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Adaptive Energy Management in 5G Network Slicing: Requirements, Architecture, and Strategies

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Abstract: Energy consumption is a critical issue for the communications network operators, impacting deeply the cost of the services, as well as the ecological footprint. Network slicing architecture for 5G mobile communications enables multiple independent virtual networks to be created on top of a common shared physical infrastructure. Each network slice needs different types of resources, including energy, to fulfill the demands requested by each application, operator, or vertical market. The existing literature on network slicing is mainly targeted at the partition of network resources; however, the corresponding management of energy consumption is an unconsidered critical concern. This paper analyzes the requirements for an energy-aware 5G network slicing provisioning according to the 3GPP specifications, proposes an architecture, and studies the strategies to provide efficient energy consumption in terms of renewable and non-renewable sources. NFV and SDN technologies are the essential enablers and leverage the Internet of Things (IoT) connectivity provided by 5G networks. This paper also presents the technical 5G technology documentation related to the proposal, the requirements for adaptive energy management, and the Integer Linear Programming (ILP) formulation of the energy management model. To validate the improvements, an exact optimal algorithmic solution is presented and some heuristic strategies.

Keywords: energy efficiency; energy management; network slicing; NFV; SDN; workload scheduling; renewable energy

1. Introduction

1.1. Background and Motivation

The deployment of 5G mobile networks introduces new services and applications to facilitate a wide range of end user demands. However, before these innovations can be made available to customers and vertical markets, some challenges need to be addressed, such as the efficient management of network resources, multi-tenancy approaches, and the management of energy consumption [1,2]. Regarding the first two points, network slicing architecture has emerged as a means to efficiently support dynamic resource management in a multi-tenant environment [3]. Specifically, network slicing for 5G mobile communications leverages on the concepts of Network Functions Virtualization (NFV) and Software Defined Networking (SDN) to implement multiple virtual and independent logical networks, referred to as network slices, on a common shared physical network infrastructure [4,5]. In network slicing, each slice (virtual network) is an isolated amount of end-to-end network resources and functions with different requirements, including energy, and with independent management and control, tailored to fulfill the diverse demands requested by a particular operator, application, service, customer, or vertical market [6].

The Mobile Network Operator (MNO) can configure and manage the control plane and user plane network functions and the corresponding resources (e.g., access, transport, and core networks) to support various Slice/Service Types (SST) [7]. These SST can be grouped according to their different requirements in functionality (e.g., priority, charging, security, and mobility), on performance requirements (e.g., reliability, latency, mobility, and data rate), or they can be targeted to specific users (e.g., public safety users, corporate customers, or virtual operators) [2]. In the technical specification TS 23.501 v16.4.0 (issued in March 2020), the 3rd Generation Partnership Project (3GPP) provides a standardized classification that groups different services, such as enhanced Mobile Broadband (eMBB) services, Ultra-Reliable Low-Latency Communications (URLLC) services, massive Internet of Things (IoT) services (MIoT), and Vehicular-to-everything communications (V2X, where the X means vehicle, infrastructure, pedestrians, etc.), within four SST categories [1], as shown in Table 1. This classification can be used as a baseline or template to implement network slices for most customer requirements. In addition, the TS 23.501 v16.4.0 does not limit the creation of other categories if necessary, and the assigned SST values do not give priority to one category over the others.

Table 1. Standardized SST values and examples [1].

Slice/Service Type	SST Value	Characteristics	Examples of Services
eMBB	1	Slice suitable for the handling of 5G enhanced Mobile Broadband	4K/8K UHD, hologram, augmented/virtual reality
URLLC	2	Slice suitable for the handling of ultra reliable low latency (e.g., 1 ms) communications	High-accuracy positioning systems, motion control, autonomous driving, automated factory, smart-grid service, augmented/virtual reality
MIoT	3	Slice suitable for the handling of massive IoT	Sensor-network services (e.g., metering, agriculture, building, logistics, cite, home, etc.)
V2X	4	Slice suitable for the handling of V2X services	Vehicular communications systems (e.g., vehicle-to-vehicle, vehicle-to-infrastructure, etc.)

Regarding energy consumption management, this feature is a key factor in the deployment and evolution of mobile networks [8], and it is also a crucial consideration for the following reasons: (i) constant growth in energy consumption because of the increasing number of devices connected to mobile networks and the corresponding network densification from the deployment of a high number base stations and related infrastructures (legacy networks 2G, 3G, and 4G must coexist with 5G and beyond networks) [9]; (ii) increased traffic demand and heterogeneity of services with different requirements (e.g., high data rate, low latency, wide bandwidth, a high operating frequency of up to 60 GHz, reliability, or connectivity) [10]; (iii) increase in the Operation Expenditures (OPEX) for the MNO, because, more energy consumption means more costs of energy supply, which can produce an impact on tariffs for consumers or less margins for the operators [8]; and (iv) sustainability issues, which call for new energy generation and consumption principles [10].

Historically, the evolution of mobile networks has implied an increase in energy consumption. However, this current reality needs to change due to sustainability considerations, the increase in CO_2 emissions, and the impact on climate change caused by the use of fossil fuels for energy production (e.g., electricity) [11]. To guarantee energy sustainability and efficiency for mobile communications, there are different solutions that fall into two major groups: (i) increasing the use of renewable energy sources; and (ii) optimizing energy consumption (e.g., using energy saving mechanisms) [12].

The use of renewable energy sources (e.g., solar and wind), also known as green energy, to power Information and Communication Technology (ICT) systems such as 5G networks, is a promising alternative that can reduce energy bills for the MNO and customers, the exclusive dependence on power grids, and is an opportunity to deliver a cleaner and more sustainable mobile communications ecosystem [10]. For instance, green energy can allow the deployment of base stations in remote areas where power grids are not available (e.g., photovoltaic installations), and it may be a choice to compensate the lack of energy capacity from the supplier. In addition, the adoption of renewable energy sources allows changing the traditional centralized energy supply scheme to distributed power grid architectures in which the energy harvesting processes can be used to improve energy distribution, as it has been demonstrated for mobile access networks [13]. For all these reasons, the use of green energy emerges as a feasible solution to deal with the ever-rising energy demand and sustainability requirements in 5G networks [12].

There are multiple benefits of using energy from renewable sources, but their intermittent nature may affect the continuity of services and the reliability of mobile networks. In addition, the use of green energy alone is not enough to make mobile networks more sustainable; they need to consume better and less. Consequently, there is a need to incorporate new methods for adaptive energy management consumption (i.e., mechanisms to adapt consumption to availability) [1]. In this regard, different strategies have been analyzed such as activation of network infrastructures on demand, the total or partial deactivation of services or devices (e.g., deactivation of sectors in base stations), periodical activation or deactivation of consumption (e.g., by using sleep or idle modes), degradation in the quality of service (e.g., decrease in transmitting power), or scale the energy consumption to the traffic dynamicity [14,15]. These strategies can be applied to specific segments (e.g., to access networks) or to the whole system, and they can be performed through the ICT infrastructures of mobile networks [14]. In 5G, for example, the enabling technologies NFV and SDN can be used to deploy an energy management framework [16,17], which offers high computing capabilities (data centers or cloud computing infrastructures), flexibility, and agility for executing management strategies (NFV benefits) [5], as well as the separation of control and data planes (SDN benefits) [18], and they can be applied for energy managing for different customers and scenarios transparently. Moreover, an NFV/SDN-based energy management architecture can potentially be used for managing virtual resources and networks [16,17], a capability that can enable energy management in 5G network slicing.

In summary, new services and applications demanded by customers impose that the current and future mobile networks have sophisticated energy management and consumption schemes. These energy management approaches must be adapted to finite energy production and the dynamic generation–consumption conditions. Natively, mobile networks lack an efficient energy management scheme for the whole system. In addition, the redundant design of mobile networks (e.g., duplication of access, transport, or core devices) for keeping the reliability and performance in communications has produced a constant increase in energy consumption (mainly for non-renewable sources) and carbon footprint related. To promote sustainable and environmentally friendly development of mobile networks, the traditional network design and operation must incorporate efficient management of energy consumption and prioritize the use of renewable energy sources. In this regard, the evolution to 5G and specifically to network slicing is an opportunity to develop a sustainable and adaptive energy management ecosystem that is capable of working in a multi-tenant approach, encourages the use of green energy, and optimize the energy consumption. In this regard, the main objective of this paper is to meet these requirements, because the existing literature on network slicing is mainly targeted at the creation of network slices by means of the partitioning of the core, distribution, and access networks resources. Thus, our proposal considering the characteristics of network slicing, NFV, SDN, and green energy represents a feasible and sustainable solution that can offer reductions in OPEX and environmental impact and an improvement in service processing.

1.2. Paper Overview and Contributions

This paper proposes an energy management solution applicable to 5G network slicing in which the service processing (i.e., the creation of network slices and corresponding services) is aware of the energy supply with the aim of optimizing power consumption, specifically by minimizing the power consumption from non-renewable energy sources. The proposal considers renewable energy sources, but non-renewable sources can also be used when extra energy is required.

Efficient energy management involves minimizing consumption, achieving a specific reduction in consumption (e.g., 20% energy saving), or optimizing the available power consumption (utilization). In this work, we chose the last option, anticipating a future in which the penetration of green energy allows meeting all energy demand and requires adaptive mechanisms to leverages its generation. Moreover, we validated this approach in [19]. The considerations of the architectural framework and the enabling technologies needed for energy management, as well as the interaction between generation and consumption sides presented in [19], are taken as a baseline for the adaptive energy management solution presented in this paper. In this regard, this paper represents an evolution of our previous work in [19] towards an efficient and environmentally friendly energy-management for mobile networks.

The proposal includes: (i) an architecture for adaptive energy management that considers provisioning from renewable and non-renewable sources, which is developed based on NFV and SDN technologies, and leverages the IoT massive connectivity provided by modern mobile networks; and (ii) various management strategies at service level such as an intra-slice prioritization scheme, service rejection, time shifting in service execution, and degradation in service quality (i.e., decrease in energy demand), all to optimize the available power consumption. In addition, this paper provides modeling of the stakeholders involved in energy management and consumption (i.e., the MNO and consumers), and the Integer Linear Programming (ILP) formulation corresponding to the problem of the adaptive energy management, which has been proven to be $\mathcal{NP}$-hard. To find the exact optimal solution, a brute-force search algorithmic strategy (OPTTSNS) is proposed. Simulation results demonstrate that the proposed energy management solution allows for efficient energy consumption in the different slices and corresponding services in accordance with the available energy resources and customer requirements, thereby realizing feasible and efficient energy management for 5G networks. Due to the non-polynomial complexity of OPTTSNS, this paper includes a discussion on the possible heuristic strategies for feasible future implementations of the energy management model and the proposed management strategies. The major contributions of this paper are summarized as follows:

- An architecture proposal that, based on NFV, SDN, and IoT technologies, is able to adaptively manage the available energy, whether 100% renewable or not, in the context of network slicing
- Several management strategies for adaptive energy consumption at the service level, including intra-slice service prioritization, service rejection, time shifting for service execution, and service quality degradation
- The mathematical model of the stakeholders involved in energy management and consumption
- The ILP formulation corresponding to the adaptive energy management model
- The performance metrics needed to confirm the improvements in energy consumption achieved with the proposed approach
- An exact algorithmic strategy denoted as OPTTSNS and its evaluation through extensive simulations to verify the effectiveness of the proposed solution as well as the improvements in terms of energy consumption and service processing
- Discussion of several heuristics solutions to tackle the complexity of the optimal solution

Table 2 presents a list of the most relevant acronyms used throughout the paper. The remainder of this article is arranged as follows. Section 2 discusses the related work. Then, Section 3 formally introduces the energy management proposal. The ILP formulation of the proposed energy management model is presented in Section 4. Section 5 describes and evaluates the algorithmic strategy OPTTSNS for optimally solving the ILP problem. The heuristics strategies are discussed in Section 6. Finally, conclusions and future work are presented in Section 7.

Table 2. List of abbreviations and corresponding definitions.

Acronym	Definition	Acronym	Definition
3GPP	3rd Generation Partnership Project	MNO	Mobile Network Operator
5G	5th Generation Mobile Network	NB-IoT	Narrow Band Internet of Things
eMBB	Enhanced Mobile Broadband	NFV	Network Functions Virtualization
ETSI	European Telecom. Standards Institute	NSI	Network Slice Instance
ICT	Infor. and Com. Technologies	OPEX	Operational Expenditures
ILP	Integer Linear Programming	SST	Slice/Service Type
IoT	Internet of Things	SDN	Software Defined Network
ITU	International Telecommunication Union	URLLC	Ultra Reliable Low Latency Com.
MANO	Management and Orchestration	V2X	Vehicle to X (e.g., Vehicle, Infrastructure)
mIoT	Massive IoT	VNF	Virtual Network Function

2. Related Work

At the time of writing this paper, in the literature, there is no proposal for adaptive energy management within the scope of 5G network slicing. Therefore, this section presents related work that addresses the two main areas of the proposal, i.e., the energy efficiency and energy management in 5G networks, and the use of network slicing architecture for resource management, including energy.

2.1. Energy Efficiency and Energy Management in 5G Networks

Improving energy efficiency has become a key pillar in the design of 5G networks due to economic and operational considerations, as well as environmental concerns [20]. In this regard, different solutions have been proposed to optimize or reduce energy consumption, which can be grouped under following broad categories: (i) resource allocation; (ii) network planning and deployment; (iii) activation of resources on-demand depending on traffic dynamic; (iv) hardware design; (v) improvements in the system operation (e.g., techniques to reduce interference); (vi) active user cooperation; and (vii) use of green energy complemented with energy-harvesting mechanisms (which can also be used to collect energy from radio signals over the air) [20]. Of these approaches, the use of green energy has gained momentum in recent years, and it represents a feasible and sustainable alternative to power mobile networks partially or even totally [21]. In this respect, different models have been proposed to characterize the production of renewable energy and the operation in the mobile networks. Even the possible interactions with smart grids to deliver demand-response schemas have been analyzed. Additionally, the need for management strategies in mobile networks to enhance integration and use of green energy has been evidenced [21], an issue that is solved with our proposal.

Regarding energy management within the 5G ecosystem, the literature shows that the enabling technologies NFV and SDN can be used as a platform to deploy optimization models (mainly based on heuristic approaches) and management applications targeting cost-efficient resource and energy usage [22]. Based on energy consumption estimations or network parameters information (e.g., traffic load, radio coverage, equipment activation intervals, or active users), the NFV/SDN architectural framework can carry out actions such as optimized routing of traffic flows or allocation of physical (networking, computing, and storage) and/or virtual (e.g., virtual machines) resources with the aim of achieving energy savings and an overall reduction of consumption in the mobile network [23,24]. In addition, NFV technology facilitates in 5G networks that the Virtual Network Functions (VNFs) can be dynamically scale-in/out to meet the desired performance level, a dynamic behavior, or to be adjusted to system capacity. These features can potentially reduce energy consumption, operating cost, and latency. In this regard, some adaptive and dynamic VNF scaling algorithmic strategies have been proposed in the literature [25,26]. Although these procedures can reduce the energy footprint of 5G networks, they operate primarily on the network infrastructure and do not constitute an adaptive energy management system. Furthermore, these solutions do not consider the available energy supply for service processing or a multi-client approach, aspects which are considered in our proposal.

2.2. Use of Network Slicing Architecture for Resource Management

The network slicing architecture supported by NFV and SDN has demonstrated to be an effective solution for implementing resource allocation schemes and algorithms to meet the diverse and simultaneous demands of consumers and vertical markets [27]. For instance, network slicing can be used as a management solution to enhance the network resources sharing required for the dynamic operation of massive IoT infrastructures such as wearable devices [28]. The network slicing paradigm can be used to define entire network slices to cover the elastic demand for network resources through the day and according to different operating and customer requirements such as bandwidth or a desired reliability level for the customers [29]. The reconfiguration, scaling, and migration of virtual resources (e.g., virtual machines) needed for the dynamic operation of mobile networks corresponding to customer-specific workloads are considerations that can also be addressed efficiently (e.g., in terms of bandwidth and latency constraints) with network slicing technology [30]. In addition, the network slicing architectural framework is flexible enough to allow discrimination in network resources allocation among slices, customers, or services according to specific operational requirements; a feature can be exploited in different scenarios and for various purposes. In [31], for example, the authors proposed a two-level prioritization scheme (inter-slice and intra-slice) to implement a heuristic-based admission control mechanism able to dynamically allocate network resources to different slices customers needs and traffic loads. In our proposal, we also use an intra-slice scheme but focused on prioritizing the consumption of certain services if the energy supply is not enough to meet all demand.

The potential of network slicing for energy management has also been explored. In [32], Xiao et al. introduced a dynamic network slicing solution for large-scale energy-harvesting fog computing networks. In the proposed architecture, a regional orchestrator coordinates workload distribution among local fog nodes, providing slices of energy and computational resources to support various types of service requested by end users. The use of network slicing in this use case shows a maximization of the utilization of available resources, dynamic resource allocation according to service demands, and balance of workloads among fog nodes. This information provides insight into the possible improvements in energy efficiency that can be obtained with network slicing in 5G networks.

3. Energy Management Proposal for 5G Network Slicing

This section presents the energy management proposal. Section 3.1 describes the requirements for energy management in the context of 5G network slicing. Section 3.2 discusses different management strategies for adaptive energy consumption. Finally, Section 3.3 presents an overview of the proposed architecture and its operation.

3.1. Requirements for the Energy Management in 5G Network Slicing

To present a feasible proposal aligned with the needs of current and future mobile networks, we surveyed the main technical specifications and recommendations issued by the most representative standardization bodies in the mobile networks landscape: the 3GPP, the European Telecommunications Standards Institute (ETSI), and the Telecommunication standardization sector of the International Telecommunication Union (ITU-T). Table 3 shows the latest version of the technical specifications and reports reviewed related to the proposal. This information can be used as reference literature to motivate future work. Regarding the proposed energy management approach, Table 4 summarizes the requirements and possible solutions for adaptive consumption in 5G network slicing. The structure of the proposed architecture and the energy management model described in Section 3.3 allow satisfying Requirements R1, R2, R3, and R4. The management strategies presented in Section 3.2 meet the need for adaptive consumption of available energy described in Requirements R5 and R6. Instead, the performance metrics to assess the optimization in energy consumption described in Requirement R7 are presented in Section 5.1.

Table 3. Technical documentation related to the proposal.

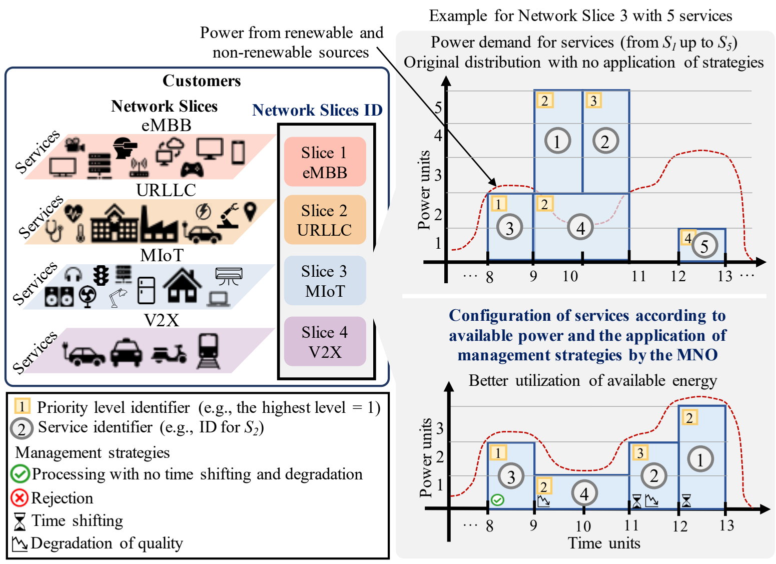
Area	Institution or Organization	Documentation	Description
Requirements and features of 5G	3GPP	Technical specification TS 23.501, release 16	System architecture for the 5G System [2]
		Technical specification TS 22.261, release 17	Service requirements for the 5G system [1]
Network Slicing	3GPP	Technical specification TS 28.530, release 16	Management and orchestration; Concepts, use cases, and requirements [3]
		Technical specification TS 28.531, release 16	Management and orchestration; Provisioning [4]
		Technical report TR 28.801, release 15	Study on management and orchestration of net. slicing for next generation network [6]
		Technical report TR 28.804, release 16	Study on tenancy concept in 5G networks and network slicing management [7]
	ETSI	Technical report GR NFV-EVE 012	Report on Network Slicing Support with ETSI NFV Architecture Framework [5]
Energy efficiency, management, and renewable energy sources	3GPP	Technical specification TS 28.310, release 16	Energy efficiency of 5G [8]
		Technical report TR 32.972, release 16	Study on system and functional aspects of energy efficiency in 5G networks [9]
	ITU-T	Recommendation L.1210	Sustainable power-feeding solutions for 5G networks [10]
		Recommendation L.1310	Study on methods and metrics to evaluate energy efficiency for future 5G systems [12]
		Recommendation L.1315	Standardization terms and trends in energy efficiency [14]
		Recommendation L.1331	Assessment of mobile network energy efficiency [15]
		Recommendation L.1360	Energy control for the software-defined networking architecture [16]
		Recommendation L.1361	Measurement method for energy efficiency of network functions virtualization [17]

Table 4. Requirements and proposed solutions for adaptive energy management in 5G Network Slicing.

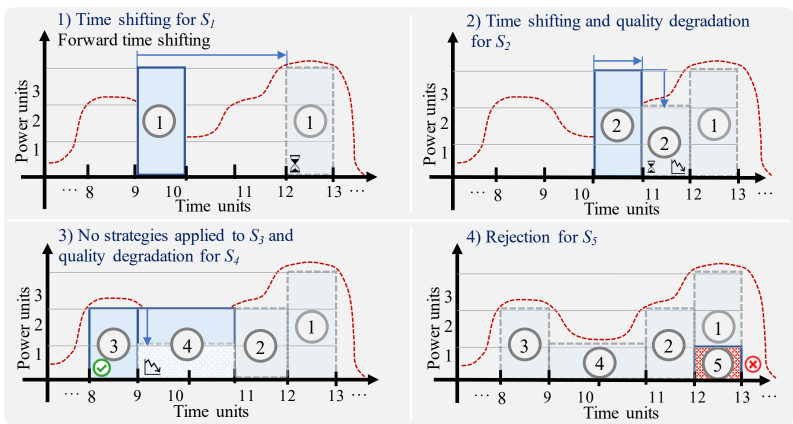
Requirements		Related Technical Documentation	Proposed Solution
ID	**Description**		
R1	Energy management for network slices and corresponding services throughout all components of the 5G system, in which the service processing is aware of energy supply with the aim of optimizing the consumption at all times.	3GPP TS 23.501 3GPP TS 22.261 3GPP TS 28.310 ITU-T L.1331	Adaptive energy management solution for 5G network slicing, in which the creation and configuration of networks slices is aware of the energy generation and consumption conditions.
R2	Definition of priority order for services within a network slice in the case the available energy at a certain time is insufficient to meet all demand. Based on this level of priority, the MNO must be able to differentiate the access to the energy resource and the application of management strategies for each service.	3GPP TS 22.261 3GPP TS 28.530 3GPP TS 28.531 3GPP TR 28.801 3GPP TR 28.804 ETSI NFV-EVE 012	Prioritization scheme at service level (intra-slice priority scheme) for the energy allocation process. In the proposed architecture, the MNO decides the number of priority levels to implement and the assigned level to each service. The assignation of priority level can also be established through agreements with customers.
R3	Use of software-based platforms and virtualization to facilitate the creation and managing of network slices, the configuration of network functions to implement energy management strategies, and the incorporation of features for serving new SST.	3GPP TS 23.501 ITU-T L.1360 ITU-T L.1361	Use of NFV and SDN technologies, to bring agility, flexibility, and reconfigurability to the proposal.
R4	Use of energy from renewable energy sources, as a sustainable and environmentally friendly alternative for powering mobile networks, and control of its contribution to the total energy supply.	3GPP TS 28.310 3GPP TR 32.972 ITU-T L 1210	Promotion and prioritization of the use of green energy, and implementation adaptive energy management strategies (see Section 3.2) to leverage its dynamic and intermittent generation.
R5	Energy management constrained to availability. The proposed energy management model must be able to automatically adapt the consumption (i.e., the configuration of network slices) to the energy capacity, producing no or minimal impact on the performance of network slices and corresponding services.	3GPP TS 23.501 3GPP TS 22.261 TS 3GPP TS 28.310	Implementation of strategies for adaptive energy consumption on network slices or services (see Section 3.2). In the proposed architecture, the customer is aware of the configuration of network slices and services (e.g., modification of execution time, the power demanded, or activation/deactivation state) performed by the MNO to optimize the energy consumption.
R6	Implementation of mechanisms to achieve energy efficiency through optimization of energy use and reduction in consumption (i.e., energy saving). These mechanisms must be executed by the MNO and must produce no or minimal performance degradation for customers. Services belonging to network slices must be able to work in energy-saving states (e.g., low energy consumption) or postpone their execution (i.e., enter into sleep or idle mode) according to the availability.	3GPP TS 22.261 3GPP TS 28.310 3GPP TR 32.972 ITU-T L.1310 ITU-T L.1315 ITU-T L.1331	To offer an adaptive energy management solution that optimizes the use of energy resources and reduce consumption, the following management strategies for services are considered in the proposed management model: (i) degradation of service quality, which represents a decrease of consumption (i.e., low power consumption); (ii) rejection or non-execution of service(s) (i.e., deactivation of service); and (iii) application of time shifting (forward or backward) in the service execution time.
R7	Definition of metrics or indicators to assess the energy efficiency achieved with the proposed energy management model.	3GPP TR 32.972 ITU-T L.1310 ITU-T L.1315	Definition of three performance metrics: (i) percentage of services processed; (ii) percentage of energy used by services processed; and (iii) amount of missing energy to process all services.

3.2. Energy Management Strategies for Adaptive Consumption

To carry out adaptive energy management in 5G network slicing, five strategies have been proposed, as described below. These strategies are executed by the MNO (see Figure 2b), are implemented through algorithmic solutions, as shown in Section 5.2, and they seek offer energy efficiency to the 5G mobile networks through optimization of power consumption (i.e., less and better energy use), while promoting the reduction of OPEX and related environmental impacts. In the energy management process, the customers are aware of the configuration of network slices and/or services performed by the MNO to optimize the consumption, and they are tolerant of the possible modifications/actions on network slices or services. Figure 1 shows an example of the implementation of the proposed strategies.



(**a**)



(**b**)

Figure 1. Example of application of the management strategies for adaptive energy management in 5G network slicing. (**a**) Application of management strategies for the network slice 3. In this example, the initial distribution of services (initial time, duration, and power demanded) causes inefficient use of energy and allows the execution of only two services (S_3 and S_5). The use of management strategies instead allows optimization in the consumption and processing of four services (S_1, S_2, S_3, and S_4). (**b**) Disaggregated representation of the management strategies applied to services belonging to network slice 3.

3.2.1. Prioritization of Services in Network Slices

In the energy management proposal, the MNO can establish priority levels to differentiate the services, as shown in Figure 1a. With this information, the MNO can prioritize the resource allocation (e.g., energy) for the configuration of a service or a set of services. The prioritization schema can be established automatically by the MNO or can be agreed with customers through contractual terms, and it may depend on several factors such as: (i) environment of applicability of services (e.g., allocation of a higher level for emergency services, services associated with search and rescue operations in disaster, or services for public safety); (ii) characteristics of the services (e.g., the number of end-users, location, average consumption, etc.); or (iii) specific requirements from customers.

3.2.2. Use of Time Shifting Capability for Service Execution

To efficiently use the energy resource and adapt consumption to generation, different strategies can be applied optionally to services belonging to a network slice. The application of the strategies on services can seek several objectives such as: (i) maximization in energy utilization, as shown in Figure 1a; (ii) maximization in service processing (acceptance rate); (iii) multi-metric objectives, e.g., maximize consumption and also service processing; or (iv) it may be linked to a scheme that prioritizes the processing of one type of service over others. These objectives, as well as priority in network slices (Section 3.2.1), can be established automatically by the MNO or can be defined in contractual agreements with consumers.

In the context of energy efficiency, a strategy that adapts consumption to existing supply is the temporal displacement in the service execution time [33]. In the proposal, this strategy is defined as *time shifting* and is useful to encourage the anticipated consumption (i.e., performing a *backward time shifting* for service execution) or a deferral in the use of energy (i.e., performing a *forward time shifting* for service execution, as shown in Figure 1b for service S_1), within a finite time horizon and according to the energy availability. In the proposed management model, the *time shifting* strategy, similar to the others described in this section, can be implemented because the service processing (and corresponding energy consumption) is not carried out immediately upon customer requests, but rather there exists a calculation process executed by the MNO (specifically at network slice management and orchestration domain), in which the configuration of network slices and services is performed by applying management strategies and considering energy generation and consumption conditions. This procedure enables the MNO to find the efficient distribution of services (service scheduling) that optimizes energy consumption, as shown in the example in Figure 1a. A detailed explanation of the operation of the architecture and the proposed energy management model is discussed in Section 3.3.

3.2.3. Degradation in Service Quality

If the available power level is not sufficient to satisfy the power demanded by a certain service (or services), the MNO may choose to apply a *quality degradation* to that service, i.e., allocate a lower amount of energy than requested, as observed for the service S_4 in Figure 1b, in which the assigned power level is half of the demanded. This strategy allows reducing consumption to a level tolerable by the service, which allows maintaining its functionality. A descriptive example of the application of this strategy is the decrease in the brightness level of a screen of a mobile terminal or computer, which allows a lower consumption at the cost of a minimum decrease in performance. Another possible action that the MNO can execute on the services consists in the implementation of a combined strategy, in which *time shifting* and *quality degradation* are applied to the service simultaneously, as shown in the example in Figure 1b for service S_2. On the other hand, considering that generation and consumption fluctuate constantly, during periods of energy surplus (due to high generation or low demand), one strategy that could be adopted is the increase in quality (i.e., deliver more energy of the demanded). Thus, the implementation of this strategy on services that tolerate the increase in energy supply would prevent the energy produced from being wasted if it is not consumed.

3.2.4. Normal Processing of Services

Although the normal processing of a service (i.e., execution without modifications or actions on it) is not a management strategy as such, it is an alternative configuration mode. If there is the availability of the supply, the analyzed service can be processed in its natural execution time and with its power level demanded, as shown in Figure 1b for service S_3.

3.2.5. Service Rejection

If the energy supply is not sufficient to guarantee the execution of a service, either due to an energy shortage or because the energy has already been allocated to another service, and also the application of the strategies described above (i.e., *time shifting* or *quality degradation*) does not allow its processing, the service in the admission stage is not processed and is categorized as *rejected*, as shown in Figure 1b for service S_5. The criteria for service rejection may be established by the MNO and in agreement with the customer, and may depend on a number of factors such as those described in Section 3.2.2.

In the example in Figure 1, each energy management strategy acts on a specific service. However, in a real implementation, the MNO with information of the services (required execution time, duration, and power demanded) and considering the use of the different management strategies described above, must be able to apply the best strategy for each service. This process is performed with the aim that the total or aggregate power of all services optimizes the use of the available supply. To this end, the MNO executes service scheduling algorithms such as the one described in Section 5.2, which allows achieving the energy efficiency required by 5G networks in a network slicing context.

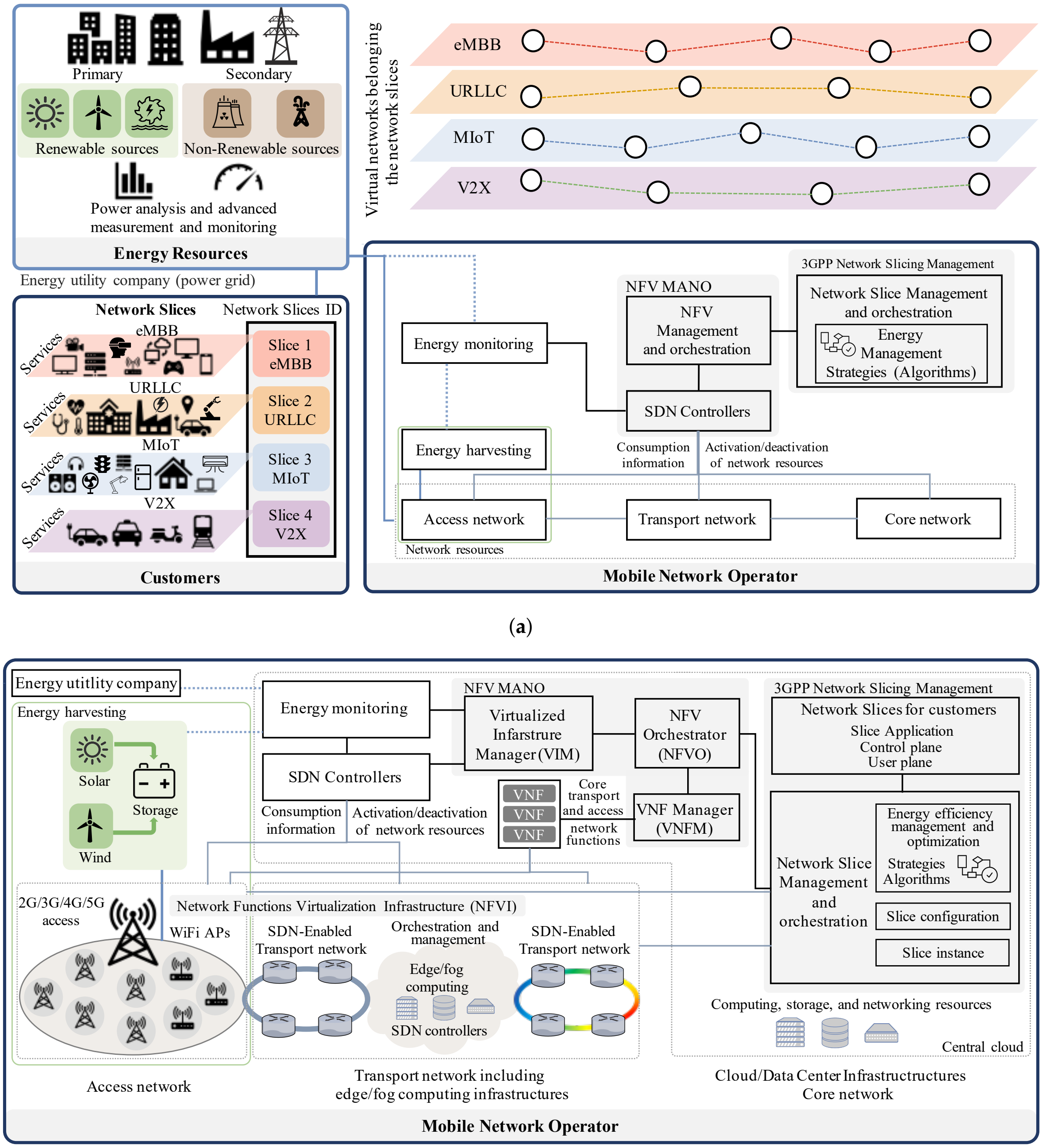
The adaptive behavior of the proposed energy management solution through the management strategies (i.e., the degradation in service quality and time shifting capability) enable to adapt the consumption to generation constantly. This feature allows dealing with the intermittent and dynamic behavior of renewable energy sources and leverage at the maximum their energy production capacity. In the event that green energy is not sufficient to meet all demand, the proposed management solution considers the possible rejection of services. Furthermore, although our approach prioritizes the use of renewable energy, the partial or total energy provisioning from non-renewable sources is an alternative, in which case the management strategies described above can also be employed.

3.3. Architecture for Adaptive Energy Management

3.3.1. Architecture Description and Operation

This section presents an architecture for adaptive energy management in 5G network slicing based on the established management and orchestration framework by the 3GPP and ETSI [5,6,9]. This architecture is composed of two stakeholders, the customers and the MNO, as shown in Figure 2. The architectural framework is focused on the efficient energy resource management from renewable and non-renewable energy sources for the creation, configuration, and deployment of network slices and the corresponding services on the mobile network infrastructure.

The architecture leverages the concepts of NFV and SDN as well as the IoT connectivity of customers to carry out the energy-aware realization of 5G network slices. From the operational perspective, the network slicing architecture can be considered to be comprised of two main blocks: (i) the first block is integrated with the NFV Management and Orchestration (MANO) framework and by 3GPP Network Slice Management framework, as shown in Figure 2a), dedicated to the network slices management and configuration considering energy management requirements (optimization of power consumption); and (ii) the second block is composed by the NFV and SDN frameworks as well as by the underlying network resources dedicated to the network slice implementation.



(**a**)

(**b**)

Figure 2. Overview of the architecture for adaptive energy management in 5G Network Slicing: (**a**) schematic of the proposed architecture; and (**b**) schematic of the network operator and management entities.

In the first block (MANO), with the information on customers (e.g., number of network slices and services, the power consumption of services, SST values, etc.) and the conditions on power generation (available from non-renewable and renewable energy sources), the MNO proceeds to create the network slice(s), starting from a base template, similar to the example shown in [34], or selecting a network slice profile from a network service catalog [7]. This template can be then customized to meet the specific requirement of the end users. To carry out the network slice(s) creation (by choosing any of the above methods) on the MANO framework, the MNO first analyzes the amount power demanded (consumed) for service processing (execution), considering the consumption in all segments of the mobile network (i.e., the power consumed in the core, transport, and access networks). This consumption estimation procedure can be performed using historical data or predictive models; however, these issues are beyond the scope of this paper. The consumption estimation process is carried out for all services and for all network slices. It has two objectives: (i) estimate/verify if the available power (managed by the MNO) is sufficient to allow the processing of all services in all network slices; and (ii) establish the actions to be performed by the MNO to optimize power consumption (optimize the service processing).

Traditionally, the increase in energy demand has been faced with the contracting or production of additional energy. However, this alternative involves an increase in OPEX and possible environmental impacts, and it is not a sustainable solution. In this regard, modern management systems demand adaptive consumption schemes restricted to availability and that prioritize the use of renewable energy, as described in Requirements R1, R4, and R5 in Section 3.1. Therefore, in the proposed architecture, the network slice process is aware of an available energy resource (i.e., services/slices and power supply considered jointly). The MNO if needed can apply various management strategies (detailed in Section 3.2) on services, which are deployed as algorithmic solutions on the Network Slice MANO (see Figure 2b) to adapt consumption to availability, optimize power consumption (avoiding peaks loads or energy shortage), and reduce dependence on non-renewable energy as much as possible. As a result of the analysis of service parameters (customer information), the available supply, and the possible management strategies at the service level (network slices), the MNO obtains the optimal service scheduling (number of processed services, service execution time, and power consumption levels) in each network slice that leads the optimization of power consumption (minimization of power from renewable energy consumptions) and the energy-efficient network slice creation and configuration. A summary of the energy-aware creation and configuration of network slices in the proposed architecture is shown in Figure 3.

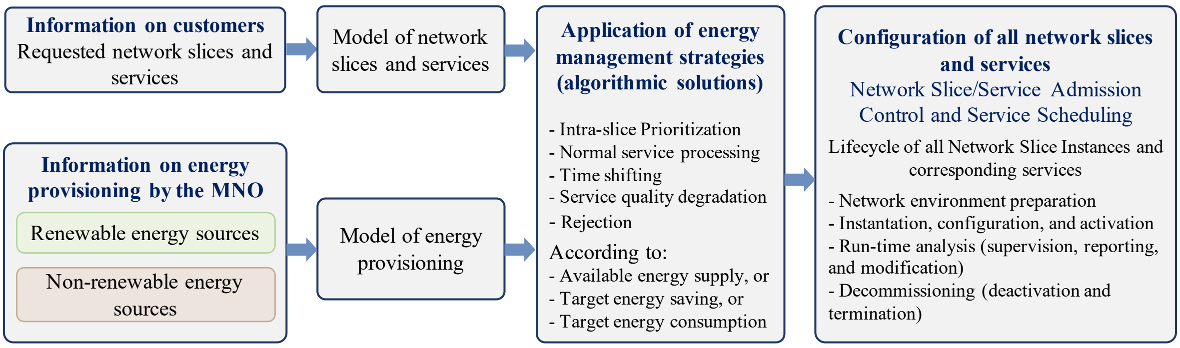


Figure 3. Description of the energy-aware network slice creation in the adaptive energy management architecture. The network slices and corresponding services are configured to achieve energy efficiency, considering a finite energy provisioning and the optimization of power consumption, specifically through the minimization of the consumption of non-renewable energy sources.

Once the general structure of the network slicing (network slice profile) has been selected, the MNO can deploy in the network slice MANO entity (at core network) the corresponding Network Slice Instance (NSI), which refers to a set of network function instances (physical or VNFs, e.g., belonging access, transport, and core networks), the connectivity between them, and the required resources (e.g., compute, storage, and networking resources) that form a deployed network slice [7]. Typically, a network slice instance is designed (preparation phase), then it is instantiated (instantiation, configuration, and activation phase), later it is operated (run time phase), and finally it may be decommissioned (decommissioning phase) when the slice is no longer needed [1]. The complete NSI lifecycle is managed by the MNO, specifically by the network slice MANO. In the process of configuring and deploying network slices, the MNO sends the NSI information to the second block of the architecture, specifically to the NFV Orchestrator (NFVO), which is in charge of coordinating with the VNF Manager (VNFM) and with the Virtualized Infrastructure Manager (VIM) the creation of VNFs (that provide specific network capabilities to support and realize the particular service(s)) and virtual networks (access, transport, and core) need for the deployment of network slices. Then, the requests from the VIM entity are sent to the SDN controllers (access, transport, and core controllers), which coordinate with the Network Function Virtualization Infrastructure (NFVI) the creation of network slices on the underlying network infrastructure (physical network resources). At this point, all created slices compose a single (end-to-end) network slice for specific customers. All of the network slices are managed and orchestrated first by an NFVO and in an upper level by the NFV and 3GPP MANO frameworks.

3.3.2. Customers (Network Slices) Modeling

In the proposed architecture, the customers correspond to the network slices owners. They have connectivity capabilities and demand from the MNO all network resources (virtual, physical, and energy) to carry out the services, applications, or verticals. In the context of the adaptive energy management model, a service is characterized by its power consumption (i.e., by the amount of power that is used in the core, transport, and access network when the service is in execution), and it is tolerant to the possible actions (management strategies) that the MNO can execute on it to carry out the adaptive energy management. Considering the parameters related to power consumption and the management strategies described in Section 3.2, a service k, with $k \in \{1, \ldots, N\}$ of priority level j, with $j \in \{1, \ldots, M\}$ belonging to the network slice i, with $i \in \{1, \ldots, L\}$, denoted as $S^i_{k,j}$ is fully characterized by the parameters of Table 5. Figure 4 depicts an example of a service and its corresponding parameters.

Table 5. Parameters of network slices and services.

Parameter	Description	Unit/Comment
L	Number of network slices	Integer number
i	Network slice identifier	$i \in \{1, \ldots, L\}$
M	Number of priority levels of services	Integer number
j	Priority level identifier	$j \in \{1, \ldots, M\}$
N	Total number of services in the system	Integer number
k	Service identifier	$k \in \{1, \ldots, N\}$
Q	Number of quality degradation levels	Integer number
$t^i_{k,j}$	Starting time of service $S^i_{k,j}$	Time units
$d^i_{k,j}$	Duration of service $S^i_{k,j}$	Time units
$p^i_{k,j}$	Power demanded of service $S^i_{k,j}$	Power units
$q^i_{k,j}$	Quality level of service $S^i_{k,j}$	Discrete values (e.g., $[q^i_{k,j\,min} = 0.1, \ldots, q^i_{k,j\,max} = 1]$)
$u^i_{k,j}$	Time shifting value of service $S^i_{k,j}$	Time units (*backward*:$t^i_{k,j} - u^i_{k,j}$, or *forward*: $t^i_{k,j} + u^i_{k,j}$)
v^i_k	Priority level of service k belonging to network slice i	Integer number

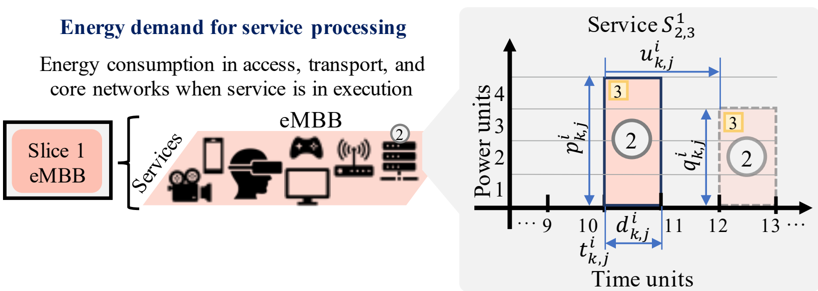


Figure 4. Graphical representation of the characterization of a service that is part of a network slice. Description: Service 2, with a priority level 3, and belonging to the network slice 1. Parameters: $t^1_{2,3} = 10$, $d^1_{2,3} = 1$, $p^1_{2,3} = 4$, $u^1_{2,3} = +2$ (*forward*), $v^1_2 = 3$, $q^1_{2,3} = 0.75$ ($p^1_{2,3} \times q^1_{2,3} = 3$).

In terms of power consumption, the total or aggregated power demanded by all network slices and corresponding services (P_D) can be expressed as:

$$\forall i \in L, \forall j \in M, \forall k \in N: \; P_D = \sum_{i=1}^{L} \sum_{j=1}^{M} \sum_{k=1}^{N} p^i_{k,j} \times q^i_{k,j} \tag{1}$$

3.3.3. Mobile Network Operator (MNO) Modeling

The MNO in the network slicing architecture is the entity that provides network resources (physical and virtual), is responsible for the creation, modification, and deletion of network slices, and is in charge of managing the energy resource for the operation of the entire mobile network.

In this context, the total available power (P_A) in the mobile network ecosystem comes from the contribution of energy from renewable and non-renewable energy. The MNO is then able to control the contribution of one source over another, and particularly can promote the primary or majority use of green energy. The mathematical model of P_A in the proposed network management model is given by:

$$P_A = P_R + P_{NR} \tag{2}$$

where P_R represents the power obtained from renewable energy sources, while P_{NR} stands for the power from non-renewable energy sources. These parameters are given by:

$$P_R = P_A \times w_R \tag{3}$$

$$P_{NR} = P_A \times (1 - w_R) \tag{4}$$

where the factor $w_R \in [0, 1]$ denotes the weight related to the contribution of renewable energy in the total generated power P_A, which can be controlled by the MNO according to the green energy availability and the application scenario.

4. Energy Management Model Mathematical Formulation

This section presents the mathematical formulation of the proposed energy management solution. Section 4.1 describes the assumptions considered in the proposed model. Section 4.2 presents the ILP formulation of the proposal, while Section 4.2 analyzes its complexity.

4.1. Assumptions Related to the Energy Management Model

The proposed adaptive energy management model is summarized in Figure 5. To provide a reasonable implementation of this proposal, the following assumptions (simplifications) have been considered:

1. Use of a discrete-time model, in which the time horizon ($\{0, \ldots, W\}$) is divided into slots of equal duration. This time model provides flexibility to energy management solution because the size of each time slot can represent different time units (e.g., a time slot equal to 10 min, or a time slot equal to 1 h) according to the applicability scenario.
2. Use of a finite and discrete-time window for performing the time shifting (forward and backward) for the service execution. In this regard, in a preliminary study [19], we proved that the use small time shifting intervals (e.g., intervals up to two or three time slots) is enough to achieve considerable improvements in energy use (e.g., 100% energy utilization and improved service processing). In addition, a small time shifting interval is preferred because increasing this parameter produces a non-polynomial increase in the complexity of the optimal energy management problem, as demonstrated in [19].
3. Use of discrete values for service quality degradation. To provide a feasible energy management model and maintain the linear condition of the problem, in the proposal, the values of degradation,

also called levels of degradation that can be applied to a service, are restricted to a finite set of possibilities. Analogously to the time shifting value, this sequence of values should be small (e.g., up to three or four degradation levels) because an increase in levels corresponds to a non-linear increase in the complexity associated with optimal energy management.

4. The proposed energy management model assumes the processing of entire (complete) services. If P_A is insufficient to meet the total power demanded by a service, this service in analysis is considered as not processed or rejected. In this regard, the partial processing of a service and related consumption can be discussed in future work.
5. In 5G network slicing, a customer (user equipment) may be served by at most eight network slices at a time [1]. However, in our proposal for simplicity, a customer can only belong to one network slice. Moreover, the customers in each network slice are different from each other (i.e., different network slices specified to different customers).
6. If needed, the MNO can deploy multiple network slices of the same slice/service type (e.g., eMBB with the same features but for different groups of customers). In this case, the MNO is able to differentiate the slices according to the network slice identifier, as shown in the example in Figure 1a.

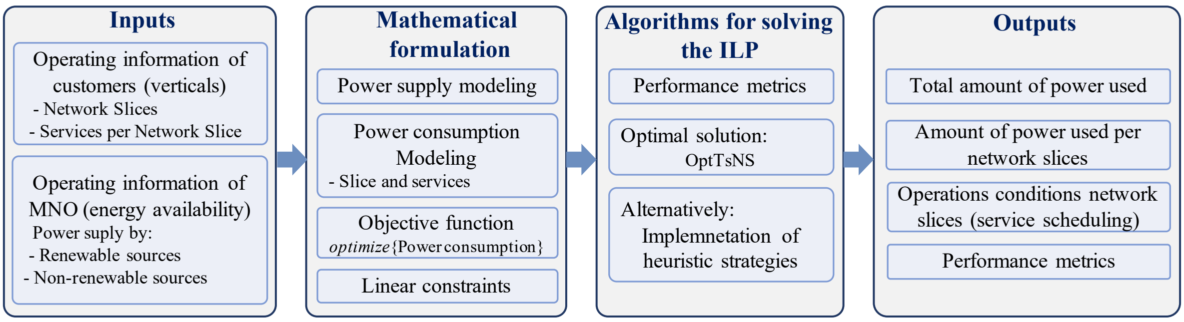


Figure 5. Schematic of the adaptive energy management model for 5G Network Slicing.

4.2. ILP Problem Formulation: OptTsNS

4.2.1. Objective Function

In our proposal, the creation and configuration of network slices and associated services is energy-aware. Thereby, the proposed management model seeks to improve energy efficiency through the optimal use of the available supply and specifically through the minimization of power consumption. Technically, this objective is expressed as indicated in Equation (5). Nevertheless, considering that an important requirement in an energy management system for mobile networks is the promotion and use of green energy (as mentioned in Requirement R4 in Section 3.1 and as shown in the energy provision model in Equation (2)), the objective of the proposed energy model should be focused on minimizing the consumption of energy from non-renewable sources. To this end, we have established a cost function associated with consumption in the 5G ecosystem from renewable and non-renewable sources as shown in Equation (6), where w_1 and w_2 can be in the range [0,1] and represent the weights associated with the individual cost functions that are proportional to renewable (c_{P_R}) and non-renewable ($c_{P_{NR}}$) energy consumption, respectively.

To promote the primary utilization of renewable energy, the cost associated with the consumption of this kind of energy in Equation (6) can be set to a minimal value ($w_1 \ll w_2$) and even to zero. In this model, we chose the second option (i.e., $w_1 = 0$) with the aim of moving toward a green mobile network ecosystem. Therefore, the objective function of minimizing power consumption in Equation (5) considering the cost function in Equation (6) translates into the minimization of the cost associated with non-renewable energy consumption as indicated in Equation (7), which in turn is equivalent to the objective of minimizing the P_{NR} in the total P_A as shown in Equation (8). This objective function must respect the available energy resources, consider the parameters of the services, the management strategies described in Section 3.2, and the constraints presented in Section 4.2.2.

$$minimize\ \{P_D\} \tag{5}$$

$$Cost_{PD} = w_1 \times Cost_{P_R} + w_2 \times Cost_{P_{NR}} \tag{6}$$

$$minimize\ \{Cost_{P_{NR}}\} \tag{7}$$

$$minimize\ \{P_{NR}\} \tag{8}$$

4.2.2. Constraints

The following constraints are linked to the proposed adaptive energy management model.

$$C1 : P_A[t] \geq 0 \tag{9}$$

$$C2 : (P_A[t] - P_D[t]) \geq 0 \tag{10}$$

$$C3 : \sum_{i=1}^{L}\sum_{j=1}^{M}\sum_{k=1}^{N} \left(p_i^{k,j} \times q_i^{k,j}\right) \times x_{ijk}[t] \leq P_A[t],\ x_{ijk} \in \{0,1\} \tag{11}$$

$$C4 : t^i_{k,j} \geq 0 \tag{12}$$

$$C5 : \{t^i_{k,j} - u_i^{j,k}\} \geq 0 \tag{13}$$

$$C6 : W \geq \max\{t^i_{k,j} + d^i_{k,j} + u_i^{k,j}\} \tag{14}$$

- *Domain constraints:* The energy supply by the MNO for service processing is assured by $C1$. Instead, $C2$ guarantees a non-negative difference between the power demanded and power provisioning. In Constraints $C1$, $C2$, and $C3$, the power variables are specified at time slot t, because the energy provisioning and consumption may vary at each time slot. Thus, the objective of the proposed model is the minimization of power consumption (from non-renewable sources) during all time slots within a finite time horizon W.
- *Capacity Constraint:* In the mobile communication system, the maximum energy capacity is limited by $C3$, in which the decision variable x_{ijk} stands for the allocation of energy resources for the processing of the service $S^i_{k,j}$, as shown in Equation (15).

$$x_{ijk}[t] = \begin{cases} 1 & \text{if the service } k \text{ belonging to the network slice } j \text{ with priority level } j\ (S^i_{k,j}) \text{ is processed at time slot } t, \\ 0 & \text{otherwise.} \end{cases} \tag{15}$$

The correspondence between the service, its priority level, and the network slice to which it belongs is validated by Equation (16).

$$p^i_{k,j} = \begin{cases} \text{Power demanded by service } k \text{ with priority } j \text{ and within the network slice } i & \text{if service } k \text{ with priority level } j \text{ belonging to a network slice } i \text{ exists,} \\ 0 & \text{otherwise.} \end{cases} \tag{16}$$

- *Time constraints:* $C4$ and $C5$ ensure a non-negative starting time for the entire system ($t = 0$). $C6$ guarantees a finite time horizon for the analysis of services. The linear condition of the objective function, the constraints, and the decision variable deliver the linear nature to the problem.

4.2.3. Adaptive Management of Network Slices and Services

Taking into account that the energy provisioning (mainly from renewable sources) in the mobile network is finite, the consumption demanded for service execution must be adapted to availability as defined in Requirement R5 in Section 3.1. To carry out this adaptive management, the MNO with the information on the available energy resource and customer requirements (i.e., characteristics of network slices and services) must execute the corresponding actions (management strategies) on each service (for all N services) to achieve energy-efficient consumption aimed at minimizing power consumption from non-renewable energy sources as established in Equation (8). Depending on the amount of energy available and demanded (e.g., $P_D > P_A$) and the features of customers, the MNO has the possibility of executing different management strategies on the services such as intra-slice priority scheme, service rejection, degradation in service quality, and use of time shifting in service execution, as indicated in Section 3.2. The execution of these strategies allows the MNO to establish an access control to the energy resources associated with the creation of the network slices and configuration of corresponding services.

To find the optimal allocation of energy resources for service execution, the MNO must analyze the action of the different strategies on the services, considering the particularities of each service and/or network slice. This procedure is carried out through algorithms implemented in the core network, as shown in Figure 2b, and can be computationally very demanding, as described in detail in Section 5.2. At the end of this analysis, the MNO obtains the optimal scheduling for the set of N services (i.e., the number of services to be executed, execution times, and respective consumptions) that allows adaptive energy consumption and the minimization of energy from non-renewable sources. Through optimal scheduling of the set of N services (set defined in the proposal as *combination of services*, *comb*) the MNO tries to process as many services as possible (in the worst case the services with lower priority can be rejected if $P_D > P_A$) and with the minimum impact on the requirements from customers (respecting as much as possible the original execution time and power level demanded by services). In our proposed model, the adaptive energy consumption is represented by a cost function, as shown Equation (17). In this equation, α, β, γ, and δ can be in the range [0,1] and correspond to the weights of the individual cost functions related to the management strategies, which are listed as follows:

$$\forall i \in L, \forall j \in M, \forall k \in N : Cost^{i,j,k}_{comb} = \alpha \times Cost_{AR_{comb}} + \beta \times Cost_{pri_{comb}} + \gamma \times Cost_{u_{comb}} + \delta \times Cost_{q_{comb}} \quad (17)$$

- $Cost_{AR_{comb}}$: Cost function related to the processing of services and defined by Equation (18).
- $Cost_{pri_{comb}}$: Cost function related to the priority level of services and defined by Equation (19). cost Equation (19).
- $Cost_{u_{comb}}$: Cost function related to the time shifting application in service execution and defined by Equation (20)
- $Cost_{q_{comb}}$: Cost function related to the quality degradation of services and defined by Equation (21).

$$Cost_{AR_{comb}} = \begin{cases} 0 & \text{if all services are processed,} \\ \text{Total rejected services} & \text{otherwise.} \end{cases} \quad (18)$$

$$Cost_{pri_{comb}} = \begin{cases} 0 & \text{if all services have the maximum priority level } (j = 1), \\ \sum_{i=1}^{L} \sum_{k=1}^{N} v_k^i & \text{otherwise.} \end{cases} \quad (19)$$

$$Cost_{u_{comb}} = \begin{cases} 0 & \text{if all services are processed without time shifting } (j = 1), \\ \sum_{i=1}^{L} \sum_{j=2}^{M} \sum_{k=1}^{N} u_{k,j}^i & \text{otherwise.} \end{cases} \quad (20)$$

$$Cost_{q_{comb}} = \begin{cases} 0 & \text{if all services are processed without quality degradation} \\ & (j = 1), \\ \sum_{i=1}^{L} \sum_{j=2}^{M} \sum_{k=1}^{N} q_{k,j}^{i} & \text{otherwise.} \end{cases} \quad (21)$$

In Equation (17), the weights of individual cost functions can be set based on specific requirements from the MNO and/or from the customer. However, a possible configuration can be $\alpha > \beta > \gamma > \delta$, because this relationship promotes the processing of a higher number of services and the minimum impact on services due to the application of time shifting in service execution or degradation in service quality. In addition, the optimal scheduling of N services (i.e., the optimal combination of services) that leads to optimal energy consumption is given by the minimum value of cost function (minimum value in Equation (17)). Thus, the objective of the proposed energy management solution is to minimize the total cost function, as shown in Equation (22). For the implementation of the adaptive energy management model represented by its cost function in Equation (22) there are a number of different possible algorithmic solutions (optimal and sub-optimal). In this paper, we present an exact or optimal algorithmic strategy, which is described in detail in Section 5.

$$\forall i \in L, \forall j \in M, \forall k \in N : minimize\{Cost_{comb}^{j,j,k}\} \quad (22)$$

4.3. Hardness of the Problem

The energy-aware resource allocation for service processing in the context of 5G network slicing, considering the finite energy supply, an intra-slice priority scheme, and different management strategies with the aim of minimizing energy consumption through optimal energy utilization is equivalent to the objective of multi-dimensional multi-choice knapsack problem of choosing the most valuable items of a set of classes (one item per class) without overloading the knapsack [35]. The literature has proven that the complexity linked to this kind of problem is $\mathcal{NP}$-hard. Establishing an analogy with our proposal, the multidimensional behavior is given by the power and time parameters of services, and the multiple-choice feature corresponds to the selection of a specific time shifting value and/or quality degradation level from a possible set of options. Thus, we can conclude that the optimal adaptive energy management in 5G network slicing falls into the $\mathcal{NP}$-hard classification.

5. Evaluation

To validate the operation of the proposed adaptive energy management model, in this section, we present an optimal service scheduling algorithmic strategy denoted as OPTTSNS. The objective of OPTTSNS is to minimize power consumption from non-renewable sources considering finite energy provisioning and the management strategies described in Section 3.2. Concerning the optimization of power consumption, the task of OPTTSNS is to find the best actions (strategies) for each service in such a way that the processed services (i.e., the combination of services that demands P_D) enable the efficient use of the available energy. The proposed algorithmic strategy, described in Section 5.2, bases its operation on an exhaustive search method. In this brute-force method, all possible combinations of N services, executed simultaneously, are explored considering all possible values of degradation and time shifting in service execution. To choose the best combination of services (i.e., the optimal distribution of services in time, with a P_D (P_{Dcomb}) that produces minimization of P_{NR} and, consequently, the optimal use of P_R), the cost functions defined in Section 4.2.3 are used. Specifically, the optimal solution delivered by OPTTSNS corresponds to the combination of services that produces the minimum cost function, as shown in Equation (22). To quantitatively verify the improvements obtained with OPTTSNS, the performance metrics defined in Section 5.1 are used and a numerical analysis is performed on a particular case study in Section 5.3. In this context, an analysis in different scenarios, as well as the online version of OPTTSNS and the development of more sophisticated and efficient methods (that use as the optimal solutions as upper bounds), will be addressed in future work.

5.1. Metrics

The performance metrics presented in this section allow meeting Requirement R7 described in Section 3.1.

1. *Acceptance Ratio (AR)*: This metric measures the number of services that are processed. If P_A is insufficient to meet all power demanded (P_D), one or several services should be rejected ($RejServ$) [19]. The AR can be expressed as:

$$AR = \frac{N - RejServ}{N} \times 100\% \tag{23}$$

2. *Available Energy Utilization* (E_{A_U}): This metric measures the amount of energy allocated to processed services respect to the total amount of available energy ($E_{A_U} = 100\%$, if $P_D = P_A$). The E_{A_U} can be defined as:

$$E_{A_U} = \frac{\sum_{i=1}^{L} \sum_{j=1}^{M} \sum_{k=1}^{N} p^i_{k,j} \times q^i_{k,j} \times d^i_{k,j}}{P_A \times W} \times 100\% \tag{24}$$

3. *Missing Power* (P_{LACK}): This metric measures the amount of power needed to process all demands under the current conditions of the system (i.e., for a given value of $u^i_{k,j}$ and $q^i_{k,j}$). The P_{LACK} can be expressed as:

$$P_{LACK}[t] = \begin{cases} |\, P_A[t] - P_D[t] \,| & \text{if } P_A[t] < P_D[t], \\ 0 & \text{otherwise.} \end{cases} \tag{25}$$

5.2. Optimal Algorithmic Strategy: OPTTSNS

Figure 6 explains the proposed algorithmic strategy OPTTSNS and the main steps carried out are summarized below.

- *Variations per service* ($VarServ$)*:* A variation of a service is the result of the application of a specific discrete time shifting value to the $t^i_{k,j}$ and/or the application of a specific quality degradation level to the $p^i_{k,j}$ of a service $S^i_{k,j}$. The analysis of all N services for each value of time shifting and for each quality degradation level produces a total number of variations $AllVarServ$. Considering that, for simplicity, the time shifting forward and backward have the same value, this number is given by:

$$AllVarServ = Q \times (2 \times N \times max\{u^i_{k,j}\} + N) \tag{26}$$

- *Combinations of services* ($CombServ$) *and computation of cost functions:* In the algorithmic strategy, the set of N different variations of services ($VarServ$) is named as a *combination of services* ($Combserv$). Each $Combserv$ has specific characteristics and requires a certain power level P_{Dcomb}. The algorithmic strategy evaluates the cost functions for each $CombServ$. Regarding the AR metric, the algorithm prioritizes the execution of the highest priority services (with $j = 1$ the highest priority level). If the services have the same priority level, the algorithm selects the set of services that produce an optimization in the consumption of available power (maximization of energy use). The combinatorial analysis of all ($VarServ$) delivers a total number of combinations of services $AllCombServ$, which is given by:

$$AllCombServ = Q \times (2 \times max\{u^i_{k,j}\} + 1)^N \tag{27}$$

The computation of combinations of services (variations) contributes largely to the growth of complexity of the problem. For instance, $N = 10$, $max\{u^i_{k,j}\} = 4$, and $Q = 3$ produce over 10 billion combinations. If a computer is able to process one $Combserv$ each millisecond, it would need over 2900 h to explore the complete search space.

- *Sorting of combinations and selection of the best combination:* In this step, a quicksort method is applied to all combinations, according to the descending value of $Cost^{i,j,k}_{comb}$. Then, the best combination (which is the first in the sorted list) is chosen. Finally, the energy is allocated to the services that can be processed, and the performance metrics are computed.

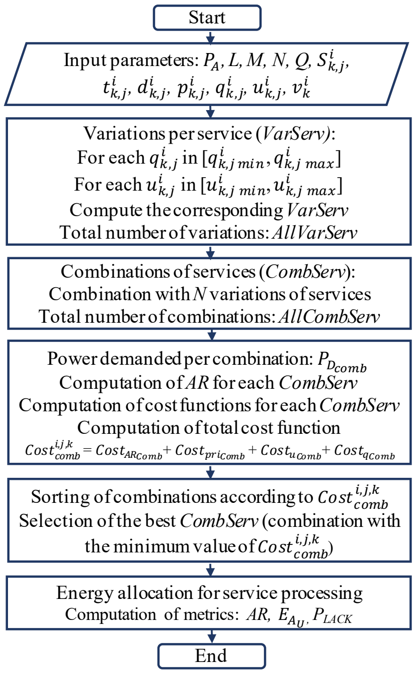


Figure 6. Flow chart of the exact algorithm strategy OPTTSNS.

5.2.1. Complexity Analysis of OPTTSNS

The complexity of the exact solution is conditioned to the processing of $AllVarServ$ and $AllCombServ$. As a function of N, the growth rate can be expressed as:

$$f(N) = N + Q \times (2 \times N \times max\{u^i_{k,j}\} + N) + Q \times (2 \times max\{u^i_{k,j}\} + 1)^N \quad (28)$$

where the third term in Equation (28) is dominant and represents the size of the search space that must be explored to find the optimal combination of services ($VarServ$) that lead to the minimization of power consumption (optimal power consumption). Therefore, the complexity the algorithmic strategy OPTTSNS is exponential with an order of growth $\mathcal{O}(2^N)$ that depends on the selected values of N, Ts, $max\{u^i_{k,j}\}$, and Q.

5.3. Numerical Results

5.3.1. Simulation Setting

For the implementation of OPTTSNS, we used Matlab (Matlab R2017b) running on a machine with a 3.33 GHz × 12 cores Intel Core i7 Extreme processor and 12 GB RAM. The algorithmic strategy leverages parallel processing, and up to three cores were used in the simulation of the case study. The evaluation of the optimal solution is given in terms of metrics AR, E_{A_U}, and P_{LACK}. The results obtained are compared with a traditional scenario in which no management strategy is applied (i.e., when $v^i_k = 1$, $q^i_{k,j} = 1$, $u^i_{k,j} = 0$, $\forall i \in L$, $\forall j \in M$, $\forall k \in N$). The total execution time for the simulation was approximately 90 min.

5.3.2. Case Study

Figure 7 shows the scenario that has been considered for the quantitative evaluation of OPTTSNS. This scenario allows the analysis of the different management strategies during states of shortage (high load) and surplus of energy produced by the lack of synchronization between energy generation and consumption. In this particular case, we also analyze the minimization of power consumption by considering a 100% green energy supply (i.e., promoting the use of energy from renewable sources). Due to the high computational requirements for the execution of OPTTSNS, the simulation was limited to $N = 8$ services, $max\{u^i_{k,j}\} = 4$ time slots (backward and forward), and $Q = 3$ quality degradation levels; the rest of parameter used are detailed in Table 6 and Figure 7. To simplify the analysis, services with equal duration and a flat energy profile and were selected. However, this does not mean a limitation for the developed algorithm, which can work with any profile of energy generation and consumption if needed.

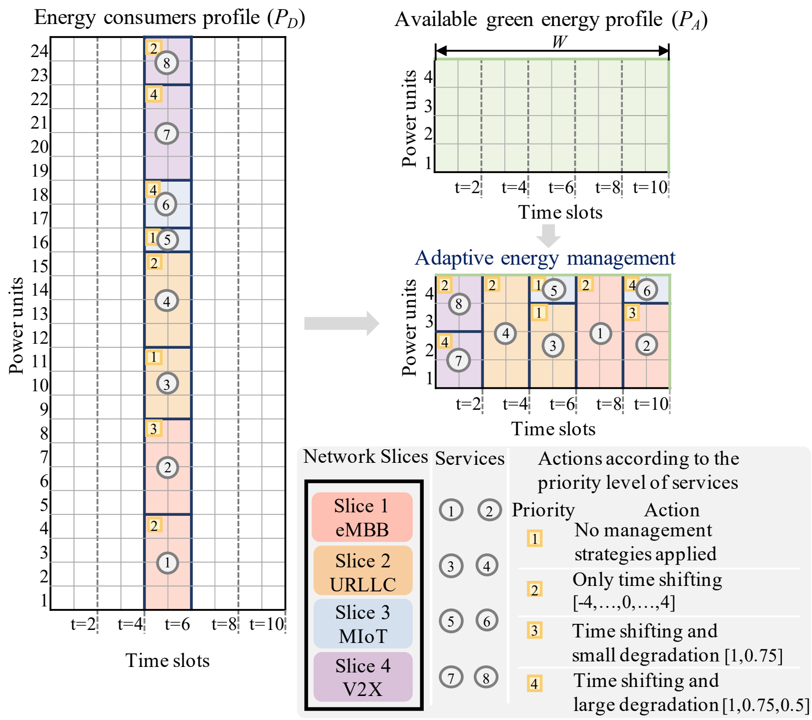


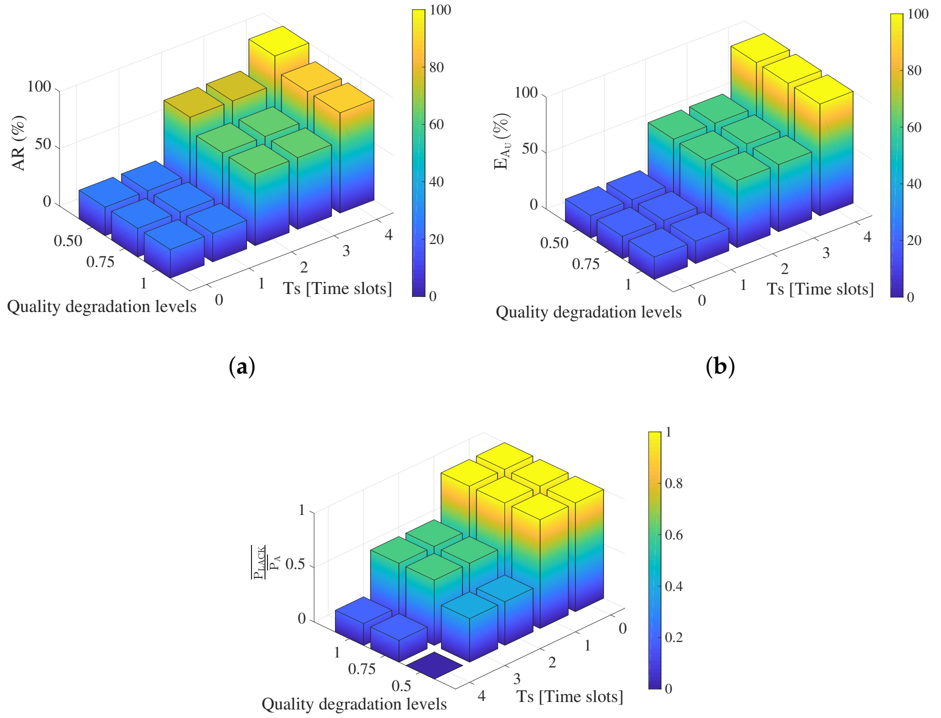
Figure 7. Energy provisioning and consumption profiles of the case study, and optimal energy allocation obtained with OPTTSNS. **Parameters**: According to Table 6.

Table 6. Parameters of OPTTSNS and values regarding the case study.

Parameter	L	M	N	W	$t^i_{k,j}$	$d^i_{k,j}$	$max\{u^i_{k,j}\}$	$p^i_{k,j}$	Q	$q^i_{k,j}$
Value	4	4	8	10	$4\ \forall k$	$2\ \forall k$	4, see Figure 7	[1–4], see Figure 7	3	[1, 0.75, 0.5], see Figure 7

5.3.3. Results and Discussion

The simulation results in Figure 8 confirm the effectiveness of OPTTSNS to improve power consumption, as reported in values of metrics AR, E_{A_U}, and P_{LACK} in Figure 8a–c, respectively. As the time shifting value increases (from 0 to 4) and as the quality degradation level decrease (from 1 to 0.5), OPTTSNS has the ability to distribute the services in time and minimize the power consumption, which consequently leads to efficient use all P_A. In this regard, the algorithmic strategy enables reducing the peak loads (i.e., the peaks of power consumption) and obtain a flat consumption profile, which can be better adapted to energy generation. Thus, the use of management strategies enables the processing of services that, in normal conditions (i.e., without a management mechanism) would be inevitably rejected. For instance, in Figure 7, only services $S^2_{3,1}$ and $S^3_{5,1}$ could be processed, which corresponds to an $AR = 25\%$, in this case the most of the energy produced could not be used and would be wasted. In addition, the simulation of OPTTSNS shows that, when this algorithmic solution is deployed at the mobile network MANO entities, as shown in Figure 2, it can offer efficient and adaptive energy management for 5G systems, considering the context of network slicing and with the ability to manage and exploit renewable energy generation.



(**a**) (**b**)

(**c**)

Figure 8. Performance evaluation of the OPTTSNS for case study of Figure 7: (**a**) AR metric OPTTSNS; (**b**) E_{A_u} metric OPTTSNS; and (**c**) P_{LACK} metric OPTTSNS. Parameters: According Table 6.

For the analyzed use case, the improvements obtained with the algorithmic strategy are given in terms of energy utilization (as shown in Figure 8b), increased service processing (from $AR = 25\%$ until reaching an $AR = 100\%$, as shown in Figure 8a), and in reducing the use of energy from non-renewable sources to meet the complete energy demand (Figure 8c). The latter is of utmost importance in modern energy management systems that aim to achieve a reduction in OPEX and with minimal environmental impact.

6. Heuristic Strategies Discussion

Given the $\mathcal{NP}$-hard nature of the problem (Section 4.3) and due to the intractability of OPTTSNS for large values of $u^i_{k,j}$ and/or $q^i_{k,j}$ (Section 5.2.1), in this section, we introduce different strategies to find feasible solutions within a reasonable computing time. Considering that the minimization of power consumption from non-renewable energy sources in the proposed adaptive energy management model falls in the category of a multiple-choice Knapsack Problem, as proven in Section 4.3, a number of techniques could be used to produce computationally efficient heuristic strategies [36]. In this regard, and based on the literature surveyed, we propose four strategies, which, according to their degree of difficulty in implementation are: (i) a pre-partition strategy, based on a divide-and-conquer method; (ii) a greedy approach, based on a constructive algorithm; (iii) a genetic algorithmic solution based on a metaheuristic template; and (iv) a dynamic programming approach, which is a general optimization and programming technique. These approaches have been selected to cover as far as possible the main categories of methods or techniques developed to solve this kind of problem. Table 7 shows a summary of the features and implementation challenges of these strategies in the context of the proposal. The implementation and evaluation of these strategies can be addressed in future work.

Table 7. Heuristics strategies analyzed to solve the P_{NR} minimization problem efficiently.

Strategy/Technique	General Description	Features and Challenges
Pre-Partitioning Strategy	Strategy based on a divide-and-conquer method. The original problem is divided into sub-problems of less complexity that are solved iteratively. The final solution is a combination of partial solutions.	- Easy implementation. Few modifications on OPTTSNS are required. - The strategy can be seen as a generalization of OPTTSNS. - The size of the search space decreases as divisions increase. - Control of the accuracy and running time based on the number of divisions.
Greedy Approach	Iterative and constructive algorithm, in which the *VarSer* to be processed, one at time, is selected based on the value of a parameter, e.g., $p^i_{k,j}$, $d^i_{k,j}$, or the ratio between $p^i_{k,j}$ and $d^i_{k,j}$, respecting the P_A and with the aim of first minimizing power consumption of P_{NR} and then increasing AR.	- Easy implementation. The strategy must be built from scratch and there are many possible implementations. - Good running time performance. However, there is no guarantee on the quality of the solution, because it can vary widely according to the parameter used to select the *VarSer*.
Genetic Algorithm	Strategy inspired in the behavior of biological systems. First, an initial population of chromosomes is created, where each chromosome represents a possible *CombServ* (solution) formed by randomly selected *VarSer*. Later, the population evolves along with generations considering the action of the genomic operators (crossover and mutation) and the selection of fittest individuals (combinations with the best performance metrics). Finally, in the last generation, the solution with the best fitness function (minimum P_{NR}) is selected.	- Medium complexity implementation due to requirements of the proposal (time shifting, priorities, and rejection). - Nondeterministic solution. It depends on the random values chosen in the creation of populations (initial and offspring) and the selection of genetic operators (crossover and mutations). - Good running time performance. However, the final solution may require many generations if the parameters for population creation or stop criteria are not properly established.
Dynamic Programming Approach	Strategy that uses a dynamic programming method. The algorithm simplifies the analysis of N simultaneous services by analyzing and solving them one at a time. Systematically, using a bottom-up approach, the results of a previous set of services (considering their *VarSer*) are stored and used for solving a greater number of services.	- Good running time performance, but difficult implementation due to the two-dimensional behavior of the problem (power and time parameters) and multiple-choice analysis for *VarSer* selection.

7. Conclusions

Network slicing is specified for 5G networks to provide new opportunities for service provisioning in order to increase efficiencies and improve revenue. Regarding energy consumption management, this feature is a key factor in the deployment and evolution of mobile networks, and it is also a crucial consideration. This paper analyzes the requirements, proposes an architecture, and presents a feasible and efficient solution for adaptive energy management in 5G network slicing that meets the requirements of energy efficiency and sustainability by current and future mobile communications networks. The proposal aims to optimize the consumption of available power, and specifically seeks for the minimization of power consumption of non-renewable energy sources. In this regard, our proposed energy management model prioritizes the use of renewable energy sources, but non-renewable energy sources can be used when extra energy is required.

The architecture proposal covers the requirements for efficient, adaptive, and sustainable energy management; the mathematical model of the stakeholders involved in energy management and consumption in the 5G ecosystem; and several management strategies at service level such as an intra-slice prioritization scheme, service rejection, time shifting in service execution, and degradation in service quality (i.e., decrease in energy demand) with the aim of optimizing available power consumption. The proposal also presents the ILP formulation of the adaptive energy management model and its complexity analysis, which has been proven to be $\mathcal{NP}$-hard.

To validate the operation of the proposed adaptive energy management model an exact optimal algorithmic strategy, OPTTSNS, is presented, of exponential complexity that depends on the values of N, $u^i_{k,j}$, and Q, as shown in Equation (28), and which reveals the need for heuristic approaches for scalable, faster, and less computationally demanding implementations. The evaluation of the exact solution for a particular case study allows us to verify the improvements obtained with the proposal in power consumption and utilization, in the increase of service processing, and in the minimization of the use of non-renewable energy sources. This latter feature is of paramount importance because it can potentially reduce the OPEX for the MNO and the energy footprint because of the operation of the mobile networks.

Future work can include the following aspects: (i) incorporation of an inter-slices prioritization scheme to apply management strategies or control actions directly to entire network slices; (ii) extension of the energy management model to the end-user side to improve energy efficiency and management of battery units; (iii) implementation and evaluation of more scalable and faster algorithmic strategies, taking as a baseline the procedures, metrics, and results obtained for the optimal solution as well as the information of the possible heuristic strategies presented in Table 7; and (iv) application of the energy management strategies to other scenarios, e.g., for managing energy production and consumption in smart homes.

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References

1. *System Architecture for the 5G System (5GS)*; Version 16.4.0; Technical Specification (TS) 23.501; 3rd Generation Partnership Project (3GPP): Sophia Antipolis, France, 2020.
2. *Service Requirements for the 5G System*; Version 17.2.0; Technical Specification (TS) 22.261; 3rd Generation Partnership Project (3GPP): Sophia Antipolis, France, 2020.
3. *Management and Orchestration; Concepts, Use Cases and Requirements*; Version 16.1.0; Technical Specification (TS) 28.530; 3rd Generation Partnership Project (3GPP): Sophia Antipolis, France, 2019.
4. *Management and Orchestration; Provisioning*; Version 16.4.0; Technical Specification (TS) 28.531; 3rd Generation Partnership Project (3GPP): Sophia Antipolis, France, 2019.
5. *Report on Network Slicing Support with ETSI NFV Architecture Framework*; Version 3.1.1; Technical Report (TR) GR NFV-EVE 012; European Telecommunications Standards Institute (ETSI): Sophia Antipolis, France, 2017.
6. *Study on Management and Orchestration of Network Slicing for Next Generation Network*; Version 15.1.0; Technical Report (TR) 28.801; 3rd Generation Partnership Project (3GPP): Sophia Antipolis, France, 2018.
7. *Study on Tenancy Concept in 5G Networks and Network Slicing Management*; Version 16.0.1; Technical Report (TR) 28.804; 3rd Generation Partnership Project (3GPP): Sophia Antipolis, France, 2019.
8. *Energy Efficiency of 5G*; Version 1.3.0; Technical Specification (TS) 28.310; 3rd Generation Partnership Project (3GPP): Sophia Antipolis, France, 2020.
9. *Study on System and Functional Aspects of Energy Efficiency in 5G Networks*; Version 16.1.0; Technical Report (TR) 32.972; 3rd Generation Partnership Project (3GPP): Sophia Antipolis, France, 2019.
10. *Sustainable Power-FeedingSolutions for 5G Networks*, Version L.1210; Recommendation ITU-T L.1210; International Telecommunication Union (ITU): Geneva, Switzerland, 2019.
11. GSMA. Energy Efficiency: An Overview. GSM Association, 2019. Available online: https://www.gsma.com/futurenetworks/wiki/energy-efficiency-2/ (accessed on 1 March 2020).
12. *Study on Methods and Metrics to Evaluate Energy Efficiency for Future 5G Systems*; L.1310 Supplement 36; Recommendation ITU-T L.1310; International Telecommunication Union (ITU): Geneva, Switzerland, 2017.
13. Wu, Q.; Li, G.Y.; Chen, W.; Ng, D.W.K.; Schober, R. An Overview of Sustainable Green 5G Networks. *IEEE Wirel. Commun.* **2017**, *24*, 72–80. [CrossRef]
14. *Standardization Terms and Trends in Energy Efficiency*; L.1315; Recommendation ITU-T L.1315; International Telecommunication Union (ITU): Geneva, Switzerland, 2017.
15. *Assessment of Mobile Network Energy Efficiency*; L.1331; Recommendation ITU-T L.1331; International Telecommunication Union (ITU): Geneva, Switzerland, 2017.
16. *Energy Control for the Software-Defined Networking Architecture*; L.1360; Recommendation ITU-T L.1360; International Telecommunication Union (ITU): Geneva, Switzerland, 2016.
17. *Measurement Method for Energy Efficiency of Network Functions Virtualization*; L.1361; Recommendation ITU-T L.1361; International Telecommunication Union (ITU): Geneva, Switzerland, 2018.
18. Kreutz, D.; Ramos, F.M.; Verissimo, P.; Rothenberg, C.E.; Azodolmolky, S.; Uhlig, S. Software-defined networking: A comprehensive survey. *Proc. IEEE* **2015**, *103*, 14–76. [CrossRef]
19. Tipantuña, C.; Hesselbach, X. NFV/SDN Enabled Architecture for Efficient Adaptive Management of Renewable and Non-renewable Energy. *IEEE Open J. Commun. Soc.* **2020**. [CrossRef]
20. Buzzi, S.; Chih-Lin, I.; Klein, T.E.; Poor, H.V.; Yang, C.; Zappone, A. A survey of energy-efficient techniques for 5G networks and challenges ahead. *IEEE J. Sel. Areas Commun.* **2016**, *34*, 697–709. [CrossRef]
21. Renga, D.; Meo, M. From self-sustainable green mobile networks to enhanced interaction with the smart grid. In Proceedings of the 2018 30th International Teletraffic Congress (ITC 30), Vienna, Austria, 3–7 September 2018; Volume 1, pp. 129–134.
22. Abdullaziz, O.I.; Capitani, M.; Casetti, C.E.; Chiasserini, C.F.; Chundrigar, S.B.; Landi, G.; Li, X.; Moscatelli, F.; Sakaguchi, K.; Talat, S.T. Energy monitoring and management in 5G integrated fronthaul and backhaul. In Proceedings of the 2017 European Conference on Networks and Communications (EuCNC), Oulu, Finland, 12–15 June 2017; pp. 1–6.
23. Li, X.; Ferdous, R.; Chiasserini, C.F.; Casetti, C.E.; Moscatelli, F.; Landi, G.; Casellas, R.; Sakaguchi, K.; Chundrigar, S.B.; Vilalta, R.; et al. Novel Resource and Energy Management for 5G integrated backhaul/fronthaul (5G-Crosshaul). In Proceedings of the 2017 IEEE International Conference on Communications Workshops (ICC Workshops), Paris, France, 21–25 May 2017; pp. 778–784.

24. Al-Quzweeni, A.N.; Lawey, A.Q.; Elgorashi, T.E.; Elmirghani, J.M. Optimized energy aware 5G network function virtualization. *IEEE Access* **2019**, *7*, 44939–44958. [CrossRef]
25. Ren, Y.; Phung-Duc, T.; Chen, J.; Yu, Z. Dynamic Auto Scaling Algorithm (DASA) for 5G Mobile Networks. In Proceedings of the 2016 IEEE Global Communications Conference (GLOBECOM), Washington, DC, USA, 4–8 December 2016; pp. 1–6.
26. Ren, Y.; Phung-Duc, T.; Liu, Y.; Chen, J.; Lin, Y. ASA: Adaptive VNF Scaling Algorithm for 5G Mobile Networks. In Proceedings of the 2018 IEEE 7th International Conference on Cloud Networking (CloudNet), Tokyo, Japan, 22–24 October 2018; pp. 1–4.
27. Ordonez-Lucena, J.; Ameigeiras, P.; Lopez, D.; Ramos-Munoz, J.J.; Lorca, J.; Folgueira, J. Network slicing for 5G with SDN/NFV: Concepts, architectures, and challenges. *IEEE Commun. Mag.* **2017**, *55*, 80–87. [CrossRef]
28. Hao, Y.; Tian, D.; Fortino, G.; Zhang, J.; Humar, I. Network slicing technology in a 5G wearable network. *IEEE Commun. Stand. Mag.* **2018**, *2*, 66–71. [CrossRef]
29. Da Silva, G.; Oliveira, D.; Gomes, R.L.; Bittencourt, L.F.; Madeira, E.R.M. Reliable Network Slices based on Elastic Network Resource Demand. In Proceedings of the NOMS 2020—2020 IEEE/IFIP Network Operations and Management Symposium, Budapest, Hungary, 20–24 April 2020; pp. 1–9.
30. Pozza, M.; Nicholson, P.K.; Lugones, D.F.; Rao, A.; Flinck, H.; Tarkoma, S. On Reconfiguring 5G Network Slices. *IEEE J. Sel. Areas Commun.* **2020**, *38*, 1542–1554. [CrossRef]
31. Jiang, M.; Condoluci, M.; Mahmoodi, T. Network slicing management & prioritization in 5G mobile systems. In Proceedings of the 22th European Wireless Conference, Oulu, Finland, 18–20 May 2016; pp. 1–6.
32. Xiao, Y.; Krunz, M. Dynamic network slicing for scalable fog computing systems with energy harvesting. *IEEE J. Sel. Areas Commun.* **2018**, *36*, 2640–2654. [CrossRef]
33. Tipantuña, C.; Hesselbach, X. Demand-Response power management strategy using time shifting capabilities. In Proceedings of the Ninth International Conference on Future Energy Systems, New York, NY, USA, 12–15 June 2018; pp. 480–485.
34. *Generic Network Slice Template NG.116*, Version 1.0; GSM Association: London, UK, 2019.
35. Kellerer, H.; Pferschy, U.; Pisinger, D. Multidimensional knapsack problems. In *Knapsack Problems*; Springer: Berlin/Heidelberg, Germany, 2004; pp. 235–283.
36. Vazirani, V.V. *Approximation Algorithms*; Springer Science & Business Media: Berlin/Heidelberg, Germany, 2013.