LUT University
School of Engineering Science
Erasmus Mundus Master’s Program in Pervasive Computing & Communications for Sustainable Development (PERCCOM)

Maliha Rahman Mishi

MATCHING GEOGRAPHICALLY DISTRIBUTED MICRO-DATA CENTERS ENERGY CONSUMPTION WITH RENEWABLE ENERGY

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Supervisors:  Dr. Colantuono Giuseppe (Leeds Beckett University)
Dr. Ah-Lian Kor (Leeds Beckett University)

Examiners:  Prof. Eric Rondeau (University of Lorraine)
Prof. Jari Porras (LUT University)
Prof. Karl Andersson (Luleå University of Technology)
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ABSTRACT
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Matching Geographically Distributed Micro-Datacenters’ Energy Consumption with Renewable Energy

Master’s Thesis

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The enormous and growing demand of datacenters are consuming more energy than ever. Energy consumption of datacenters has become a significant issue. High energy consumption not only results in high carbon emission, but also experiences large electricity costs. For this reason, IT carbon footprints are the reason of 2 percent of global greenhouse gas (GHG) emissions. Recent research works suggest geographical load-shifting for reducing carbon emission as well as energy cost. This research work focuses on integrating renewable energy sources in small-scale micro-datacenters by considering load-shifting strategy. Our work specifically explores and analyses geographical load-shifting to encourage use of renewable energy instead of brown energy. We make two contributions. First, we explore systematic approaches for finding the best combination of solar panel angles to ensure more solar energy production during a day. Second, a distributed micro-datacenter scenario is conducted in Amazon cloud infrastructure to track energy consumption behaviour by considering real-weather updates. The aim of our work is to explore possibilities of integrating renewable sources to replace dependency on brown energy while maintaining Quality of Services (QoS).
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<tr>
<td>AWS</td>
<td>Amazon Web Service</td>
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<td>CO₂</td>
<td>Carbon dioxide</td>
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<td>DSM</td>
<td>Demand Side Management</td>
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<td>EA</td>
<td>Evolutionary Algorithm</td>
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<td>ICT</td>
<td>Information and Communication Technology</td>
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<td>IDC</td>
<td>Internet Data Center</td>
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<td>IoT</td>
<td>Internet of Things</td>
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<td>IT</td>
<td>Information Technology</td>
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<td>MDC</td>
<td>Micro-Data Center</td>
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1 INTRODUCTION

Datacenters are large scale, critical computing infrastructures that operate around the clock and are top priority for IT infrastructure requirements (Wenden, 1981). They are now seen as a key component for organizations, and not as an external facility. Demand for processing power, storage capacity and information in general is constantly growing. To meet this increasing demand, it is estimated that by 2021, the number of overall DC will reach almost 7 million as shown in figure 1. Information Technology (IT) is expected to have the highest amount of global datacenter storage capacity by 2021 as well which will around 470 exabytes (figure 2).

Datacenters are one of the key enabling technologies for the fast growing IT industry resulting in a global market size of 152 billion US dollars by 2016 (Canalys Newsroom, 2012). Being large scale infrastructures, Datacenters have huge energy budget. Energy efficiency of Datacenters has attained a key importance due to its (i) environmental and (ii) performance issues (Dayarathna, Wen and Fan, 2016). Energy usage incurs a number of environmental issues (Whitehead et al., 2014). In 2005, the total datacenter power consumption was 1% of total US power consumption which created as much emission as Argentina (Mathew, Sitaraman and Shenoy, 2012). The global electricity usage of
Datacenter was estimated to be between 1.1% and 1.5% of the total worldwide electricity usage in 2010 (Corcoran and Andrae, 2017). In US, the datacenters consumed almost 2.2% of all electrical usage inside US. For these reasons, energy efficiency is now considered as a main concern for datacenter, compared to other issues such as security and availability. The energy consumed by a datacenter can be categorized into two parts (The E and Program, 2014): energy use by IT equipment (servers, networks, storage, etc.) and usage by infrastructure facilities (cooling and power conditioning systems). This research focuses on datacenters server energy usage which is ranked second in the energy consumption hierarchy as shown in figure 3.

![Datacenter Energy Consumption](image)

**Fig. 3. A breakdown of energy consumption by different components of a datacenter**

(Top 10 Energy-Saving Tips for a Greener Data Center, 2007)

According to Gartner (2007), nearly 23% of global carbon dioxide (CO₂) is emitted by the ICT industry. Andrae (2017) predicts that by 2025, datacenters will amount to ICT’s largest share of global electricity production at 33%. For these reasons, a necessity of energy efficient DCs is now a big concern for reducing effects on global climate issues. Datacenters need to be energy efficient by integrating renewable energy instead of depending on fossil fuel. Moreover, delivering a response in edge location with low latency is challenging for centralized datacenter infrastructure.
energy efficient DCs is now a big concern for reducing effects on global climate issues. Datacenters need to be energy efficient by integrating renewable energy instead of depending on fossil fuel.

To address these problems mentioned above, geographically distributed micro-datacenter (MDC) plays an important role (*Life On The Edge: Why Micro Data Centers Are The Next Frontier*, no date). It is a comparatively new trend initiated by Microsoft, which is relatively small in size, hosts a maximum of ten servers and hence, very easy to install, and manage. Additionally, it is a low-cost structure. For all these characteristics of an MDC, it is gaining popularity day by day (*Micro Data Centers Evolve to Fit New Business Requirements of Edge Computing* | *Network World*, no date). It is also possible to power an MDC primarily with renewable energy sources which will result in low carbon emission by reducing pressure on the grid.

### 1.1 Motivation

Internet of Things (IoT) is contributing to the future of connectivity and reachability. IoT oriented services are rapidly increasing momentum. Most of these services are mission critical and latency sensitive which requires very quick response and processing (Aazam and Huh, 2015). Micro-Datacenter (MDC) plays a vital role as they are deployed to the geographical area close to end users. According to Kim and Lee (2016), MDC is a smaller rack-based DC system that is designed to solve latency sensitive tasks. Though these tasks can also be served by traditional central datacenters, serving by MDC close to end users has better impact. Current trend in datacenter is now focusing on MDC due to its easier installation, maintainability, and cost effectiveness. As the concept of MDC is relatively new, integrating renewable energy has not been done in this area.

MDC paradigm aims to serve IoT and wireless sensor computations efficiently and in-time decreasing the latency (Aazam and Huh, 2016). This study seeks to make a comparison of different scenarios of MDCs energy consumption behavior based on load-shifting paradigm while connected with grid and solar power. Although installing more resources in a single datacenter can be an alternative of load-shifting, this work analyses different
energy consumption behavior of MDC where load-shifting is considered as a scenario. Analysis of carbon index is analyses in this work rather than causes of load-shifting. It provides a simpler way of evaluating performance and making important analysis such as datacenter carbon index calculation, installation of PV and future growth. This analysis and overview of datacenters impact on the environment provides a basic understanding of energy consumption behavior of MDC where the load-shifting paradigm plays an important role. This also ensures that by shifting load based on availability of solar generation during daytime, can reduce carbon emission significantly. To objectively measure the load-shifting behavior of a datacenter, choosing appropriate algorithms can be a very complex process. For performing load-shifting, several job scheduling algorithms i.e. First-Come-First-Serve, Shortest-Job-Scheduling, Priority scheduling, Round-Robin, Weighted Round-Robin etc. are mostly used (Singh, Goyal and Batra, 2010). Selection of a proper algorithm is just one example, installing a number of PV panel in a MDC also plays a crucial role. Consequently, this research makes use of several analytical approaches for matching MDC energy consumption profile with renewable energy generation by implementing load-shifting algorithms which aim at lowest carbon emission.

1.2 Problem Definition

While several different approaches have been proposed in previous research work in this domain, a few gaps have been identified:

1. The increased demand for ICT for data storage and processing has resulted in a high growth of large-scale datacenters globally to satisfy the demand. There are now over 5,300 colocation datacenters around the world (Data Centers ‘Going Green’ to Reduce a Carbon Footprint Larger than the Airline Industry - Data Economy, no date). The challenge of rapidly growing datacenter is high energy consumption which results in high carbon emission. Datacenter emissions 14% of the 2.3% of ICT carbon footprint. In 2015, datacenter consumed 1500 TWh which was greater than the entire power consumption of the United Kingdom (Reddy et al., 2017). MDCs can be seen as the future trend of traditional datacenter due to
their small carbon footprint. *(What’s next for data centers? Think micro data centers | ZDNet, no date).*

2. Traditional datacenters are usually built in large sizes with highly clustered resources in a distant area. Whereas in future there will be need of DCs which could be more geographically distributed and closer to users to deliver more flexible services with less access latency (Fiorani *et al.*, 2016), (Zhao *et al.*, 2014). By 2020, there will be 25 billion smart IoT devices, to store and process information of these objects, datacenters in edge location are reliable solution rather than serving workloads from centralized datacenters.

3. Load-shifting paradigm is predominantly used in DC but is hardly based on available green energy. Thus, most of the loads are supplied by grid power where both electricity cost and carbon intensity are typically high. While several studies have compared and analyzed energy aware load-shifting of DC (Da Silva and Da Fonseca, 2016), for geographically distributed MDC various analysis of sustainability based load-shifting (e.g. availability of renewable energy) still needs to be studied.

This thesis attempts to identify and address the above-mentioned gaps in research. Geographically distributed MDC’s load-shifting paradigm based on available solar energy, backup by grid power have been investigated via the implementation of several static algorithms in this work. This scenario is implemented in simulation-based environment and then conducted in cloud by deploying in Amazon Web Service (AWS).

### 1.3 Aim, Research Questions and Objectives

This research aims to analyze micro and traditional datacenter’s energy consumption scenario by calculating carbon index. For analyzing, three phases of scenarios are considered where the first two phases consider MDC scenario and the last phase considers traditional datacenters.
After an inclusive literature review, several research gaps in this field have been identified. This section presents the research questions and the corresponding objectives that are addresses in this research.

RQ1. What are the current approaches of energy efficient datacenters?
   RO1. Investigation of state-of-the-art
      RO1.1 Investigation of current energy challenges

RQ2. How can demand be matched with renewable power supply in an MDC?
   RO2. Investigate possible scenarios of MDC demand and supply mechanism
      RO2.1 Build a distributed MDC scenario
      RO2.2 Conduct workload analysis including power measurement
      RO2.3 Implement load-shifting algorithm and analyzing energy usage
      RO2.4 Analyze carbon index for both solar and grid power input

RQ3. How will this load-shifting strategy perform in a public cloud?
   RO3. Select the same MDC scenario conducted in RO2.
      RO3.1 Build a distributed MDC scenario in Amazon cloud service
      RO3.2 Implement load-shifting algorithm and analyzing energy usage in AWS
      RO3.3 Analyze carbon index for both solar and grid power input in AWS

RQ4. What is the impact of the solution on Sustainability?
   RO4. Conduct a Sustainability Analysis using frameworks and open data

1.4 Delimitation

In order to investigate energy usage of a load-shifting paradigm on distributed MDC, a real datacenter infrastructure is required. Considering limited available resources and access to physical data center, a small scale physical simulated lab with laptops served as a client-server is set up to achieve relationship between energy consumption and different user requests. The experiments are designed based on availability of resources. To match MDC energy consumption profile with renewable energy sources by integrating load-shifting
paradigm, experiments are conducted in a simulation and in real cloud infrastructure using AWS. Some of the experiments are repeated over a period of 24 hours which required data to be continuously processed. The data from a simulation and cloud setup are collected and stored over time. The collected data is continuously streamed and served during 24-hour long experiment to mimic a real datacenter system.

Selecting tools and platforms for a simulation and cloud testing is done based on literature review. Amazon AWS is chosen for deploying the experiments in a cloud environment. For simulation, Java and MATLAB simulation tools are selected. Load-shifting algorithms, workload dataset, PV generation data and MDC server structures are chosen from the literature based on their performance in datacenter workloads.

1.5 Contributions

The following are the key contributions of this work:

1. Investigation of MDC load-shifting paradigm based on availability of renewable energy with real workload data and analysis of energy usage in a simulation and real cloud infrastructure;

2. Comparing different algorithms for load-shifting problems and evaluating their performance and energy efficiency. Providing recommendations on installing PV panel for processing workloads and giving an insight of carbon emission per workload;

3. Analysis of the impact of the solution on Sustainability using open data and Sustainable analysis framework;

1.6 Organization of the Thesis

The structure of this manuscript is as follows:

- **Chapter 1: Introduction** provides a brief understanding of the background, problem structure, motivation, objectives and goals, and contribution of the work presented in this thesis.
• **Chapter 2: Review of Related Work** offers a broad study of datacenters, energy efficiency techniques, state-of-the-art energy-efficient datacenters, load-shifting algorithms, their methods and approaches.

• **Chapter 3: Methodology** presents details about the systematic approach of the work with images that are relevant for the experimental set up and describes the architecture in detail, design and conduct of the experiments.

• **Chapter 4: Results and Discussion** dives into details of results of the experiments conducted with relevant performance and evaluation parameters.

• **Chapter 5: Conclusion and Future work** presents the outcome of the thesis and possible direction of future work
2 REVIEW OF RELATED WORK

This chapter is divided into five sub-sections to discuss the following topics: (a) Best practice for energy-efficient datacenter; (b) Energy efficiency policies in datacenter; (c) Load-shifting policies in datacenter; (d) Load-shifting algorithms and (e) Geographical load-balancing of datacenter.

2.1 Best practice for energy-efficient datacenter

Datacenters are consuming an enormous amount of energy every year which is increasing at an exponential rate. Most of this energy is supplied by the grid. The energy used in Grid is primarily produced from burning fossil fuels which releases GHG to the environment. To reduce energy consumption in datacenters, the following things is necessary (Lintner, Tschudi and VanGeet, 2011):

I. Information Technology (IT) Systems: In a typical datacenter, IT equipment loads can account for more than half of the entire facility’s energy usage. Use of highly efficient IT equipment will significantly reduce the loads of a datacenter. Using servers with energy-efficient cooling system, high-efficient network equipment deployment, and storage devices consolidation are the most optimized way to reduce IT equipment energy usage.

II. Cooling Systems: At the initial stage of datacenter cooling system design, it is essential to consider current requirements and future trends. It is recommended that the design of cooling systems be flexible to cater for future changes.

III. Virtualization: With server virtualization, a datacenter does not need many servers to handle its workload. By integrating less servers, the total energy consumption can be greatly reduced.

IV. Server Consolidation: Servers typically consume 30% energy when it is in an idle mode. Consolidating or switching on/off state of a server based on its usage can save high amount of carbon emission by every datacenter.
V. Load management: Considering loads of datacenters when designing and selecting datacenters electrical system equipment.

VI. Load-shifting: Load-shifting to a datacenter with available renewable sources are available can reduce production of carbon emission significantly.

Many factors contribute to overall the energy trends of a datacenter. The amount of electricity used by servers and other ICT infrastructures has become an important issue in recent years. From the above-mentioned sections, it is clear that to reduce carbon emission of a datacenter, both hardware and software part of a datacenter need to be considered.

2.2 Energy-efficiency policies in datacenter

Information and Communication Technologies (ICT) ought to consider sustainable cost reduction. The latest trends of datacenters show that their infrastructure represents approximately 2% of global energy consumption (Koomey and Ph, 2011) with a 5% yearly growth rate (Van Heddeghem et al., 2014). Effect of datacenters must be taken into account (Cook et al., 2017). For long term use, the whole system has to be optimized for energy efficiency and resource utilization. Therefore, innovative and transparent energy policies are needed to improve energy consumption and deliver the best performance. Fernández-Cerero and colleagues (2018) compare, analyze, and evaluate various energy efficiency policies by shutting down underutilized machines. Workload migration by choosing groups of Virtual Machines (VM) including datacenters network topology on energy consumption are considered in by Da Silva and Da Fonseca (2016). Li et al. (2014) propose a power management framework for managing datacenter power across several layers of datacenter servers powered by renewable energy sources. According to G. Burch (2001), datacenters are expected to be powered by hybrid renewable energy systems that combine multiple power generation mechanisms from multiple renewable sources. In some research, a common pattern can be identified which mainly focuses on specific type of green power supplies for delivering incoming workloads of datacenter. Such work can be classified into three broad categories (Li et al., 2014):
a) Load shedding: Focuses on utilizing intermittent power. Generally, reduces load when renewable energy drops.
   i. A solar energy driven power management scheme uses real-world meteorological data of different geolocation for optimization of workload. This work focuses on reducing carbon footprint of computing systems through usage of renewable energy sources (Li et al., 2011).
   ii. In (Goiri et al., 2012), authors propose GreenHadoop, a MapReduce framework for datacenter powered by photovoltaic solar array and electrical grid as backup. GreenHadoop predicts amount of solar energy in near future and schedules MapReduce jobs such that jobs could be executed using green energy.

![Diagram of distributed generation of powered datacenter](image)

**Fig. 4. Distributed generation of powered datacenter** (Nadjaran Toosi et al., 2017)

b) Load boosting: In this category, research work utilizes both intermittent and grid power by integrating energy storage system to maintain desired performance when renewable generation is inadequate.
   i. iSwitch: a lightweight server power management that follows renewable power variation characteristics and applies supply/load scheme to mitigate
performance overhead. This work contributes to making decisions on sustainable and high-performance system design (Li, Qouneh and Li, 2012).

ii. GreenSwitch: A model for dynamic workloads scheduling and appropriate energy source selection to reduce cost. Moreover, the work includes storing energy on the grid and delayed MapReduce jobs to imply green energy usage (Goiri et al., 2013).

c) Load following: Research work under this category assumes that backup power and baseload by integrating tunable generator to supply datacenter load demand when there is shortage of renewable energy generation.

i. Development of Power Demand Shaping (PDS) to effectively utilize onsite distributed green energy by including power supply features to avoid high performance penalty as shown in figure 1. This work aims to save 100 metric tons of CO₂ emissions annually for a 10MW datacenter (Li, Zhou and Li, 2013).

![Distributed generation of powered datacenter](image)

Fig. 5. Distributed generation of powered datacenter
2.3 Load-shifting policies in datacenter

Datacenters energy consumption and costs are becoming increasingly high. Emerging load-shifting paradigm for datacenters is one of the innovative approaches to maintain energy-efficiency and performance. This section discusses datacenter load-shifting technique based on current research trend in this field.

a) Smart grid: Various power management methodologies based on geographical load balancing have been proposed by utilizing several features of a smart grid to increase energy efficiency of 20th century power grid (Rahman, Liu and Kong, 2014). Smart grid technology provides dynamic power management of datacenters. The Energy Independence and Security Act (EISA) defines a smart grid as follows (England, 2009): “A modernization of the Nation’s electricity transmission and distribution system to maintain a reliable and a secure electricity infrastructure that can meet future demand growth.” For energy efficient datacenter management, smart grid might face challenges due to variation in electricity market, uncertainty of workload and renewable energy and performance objective. In (Logenthiran, Srinivasan and Shun, 2012), authors present a Demand Side Management (DSM) strategy of smart grid based on day-ahead load shifting technique. It uses Evolutionary Algorithm (EA) to achieve cost reduction by reducing peak load demand.

b) Workload distribution based on power costs: Rao et al. (2010) proposes a joint load-balancing scheme for distributed datacenters where load balancing is conducted on a datacenter level and power control on the individual server level. Both load balancing and server-level power control work together to minimize total electricity cost while ensuring quality of service (QoS). Qureshi et al. (2009) develops and analyzes a new method to reduce energy costs of running datacenters by developing cost-aware request routing policy that maps requests to locations where energy is cheaper. The research work of (Rao, Liu, Xie, et al., 2010) focuses on power management problem for minimizing electricity cost considering multiple electricity market while guaranteeing QoS. Cost optimization of geographically distributed datacenter are also done extensively while considering delay cost vs delay trade-off. In (Yao et al., 2012) authors develop an optimization approach for
distributed routing which considers power cost reductions with different time scales. Capping the electricity cost of cloud-scale datacenters is important for cloud-service providers and challenging due to high variation in datacenters workload. An electricity cost capping algorithm is proposed in (Zhang, Wang and Wang, 2011a) to minimize electricity cost based on a cost budget on the monthly electricity bill.

c) Workload distribution based on energy efficiency improvement: Datacenters often draw electricity from local electricity market where reducing electricity costs is challenging. In (Narayan et al., 2011), authors propose a novel solution by exploring heterogeneous datacenters and global electricity market diversity to reduce operational cost. They achieve 21% energy saving over a load balancing paradigm which distributes workload requests evenly to all datacenters. A programming model of Internet datacenter (IDC) electricity management solution is proposed in (Li et al., 2012), which aims to reduce cost and energy of IDC by scaling as well as scheduling individual and cluster servers via dynamic workload dispatching. The authors of this paper (Parolini et al., 2012), investigate several aspects of datacenters energy consumption and propose a control algorithm to evaluate energy efficiency and computational performance. They model the datacenter as two coupled networks i.e. computational and thermal to separately examine energy efficiency performance.

d) Reducing carbon footprint: According to Natural Resource Defense Council (NRDC), the total datacenter energy consumption was 91 billion kilowatt-hours (kWh) in 2013 which will rise to 139 billion kWh by 2020. Increasingly more research work is devoted to reducing high carbon emission of datacenters. In (Le et al., 2010), authors present a policy for managing multi datacenter brown energy consumption and leveraging green energy while considering Service Level Agreement (SLA) and minimizing energy costs. The main contribution of this work is the development of software support for capping brown energy without increasing cost. It is also important to maintain the QoS while considering workload distribution based on carbon emission. A framework for characterizing the trade-off between carbon emission and QoS is proposed in (Doyle, O’Mahony
and Shorten, 2011). The result of this work demonstrates that reduction of carbon emission is possible without affecting QoS under non-variant traffic condition.

e) Maximizing renewable energy usage [64]: It is challenging for future electric grid to integrate renewable energy such as wind or solar power because such sources are variable and intermittent. Integrating renewable sources into energy mix requires backup power or energy storage system. Krioukov et al. (2011) present a workload analysis for addressing the problem of integrating renewable energy. An aim of integrating renewable sources for IT energy consumption is to reduce the environmental impact of carbon emission. In (Carroll et al., 2011), authors propose a solution for determining the optimal datacenter service placement to maximize renewable energy usage and minimize the cooling energy consumption. In (Zhang, Wang and Wang, 2011b), they propose a dynamic request dispatching for maximizing the renewable energy usage for distributed datacenters. The evaluation is done based on real-world weather data, electricity prices and workload traces.

2.4 Load-shifting algorithms

Datacenters have high demand for supplying continuous computing resources. As computing capacity increases, operational expenses also increase. Two techniques have been identified for power saving in computing systems (Sami, Haggag and Salem, 2015):

I. The Dynamic Voltage and Frequency Scaling (DVFS): This technology maintains balance between power usage by hardware devices and computational load.

II. Dynamic Power Management (DPM): Reduce power usage by shutting down devices.

Job scheduling is one of the fundamental features in delivering excellent services to the user. Scheduling aims at making decisions on which job to select and run from a ready queue (Dash, Sahu and Samantra, 2015). Scheduling is done to ensure equality among tasks i.e. no priority is used to determine value of tasks. There are mainly two types of scheduling algorithm (Alsheikhy, Ammar and Elfouly, 2016):
I. Preemptive algorithms: In these algorithms, priority number determines value of tasks. Tasks can be stopped by higher priority processes.

II. Non preemptive process: The tasks finishes its execution life despite the arrival of a high priority process.

Several factors can be used to determine the efficiency of a scheduling algorithm:

I. Waiting time: the time needed for a task before going to be executed.

II. CPU utilization: it determines the amount (in percentage) of CPU in working state. The idle state is usually calculated by subtracting busy state from 1.

III. Turn-around time: total amount of time in working and execution state.

A comparison between multiple scheduling algorithms is presented below:

I. First-Come-First-Serve (FCFS): After arriving of process in queue, it’s immediately being allocated to the CPU. The main drawback is that jobs with small burst completion time have to wait longer when a job with a longer completion time is being executed.

II. Shortest Job First (SJF): This algorithm gives priority to processes with shortest bursts completion time. This algorithm has better efficiency compare to FCFS because it minimizes the average waiting time for smaller jobs though there is always a chance of starvation due to waiting time for longer jobs.

III. Round-robin (RR): It is a commonly used load-shifting algorithm. For each task, CPU assigns a time which determines how long a process can use the CPU. Performance of this algorithm highly depends on this time. Round robin policy uses a circular queue of jobs where each process has equal time slicing.

IV. Earliest Deadline First (EDF): This algorithm is very similar to SJF. It first allocates the job with the earliest deadline since it has higher priority compared to other jobs.

In this research work, RR and WRR algorithms are chosen for testing. From the selected algorithms, two different combinations are considered. Table 1 shows the two proposed combinations for this research. Performance of each algorithm is evaluated based on the amount of carbon emission with and without renewable sources.
Table 1. Combinations of algorithms

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Combination 1</th>
<th>Combination 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>With Renewable</td>
<td>RR</td>
<td>WRR</td>
</tr>
<tr>
<td>With Grid</td>
<td>RR</td>
<td>WRR</td>
</tr>
</tbody>
</table>

2.5 Geographical load balancing (GLB) of datacenter

Web service delivery incurs massive geographically diverse distributed systems comprising several datacenters, each with several hundreds of servers. To reduce demand of power-hungry datacenters and to consider economical and environmental aspects of high demand, research work focuses on greening geographical load balancing of datacenters.

I. Social impact of GLB: In this work (Wierman et al., 2014), they explore how geographical load balancing encourages usage of renewable energy instead of brown energy by deriving algorithms for achieving minimal load balancing. Dynamic pricing is considered to ascertain how the load balancing impact depends on pricing.

II. Cost saving GLB: Energy consumption results in high operational costs for datacenters that can be significantly reduced by trimming excess service capacity when the load is low. An online algorithm is proposed for dynamically sizing datacenter by switching off idle servers during low demand (Lin et al., 2011). Using real datacenter workload, this research demonstrates that significant cost savings are possible. In (Pakbaznia and Pedram, 2009), authors focus on power minimization in a datacenter through server consolidation for parallel task assignment. Experiments reveal 13% power saving for different datacenter utilization rate compared to non-consolidated servers.

III. Renewable-aware GLB: To reduce increasing amount of carbon emission of datacenters powered by brown energy, service providers are motivated to move traditional grid powered datacenters towards sustainable datacenters powered by renewable sources. A framework for balancing and distributing loads of web
requests amongst other distributed datacenters based on availability of renewable sources is proposed (Nadjaran Toosi et al., 2017). It aims at reducing cost and brown energy usage. The experiments are conducted using real infrastructure and workload traces. Challenges arise when considering real-time decisions to estimate long-term budget without information about future workload. This issue has been considered in (Zhou et al., 2013) where researchers integrate various parameters (electricity cost, SLA requirement and carbon emission reduction budget) using a carbon-aware online control framework for effective incorporation of long-term carbon emission constraints.

The aim of GLB is to serve workloads with minimum amount of brown energy. The above-mentioned types of GLB clearly concretize this objective. Our work is based on the GLB approach and it focuses on renewable-aware and cost saving approach. The cost saving shifting considers the grid energy price while renewable-aware shifting considers availability of renewable energy.

In summary, datacenters are energy-hungry infrastructures that deliver large-scale services. Datacenter energy consumption is increasing and consequently, this indicates need of alternative energy sources and efficient usage. Energy efficiency for processing services in data centers is needed for energy hungry servers. Different load-shifting approaches for carbon- emission reduction have been promising. Both load-shifting policy and algorithms need to be carefully chosen to gain optimum results. For traditional large datacenters with enormous number of servers, powering them with renewable energy requires large backup infrastructure because of the intermittency of renewable sources. Sometimes the initial cost for the installation of renewable source infrastructures, battery integration, and maintenance cost is more than the brown energy cost. However, it will bring about cost savings in the long term. Integrating renewable energy sources in a Micro-Datacenter (MDC) is more accurate than traditional datacenters because an MDC is small-scale infrastructure combined with fewer servers hence consumes less energy. For this reason, renewable energy can be integrated to MDC only when it is produced without need of energy storage facility (Neglia, Sereno and Bianchi, 2016). One drawback of MDC can be integrating energy storage due to the setup cost of battery which could be more than the
setup cost of the MDC itself. A geographically distributed MDC can resolve this issue where each datacenter will be placed in different geographical locations to achieve maximum usage of renewable sources. Placing datacenters in different geographical locations increase better availability of renewable energy for example, requests sent to a datacenter located in Australia at night can be forwarded to datacenters where it is sunny. This research aims to evaluate the scenarios of geographically distributed micro-datacenters load-shifting paradigm both in a simulation and its deployment in Amazon AWS cloud datacenters.
3 METHODOLOGY

Research is an integral part of professional practice and methodology is the process used to collect information and data for making scientific research. The following section provides a brief introduction of the research method used in this work, the phases of this research and experimental details.

3.1 Research Method

Research can be defined as searching for knowledge to accomplish a specific task. According to (Kothari, 2004), “Research is a scientific and systematic search for pertinent information on a specific topic”. Research methodology is any constructive activity, under a given set of conditions. It shows the way of systematized effort for achievement of knowledge (Sampey 1934). In this thesis, a Simulation and Modelling Research Methodology (Figure 1) is employed and it encompasses four phases: problem structuring, model design, model implementation, model testing and model validation. Further discussion of this methodology is found in section 3.1.1.

Carson (2005) defined simulation as a powerful tool for the evaluation and analysis of new system designs, modifications to existing systems and proposed changes to control systems
Simulation is the imitation of a real-world system or process which involves the generation and observation of artificial history to draw an operating characteristic of the real system (Banks, 1999). It is typically used to describe behavior of a system by analyzing “what if” questions of that real system. Many aspects of natural world can be transformed into mathematical models and simulation allows systems to mimic the outcomes that happen in the natural world. This research focuses on energy consumption behavior and load-shifting paradigm of micro distributed datacenters by considering various research scenarios which are difficult to construct in a real datacenter. However, modeling this complex system allows to explore many possibilities of real system by mimicking the real scenario. For these reasons, this research followed a simulation-based research methodology using MATLAB and Java.

There are three main simulation practice (Dooley, 2015):

1. Discrete event simulation: involves modeling a system as set of entities which evolves over time based on resources and the triggering of events.

2. System dynamics: involves identifying key state variables which defines the behavior of system and then relating those variables.

3. Agent-based: involves multi-agent resource sharing system which attempts to maximize fitness function.

Discrete event simulation model is best fit for experiments where each event occurs at a particular instant in time and marks a change of state in the system. This methodology embraces modeling, programming, input-output data analysis and presentation of results (Fishman, 2001). This thesis focuses on modeling behavior of the system and simulates processes that lead to change over time following discrete event simulation research method. This model characterizes systems behavior which includes:

- Modeling concepts of a system and mathematical relationship among its elements
- Specially designed software for converting relationships into codes
- Procedures for converting data to evaluate systems performance
- Model for estimating system behavior based on performance tests
3.1.1 Steps of research method

This research work is developed in three different phases. Phase 1 focuses on load-shifting with historical solar generation data, phase 2 analyses load-shifting for different combination of PV panel faces and phase 3 aims at analyzing load-shifting paradigm of datacenters in real cloud infrastructure. The following section provides overall research methodology steps used in this work for all of the three phases.

3.1.1.1 Step 1: Problem structuring:

During this phase, at first the current research works are studied in the field of renewable energy-based datacenters and the research gaps are identified. Several researches on this domain are critically reviewed for understanding the current research trend and state-of-art for this area. Based on the study and research gaps, a set of research questions, objectives of this research, approaches and limitations are formulated.

3.1.1.2 Step 2: Defining scenario:

The designing of model is divided into two sub phases.

i. Step 2.1: Load-shifting with historical solar generation data

Different datasets of datacenter’s server load and PV generation are collected and studied. From a range of diverse datasets, the appropriate ones are selected. A linear mathematical model of that workload and PV generation is achieved and an architecture of the modeling system is defined. In this design phase, different pre-defined load-shifting algorithm is applied in a set of micro distributed datacenters in same regions where each datacenter has its own photovoltaic solar panel mounted in different angles so the PV generation in these panels varies hour by hour. Based on the algorithms, Datacenters carbon footprint is calculated, and a set of decisions are made.

ii. Step 2.2: Load-shifting analysis for different combination of PV panel faces

In the second phase, datacenters load-shifting algorithms are analyzed for a different combination of solar panels where they are tilted in different angels. Datacenters carbon footprint is calculated for the combination of PV angles generating energy at different rate
based on hours. From these ranges, the appropriate PV faces are chosen aiming to achieve lowest carbon emission in datacenters.

iii. Step 2.3: Load-shifting analysis in real cloud infrastructure

In the third and last phase of this research, integration of renewable sources and load-shifting paradigm of datacenters are implemented in Amazon cloud infrastructure. Datacenters carbon footprint is calculated while considering the workload transfer latency and real time weather data. From this phase, a real experiment is done where all the real scenarios that was not possible to analyze in simulation, are analyzed here.

3.1.1.3 Step 3: Implementation

In this phase, the selected selected algorithms (RR and WRR) are implemented to calculate carbon index of datacenters by matching supply of renewable source with real workload data. Data of solar energy generation is considered as renewable source.

3.1.1.4 Step 4: Conducting Experiments and providing recommendations

To perform and analyse datacenters load-shifting strategies, a set of experiments are designed and conducted. Specific conditions are set for each experiment. Also, each experiment is conducted multiple times to obtain reliable and refined results. In some cases, experiments are run multiple times over a long period of time. During the testing phase, data is collected for the whole period. The data obtained by running experiments are analyzed. Based on the results obtained, the effective combination for load-shifting algorithms and PV panel panels tilted in particular angle is recommended for achieving minimal carbon index in micro datacenter.

3.1.2 Strengths and weakness of simulation-based research

One of the important impacts of simulation that its ability to support investigation that are hard to do in more conventional ways. Davis et al. (2007) pointed out that simulation have empirical advantages over analytical statistical modeling. Simulation-based research can be technically challenging. Mistakes can be made in developing computer program (Harrison et al., 2007). Moreover, simulation-based researches have less acceptance rate in compare to other research methods. One of the main reasons behind this is due to modeling
limitations, it’s not possible to consider all the possible real-world scenarios, in result models fail to identify potential outcomes.

3.2 Phase-1: Load-shifting with historical solar generation data

In the first phase, two load-shifting algorithms are analyzed between distributed micro datacenters. Each datacenter has a solar panel facing the sun from a different angle i.e. datacenter-1 has north faced panel whereas datacenter-2 has south faced panel. As a result, at the same time, both solar panels generate different amount of energy, based on this the load is shifted.

3.2.1 System Architecture

The overall architecture of the of load-shifting between multiple micro datacenters based on PV generation is depicted in this figure. The simulation of this architecture is built in Java and the data analysis is done in MATLAB. To simulate and analysis load-shifting paradigm between two datacenters based on PV data, two algorithms Round-Robin (RR) and Weighted Round-Robin (WRR) are used.

![System architecture of phase 1](image)

**Fig. 7. System architecture of phase 1**

3.2.2 Experimental Details

The experiment of this research is conducted in three steps: Plan, Execute and Analyze as showed in figure 3. After defining research objectives and outcomes, required
Experimental setup is defined during the plan step. In the next step, data collection is performed and saved as csv files. Experiments are executed multiple times to achieve accurate results. Analyzing of data and providing recommendation are conducted in last step. The results of these three steps are documented.

![Design of experiments diagram](Ganesan, no date)

### 3.2.2.1 Workload data analysis

In this research, two-weeks real datacenter workloads have been used. This workload is collected from ClarkNet dataset. Figure 4 shows a MATLAB analysis of two-week ClarkNet workload dataset. The ClarkNet dataset consists of 14 days of HTTP requests served by their server. The logs were served from 00:00:00 August 28 to 23:59:59 September 10. In these two weeks there were 3,328,587 requests with 1 second timestamps resolution. The analysis of dataset shows that servers served more requests in weekdays rather than in weekends.
Fig. 9. Two-week time series analysis of ClarkNet workload
Table 1 describes important log information collected from the ClarkNet dataset. It represents brief analysis of ClarkNet dataset based on its activity log, total incoming user requests, total size etc.

Table 2. Summary of access log characteristics (reduced data) (Arlitt and Williamson, 1996)

<table>
<thead>
<tr>
<th>Item</th>
<th>ClarkNet dataset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access Log Duration</td>
<td>2 weeks</td>
</tr>
<tr>
<td>Access Log Start Date</td>
<td>August 28</td>
</tr>
<tr>
<td>Access Log Size (MB)</td>
<td>195.5</td>
</tr>
<tr>
<td>Total requests</td>
<td>2,940,712</td>
</tr>
<tr>
<td>Avg Requests/Day</td>
<td>210,050</td>
</tr>
<tr>
<td>Distinct Request</td>
<td>32,294</td>
</tr>
<tr>
<td>Distinct Requests/Day</td>
<td>2,307</td>
</tr>
<tr>
<td>Total Bytes Transferred (MB)</td>
<td>27,591</td>
</tr>
<tr>
<td>Avg Bytes/Day (MB)</td>
<td>1970.8</td>
</tr>
</tbody>
</table>

3.2.2.2 Measuring power consumption data for workloads

For datacenter workload analysis, ClarkNet dataset is used. The dataset contains two weeks of all HTTP requests to the ClarkNet WWW server which includes host name, timestamp, request, HTTP reply code and bytes in the reply. As the dataset was missing information of
energy consumption for corresponding response size, a client-server experiment was conducted to measure the energy usage per client request served by server. In the client side, thousand requests per second were sent to the server using Apache JMeter load testing tool. A combination of response sizes was used to determine the watts produced for serving the workload. From each response size, watt per byte is calculated. The responds served by server vary in size i.e. from 10 kilobyte to 100 megabytes. The power consumed by server for serving these requests are measured using Linux powerstat\(^1\) tool running in the server. The overall measurement of this experiment is listed in table 2.

![Diagram](image)

**Fig. 10. Mapping response size with byte**

After repeating the same experiment for a different response sizes, a proportional relationship between energy consumption (Wh) with response sizes (byte) are seen which can be defined as a linear relationship. For serving higher number of response sizes, server consumes higher energy. When the response sizes are increase, it results low response numbers. At the end, power consumption by each byte for all these file sizes are nearly same. From this result, an estimation of energy usage for ClarkNet response sizes is achieved.

\(^1\) Power measurement tool for CPU activity
Table 3. Summary of power measurement experiment in client-server model

<table>
<thead>
<tr>
<th>File size (Kilobyte)</th>
<th>Total power (Watt)</th>
<th>Response count</th>
<th>Total bytes</th>
<th>Watt per Byte</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>180.94</td>
<td>7898</td>
<td>7898000</td>
<td>4364.9</td>
</tr>
<tr>
<td>2</td>
<td>152.76</td>
<td>7331</td>
<td>14662000</td>
<td>95980.62</td>
</tr>
<tr>
<td>3</td>
<td>171.6</td>
<td>7131</td>
<td>21393000</td>
<td>125105.26</td>
</tr>
<tr>
<td>4</td>
<td>162.74</td>
<td>7340</td>
<td>29360000</td>
<td>180122.69</td>
</tr>
<tr>
<td>5</td>
<td>178.96</td>
<td>6501</td>
<td>32505000</td>
<td>181592.17</td>
</tr>
<tr>
<td>6</td>
<td>140.76</td>
<td>6484</td>
<td>38904000</td>
<td>275914.89</td>
</tr>
<tr>
<td>7</td>
<td>154.57</td>
<td>5020</td>
<td>35140000</td>
<td>226709.76</td>
</tr>
<tr>
<td>8</td>
<td>155.54</td>
<td>5335</td>
<td>42680000</td>
<td>273589.74</td>
</tr>
<tr>
<td>9</td>
<td>166.89</td>
<td>4983</td>
<td>44847000</td>
<td>268544.91</td>
</tr>
</tbody>
</table>

After achieving a mapping between ClarkNet response sizes with energy consumption data, following Matlab analysis is done to represent a polynomial equation of the relationship between workload size (bytes) and energy consumption (watt) data. During these two-week, plotting of response size with power consumption data can be defined as following five-degree polynomial function where x denotes bytes:

\[ p(x) = p_1x^n + p_2x^{n-1} + p_3x^{n-2} + p_4x^{n-3} + p_5x^{n-4} + \ldots + p_nx + p_{n+1}. \]

\[ p(x)=0+0.0007x^4 - 0.0355x^3 + 0.7529x^2 - 6.0264x +143.1252 \] .................. (1)
3.2.2.3 Measuring energy consumption data by using ‘powerstat’ tool

The ClarkNet dataset contains two weeks of HTTP requests to ClarkNet server. It doesn’t contain energy consumption data for any request. To have sample measurements of power usage by tasks based on their CPU utilization, we run ‘powerstat’ tool in our server which served the HTTP responses requested by clients. This tool calculates the power consumption of any devices depending on CPU usage, IO time, number of processes running etc., and it requires that device needs to be running on battery. Once running in default mode, the tool takes 180 seconds to prepare by gathering relevant information and monitors the system for about 300 seconds. Within this time period 30 samples at 10 seconds intervals are collected. At the end of each run, powerstat shows power consumption statistics and calculates the average, standard deviation, minimum, maximum and mean of the gathered data (Colin, 2017).

During the run mode, the following information is displayed:

1. **Time**: Startup time for each monitoring instance.
2. **User**: CPU usage (CPU time) of processes running by current user.
3. **Nice**: A special value that represents Kernel function that prioritize the CPU time for applications. This value changes depending on the importance of the process.
4. **Sys**: CPU usage (CPU time) for system software.
5. **Idle**: Represents in percentage, this value indicates the idle state of CPU. For example, if the value is 90%, it means 90% of the CPU was in idle state for that period. In other word, it also means that only 10% of the CPU was consumed by applications.

6. **IO**: Waiting time of CPU after sending a signal until it gets a reply.

7. **Run**: Currently running processes.

8. **Ctx/s (Context switch rate)**: Shows times CPU paused and resumed programs per second.

9. **IRQ/s**: Amount of IRQ requests from hardware. (IRQ=especial signal for hardware devices to communicate with CPU).

10. **Watts**: Shows current power consumption rate.

### 3.2.2.4 Selection of Algorithms

Load-shifting algorithm determines to which remote server to forward a incoming task. Static and dynamic are two types of algorithms depending on state of server. Static algorithm assigns the task to a new node depending on whether the node has ability to process incoming requests (Al Nuaimi et al., 2012). This will include nodes processing power, memory and storage capacity. These algorithms are appropriate for systems with low variation in load. In the phase-1 of this research, two most common static algorithms are considered: Round-Robin (RR) and Weighted Round-Robin (WRR). Pseudo code of both algorithms are given below:

i. Initialize values (server status, PV generation and carbon index API)

ii. Load workload dataset

iii. For each feature in dataset
   a. Calculate response size and time required to serve it
   b. Choose a datacenter where PV>grid
      Check server status in that datacenter
      - IF a server is free, serve the response
      - IF a server is busy calculate its waiting time
      - IF no server is free, wait for the server with least waiting time
   c. IF PV<grid, choose any datacenter
Repeat steps of 3.2.1

iv. Calculate carbon index of that datacenter for each hour: \( E(\text{total}) = E(\text{PV}) + E(\text{grid}) \)

WWR algorithm works same as RR. In addition, a weight of 1 to 3 is assigned to each of the workload which indicates priority i.e. 1 is lowest priority and 3 is highest priority (Reiss, Wilkes and Hellerstein, 2011). Other part of the algorithm is the same as RR.

4 RESULTS AND DISCUSSION
This chapter presents the results of the experiments conducted in three different phases.

4.1 Phase-1

In phase-1 of this research work, the scenario of two interconnected micro datacenters in the same regions are chosen. Each datacenter having its own solar panel faced with the sun from different angles i.e., each panel generates different amount of energy in a day. Both of the datacenters are connected with grid as a backup.

![Fig. 12. Scenario of phase-1](image)

4.1.1 Power Consumption of Workloads

As discussed in the previous chapter, powerstat tool of linux is used to measure the power consumption of the datacenter workload of ClarkNet dataset. To achieve the mapping of the energy consumption of the workload, several experiments were done by transferring
different file sizes from server to client. As there are two types of files i.e., binary and text, the experiments are also conducted by transferring these two types of files. After having a general mapping of power consumption data and response size, the information is used in simulation environment.

4.1.2 Performance Metrics

To compare the energy efficiency of datacenters, first the total energy is computed without integrating renewable energy. After that, this total energy is compared with the energy consumption while integrating renewable source. Both of this experiment are conducted for RR and WRR algorithms.

**Total Energy Consumption (E) with and without Renewable Source:**

After conducting experiments with RR algorithm, the following results are found. Figure 8 depicts carbon emission with and without PV generation. When the energy is drawn from grid, carbon index becomes 400 grams at most depending on the response size. On the other hand, from 8.00 am to 7.00 pm the demand is generally fulfilled by solar energy, as a result the carbon index remains very low.

\[
E_{\text{total}} \equiv 986 \text{g CO}_2
\]

\[
E_{\text{total}} \equiv 299 \text{g CO}_2
\]

*Fig. 13. Carbon index comparison based on PV generation*

The following Figure 13 shows comparison between load-shifting with and without considering PV>grid. Without considering solar energy availability, the shifting is only
done by checking available server capacity. For this reason, datacenters carbon emission results a higher value for the same amount of load.

**Fig. 14.** Carbon index comparison with and without load-shifting

![Carbon Index Comparison](image1)

**Fig. 15.** Comparison of workload distribution between datacenters

![Served Response by Datacenters](image2)

Figure 14 shows 7-days comparison of workload distribution between two datacenters. As the distribution of workload is based on available renewable energy, datacenter having more availability than other, serves more.
4.2 Phase-2

In the phase-2 of this research work, a systematic approach is followed to achieve the best combination of different faced solar panels. For this, the same scenario of phase-1 is considered.

Table 4. Comparison of different solar panel orientation

<table>
<thead>
<tr>
<th>Combination</th>
<th>PV panel orientation in DC1</th>
<th>PV panel orientation in DC2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Comb. 1</td>
<td>East</td>
<td>East-South</td>
</tr>
<tr>
<td>Comb. 2</td>
<td>East-South</td>
<td>West</td>
</tr>
<tr>
<td>Comb. 3</td>
<td>East</td>
<td>North</td>
</tr>
<tr>
<td>Comb. 4</td>
<td>East</td>
<td>East</td>
</tr>
</tbody>
</table>

The following figures present the results of different combination of solar panel orientations. Combination 1 (east and east-south) has the least carbon-index (350g/kWh) whereas combination 3 has the maximum carbon-index (818g/kWh). The results show data from 6am to 7pm during generation of solar energy.

Figure. 16. Solar panel combination 1 and 2
Figure 17. Solar panel combination 3 and 4

4.3 Phase-3

This is the final phase of this research where the work is validated in an Amazon cloud infrastructure. In this real-world experiment, three data centers in three different continents i.e., Australia, UK and USA are installed. For load-shifting paradigm, previously described algorithms are used. Historical solar generation data for UK, Australia and USA is considered in this phase. As the Amazon AWS has its own load-shifting paradigm, for creating our own load-shifting method, artificial workloads are generated which can be transferred to another data center using proxy server concept.
In this phase, three datacenters in UK, Australia and USA are considered in Amazon cloud platform. Different incoming loads from ClarkNet dataset are supplied to each datacenter. Fig. 19 shows load shifting among these datacenters and the carbon index calculation. Having most solar generation in UK, the carbon index is comparatively lower compare to other two countries with different timezone. Load is shifted to other datacenter where solar generation is available which results low carbon emission.

Fig. 20 shows incoming workload variation in two datacenters located in Australia and UK respectively. At first, requests are sent to datacenter in Australia. Solar energy shortage in requested datacenter and it’s availability in UK for that specific time, all the requests are redirected to UK. After that, the requests are served to users from this redirected datacenter.
with available renewable energy. Load-shifting is done based on availability of renewable sources in each of these places.

Table 5. Data analysis of load-shifting in Amazon cloud platform for an hour

<table>
<thead>
<tr>
<th>Carbon Index gm (without load-shifting)</th>
<th>Carbon Index gm (with load-shifting)</th>
<th>Australia (request received in ms)</th>
<th>UK (request served in ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.349</td>
<td>3.013</td>
<td>1257</td>
<td>1260</td>
</tr>
<tr>
<td>10.846</td>
<td>2.895</td>
<td>963</td>
<td>967</td>
</tr>
<tr>
<td>13.423</td>
<td>3.809</td>
<td>902</td>
<td>905</td>
</tr>
<tr>
<td>13.682</td>
<td>4.137</td>
<td>970</td>
<td>973</td>
</tr>
<tr>
<td>12.354</td>
<td>3.427</td>
<td>968</td>
<td>971</td>
</tr>
<tr>
<td>11.372</td>
<td>2.834</td>
<td>962</td>
<td>965</td>
</tr>
<tr>
<td>12.863</td>
<td>2.423</td>
<td>961</td>
<td>964</td>
</tr>
<tr>
<td>12.459</td>
<td>3.552</td>
<td>896</td>
<td>900</td>
</tr>
<tr>
<td>10.288</td>
<td>4.482</td>
<td>979</td>
<td>982</td>
</tr>
<tr>
<td>11.139</td>
<td>3.122</td>
<td>892</td>
<td>895</td>
</tr>
</tbody>
</table>

In table 5, the values of the last two columns are normalized. They represent time of request sent to a datacenter and served from redirected datacenter respectively. This table shows carbon index (in gm) calculation for workload shifting from Australia (8.00 pm local time) to UK (11.00 am local time). The first column shows carbon index when the load is served by the requested datacenter (Australia) without having available renewable resource. In the second column, carbon index is calculated after shifting load in UK. Although the carbon index impact is overall lower, but the there is a delay of around ~3ms for each request. Collected json data is documented for further study, Screenshots for this experiments are attached in appendix section.

4.4 Sustainability Analysis

Sustainability was first introduced by UNEP in Rio de Janeiro (1992) as one of the main goals of future humankind development. The United Nations declared sustainability as the guideline for 21st century in Rio de Janeiro (Kloepffer, 2008). Sustainability is a concept which considers environmental, social and economic aspects as three dimensions which has been denote as three pillars of sustainability. The objective of the PERCCOM program is to understand the existing sustainable challenges in the society and to address them with
ICT education to build greener and energy efficient systems (Porras et al., 2016) (Rondeau, Andersson and Porras, 2019). This research work is directly correlated with sustainability. This work contributed towards sustainability by making efficient use of renewable energy and cost-saving approach.

![Figure. 21. Three pillars of sustainability](image)

Considering the three-pillar approach of sustainability, this research work directly contributes to two pillars from three of them.

I. Environmental: This research work focuses on reduction of carbon emission by integrating renewable energy in micro-datacenter. This is achieved by considering carbon-aware load-shifting paradigm. It increases the energy efficiency of datacenters by reducing significant carbon emissions which as a result increases datacenters lifetime.

II. Economical: Previously described carbon reduction goal of this research work translates to reduction of energy production and utility costs. Datacenters depending mostly on renewable energy can cut-off the cost of drawing energy from high-cost power grid.
4.4.1 Five Dimensions of Sustainability

Five dimensions of sustainability is proposed by Becker et al. (2015). In the following section, impact and contribution of this research work to achieve sustainability is discussed.

- Individual: The result of this research work represents the carbon index calculation for serving each incoming workload by datacenter. Each record of carbon emission shows how a single request can contribute in carbon footprint. This study helps individual to increase awareness and practice sustainability.

- Social: This study can help to establish trust between people and service provider. As the cost of service to end user is calculated based on the energy usage, the study
results aim to show energy source for each. People can have estimation about their energy costs as well as carbon footprint.

- Economic: The main economic aspect of this research work is that it helps to reduce energy expense. The energy source of datacenters are partially replaced by renewable source during the availability of solar energy in daytime. During this time, a workload served by solar energy has no impact on carbon emission.

- Technical: In this work, load is shifted where renewable energy is available. A better energy management can be done by load-shifting.

- Environmental: Integrating renewable energy in datacenter can significantly reduce carbon emission in environment. Also the carbon-aware load-shifting of this research work aims to serve workloads with renewable sources as much as possible.

These five dimensions of sustainability analysis also consider immediate, long-run and future impacts. Based on the model, a sustainability analysis is conducted in figure 21.
5 CONCLUSION AND FUTURE WORK

This thesis work has investigated the energy consumption behavior and performance of micro-distributed datacenters both in simulation environment and in real cloud infrastructure. First, the experiments are done in simulation environments which cannot mimic all the possible real-world scenario. Later, results obtained from cloud environment overcome the drawback of testing datacenter energy consumption and load-shifting scenario with simulated workloads. The main focus is on understanding algorithms for geographical load-shifting in interconnected small-scale datacenters. Integrating renewable sources in datacenters considering load-shifting overall reduces the energy usage and operational costs. From the observations made, it is clear that serving workloads solely from grid energy results high carbon-emission and not cost effective as well. So, it is important to include renewable energy generation and load-shifting strategy in datacenters. Our experiments highlight that carbon-aware load-shifting can provide an effective tool for reducing carbon emission. All these cases ease the incorporation of renewables and reduce datacenters brown energy consumption.

Moreover, an energy-efficient system is effective when it meets the QoS requirements. Therefore, selection of load-shifting algorithms for datacenters job scheduling plays an important role. Both RR and WRR algorithms can be a good combination in small-scale edge datacenter to analyze the load-shifting pattern by following renewable sources.

There can be several interesting directions for future work that are motivated by the studies in this work. With respect to the design of load-shifting algorithms, this work didn’t consider the switching cost (in terms of delay) associated with workload transferring from a datacenter to another. Our work also ignores server on/off scenario which is quite common in general.
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APPENDIX

Screenshot of experiments of phase-3 in Amazon cloud platform.
REST API to get data – GET method


Sample output:

```
{ "id": "cf3fe9e2-c531-44d3-9dda-a2edbf8e0fdee", "name": "mdc", "allTests": [], "timestamp": "2019-08-15T17:30:47.823Z", "collectionId": "e3af05b-53a6-499a-b0df-af280a7addde", "folderId": 0, "targetType": "collection", "environmentId": "0", "data": [], "delay": 0, "count": 100, "collection": { "id": "e3af05b-53a6-499a-b0df-af280a7addde", "name": "mdc", "description": null, "auth": null, "events": null, "variables": null, "order": [ "3eebe575-5ddb-4fc3-8a31-eac77328807a" ], "foldersOrder": [], "owner": "0", "permissions": {}, "favorite": false, "shared": false, "type": "collection", "depth": 0 }, "folder": null, "environment": null, "globals": [], "results": [ { "name": "mdc-base", "id": "3eebe575-5ddb-4fc3-8a31-eac77328807a", "totalTime": 0, "responseCode": { "code": 200, "name": "OK" },
```
