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GREEN GRID METRICS IN NETWORK INFORMATION SYSTEM FOR MONITORING ICT SUSTAINABILITY IN DATA CENTERS

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ABSTRACT

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Green Grid Metrics in Network Information System for Monitoring ICT Sustainability in Data Centers

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Data center infrastructure is critical to manage the ever-increasing volume of data of today's connected world, consuming excessive amounts of energy in the process. This concern is the subject of several research and development projects, which have resulted in energy-aware and cost-effective solutions like routing and load balancing algorithms, energy and cost models, virtualization, and techniques for hardware and software optimization. However, when it comes to implementing monitoring, optimization, and energy management processes, new difficulties arise as a consequence of the difficult cooperation between the electric and the IT networks. This generates an opportunity for Smart Grid technology to provide an interconnection between the two. With the help of "smart" sensors and meters, real-time grid information from the generation plant, transmission lines, energy sources distribution, and end user's consumption can be provided as metrics into an intelligent system, in order to optimize the energy consumption of a data center facility. The goal is to propose a framework that integrates the information coming from the Smart Grid metrics into an ICT system, in order to improve the overall sustainability of a data center infrastructure and evaluate the impact on a green or cost-effective scenario.

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LIST OF SYMBOLS AND ABBREVIATIONS

AMI	Advanced Metering Infrastructure
DC	Data Center
DSO	Distribution System Operator
ICT	Information and communication technology
IoT	Internet of Things
MIB	Management Information Base
NMS	Network Management System
NIST	National Institute of Standards and Technology
PUE	Power Usage Effectiveness
PDU	Power Distribution Unit
QoS	Quality of Service
SCADA	Supervisory control and data acquisition
SG	Smart Grid
SNMP	Simple Network Management Protocol

1 INTRODUCTION

The growth of the Internet and new technologies such as Cloud computing and Internet of Things have caused a significant increase of data that needs to be stored, processed and available for large periods of time [2]. In order to accomplish these needs, the demand in both network infrastructure and energy to support it has grown at a very high rate. Moreover, by fulfilling these demands, large expenditures of non-renewable resources are being consumed and, as a consequence, large amounts of carbon emissions are being produced, increasing the environmental impact [3].

By 2030, the European energy consumption is expected to continue growing at an average annual rate of 1.4% [4]. A significant portion will come from data centers, which can consume as much energy as 25,000 households. In the results of [5] it is mentioned that in 2012, data centers consumed a total of 270 TWh worldwide; where the main sources of power consumption were cooling, networking, and compute devices. Furthermore, on 3-tier data center architecture [6], 70% of the total data center energy is consumed by servers, switching, and communication links, with the remaining 30% spent on cooling.

Energy expenditure is a big concern for companies, both in terms of the environmental impact of their equipment and the electricity price to maintain their infrastructure. Therefore, “green data center” approaches are starting to be implemented in order to decrease said impact. It is said that by 2030, the ICT global emissions will fall to 1.97% due to the investments that more companies are making to reduce their footprint and increase efficiency of devices [4].

Today’s research is focusing on concepts such as virtualization, energy-aware algorithms, and energy efficient solutions on the cooling, computing, and networking elements, in order to reduce electricity cost, improve management, and reduce the carbon emissions. The approach of this research is to exploit the interconnection of the Smart Grid and an ICT environment such as data centers as shown in Figure 1 [7], with the purpose of using the information of some metrics provided by the Smart Grid technology and combine it with information of a data center. This technology brings an “intelligent” grid concept in which energy and data are both distributed and monitored in real time, enabling a communication channel between consumers and suppliers. In addition, it also integrates renewable resources such as solar and wind power to the grid, allowing distributed green alternatives to be used by customers, thus, decreasing carbon emissions [8].

Nowadays, the information provided by the Smart Grid can be difficult for customers to get and use. With access to this information, customers can be aware of the quantity of energy received, the source (renewable and non-renewable) and CO_2 emissions of their equipment. By leveraging the metrics provided by Smart Grids, customers could improve the sustainability of the data center in terms of people, planet and profits, while meeting the capacity of the day-to-day operations, and reducing the economic impact of energy consumption. In summary, the research concentrates on a model that proposes an interaction of the communication network layer of the Smart Grid with the data center layer in order to use the information of the Smart Grid metrics as additional information that can have potential impact on the three pillars for sustainable development: people, planet, and profits of a data center.

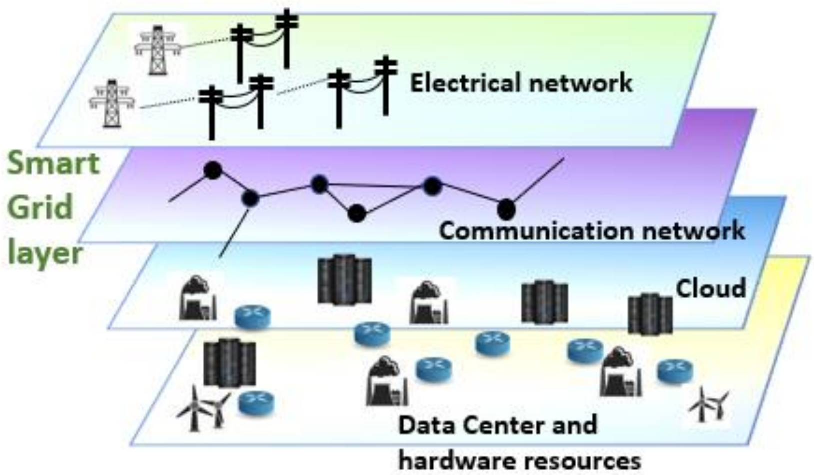


Figure 1. Approach of the interconnection with Smart Grid

1.1 Background

This section summarizes the principles of the Smart Grid technology, the fundamentals of how it works, the benefits of the technology including, among others, the services and information in the form of metrics that provide useful dynamic information. In addition, the data center metrics that are known in research nowadays are mentioned in order to have a further understanding on how smart grid systems can collaborate with data centers.

1.1.1 Smart Grid fundamentals

The typical electric grid consists on a one-way flow of electric power that barely provides an opportunity of information exchange between the power generators and the customers. Therefore, with the integration of information and communication technology, the concept of smart grid is born [9], allowing a bidirectional communication of power and data coming from smart devices, monitoring computers, and sensors that allows a better grid operation, automation and informed customers. In addition, this technology allows the connection of electric vehicles and renewable energy generators into the grid, increasing the use of green energy and reduction of carbon emissions [10].

The National Institute of Standards and Technology (NIST) presented a model in which the Smart Grid is divided into seven domains as described in [11], [12]:

a) Bulk generation, this refers to the first stage in which the power generators produce the electricity to be transmitted and distributed.
b) Transmission, where the generated power is transported by the electricity carrier over long distances.
c) Distribution, where the infrastructure components, actors and organizations involved on the distribution of electricity to the customer are involved.
d) Customer, refers to the section where the power is consumed by the different types of customers. Also, in here is where Smart Grid allows them to contribute with power generation of their own.

e) Market, this is where electricity markets exchange the resources.

f) Service Provider in charge of services for the different actors involved.

g) Operations, brings up the management of the electrical system.

The Smart Grid system consists on the layers described previously, the gateways and devices, as well as different services and applications. The information and services offered through the Smart Grid depend mainly on the number of advanced measurement devices connected, the number of meters installed, the voltage and power flow sensors, and the system automation architecture.

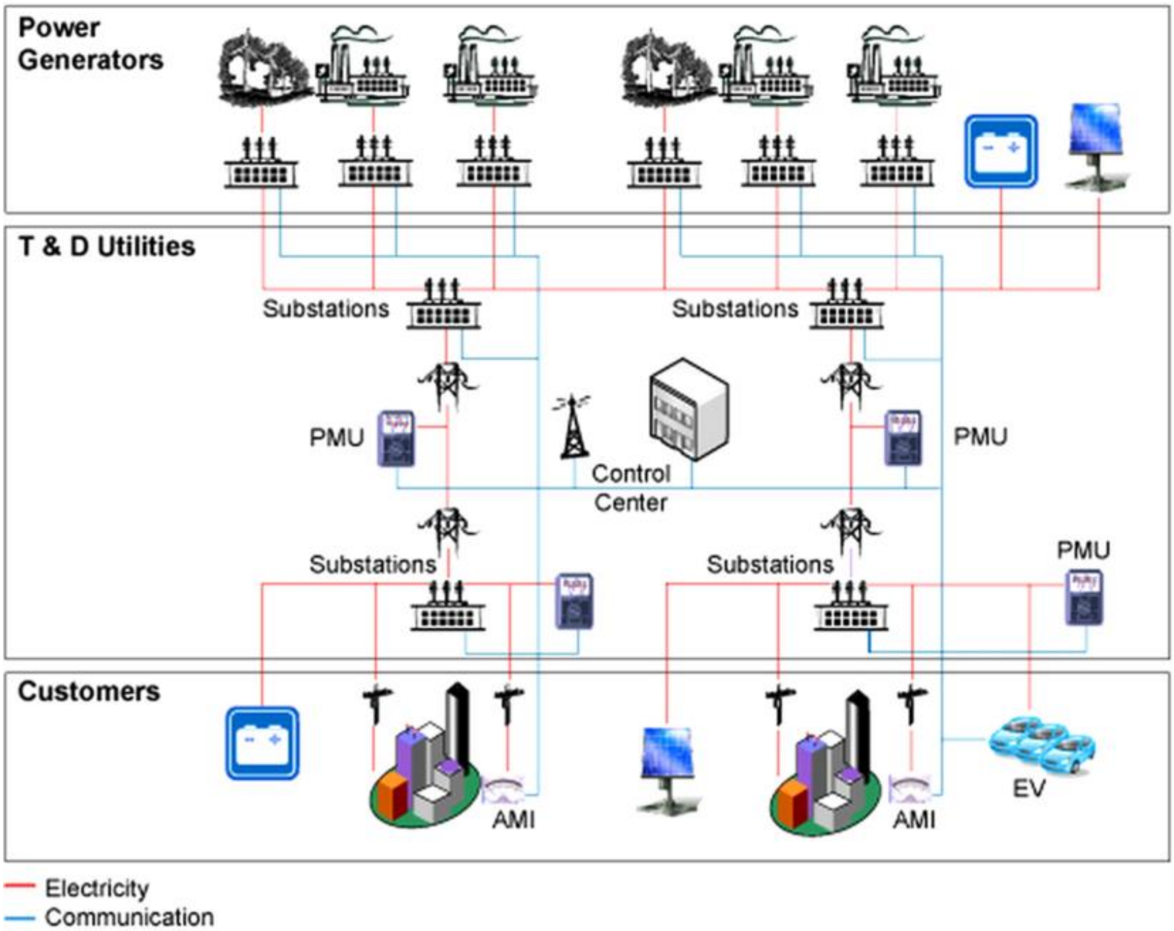


Figure 2 Smart Grid measurement diagram [10].

As mentioned, the Smart Grid allows the connection of numerous distributed power generators, both renewable and non-renewable, on the bulk generation layer. Once power is generated it travels through the transmission and distribution layer where the power is monitored with the help of sensors and the use of Phasor Measurement Units (PMU) close to the substations. PMUs assess the power flow, voltage, outages, and can search for faults as well in order to improve the reliability of the grid [10]. On the intersection of the customers layer, the Advanced Metering Infrastructure (AMI) [13], is the one that manages the collection and analysis of data from the smart meters. In the AMI infrastructure, different systems are involved such as meter data management, customer information systems, and demand response management systems. Both the substations and the AMIs are connected to the control center where the monitoring, the supervisory control, and data acquisition of the infrastructure is executed and services such as billing and dynamic pricing are applied. Moreover, applications such as Outage Management Systems, Distribution Management Systems, and Measurement Data Information Systems are involved as well [10].

The Smart Grid consists of networks from different parties such as electric districts and Telecommunications operators, hence, a network control center that evaluates and administrates the network interfaces is used. The entity that has access to the network control center is the Telecommunications operator itself and the Distribution System Operator (DSO) which is responsible for the maintenance and operation of the different devices and meters [14]. In order to enable communication between devices, different technologies are used such as Radio Frequency (RF), Satellite, fiber, Wi-Fi, cellular, and power line carriers.

In terms of the market domain, the demand response is one of the most popular services that the Smart Grid offers. It consists on the reduction of the customers consumption in peak times by offering price incentives. The service focuses on the load management depending on the demand [11]. All of the domains and elements information are considered in the form of metrics [15], in order to monitor, coordinate, and operate the components and the real-time information generated.

1.1.2 Smart Grid Metrics

To measure the performance and capabilities of the Smart Grid technology, the U.S Department of Energy brought a group of experts in 2012 propose and select metrics for this new technology. The document with the information of all metrics, their elements, stakeholders and challenges is reported in [16]. The metrics description and respective units stated on the U.S Department of Energy report are shown in the following table:

Table 1 **Smart Grid metrics** [15], [16]

Smart Grid Metric	Description
Dynamic pricing	This metric proposes a dynamic change in price depending on the customer type and the load they need to use, with prices varying on hours of the day and load served. The units: €/kWh
Load participation	It is a metric measured in MW, that enables a demand response program in which the customers can manage their load, reducing it on peak periods, and be rewarded with incentives
Load served by microgrids	It focuses on the capacity of the microgrids in MW and the percentage of total grid load that is served by microgrids
Grid connected distributed generation (renewable and non-renewable)	Refers to the quantity and the type of distributed energy generation (fossil-fired, hydrogen, and biofuels) and storage equipment connected to the grid (batteries, flywheels and thermal)
Non-generating demand response	This metric only refers to the load capacity of communication thermostats, HVAC, energy monitors, lighting control and water heaters.

Transmission and distribution reliability	Metric for performance of the grid that can prevent faults, isolate and reconfigure devices. It measures the System Average Interruption Duration, the System Average Interruption Frequency Index, and the Customer Average Interruption Duration Index.
Capacity factor	Metric of the grid performance that refers to the rate of electrical energy output over a period of time to the maximum possible energy output on that time. For instance, it is used to compare different types of electricity production.
Power quality	It refers to the percentage rate of the number of complaints in terms of power fluctuations over total customers.
Grid- connected renewable resources	Is a metric that measures the renewable energy as a percentage of total electricity and the CO2 reduced by renewable energy resources in tons.

1.1.3 Data Center metrics

Nowadays, the amount of data centers infrastructures is increasing in order to support the process, storage and availability of the data generated. The redundancy and reliability of the equipment, backup power supplies, air conditioning, and ventilation in the data centers are all concerns in terms of energy consumption, carbon emissions, and operational costs. According to [17], the servers are the main driver of financial impact with 45% of the total cost, the infrastructure with a 25% and the power draw and networking area both with 15% each. As a consequence of the growth on energy consumption, the costs and emissions increase as well. Therefore, the concept of energy efficiency and green ICT has been lately introduced onto existing data centers and is being considered on the new ones to come.

The Green Grid and the Energy Star Program proposed metrics [18] such as Power Usage Effectiveness (PUE), Data Center Efficiency (DciE), Data Center Productivity (DCP), and more, as well as benchmarks and best practices to improve the energy efficiency of devices and infrastructure. In [19] an analysis of over 130 data center metrics that goes from the starting point of the electric grid up to the delivery at the facility are discussed. Each of them are classified depending the dimensions of the data center infrastructure, with the following categories covered:

i. Energy efficiency metrics
ii. Cooling metrics
iii. Green metrics
iv. Performance
v. Thermal and air
vi. Network
vii. Storage
viii. Security
ix. Financial impact

The taxonomy of these metrics is shown in detail, each one of them with the description, advantages and disadvantages, units, objectives, and the equations on a separate appendix referenced on the paper [19]. In addition, diagrams that show the relationship between metrics and per category is presented as well.

The benefit of having the information provided by these metrics is that it can improve the design process, build, operation, and capacity management of data centers. Furthermore, it can enhance the energy efficiency by implementing improved monitoring, as well as optimization of the cost and energy consumption of the infrastructure.

Apart from the paper with different metrics discuss above, a complete table with the data center metrics classification is presented in [20]. On this table it is well observed which metrics are focused on energy power or on IT performance. Additionally, it can also be observed in which part system is the metric used, either on infrastructure or on IT, HVAC, or other components. The information is shown in the following figure.

	Energy/ Power	IT perform. (work)	Data center					Objective				
			Infrastructure	Component				Minimize energy use	Mimimize emiss./ source cons.	Renewable energy	Energy reuse	Scalability
				IT	*Support*							
					HVAC	Lighting	Others					
DC infrastructure Efficiency (DCiE)	x		x					x				
Power Usage Effectiveness (PUE)	x		x					x				
Key Performance Indicator of Task Efficiency	x		x					x				
IT-power Usage Effectiveness	x			x				x				
Total-power Usage Effectiveness	x		x	x				x				
Compute Power Efficiency (CPE)	x		x	x				x				x
DCeP energy Productivity	x	x	x					x				
Energy Reuse Factor (ERF)	x		x								x	
Green Energy Coefficient (GEC)	x		x							x		
Energy Reuse Effectiveness (ERE)	x		x					x			x	
Key Performance Indicator of Energy Reuse	x		x								x	
Key Performance Indicator of Renewable Energy	x		x							x		
DC Performance												
Coefficient of Energy Efficiency (CEE)	x		x	x				x				
DC Energy Efficiency & Productivity	x	x	x					x				
DC Performance Per Energy (DPPE)	x	x	x					x		x		x
Facility Efficiency (FE)	x		x					x				x
Carbon Usage Effectiveness (CUE)	x		x					x	x			
Carbon Emission Factor (CEF)	x		x						x			
Water Usage Effectiveness (WUE)	x			x					x			
Water Usage Effectiveness source (WUEsource)	x		x	x					x			
Energy Water Intensity Factor (EWIF)	x		x						x			
Energy Carbon Intensity (ECI)	x		x		x	x	x					
Onsite Generation Efficiency (OGE)	x		x						x	x		
Facility Utilization (FU)	x		x									x
Power Load Factor (PLF)	x						x	x				
Electricity Production Rate (EPR)	x		x							x		
(energy) Storage Efficiency (eSE)	x						x	x				
(energy) Distribution Efficiency (eDE)	x						x	x				
(energy) Conversion Efficiency (eCE)	x						x	x				

Critical Power Path Efficiency (CPPE)	x						x	x				
UPS Load Factor (UPS-LF)	x						x					x
UPS System Efficiency (UPS-SE)	x						x	x				
HVAC System Effectiveness (HVAC-SE)	x				x			x				
Cooling Load Factor (CLF)	x				x							x
Chiller Efficiency (Ch-E)	x				x			x				
Cooling Tower Efficiency (To-E)	x				x			x				
Water Pump Efficiency (WP-E)	x				x			x				
Lighting Power Density (LPD)	x					x		x				
Airflow Efficiency (AE)	x				x			x				
Air/Water Economizer Utilization Factor AEU or EUF	x		x		x					x		x
Others Load Factor (OLF)	x						x	x				
Cooling System Efficiency (CSE)	x				X							x
DC Cooling System Sizing Factor (CSSF)	x				X							x
IT Productivity per Embedded Watt (IT-PEW)		x										
IT energy Productivity (ITeP)		x										
IT Asset Efficiency (ITAE)	x	x		x								x
IT Equipment Efficiency (ITEE)		x										
IT Equipment Utilization (ITEU)	x			x								x
Data Center & Server compute Efficiency(DCcE/ScE)		x										
DC storage Efficiency (DCsE)												
DC network Efficiency (DCnE)												
IT Hardware Energy Overhead Multiplier (H-EOM)	x			x				x				
Deployed Hardware Utilization Ratio (DH-UR)		x										x
Deployed Hardware Utilization Efficiency (DHUE)		x										x
Server utilization (Server-U)		x										x
Storage utilization (Storage-U)		x										x
Network utilization (Network-U)		x										x
Compute Load Density (CLD)	x			x				x				
IT Recycling Metric (ITRM)	x			x					x			

Figure 3 Data Center metrics [20]

1.2 Motivation

The motivation of this research consists on brining awareness on the main aspects to consider in an ICT environment such as a “green data center”, by incorporating Smart Grid technology and the ICT network monitoring approach. In summary, the idea is to focus on how to improve the lack of collaboration between a data center and the Smart Grid in order to create a bridge to get useful information from the grid and use it for monitoring the energy use of a data center facility, analyzing the impact in terms of costs and environment.

1.2.1 Green Data Centers

As a consequence of the digital era and the growth on cloud computing in recent years, operators and ICT industries have been focusing in decreasing the energy consumption, costs and footprint of the datacenter. In the report [4], GeSI stated that ICT is considered to be responsible for the 2% of the global CO2 emissions, and projected to keep rising mostly because data centers are the primary energy consumers on the sector. It is worth noting that, from 2002 to 2011, the increase of the carbon footprint only on data centers was 9% per annum [21]. Hence, the concept of “green data centers” has been developed by focusing on green approaches and technologies that have been emerging in order to optimize the efficiency, utilization and performance on each of the data center elements and areas, the use of renewable sources, and to increase the overall sustainability of the infrastructure.

In[6], [22] a taxonomy for green data centers is described in which concepts, techniques, and surveys for each of the different areas of the data center are described. For instance, in terms of the network and computing part of the data center there are a big amount of different approaches that focus mostly on sleep modes in servers, switches and links, load scheduling, resource management, energy efficiency algorithms, and so on.

In order to apply a green approach on their data centers, companies are focusing on a better management of resources and energy consumption of the infrastructure. For instance, Schneider Electric is a company that has developed different tools and calculators for customers to use for estimation of energy use, carbon emissions, total cost, and so on as shown in Figure 4.

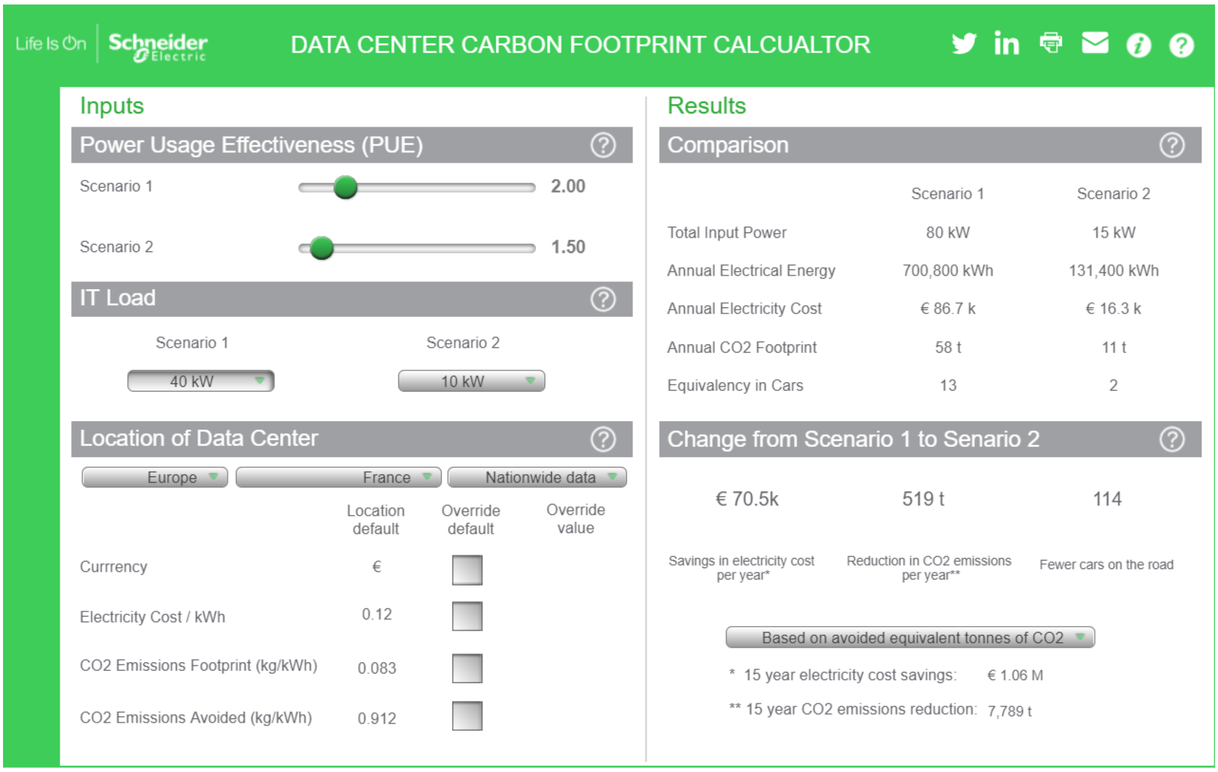


Figure 4 Schneider Carbon footprint calculator [23]

1.2.2 ICT Network monitoring

The importance of having real-time information such as the energy consumption regularly monitored can help ICT organizations to mitigate resources, optimize costs and waste, make maintenance easier, manage their networks, and so on.

The need of a monitoring method in which organizations can collect the information necessary of electricity and energy use of the whole network and of each component is essential. Current research in network monitoring [24] describes the use of a Management Information Base (MIB), a hierarchical structure where the data collected is stored, and

Simple Network Management Protocol (SNMP) as the communication protocol that will be used by the monitoring system to pull the requested information from the MIB.

In addition, the demand of equipment that supports monitoring, management and efficient energy transport is fundamental. In data centers, the use of Power Distribution Unit (PDU) is popular in terms of power and environmental monitoring. This device [25] can distribute the electric power through all the devices of the network that are connected and provide real-time data of power and even temperature and humidity. All the information provided makes the monitoring and control of the network and its elements easier and accessible.

It has been discussed that there are different approaches and techniques to enhance the "greenness" of a data center and improve the power efficiency of the facility focusing on more efficient hardware such as servers, power supplies, network elements, and CPU, as well as better software solutions like virtualization. However, being able to measure certain variables and collecting real-time data allows for better management of the facility, which can have an impact on future capacity planning. Moreover, knowing the conditions of each data center network element can also have significant impact on failure prevention, optimal performance, and the overall reliability, availability, and serviceability of the infrastructure.

1.2.3 Interconnection with Smart Grid

The bidirectional communication of electric power and data is what makes the grid "smart" and different from the conventional grid. The real-time data is coming from different smart sensors and meters that send information to the control center on the transmission and distribution domain. This information is shared to distributed energy management systems that can analyze the data for improvements on the efficiency and reliability of the grid services and future issues detection, decision making and optimization [26]. Numerous Smart City projects have been developed in the past years. In parallel, more and more data centers are created every year, having a big impact on energy use, cost, and environment impact. For projects such as DC4Cities [12], the main objective is to have eco-aware data centers on smart cities that can use renewable energy. Since, the Smart Grid allows for connection of renewable sources and provides dynamic information useful for monitoring and management, it serves as a solution for the issues discussed on the DC4Cities project.

As stated before, the Smart Grid consists of a combination of the electrical and the IT network and provides a big amount of real-time information. One of the problems identified though, is that is difficult for customers, in this case a data center manager, to have access to the information going through the smart grid because of the heterogeneous interaction of different entities and networks. There is no direct connection between the electrical network and the communication network of a data center.

1.2.4 Sustainability development pillars

The concept of green data centers is focusing on the mitigation of resources and energy use which has a positive impact in terms of costs and environment. [27] emphasizes that an ICT analysis should not only focus on the beginning of the product life to the validation and verification, but that, in order to truly make a system sustainable, the ecological, ethics and profit areas should be included in the full engineering of ICT [28]. For instance, the environment aspect can be improved with the use of renewable sources, reduction of e-waste and carbon emissions. Furthermore, the health and other factors that improve the quality of life should be considered on the people pillar. A key aspect is to have a balance between the three pillars shown in the following figure, where the improvement of the environment area, can generate a positive impact on the health and on the costs in long term, which creates a meaningful equity that improves the “greenness” of the entire ICT.

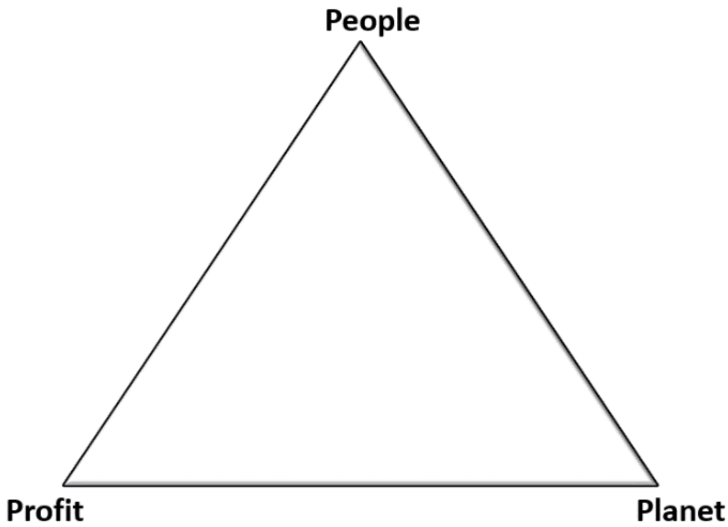


Figure 5 Pillars of sustainable development

1.3 Research questions

This research focuses on identifying the gap between the use of dynamic information going through a sustainable solution such as Smart Grid on a data center and propose a way to manage this information for further use. Moreover, the importance of the concept of sustainability applied on a data center is highlighted in order to explore if the information of the Smart Grid metrics in combination with the data center information can have some impact in terms of financial and environmental aspects.

The questions that this research is trying to answer are the following:

i. How does the Smart Grid dynamic information impact a data center budget and environmental footprint?
ii. Does the combination of metrics proposed, influence the evaluation of the environmental and economic impact of a data center?

iii. What is the impact on budget and footprint of different data center equipment specifications?

The previous questions will be evaluated on each step of the methodology of this research and will depend on the literature review of the technology and the design and implementation phases. There, the proposed model will show the combination of information of different systems that will be used on a software dashboard. Additionally, to test the potential impact of different values, the creation of different scenarios will be shown to analyze how would different metrics affect the overall sustainability in terms of the profit and planet pillar.

1.4 Research structure

The remaining part of this research is organized as follows: Section 2 includes the related work, which is comprised on relevant work that is complementary to the focus of the thesis. Section 3 presents the methodology of the research, with the main purpose of describing the objective of the research and present the logic behind the developed solution with the different steps that were followed during development. The whole implementation of the model is described thoroughly in Section 4, including the architecture for the model. More specifically, the model will show the selected data center and smart grid metrics integrated, the graphical display of the information, model equations, and the different scenarios to evaluate it. Section 5 concludes the research and discusses future work.

2 RELATED WORK

In the related work section, the investigation on the green approaches of data centers in terms of energy, cost and carbon management are covered. Different techniques, models and algorithms for better administration of information that can improve the sustainability of a data center are discussed. The work shown in this chapter also shares the point of view of this research in terms of the use of dynamic information for management of data centers. Moreover, the exploration of existing network monitoring approaches on ICT and on Smart Grids are investigated as well.

2.1 Green approaches on data centers

In terms of energy-aware routing algorithms, the authors in [29] discuss an algorithm that focuses on minimizing the carbon emissions of data centers, while taking into account the available renewable energy. The analysis is made by evaluating the brown energy consumed by a shortest path-based routing algorithm that selects the closest data center in comparison to a renewable energy-aware routing which uses a longer route but green powered. The paper shows a comparison between the algorithms in order to observe which one minimizes more brown energy and emissions. In addition, a comparison on different networks is also done. The proposal is made with the use of three algorithms for CO2 emissions:

a) SWEAR (Sun and wind energy-aware routing), which compares the path with the lowest transport power consumption and the path with maximum usage of renewable energy.

b) GEAR (Green energy-aware routing), which finds the path with the lowest non-renewable energy consumption.

c) BGD (Best green data center), which chooses the data center with the highest renewable energy availability and routes the connection to that data center, such that the renewable energy utilization is maximized.

Similarly, the design of a carbon-aware algorithm is explored in [30]. in this paper, the authors explain the use of Lyapunov optimization methods in order to create a framework that can support dynamic decision making for a better control in terms of server speed scaling, capacity sizing, and geographical load balancing. An important factor on the load balancing technique is shown, basically, it is based on the variability of electricity price and carbon output, which are some of the metrics that this thesis is selecting as well.

In addition, there is more research on the dynamic information of electricity pricing and availability of renewable energy discussed in [31]. The contribution is a system that increases the use of renewable energy in cloud-scale data centers. Basically, the goal is to manage the data center network with the use of request dispatching on the proposed middleware. This investigation shares the focus of this research in terms of implementing a management framework of the data center with the use of dynamic information such as the electricity cost and renewable energy, while analyzing the budget impact.

Another important work that reflects the importance of reducing brown energy and the use of dynamic information is presented in [32]. The investigation proposes three algorithms for the optimization of load balancing in distributed geolocations. The aim is to evaluate that the geographical load balancing can minimize the brown energy use, while considering dynamic energy pricing. The authors describe three different models, one for the workload, another for the energy cost, and finally one that focuses on the lost revenues for delays. One thing that makes this research quite complete is the fact that it focuses on 14 different data centers, each one on a different state of the United States of America.

The previous work shares some of the important points of this thesis such as the focus on the environmental impact with the use of green energy and with the use of dynamic electricity price. However, none of them mention the use of Smart Grid as a direct connection to the data center for it to provide real-time information. Moreover, only the selection of electricity cost is considered.

2.1.1 Data center cost-aware approaches

Numerous investigations on the cost-aware field are being done for data centers by means of algorithms, models, and techniques that focus on the minimization of cost.

An interesting paper about an algorithm for green data centers using renewable energy and reducing the cost of the fossil fuel energy with the use of a virtual machine allocation algorithm is described in [33]. Although the approach is good, it is based on a stand-alone power system, meaning that is not connected to the national electric grid, unlike the Smart Grid proposal pf this thesis.

The authors in [17] describe resource problems in terms of cost of a data center cloud. It proposes geolocation techniques to optimize the data center resources. Also, it describes how to reduce the cost in the case of servers, infrastructure, power and network. It is a useful paper for this thesis in order to know todays difficulties in the management and selection of data center elements, and the cost impact per element.

Additionally, a paper that describes the cost-effective operation of a data center that takes into account real-time electricity pricing is shown on [34]. The authors propose a stochastic dynamic program for predicting workload and electricity price, and tested on different scenarios. Besides that, crucial concepts like demand drop and demand delay are discussed and later evaluated in terms of workload and electricity cost impact.

Another interesting research was made in [35], focused on the cost minimization of a data center with the use of energy storage. Different models are proposed and described on this work: workload, battery, QoS, power consumption, and electricity price models, each of them is used on a stochastic program. The idea is to use a Lyapunov optimization method in order to create an algorithm that distributes the amount of traffic of a data center, while lowering the electrical power required.

2.2 Network monitoring

There are different investigations for monitoring of networks on an ICT environment. For instance, in [36], the importance of real-time monitoring is discussed. The paper is based on the monitoring of the distributed energy resources of the Smart Grid. Basically, the 7th Framework Program European Project INTEGRIS is introduced, and the authors highlight the improvement of the Quality of Service (QoS), explaining the lack of efficient information exchange. However, the proposed analysis is focused on the own centralized SCADA system of the Smart Grid. Nonetheless, the importance of real-time monitoring for detecting faults, fix them and change Network configuration is described. Similarly, in [37], the authors focus on the reliability and control of the network in order to improve the QoS. A framework for the data aggregation and management of the energy distribution grids is discussed.

The previous papers show the benefits of network management and its importance for the focus of this thesis, in terms of the proposed model for collecting information from the Smart Grid. A very detailed paper that explains each phase of the network monitoring based on SNMP protocol and a MIB to collect the data is presented in [24], the basis of the concepts and theory is well shown.

Also, the authors of this paper [38], present a Network Management System (NMS) which is also based on SNMP and the use of MIB to monitor, collect and process the data with the help of multithreading. The implementation of the framework of the NMS is explained and the elements that it consists on are:

- An agent which is the one responsible for the tasks of all the network components.
- A network management protocol, which is SNMP.
- A management model.

Moreover, the work in [39], presented a novel NMS that is energy-efficient in order to monitor the power consumption on an ICT environment. For the monitoring, the use of SNMP and MIB was explored as well to further implement a platform that can detect and then isolate faults on the network. The architecture proposed demonstrates the use of a PDU to obtain the power consumption information of the devices of the network and for executing the monitoring directly from it.

2.3 Smart Grid technology approaches

Supporting research is discussed in [7], where the potential impact of an interconnection between Smart Grid and Cloud infrastructures is highlighted with the objective of exploiting capabilities of the Smart Grid; such as the availability of renewable energy, real-time monitoring, and measurements, to optimize energy management in distributed Clouds.

A similar approach but on a different environment is reviewed in [40], where the authors explore how the Smart Grid infrastructure can be able to communicate with a Telecom network control plane in order for the network to have information about energy sources, cost, and request energy quality and quantity depending on the network task. In the paper, a service orchestration is proposed that combines two approaches:

I. Energy-Follows-the-Data, where energy routers are used to connect microgrids, and one microgrid that has additional green energy can transmit it to other microgrids that do not have green energy.
II. Data-Follows-the-Energy, where the telecommunications network can send their data to the sites that are powered by green energy sources.

An approach of the use of Software Defined Networks (SDN) in the context of Smart grid is described in [41], where the authors developed a platform to support resiliency whenever a failure occurs, with dynamic and real-time information for control and monitoring. Additionally, an architecture using SDN and integrating it with all the layers of the grid is proposed.

The work presented in [42] introduces the service of voluntary load reduction in cloud computing data centers. Basically, the concept of demand response of Smart Grid is explored. This technology allows the load participation of the customers to be a part of the Smart Grid model, therefore, a data center is considered as a load resource to the grid. The use of mathematical models and queuing theory is leveraged to optimize data center demand levels, bids, and service rate.

Authors in [43] explore the concept of utilizing Smart Grid technology, presenting a potential solution to improve the reliability of the network by the use of smart grid sensors along with global positioning systems in order to perform a decrease of the duration of interruptions and their cost.

A contribution on the topic of minimizing the electricity cost of data centers is presented in [44], where the use of energy storage in Smart Grid environments to minimize costs is discussed. The authors use a Markov decision process to create an energy management model and they also present a Q-Learning algorithm for the energy storage control policy.

Each of the previous investigations focus on the potential use of Smart Grid technology to improve allocation decisions for cloud resources, communicate with a telecommunication network to control the energy, or exploit the services and capabilities of the Smart Grid to decrease costs. However, in terms of the literature review made on this research there is a lack of existing work that uses the dynamic information of the Smart Grid. The research gap on this issue generated the initial motivation to write a proposal to use the Smart Grid metrics as additional data that can be combined with other metrics in order to evaluate if there is an actual contribution and impact on the whole sustainability of a system.

3 METHODOLOGY

This thesis is approached in

i. The first step of the research consists on the critical review of the different works of the potential use of Smart Grid technology on ICT. Research on the information coming from metrics of this technology is made, with emphasize on: data center cost and environmental impact and the existing solutions to improve the greenness and reduce costs with the use of data center metrics. Based on the literature review a gap analysis and research questions are formulated with the idea of using the metrics available to provide valuable information to be used on a data center environment.
ii. The second phase consists on the first contribution of this research that focuses on the design and proposal of a theoretical model that shows the potential interaction between the smart grid and the data center systems. The system model enables the combination of information coming from the Smart Grid metrics and from the data center and generates results that will allow the data center to estimate energy use, cost and greenness of the facility.
iii. Next, the third step consists on the implementation of a dashboard that shows the interaction described on the previous phase. The dashboard works as a calculator like the ones shown from Schneider, and allows for different inputs of data to observe different outcomes on a daily, yearly and per server manner.
iv. Then, the structuration of the data is executed in order to apply the model in different scenarios. Three scenarios are done by changing the value of the selected Smart Grid and data center information, this is made for the purpose of comparing the outcomes on a low, average and high value cases.
v. Finally, this phase concentrates on the results of the previous scenarios, all the values calculated for each scenario are normalized in order to generate graphs that will help us assess the sustainability part of the outcome of each case in terms of cost and environment.

4 DESIGN AND IMPLEMENTATION

As explained on the methodology on the previous section, a set of steps with different analysis and implementation has been done for this research. The main three contributions will be discussed on this section.

4.1 Smart Grid Information

One of the concerns that has been discussed since the beginning of the research is a way to create a connection for collaboration between the data center and the Smart Grid layer. As mentioned on the fundamentals section of this work, the Smart Grid has a network control center in which the Network Management System evaluates the network interfaces. With the use of agents, the management of each network element is executed, but in order to allow the communication between the agent and the network control center, a network management protocol is necessary.

The authors of this research previously worked on this concern, since the research is not only focusing on the proposal of using the information of the metrics but also for the customer to be able to access this data. In [45], the idea of the use of a Power Distribution Unit for monitoring network devices and a green Management Information Base (MIB) with the objective of making the metrics accessible via SNMP is proposed.

An MIB is composed of a tree structure where the data is arranged in a hierarchical manner. The identification of the different parameters in the tree is done by the use of Object Identifiers (OID). The Smart Grid metrics are the ones discussed in [15] and based on those the MIB tree was proposed selecting grid metrics sets that would provide meaningful information. On the tree in the following figure, we can observe cost, power load, reliability. energy sources, and CO2. Each metric set encompassed has sub-metrics that were proposed in order to present more relevant information of a network system.

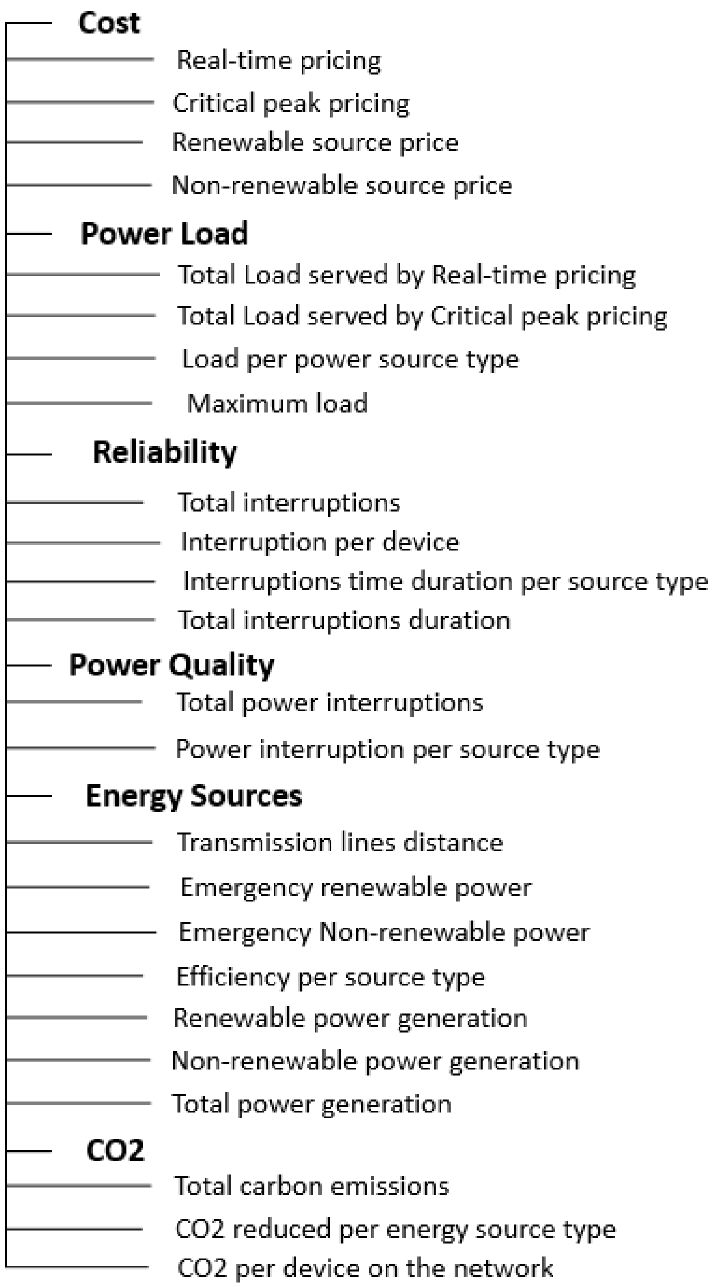


Figure 6 Smart Grid metrics tree [45]

The SCADA model of this research, proposes the interconnection of the different layers in order to collect and use the data from the grid. The Smart Grid metrics should be pulled in order to feed information for a Network Information System. The paper explores the use of protocols such as SNMP or also NETCONF/YANG.

The selected metrics would need to be transferred to the MIB, making it possible to get the information and use it later on different scenarios. Combining both approaches results in a solution that facilitates the collaboration between the data Center network and the Grid information.

4.2 Smart Grid and Data Center Interaction

The design of the model considers the investigations made on the literature review of the Smart Grid technology and information that is going through it along with the research on the data center information. For the objective on the interaction of both systems, a selection of specific metrics on both systems needs to be made to evaluate the model with different scenarios.

4.2.1 Data center Information

Data center facilities have been exploring different methods and technologies to improve the energy efficiency of the facility and individual components. It has been mentioned that the importance of having energy-efficient metrics can help data centers improve their future capacity planning, provide information for benchmarking different facilities, costs optimizations, and enhance the eco-friendliness of the infrastructure. However, categorizing and tracking data center metrics is complicated, since it needs to be categorized but also kept independent to understand which metric is for which component of the facility. A framework of data center energy metrics is explained in [20], where each of the metrics is described and categorized depending on the components of the data center such as the site infrastructure which refers to the power delivery and cooling and the IT equipment that refers to the computing equipment such as storage, network, workstations, monitors, and so on.

For a better understanding on how the model is developed, an explanation of the interaction process needs to be described; first of all, the information of the energy supplied, available renewable energy, carbon emissions, and power quality are going through the Smart Grid provided by many sensors, meters, and gateways on the infrastructure and then sent to the network control center. The energy supplied is consumed by a data center facility infrastructure, mainly on the network, storage, and computing components.

The analysis made on this research focuses more into some of the smart grid metrics that can contribute to the overall expenses and green metrics category. For example, the quality of energy of a data center facility improves with the use of renewable sources and consequently produces a reduction of the CO2 emissions and even long-term energy cost savings. This information can be provided in real-time by a smart grid metric. The metrics analyzed were the ones mentioned on section 1, the metrics were evaluated from the equation form, breaking down the parameter used for its calculation, and identified which ones could be linked with the information coming from the Smart Grid. The following diagram show an example of expected relations for some of the Smart Grid metrics identified to provide useful information to the data Center metrics or that can be used in combination for further data center evaluation.

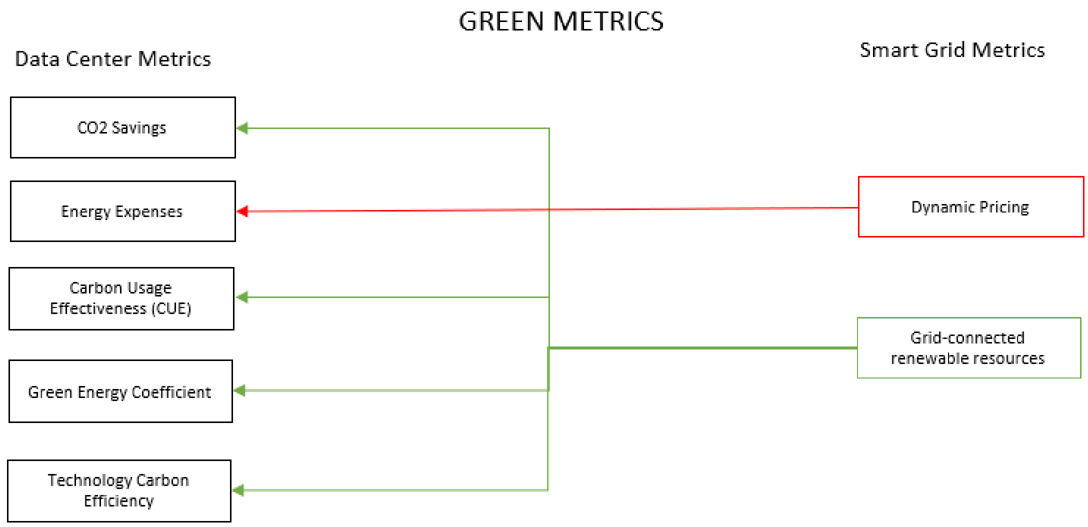


Figure 7 Relation between green DC and SG metrics

The previous diagram serves as an example that shows how the information coming from both of the Smart Grid metrics can be used on the calculation of data center metrics. For instance, the dynamic pricing metric contributes with dynamic information of the electricity price that will depend on the load and energy that the data center equipment uses. Moreover, the grid connected renewable resources metric provides information about the amount of green energy that is being fed and used by the data center infrastructure and the carbon emissions that are generated, or reduced by the use of renewable energy. This information can be used on the calculation of green metrics such as CUE, carbon efficiency, green energy coefficient and so on.

On one of the papers of the DC4Cities solution a table with the metrics and the level of popularity is provided [20], where the PUE metric is the one with high popularity and usability. Thus, it is one of the metrics taken for scenarios and model evaluation on this thesis.

4.2.2 Systems interaction model

The concern that has been accentuated on some related work investigations and along this research is the involvement of the smart grid into an ICT environment, as mentioned in [7], for a better management of a data center energy there should be a collaboration between the electric and the data center network that allows the access of this information. Some of the benefits that can come of this interaction are:

a) Resource mitigation
b) Monitor of real-time energy information
c) Exploitation of renewable sources
d) Minimization of emissions
e) Energy optimization

The proposal of a mediator system that can enable interconnection of the two systems (ICT: data Center and Smart Grid) would allow the transparency of information to the user and make future decisions based on data to be gathered from a single interface. In addition, the benefits of having real-time information can improve resource mitigation, the optimization of costs, capacity and eco-friendliness.

The architecture of the model presented in Figure 8, basically shows how the SCADA system will work as an intermediary for Smart Grid and data center systems. The first stage of the integration is developed based on the idea of the collection of the information coming from the SG with the MIB and SNMP idea presented on the first stage of the implementation. It is important to mention that in terms of the accessibility on the network control center that contains the information of the SG architecture is complex since there are permits policies and entities that needs to be considered. Once the SG information is collected, the second stage, is to select some data center information on a specific case and the system will combine the information.

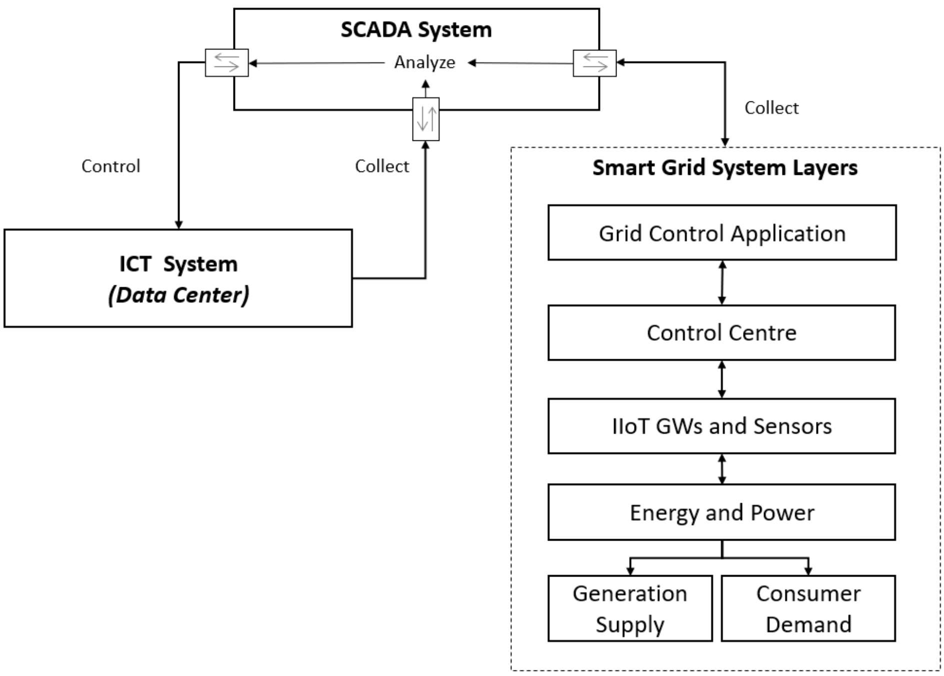


Figure 8 SCADA system model architecture

On the Smart Grid System, the metering and sensing elements, communication infrastructure for the bidirectional flow, applications, and control center for the Smart Grid to work are all included. The SCADA system should be able to collect, analyze, decide and control the information coming from the metrics of the Smart Grid in order to use it on a data center. The collection and analysis can be used in different scenarios depending on the data of the ICT System and the decision and control can be further implemented in the form of optimization algorithms, load balancing, routing and so on.

In terms of the data center information, data such as the PUE, the server load, the power supplied to the facility, and the input power that depends on the number of servers and respective load was selected for a specific data center case; this information will be combined with the SG metrics selected. It is worth noting that there are numerous data center metrics, thus for this first proposal, only some of them were selected to be used and tested in different scenarios. The selected information in both systems is presented for better understanding on the following figure, the diagram shows which information of the grid and of the data center is utilized in further calculations that results into useful information about the data center energy supply, cost and emissions.

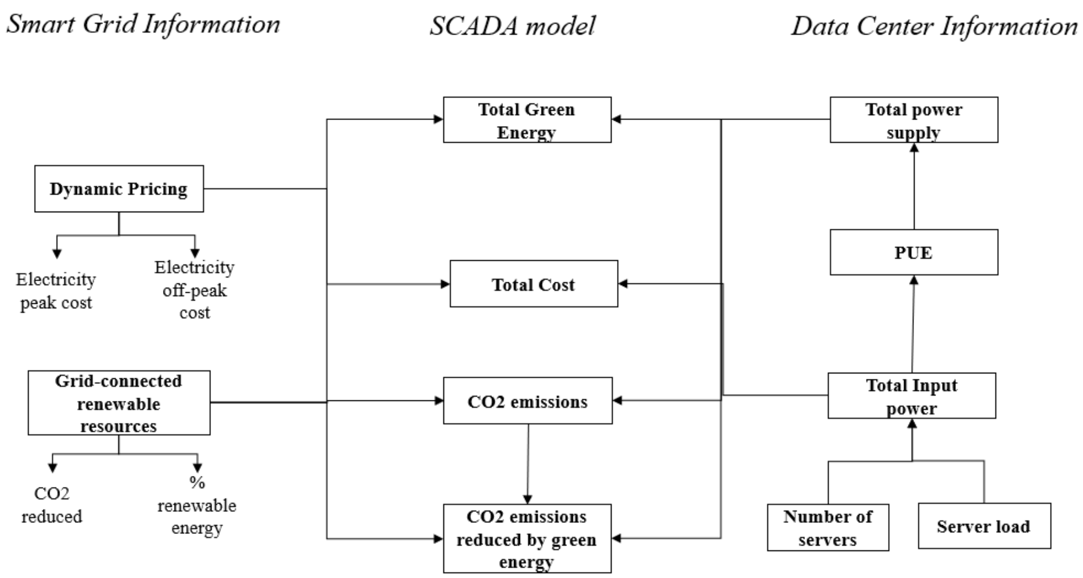


Figure 9 Interaction of Smart Grid and Data Center information

The information of the SCADA model shown on the previous diagram is the result of the combination of certain metrics of the other two systems. For further implementation, the model needs to put the information together in the form of equations. These equations will later be tested with different data assumptions and applied on particular scenarios that show the change on the results while varying some of the metrics selected. It is important to mention that the information selected can be changed in order to test different scenarios.

First, for the input power, the assumption is that the only one of the components of the data center are the servers. It is known from the background that the servers are the main component, and contribute to the largest amount of energy consumption in network components. Therefore, the two important data points to consider for the calculation of this metric are the number of servers and the load. The load can vary depending on the utilization and the capacity of the equipment.

$$Input\ power\ supplied = Number\ of\ servers * server\ load \tag{1}$$

This metric is of data center information only but is important in order to calculate the total energy of the data center, which is needed for further calculations. With the PUE given as an input and the calculation of the input power supplied, the total power of the facility can be calculated. In order to transform power to energy, the result of the total input power is multiplied by the 24 hours of one day, leaving the units of the metric in Watt per hour.

Next is the calculation of the total green energy. The connection of renewable sources is possible as one of the many benefits of the Smart Grid. Certainly, the energy coming from these sources is included on the total power supplied and as described on the Smart Grid metrics on the U.S Department of Energy report, this metric comes as a percent of the total load.

$$Total\ Green\ Energy = Renewable\ energy\ percentage * total\ input\ energy \quad (2)$$

In terms of the carbon emissions calculation, the need of the carbon emissions factor is crucial. For this research, the factor used is for only one country. The carbon emission factor varies depending on the country, and in our particular case, the country selected is France. Moreover, the renewable energy must be subtracted from this calculation since the renewable energy doesn't produce carbon emissions.

$$CO2\ emissions = (Total\ input\ energy - Total\ Green\ Energy) * CO2\ factor \quad (3)$$

This metric shows the CO2 emission generated in tons but as mentioned on the report, Smart Grid provides the information of the tons of CO2 emissions reduced by the renewable energy.

Finally, for the total cost metric, different information coming from the Smart grid is used. The dynamic pricing metric of the grid provides real-time information of the electricity cost depending on the load and also on the off and on peak hours. The information of the number of off-peak hours and the cost on peak and off-peak hours considered in this research is for France, since electricity price and peak hours are different on each country and sometimes even on regions.

$$Total\ cost = \left((Off_{peak\ hours\ per\ day} * \ Electricity_{average\ cost})\right) + \left(24 - Off_{peak\ hours\ per\ day)} * \ Electricity_{peak\ cost}\right) * Total\ input\ power \quad (4)$$

The previous equations are based on the theory of collecting dynamic information from the Smart Grid, so on a real-time scenario the variables could be changing even every hour. The outcome data from the equations will be used for an evaluation in terms of the greenness and cost of the data center. The assumption made on this research is that the equations presented are per hour data. Hence, in order to get the yearly data, we just need to multiply it by the number of hours on a year and for the data per server just divide the different results by the number of servers.

The information presented for both smart grid and data center serve as inputs and the equations presented use the inputs of the two systems in order to calculate meaningful information for a better resource mitigation and sustainability analysis.

4.3 Dashboard Implementation

In the case of a data center, it is important to have good management tools for the information of each of the devices and components of the facility. The second contribution of this research encompasses the need of an interface that allows the user to observe the information that is being provided. A simple graphical display would help simplify administration and monitoring in order to improve the supervision and future data center analysis. This interface is implemented as a web server using HTML, Bootstrap, jQuery and CSS for the frontend, and JavaScript for the backend.

The dashboard needs to show the input information of the smart grid and the data center system for a better visual of which metrics are being used. Two important tools are shown, first, is the annual and per server results and second, the option for the user to change values of the input information as a simulation mode, which enables users to view different scenarios that can help on the design and analysis of future capacity planning of a data center, evaluation of costs, and greenness with different data center requirements and configurations.

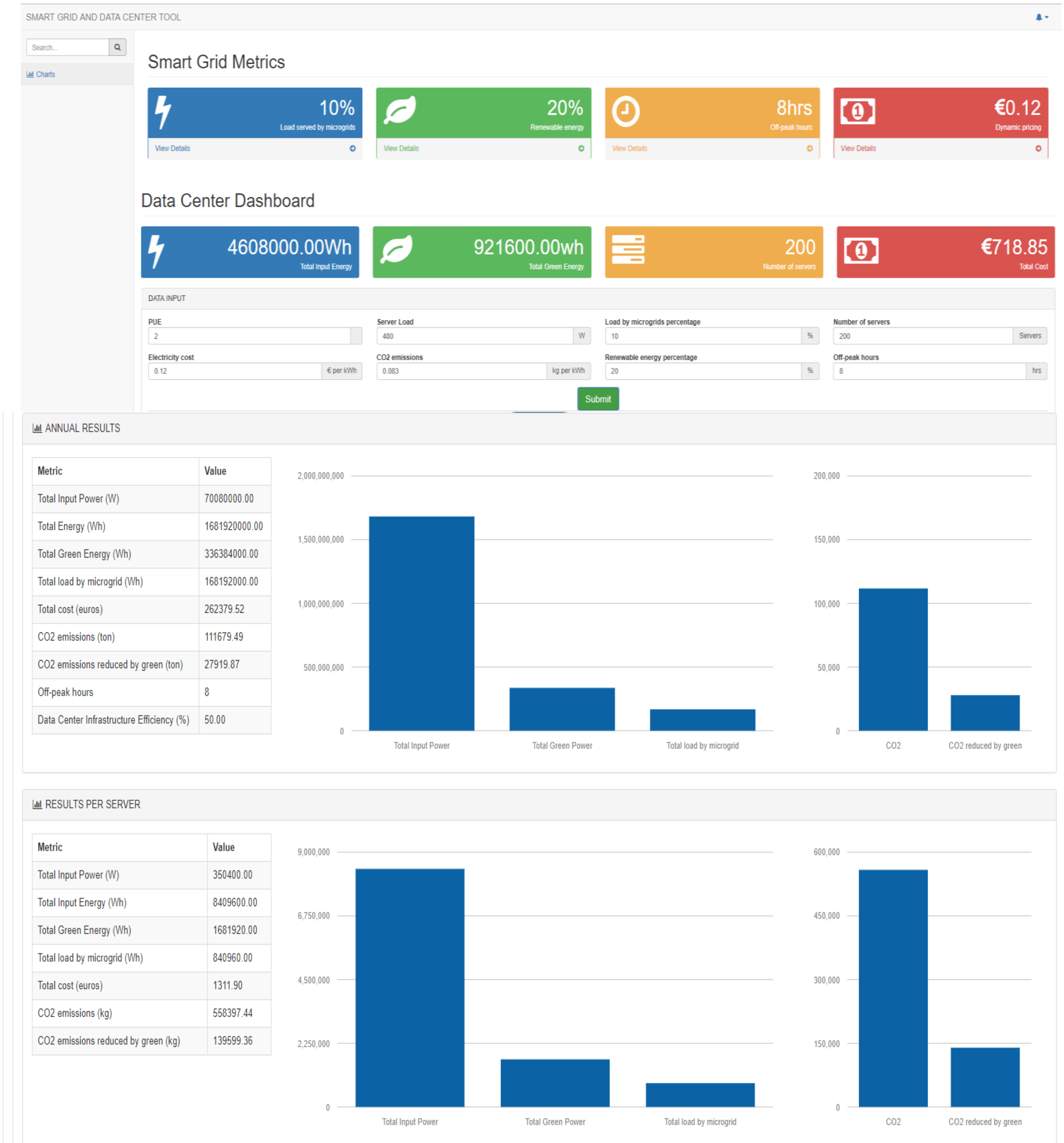


Figure 10 Smart Grid and Data Center information dashboard

The information shown on the dashboard has the inputs of a basic scenario created for a comparison and evaluation purpose that will be explained in details in the following section. It is important to mention that this dashboard works as a calculator as well, similar to Schneider's tool. The user can observe the final results of the inputs that want to be measured or tested for both, the smart grid and the data center information. However, on the real scenario the information of the smart grid is dynamic and it can be changing even every hour automatically.

4.4 Data Scenarios

The dashboard presented allows the user to change the values of the information in order to observe the impact and to evaluate the outcomes of different decisions or configurations. On the research questions of this work, the impact in terms of cost and environment is mentioned, thus, different scenarios were assumed in order to monitor the impact and how each of the values is affected when a different input is given.

For the purpose of comparison, a basic scenario is needed. This scenario will be taken as a basis of a certain data center with a fixed number of servers, an average value of server load, and an average value of PUE.

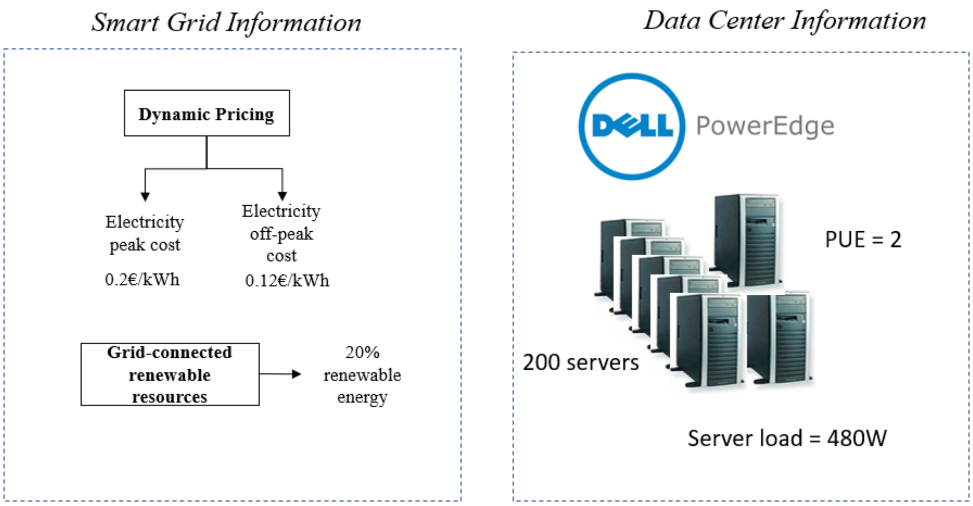


Figure 11 Basic scenario

The different scenarios that are proposed in this research consist on the change of data center parameters such as the server capacity and peak hours and change on smart grid information such as the renewable energy percentage, the pricing depending on the off-peak and critical hours and the carbon emission factor in France. The model presented previously, with the different equations is executed with the information of the basic scenario.

The following scenarios were proposed in order to have an answer to the questions of this research.

I. **Server capacity scenario.** One of the questions on this research was formulated around the impact that a data center with different specifications can have. Therefore, this case is implemented in order to analyze the impact (financial or environmental) when different servers are used. The servers analyzed on this scenario are all Dell Power Edge, but the model and the capacity differ from each other, so they are categorized as low, average, and high capacity power servers. The high capacity server is a R440 with a load of 550W and the low capacity server is an 850 model with 345W. The specifications of each of the models are found on the data sheet of the Dell Power Edge products.

II. **Green supply scenario.** The metric of renewable percentage injected on the data center is good in terms of the environmental impact since it allows more green energy to be used. Thus, this scenario changes the value of that percentage to observe the impact when there is a high or a low supply of green energy. For the low green supply the percentage is 10%, for the high is 30% and the basic scenario shows the middle value which is 20%. The percentage of this energy supply depends on the number of renewable resources connected to the grid and close to the data center facility.

III. **Peak hours scenario.** The dynamic pricing metric that the Smart Grid technology provides consists on the variation of electricity prices depending on the amount of load and the hours. On the research articles, it is said that the average of off-peak hours is 8 and most of the time on late night since the workload and busy user requests are generated in the morning. This is a value that is dynamic and can change depending also on the season and country. The scenario presents the options of a smaller number of peak hours with the average of 8 hours as the middle comparison point.

The application of the higher green energy supply scenario on the implemented dashboard can be observed on the Appendix I, showing how the variability of the system. It clearly shows the results of the calculations of the model with the high supply of 30% of renewable energy as the best alternative for a sustainable the data center facility.

4.5 Model Evaluation

The model evaluation consists on the structuration of the information that is valuable in order to be used for the evaluation of the scenarios presented and to observe the expected results of impacts on each of them. When the changes on the input variables on each scenario are made, the table of result with the metrics that uses the information of both systems needs to be analyzed. This analysis consists on the selection of the metrics that are actually having impact after the change of input.

The purpose of the evaluation of the model is to observe the impact in terms of environment, cost and different data center specifications when the data of the systems working on our model varies. It is important to monitor the final outcome of the model since ideally the information of the smart grid is dynamic and can change within the hour. By modifying the inputs, different scenarios can be generated and the impact of this assumed dynamic information can be tested. The metrics that use the information of both systems on an equation as shown previously generate useful data, consequently, these metrics are the ones that are calculated on each scenario with the different input changes.

For instance, on the Server Capacity scenario, the server load is different depending on the specification of the equipment, hence, an impact on the input energy, the carbon emissions and the total cost is expected. When the capacity of the server is higher, the energy consumption and carbon emission increase and, as a consequence, the total cost will increase as well. The annual and per server results of the three impacts mentioned previously are observed on the following figure.

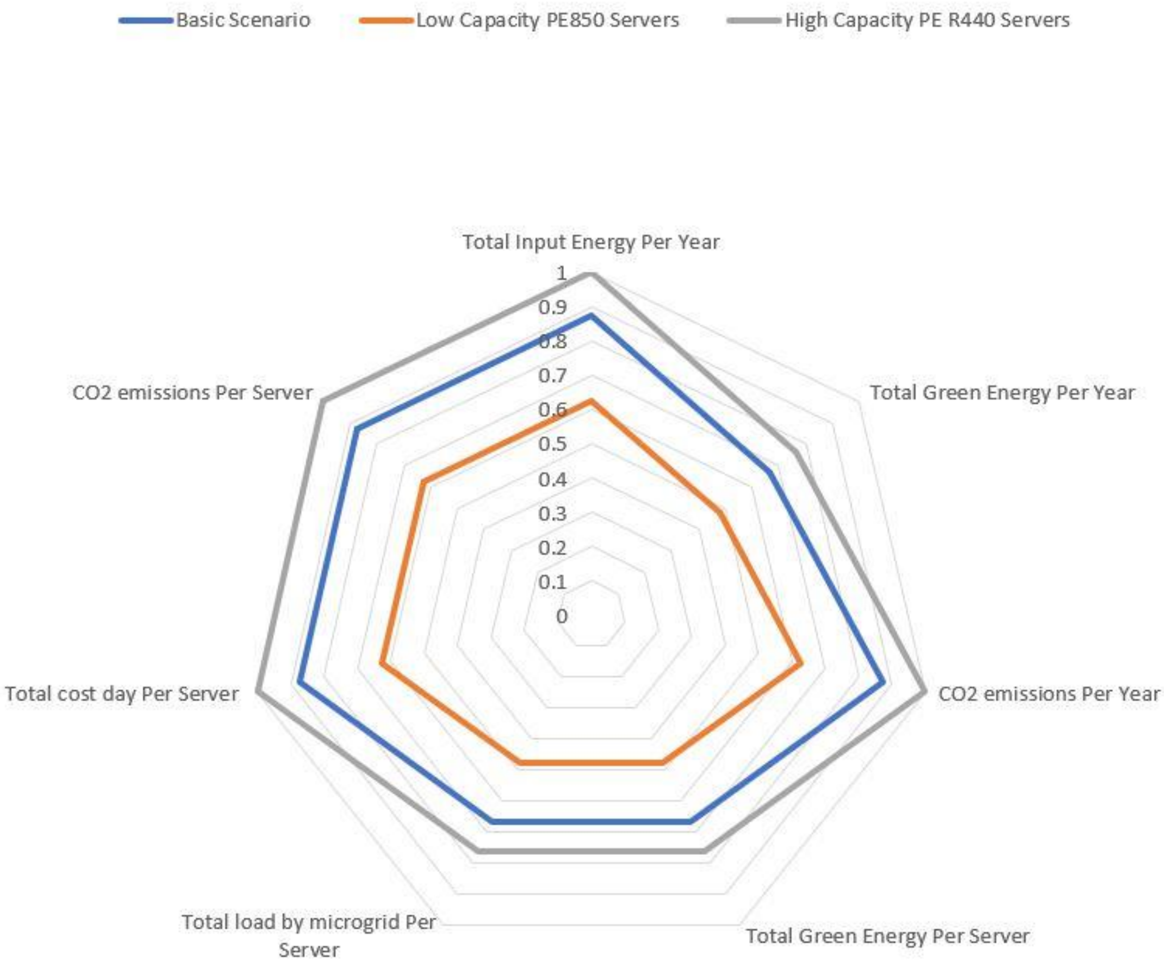


Figure 12 Server capacity scenario results

In terms of the Green supply scenario, the model needs to evaluate how the percentage of renewable energy can have an impact on the environment since it provides green energy to the facility and also reduces the carbon emissions. It is expected that if the percentage of green supply is lower the reduction of the emissions won't be that significant as shown in the following graph. Of course, the green supply will depend on the number of renewable generators that are connected to the grid. It is not possible to know which percentage comes from which type of renewable source but only the percent of the total load that is green and the carbon emissions that are being reduced by that percentage.

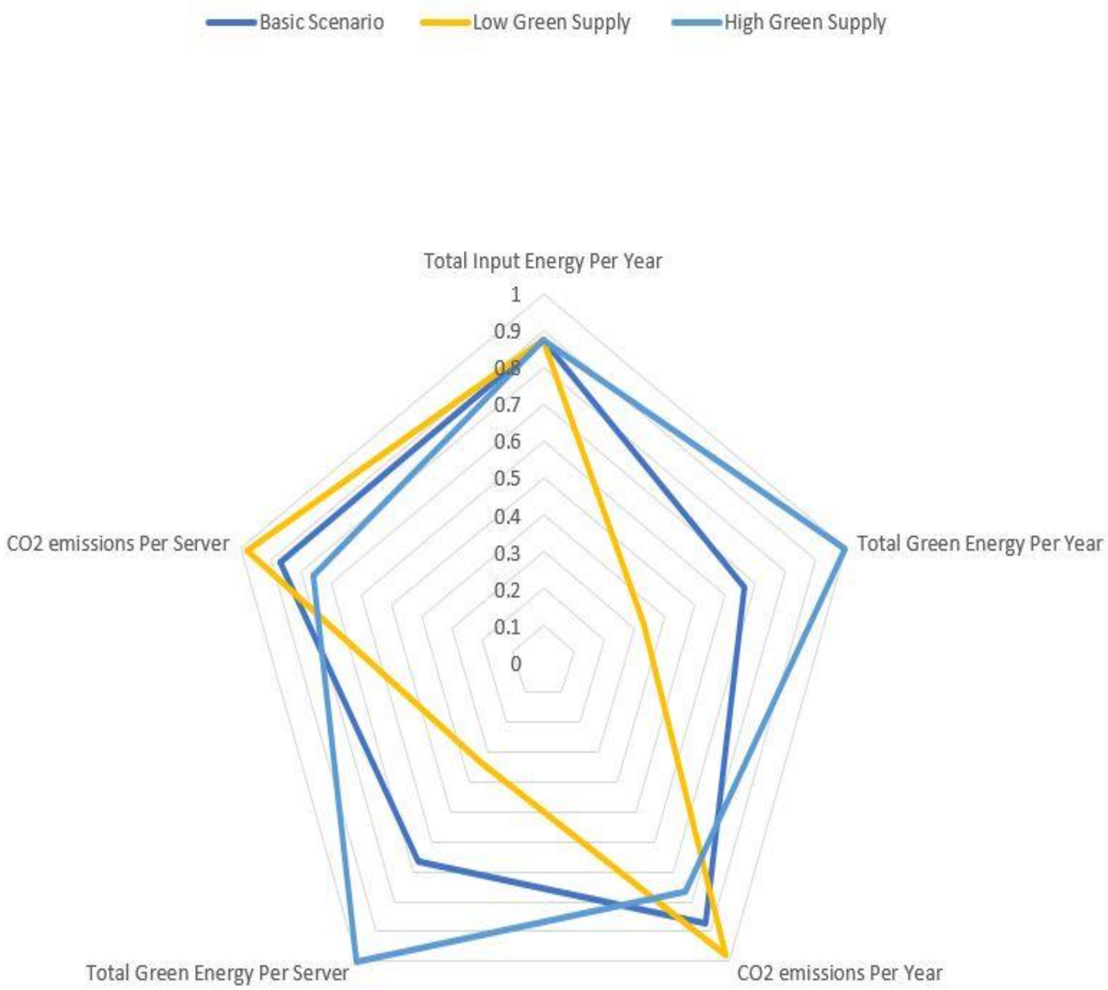


Figure 13 Green supply scenario results

Finally, on the Variation of peak hours scenario the impact relies on the financial pillar. The dynamic pricing metric of the smart grid carries the information of the electricity pricing that differs depending on the load. For instance, the peak hours the load is higher and therefore the cost is bigger. The metric dynamically changes the value depending on the critical peak time, if the hours of peak load are higher, the total cost will increase as well since the electricity price increases on this number of hours.

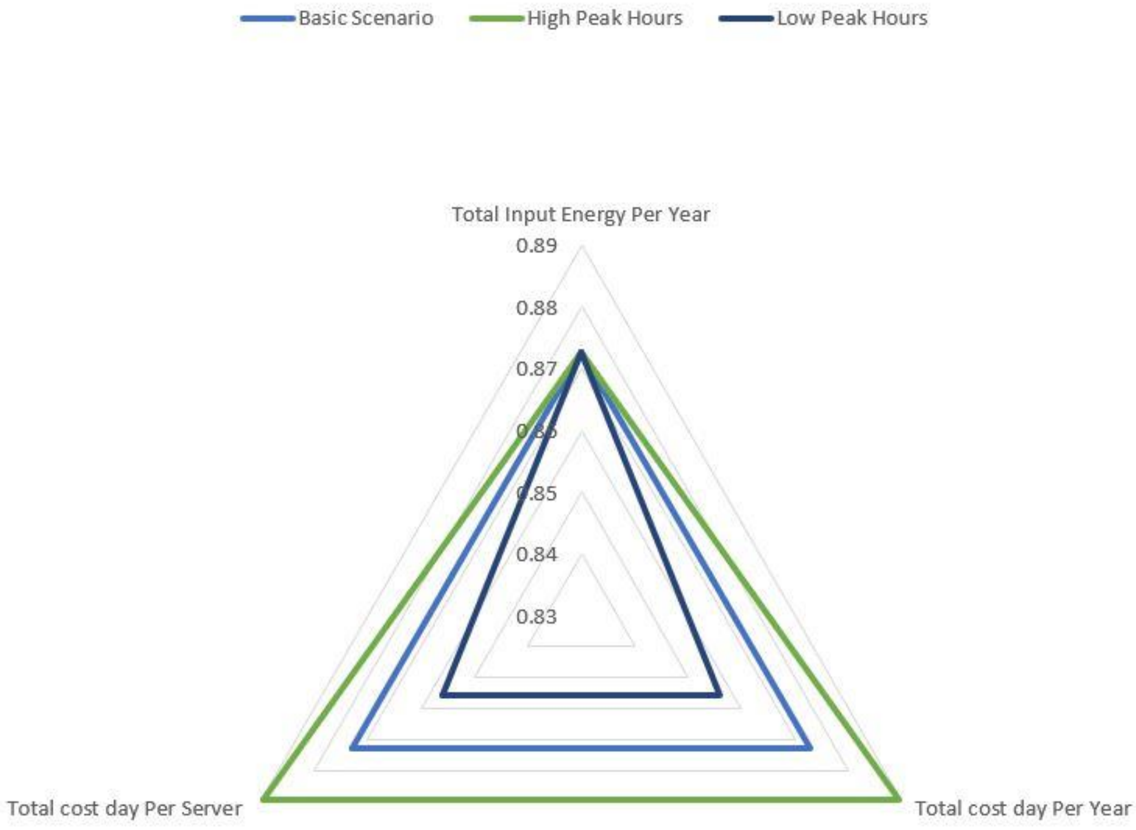


Figure 14 Variation of peak hours scenario results

The complete calculations of each of the variations on the input of the scenarios is annexed on the Appendix II, this final data was then normalized in order to create graphs of each scenario that can help for a better evaluation since the impact on the model metrics can be observed more clearly.

4.6 Sustainability impact

The addition of the Smart Grid metrics on a sustainable system can be observed on the following figure. To provide additional real-time information regarding the greenness of the energy, the carbon emissions generated and reduced by the renewable energy, and the cost that varies depending on the load and peak time of use has a potential impact on the profit and planet pillar.

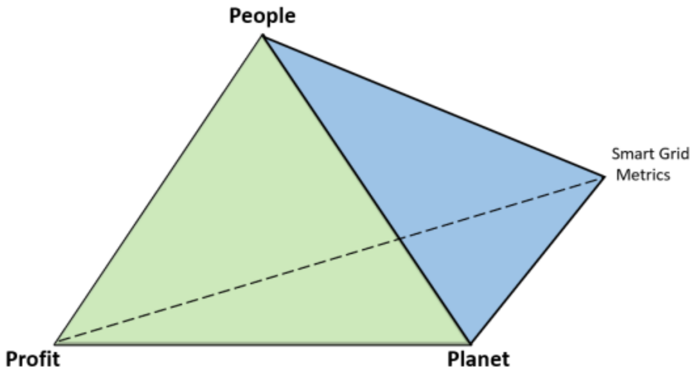


Figure 15 Smart Grid metrics on a sustainable system

All the previous scenarios showed an impact on the financial and environmental sectors. With this information, further decisions can be made in order to optimize the costs, plan the data center configuration, implement more green energy, or even not only be a consumer of energy but a producer too, since the Smart Grid load participation service allows this possibility.

On the Appendix III, a sustainability analysis of the model proposed is shown. On this analysis, the general impact can be observed. For instance, in terms of the Social pillar, our model is assumed to be working with dynamic information which allows the transparency of information to the user. In terms of environmental impact, the model provides resource mitigation as well as renewable energy and carbon emission reduced information. moreover, for the profit domain, the model allows long term cost savings.

5 CONCLUSION AND FUTURE WORK

The objective of this thesis was to research the possibility of a system that could introduce the key value of the interaction between the Smart Grid and a Data Center environment from which the possibility of collecting and using the dynamics of the grid in combination with data center information was explored. This chapter concludes the research and presents some future work.

5.1 Conclusion

In this thesis we proposed the interaction of two systems: The Smart Grid system and the ICT system, more specifically, a data Center on a theoretical model. The proposed model assumes that selected Smart Grid metrics can be collected. The information coming from the grid can be combined with selected data center information in the form of equations that use these inputs in order to create the link between the two systems, and drive decision making. Therefore, a framework for analysis and data exchange of data centers and Smart grids is not only feasible, but impactful in the overall design and capacity management of the data centers.

In addition, an evaluation of the model with different scenarios was made, where the analysis on the financial and environmental impact was shown depending on the outcome of the combined information of the model. For instance, in terms of the financial aspect of a data Center, dynamic pricing metric depending on the peak hours had a big impact on the total cost. Also, in terms of the environmental aspect, the renewable energy metric is the one that provides valuable information and impact on the carbon emission and greenness of the data center. Furthermore, the data center infrastructure with different specifications specification (in this case, the different server capacity), has a final impact on both, the data center budget and carbon emissions.

The model allows the user to have information transparency with an interface that shows valuable information and that allows system analysts to further evaluate different proposals.

Finally, the metrics gathered by this system can serve as inputs for future optimization algorithms, closed-loop metric control systems, management of information, resources, and cost optimization, while increasing the greenness of a data center.

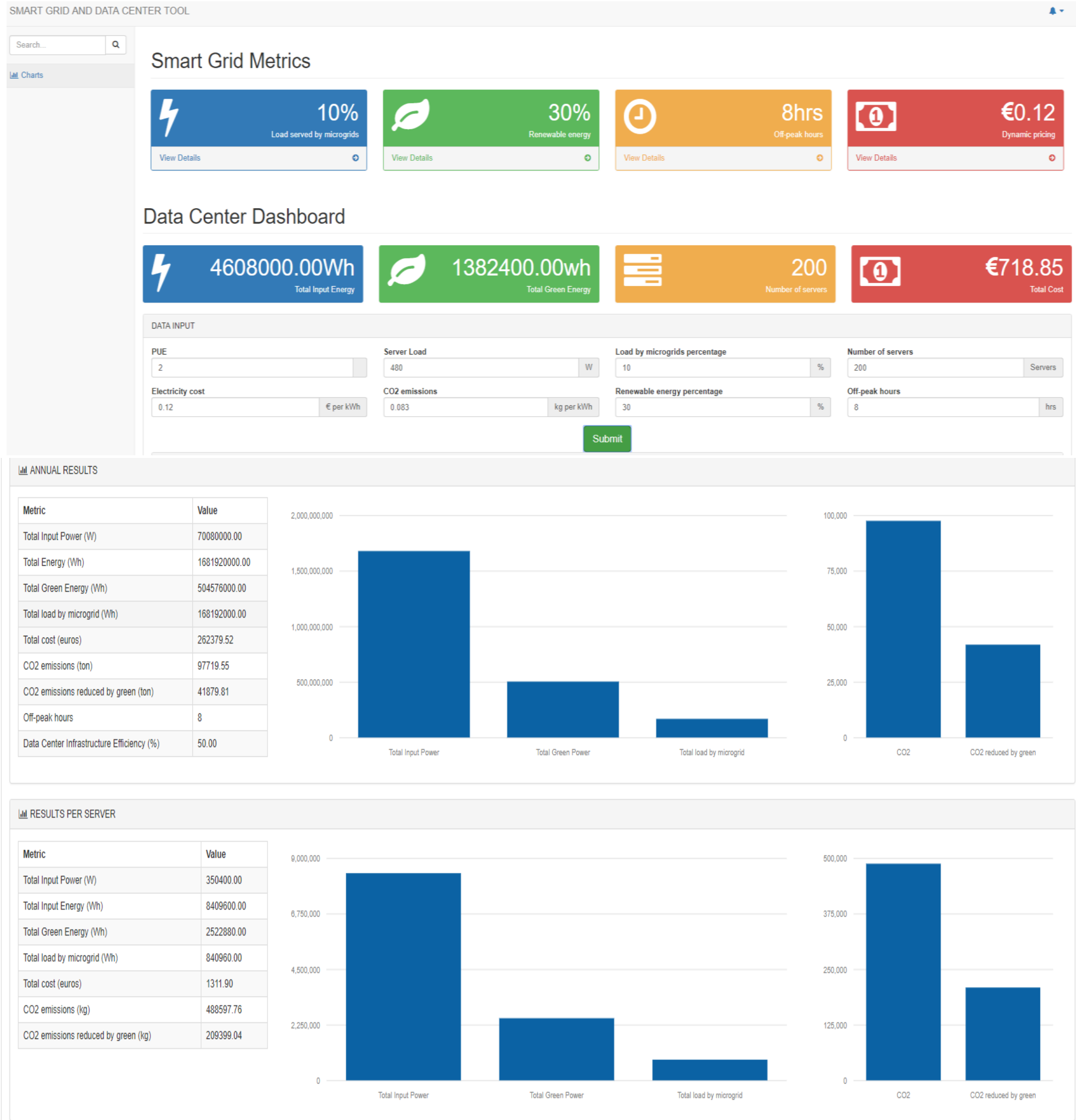
5.2 Future Work

The information presented on this research is the first stage of the integration of the systems where the collection and evaluation of data is made, the next step would be to implement some control loops on the metrics, with this, we can manipulate and make decisions depending on the information given. Today's research has been focusing in cost and carbon-aware algorithms, hence, further actions and control can be explored with the use of the information of smart grid and data center by developing load balancing routing algorithms that optimizes price and eco-friendliness.

For better management and evaluation, more data center metrics that were presented and investigated on this research could be implemented on the model and the dashboard. On the related work, numerous data center metrics were evaluated, however on this research, only the most significant ones were included. Hence, additional metrics can be added, or some assumptions can be relaxed, like the focus of the servers as only loads.

In addition, this research assumed that a data center would be located in France, since there are metrics that can be influenced depending on the country. An extension of this thesis on different countries can be considered as a future work opportunity as well.

APPENDIX I.



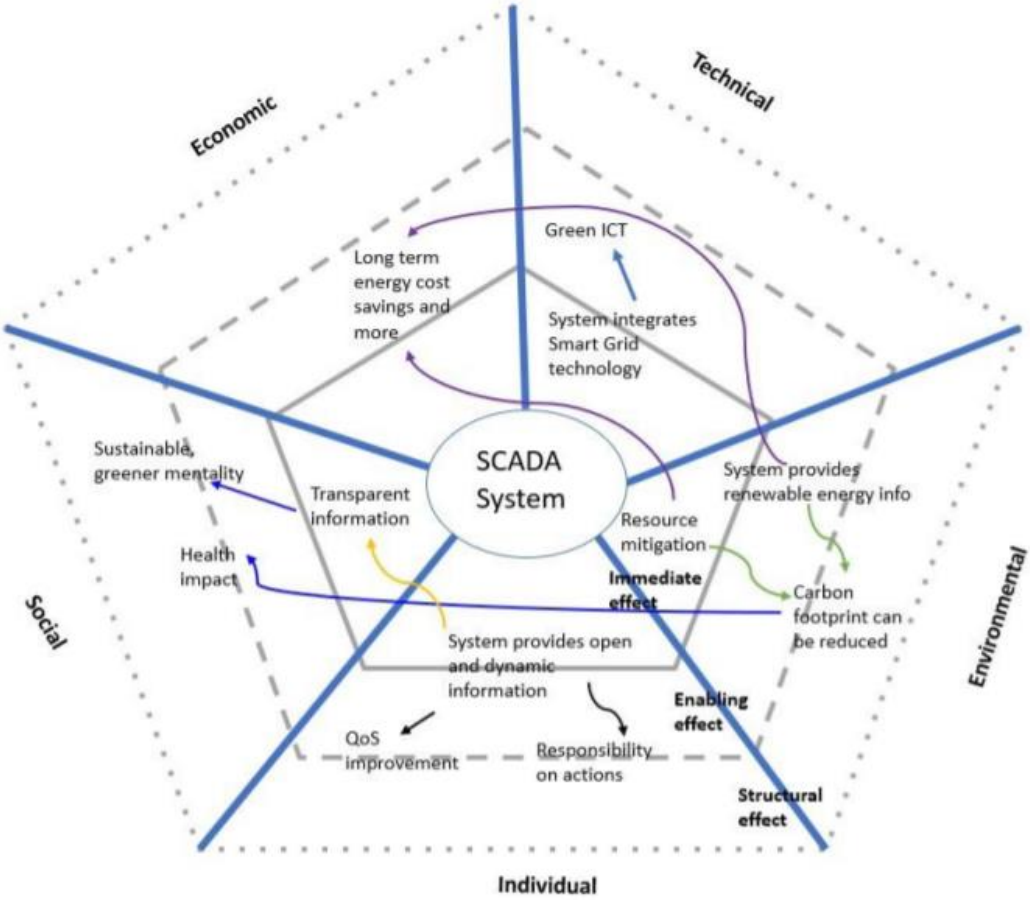
Metric	Value
Total Input Power (W)	70080000.00
Total Energy (Wh)	1681920000.00
Total Green Energy (Wh)	504576000.00
Total load by microgrid (Wh)	168192000.00
Total cost (euros)	262379.52
CO2 emissions (ton)	97719.55
CO2 emissions reduced by green (ton)	41879.81
Off-peak hours	8
Data Center Infrastructure Efficiency (%)	50.00

Metric	Value
Total Input Power (W)	350400.00
Total Input Energy (Wh)	8409600.00
Total Green Energy (Wh)	2522880.00
Total load by microgrid (Wh)	840960.00
Total cost (euros)	1311.90
CO2 emissions (kg)	488597.76
CO2 emissions reduced by green (kg)	209399.04

APPENDIX II.

Information input	Basic Scenario	Low Capacity PE850 Servers	High Capacity PE R440 Servers	Low Green Supply	High Green Supply	More Peak Hours	Less Peak Hours	UNITS
PUE	2.00	2.00	2.00	2.00	2.00	2.00	2.00	
UPS Load	96000	69000	110000	96000	96000	96000	96000	**W**
Server Load	480	345	550	480	480	480	480	**W**
Number of servers	200	200	200	200	200	200	200	**servers**
Electricity off-peak cost	0.12	0.00012	0.00012	0.12	0.00012	0.12	0.12	**euros per kwh**
Electricity peak cost	0.2	0.0002	0.0002	0.2	0.0002	0.2	0.2	**euros per kwh**
Off-Peak hours per day	8	8	8	8	8	9	7	**hours**
CO2 emissions	0.083	0.083	0.083	0.083	0.083	0.083	0.083	**kg per kwh**
Renewable energy percentage	20.00%	20.00%	20.00%	10.00%	30.00%	20.00%	20.00%	**percent**
Total Power Supply	192000	138000	220000	192000	192000	192000	192000	**W**
Total Energy Per Day	4608000	3312000	5280000	4608000	4608000	4608000	4608000	**Wh**
Total Green Energy Per Day	921600	662400	1056000	460800	1382400	921600	921600	**Wh**
Total cost day Per Day	678.912	487.968	777.92	678.912	678.912	665.856	691.968	**euros**
CO2 emissions Per Day	305971.2	219916.8	350592	344217.6	267724.8	305971.2	305971.2	**kg**
CO2 emissions reduced by green Per Day	76492.8	54979.2	87648	38246.4	114739.2	76492.8	76492.8	**kg**
Total Input Energy Per Year	1681920000	1208880000	1927200000	1681920000	1681920000	1681920000	1681920000	**Wh**
Total Green Energy Per Year	336384000	241776000	385440000	168192000	504576000	336384000	336384000	**Wh**
Total cost day Per Year	247802.88	178108.32	283940.8	247802.88	247802.88	243037.44	252568.32	**euros**
CO2 emissions Per Year	111679.488	80269.632	127966.08	125639.424	97719.552	111679.488	111679.488	**ton**
CO2 emissions reduced by green Per Year	27919.872	20067.408	31991.52	13959.936	41879.808	27919.872	27919.872	**ton**
Total Input Energy Per Server	8409600	6044400	9636000	8409600	8409600	8409600	8409600	**Wh**
Total Green Energy Per Server	1681920	1208880	1927200	840960	2522880	1681920	1681920	**Wh**
Total cost day Per Server	1239.0144	890.5416	1419.704	1239.0144	1239.0144	1215.1872	1262.8416	**euros**
CO2 emissions Per Server	558397.44	401348.16	639830.4	628197.12	488597.76	558397.44	558397.44	**kg**
CO2 emissions reduced by green Per Server	139599.36	100337.04	159957.6	69799.68	209399.04	139599.36	139599.36	**kg**

APPENDIX III.



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