Design of an interface between the Smart Grid Control Plane and the Telecommunications Network Control Plane/Data Center Control Plane

MASTER THESIS

by

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Abstract

As we move towards the Smart Grid era, the different industries, including the Information and Communications Technology (ICT) industry, are trying to find ways of reducing their energy consumption, energy costs and carbon footprint. The current use of fossil fuels such as oil, coal and gas, to power up the rapidly increasing number of ICT devices and their energy demands, directly or indirectly contribute to the following four factors: energy consumption, energy costs, Green House Gas emissions and Climate changes (global warming). Introduction of alternative energy sources, such as solar panels, wind farms and/or hydroelectricity through the Smart Grid are some of the solutions towards reducing the carbon footprint. The Smart Grid is the new generation energy infrastructure consisting of the old centralized energy sources plus distributed alternative energy sources grouped into Micro grids. For the Information and Communications Technology industry, one of the ways in which to reduce energy costs and emission of Green House Gases would be through an interface between the ICT energy consumers control planes, for example the Telecommunications Network Control Plane or the Content Delivery Network Data Center Control Plane and the Smart Grid Control Plane. This thesis studies the design of an interface between the Smart Grid control plane and the Telecommunications Network or the Data Center Control Plane in order to enable communication between the two networks. This interface would enable the Smart Grid to share information that would be used by the ICT Networks to make decisions such as the source of energy information, the cost of energy production and the percentage of green and dirty energy available (i.e. the amount of GHGs emitted) in the Smart Grid. The Telecommunications Network would use this information to make decisions about where to route connections while Data Centers would use the information to make decisions about which Data Center to use to retrieve Data. The main objective of achieving communication between the Smart Grid and the Telecom...
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Networks/Data Centers is to minimize the overall energy costs and the amount of Green House Gases emitted by Telecommunications Networks and Data Centers.

Keywords
Telecommunications Network, Smart Grid, Green House Gases, Micro Grid, ICP Interface, Content Delivery Network, Data Centers
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Introduction on the energy problem in ICT

The ICT industry has been growing and will continue to grow at a very fast rate as more and more ICT devices such as laptops, tablets, phones, company data centers and the like are used and all these are connected to the Internet, furthermore resulting in the exponential growth of the Internet [1]. The ICT industry is currently growing at a rate of 2% per year. As the ICT devices' technology advances, so does its energy needs, resulting in higher energy demands from the energy industry. The ICT industry now consumes about 7.15% of the global energy produced and is estimated to consume up to 14.5% in 2020 due to the continued high growth rate [1]. Studies show that the ICT industry is responsible for 2% of the global carbon emissions (greenhouse gases), with Data Centers contributing 23%, PCs and monitors 40% and fixed and mobile telecommunications contributing 24% of the total emissions. It is estimated that due to the increase in number and size of Data Centers used by all sectors, the percentage of greenhouse gases emitted by Data Centers will increase fivefold between 2002 and 2020 [34].

Currently the energy industry mainly makes use of fossil fuels such as oil, coal and natural gas and these are quickly diminishing due to the high energy demands from all industries [2]. Due to the aforementioned high demands and the finite availability of resources, energy is becoming more and more costly. [2]. Global warming is another and increasing problem faced as a result of the emission of Green House Gases into the atmosphere. The ICT industry indirectly contributes to the emission of Green House Gases, because in order to produce the energy that is consumed by the ICT industry, fossil fuels are burnt, with GHGs being released into the atmosphere in the process. Efforts are being made by the ICT industry to reduce its energy consumption and as such its carbon footprint by manufacturing devices that require less energy to power them and by implementing energy saving
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Technologies such as putting device input/output ports, line cards into sleep mode etcetera[6]. Governments are also playing a role in trying to offset the amount of Green House Gases emitted by imposing carbon taxes on all industries, thus increasing operational costs [29].

By using alternative sources of energy such as solar panels, wind farms and/or hydroelectricity which do not emit or emit very little GHGs into the atmosphere as compared to the fossil fuels, and by using ICT to optimize the energy generation, transmission and distribution, the Smart Grid, is a major solution towards reduction of energy costs and emission of GHGs.

Table 1 below shows the different energy sources, and whether they emit GHGs (mainly Carbon dioxide into the atmosphere during production of energy and the level of their impact on the environment [2].

<table>
<thead>
<tr>
<th>Source of Energy</th>
<th>GHGs emission</th>
<th>Environmental impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar, Wind</td>
<td>no</td>
<td>low</td>
</tr>
<tr>
<td>Hydro-electrical</td>
<td>no</td>
<td>medium</td>
</tr>
<tr>
<td>Nuclear</td>
<td>no</td>
<td>high</td>
</tr>
<tr>
<td>Geothermal</td>
<td>no</td>
<td>low</td>
</tr>
<tr>
<td>Biomass</td>
<td>yes</td>
<td>medium</td>
</tr>
<tr>
<td>Fuel</td>
<td>yes</td>
<td>high</td>
</tr>
<tr>
<td>Coal</td>
<td>yes</td>
<td>high</td>
</tr>
</tbody>
</table>
Organization of the thesis

In the next sections, we will briefly talk about the electricity grid, both the Smart Grid and the traditional electricity grid, the architecture of the Smart Grid and the protocols used in the different portions of the Smart Grid plus a data communication protocol.

We will then briefly study Telecommunication Networks, mainly the MAN/WAN, protocols and Data Centers, focusing on Content Delivery Networks and cloud computing.

Finally we will introduce the techniques to be used to achieve our goal of designing an interface between the Smart Grid and the Telecommunication Network/Data Center Networks to enable communication between the two networks.
Smart Grid Analysis

The Smart Grid is an improvement of the traditional power grid which has been serving us for more than 50 years by introducing ICT technologies in all domains of the grid, i.e. from production to consumer. Currently there is poor communication in the traditional power grid with energy being produced and distributed to the consumers without any knowledge of the exact energy requirements of the consumers. Consumers are unable to manage their energy consumption due to the one-way flow of information. Power outages are manually resolved, and meter readings are still mainly done manually. As a result of these shortcomings and in order to improve on the effectiveness of the production and delivery of energy, the Smart Grid was introduced.

The figure 2 [17], below shows the current power grid. Energy flow is unidirectional, from generation, down to the consumers.
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Figure 2: Current power grid

The Smart Grid introduces two way energy and information flow in order to create an automated and widely distributed delivery network [4]. Two way energy flow means that the energy not only flows from the power generation plant to the consumer, like in the traditional energy grid, but also gets put back into the energy grid by the consumer. For example consumers can produce energy using solar panels and put the excess energy they produce into the main grid [5]. Using the Advanced Metering Infrastructure (AMI), two way information flow between a smart utility meter and a utility company is made possible.

The smart meter identifies energy consumption in much more detail than a traditional meter and communicates the collected information back to the utility
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for load monitoring and billing purposes. In addition to receiving real time information about their energy consumption, consumers will also receive real time information on energy prices per Kilo Watt, giving consumers the ability to control their energy consumption, and as such lower their energy consumption during peak hours and consequently lower their Green House Gases emissions [4]. The producers will receive information on exact energy requirements by the consumers and only produce energy according to the demand.

Figure 3, shows the two way communication in a Smart Grid [18]

![Figure 3, General topology of a Smart Grid, with two way communication](image)

The Smart Grid is made up of the traditional centralized energy sources and distributed energy sources that are grouped together in Micro grids. Micro grids contain both renewable and fossil fuel energy sources, but as we move towards a
more Green energy system, the final aim is to have only renewal energy sources in the Micro grids. When Micro Grids have excess energy, they can share it with a neighboring Micro Grid that is in need of energy, send it to the Smart Grid or store it. The main problem with renewable energy sources is the lack of continuous availability due to changes in atmospheric situations (lack of wind, cloud cover) and in places where this is not an issue there is often an overproduction of energy that cannot be stored for use when the circumstances change. i.e. in California for example the highest production of solar energy is when the demand is at his lowest [33]. Energy storage technologies that will help with this problem are being developed.

Figure 5, shows the future Smart Grid with Micro grids [28]
Micro grids have the ability to disconnect and reconnect to the main grid (Smart Grid). When they are producing sufficient energy for the consumers connected to them, they can disconnect from the Smart Grid. The smart grid is made up of different components that require different infrastructures and protocols to enable communication between them. We will briefly discuss the architecture and protocols of the Smart Grid in the next sections.

**Smart Grid Architecture**

The Smart Grid components interact through several layers namely: the power system layer, the power control layer, communication layer, the security layer and the application layer. Power generation, transmission and distribution fall under the power system layer.

The control layer enables the monitoring, management and control of the Smart Grid. The Security layer ensures the secure flow and the integrity of data within the Smart Grid, by safeguarding the data from hackers. The communication layer provides the two-way flow of information within the Smart Grid, i.e. between the producers to the consumers. The application layer provides the consumers with the different applications and utilities in the Smart Grid depending on the information infrastructure [8]. Let us take an example of the smart metering application. In order for this to function, an electric grid must have the power system layer that delivers electric energy to the consumers; a power control layer that monitors the consumers' power consumption and provide real time energy rates to the consumers, using the Smart meter; a communication layer that facilitates the flow of information between a consumer to a utility; and a security layer ensuring that this information is not tampered with or stolen.

The communication layer plays a major role in enabling Smart Grid applications. The communication network can be represented by a hierarchical multi-layer architecture, covering the whole electric power grid, i.e. from generation to
consumers [7] It consists of three major categories classified by data range and coverage range, each responsible for a different geographical area, namely; Home Area Network (HAN), Neighborhood Area Network (NAN), and Wide Area Network (WAN) [9].

Table 2, shows the different layers of the Smart Grid architecture and their components/functionalist.

<table>
<thead>
<tr>
<th>Smart Metering and Grid Application</th>
<th>Customer Applications</th>
<th>Application layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Authentication, Access control, Integrity, Protection, Encryption, Privacy</td>
<td>Security</td>
<td></td>
</tr>
<tr>
<td>Cellular, WiMax, Fiber Optic PLC, DSL, Coaxial Cable,</td>
<td>Home Plug, ZigBee, WiFi, Z-Wave</td>
<td></td>
</tr>
<tr>
<td>Cellular, WiMax, Fiber Optic</td>
<td>Communication layer</td>
<td></td>
</tr>
<tr>
<td>WAN</td>
<td>NAN/FAN</td>
<td>HAN/BAN/IAN</td>
</tr>
<tr>
<td>PMUs</td>
<td>Cap Banks</td>
<td>Reclosers Switches Sensors Transformers Meters Storage</td>
</tr>
<tr>
<td></td>
<td>Power control layer</td>
<td></td>
</tr>
<tr>
<td>Power transmission/Generation</td>
<td>Power distribution</td>
<td>Customer</td>
</tr>
<tr>
<td></td>
<td>Power System layer</td>
<td></td>
</tr>
</tbody>
</table>

Table 2, The system multi-layer architecture of smart grid

**Home Area Network (HAN)**

The Home Area Network facilitates applications like Demand Response (DR), Automatic Metering Infrastructure (AMI), smart devices monitoring and control at
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the customer’s premises. The Building Area Network (BAN) is similar to a HAN, but is implemented in a Business and Industrial Area Network (IAN) is implemented in an Industry. Customers use these applications to receive real-time energy prices and send their energy consumption information towards the central data systems. These applications do not require frequent/continuous sending of their data therefore communication technologies that provide data rates up to 100 kbps with short distance coverage (up to 100m) are sufficient for their functionality. ZigBee, WiFi, ZWave, power line carrier (PLC, or known as HomePlug), Bluetooth, and Ethernet technologies are widely used to support HAN/BAN/IAN applications [7].

Neighborhood Area Network (NAN)
The Neighborhood Area Network facilitates data flow between customers/field devices and a data concentrator/substation. This data comes from the smart metering, demand response and distributed automation, which are also known as Advanced Metering Infrastructure applications. A Field Area Network (FAN) is deployed to collect data from power lines, mobile workforce, towers, and so on, for power grid monitoring [7].
The NAN/FAN applications need communication technologies that support higher data capacity rates (100kbps – 10Mbps) and larger distance (up to 10km), ZigBee, WiFi, PLC long distance wired and wireless technologies, such as WiMAX, Cellular, Digital Subscriber Line (DSL) and Coaxial Cable [8] can be used for this purpose.

Wide Area Network (WAN)
The Wide Area Network forms the communication backbone of the Smart Grid, linking the grid to the core utility systems [9]. The Wide Area Network consists of two types of networks; the Core network, which connects the Metro network to the utility and substations; and the Backhaul network which connects Neighborhood Area Networks to the Core network [7].
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In situations where control centers are located far from the substations or consumers, the real-time measurements taken at the electric devices are sent to control centers through the Wide Area Network and instructions are sent to the electric devices from the control centers [9]. WAN applications such as wide-area control, monitoring and protection, require transmitting a large number of data points at a very high frequency to be able to ensure real-time delivery of control and monitoring information in the grid. This implies that communication technologies that provide long distance coverage (up to 100km), and support a much higher data rate (10Mps – 1Gbps) such as Fiber Optic, Cellular and WiMax are required, [7] [8].

Protocols
The protocols used in the different categories of the communications network depend on the technology being implemented. As the Smart Grid is a new development, there are no standard protocols being used at the moment. There are many different possibilities for each different network category and we will mention the common possibilities here.

In HANs/BANs/IANs, wireless communication is preferred over wired because it saves on costs, as there are no installation costs and addition/removal of devices is easily done. Protocols that can be used in HANs are IEEE 802.15.4, IEEE 802.11, Z-Wave and Powerline Communications (PLC).

NANs and WANs share some similar protocols such as RF Mesh and Worldwide Interoperability for Microwave Access (WiMAX). NANs also use PLC and IEEE 802.11s like in HANs. The other protocols used in NANs are 3G, 4G LTE, Ethernet and Data over Cable Service Interface Specification (DOCSIS).

The WAN is divided into two networks, in the Backhaul Networks, wireless technology protocols such as WiMAX, 3GPP, RF Mesh may be used. For wired options, DSL or Passive Optical Networks (PONs) can be used. In the Core Network,
Metro Ethernet can be implemented with wired technologies Internet Protocol/Multi Protocol Label switching (IP/MPLS) and fiber (SONET) [7][8].

**Smart Grid data communication protocol**

The Smart Grid technologies are designed to support applications and functionalities of the grid such as monitoring /controlling applications, for example Supervisory Control and Data Acquisition (SCADA)/Energy Management Systems (EMS), Distribution Management Systems (DMS), distribution feeder automation for facilities in wide range areas with very limited bandwidth and capacity in closed networks [26].

As the Smart Grid develops, research organizations and governments like the European Telecommunications Standards Institute (ETSI) are working towards standardizing the technologies and protocols in the Smart Grid to enable interoperability between the different sections of the grid[30][27] and some of these protocols can be extended to enable communication between the Smart Grid network and other networks, in our case ICT networks. Open Smart Grid Protocol (OSGP), was approved by the ETSI and is currently one of the most widely used and field-proven smart meter and smart grid device networking standards [27]. It provides reliable and efficient delivery of command and control information for smart meters, direct load control modules, solar panels, gateways, and other smart grid devices[31]. OSGP is designed to be very bandwidth efficient, enabling it to offer high performance and low cost using bandwidth constrained media such as the power line. OSGP builds on ISO/IEC 14908, which is media independent, therefore this protocol can be used with any current or future physical media[31].
Telecommunication Networks & Data centers Study

Telecommunication Networks

A telecommunications network is a collection of terminal nodes, links and any intermediate nodes which are connected in order to enable telecommunication between the terminals [19]. The telecommunications network uses different network structures, namely Metropolitan Area Network and Wide Area Network.

Metropolitan Area Network (MAN)

A Metropolitan Area Network covers a city or a district. It covers up to 10km. The earliest known MANs are cable television networks. Recent developments in high-speed wireless Internet access have resulted in another MAN, known as WiMAX. Networking technologies used in MAN include Asynchronous Transfer Mode (ATM), Fiber Distributed Data Interface (FDDI), RS-232, X.25, Frame Relay, Integrated Services Digital Network (ISDN), Asymmetrical Digital Subscriber Line (ADSL) etc [36].

Wide Area Network (WAN)

A Wide Area Network covers a large geographical area, often a country or continent etc. It covers a range between 100 to 10,000Km. The internet is the largest WAN [37]. Technologies such as High-Level Data Link Control (HDLC), Point-to-Point (PPP), Packet over SONET/SDH, MPLS, ATM, Frame Relay and X.25, High-Speed Serial Interface, Integrated Services Digital Network (ISDN), Switched Multimegabit Data Service, Synchronous Data Link Control and Derivatives for connectivity over the longer distances. WAN technologies generally function at the lower three layers of the OSI reference model: the physical layer, the data link layer, and the network layer[35].
Telecommunications Network routing Protocols

General MultiProtocol Label Switching (GMPLS)

General MultiProtocol Label Switching is an extension of MultiProtocol Label Switching. In addition to supporting packet switching interfaces like MPLS, it also supports layer 2 switching interfaces like Time-Division, (e.g. SONET/SDH, PDH, G.709), wavelength (lambdas), and spatial switching (e.g. incoming port or fiber to outgoing port or fiber) [16] [23]. It is a connection-oriented technology that originated from MPLS [25]. GMPLS improves IP scalability and quality of service by creating virtual label-switched paths (LSP) across a network of label switching routers (LSR). GMPLS' primary enhancement to MPLS is its capability to establish connections at Layer 1. GMPLS also extends two traditional link-state routing protocols already extended for Traffic Engineering (TE) purposes, i.e., OSPF-TE and IS-IS-TE [23].

Open Shortest Path First (OSPF)

The internet is made up of numerous Autonomous Systems operated by different organizations, usually a company, university, or ISP. The Shortest Path First protocol is an intradomain routing protocol, also known as an interior gateway protocol, meaning that it distributes routing information between routers belonging to a single Autonomous System. OSPF is a link state protocol [25] [24]. Earlier intradomain routing protocols used a distance vector design, based on the distributed Bellman-Ford algorithm inherited from the ARPANET. Routing Information Protocol (RIP) is an example of a distance vector routing protocol. In large networks it suffers from the count-to-infinity problem and general slow convergence. These problems prompted the ARPANET to switch over to a link state protocol.

OSPF is a dynamic routing protocol. It quickly detects topological changes in the AS (such as router interface failures) and calculates new loop-free routes after a
period of convergence [25]. This period of convergence is short and involves a minimum of routing traffic, making it an ideal routing protocol in the core network.

**Data Centers**

A data center is a facility used to house computer systems and associated components, such as telecommunications and storage systems. This includes redundant or backup power supplies, redundant data communications connections, environmental controls (e.g., air conditioning, fire suppression) and various security devices [20].

**Content Distribution Network**

A content distribution network (CDN) is a large distributed system of servers deployed in multiple data centers across the Internet [21].

With the high rate of growth of the World Wide Web, popular web sites receive an a lot of Internet traffic in the form of web search, scientific computations, video streaming, social networks, distributed file systems [10] to mention but a few. In an effort to offer their clients better services at a lower cost, with high availability and high performance, these sites have placed their content (globally or partially) in content delivery networks [11]. The contents are hosted on servers, called surrogates in data centers, at different geographical locations closer to the end users. Instead of the end users accessing the original server, their requests are redirected to the nearest available server, putting into consideration bandwidth cost and distance [11].

As user-generated content, over-the-top videos, personalized TV with CatchUP/PauseLive become more and more popular, there is a high increase in
the use of content-based services over telecom network infrastructures [12]. One of the world’s largest content distribution networks is owned and operated by Akamai. It consists of more than 100,000 servers located in more than 80 countries around the world.

**Content Distribution Network Architecture**

Peng [11], proposed an architecture for a Content Distribution Network which consists of six basic elements that work together to enable its functionality, as shown in Figure 6. The origin server that delegates its URI namespace to the request routing system (1), and publishes content (2) to be distributed to the remote surrogates (3) by the distribution system. A client requests content from what he perceives to be the origin server, but his request is treated by the request routing system (4) which redirects him to the optimum surrogate server (5). The surrogate servers periodically send information to the accounting system (6), which summarizes it in detail statistics and sends it as feedback to the origin server (7) and the request routing system (8).

![Figure 6, shows the general architecture of a CDN [11]](image-url)
Data centers host numerous types of applications, one of which is cloud computing. Cloud computing offers IT services such as Software as a Service (SaaS), Infrastructure as a Service (IaaS) and Platform as a Service (PaaS) to end users based on a pay-as-you-go model [13] [14]. Studies show that data centers hosting Cloud applications consume huge amounts of electric energy, contributing to high operational costs and carbon footprints to the environment [13] [15].

Most data centers are powered by traditional energy sources instead of green and renewable energy resources and as a result their carbon footprints are very high due to their high energy requirements [13].

Cloud Computing Architecture Common Elements

The cloud computing architecture mainly consists of the following elements [22]:

Virtualization layer. This plays a major role in cloud computing as it enables flexibility of the services, by the creation of Virtual Servers. Cloud Services can then be easily allocated and de-allocated depending on demand.

Horizontally scalable storage. This involves large clusters hardware that can be easily and economically expanded as the demand for infrastructure and storage resources grows.

Mechanisms for supporting multi-tenancy. A cloud service provides physical or virtual segregation of stored data on a per-tenant basis, and keeps track of service usage per tenant.

Web APIs. This implies to the ways through which the cloud services are invoked. Standard methods such as RESTful HTTP calls, XML, and SOAP may be used,
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enabling services to be made available through a standard web browser or other HTTP client application.
Introduction of Solution

As ICT infrastructures such as data centers, telecom networks and cloud computing services continue to grow at a very high rate, their energy consumption and emission of Green House Gases are a major concern in the ICT industry due to a great increase in operational costs of the companies. Here we introduce cost aware and environmental friendly Telecom Networks and Data centers which take into consideration the cost of energy production and amount of Green House Gases emitted to the atmosphere when performing tasks like data routing through the Telecom Network, data retrieval in Data centers and Energy requests from the Smart Grid. The following techniques will be used to archive these goals; data-follow-the-energy, energy-follow-the-data and designing an interface that will enable communication between the Smart Grid control plane and Telecom Network/ Data Centers control planes. In our approach, we aim to minimize energy costs and greenhouse gas emissions by putting more emphasis on energy costs.

Data-follow-the-energy

In the data-follow-energy approach the Telecom Network and Data Centers will make decisions, such as data routing, data retrieval or storage based on the cost of the energy and the amount of Green House Gases emitted by each site. The Telecom Network/ Data Centers will need to gather information about the cost of energy production and Green House Gases emission from the different sites. The site(s) with the lowest costs of energy will be selected.

Figure 8.1 shows the path the Telecom Network would take to route its data to the destination, the one that is powered by less costly energy [3].

Figure 8.2 shows the Data Center site that will be selected during a data retrieval process, the one powered by less costly energy [3].
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Fig 8.1: Data routing through a site powered by cheaper energy
Energy-follows-the-data

In the energy-follows-data approach, a Micro grid A that has excess energy, (i.e. producing more energy than is being consumed by the devices connected to it), can be connected to another micro grid B that is in a state of deficit and therefore in need of energy. The surplus energy flows from Micro grid A to Micro grid B, implying that Micro grid B does not have to obtain energy from the grid, nor does it have to increase its dirty energy production, thus not increasing its carbon footprint.

Interconnection of the micro grids can be done by use of energy routers. Energy routers enable connection of different micro grids following circuit-switching techniques [3].
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Fig 9, shows the flow of surplus energy from Micro grid A to Micro grid B in order to satisfy the energy requirement of Micro grid B [3].

Fig 9, A micro grid shares its surplus energy with a neighboring micro grid

Service Orchestration between Smart Grid & Telecom Network

The Smart Grid and Telecommunications Network service orchestration involves combining the data-follow-the-energy and energy-follows-the-data approaches. In this case, the Telecom Network can select a network element in a given micro grid B to perform a task, for example route traffic, into which the Smart Grid can simultaneously provide with energy. In case micro grid B to which this network element is attached does not have enough energy to power the network device, a neighboring micro grid A with an energy surplus will send its surplus energy to micro grid B in order to satisfy this energy requirement. Energy transfer between the two micro grids is made possible by an energy routing switch which connects the two micro grids. All this occurs in an orchestrated way, hence the name service orchestration. This goal can be achieved through an interface, between the Smart Grid control plane and Telecom Network control plane/ Content Deliver
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Network Data Centers control plane (ICP) that will enable these ICT elements to interact with the Smart Grid, for example send energy requests to the Smart Grid. Fig 10, shows the interface between the Smart grid control plane and Telecom Network control plane, and how data-follow-the-energy and energy-follow-the-data approaches are combined [3].

![Diagram](image)

*Figure 10: Service Orchestration diagram*
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System description
Hereafter a more detailed description of the system, given the different approaches mentioned above, will be provided.

Each micro grid will be connected to an energy router. The Smart Grid control plane will monitor and share information such as the cost of energy production and percentage of green and dirty energy present in both the Smart grid and micro grid. The smart grid control plane will also control the transfer of energy to and from the Smart grid and micro grids. The smart meter will monitor and share information on energy consumption and the current energy cost/source to each client and provide the client’s energy consumption information to the Smart Grid control plane. This will enable the achievement of the main objective which is to minimize the energy costs while minimizing the percentage of Carbon dioxide emitted to the atmosphere.

Scenario:
A MicroGrid (MG) has an energy deficit (it needs more energy). It can take the energy from different “origins” (index \( i \)), even at the same time:

- \( i=1 \): produce its own energy
- \( i=2 \): obtain energy from a neighbor MG
- \( i=3 \): obtain energy from the Smart Grid (SG)\(^1\)

\(^1\) Assumption: the SG can always satisfy an energy demand
**Example:** A Micro Grid needs 40 kWh of energy

<table>
<thead>
<tr>
<th>Produce its own energy</th>
<th>Obtain energy from a neighbor MG</th>
<th>Obtain energy from the SG</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost = 10€ cent/kWh</td>
<td>Cost = 20€ cent/kWh</td>
<td>Cost = 30€ cent/kWh</td>
<td>10 kWh from itself → cost = 100</td>
</tr>
<tr>
<td>Availability = 10 kWh (max q.ty)</td>
<td>Availability = 20 kWh</td>
<td>Availability = ∞</td>
<td>20 kWh from neighbor MG → cost = 400</td>
</tr>
<tr>
<td>Emissions = $x_1$ g CO₂/kWh</td>
<td>Emissions = $x_2$ g CO₂/kWh</td>
<td>Emissions = $x_3$ g CO₂/kWh</td>
<td>10 kWh from the SG → cost = 300</td>
</tr>
</tbody>
</table>

Total provisioning: 40 kWh
Total cost: 800 € cent
Total emissions: $(10 \times x_1 + 20 \times x_2 + 10 \times x_3)$ g CO₂

The problem can be formulated as a *Linear Problem (LP).*
**Mathematical formulation** [32]

**Objective function:**

$$\min \left( \sum_{i=1,2,3} (c_i + \varepsilon \cdot d_i) x_i \right)$$

Subject to:

1. $$x_i \in [0,1]$$ (decision variables): percentage of energy taken from energy origin $$i$$
2. $$\sum_{i=1,2,3} x_i = 1$$ (all the required energy is taken from one or more energy origins)
3. $$c_i, d_i \in [0,1]$$ (costs and emissions are normalized in the interval [0,1])
4. $$0 < \varepsilon < 1$$, \(\varepsilon\) is a small factor (to lessen the importance of \(d_i\) with respect to \(c_i\))

Note: the time factor can be used only after the energy provisioning (e.g., in a simulation environment) to calculate the costs, emissions and energy consumptions during the simulation runtime.

Each origin of energy $$i$$ has a vector of energy sources:

$$\text{energy sources} = (\text{solar}, \text{wind}, \text{fuel}, \text{coal}, \text{nuclear})$$ (index $$j$$) from which it produces energy.
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Each energy origin can choose to produce energy from a subset of its energy sources, while they have the possibility to increase their energy production.

Each origin has:

- a vector of availability, measuring the current energy production increment of each energy source $j$ (i.e., how much energy can be still produced by the energy source $j$);
- a vector of emissions, measuring the CO$_2$ emissions for each energy source $j$;
- a vector of costs, indicating the cost (€ cents) per kWh produced by energy source $j$;

Therefore, each energy origin has a maximum energy production increase, given by $\sum \text{availability}$ and selects, according to its internal criteria, the energy source(s) it is using at each moment; when a new energy request arrives, or during periodic information updates, the energy origin selects, according to its internal criteria, the subset of energy sources from which the additional energy has to be produced, should the energy origin have been finally selected, and calculates the aggregated (among the various energy sources selected) values of emissions and costs.
Relationship between Smart Grid and Telecom Network/ Data Center
The diagram in Figure 10 shows the relationship between the different possible scenarios in the proposed system. A micro grid can produce more energy than is being consumed by its components (Energy surplus) or require energy to power one of its component or and in the given time not have sufficient energy (energy deficit). When a Telecom Operator/ Data center needs to perform a given task, it requires energy to do so. It would request the Smart Grid for the required energy. We will go on to describe in more detail each scenario in the next sections.

Figure 10: Energy System Use Case diagram
Micro grid state diagram
The diagram in Figure 12, displays the different states of a Micro grid, namely from having sufficient energy (that is energy demand by its devices is less or equal to the energy produced by the micro grid), to being in a state of energy deficit (producing less energy than is required by its devices) and how the energy deficiency is resolved.

When a micro grid is producing sufficient energy to power all the devices attached to it, it can disconnect from the electricity grid. When the devices consume more energy than the micro grid is producing, for example in case a telecom operator...
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needs energy to send data and there is not enough energy in the micro grid, the micro grid can reconnect to the electricity grid. Using the above given functions, the micro grid chooses between obtaining the required energy from a neighboring micro grid, the smart grid or producing its own. If the micro grid obtains energy from a neighboring micro grid, the energy obtained might not be sufficient to satisfy the amount of energy required by the micro grid. Therefore the micro grid will take the amount of energy being offered by the neighboring micro grid, then given the energy deficit, it can obtain a given percentage from the Smart Grid and or produce the energy itself depending on the energy cost and amount of greenhouse gases emitted by the given sources of energy.

How a Micro grid obtains energy
A Micro grid that needs to provide one of its devices (e.g Telecom Operator) with energy but does not have enough energy can choose amongst three options; Increase its own production of energy, Obtain the energy from a neighboring Micro grid or Obtain the energy from the Smart grid. The source of energy will be chosen depending on which option minimizes the main objective.
Micro Grid Energy deficit

The micro grid enters this state when it does not have sufficient energy to satisfy an energy request. For example, the micro grid needs to provide to one of the telecom operators connected to it, the energy to perform a given task and it does not have the energy required.
The telecom operator communicates its energy requirement to the smart grid control plane via the smart meter. The smart grid control plane which keeps track of the percentage of green and dirty energy in a micro grid responds to this by asking micro grid A or micro grid B or a combination of both to supply the telecom operator with energy. If one of the micro grids does not have sufficient energy to provide to the telecom operator, it will enter the state of energy deficit and then will choose to either increase its dirty energy production, or request energy from a neighboring micro grid or request energy from the smart grid, depending on which option minimizes the main function objective.

**Fig 13:** Sequence diagram showing how a Telecom Operator makes an energy request

**Micro grid Energy Surplus**
A micro grid produces more energy than the devices attached to it are consuming. The micro grid can send its surplus energy to another micro grid that is in need of this energy or store the surplus energy in batteries or send it to a telecom operator
that requires energy to perform a task or lower the dirty energy it is producing. In this case, the customer can be another micro grid or a telecom operator.

A micro grid receives a request for energy from either another micro grid or a telecom operator. Information about the amount of energy in the micro grid is managed by the grid control plane that monitors the percentage of green and dirty energy in the micro grid. A telecom operator is able to request energy from the micro grid via the interface between the two control planes.

Figure 14: Micro grid sends energy to a consumer

**Micro grid updates energy information**

The Smart grid control plane keeps track of the amount of energy each micro grid produces, i.e. the percentage of green energy and dirty energy in each micro grid. Whenever there are changes in the quantity of energy in a micro grid, for example an energy deficit or sharing of surplus energy with another micro grid, the Smart grid control plane updates its records to reflect the current status of the given micro grid.
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The smart meter will update such changes and inform the clients of the current energy cost/source. As energy is produced and consumed, both the Grid control plane and the smart meter will update their respective information.

Figure 15: Information update by Smart Grid
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Figure 16: Energy information update by Smart Meter

**Telecom operator serves a demand**
When a telecom operator needs to send data or process a query, there is a certain quantity of energy required to perform this task.

**Telecom operator sends an energy request**
In order to obtain the energy required to perform any given task, the telecom operator can chose to send an energy request to the micro grid to which it is attached or to the Smart grid. This is made possible by the interface between the smart grid control plane and the telecom network control plane.
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Figure 17: Energy request by Telecom operator

Energy-Follows-the-Data
A Micro grid A that has excess energy at a given moment, sends its surplus energy to Micro grid B that is in need to energy. The Smart Grid control plane contains up-to-date information about all the micro grids, therefore when the Smart Grid receives the status of the two Micro grids, it checks whether the surplus energy in micro grid A would satisfy micro grid B’s energy requirements/deficit. If it does, the Smart grid sends micro grid A, a message requesting it to send its surplus energy to micro grid B. This energy flow is made possible by the Energy routing switch that connects micro grid A to micro grid B.

In case the surplus energy is not enough to satisfy the energy requirements of micro grid B, micro grid B would obtain the required energy from the micro grid A, and the rest from the Smart grid, or by increasing its dirty energy production, or from a combination of the three mentioned energy sources.
Data-Follow-the-Energy

The Telecom Operator can choose the Micro grid, through which it can send or from which it can retrieve data depending on which Micro grid is best suited to optimize the main objective, being to minimize cost and carbon dioxide emitted. The Smart Meter provides the Telecom Operator with information on the emissions of each Micro grid and on the cost of energy.

In the scenario below, the Telecom Operator compares the information received about each Micro Grid and sends its data through the Micro Grid that optimizes the main Objective.
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![Diagram](image)

**Figure 19: Data-follow-energy**

**Service Orchestration**

Service orchestration combines the data-follow-energy and energy-follow-data approaches. Among different functionally equivalent possibilities, the Telecom Network can select a network element in a micro grid (data routing in the Telecom Network) to which the Smart Grid can simultaneously provide low cost energy (energy routing in the Smart Grid between micro grids).

The smart grid control plane communicates to the chosen micro grids the destination and amount of energy required by the Telecom operator/ Data Center, which we will refer to as ICT elements. The micro grids after checking whether they have surplus energy, provide information on cost of energy production and emissions. This information is communicated to the telecom operator which decides which energy source to select. In the scenario below, both micro grids do not have enough energy to supply to the ICT element. Both micro grids will
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compare the three energy source options, that is produce their own energy, obtain from a neighboring micro grid or obtain energy from the smart grid. In the diagram below, Micro grid B is connected to micro grid A which has surplus energy. Micro grid A sends its surplus energy to Micro grid B, resulting in lower costs as compared to obtaining energy from the Smart grid or increasing its dirty energy production. The amount of greenhouse gases emitted by micro grid B would also be lowered because it wouldn’t have to produce its own energy. Micro grid B and Micro grid C would communicate the energy costs and greenhouse gas emission to the Smart Grid Control Plane which would in turn send this information to the ICT element. In this case Micro grid B meets our main objective, which is minimize energy costs and minimize greenhouse gas emissions to the atmosphere. The ICT element selects Micro grid B as its energy source. The Smart Grid then sends a request to Micro A to send its surplus energy to Micro grid B which subsequently powers the ICT element.

In such a case, the ICT element and the Smart Grid can act in concert through the ICP interface: the ICT element’s control plane will ask the Smart Grid control plane to provide energy to its router/data center in micro grid B, thus selecting micro grid B instead of micro grid C according to a data-follow-the-energy approach, and simultaneously, the Smart Grid control plane will provision the required energy from micro grid A to micro grid B, according to an energy-follow-the-data approach.
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Figure 20: Service orchestration between the Smart Grid and Telecom Network control planes
Conclusion

This thesis has explored the design of an interface between the Smart Grid control plane and the Telecommunications Network control plane to enable communication between the two networks. The Smart Grid provides the Telecom Network with information about the current source of energy, cost of energy production, percentage of dirty and green energy available, and the Telecom Network selects its source of energy depending on cost and amount of Green House gases emitted. This in turn leads to a reduction of the operation costs of Telecom Networks, by reducing the costs of energy and also the amount of Green House Gases emitted to the environment.

The Smart Grid is still new, so the process of standardizing the technologies and protocols used in the Smart Grid Network is still on-going.

The move towards green energy sources is still in progress, so we hope to be able to choose sources of energy depending on the cost and amount of GHGs emitted as equal factors in the future.
References


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