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# Future Sustainable Internet Energy-Defined Networking

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**Abstract:** This paper presents a comprehensive set of design methods for making future Internet networking fully energy-aware and sustainably minimizing and managing the energy footprint. It includes (a) 41 energy-aware design methods, grouped into Service Operations Support, Management Operations Support, Compute Operations Support, Connectivity/Forwarding Operations Support, Traffic Engineering Methods, Architectural Support for Energy Instrumentation, and Network Configuration; (b) energy consumption models and energy metrics are identified and specified. It specifies the requirements for energy-defined network compliance, which include energy-measurable network devices with the support of several control messages: registration, discovery, provisioning, discharge, monitoring, synchronization, flooding, performance, and pushback.

**Keywords:** energy-aware Internet networking; energy management; energy instrumentation; energy metrics

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## 1. Introduction and Motivation

The Internet infrastructure has developed in the last fifty years into a hyperscale digital infrastructure which significantly contributes to worldwide energy consumption, accounting for 2–3% of the world's annual electricity production [1], from which ~40% is needed at the data plane [2]. This constitutes 33% of network operational expenditure (OPEX) [1].

This paper focuses on the critical challenge of radically reducing the energy consumption of modern communication and compute infrastructures, which will also cut the underlying expenditure of operating complex infrastructures, thus allowing services to be provided at a lower cost. As such, this paper takes a holistic approach to Internet infrastructure energy awareness and addresses the infrastructure energy consumption problem in five dimensions (connectivity, computation, management, services, and architecture), as shown in Figure 1, whereby networking resources will be optimized jointly to ultimately deliver energy-efficient services.

The derivation of relevant configurations in all five dimensions will be automated through closed-loop control. The paper's main contribution is the identification and specification of 41 energy design methods with associated research challenges for making future Internet networking fully energy-aware and continuously minimizing and managing the energy footprint in a sustainable way.

The structure of this paper is as follows: Section 1 presents the motivation behind the making of the paper; Section 2 presents related work and the state of the art (SoA); Section 3 presents a proposed Future Internet Architecture; Section 4 presents new energy design primitives, making future Internet networking fully energy-aware, including the energy consumption metric and Network Energy Application Programming Interface (API) capabilities. It then presents the functional description of 41 design methods for network energy management. This set of energy design methods is based on analyzing how to expose the energy measures and the impact of any networking operations at an adequate granularity level. The concluding section, Section 5, summarizes the main novel aspects of the paper. A section with 57 references follows the concluding remarks.

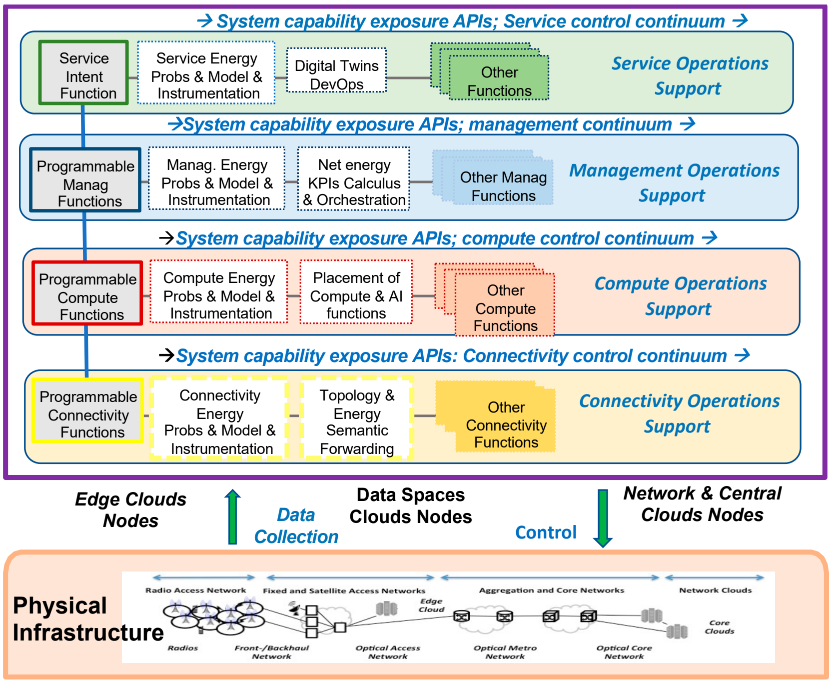

**Figure 1.** An energy-functional future Internet architecture.

## 2. Related Work and the State of the Art

Currently, Internet networks enable users and industrial vertical systems to minimize energy consumption; as such, they are considered “green”. They allow services to reduce their energy footprint and become more sustainable. Future Internet networking realization will depend on significantly reducing energy consumption with very high energy efficiency for economic and social sustainability. New comprehensive methods and frameworks to make networking minimize energy consumption ought to be designed and validated without impacting networks’ functionalities and efficiencies.

While connectivity infrastructure has traditionally driven consumption, deploying physical and virtual resources, considered key features of Internet networks, poses a significant challenge, as they will further contribute to the already high energy needs. The latter results from the ever-increasing user traffic/compute functions/management functions/service functions that enable operators to deploy resource overprovisioning and redundancy to cope with peak demand and provide some levels of reliability.

An idle network system is assumed to have an energy consumption of ~30–40% over the same system running at full capacity [2]. In addition, in typical networking devices, only roughly half of the energy consumption is associated with the data plane [2]. An idle base system typically consumes more than half of the power over the same system running at full load [3,4]. The incremental transmission cost of additional bits (beyond the first) is much lower than sending the first as it requires powering up a device. This means a device’s power consumption does not increase linearly with the volume of forwarded traffic/computational/management/service functions. Instead, it is approximated as a step function in which power consumption stays roughly the same up to a specific traffic volume, followed by a sudden jump when additional resources must be procured to support a higher traffic volume. As such, the transmission duration dominates the energy consumption, not the actual data rate.

The aim of utilizing all the above design measures for future Internet energy consumption is 10% of the current Internet, with an orchestrated trade-off of data usage, resources, trust, and energy efficiency. This includes a 90% reduction in energy consumption per energy/bit.

Future Internet networks aim to be fully energy-aware (i.e., currently, the networks are energy-agnostic). As such, potential solutions need to take a holistic approach that covers all physical and virtual network resources. High-energy precision services, management, computation, and connectivity multi-domains would include energy demand and supply prediction, programmable [5] and dynamic adjustment, and the configuration [3] of resource allocation in a domain/slice for a sustainable, greener inter-service, management, computing, and connectivity system.

Research on energy efficiency has mainly focused on the data plane [6–16], which is a more significant part, accounting for more than 50% [2]. The solution space revolves around routing [3,17] and traffic engineering approaches that mainly aim to consolidate traffic on the part of the infrastructure so that some network components, such as links or even entire routers, can be put into sleep mode, e.g., [3,18], and thus reduce the network topology.

Other approaches propose adapting the traffic sending rate to conserve energy, e.g., [19], which maintains the connectivity of the network topology and does not require new routing information distribution and re-convergence. Motivated by forwarding decisions consuming the most energy among data-plane operations, some solutions have focused on circumventing table lookups by encoding the entire routing path in packet headers [20].

More recent research has focused on energy-saving techniques for edge computing resources that are expected to facilitate latency-sensitive applications, process offloading from small IoT devices with limited capabilities, and execute AI algorithms close to the location of data sources [21]. Solutions in this domain include workload orchestration to warrant the efficient use of compute resources, e.g., [22] energy-aware scheduling for executing different types of Artificial Intelligence (AI) tasks considering heterogeneous resources and latency boundaries [23,24] and the placement as well as the configuration of virtualized network components to reduce power consumption, e.g., [4,25].

Prior research mainly concentrated on centralized offline approaches to optimize energy consumption by turning part of the infrastructure off [2,4,26]. These approaches rely on demand prediction, which may only sometimes be precise. They can also not react to unexpected events because of user behavior or changes in the infrastructure itself. In addition, connectivity and computation resources have been treated in isolation, leading to sub-optimal energy-efficient configurations due to their intrinsic coupling.

## 3. Internet Energy-Defined Networking—Solution Architecture

This paper proposes a new energy-aware functional architecture for the Future Internet, as depicted in Figure 1. It includes the placement of specific energy components (i.e., probes and instrumentation functions, energy operation functions) at each of the four layers (i.e., Service Operation Support, Management Operations Support, Compute Operations Support, and Connectivity Operations Support) and their interactions with other networking functions at each layer and between layers via systems capable of exposing APIs. It covers all Internet infrastructure segments: Edge–Access–Core–Clouds. It helps identify and specify a comprehensive set of design methods for making future Internet networking fully energy-aware, continuously minimizing and managing the energy footprint sustainably, which is this paper's main novelty and focus.

Some of the design methods for making future Internet networking fully energy aware would require appropriate standardization across all network components (marked with (*) below), and some are more complex to implement/realize due to the high level of interworking of network comports (marked with (**) below).

More specifically, this paper presents the design of the following comprehensive set of design methods and solutions that will collectively meet the expected net reduction in energy consumption:

- (*) Efficient energy instrumentation definition and design (probes, monitoring, models, APIs /interfaces, guarantees); network-level energy calculus and analysis.
- Accurate energy consumption model(s) and energy metrics: User demand and its characteristics and the decisions on how this is handled directly impact the infrastructure's energy consumption. This paper elaborates on an energy consumption model for connectivity and computational resources, which will assist in predicting and optimizing consumption for various service offerings. This paper will investigate

the relationship of a wide range of operational parameters, such as packet rates, queue lengths, central processing units (CPUs)/storage utilization, and system load with energy consumption and running services. These models will subsequently guide network and service management decisions to derive greener configurations for the infrastructure and service.

An initial energy model is depicted in Figure 2, and this model explicitly accommodates the network energy operations aimed at the following:

- (**) Improving operational efficiencies for network operators through typical organization and the autonomicity of all energy functions throughout the separate network slices or domains.
- (**) Adaptive resource management: Unlike most state-of-the-art offline and centralized solutions, this paper will present adaptive resource management approaches that execute at run-time. These will closely track connectivity and computation demand and regulate its distribution intelligently. More efficient resource utilization can be achieved, allowing part of the infrastructure to go into sleep mode or operate at an energy-conserving pace. Simultaneously, realistic performance and reliability constraints will be considered.

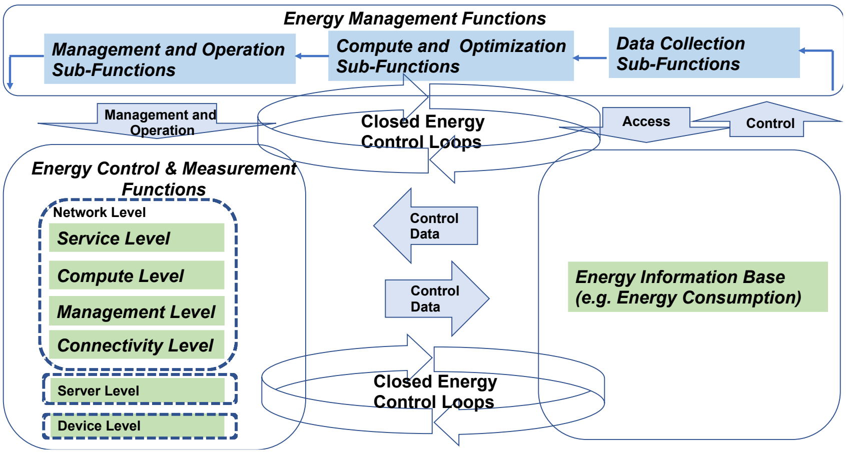

**Figure 2.** Proposed Network Energy Model.

In addition, workload orchestration to warrant the efficient use of computing resources will be considered. Energy-aware scheduling for executing different types of AI tasks [24] will also be needed based on heterogeneous resources, latency bounds, and autonomic network systems' increasingly automated management functions (e.g., the orchestration, self-configuration, and organization of energy control loops).

- (*) (**) Energy-friendly networking: As indicated in prior studies [3,17] on the energy profile of network devices, forwarding decision-making, i.e., table lookups, is the foremost energy-consuming process. Thus, this paper will investigate alternative schemes that circumvent expensive table lookups by encoding semantic forwarding information other than Internet Protocol (IP) addresses in packet headers for direct processing.

Source routing can inspire such schemes to reduce the necessary information to deliver traffic to the desired destination and simplify hop-by-hop processing.

In addition, flexibility in supporting multiple semantics will be a crucial trade in designing new schemes to cope seamlessly with changing network topologies due to infrastructure components going into sleep mode.

This will not only avoid the need to maintain and update topological IP addresses frequently but can allow for richer policies that enhance packet treatment according to the expected energy performance.

It also includes enablers for domains/slices of a network to go into sleep mode or operate at an energy-conserving pace, programmability enablers of the traffic sending rate to conserve energy (energy-aware semantic routing), and programming and encoding the entire routing path in packet headers to circumvent table lookups, which consume the most energy among data-plane operations.

- (*) Energy-aware Network Function Virtualization (NFV) Networking: This refers to a networking architecture standardized by the European Telecommunications Standards Institute (ETSI) [27] that uses virtualized networking functions to replace hardware-based network devices. It enables more flexibility, scalability, and cost-efficiency in network operations using software-based network functions instead of traditional hardware appliances. Energy-aware NFV networking would include energy instrumentation and computation for software-based network functions.
- (**) Energy-aware Digital Twin Networks (DTNs): A DTN requires collecting significant amounts of connectivity, computation, management, and service data from networks' domains, slices, layers, nodes, and links. It also performs filtering, correlation, cleansing, anonymization, pseudonymization, augmentation, and labeling operations on data collected with a high degree of correctness using data models.

Collected input data are then normalized and mapped into a unified data format for further processing and interactions with the APIs of the networking systems. The creation of DTNs was studied in [28]. DTN-efficient energy consumption was studied in [29]. The architectural framework of DTNs, along with the critical design requirements for communication systems, was reviewed in [30]. The DTN framework, augmented by AI, focuses on handling the complexity inherent in networks by providing intelligent resource management and orchestration, and it was presented in [31]. The relations between DTNs and networks are analyzed in [32].

Figure 3 depicts the placement of specific DTN energy functions: network data repository, data model management and operation, network emulation and topology, model management, and integrity synchronization management of network emulation with network physical elements in the overall energy future Internet architecture (Figure 1).

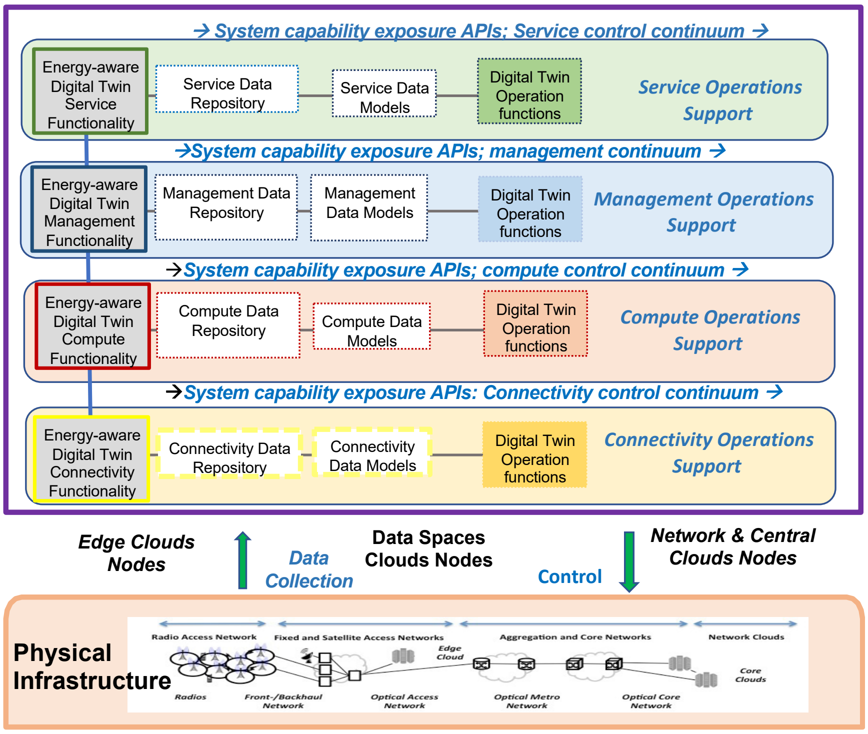

**Figure 3.** An energy-aware Digital Twin Network.

## 4. Future Internet Energy-Defined Networking—Design Methods

This section introduces the new design primitives underlying all the design methods envisaged for making future Internet networking fully energy-aware, including the energy consumption metric and Network Energy Application Programming Interface (API) capabilities. It then presents the functional descriptions of 41 methods for network energy management. Regarding the directions for future work, functional and performance evaluation methods for prototype implementation are envisaged for all design methods.

### *4.1. Infrastructure Energy Consumption Model*

An initial overall network energy model which explicitly accommodates the network energy operations aimed at the following is depicted in Figure 3:

- Improving control efficiencies through the autonomic configuration, set-up, and optimization of all energy functions in a network at the communication, computational, management, and service levels.
- Enabling a cooperative arrangement of energy management functions across the network.

It includes specific energy consumption functions—an Energy Information Base, energy data collection, the optimization of the energy functions, energy operation at each of the four layers (i.e., Service Operation Support, Management Operations Support, Compute Operations Support, and Connectivity Operations Support)—and their control interactions in closed energy control loops.

### *4.2. Network Energy API Capabilities and Metrics*

Network Energy APIs are Representational State Transfer (REST) Application Programming Interfaces [33] wherein the clients are the network controllers or network orchestrators of slices or subnetworks. The REST resources/devices/elements are the service and network energy-aware entities (data-plane entities, management-plane entities, computational-plane entities, and service-plane entities).

Through Network Energy APIs, network Controllers or Orchestrators can synchronize the operating state in a Domain/Slice or subnetwork. They also collect energy-related information from all entities in a synchronized session, enabling the energy-related domain computation. Network Energy APIs are interfaces between the data plane/management plane/computational plane/service plane responsible for exchanging data regarding the energy status of an Energy-Aware Entity (EAE).

An Energy-Aware Entity (EAE) is a network domain, slice, or subnetwork entity that can trade, via REST APIs, its energy consumption, performance, energy states, and other descriptive energy information (e.g., operational rate, transmission, and reception speed) at a given time. Energy-Aware Entities (EAEs) are grouped under a Controller or a network Orchestrator in a domain/network slice/subnetwork.

The energy-aware information includes energy performance specification and energy standby specification. Energy performance information is the EAE's capability to dynamically regulate its operational transmission rate or reception speed. EAE energy standby is the energy information that switches itself into a low-energy mode by providing only some critical functionalities (e.g., wake-up, discoverable, rollback triggers).

#### Energy Consumption Metric

Network energy metrics can be defined as an extension of the energy metrics identified in the context of clouds/data centers [34–49].

The following normalized energy metric is applicable per domain/network slice at a given time:

Equation (1) Network Energy of a Domain/Slice:

$$\text{Network Energy} = \frac{\sum\left[(\mathrm{EAE_i})^{current} - (\mathrm{EAE_i})^{energy\ standby}\right]}{\sum(\mathrm{EAE_i})^{energy\ standby}} \tag{1}$$

where $EAE_i$ is the energy value for an EAE in a domain /slice/subnetwork; i = 1 to N.

To comply with an energy-defined network, all network elements must be energy-measurable and support several energy control messages (e.g., registration, discovery, provisioning, discharge, management, synchronization, flooding, rollback, and commit messages).

The Network Energy API's main functionality is designed to be compatible with and an extension of [26]. It includes the following:

- Registration: Information response EAE to Controller/Orchestrator: Allows an EAE to register with the Controller/Orchestrator for its energy operations and information.
- Discovery 1: Information request Controller/Orchestrator to Entities: Retrieves information about available energy states and other descriptive information of the entity (e.g., operational rate, transmission, and reception speed).
- Discovery 2: Information response Entity to Controller/Orchestrator: Returns the list of individually manageable parts of the entity with their information about available energy states and other descriptive information of the entity (e.g., operational rate, transmission, and reception speed).
- Provisioning 1: Configuration command Controller/Orchestrator to Entities: Enables the configuration of an entity into a different energy state (i.e., energy performance state; energy standby state).
- Provisioning 2: Configuration notification: Entity to Controller/Orchestrator: Returns the operating energy state results (i.e., energy consumption, energy performance state, and energy standby state).
- Discharge 1: Discharging command Controller/Orchestrator to Entities: Allows configured energy entities to discharge into its default configuration.
- Discharge 2: Discharging notification Entity to Controller/Orchestrator: Returns the operating results.
- Monitoring 1: Parameter request Controller/Orchestrator to Entity: Permits monitoring the device's relevant parameters (state, energy consumption, etc.).
- Monitoring 2: Parameter notification Entity to Controller/Orchestrator: Returns the operating results.
- Synchronization: 1. Configuration command Controller/Orchestrator <-> all EAEs in the domain: Allows for changing the state to Active or Standby (switching itself off), or Idle or Smart standby.
- Synchronization: 2. Configuration notification for all EAEs <-> Controller/Orchestrator: Returns the operating results. An EAE can act as an initiator or responder (listener and data source) for a domain synchronization session.
- Flooding 1: Information request Controller/Orchestrator <-> all Entities in the domain: Allows a Domain Controller to send requests to all EAEs of the domain within a synchronization session.
- Flooding 2: Information notification to all Entities in the domain<-> Controller/Orchestrator: Returns the operating results within a synchronization session.
- Perform 1: Configuration command: Controller/Orchestrator to Entities: Confirms the changes made due to the provisioning request.
- Perform 2: Configuration notification EAE to Controller/Orchestrator: Returns the operating results.
- Pushback 1: Configuration command: Controller/Orchestrator to Entities. Reverses the changes made due to the provisioning request or the last committed configuration.
- Pushback 2: Configuration notification Entity to Controller/Orchestrator. Returns the operating results.

### 4.3. REST Interfaces

REST (Representational State Transfer) [33] lets subsystems interact (Figure 4) with any server over Hypertext Transfer Protocol (HTTP); in other words, REST-type interfaces are different to web APIs, which let subsystems interact with a web server through HTTP requests (e.g., GET, PUT, POST, DELETE, etc.). A REST-type interface conforms to the design principles of the representational state transfer architectural style. It implements functionality through a series of read and write operations on an object-oriented database, including documents [Extensible Markup Language (XML) or JavaScript Object Notation (JSON) documents [50]] during client–server communication. Its advantages include its scalability in methods of machine-to-machine communication and its interoperability, as it is based on the same norm used for the web, providing a great deal of flexibility and relatively easy realization.

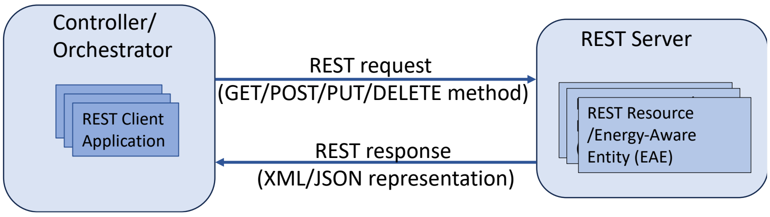

**Figure 4.** REST client (Controller)—REST server (resources/EAE) communication.

REST API components include a client application that initiates communication and sends an HTTP request, a server over HTTP offering access to its data and generating an HTTP response, and several resources/devices/entities, which are any elements that can provide a text file to the client's application (i.e., a machine-readable description of its current state that be represented in different formats, including XML and JSON).

### *4.4. Methods for Network Energy Management and Associated Research Challenges*

This paper presents a comprehensive set of design methods for making future Internet networking fully energy-aware and continuously minimizing and managing the energy footprint in a sustainable way. This comprehensive set of energy design methods is based on analyzing how to expose any networking operation's energy measures and impact at an adequate granularity level. The following are the methods and challenges for efficient network energy management, presented in five dimensions (connectivity, computing, management, services, and architecture), as depicted in Figure 1.

#### 4.4.1. Service-Level Energy Design Methods

Service operational support functions (~10% of energy consumption); the methods' main goal: accurate service energy consumption models.

The specific critical methods include the following:

(1) Building energy service consumption models which will assist in predicting and optimizing consumption for various service offerings.
(2) Building a service energy-aware digital twin that will consider the relationship of a wide range of operational parameters, such as packet rates, queue lengths, CPU/storage utilization, and system load with energy consumption and running services.
(3) User demand, its service characteristics, and the decisions on how these aspects directly impact the energy consumption of the service infrastructure and operations should be accommodated explicitly in the service intents.
(4) These digital twin models will subsequently govern the network and service management decisions and drive greener configurations for the infrastructure and services.
(5) The fast evolution of underlying instrumentation and tools for energy-defined Development Operations (DevOps).

#### 4.4.2. Management-Level Energy Design Methods

Management operational support functions (~10% of energy consumption); the methods' main goal: network and resource energy-efficient operations.

The specific critical methods include the following:

(1) Specific energy instrumentation (monitoring and models) with realistic performance and reliability constraints will be considered and incorporated in closed network-level energy loops, including energy monitors, energy analysis, energy-federated choreography, energy response management, energy decisions, and energy configuration executions [51].
(2) Network-level energy calculus and analysis—Domain network-level topology hot spot maps will be updated periodically. These will be realized through efficient heuristics that can meet real-time requirements, while a critical characteristic will be their decentralized nature for scalability purposes.
(3) Further efficient resource utilization can be achieved, allowing part of the infrastructure to go into sleep mode or operate at an energy-conserving pace.
(4) Guarantees and Key Performance Indicators (KPIs) for energy consumption and optimization.
(5) Adaptive resource management and network operation approaches that execute at run-time. These will closely track connectivity and computation demand and regulate their distribution intelligently.
(6) Multi-domain energy optimization and management—Chaining energy methods across multiple domains.
(7) Energy instrumentation that allows for the adequate measuring and monitoring of energy usage at different levels of granularity.
(8) Energy applications that aim to optimize energy consumption across the domain, network slice, or subnetwork.
(9) Support for energy-saving methods enabling significant energy consumption reduction to a standby level.

#### 4.4.3. Computational-Level Energy Design Methods

Computational operational support functions (~10% of energy consumption); the methods' main goals: to delegate/distribute computational/processing tasks across the network, focusing on energy efficiency.

The specific critical methods include the following:

(1) Workload orchestration to warrant the efficient use of computing resources.
(2) The placement and configuration of virtualized network components to reduce energy consumption.
(3) Methods for solving the energy optimization problem following a meta-heuristic technique for allocating the AI algorithms/workloads to physical nodes.
(4) Energy-aware scheduling for executing different AI tasks, considering heterogeneous resources and latency boundaries.
(5) The adaptive configuration of a target computational platform (a central processing unit (CPU), graphics processing unit (GPU), neural processing unit (NPU), etc.) is abstracted from the offloading workload API.
(6) Continuous cloudification for network functions and data spaces for energy efficiency, RAN functions, and edge clouds.

#### 4.4.4. Connectivity-Level Energy Design Methods

Connectivity /forwarding operational support functions (~40% of energy consumption); the methods' main goal is ensuring forwarding decisions consume the most energy among data-plane operations).

The specific critical methods include the following:

(1) The proposed programmability [5] of the traffic sending rate is designed to conserve energy, maintain the network topology's connectivity, and not require new routing information distribution and re-convergence.
(2) Energy-aware semantic routing and approaches are mainly aimed at consolidating traffic on the part of the infrastructure so that some network components, such as links

or even entire routers, can be put into standby mode and thus reduce the network energy consumption.

(3) Programming and encoding the entire routing path in packet headers to circumvent table lookups, which consume the most energy among data-plane operations.

(4) Flexibility in supporting and addressing multiple semantics will be crucial in designing new schemes to cope seamlessly with changing network topologies due to infrastructure components going into sleep mode. This will not only avoid the need to maintain and update topological IP addresses frequently but can allow for richer policies that enhance packet treatment according to the expected energy performance.

Connectivity/traffic engineering functions (~10% of energy consumption); the methods' main goal: traffic optimization.

The specific critical methods include the following:

(1) Designing protocols to reduce wasteful data transmission enables greater energy consumption efficiency.

(2) The dynamic reconfiguration of network components for the activation/deactivation of services is contingent on network-changing conditions.

(3) New network addressing schemes allow for the minimization of lookup table sizes and their associated energy use.

(4) Optimizing energy efficiency involves directing traffic towards other areas; some isolated equipment may be brought into energy-saving mode.

(5) Calculating alternative traffic paths for which the incremental energy cost is low or zero.

(6) Alternative transmission duration optimizations are envisaged as, mainly, the transmission period determines the energy consumption, not the actual data rate. A device's energy consumption is not correlated linearly with the volume of data traffic. As such, energy consumption increases are a scale function (i.e., consumption is the constant for a specific traffic volume, and when support for higher traffic volume is needed, the energy consumption is changed to another level).

(7) New transport protocols that react to congestion without dropping packets. The Transmission Control Protocol (TCP) and QUIC transport protocol respond to congestion by dumping packets, which is a highly energy-inefficient method since the effort to transmit the packet until it is dumped is wasted.

(8) Segment routing (SR) has been employed for energy-efficient networking in various contexts [52], usually through combining Software-Defined Networking (SDN) and SR. In [53], the authors provide a solution for reducing energy consumption in backbone networks by describing a three-step process that includes the selection of nodes to switch off, the computation of new routes excluding the latter harvesting on an intra-domain SDN, and employing segment routing [52,53] to reroute traffic dynamically. [54] proposes an energy-aware SDN-based routing solution targeting Data Center Networks utilizing segment routing, mainly focusing on per-packet load balancing instead of per-flow load balancing, and improved results regarding the number of links switched off were reported. Designing new SR methods involves the following: (i) green routing approaches harvesting on segment routing to reduce necessary information to deliver traffic; (ii) P4 models for data-plane programmability, supporting energy-aware routing techniques; and (iii) techniques to reduce SR headers to minimize packet size, with respective energy benefits.

### 4.4.5. Architectural-Level Energy Design Methods

Architectural-level support for energy instrumentation functions (~10% of energy consumption); the methods' main goal: architectural integration.

The specific critical methods include the following:

(1) The main aim is to deliver a flexible monitoring framework with programmable probes [5] deployed to enable the collection of energy consumption data from network (virtual) functions, devices, and slices that remain an issue; as such, this involves

designing precision telemetry, including probing agents that collect energy data from elements and components distributed and used by a cloud/edge-level energy analyzer. Such probes will be deployed near the corresponding devices, providing real-time information about energy consumption.

(2) Precision network telemetry will provide data for energy self-management loops that will drive energy-related decisions affecting the devices' energy state. One such result is the ETSI's interface between network control and devices [23,29], providing access to the energy management capabilities of future energy-aware telecommunication fixed-network nodes.

Architectural-level network configuration functions (~10% of energy consumption); the methods' main goal: achieving optimal network reconfiguration.

The specific critical methods include the following:

(1) Energy network optimization could be performed periodically through closed-loop control. An approach involving closed control loops in three dimensions—connectivity, computing, and services—is needed to achieve this goal.
(2) Novel energy consumption models: The development of power consumption models for connectivity and computational resources will assist in predicting and optimizing consumption for various service offerings. These models will guide network and service management decisions to derive greener configurations for the infrastructure and services.
(3) Novel adaptive energy-aware resource management focusing on adaptive resource management approaches that execute at run-time to track connectivity and computation demand and regulate its distribution intelligently, allowing for more efficient resource utilization and energy conservation.
(4) Semantic-aware real-time green routing: Alternative schemes for forwarding decision-making that circumvent expensive table lookups by employing a semantic networking paradigm, significantly increasing data-plane scalability and real-time network management.
(5) Continual deterministic orchestration: The development of mechanisms by which connectivity and computational resources can be optimized jointly. These mechanisms will be realized through efficient Artificial Intelligence/Machine Learning (AI/ML) mechanisms based on a continual learning paradigm. At the same time, a crucial characteristic will be their distributed nature for scalability purposes. Such schemes will allow for richer policies that enhance packet treatment according to the expected energy performance, ultimately reducing the underlying expenditure of complex infrastructures in operation and permitting the provision of services at a lower cost and with higher efficiency levels.
(6) Enabling slices of a network to go into sleep mode or operate at an energy-conserving pace is an essential technique in achieving energy efficiency in network infrastructures. In this context, developing enablers that allow slices of a network to go into sleep mode or operate at an energy-conserving pace can help reduce the energy consumption of networks, thereby promoting sustainability and reducing operational costs.
(7) Moreover, dynamic resource allocation is a critical enabler in conserving energy in the network. This technique involves allocating resources to different network slices based on their current demand. When a network slice is not in use, the resources allocated to that slice can be de-allocated, which helps reduce the network's energy consumption. Additionally, dynamic resource allocation [55] can help avoid overprovisioning, where resources are provided with more than they demand, thereby reducing resource wastage [56,57].

## 5. Conclusions

This paper aimed to provide a holistic approach to defining Internet energy-defined networking, addressing all the related systemic problems in five integrated dimensions: connectivity, computation, management, services, and infrastructure architecture. The paper includes specific energy-aware methods that can be used to design, in a sustainable way, new Network Energy APIs, ensure the requirements for network components and devices are energy-measurable, and help with energy consumption models and energy metrics and these methods are expected to be fully developed and deployed by 2030. This paper also describes the definition of and measures for Energy-defined Network compliance, including the energy-measurable network components and devices which support several control messages: registration, discovery, provisioning, discharging, monitoring, synchronization, flooding, performance, and pushback.

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