the available power is insufficient to meet all demands (i.e., $P_{ES} < P_D$).

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[1] Process to obtain energy for direct use, combining different primary energy sources [30].

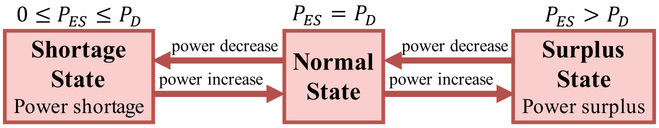


FIGURE 2. Interaction between energy operation states.

Accordingly, in order to deal with this situation, the EM can apply different management strategies, such as the described in Section III-B2, to adapt power demanded to the available power. By contrast, the *surplus operation state* is defined by an abundance of available power (finite power level) [5]. This state originates from a high supply (for instance, from renewable energy sources) or from a low demand (demand decrease). The ratio between P_{ES} and P_D in a *surplus operation state* is given by:

$$\frac{P_{ES}}{P_D} > 1 \tag{5}$$

In a *surplus operation state*, the ES fosters energy consumption, because the available power is greater than the power demanded (i.e., $P_{ES} > P_D$). If after processing all the demands, the system still has energy (i.e., $(P_{ES} - P_D) > 0$), this amount of energy can be stored in battery units for later use. Periodically, changes in generation and consumption cause a transition between the different energy states. This transition goes from a *shortage operation state* to a *surplus operation state* and vice versa, always going through the *normal operation state*, as illustrated in Fig. 2.

2) ENERGY CONSUMERS (ECS)

The ECs comprise the IoT devices (or in general IoT infrastructures) that demand energy to execute tasks, jobs, applications or processes. They have processing, networking (are SDN compatible), and control (automation systems to activate or deactivate the consumption) capabilities, and they can be managed by the ES through the EM. In the architecture, each EC interacts with communications (SDN network) and energy (power grid) interfaces and participate in the energy management process by sending its consumption parameters to the ES and receiving the energy use conditions from the ES (using as an intermediate component the EM). Thus, the ECs are able to active, deactivate or adapt its consumption (e.g., increasing or decreasing the power consumption within minimum and maximum established ranges) according to the instructions received from the EM (workload scheduling). The energy consumption negotiation is detailed in Section III-C.

The use of IoT technology in the proposed management solution is an ideal alternative because it allows for the use of existing protocols, interfaces, and frameworks (e.g., Ethernet, IP, TCP, SDN, and IoT protocols) used in the exchange of energy-related data (collected from ECs) and for the control of energy resources needed in efficient energy management [17], [18]. In this regard, an environment in which all devices (services and applications) have a communications interface to exchange information (consumption and related parameters) and interact with the rest of the architecture is a completely feasible scenario and not very distant because a growing number of devices are manufactured with embedded communication systems, especially with the proliferation of massive connectivity driven by technologies such as 5G [10]. Moreover, today, there are very affordable platforms (e.g., Arduino or Raspberry platforms) that can be integrated into any device to offer connectivity, management, and control capabilities, converting a traditional device into a smart device (e.g., smart dishwasher).

Considering that in a realistic environment all services are not equal, because the execution of some services is more important than that of others, the architecture is able to categorize them by including priority levels. Thus, a service k (S_k) can belong to a category or priority level l, with $l \in \{1, \ldots, L\}$, and its initial categorization or prioritization is defined in the in the agreements between ES and ECs. In this regard, the proposal assumes that at all times the architecture knows the priority level information of the set of N services to be processed. The architecture uses these priority levels to differentiate the importance or criticality of each service, and with this information, the EM can identify the processed (accepted) and unprocessed (rejected) demands. In this way, the system prioritizes the processing/execution of the services with the highest priorities, i.e., the demands are processed in descending order, being $l = 1$ the highest priority level. The power demanded by a service S_k with priority level l is defined as $P_d^{k,l}$, so that the aggregated power demanded by the ECs (P_D) is equal to the sum of the power demanded by each EC and can be expressed as:

$$\forall k \in N, \forall l \in L : P_D = \sum_{k=1}^{N} \sum_{l=1}^{L} P_d^{k,l} \tag{6}$$

According to the level of priority, services can be categorized as *Critical Services (CS)* and *Non-Critical Services (NCS)*, as follows.

- *Critical Services (CS):* Critical services are those services whose execution is essential (they must be processed obligatorily), therefore, they have the highest priority and consequently the architecture must always guarantee the provision of energy for their execution. Examples within this category are: services (devices) used in first aid and surgical interventions, services to provide human life support, services that guarantee road safety for passengers and drivers, communication and information services in disasters or catastrophes, emergency services, among others. The CS are labeled with the highest priority level, i.e., $l = 1$, and the architecture prioritizes the execution of these services, respecting their original or natural starting time (no time-shifting performed). The power demanded exclusively by critical

TABLE 2. Parameters of services or power demands.

Parameter	Description	Unit/Comment
N	Number of services	Integer number
S_k	Service identifier	$k \in \{1, \cdots, N\}$
L	Number of priority levels	Integer number
l	Priority identifier	$l \in \{1, \cdots, L\}$
P_d^k	Power demanded by service k	Power units
T_{init}^k	Starting time of service k	Time units
T_d^k	Lifetime of service k	Time units
$T_{s_{bw}}^k$	Backward time-shifting of service k	Time units
$T_{s_{fw}}^k$	Forward time-shifting of service k	Time units
U^k	Priority of service k	Integer number

services is given by:

$$P_d^{k,cs} = \sum_{k=1}^{N} P_d^{k,1} \tag{7}$$

- *Non-Critical Services (NCS):* Non-critical services comprise all services whose execution is not critical. Some examples of these type of services include air conditioning systems in homes, entertainment systems, services associated with cleaning (washing machines and dryers), non-essential home automation system, etc. The NCS have lower priority than CS, and in the architecture, they are identified with a lower priority level identifier, i.e., $l \in \{2, \dots, L\}$. These types of services can tolerate temporary displacements in their runtime, as well as the incorporation of other additional parameters such as service-quality degradation (e.g., a decrease in the brightness level of the screens). In the proposal, the temporary displacement of a service k (S_k) is defined as *time-shifting* (T_s^k). Thus, a service S_k with a power demand of $P_d^{k,l}$ can move its execution (T_init^k) forward or backward in time, i.e., a service is susceptible to perform a backward time-shifting ($T^k_{s_{bw}}$) or a forward time-shifting ($T^k_{s_{fw}}$), respectively. The NCS are processed by the system according to their priority (from highest to lowest priority), and if the system does not have sufficient power to meet all demands, those with the lowest priority level can be rejected. The power demanded by non-critical services can be expressed as:

$$P_d^{k,ncs} = \sum_{k=1}^{N} \sum_{l=2}^{L} P_d^{k,l} \tag{8}$$

Considering the criticality differentiation of the services, the total power demanded by the ECs can be defined by:

$$P_D = P_d^{k,cs} + P_d^{k,ncs} \tag{9}$$

In the proposed architecture, the mathematical modeling of the ECs is represented by services, workloads, or power demands. Considering the parameters related to management strategies such as prioritization and time-shifting capability, a service (S_k) is completely defined by the parameters of Table 2. Fig. 3 illustrates an example of a power demand and its corresponding parameters.

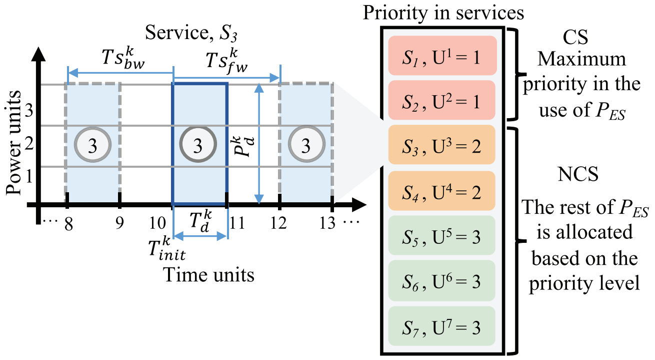


FIGURE 3. Graphical representation of a service. Parameter of S_3: $N = 1$, $L = 3$, $l = 2$, $P_d^3 = 3$, $T_{init}^3 = 10$, $T_d^3 = 1$, $T_{s_{bw}}^3 = 2$, $T_{s_{fw}}^3 = 2$, and $U^3 = 2$.

3) ENERGY MANAGER (EM)

From the operational point of view, the EM comprises the ICT infrastructure, where the necessary calculations for the scheduling of services and the management entities are deployed (NFV-based solution). In the architecture, the EM is the intermediate component that provides the functions of management and control of energy consumption. The EM allows the interaction between the ES and the ECs, governs the actions of the two subsystems, ES-EM and EM-ECs, simultaneously, and it is responsible for adapting the ECs demands to the capacities of the ES. The EM receives consumption parameters from ECs (P_D), runs management strategies and algorithms (DR strategies) to determine the optimal/efficient service execution (ECs consumption) considering the operating states of the ES (e.g., normal, surplus, or shortage), then it sends the consumption information to the ECs. Thus, the EM can be considered the brain of the architecture, because its operation decides how and when the available power is used. Fig. 4 illustrates the different management strategies that are considered in the proposal to enable an efficient utilization of available energy, their descriptions are provided below.

1) *Service processing without time-shifting:* If the available energy is sufficient to meet all the demanded consumption, which occurs in the normal or surplus power states (i.e., if $P_{ES} \geq P_D$), all N services that demand energy can be processed in their required execution time (T^k_{init}).
2) *Time-shifting for service execution:* The proposed energy management solution has the ability to adapt consumption to the available P_{ES}, by stimulating the anticipated consumption or deferring the service execution during periods of surplus or shortage, respectively. To this end, based on the agreements reached with the ECs (i.e., service and consumption parameters), the ES, through the EM, can move the execution of services (T^k_{init}) within a finite time window ([$T^k_{s_{fw}}, \dots, 0, \dots, T^k_{s_{fw}}$]). Then, a service S_k can be advanced ($T^k_{s_{fw}}$) or delayed ($T^k_{s_{fw}}$) to leverage the available energy resource. Given that the execution

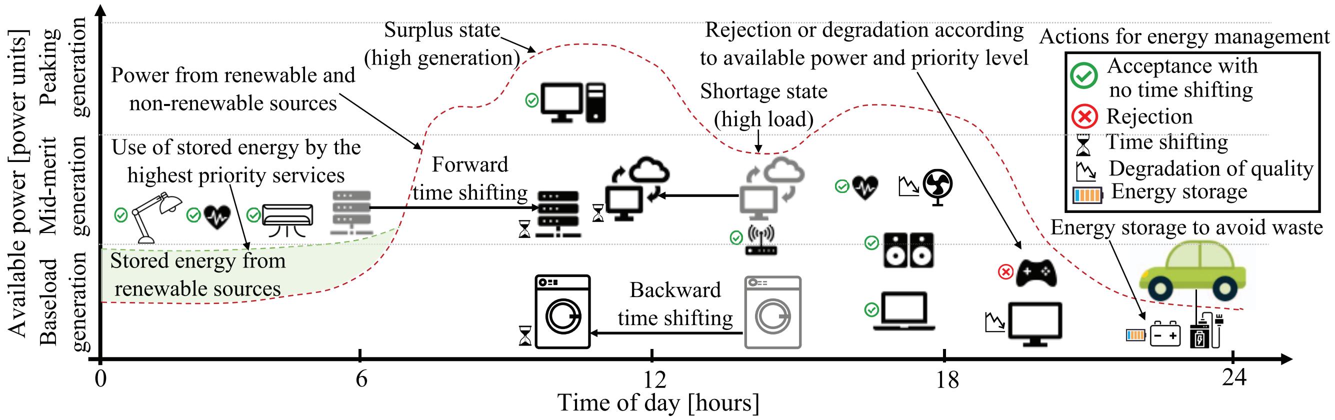


FIGURE 4. Example of application of the management strategies for efficient energy consumption.

of services is not performed in isolation, but rather, simultaneously, the proposal considers the analysis of a group of N services, which together demand a total P_D and are analyzed within a finite interval of time W. Thus, with the information about time-shifting of each service, the task of the EM in the NFV domain is to obtain the efficient/optimal scheduling of services (distribution of services in time), with the aim of optimizing the use of P_{ES}. The detail of the time-shifting value to which a service may be subject is defined in the agreements between the ES and the ECs. From this point of view, there may be schedulable services, for which the demand can be scheduled among a pre-specified set of operating points ($[T^k_{s_{fw}}, \ldots, 0, \ldots, T^k_{s_{fw}}]$), and non-schedulable services ($T^k_s = 0, \forall k$), which must be satisfied immediately regardless of whether the price of energy is high or low. In the proposal, the schedulable and non-schedulable services corresponds to NCS and CS, respectively. In addition, the time-shifting capability of workloads in energy management, have already been validated in previous work [32], [33], and the evaluation results demonstrate that this strategy allows for an efficient use of available energy (100% energy utilization in some cases) and the processing of services that under normal conditions (without strategy, i.e., $T^k_{s_{bw}} = T^k_{s_{fw}} = 0$) would be rejected.

3) *Prioritization in energy supply:* The architecture prioritizes the energy supply for the execution of services that belong to the highest priority level (i.e., CS with $l = 1$), and the remaining available energy is allocated to services that belong to the other priority levels (i.e., NCS with $l = \{2, \ldots, L\}$). In the proposal, each service can belong to a single priority level and its value is defined in the contractual terms between EC and ES.

4) *Rejection in service processing:* If $P_{ES} < P_D$, or if the demands cannot be shifted to a time window in which there is energy, one or more services can be rejected. This process is carried out on the basis of the priority of services, starting with those with the lowest priority level (i.e., NCS).

5) *Other strategies:* There are different strategies that can be developed for the proposed architecture, and that can complement the operation of the aforementioned strategies. Among the different alternatives are the variation of consumption (e.g., degradation of quality) and energy storage. Regarding the former, in order to adapt P_D to the P_{ES} in both surplus or shortage operation states, a possible strategy, that enables the P_{ES} is not wasted and a greater amount of services can be executed is the variation of power consumption proportional to the P_{ES} value (e.g., a decrease in the brightness level screens of devices, when $P_{ES} < P_D$). The candidates for performing these strategies are the NCS and the ranges of variation are conditioned to the features of each device and the agreements between the ES and the ECs. Regarding energy storage, although the proposal mainly focuses on the optimal use of available energy and not on its storage, the architecture can leverage the energy storage infrastructure (i.e., the battery units) that is part of the renewable-energy generation, for storing the surplus energy that, if not used, would potentially be wasted. Then, the stored energy could be used to partially or totally meet the demands from ECs. In this context, an important aspect to be addressed in future work is the sizing of storage devices, to ensure, for a finite period of time, the execution of CS, if P_{ES} is insufficient to meet all these demands.

6) *Promotion of the use of renewable energy:* The architecture encourages the use of renewable energy as a primary source and allows its gradual contribution (w in Eq. (1)) in the total energy supplied. In this regard, the architecture has an adaptive consumption capacity conditioned to P_{ES}, which is obtained by exploiting the time-shifting capabilities of the services and the optimal service scheduling performed by the EM. In

this way, consumption can be adapted to the time intervals where there is an excess of renewable energy. In addition, renewable energy can be stored in battery units and subsequently used for the execution of services, mainly for CS, as shown in the example of Fig. 4.

C. ENERGY CONSUMPTION MODEL

In the proposed architecture, the implementation of management strategies is complemented by a consumption model that requires the active participation of the ECs. This section describes the energy negotiation and adaptation between the ES and ECs in order to efficiently use the available energy.

1) DESCRIPTION OF THE ENERGY CONSUMPTION MODEL

In contrast to traditional energy systems in which the user is not aware of consumption and immediately uses energy through the activation of services, our proposal establishes a two-way handshake between the ECs and the ES prior to the use of energy. This procedure can be summarized in the following steps: (i) the ECs (devices with connectivity capacity and manageable) send the information about the services (e.g., priority level, duration, power level, possibility or percentage of rejection) to the ES, through a communication network (SDN); (ii) the ES (specifically the EM) with the information about P_{ES} and the services calculates (through the execution of algorithms) the optimal/efficient scheduling of the services, using management strategies deployed at NFV domain, which enable the efficient energy utilization (i.e., the maximization in the use of the available energy); (iii) the ES (specifically the EM) sends the consumption parameters (services that can be executed and execution times) to the ECs; (iv) the ECs confirm the consumption conditions and request energy for services to be processed; and (v) the energy is allocated, the devices are activated and the ES supplies the demanded energy (P_D) for service execution. Fig. 5 shows a general representation of the bidirectional dialog carried out between ES and ECs to enable efficient energy consumption.

2) ENERGY ADAPTATION

In the previous section, the interaction between ES and EC is summarized. This section presents a brief description of the energy adaptation process (energy consumption model) considering the participation of the three stakeholders and their corresponding GreenSDAs and GreenSLAs. The actions involved in the energy adaptation process are related to the procedures performed in the two subsystems ES-EM and EM-ECs. Consequently, different *energy states* can defined for the ES-EM subsystem (Section III-B1), whereas several *types of services* can be specified for the EM-EC subsystem (Section III-B2). Fig. 6 shows a summary of actions/processes (handshake) carry out between the three stakeholders to offer an efficient energy management solution. In short, whenever there is an energy demand from the ECs, the following processes/actions are performed.

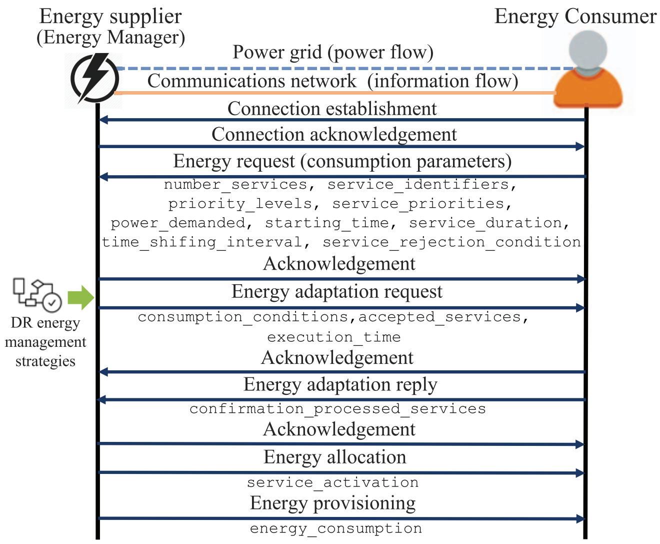


FIGURE 5. Summarized handshake process between the ES and the ECs.

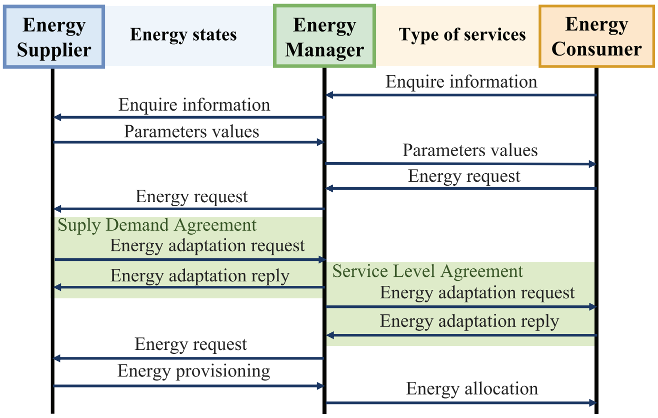


FIGURE 6. General scheme of the energy adaptation process (handshake process between the three stakeholders).

- The ECs enquire the EM if the system has available energy to execute their services. Because the EM is a management entity and not an energy supplier, it sends this inquiry to the ES. When the EM has the information about the status of the ES, it reports to the ECs the amount of available energy (P_{ES}). At this point, the EM cannot specify to the ECs how many demands are going to be accepted, shifted in time, or rejected because the EM has not yet implemented any strategy (workload scheduling).
- Subsequently, the ECs formally initiate the energy request by sending the different parameters of the services to be processed (see Table 2).
- At this stage, the EM knows the total number of services (N) and the aggregated power demanded (P_D). Thus, the EM proceeds to communicate this requirement to the ES, and, in a bidirectional data flow exchanged between the ES and the EM (GreenSDAs), the ES-EM subsystem chooses the working energy state, which can be either

normal, shortage or surplus. Depending on the energy state, the ES can foster energy consumption, deferral in service execution, or service degradation on the basis of actions and indications that the EM gives to the ECs.

- Once the energy state has been established, the EM can use the information about P_{ES}, P_D, and the parameters of the services as input in algorithms (NFV-Based scheduling strategies) to compute the optimal (or near-optimal) energy allocation. This information allows the EM to know which demands are going to be processed and their respective execution times. The workload distribution enables the efficient use of the P_{ES} at each time.
- The scheduling of the demands is communicated to the ECs. Then, thanks to the cooperation established between the EM and the ECs in the subsystem EM-EC (GreenSLAs), the ECs accept the distribution of the tasks performed by the architecture (EM). In this sense, and if the energy is insufficient, the ECs accept that their demands may or may not be processed. As aforementioned, the architecture can prioritize the energy supply for CS execution.
- Finally, on the basis of the information about the services (services without time-shifting and services with time-shifting), the EM requests from the ES the corresponding amount of energy. Then, the EM sends the activation instructions to the ECs (devices) and performs the allocation of energy resources. Finally, the ES supplies energy to ECs.

D. COMPLEXITY OF THE PROPOSAL AND RELATED PROCESSING REQUIREMENTS

Before formally presenting the architectural framework of our proposal, in this section, we discuss the computational complexity and processing requirements related to the efficient management of available power consumption. In addition, we analyze the technological enablers that allow to meet the requirements of the architecture, with the aim of demonstrating that our envisioned energy management solution is entirely achievable with existing technologies.

1) COMPLEXITY OF THE PROPOSAL

In our proposal, a key aspect to efficiently use P_{ES} is the (optimal) workload scheduling by exploiting the time-shifting capabilities of services. Mathematically the process of selecting the services to be processed (considering those subject to time-shifting) with the aim of efficiently using a finite P_{ES} is analogous to the objective of the 1/0 Knapsack Problem of placing the most valuable or useful items without overloading the knapsack [34]. Specifically, the prosed energy management solution can be seen as a multiple-choice Knapsack Problem [35], due to the possible variations or versions of a service S_k produced by the analysis within the time-shifting interval $[T^k_{s_{fw}}, T^k_{s_{fw}}]$. In this regard, the literature has proven that this kind of problem has complexity $\mathcal{NP}$-hard [34].

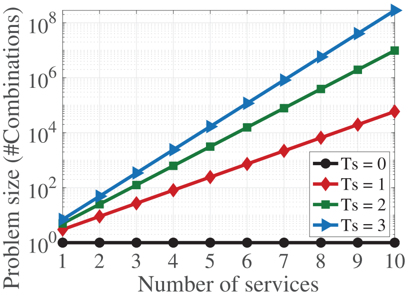


FIGURE 7. Example of growth rate associated with the problem of optimal scheduling of services. Growth rate based on *N* and T_S^k Parameters: $N = \{1, \ldots, 10\}$, $max\{T_S^k\} = \{0, \ldots, 3\}$.

For solving the problem optimally (i.e., optimal energy utilization in the context of the proposal) there are several options, and one of the best-known strategies is the exhaustive search based on the combinatorial analysis of all possible solutions. Translated into the scope of the problem, the exhaustive or brute-force search consists of analyzing all possible combinations of N services considering all possible time-shifting intervals to which a service may be subject. In this regard, Section V-B, using a discrete time model, presents an optimal algorithmic solution (OptTs) based on a combinatorial analysis (a technique that have been validated in a previous work in [32] for efficient energy management in the context of DCs). Then, the analysis of the algorithmic strategy reveals that this method has exponential complexity (as discussed in detail in Section V-B1), with a growth rate that depends on the values of N and T_s^k, specifically as shown in Eq. (27). Fig. 7 shows an evaluation example of Eq. (27) and the results obtained indicate that an increase in N, T_s^k, or both lead to an increase in the size of the problem (i.e., in the size of the search space to find the optimal solution), which can potentially demand a greater amount of computational resources and runtime. For example, with $N = 9$ and $T_s^k = 3$ the number of combinations to be processed is over 40 million, and for a computer equipment of the characteristics described in Section V-C1 the total running time needed to obtain the optimal solution (optimal workload scheduling) is about 90 hours, which can be an expensive computing time especially considering the density of current IoT deployments and the low latency required by modern networks [9].

In summary, the problem of the optimal management of available energy consumption presents a hardness $\mathcal{NP}$-hard and its optimal solution has an exponential complexity. This information reveals the drawbacks and needs of the proposed architecture, in terms of computational resources (processing and memory) for calculations and the development of faster algorithmic solutions (e.g., based on heuristic methods). The following discusses the requirements and enabling technologies to address computational complexity related to the execution of management strategies, while the development of faster strategies is out of the scope of this paper, it will be addressed in future work.

2) PROCESSING REQUIREMENTS

Based on the analysis in Section III-D1, we highlight two relevant aspects that must be considered in the deployment of the architecture: (i) establishment of maximum T_s values in the agreements between the ECs and the ES, and (ii) use of sophisticated computational resources to execute management strategies. Regarding the first point, although we do not address the contractual terms between ES and ECs, an important parameter that must be considered is the maximum time windows of services (i.e., $[T^k_{s_{bw}}, T^k_{s_{fw}}]$), or the specific T^k_s values because, as demonstrated in the growth rate of Fig. 7 an indiscriminate increase or selection of this parameter has a direct impact on the complexity. As for the second point, the complexity related to calculations for efficient energy utilization reveals the need for a sophisticated infrastructure both for the processing of services (high computational capabilities) and for the interaction of the components in the architecture (efficient network infrastructure), especially for applications that are delay sensitive.

In addition, the fact that several algorithmic solutions of different complexity and characteristics (optimal or heuristics) can be executed to meet the varied requirements of services and scenarios, demands that the proposed architecture (specifically in the EM) has reconfigurability and/or programmability capabilities, as well as being agile enough to execute changes on the fly without affecting or degrading the performance of any stakeholder involved in energy management. Related to this requirement, an important aspect is the scalability to cover the dynamic increase/decrease of ECs; so, the architecture must have the capacity to be deployed using hierarchical or distributed infrastructures according to the requirements of the ECs. Other relevant requirements in the proposal are the abstraction between the components through a separation in layers or domains (to promote the transparent evolution of ES, EM and ECs) and the unified management of the whole architecture.

In summary, the architecture for an efficient use of P_{ES} presents the following requirements: (i) high performance computing infrastructures for management calculations, considering P_{ES} and P_D information, (ii) reliable, flexible and scalable communications network to exchange the management information and instructions between the ES and ECs, (iii) agile deployment of management strategies and reconfigurability and programmability capabilities to implement diverse algorithmic solutions, and (iiii) unified orchestration (coordination and interaction) of all stakeholders to ensure an efficient energy management in scenarios of varied sizes (from residential users to clients that may be companies, populations, smart cities or even countries) and features.

3) ENABLING TECHNOLOGIES

The structure of the proposed architecture, as shown in Fig. 1 allows for the adoption of different technological enablers for each stakeholder. Existing protocols, interfaces, and mechanisms developed for power grids, DR systems, and IoT infrastructures can be used and adapted to the context of the proposal. For example, the communications network necessary for the exchange of indications, and instructions between ES and ECs could be facilitated by technologies such as OpendADR [24], Supervisory Control And Data Acquisition (SCADA), or Power Line Communications (PLC) [17]. In the proposed energy management solution, however, we have decided to use NFV and SDN technologies to carry out the proposal, because they perfectly meet the functional requirements described in Section III-D2. In addition, NFV and SDN are already key participants in modern communications systems, such as 5G [10], which facilitates the deployment of the proposed energy management solution. In this context, the architecture presented is open to include new technological enablers as the ICT and energy systems evolve.

In the architecture, NFV deployed at DC level or in general in a cloud computing environment disposes of all the computational resources needed to execute the management strategies (e.g., workload scheduling) and perform all necessary calculations to efficiently adapt the power consumption demanded (P_D) to the availability (P_{ES}). This technology also provides the architecture the management entities so that all components work orchestrated, which is essential to ensure that both the processes of the calculations and the communications and notifications between the stakeholders have a very low latency associated. In the NFV scope, the energy management strategies are represented by Virtual Network Functions (VNFs) forming Service Function Chains (SFCs). Then, these VNFs can be created, modified or upgraded, even on the fly, according to the desired functionalities and objectives, which provides programmability and reconfigurability to the proposed architecture. In addition, thanks to NFV technology, the management of the ECS and the underlying network (SDN) is separated (abstracted) from the functionality (i.e., management strategies), a feature that enable the proposal to be applied in different scenarios, such as small households, intelligent transportation systems, and smart cities.

The SDN technology instead provides the architecture reliable, secure, and scalable connectivity necessary for the dynamic interaction and the exchange of information between components (ES-EM-ECs), mainly between the ES and the ECs (parameters and consumption conditions). This technology is also scalable enough to allow the management (connectivity) of both a small and massive number of devices, and agile and flexible enough to allow rapid deployment of indications and changes necessary for energy management. SDN can easily adapt the network infrastructure (underlying network) to the requirements from the EM (NFV realm and management strategies implemented as SFCs).

Regarding the operational and ownership aspects of the ICT systems (i.e., the NFV-enabled EM and the underlying SDN network) needed to carry out the proposal, in the first instance, the ES could lease these infrastructures to ICT and telecom providers, and multiple interoperability and negotiation schemes (contracts) that are outside the scope of this paper could be considered. It is expected, however, that, following the guidelines for future energy systems as described in Section II-A, the energy sector will invest in and incorporate sophisticated communications systems into the power grids in the coming years. A scenario that is very feasible to be achieved, because currently the energy providers/distributors have large operation centers, to monitor and manage energy production and consumption and where NFV can be easily deployed, and also have optical transport networks (e.g., using optical ground wire technology) for data exchange. Then, these infrastructures could serve as a baseline for the deployment of our architecture.

In summary, NFV and SDN are scalable architectures that can grow proportionally (increased use of servers, controllers or switches) according to need and are able to work in distributed environments (e.g., multiple SDN controllers may be used to manage a massive number of ECs), enabling an automated, agile, flexible, scalable, dynamically reconfigurable, and programmable energy management for IoT devices, services, and applications with different requirements. The NFV and SDN technologies can fully interact with power grids networks [36], allowing DR systems to be easily deployable and they can be successfully integrated into a unified architectural framework for the deployment of agile, flexible and scalable services as demonstrated by the European Telecommunications Standards Institute (ETSI) [37]. In this regard, our proposal can be seen as an NFV use case (an energy management optimizer) [7], of rapid deployment that is capable of introducing new features and functionalities in an agile manner as the services and the energy market evolve.

E. ARCHITECTURAL FRAMEWORK PROPOSAL

As seen in the previous section the computational complexity of the proposal requires flexible and powerful architecture. Then, the enabling technologies to carry out the efficient management of P_{ES} are NFV and SDN technologies not only because they are inherently complementary, but also because when they work together they can offer great capabilities and benefits in the deployment of applications and services [37], [38]. In our proposal, the NFV/SDN integration adapted to the concept of DR systems gives rise to a robust and sophisticated energy management system that can be used in a wide range of IoT implementations. This solution, as a modular and open ecosystem divided into layers or domains, corresponding to ECs, SDN, NFV and the ES, allows the adoption of technological solutions for each domain (the domains can be developed independently), which can potentially improve the performance of the entire architecture. For example, in our proposal we have considered the possible inclusion of Fog Computing (FC) (see Fig. 8). FC is a technology that allows to extend the functionality of cloud computing (processing resources) close to the end user [39]. Thus, in the architecture FC is seen as an alternative domain to bring the NFV functionality (computations for service scheduling) closer to the ECs. Several studies shown that NFV capabilities placed at the network edge can result in a more efficient network-wide resource utilization, bandwidth, low latency, mobility and heterogeneity [40]. The proposed architecture for efficient energy management is show Fig. 1, and its low-level representation including all domains and FC technology is illustrated in Fig. 8). The description of the different architectural domains is presented below.

1) ENERGY SUPPLIER DOMAIN

The ES belongs to this domain and is responsible for feeding the entire ecosystem using renewable and non-renewable energy sources, which have been categorized as primary and secondary sources, respectively. This categorization has been adopted because the proposal has as a collateral objective to promote the majority use of renewable sources because their adoption is envisioned as a promising long-term and environmentally friendly alternative.

2) NFV DOMAIN

NFV, operating at cloud computing level (or alternatively at fog or edge computing levels) and applied within the context of a DR system, is the domain responsible for making decisions/actions to manage the power demands. In the NFV domain, the strategies or algorithms that enable the workload distribution according the availability are implemented through one or more VNFs, as shown in the generic example of Fig. 8. These VNFs, running on the NFV Infrastructure (NFVI), i.e., on generic general-purpose servers with processing, storage and networking capabilities, form an SFC and, in turn, a Network Service (NS), which is intended to optimize the energy consumption. The NFV domain in the scope of the proposal comprises: (i) VNFs that corresponds to the algorithms or subroutines deployed to perform the energy management of services (scheduling strategies), (ii) the NFVI that consist of all hardware and software resources to host and connect VNFs (as shown in Fig. 11) and the entire infrastructure that enable the energy provision, energy management and connectivity of ECs, and (iii) the Management and Orchestration (MANO) framework that coordinates the necessary resources (resource allocation), tasks, and actions between the three different domains (energy, NFV and SDN) to setup and implement the NFV functionalities.

From the information of energy provisioning (from ES through the Virtualized Infrastructure Manager (VIM)) and the users demands (from the ECs through the VIM), the NFV Orchestrator (NFVO) determines the allocation of energy resources for those demands that can be processed. The process of resource allocation is made based on calculations and service scheduling algorithms implemented as VNFs and forming SFCs, which are executed in the NFVO and managed by a VNF Manager (VNFM). In this context, the NFVO can decide the number and sequence of activation of the VNFs, it can also determine the use or not of a set of

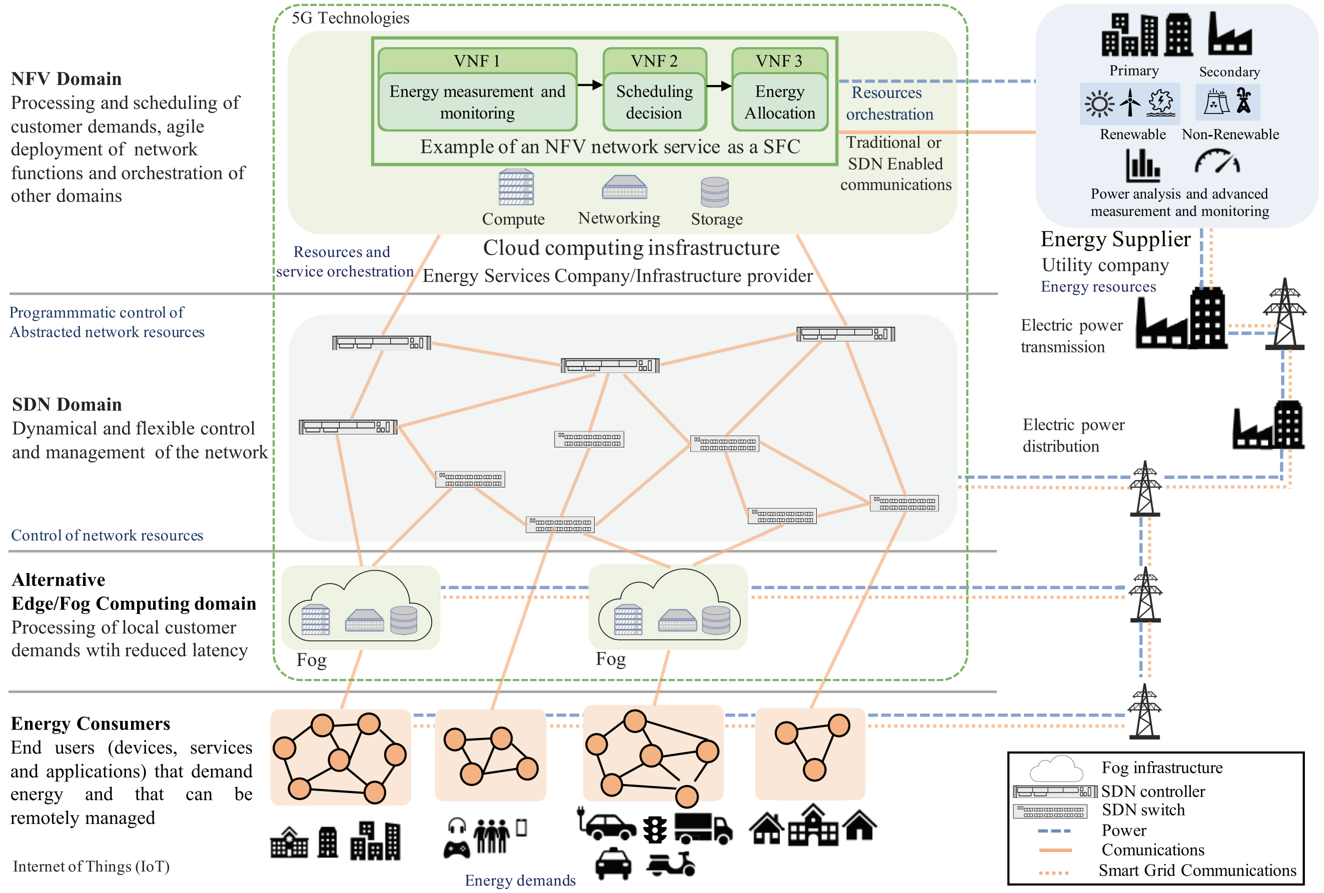


FIGURE 8. Low-level schematic representation of the proposed architecture.

VNFs in order to change the behavior of the energy management on the fly, if necessary. Thus, the NFVO functionality is divided into resource orchestration (NFVI) and service orchestration (VNFs).

The processing of energy demands (from VIM to NFVO) and the allocation of resources (from NFVO to VIM) is constantly carried out, the architecture, therefore, must be able to send the information through its different domains in order to guarantee an efficient management of energy at all times. In summary, once the computation of the energy allocations has been performed, the NFVO uses the VIM entity to notify the ECs (NFVI) of the consumption conditions, i.e., the services that can be processed and their respective execution time. At all times, the energy consumption from the ECs is restricted to the actions performed by the NFVO (energy allocation procedure) and the amount of available energy in the architecture (P_{ES}).

3) SDN DOMAIN

The NFV and Energy domains assume that all necessary connectivity can be dynamically established. To this end, SDN has been considered since it makes it possible to directly program, manage, and orchestrate the network infrastructure (ECs). The SDN paradigm facilitates delivery and operation of notifications and actions/instructions from ES, EM and ECs through the interaction between the NFVO and the VIM entities. In this regard, all changes made by NFV (algorithms executed in the NFVO) are transparently adopted by the underlying infrastructure (ICT infrastructures or power grids infrastructures [21]).

The SDN within the architecture is mainly responsible for two functions: (i) the dynamic connectivity of devices (ECs) and (ii) the energy management tasks. In the first case, the SDN network allows communication between the devices and components of the ecosystem (even the connectivity required for communicating VNFs inside the EM if needed). By means of a controller or group of controllers, which can be managed by the MANO component through the VIM as shown in Fig. 8, the SDN-compatible devices (ECs) receive the forwarding (energy consumption) instructions. Thus, the SDN controller interfacing with the device management agents is able to carry out the monitoring, configuration, and control functions of network resources as needed for the provision of data services. Depending on the size of the network (ECs to be managed) the ecosystem can be nested in different levels of controllers and SDN switches. Regarding the second case (the energy flow management), the controller receives the messages from the VIM and notifies the devices to modify their power usage condition, i.e., whether or not to execute their services. In a similar procedure, the controller sends the power requests to the NFVO through the VIM. In this way, the VIM, the SDN controller, and the underlying connectivity infrastructure form a hierarchy for delivering the energy management service throughout the architecture.

Once the architectural framework of the proposal and its respective domains have been described, its most relevant properties are presented below:

- *Stability:* The DR operation enables constant maintenance of the balance between energy provisioning (P_{ES}) and consumption (P_D).
- *Environmentally friendly energy management:* The architecture has been designed to be powered by renewable (P_R) and non-renewable (P_{NR}) energy sources. In a particular case ($w_R = 1$), the system could be powered only by green energy.
- *Scalability and dynamic operation:* The architecture can scale its performance based on the requirements from ECs and the network conditions. The dynamic management of resources (virtual or physical) can also be exploited to achieve additional energy efficiency through consolidation, migration, or the on-demand utilization of resources, for example within the EM.
- *Flexibility and agility:* The architecture allows that the VNFs associated with a SFC can be executed without being linked to a specialized hardware and in cloud, edge or FC infrastructures. Additionally, the independence of software and hardware promotes a suitable space for the integration of solutions (hardware or software) from different manufacturers and providers.
- *Programmability:* The energy management functionalities of the architecture can change on the fly. The EM can decide the execution of a specific SFC (algorithms) to address the needs or requirements of a particular scenario, and all changes are transparently adopted by ECs.
- *Simplified and improved system management:* The management entities of NFV (NFVO, VNFM and VIM) and of SDN (control plane) by working together ensure a consistent control and management to deploy the scheduling strategies and allocation of resources for different IoT devices services, and applications.
- *Open ecosystem:* The proposed solution, based on open architectures (NFV and SDN), can adopt open-source interfaces and solutions developed from different players. For example, the Openflow protocol [14] to provide an SDN southbound interface and the OpenDaylight SDN controller [14] with the OpenStack [41] project as NFVI. The architecture could be even implemented using sophisticated projects, such as Open Source Mano (OSM) [42], or Open Platform for NFV (OPNFV) [43].
- *Critical services guarantees:* The dynamic generation-consumption operation of the architecture enables the distribution/reduction of consumption in order to guarantee the provision of energy for the execution of CS in accordance with the terms agreed between ES and ECs.

F. EXAMPLE OF A USE CASE IN DOMESTIC ENVIRONMENTS

This section aims to provide a description of the operation of the architecture in a particular case and describe aspects that must be considering in the energy management process. Although the basic structure of our proposal is shown in Fig. 8, it can easily be adapted or complemented with other infrastructure(s) in order to meet the requirements of ECs, as shown in the example depicted in Fig. 9.

1) CONTRACTUAL TERMS

Prior to proceed with energy management, the EC and the ES must define the contractual terms. These agreements cover both economic a technical aspects. Regarding the economic considerations, the ES defines tariffs for the ECs according to energy use and availability. For example, if the workloads are adapted to the available resources, the EC can receive reduced tariffs or free periods of use. Instead, if the workloads cannot be shifted in time, different actions can be carry out, such as: i) that the workload is rejected because the ES does not have sufficient energy or ii) that the workload is processed but requires a costly tariff or even a penalty due to the effort (extra generation) performed by the ES to meet the demand. Then, these and other actions can be executed in order to guarantee the stability of the generation-consumption ecosystem.

Under the technical considerations, the ES and the EC must agree the parameters of the services to be processed, this information is summarized in Table 2, however, other technical considerations can be included depending the particularity of each scenario. Then, the architecture can start energy management, which is summarized in the initial handshake between the ES and the ECs, the scheduling of services, and the allocation of energy resources (see Fig. 6). For example, if the operation of a refrigerator has been categorized as a CS, the ES must guarantee the provision of energy for that device during the time intervals defined in the agreements. Instead, if the charge process of an electric vehicle has been treated as an NCS, it is conditioned to the available resources and in the worst-case scenario, this service may not be performed even if it is required by the user. Although this measure may seem drastic, it is still a possibility in the traditional systems, since, to a greater or lesser extent, users are aware that activating many loads (devices) can cause an overload in the electrical system and a subsequent service interruption; the difference is that in our architecture these processes are carried out with the consent of the users and in an automated manner.

2) SERVICE PROCESSING

In order to perform efficient energy management, the architecture uses scheduling strategies and considers the

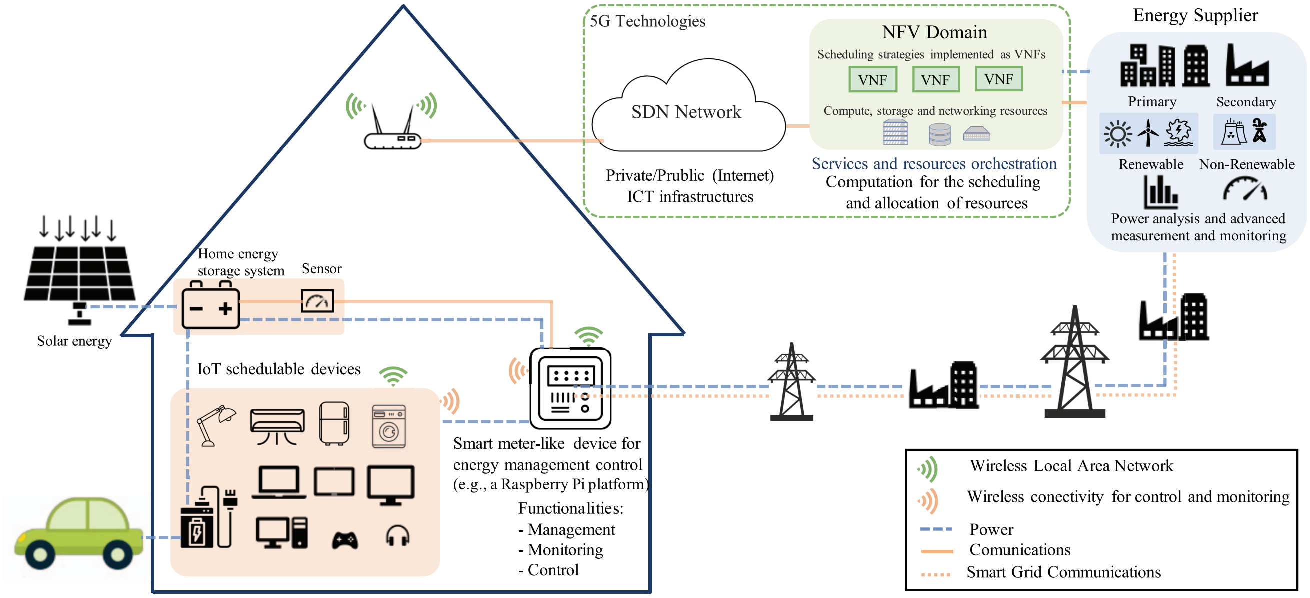


FIGURE 9. Schematic example of the use of architecture for home energy management.

parameters defined in the agreement to determine the suitable (optimal) time windows in which the devices can use energy. This process is completely automated and enables the services to consume energy according to the indications of the architecture (EM); however, there exists services/devices that require a different level of interaction to participate in energy management. For example, energy management in computing processes, sensors, and other similar services can be totally automated by the architecture; other services, such as the operation of a microwave instead require direct user participation and the consumption is restricted to the need for the service. For these kinds of services, the ES and the ECs can agree the time windows (time slots) to stimulate consumption, and the architecture can consider these parameters in the service scheduling process, and, as previously stated, these actions can be complemented by economic incentives. In addition, for scenarios in which the management cannot be fully automated, the architecture could enable the incorporation of intermediate devices, as shown in Fig. 9, with the objective that user can send updated information of the workloads. This information can then be used by EM to carry out a more precise allocation of resources. In summary, the architecture contemplates the nature of the services in the calculations for the efficient energy management.

3) INTERACTION WITH ARCHITECTURE

Regarding the use of architecture in domestic environments, we describe two possible options. In the first option, the home devices can interact directly with the components of the architecture (EM and ES), and due to the relatively less demanding complexity, the calculations can be carrying out in FC infrastructures. In the second option, which is a more realistic approach and is illustrated in Fig. 9, the customer interacts with the architecture through an intermediate smart meter-like device, which act as an aggregator point to collect consumer requests and communicate scheduling decisions.

From the two options presented, the second is a better alternative because it provides a simplified management and a better organization of the workload. In this approach, the smart meter-like device (which, in real applications, can be implemented on an embedded platform such as a Raspberry Pi), apart from providing a bidirectional communication between the ECs and the ES, can be responsible for executing the same functionalities performed in the NFV domain, i.e., the management and monitoring of energy flows, execution of scheduling strategies (heuristics), and the allocation of energy resources to the different appliances, but locally. If the computational resources of the home management device are not sufficient to process the demands, it can interact with the rest of the architecture and send the calculation and processing tasks to FC or cloud computing infrastructures, similar to the process performed by mobile devices (e.g., cell phones) where the processing of some applications is not carried out on the device but in the cloud. In addition, the smart-meter like device can manage the energy production (e.g., from solar panels) storage and distribution to cover home demands, especially when the ES is facing shortage periods.

IV. ILP FORMULATION: MINIMIZATION OF P_{RES}

Considering a discrete time model divided into time slots, the objective of the energy management proposal is the optimization of energy consumption, technically this objective is achieved through the minimization of the wasted or unused available power. Thus, the difference between the finite P_{ES} and the total power demanded by the ECs P_D represents the objective function to be minimized. Conceptually, this objective function is expressed as shown in Eq. (10).

However, considering that the P_{ES} and P_D may vary at each time slot i the implementation of this objective function within a finite time horizon W can be expressed as shown in Eq. (11). Then, the aim of proposed strategy is the minimization of wasted power at each time slot considering the energy provisioning conditions and the parameters of the ECs (services or power demands). Therefore, the minimization of the wasted power in all time slots, within W, produces the optimal/efficient use of available energy.

A. OBJECTIVE FUNCTION

$$minimize \ \{P_{ES} - P_D\} \tag{10}$$

$$\forall i \in W : minimize \ \left\{ \sum_{i=1}^{W} (P_{ES}[i] - P_D[i]) \right\} \tag{11}$$

In the proposal the difference shown in Eq. (10), is defined as Residual Power P_{RES} and can be expressed as:

$$\forall i \in W : P_{RES} = \sum_{i=1}^{W} (P_{ES}[i] - P_D[i]) \tag{12}$$

Therefore, the objective of the proposed management model is the minimization of P_{RES}, respecting the available energy resources, considering the parameters of each service and the constraints presented below.

B. CONSTRAINTS

$$C1\colon P_{ES}[i] \geq 0 \tag{13}$$

$$C2\colon (P_{ES}[i] - P_D[i]) \geq 0 \tag{14}$$

$$C3\colon \sum_{k=1}^{N} \sum_{l=1}^{L} P_d^{k,l} \times x_k[i] \leq P_{ES}, \ x_k \in \{0, 1\} \tag{15}$$

$$C4\colon T_{init}^{k} \geq 0 \tag{16}$$

$$C5\colon \left\{ T_{init}^{k} - T_{bw}^{k} \right\} \geq 0 \tag{17}$$

$$C6\colon W \geq \max\{T_{init}^{k} + T_d^{k} + T_{fw}^{k}\} \tag{18}$$

$$C7\colon T_{init}^{P_{ES}} \geq 0 \tag{19}$$

$$C8\colon T_{init}^{P_{ES}} + m \leq W. \tag{20}$$

1) DOMAIN CONSTRAINTS

The energy provisioning by the ES is constrained by $C1$. Instead, $C2$ ensured a non-negative P_{RES}.

2) CAPACITY CONSTRAINT

The maximum capacity of the system is determined by $C3$, where, the decision variable x_k represents the allocation of energy resources for the processing of the service S_k as described in Eq. (21).

$$x_k[i] = \begin{cases} 1 & \text{if the service } S_k \text{ is processed at time slot } i, \\ 0 & \text{otherwise.} \end{cases} \tag{21}$$

The proposal assumes the management of complete services. In this regard, the partial execution of service can be addressed in a future work. Thus, as presented in $C3$, the total aggregated power (P_D) of the processed (accepted) service(s) must guarantee the minimum P_{RES} value (as long as $P_{RES} \geq 0$). In addition, the consistency between the service and its priority is validated by Eq. (22). This condition ensures the existence of the service for its corresponding unique priority level.

$$P_d^{k,l} = \begin{cases} \text{Power demanded by } S_k \text{ with priority } l & \text{if the } S_k \text{ with priority } l \text{ exists,} \\ 0 & \text{otherwise.} \end{cases} \tag{22}$$

3) TIME CONSTRAINTS

The non-negative starting time of the whole system ($t = 0$) is assured by $C4$ and $C5$. Instead, $C6$ ensures a finite time horizon for the analysis or all N services and all the changes to which they may be subject (i.e., $[T_{bw}^{k}, T_{fw}^{k}]$). In addition, linked to $C1$, $C7$ and $C8$ ensure the supply of non-zero power during a time interval m, within the total time horizon of the system W. The linear nature of the objective function, the decision variable and the constraints give the ILP condition to the problem.

For simplicity in the nomenclature in the rest of the paper the parameter that represents the time slot identifier (i) has been omitted, however, it has been considered in the design of the scheduling strategy in Section V.

V. EVALUATION

To evaluate the impact of our proposal on energy management, in this section we present an exact or optimal service scheduling algorithm defined as OptTs whose objective is to optimize the use of available energy considering the time-shifting capabilities in the service execution and the service rejection if $P_D < P_{ES}$. Regarding the optimization of energy consumption, the task of OptTs is to find the combination of services whose P_D allows minimize the P_{RES}. The algorithmic solution developed, described in detail in Section V-B, bases its operation on an exhaustive brute-force search method, in which all possible combinations of N services, executed simultaneously, are explored, considering all possible values of time-shifting. To select the best combination, i.e., the optimal distribution of services in time, with a P_D (P_{Dcomb}) that produces the optimal energy consumption, the performance metrics defined in Section V-A are used. To quantitatively assess the improvements obtained with OptTs in Section V-C we present the analysis for a case study. In this context, a more detailed study in different scenarios, as well as, the online version of OptTs and the development of more sophisticated and efficient methods, that use as the baseline the optimal solution developed, and, that consider the other aforementioned management strategies, such as quality degradation or energy storage, will be addressed in future work.

A. METRICS

1) STANDARD DEVIATION OF RESIDUAL POWER ($\sigma_{P_{RES}}$)

This metric aims to measure the amount of P_{RES} of a given combination of services (*Combserv*) that is part of the set of all possible combinations (*AllCombserv*). A lower $\sigma_{P_{RES}}$ depicts a better use of P_{ES} and the best case is reached when $\sigma_{P_{RES}}=0$. The expression of $\sigma_{P_{RES}}$ within m is:

$$\forall j \in AllCombServ : \sigma_{P_{RES_j}} = \sqrt{\frac{\sum (P_{REScomb_j})^2}{m}}. \tag{23}$$

2) ACCEPTANCE RATIO (*AR*)

This metric measures the number of services processed. If P_{ES} is insufficient to meet all the demands, one or several services should be rejected (*RejServ*). The *AR* can be expressed as:

$$AR = \frac{N - RejServ}{N} \times 100\% \tag{24}$$

The computation of the metric *AR* as well as the computation of $\sigma_{P_{RES}}$ and σ_{Ts} is performed for each combination of services (*Combserv*). Specifically for *AR*, the algorithm first verifies the P_{RES} value of the combination in analysis. If $P_{RES} \geq 0$ this means that all N services can obtain the power they demand and consequently the combination obtains an $AR = 100\%$. Otherwise (i.e., if $P_{RES} < 0$) the algorithm performs a combinatorial analysis of the service(s) that must be rejected so that the resulting P_{RES} is the minimum possible, as long as the $P_{RES} \geq 0$. The proposed strategy prioritizes the minimization of the residual power. In the event that two or more combinations of services produce the same P_{RES} value, the algorithm uses as a second selection criterion the number of services that could be processed, i.e., the *AR* value achieved by the processed services. Then, the strategy selects the combination of services that produces the highest *AR* value. Thus, this performance metric is computed only with the set of services (belonging to the same *Combserv*) to which energy can be allocated. In addition, if necessary with the information of the mean P_{ES} value, the estimation of the papameter m so that all power demands are met ($AR = 100\%$) can be computed as:

$$m = \frac{\overline{\sum_{k=1}^{N} P_d^k \times T_d^k}}{\overline{P_{ES}}} \tag{25}$$

where, the numerator and denominator represent the mean values of consumption and provision, respectively.

3) STANDARD DEVIATION OF TIME-SHIFTING (σ_{TS})

This metric measures, within the combination, the T_s^k (backward or a forward) performed by the different services. A lower σ_{Ts} represents a minor change in the original execution of the services. The best case is $\sigma_{Ts} = 0$, which is given if $T_s^k = 0\, \forall k \in N$. The σ_{Ts} can be defined as:

$$\forall j \in AllCombServ : \sigma_{Ts_j} = \sqrt{\frac{(\sum_{\forall k\in N} T_s^{k,j})^2}{N}}. \tag{26}$$

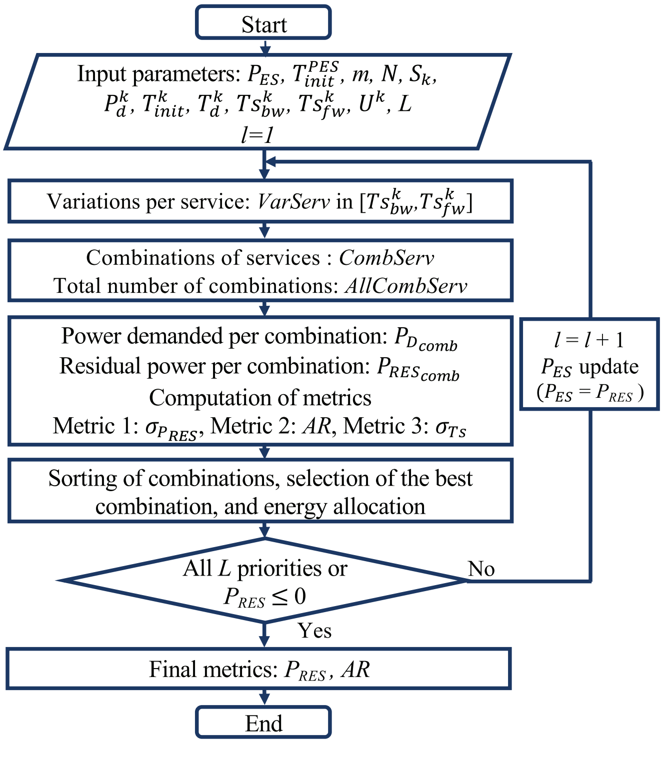


FIGURE 10. Flow chart of the exact scheduling algorithm.

B. OPTIMAL SOLUTION: OPTTS

The exact solution OPTTS is explained in Fig. 10 and the main steps carried out are summarized below.

- *Variations per service* (*VarServ*)*:* A variation of a service is the product of the application of a specific discrete time-shifting value to the T_{init}^k of a service S_k. The analysis of services within $\{T_{s_{bw}}^k, \ldots, 0, \ldots, T_{s_{fw}}^k\}$ produces a total number of variations *AllVarServ*. Then, considering that, for simplicity, $T_{s_{bw}}^k = T_{s_{fw}}^k = Ts$, this number is given by:

$$AllVarServ = 2 \times N \times Ts + N \tag{27}$$

- *Combinations of services* (*CombServ*) *and computation of metrics:* The set of N different variations of services (*VarServ*) is defined as a *combination of services* (*Combserv*). Each *Combserv* has specific characteristics and demands a certain power level P_{Dcomb}. The algorithm evaluates the performance metrics for each *CombServ*. The combinatorial analysis of all (*VarServ*) produce a total number of combinations of services *AllCombServ* given by:

$$AllCombServ = (2 \times Ts + 1)^N \tag{28}$$

This step contributes largely to the growth of complexity, for instance, $N = 10$ and $Ts = 4$ produce over 3 billion combinations, so if a computer is able to process one *Combserv* each millisecond, it would need over 800 hours to explore the entire search space.

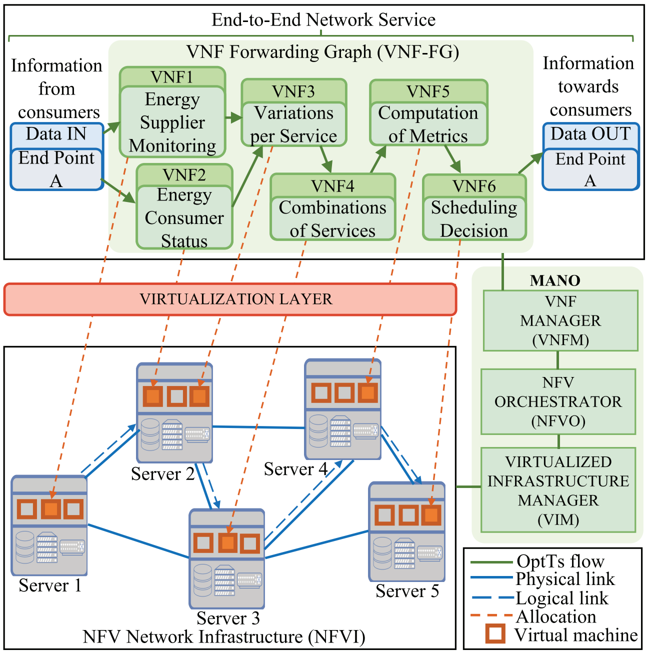


FIGURE 11. Example of the OptTS algorithm as an SFC.

- *Sorting of combinations and selection of the best combination:* Nested quicksort applied to all combinations, according to: (i) ascending $\sigma_{P_{RES}}$, (ii) descending AR, and (iii) ascending σ_{Ts}. Then, the best combination (i.e., the first in the sorted list) is selected and the metrics P_{RES}, AR are computed.
- *Iterative analysis of priorities:* The steps above are executed iteratively until all priority levels are analyzed or until the system has no power ($P_{RES} \leq 0$). In each iteration, the P_{ES} value is updated, which is equal to the P_{RES} of the previous priority. The algorithm finishes its execution presenting the final metrics P_{RES}, AR.

As an example of the deployment of energy management strategies in the NFV environment, Fig. 11 shows the representation of the procedures of OptTs as VNFs forming an SFC. Then, this implementation can exploit all the benefits that NFV realm can offer, i.e., the VNFs could be moved, migrated, shared, deployed in parallel mode or used by other SFCs if necessary. In addition, the operation of management strategies through SFCs is susceptible to be further improved by addressing aspects such as optimal allocation of VNFs or the optimal composition and allocation of SFCs taking into account energy efficiency, as discussed in [44] and [45], respectively. These considerations are beyond out of the scope of this paper and can be addressed as future work.

1) COMPLEXITY OF OPTTS

The complexity of the exact solution is related with the processing of *AllVarServ* and *AllCombServ*, and as function of N the growth rate can be expressed as:

$$f(N) = N + (2 \times N \times Ts + N) + (2 \times Ts + 1)^N \qquad (29)$$

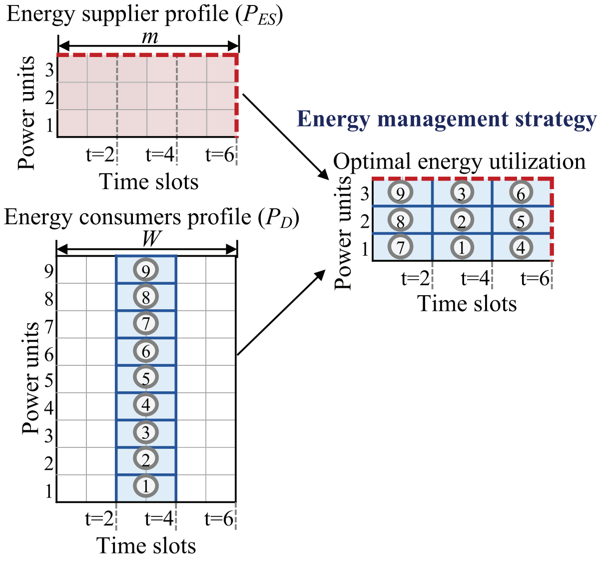


FIGURE 12. Energy and consumption profiles of the case study, and optimal energy allocation obtained with OptTs. Example for $T_d^k = 2$ [time slots], for all S_k.

where, the last term in Eq. (29) is the dominant within the expression and represents the size of the search space that must be explored to find the combination of services (*VarServ*) that enable the P_{RES} minimization. Thus, the complexity of OptTs is exponential with an order of growth $\mathcal{O}(2^N)$ that depends on the selected values of N and Ts.

C. NUMERICAL RESULTS

1) SIMULATION SETTING

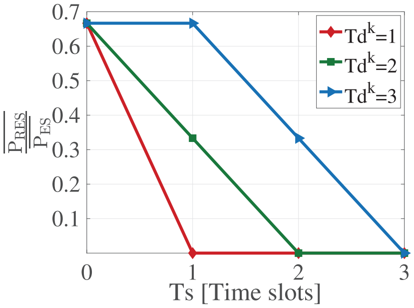
The OptTs solution is implemented using MATLAB (MATLAB R2017b) running on a machine with a 3.33 GHz x 12 cores Intel Core i7 Extreme processor and 12 GB RAM. The implementation leverages parallel processing and up to 4 cores are used in the simulation of the case study. The total running time for the simulation exceeded 90 hours. The evaluation of the optimal solution is given in terms of the AR metric and the normalized value of P_{RES}. The results obtained are compared with a traditional scenario in which no strategy is applied, i.e., when the $T_s^k = 0$.

2) CASE STUDY

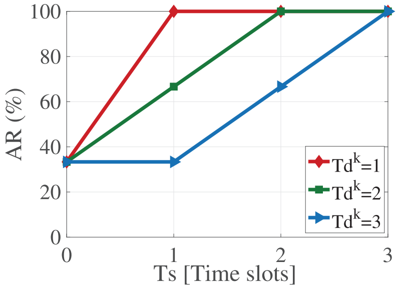
For the quantitative evaluation of OptTs we have considered the scenario shown in Fig. 12, which allows to analyze the action of the strategy during states of shortage (high load) and surplus of energy caused by the lack of synchronization between the generated power and the consumption demanded. Due to the high computational demand of the exact solution the simulation has been limited to N =9 services and $max\{T_{s_{bw}}^k\} = max\{T_{s_{fw}}^k\} = 3$ time slots, the rest of the parameters used are detailed in Table 3. To simplify the analysis, a flat energy profile and demands with equal value of P_d^k and T_d^k have been selected, however, this does not represent a limitation for the developed algorithm, which can work with any profile of energy and demands

TABLE 3. Parameters of the optimal strategy OptTs and values regarding the example of Fig. 12.

Parameter	Description	Unit/Value
W	Max. time horizon of analysis	6 Time slots
$T_{init}^{P_{ES}}$	Start time of power supply	0 Time slots
m	Time interval of P_{ES}	Time slots, Eq. 25
P_{ES}	Available power	3 Power units $\forall m$
N	Number of services	9 Services
l	Priority identifier	1 priority level $\forall k$
S_k	Service identifier	$k \in \{1, \cdots, 9\}$
T_{init}^k	Starting time of service k	2 Time slots $\forall k$
T_d^k	Lifetime of service k	$\{1, 2, 3\}$ Time slots
P_d^k	Power demanded by serv. k	1 Power unit $\forall T_d^k$ and $\forall k$
$T_{s_{bw}}^k$	Backward shifting of serv. k	$\{1, 2, 3\}$ Time slots
$T_{s_{fw}}^k$	Forward shifting of serv. k	$\{1, 2, 3\}$ Time slots
U^k	Priority of service k	1 $\forall k$



(a) P_{RES} metric OptTs.



(b) AR metric OptTs.

FIGURE 13. Performance evaluation of the OptTs for case study of Fig 12. Parameters: According Table 3.

if necessary. In addition, in the simulation the time is discretized into time slots, that in practical implementations can correspond to different time intervals (e.g., 10-minute or 1-hour time intervals) depending on the application. Thus, all time variables for the analyzed scenario are given in terms of time slots.

3) RESULTS AND DISCUSSION

The simulation results shown in Fig. 13 confirm that OptTs improves energy consumption for all T_d^k cases, as reported in values of metrics P_{RES} and AR in Fig. 13(a) and in Fig. 13(b), respectively. As the time-shifting value increases, the algorithm has the ability to distribute the demands and use all P_{ES}. In this way, services that would normally be rejected can now be processed using our management strategy. For the analyzed use case, the reported increase is 66%, from an initial processing with $AR = 33\%$ until reaching $AR = 100\%$. In a particular scenario, if a sufficient level of P_{ES} is available, even though all the demands are out of the m interval, with an adequate time-shifting value, it is possible to obtain an improvement of 100%. It is expected that, in practical implementations, the time-shifting interval would be in the range of units or tens of minutes or hours (e.g., 2 or 3 hours). Hence, to evidence improvements in power consumption would not require excessively large values. Of course, the value of this parameter is conditioned to the profile of the available energy and the size of the demand (this if to use P_{ES}, the entire demand needs to be displaced from its original position).

In addition, as discussed in Section V-B1, considering the exact method, the maximum value of the time-shifting must be previously assessed because it has an impact on the growth of complexity (Eq. (29)). Computational complexity can be solved if OptTs is executed in ICT infrastructures of high processing and memory resources, such as those used for NFV deployment. For practical reasons, however, the exact solution may not necessarily be used, but it could be used as a baseline for the development of other, more scalable methods, i.e., for larger values of N and/or Ts. Thus, the work presented in this paper provides the foundations for the future development of faster and less computationally demanding heuristic methods, by providing the management strategies to be implemented, the parameters to be considered, and the performance metrics for the selection of service distribution that minimize the P_{RES}.

VI. OPEN RESEARCH CHALLENGES OF THE PROPOSED ARCHITECTURE

This section summarizes open research issues with the aim of motivating future work in this field.

A. COMPLEXITY AND SCALABILITY

Our proposed architecture aims to be flexible and scalable enough to be applied from small scenarios with few services (devices), as is the case of domestic environments, to very large scenarios that can cover entire cities. Regarding the algorithmic solution to be used, for small-scale scenarios, the developed solution OptTs could be used. However, to meet the very low latency requirements of modern networks that are in the order of milliseconds [8] and to deal with the billions of devices that are connected to the Internet [46], it is necessary to develop strategies that require a low running time, demand low computational resources, and produce high-quality solutions. In this regard, there are a number of heuristic and metaheuristic techniques and methods. However, considering that the P_{RES} minimization problem falls into the category of a 1/0 Knapsack Problem and based on the literature reviewed, we indicate the following methods as promising solutions: (i) a prepartitioning strategy based on a divide-and-conquer approach, (ii) a genetic-algorithm-based solution, and (iii) a dynamic-programming-based approach. For the development and evaluation of these strategies, the parameters, mechanisms, and results obtained with the exact method can be taken as a baseline.

B. ENERGY STORAGE MANAGEMENT

As mentioned in Section III-B3, the integration into the architecture of an element that stores the energy produced by renewable and non-renewable sources (e.g., battery units), is expected to contribute to a better use of energy, since this component can act as a buffer to store or deliver energy according to the conditions of generation and consumption (energy states). This component can potentially improve the overall performance of the architecture, but its prime benefit would be to contribute to the execution of CS. Among the different topics that can be addressed in future work are mathematical modeling and sizing, optimal location within the architecture, and coordination with other domains.

Another important aspect to analyze is the management of energy produced and stored by users, as illustrated in the example of photovoltaic-energy generation in Fig. 9. Traditionally, energy is used by the owner of the generation system, but in a more ambitious approach, under the coordination of the proposed architecture, this generated/stored energy could be distributed to other users or locations. This process would increase complexity in management, since continuous monitoring and coordination of potential energy consumers/producers (a.k.a. prosumers) would be necessary, but in turn, it would improve the use of all produced energy.

C. SECURITY AND PRIVACY

The security concerns have been addressed in different studies for SDN [47], NFV [48] and smart grids [49] independently. However, for the proposed architecture, a security framework that cover services such as integrity, authentication, privacy, and availability must be developed, which could be a very challenging task since each domain has different characteristics and requirements. Among the different aspects of security to consider, privacy and data integrity should be highlighted. The architecture must guarantee the anonymization of ECs in order to avoid targeted attacks, especially on CS. With respect to data integrity, the DR system must provide reliable transmission and processing to avoid alteration in control and management information and bill modifications.

D. DATA ANALYTICS

The information about ECs and the network resources used is constantly sent to the EM. This information can be stored and used not only for billing, but also for monitoring of service quality, network utilization, and for obtaining performance indicators. Also, the stored data can be exploited to discover patterns or predict trends through the use of machine learning techniques, with the objective of performing accurate resource allocations and offering personalized services.

VII. POTENTIAL APPLICATION FIELDS OF THE PROPOSAL

In Section III-F we present a potential use case; in this section we briefly describe other application scenarios.

A. MANAGEMENT OF THE PUBLIC INFRASTRUCTURES ENERGY CONSUMPTION AND PROVISIONING

The proposed architecture can be applied to perform tasks of monitoring, management and control of energy resources in cities, municipalities, neighborhoods, and other locations. In these environments, the architecture can collect energy demands through a centralized or distributed implementation and perform an efficient energy allocation for a specific place, group of services or users according to resource availability. For example, our architecture can interact with ICT infrastructures of municipalities or local governments to manage and control smart power grids, intelligent transport systems, street lighting, controllers and other public infrastructures.

B. ENERGY MANAGEMENT OF ELECTRIC VEHICLES

Preliminary studies have demonstrated the application of NFV concepts in the field of electric vehicles [50]. In this regard, our proposal can replace, complement or improve the energy management tasks traditionally performed by traffic controllers or intelligent transportation systems. Through communications systems (mainly based on SDN), the architecture could monitor available energy, charging points, and consumption levels (battery levels). Thus, based on the information gathered, the DR architecture (NFV domain) could indicate to users the periods during the day for the use of vehicles or battery recharging. In addition, information on energy resources and consumption can be used to carry out weekly or monthly planning of energy distribution to avoid shortages or possible collapses of the electrical grid.

C. ECOSYSTEMS POWERED BY RENEWABLE ENERGY SOURCES

The DR architecture has the capacity to efficiently manage the gradual contribution of renewable sources, being able to work entirely with green energies ($w_R = 1$ in Eq. (2) and Eq. (3)) if necessary. It is expected that a greater contribution of renewable energy, mainly from sources such as solar and wind, will demand greater dynamics in the generation-consumption ecosystem in order to take special advantage of periods of surplus. Our approach responds to these requirements and can be envisioned as a promising alternative toward the deployment of high performance zero-emissions ICTs or power grid infrastructures.

VIII. CONCLUSION

This paper proposes an architecture for the adaptive consumption of available energy, whether 100% renewable or not, for IoT infrastructures, and it is envisioned as a candidate for the deployment of the IoE. The proposal covers the description and interaction of the stakeholders (ES, EM, and ECs), several management strategies, including service scheduling using time-shifting capabilities and prioritization of the energy supply, and a consumption model where consumers are an active part of the energy management process.

The complexity analysis has demonstrated that the proposed energy management solution has a hardness $\mathcal{NP}$-hard and requires sophisticated ICT infrastructures for its operation. These requirements in the architecture are met by NFV and SDN technologies. Specifically, all the management strategies and calculation, such as workload scheduling, needed to adapt P_D to P_{ES} are carried out by NFV, whereas all connectivity for data exchange corresponding to instructions and notifications between ES and ECs is provided by SDN. Thus, NFV and SDN, both key participants in 5G, enable automated, agile, flexible, scalable, dynamically reconfigurable, and programmable energy management for IoT implementations with varied requirements.

This paper also provides the mathematical model of both the ES and the ECs. In addition, the problem of the optimal use of P_{ES} is modeled using an ILP formulation in which the objective to optimize is the P_{RES} that represents the energy that would be wasted if not used. To solve the ILP problem, an optimal algorithmic solution is developed (OptTs), of exponential complexity that depends on the values of N and T_s^k, as shown in Eq. (27). The evaluation of the exact solution reveals that the proposal allows for improvements in the use of P_{ES}, which is verified in the values of the metrics P_{RES} and AR and in the increase of the services that can be processed. At the end of this paper, some research challenges and possible application scenarios are described.

Future work must include the following aspects: (i) analysis of the architecture, considering that an interesting point to be addressed is the modeling and sizing of the battery units, to guarantee the execution of CS; (ii) deployment of fast and scalable algorithmic solutions, taking as a baseline the metrics, procedures, and results obtained for the optimal solution; (iii) application of the concepts and strategies presented in the proposal to specific scenarios, e.g., managing battery power in a communications system supported by drones, as shown in [33]; and (iv) analysis in other areas including, regulation, standardization, economics, and market, considering that this paper is focused strictly on technical aspects.

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