School of Electronic and Electrical Engineering
FACULTY OF ENGINEERING

UNIVERSITY OF LEEDS

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Project Report

Optimisation of Virtual Machines Placement Over a Cloud-Fog Architecture Considering the Availability of Renewable Energy.

IBEABUCHI CHIGOZIRIM ADANNA

SID: 201071770	Project No. 41
Supervisor: Dr. Taisir Elgorashi	**Assessor:** Dr. Andrew. H. Kemp

School of Electronic and Electrical Engineering
FACULTY OF ENGINEERING

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Abstract

There has been a rapid increase in the power consumption of cloud data centers all around the world. The use of Virtual machines is very key in the operation of data centers as the utilisation of these virtual machines reduce the number of physical machines that may be active at a certain point in time. The main aim of this project was to develop a Mixed Integer Linear Programming (MILP) model to optimize the placement of these virtual machines over a cloud-fog architecture while considering the availability of renewable energy. A cloud architecture is used in this project. Two Virtual machine placement schemes: VM Replication and VM Migration are used to optimize the placement of these virtual machines. The objective function minimizes the network and cloud non-renewable power and any transmission losses. Three approaches are examined for each of the virtual machine placement schemes and for one case it is found that that when the user-virtual machine traffic is normal and the workload assigned to the virtual machines is low, approaches 1 and 3 are the best to use when there is sufficient renewable energy because there are no transmission losses unlike the 2nd approach that has a transmission loss of about 45kW. Also, all the power available to power clouds is non-renewable hence reducing CO_2 emission.

Keywords: Virtual Machine, Cloud Computing, Data Center.

Acknowledgements

I want to thank my supervisor, Dr. Taisir, for her guidance throughout the duration of this project. Let me also thank Hatem for helping me understand the AMPL programming language better and in resolving the difficult questions I presented to him. I remain eternally grateful to God for granting me grace to finish the work. My family and friends deserve my gratitude for their support and prayers. I am truly grateful to everyone who has supported me in this project.

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1 INTRODUCTION

Apart from the fact that cloud computing is the standard for providing services on the internet, a lot of business owners now utilise cloud computing as a means to attract more customers because of benefits like: easily accessible services, reduced cost of operation, flexibility and good security [1]. The data centres which host servers that help to carry out cloud computing services continually have issues of high energy consumption. In 2012, 270TWh of energy was consumed by data centres all over the world according to the authors in [2]. Matthew et al. have made a prediction that a data centre that has approximately 100,000 servers will use up to 190,000MWh of energy ever year [3]. It is said that this amount of energy can power up not more than 10,000 homes. The use of virtual machines is very key in cloud computing because these virtual machines allow users to access resources in the cloud hence enhancing resource utilisation [4]. If the energy consumed by data centres is so much, it means that these virtual machines will also consume a lot of energy.

There have been some attempts to minimise the energy consumed by these data centres. An algorithm called ABBSH is created in [5] to set specific times and dates for tasks which will be carried out by servers in a data center while considering energy from solar panels. The authors in [6] suggest the use of optical wireless communication links to change the routes of workloads so that workload racks that are completely loaded can be offloaded onto workload racks that are not fully loaded in order to allow more racks to change to an idle system of operation. Another paper aims to reduce the amount of CO_2 released from IP over WDM networks by examining the use of renewable energy [7]. These authors construct a linear programming model to reduce the energy consumed in the network while examining the use of renewable energy.

There has not been much work done in optimising virtual machine placements while considering renewable energy. However, a study analysed three different ways to migrate virtual machines and one of these methods considered migrating these virtual machines while maximising the available solar energy [8]. The authors in [9], create a Mixed Integer Linear Programming (MILP) model to analyse the effects of having renewable energy on where the clouds are located, and the different ways content is replicated to these clouds. This project extended this model not to analyse the content replication of this cloud content while considering renewable energy availability instead this model was used to analyse the placement of virtual machines while considering renewable energy availability. In this case, wind farms were chosen as the source of renewable energy. The main aim of this project to optimise the placement of these virtual machines while considering renewable energy and scrutinise the impact made when the power losses between the wind farms and these clouds are considered. The model which is finally created optimises the placement of these virtual machines while considering the user-virtual machine traffic and the workload assigned to these virtual machines. Three scenarios are examined for both the Virtual Machine Replication and Migration Schemes which will be discussed later. Several simulations are run and all the graphs gotten from those simulations are explained in detail in this report.

This dissertation is organised as follows: Chapter 2 discusses the literature review on relevant topics like Cloud Computing, IP over WDM Networks and Virtual Machine Placement Optimisation. Chapters 3 and 4 introduce a model that optimises the placement of virtual machines without considering renewable energy. Chapter 5 also discusses the main model and results from this model that optimises the placement of virtual machines while considering the availability of renewable energy (wind farms).

2 LITERATURE REVIEW

2.1 Cloud Computing

The National Institute of Standards and Technology (NIST) defines Cloud Computing as " a model for enabling ubiquitous , convenient, on-demand network access to a shared pool of configurable computing resources (e.g. network servers, storage, applications and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction" [10]. Cloud computing is commonly characterised by multi-tenancy, dynamic resource provisioning, geo-distribution/ubiquitous access, self-adaptability and virtualisation [11] [12]. The typical cloud computing architecture is shown in the figure below:

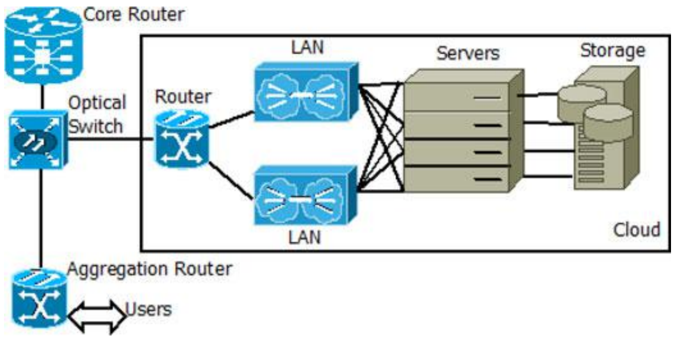

Figure 1 Cloud Architecture Adapted From [15]

Hardware, Infrastructure, Platform and Application are the major layers that make up the entire cloud computing architecture. These cloud computing services comprise of Software as a Service (SaaS), Platform as a Service (PaaS) and Infrastructure as a Service (IaaS). They will be briefly described below according to the information provided in [1].

- Software as a Service (SaaS) - This particular cloud service adopts multi-tenancy on its platform. Accessible software applications are delivered by cloud providers and these services are normally purchased on a pay-as-you-go basis. Common examples of these services include: Google Mail, Amazon, Microsoft 365, SalesForce.com, Oracle etc. [1] [12] [13].
- Platform as a Service (PaaS) - Here, software developers are provided with platforms and tools that can be used to create software applications that will be used on the cloud. Typical examples include Microsoft Windows Azure, Google App Engine and Force.com [1].
- Infrastructure as a Service (IaaS) - In IaaS, the hardware (physical infrastructure) utilised by end users are hosted by the cloud providers. Virtualisation lies at the basis of Infrastructure as a Service (IaaS). This service allows for a lot of adaptability. Examples of this type of service are: AmazonEC2, FlexiScale, GoGrid, Layered Technologies etc. [1] [12] [13].

In the world of cloud computing, there are various types of clouds and they include: Public Clouds, Private Clouds and Hybrid Clouds. These types of clouds will be explained below:

- Public Clouds: Here, the services provided by these cloud providers are available to the general internet users. Anyone can gain access to the services offered by these cloud providers. Another major feature of public clouds is that these cloud providers own these public clouds fully and some of these services offered may be free or require a payment plan. A big disadvantage of public clouds is that these cloud providers do not have much command over consumer's data, and this may bring up the issue of poor security in these public clouds. Typical examples are: Amazon EC2, Google App Engine etc. [1] [14].
- Private Clouds: These are specially constructed for business organisations and may be managed either by the business organisation or the cloud provider. This type of cloud is very advantageous because security is improved, and they tend to be more reliable [1].
- Hybrid Clouds: These clouds serve as a mix of some of the features of public clouds and private clouds. Some components of these cloud will operate on private cloud while the rest will operate in public clouds. Since they have features of private clouds, there is better security in these types of clouds. A problem with this type of cloud may be the difficulty in choosing the fragments of the cloud that will serve as public or private [1].

2.2 IP/WDM NETWORKS

The objective function in the model which will be created will involve minimising the IP/WDM Network Consumption so a basic understanding of how this network operates will be helpful. Two major layers form the entire IP/WDM network and these layers are called the IP layer and the Optical layer. The main purpose of an IP router in the optical layer is to collect data traffic which originates from access networks [15] while the optical layer enables the transmission between the IP routers to have capacity.
There are devices that make up the IP/WDM network. Their uses will be summarised according to the information provided in [15]:

- Optical Switches - These are normally attached to optical fibre links.
- Multiplexers/Demultiplexers- These are utilised for the purpose of wavelength multiplexing and demultiplexing.
- Optical Fibres- Supply a sufficient amount of capacity so that transmission between IP routers can occur efficiently.
- Transponders- These carry out optical-electrical-optical (OEO) processing.
- EDFAs (Erbium Doped Fibre Amplifier) - These are used to boost the optical signal coming out from the optical fibres. The typical IP/WDM architecture is shown in the diagram below:

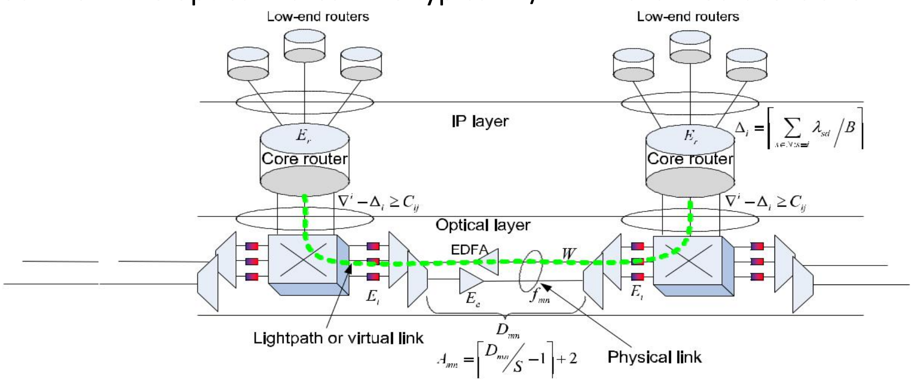

Figure 2 IP/WDM Network Architecture adapted from [16]

Two common methods of executing IP/WDM networks are lightpath bypass and non-bypass [15]. By using the lightpath bypass method, there will be no requirement to use IP router ports in the network because lightpaths are permitted to divert the IP layer of intermediate nodes while in the non-bypass approach does the opposite [16]. This therefore makes the lightpath bypass approach to be more energy efficient.

2.3 Virtual Machine Placement Optimisation

In simple terms, the use of virtual machines allows a technology that enables more than one operating system to run on a physical machine [17]. There have been several proposals to optimise the placement of some of these virtual machines. Zhang et al. propose an optimisation model where a heuristic ant colony algorithm is formulated [4]. The model created helps to link virtual machines to the appropriate physical machines based on how much resources are employed by these physical machines in order to reduce power consumption. The authors then go further in their work by expanding the optimisation model previously created to a multi-objective model through creating two smaller models namely: “energy consumption” and “resource idle”. Results from the model created in the paper show the energy consumption reduced by a factor of 0.18 when compared to similar models [4].

Another paper makes use of utility functions to solve the virtual machine placement problem [17]. An algorithm that scans through virtual machine- physical machine allocation chooses the best possible virtual machine-physical machine allocation that makes the best use of resources. The main aim of the authors in this paper is to create a virtual machine placement scheme that not only optimises energy consumption but also keeps to the service level agreement (SLA). The results from this scheme show that the energy consumption is reduced by 6% and the SLA violations drop by a percentage of 38% when compared to a virtual placement scheme that made use of heuristics [17]. Shaw et al. create a Predictive Anti-Correlated Placement Algorithm (PAPCA) that determines the placement of virtual machines based on the previous and expected CPU resource demands of the virtual machines that are migrating [19]. The results show that this algorithm which has been formulated correctly predicts the resource utilisation of the virtual machines and when compared to similar placement schemes the overall power consumption reduces by 18% [19]. Another study optimises the placement of virtual machines on IP over WDM networks by considering three virtual machine placement schemes: Virtual Machine Migration, Virtual Machine Replication and Virtual Machine Slicing. These schemes will be further explained in this dissertation. However, it is found that the virtual machine slicing scheme saves the highest amount of power consumption (25%) when compared to a scheme in which all the virtual machines are placed in one cloud [15].

There have also been several attempts made to optimise the placement of virtual machines while considering renewable energy in data centres. Camus et al. propose “NEMESIS- Network-aware Energy-Efficient Management Framework for Distributed Clouds Infrastructures” [20]. NEMESIS consists of various algorithms. The first algorithm is supposed to assign virtual machines to servers which are present in data centres, the second algorithm migrates these virtual machines that have been assigned while the last two algorithms determine what servers should not be in operation while the virtual machines are migrating. It is helpful to note that in these data centres the power supply used is from a photovoltaic system and the production rate from this photovoltaic system serves as a factor when these algorithms are produced. The results from using the NEMESIS approach see high power savings of 1.6% and 3.2% when compared to similar approaches [20].

3 VIRTUAL MACHINE PLACEMENT OPTIMISATION WITHOUT THE CONSIDERATION OF RENEWABLE ENERGY.

For this scenario, the MILP model developed will be used to optimise the placement of virtual machines without considering the availability of renewable energy. The virtual machine placement schemes which have been considered in [15], will be used for this model.

The schemes are:

1) Virtual Machine Replication- Here, multiple copies of each virtual machine are allowed in the network.
2) Virtual Machine Migration- This scheme permits only one replica of each virtual machine to be in the network.

Sets:

N- Set of IP/WDM nodes.
Nm_i- The set of neighbours of node i.
VM- Set of Virtual Machines.

Parameters:

Prp- Power Consumption of Router Ports.
Pt- Power Consumption of Transponders.
Pe- Power Consumption of EDFAs.
PO_i- Power Consumption of Optical Switch i.
Pmd- Power Consumption of Multiplexer/Demultiplexer
W- Number of Wavelengths Per Fibre.
B- Wavelength Bit Rate.
S- Distance between EDFAs.
D_{mn}- Distance between Node pair (m,n).
A_{mn}- Number of EDFAs between node pair (m,n).
PUE_n- IP/WDM network power usage effectiveness
PUE_c- Cloud power usage effectiveness
Red- Storage and Switching Redundancy
Sw_PC- Cloud Switch Power Consumption
Sw_C- Cloud Switch Capacity
Sw_EPB- Cloud Switch Energy Per Bit, this is Calculated as: Sw_PC/Sw_C.
R_PC- Cloud Router Power Consumption
R_C- Cloud Router Capacity
R_EPB- Cloud Router Energy per bit, this is calculated as: R_PC/R_c
NVM- Total number of virtual machines.
P_{max}- Maximum power consumption of a server
W_{max}- Maximum normalised workload of a server

Variables:

C_{ij}- The amount of wavelength channels on the virtual link that are between node pair (i, j).

λ_{ij}^{sd}- The amount of traffic between the source and destination nodes that travels through virtual link (i, j)

W_{mn}^{ij}- Amount of wavelength channels between nodes i and j that travels through physical link (m, n).

W_{mn} – Amount of wavelength channels that are on physical link (m, n).

F_{mn} – The amount of fibres on physical link (m, n).

Cup_s- Cloud s upload capacity.

L_{sdv}- Traffic demand from virtual machine v in cloud s to node d.

PSN_s- Amount of processing servers in cloud s.

Q_i- This represents the number of ports used for aggregation on router i.

The model is defined as follows:

Objective: Minimise

$$
\begin{aligned}
PUE_n \cdot \Bigg(\sum_{i \epsilon N} Prp \cdot Q_i + Prp \cdot \sum_{m \epsilon N} \sum_{n \epsilon Nm_m} W_{mn} \\
+ \sum_{m \epsilon N} \sum_{n \epsilon Nm_m} P_t \cdot W_{mn} + \sum_{m \epsilon N} \sum_{n \epsilon Nm_m} P_e \cdot A_{mn} \cdot F_{mn} \sum_{i \epsilon N} PO_i \\
+ \sum_{m \epsilon N} \sum_{n \epsilon Nm_m} Pmd \cdot F_{mn} \Bigg) \\
+ PUE_c \cdot \left(\sum_{s \epsilon N} \nabla \cdot CW_s + \sum_{s \epsilon N} Cup_s \cdot (Sw_{EPB} \cdot Red + R_{EPB}) \right)
\end{aligned}
\tag{1}
$$

Subject to:

$$
\sum_{j \in N: i \neq j} \lambda_{ij}^{sd} - \sum_{j \in N: i \neq j} \lambda_{ji}^{sd} = \begin{cases} \lambda^{sd} & i = s \\ -\lambda^{sd} & i = d \\ 0 & otherwise \end{cases}
$$
$$
\forall s, d, i \in N: s \neq d, \tag{2}
$$

$$
\sum_{s \in N} \sum_{d \in N: s \neq d} \lambda_{ij}^{sd} \leq C_{ij}.B \quad \forall i, j, \in N: i \neq j, \tag{3}
$$

$$
\sum_{n \in N_m} w_{mn}^{ij} - \sum_{n \in N_m} w_{nm}^{ij} = \begin{cases} C_{ij} & m = i \\ -C_{ij} & m = j \\ 0 & otherwise \end{cases}
$$
$$
\forall i, j, m \in N: i \neq j, \tag{4}
$$

$$
\sum_{i \in N} \sum_{j \in N: i \neq j} w_{mn}^{ij} \leq W.f_{mn}
$$

$$
\forall m \in N \quad \forall n \in Nm_m \tag{5}
$$

$$
\sum_{i \in N} \sum_{j \in N: i \neq j} W_{mn}^{ij} = W_{mn}
$$
$$
\forall m \in N \quad \forall n \in Nm_m \tag{6}
$$

$$
Cup_s = \sum_{d \in N} L_{sd}
$$
$$
\forall s \in N \tag{7}
$$

$$Q_i = \frac{1}{B} \cdot \sum_{d \in N : i \neq d} L_{id}$$
$$\forall i \in N \qquad (8)$$

$$\sum_{s \in N} L_{sdv} = D_{dv}$$
$$\forall d \in N \ \ \forall v \in VM \qquad (9)$$

$$M \cdot \sum_{d \in N} L_{sdv} \ \geq \ \delta_{sv}$$
$$\forall s \in N \ \ \forall v \in VM \qquad (10)$$

$$\sum_{d \in N} L_{sdv} \ \leq \ M \cdot \delta_{sv}$$
$$\forall s \in N \ \ \forall v \in VM \qquad (11)$$

$$\sum_{v \in VM} \delta_{sv} \ \geq \ Cloud_s$$
$$\forall s \in N \qquad (12)$$

$$\sum_{v \in VM} \delta_{sv} \ \leq \ M \cdot Cloud_s$$
$$\forall s \in N \qquad (13)$$

$$CW_s = \sum_{v \in VM} \delta_{sv} \cdot W_v$$
$$\forall s \in N \qquad (14)$$

$$\sum_{s \in N} \delta_{sv} = 1$$
$$\forall v \in VM \qquad (15)$$

$$PSN_s = \ CW_s / W_{max}$$
$$\forall s \in N \qquad (16)$$

The main aim of the objective function is to minimise the total cloud power consumption and total IP/WDM network power consumption. The cloud power consumption is made up of the power consumption of servers, switches and routers while the IP/WDM network power consumption is made up of power consumption of routers, transponders, EDFAs (Erbium-doped fibre amplifiers), optical switches and Multiplexers/Demultiplexers.

Constraint (2) is commonly known as the flow conservation constraint in the IP layer. It makes certain that all the traffic demand between neighbouring routers do not pass through a single path but rather this traffic demand can be split and have a variety of flow paths. It verifies that the amount of traffic entering and leaving a node are equal while excluding the source and destination nodes.

Constraint (3) ensures that the traffic demand between node pair (s, d) traveling through virtual link (i, j) does not exceed the total wavelength capacity.

Constraint (4) is another flow conservation constraint but for the optical layer. It ensures that the summation of all the outgoing wavelength channels travelling through the physical link (m, n) is the same as the incoming wavelength channels passing through the physical links (m,n) with the exclusion of nodes i and j.

Constraint (5) guarantees that the number of wavelength channels between node pair (i, j) that are travelling through physical link (m,n) does not exceed the number of fibres in that physical link. W represents the number of wavelengths per fibre while f_{mn} stands for the number of fibres in that physical link. Hence, the multiplication of these two variables can determine the amount of fibres present in that physical link.

Constraint (6) confirms that the number of wavelength channels between node pair (i,j) that are travelling through physical link (m,n) is equivalent to the number of wavelengths in the physical link.

Constraint (7) calculates the cloud upload capacity by summing up the traffic which has been sent from the cloud.

Constraint (8) calculates the amount of aggregation ports required for each router.

Constraint (9) makes sure that the traffic demand from virtual machine v in cloud s to node d is equal to the traffic demand from virtual machine v to node d. If this condition is not satisfied, the demand of some of virtual machines may not be met as a result of insufficient traffic.

Constraint (10) and (11) ensures that virtual machine v is replicated to a cloud s as long that cloud s has been selected to have a copy of virtual machine v. This means that if δ_{sv}=0, no virtual machine will be replicated to cloud s. Therefore, M has to be a very big number so that δ_{sv}=1 under the condition that $\sum_{v \in VM} \delta_{sv} > 0$.

Constraints (12) and (13) help to form a cloud in location s as far as it has been chosen to host a copy of a virtual machine. This is because if δ_{sv}=1 (cloud has a virtual machine copy) the cloud has already been built in node s because $Cloud_s$ helps to determine if a cloud is present in node s and as far as this cloud is present ($Cloud_s$=1). M represents a very large number.

Constraint (14) determines the total normalised workload of each cloud by aggregating the normalised workload of each virtual machine.

Constraint (15) is the virtual machine migration constraint that allows just a single copy of each virtual machine in the network.

Constraint (16) determines the number of processing servers that will be required in each cloud by dividing the normalised workload of each cloud by the maximum normalised workload of the server which in this case is 100%.

4 CLOUD VIRTUAL MACHINE MODEL RESULTS

The BT network is the core network which was used to analyse the placement of these virtual machines. This network has 20 nodes and 68 bidirectional links. The BT network is shown below:

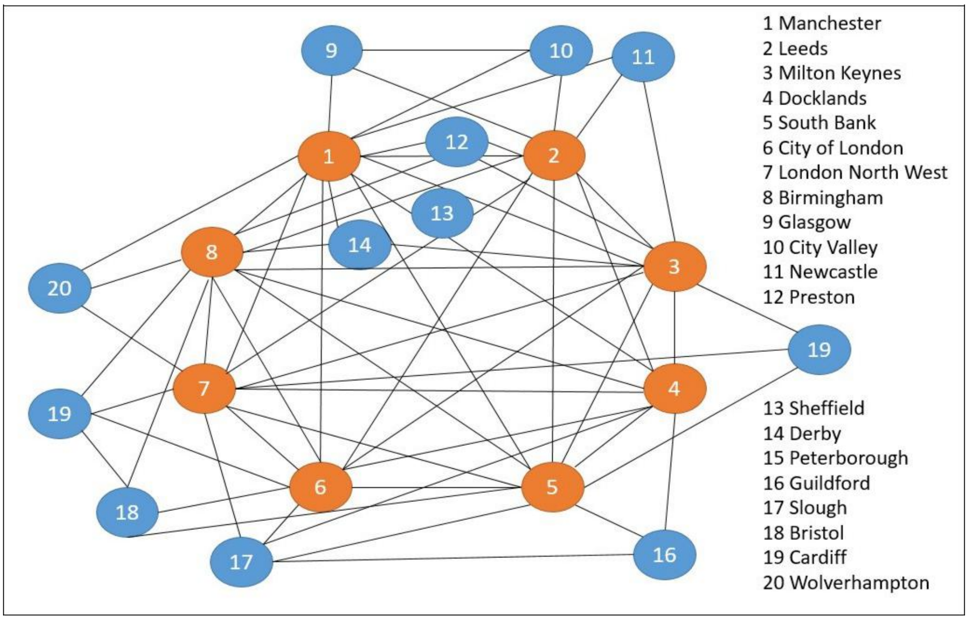

Figure 3 BT Core Network

According to the information provided in [21], 91.3% of the population in the United Kingdom are Internet Users. The average traffic per capita per month is 79.6 Gb. 75% of this traffic is then used to estimate the user-datacentre traffic i.e. 59.7 Gigabyte or 477.6 Gigabit. It is also useful to note that this same 75% is used to estimate the number of end users that utilise software applications which are hosted by virtual machines i.e. 75% of the 91.3% population of the internet users calculated before [21]. This means that the models developed will consider the distribution of users at each node to be non-uniform.

The city of London has approximately seven million that make use of software applications hosted by virtual machines while City Valley has the lowest number of users. This figure is approximately ten thousand internet users. The population of each of these cities was gotten with the help of The Office for National Statistics [22]. The datacentre here is located in London (node 6). With this data, the user-datacentre traffic is calculated for each node. To calculate the traffic demand from virtual machine v to node d, the user-datacentre traffic is divided by the number of virtual machines (12). For example, the user-datacentre traffic for Leeds was calculated to be 96.08 Gbit/s. To estimate the traffic demand from virtual machine *v* to node 6, 96.08 was divided by 12 i.e. 8.007 Gbit/s.

The input parameters for this model are displayed in the table below. The initial plan was to analyse 100 Virtual Machines but the CPLEX solver could not take this amount, so 12 virtual machines were considered instead. To compensate for the fact that 100 virtual machines could no longer be analysed, each virtual machine was given workloads of 5%, 10% and

100%. High traffic here could be referred to when the normal traffic demand from virtual machine v to node d is multiplied a weight of 10 while very high traffic could be referred to when the normal traffic demand is multiplied by a weight of 100.

This MILP model was solved with the use of a 64-bit AMPL/CPLEX software on an AMD A9-9410 RADEON R5 processor with 8GB memory and an intel® Core™ i3-6100U processor with 8GB memory.

The three different considerations for optimising the placement of virtual machines.

- When the traffic in the network is normal and workloads of 5%,10% and 100% are assigned to virtual machines.
- When the traffic in the network is multiplied by a factor of 10 and workloads of 5%,10% and 100% are assigned to virtual machines.
- When the traffic in the network is multiplied by a factor of 100 and workloads of 5%,10% and 100% are assigned to virtual machines.

The virtual machine placement under both the replication and migration schemes will be analysed. The total power consumption under the various schemes will also be analysed.

TABLE I
INPUT DATA FOR MODEL

Power Consumption of Router Port (Prp)	**1000W [16]**
Power Consumption of Transponder (Pt)	73W [16]
Power Consumption of Optical Switch (PO_i)	85W [15]
Power Consumption of EDFA (Pe)	8W [15]
Power Consumption of Multiplexer and Demultiplexer (Pmd)	16W [15]
Number of Wavelengths in a Fibre (W)	16 [16]
Bit Rate of Each Wavelength (B)	40 Gbps
Span Distance between EDFAs (S)	80km
Server Maximum Power Consumption (P_{max})	300W
Server Maximum Normalised Workload (W_{max})	100%
Number of Virtual Machines (NVM)	12
IP/WDM Network Power Usage Effectiveness (PUE_n)	1.5
Cloud Power Usage Effectiveness (PUE_c)	2.5
Storage and Switching Redundancy (Red)	2
Cloud Switch power consumption (Sw_PC)	3.8kW [23]
Cloud Switch Capacity (Sw_C)	320Gbps [23]
Cloud Router power Consumption (R_PC)	5.1kW [23]
Cloud Router Capacity (R_C)	660Gbps [23]
Workloads of Virtual Machines (W_v)	5%, 10%, 100%.

4.1 Virtual Machine Replication

4.1.1 Normal Traffic

When the traffic demand is normal, all the virtual machines are placed in node 6 regardless of the amount of workload which has been assigned to them. However, the total power consumption under the different workloads is different. As expected, when the workload assigned to each virtual machine is 5% (the lowest possible workload), the total power consumption here is the lowest because the virtual machine does not have so much processing to do hence the power consumption here will be the lowest. It can also be noted that at all workloads, the network power consumption stays the same.

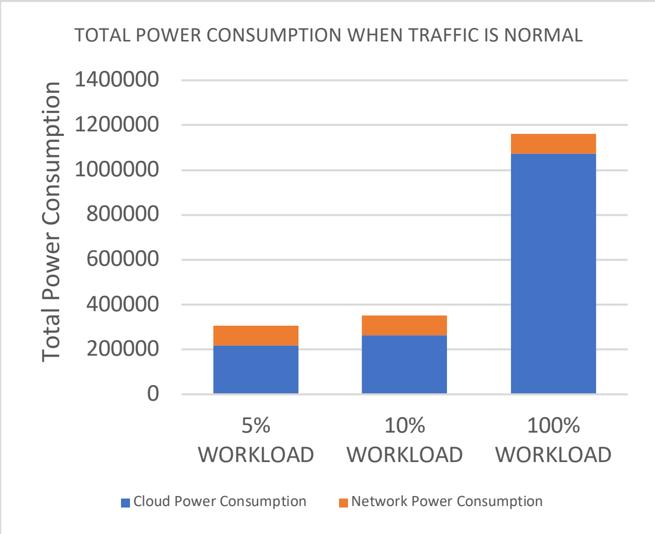

Figure 4 Graph Illustrating Total Power Consumption

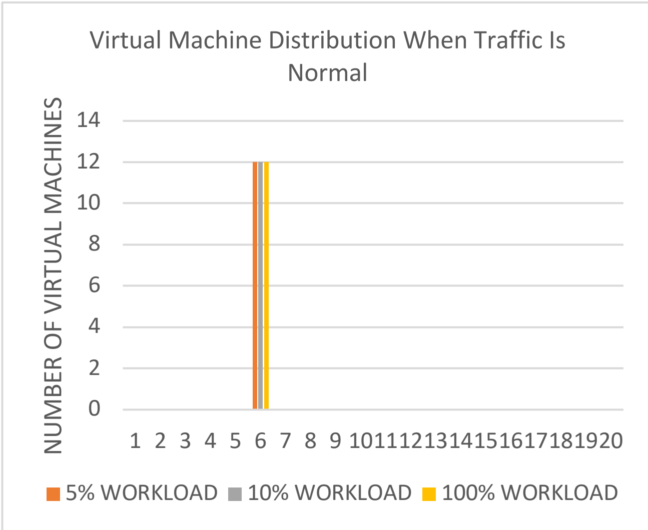

Figure 5 Virtual Machine Distribution

4.1.2 High Traffic

When the traffic demand is high the virtual machines are not replicated in every node. However, when the workloads assigned to the virtual machines are low i.e. 5%, the virtual machines are replicated to more nodes (8 nodes) compared to when the workloads assigned to the virtual machines are high i.e. 100%. For this condition, the virtual machines are only replicated to nodes 6 and 8.

The total power consumption attained when the traffic is high is greater when compared to when the traffic is normal. The total power consumption gotten is higher because periods when the traffic is high are also referred to as high demand periods and during these periods more virtual machines are replicated in clouds when compared to the normal traffic scenario where all virtual machines are placed in node 6 regardless of the workload that has been assigned to that virtual machine. It can also be noted that in the previous scenario, the network power consumption was kept constant at all workloads but when the traffic is high, the network power consumption increases as the amount of workload assigned to each virtual machine increases. This is because not every workload has the same virtual machine distribution and to replicate more virtual machines to clouds the model will achieve a trade-off attained between having more virtual machines (while considering workloads assigned to virtual machines) and the rise in overall power consumption as a result of having more of these virtual machines.

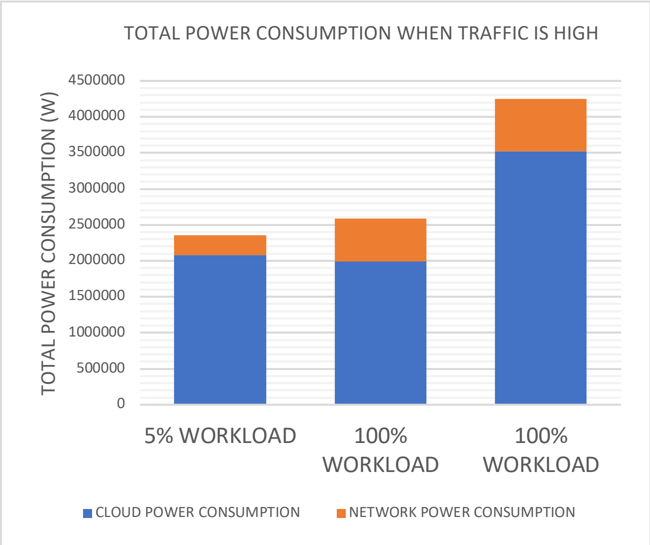

Figure 6 Graph Illustrating Total Power Consumption

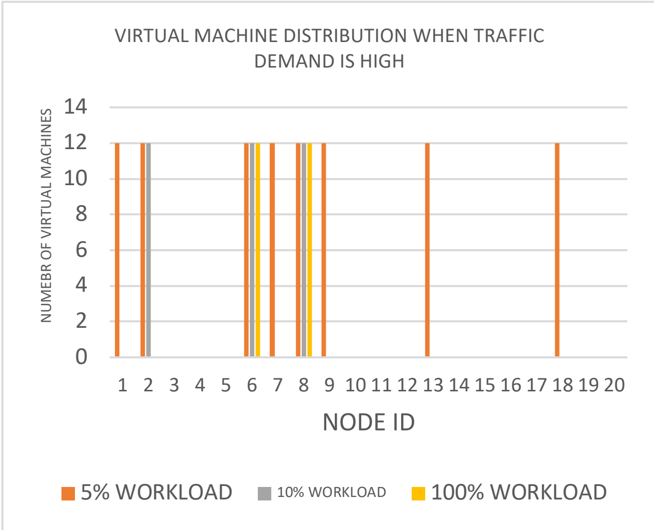

Figure 7 Virtual Machine Distribution

4.1.3 Very High Traffic

When the traffic demand is extremely high, the model replicates the virtual machines at all nodes except node 10. The total power consumption attained here is higher than the 5% and 10% workloads because once again the very high traffic periods can be assumed to be when the user-datacentre traffic demand is very high. However, it can be noted that the network power consumption is kept constant at all workloads. This is because the replication at all workloads is equal i.e. each node apart from node 10 replicates 12 virtual machines.

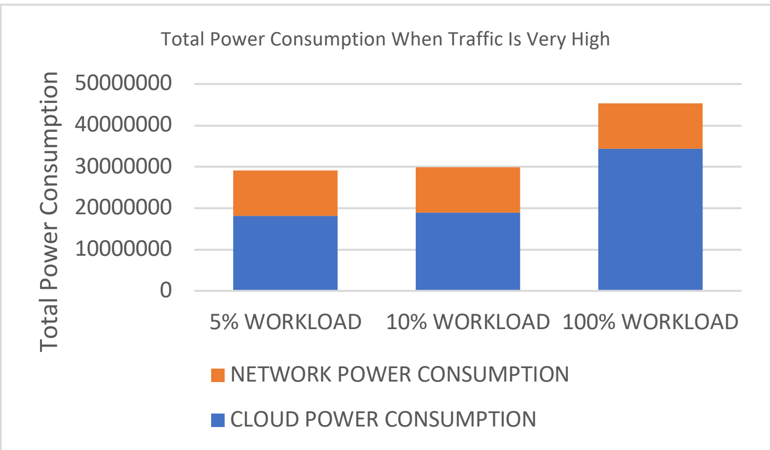

Figure 8 Graph Illustrating Total Power Consumption

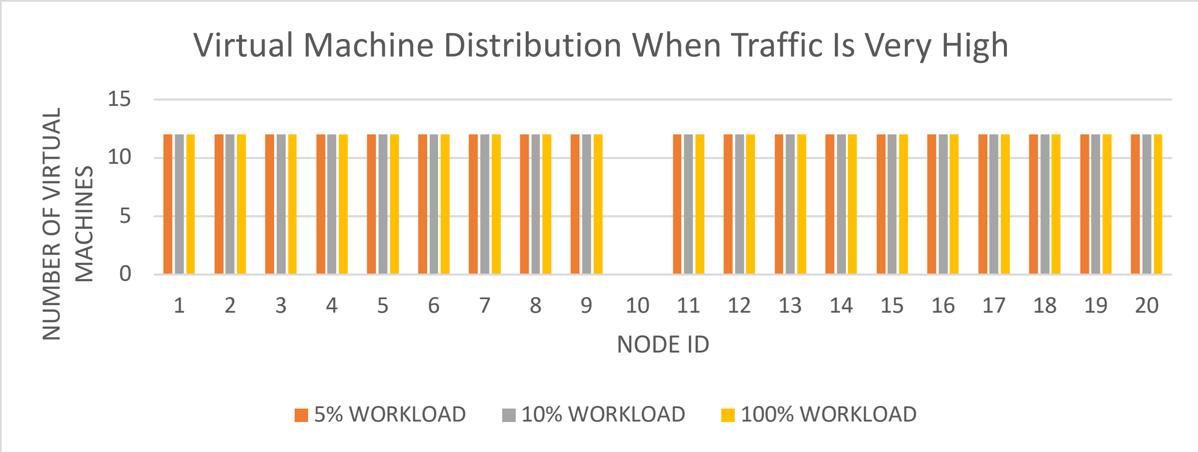

Figure 9 Virtual Machine Distribution When Traffic Is Very High

4.2 Virtual Machine Migration

As previously explained, for the virtual machine migration scheme, only one replica of each virtual machine will be permitted in the network. Constraint (15) governs the virtual migration scheme.

4.2.1 Normal Traffic

As the workload assigned to each virtual machine increases, the cloud power consumption increases but the network power consumption is kept constant because, since this is the virtual machine migration scheme, all the virtual machines are placed in node 6. Hence, the virtual machine distributions under all conditions is the same which will lead to no change in the overall network power consumption. This migration scheme imitates the virtual machine replication scheme for the normal traffic scenario where also all the virtual machines are placed in node 6.

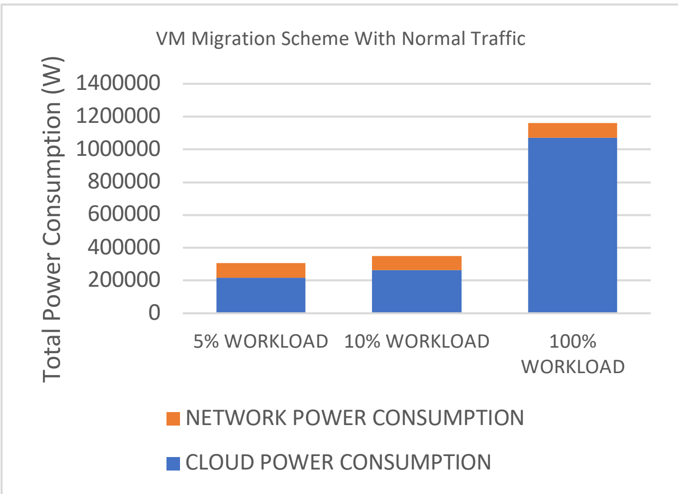

Figure 10 Graph Illustrating Total Power Consumption

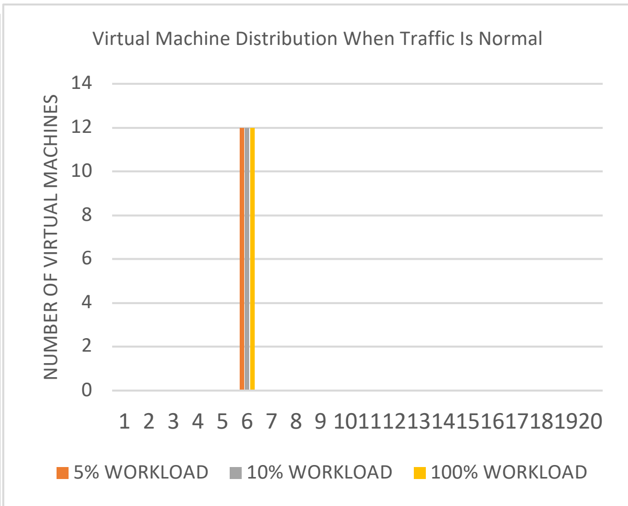

Figure 11 Virtual Machine Distribution

4.2.2 High Traffic and Very High Traffic

When the traffic is high under the virtual machine migration scheme, the power consumption at workloads of 5% and 10% are almost the same but when the workload has increased to 100%, the total power consumption has greatly increased. The virtual machine distribution attained when the traffic is high and very high is the same gotten when the traffic is normal. Regardless of any workload assigned to the virtual machines, all the virtual machines are still placed in node 6.

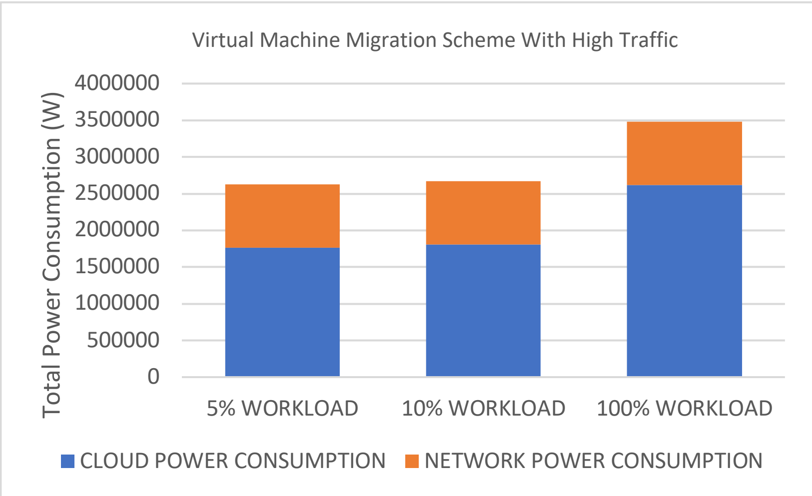

Figure 12 Graph Illustrating Total Power Consumption

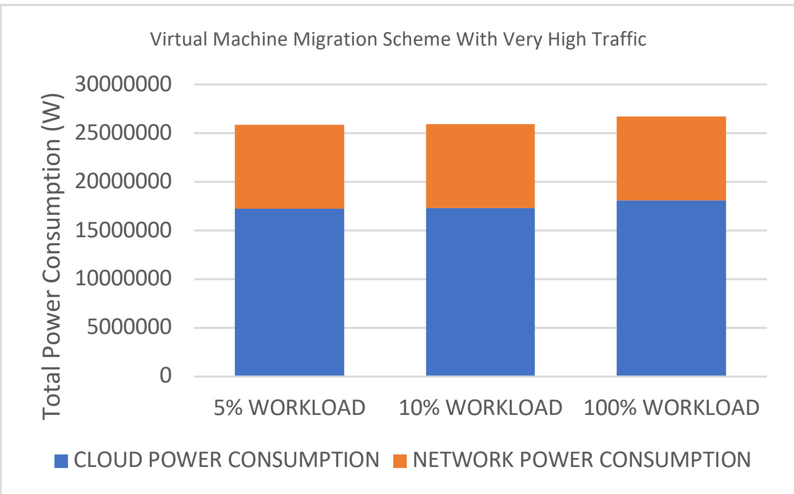

Figure 13 Graph Illustrating Total Power Consumption

5 VIRTUAL MACHINE PLACEMENT OPTIMISATION WITH THE CONSIDERATION OF RENEWABLE ENERGY (MODEL).

This chapter will extend the model created in [9] and optimise the placement of virtual machines while considering renewable energy.

The following assumptions are made:

- The power supplied to the IP/WDM Network is completely non-renewable.
- The source of renewable energy available to power clouds is wind farm power.
- Any amount of wind farms can supply power to a particular cloud.
- The entire capacity of the wind farm will not only be used to power clouds hence only a portion, ρ, will power the clouds.
- The electric power transmission loss to deliver power from wind farms to clouds is assumed to be 7.5% per 400km.

While considering the variables and parameters used for the condition without renewable energy, the additional sets, variables and parameters will also be considered:

Sets:
WF- Set of Wind farms.

Variables:
$CNRP_s$ – Non-renewable power consumption of cloud s.
CRP_s – Renewable power consumption of cloud s.
TNNRP- Total network non-renewable power consumption.
TCNRP- Total cloud non-renewable power consumption.
$TCPC_s$- Total power consumption in cloud s.
TPLOSS- Total transmission power losses.

The total clouds power consumption is made up of:

1) Power Consumption of Servers:

$$PUE_c \cdot \sum_{s \epsilon N} \nabla \cdot CW_s$$

2) Power Consumption of Switches and Routers:

$$PUE_c \cdot \sum_{s \epsilon N} Cup_s \cdot (Sw\_EPB \cdot Red + R\_EPB)$$

Objective: Minimise

$$\alpha.TNNRP + \beta \cdot TCNRP + \gamma.TPLOSS \tag{17}$$

$$CRP_S = \sum_{w \in WF} \Delta_{ws} \cdot (1 - PL_{ws})$$
$$\forall s \in N \tag{18}$$

$$TCNRP = \sum_{s \in N} CNRP_S \tag{19}$$

$$TCPC_s = CNRP_s + CRP_s$$
$$\forall s \in N \tag{20}$$

$$\sum_{s \in N} \Delta_{ws} \leq WP_w \cdot \rho$$
$$\forall w \in WF \tag{21}$$

The objective function here is similar to the objective function which was considered before renewable energy. The only difference is that apart from just minimising the cloud and network non-renewable power, the objective also minimises the transmission power losses.

Constraint (18) determines the renewable power delivered to each cloud by considering the allocation of renewable power to the cloud in node s while subject to any transmission losses that may have occurred.

Constraint (25) calculates the total cloud non-renewable power by summing up the non-renewable power delivered to each cloud in node s.

Constraint (20) determines the total power consumption of cloud s by summing up the non-renewable and renewable power consumed by each cloud s.

Constraint (21) first of all estimates the amount of renewable power available to clouds and also makes sure that the renewable power which has been assigned to a specific cloud is not more than the renewable power that is available to power that particular cloud.

5.1 MODEL RESULTS

To analyse the placement of the virtual machines while considering renewable energy, the same BT network is used. The number of virtual machines used still remains at 12. There are 5 windfarms which are located at nodes 2, 3, 15, 18 and 19. The maximum capacity of these windfarms are 10.2MW, 14MW, 23.4MW, 9MW, 2.3MW respectively. The input data used for this model is the same used when renewable energy is not considered. The additional input for this model is the fraction of wind farms power which is available to power the clouds (ρ). The fraction of wind farms power which will be considered are 0.005 and 0.1. The value 0.005 represents the clouds having little renewable energy being supplied to them from the cloud while the value 0.1 represents the clouds having sufficient renewable energy available to power the clouds.

The two virtual placement schemes will be considered, and the model will optimise the placement of virtual machines while considering the availability of renewable energy. Three major approaches will be considered. They are explained below.

5.2 Virtual Machine Replication:

5.2.1 $\boldsymbol{Approach\ 1: \alpha = 1, \beta = 1\ and\ \gamma = 1}$

5.2.1.1 *Normal Traffic:*

In this first scenario, each of the variables in the objective function is given an equal weight of 1. At low workloads and when p=0.005, virtual machines are only replicated to four clouds. But when p=0.1. Virtual machines are replicated at all clouds with only renewable power supplied to the clouds mainly from the wind farm at node 15. When p=0.1, the lowest network power consumption is also attained.

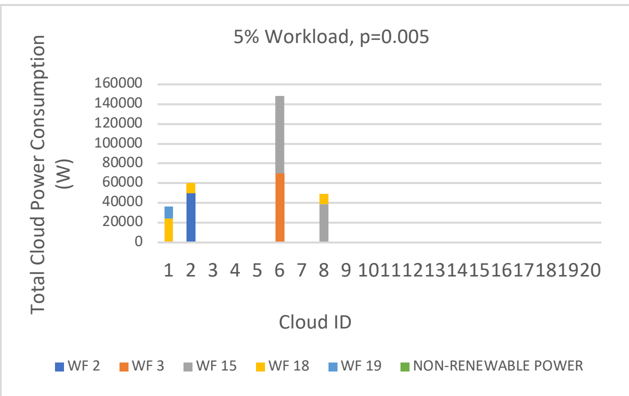

Figure 14 Graph Illustrating Total Cloud Power Consumption

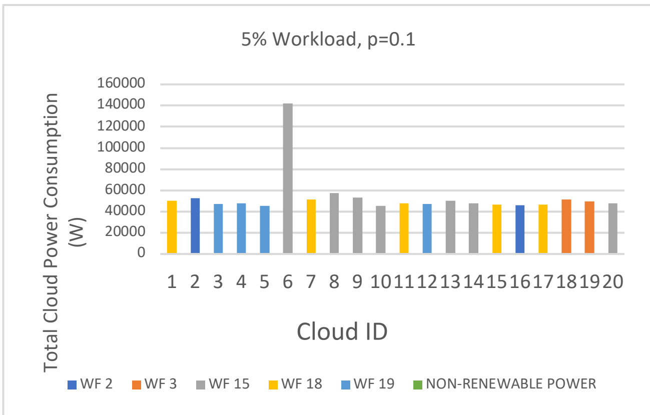

Figure 15 Graph Illustrating Total Cloud Power Consumption

When the workload increases at p=0.005 (100% workload), virtual machines are only replicated at two clouds while when p increases to 0.1, virtual machines are replicated to more clouds. It can be seen that when p=0.1, cloud 2 is entirely powered by its wind farm while cloud 18 is powered by all the wind farms except the one present at cloud 18.

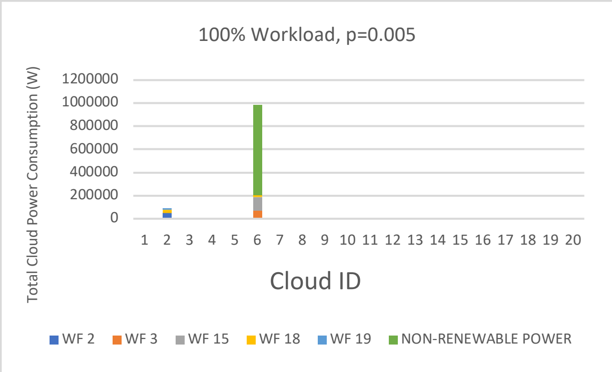

Figure 16 Graph Illustrating Total Cloud Power Consumption

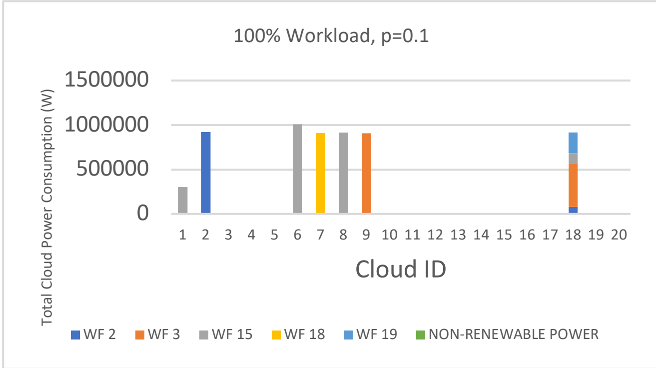

Figure 17 Graph Illustrating Total Cloud Power Consumption

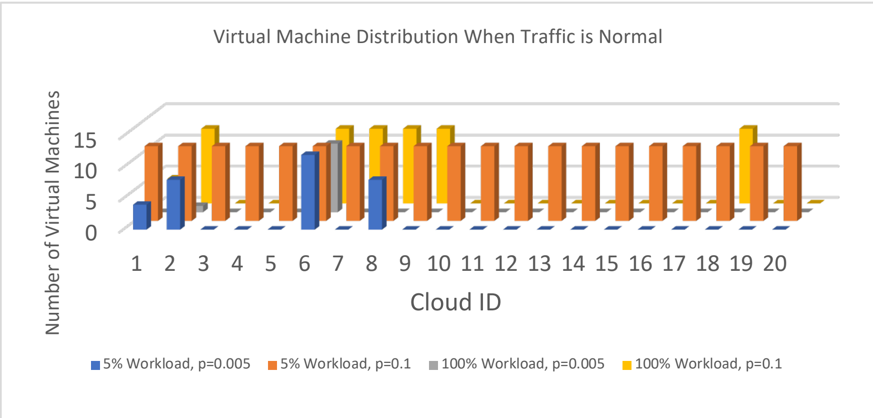

Figure 18 Virtual Machine Distribution

5.2.1.2 *High Traffic:*

The figure below shows the total clouds power consumption attained when the traffic is high and the workload is low i.e. 5%. It can be seen that at p=0.005, the model builds virtual machines in just 8 nodes but when there is sufficient renewable energy i.e. when p=0.1, the model builds virtual machines at all nodes with cloud 6 having the highest power consumption. This is because this cloud serves the highest amount of users. At these conditions (p=0.005 and p=0.1), there are no transmission losses gotten.

When the workload assigned to the virtual machine has increased to 100%, at p=0.005, virtual machines are replicated to only the clouds built at nodes 2, 6 and 8 while when p=0.1, virtual machines are replicated to more clouds. However, at p=0.005, most of the power available to power the clouds is non-renewable. This is not the case at p=0.1, because all the power supplied is from wind farms. Cloud 2 is mainly powered by its wind farm whereas other clouds are powered by wind farms nearby. It is useful to note that the only cloud with a wind farm that has virtual machines is cloud 2.

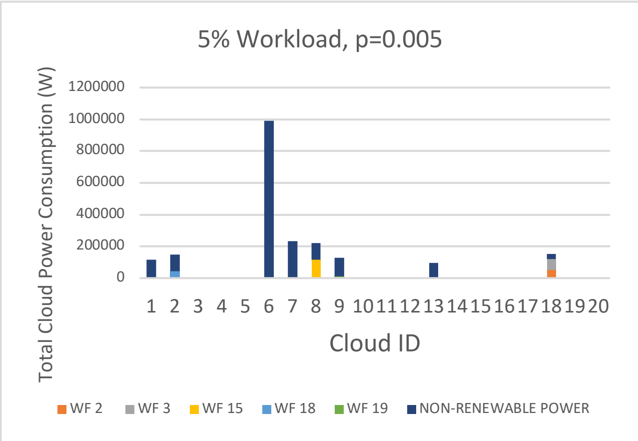

Figure 19 Graph Illustrating Total Cloud Power Consumption

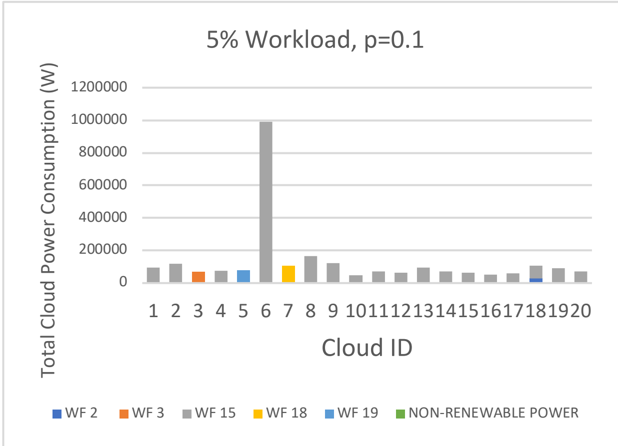

Figure 20 Graph Illustrating Total Cloud Power Consumption

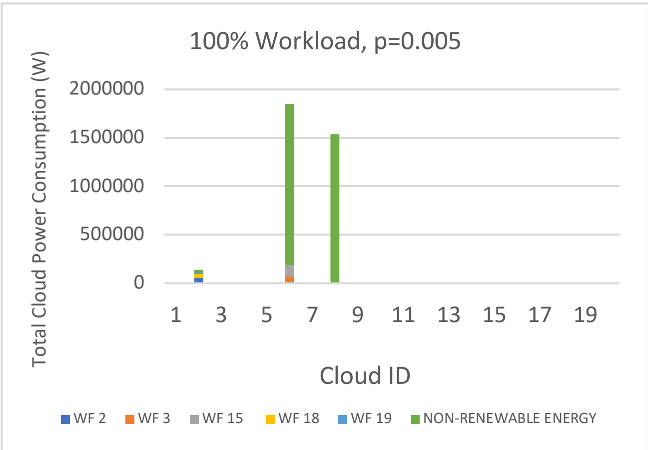

Figure 21 Graph Illustrating Total Cloud Power Consumption

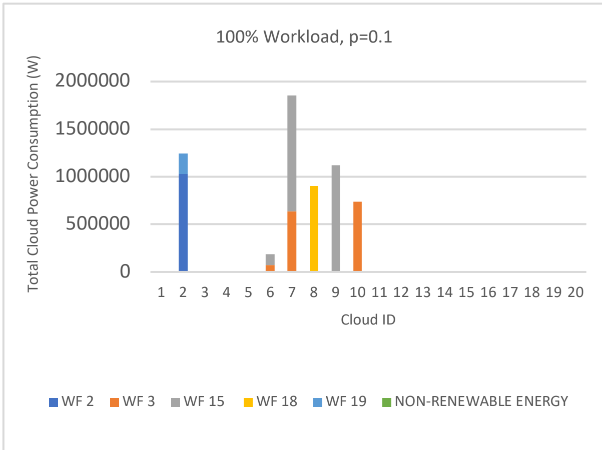

Figure 22 Graph Illustrating Total Cloud Power Consumption

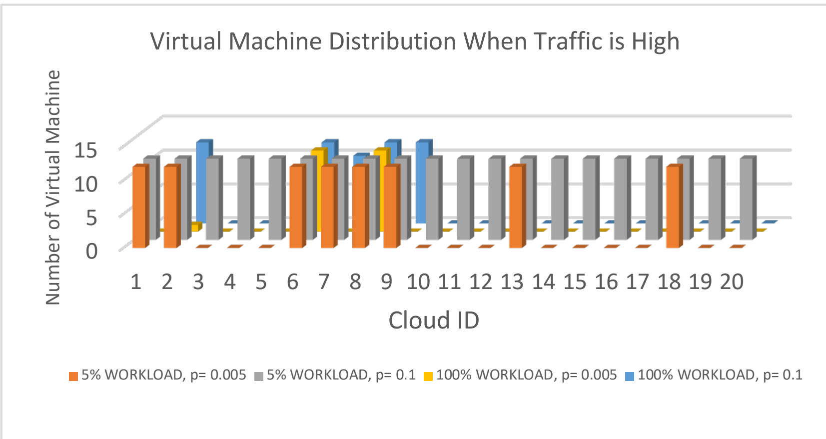

Figure 23 Virtual Machine Distribution

5.2.1.3 *Very High Traffic:*

Due to the increase in traffic, the total clouds power consumption has increased in both cases i.e. When p=0.005 and p=0.1. When p=0.005, majority of power supplied to clouds is non-renewable but when p=0.1, more renewable energy is supplied to the clouds built at nodes 2, 3, 4,6,8,9 and 19. However, it is noticed that although the cloud at 19 has a wind farm, all the power supplied to that cloud is from the wind farm built at node 2. This is because the electric power lost as a result of transmission losses is so small and can be negligible which makes power to be supplied from any wind farm regardless of distance.

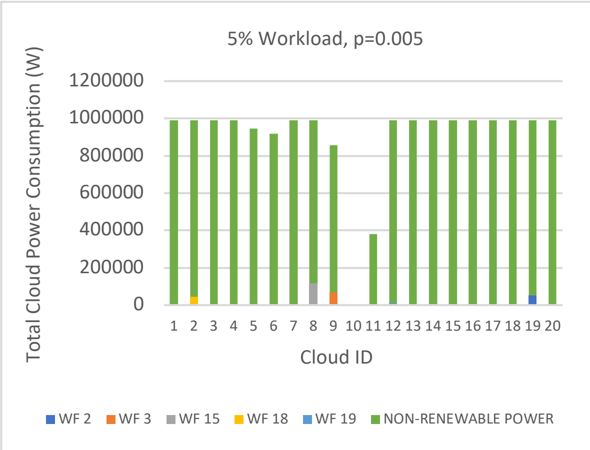

Figure 24 Graph Illustrating Total Cloud Power Consumption

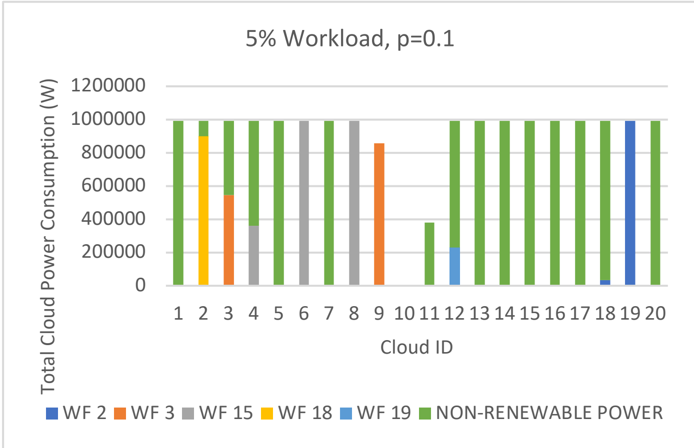

Figure 25 Graph Illustrating Total Cloud Power Consumption

When the workload increases, the overall power consumption increases. However, the virtual machine placement is similar to what was gotten when the workload was 5%. At node 2, since the workload has been increased, the cloud built at that node is not entirely powered by the wind farm at node 18. It is useful to note that in all cases (low and high workloads), there are no virtual machines built at node 10 and the total transmission losses sum up to 0. The total network power consumption is very high in all cases.

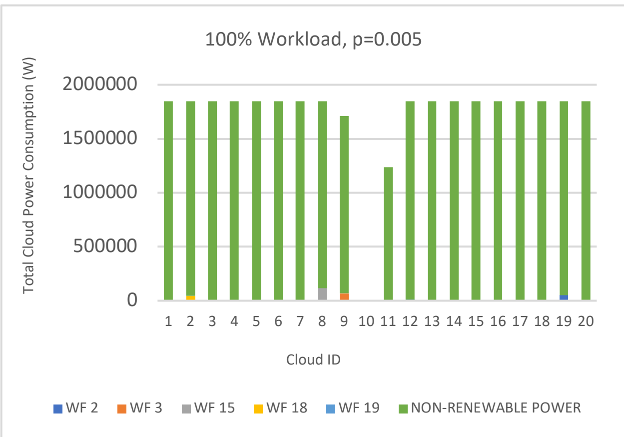

Figure 26 Graph Illustrating Total Cloud Power Consumption

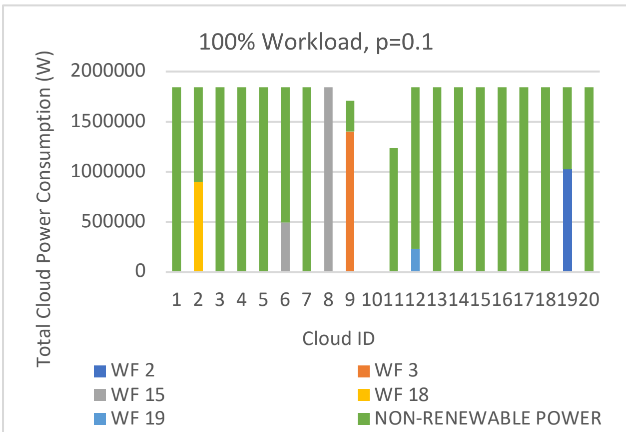

Figure 27 Graph Illustrating Total Cloud Power Consumption

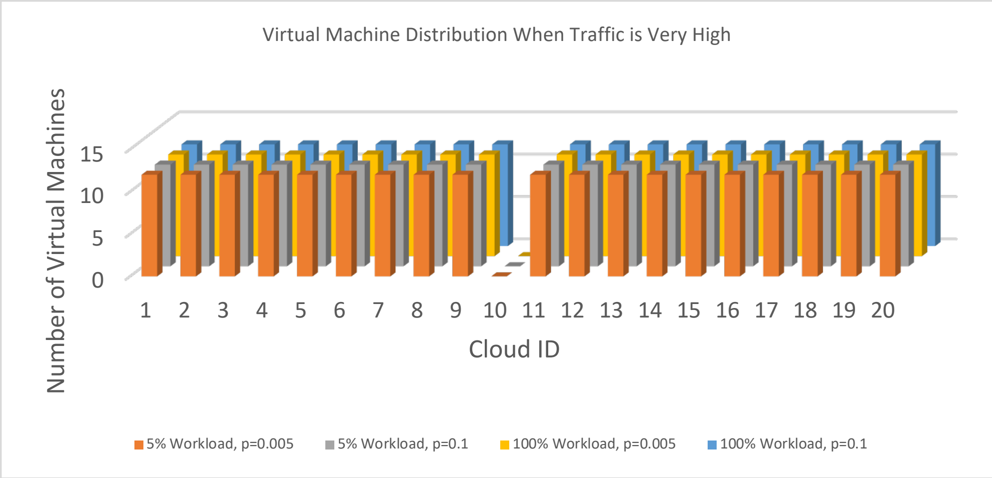

Figure 28 Virtual Machine Distribution

5.2.2 Approach 2: $\alpha = 1, \beta = 1$ and $\gamma = 0$

5.2.2.1 *Normal Traffic:*

In this second approach, the model attempts to minimise the cloud non-renewable power consumption and the network non-renewable power consumption without examining the transmission losses. When the workload is low and at p=0.005, virtual machines are only replicated in three nodes. When p=0.1, virtual machines are replicated in all nodes with most of the renewable power being supplied from the wind farm located in node 2. The network power consumption gotten here is very low. Although, when p=0.1, approximately 45kW of renewable power is lost as a result of transmitting the power from the wind farms to the clouds.

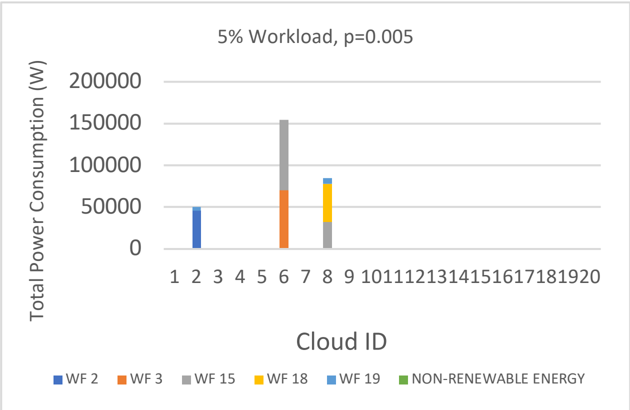

Figure 29 Graph Illustrating Total Cloud Power Consumption

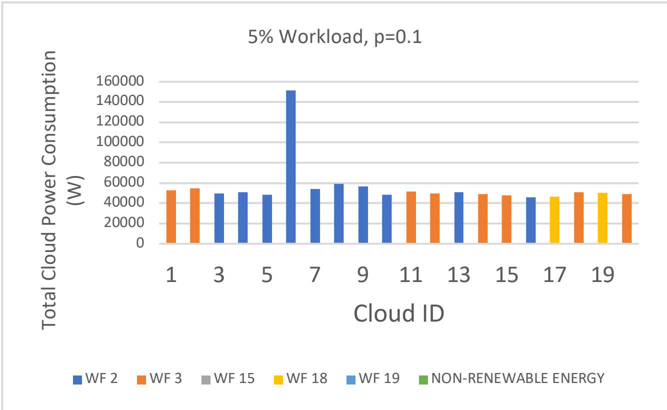

Figure 30 Graph Illustrating Total Cloud Power Consumption

With the workload now increased, at p=0.005 twelve virtual machines are placed in only one cloud and that is in cloud 6. Most of the power supplied here is non-renewable but when p=0.1, all the power supplied is renewable and more virtual machines are replicated in more clouds. The transmission loss when p=0.1 is lower than the transmission loss attained when p=0.005.

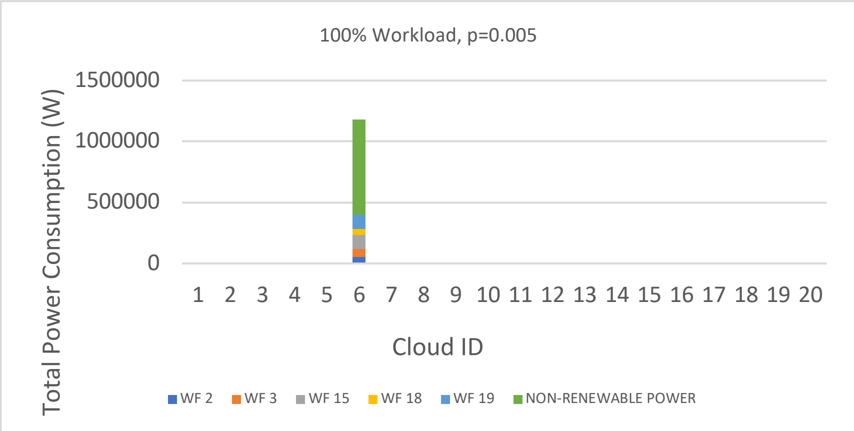

Figure 31 Graph Illustrating Total Cloud Power Consumption

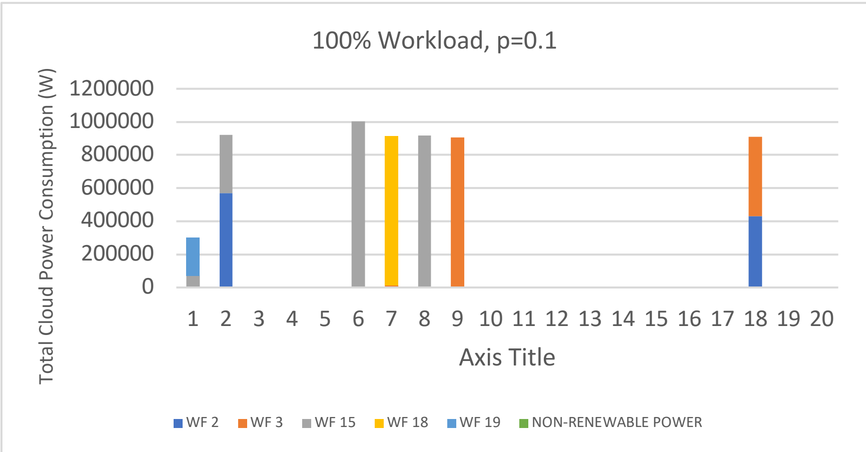

Figure 32 Graph Illustrating Total Cloud Power Consumption

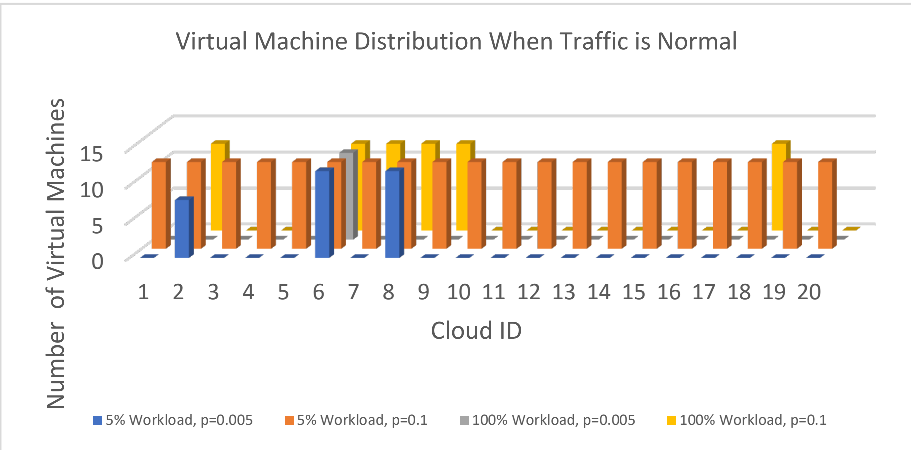

Figure 33 Virtual Machine Distribution Scheme

5.2.2.2 *High Traffic:*

When the workload is 5% and p=0.005, the virtual machine distribution is similar to what was attained in approach 1. When p=0.1, the total power consumption stays the same for all the nodes and majority of the nodes are powered from the wind farm in node 18 compared to approach 1 where majority of the nodes were powered from the wind farm in node 15.

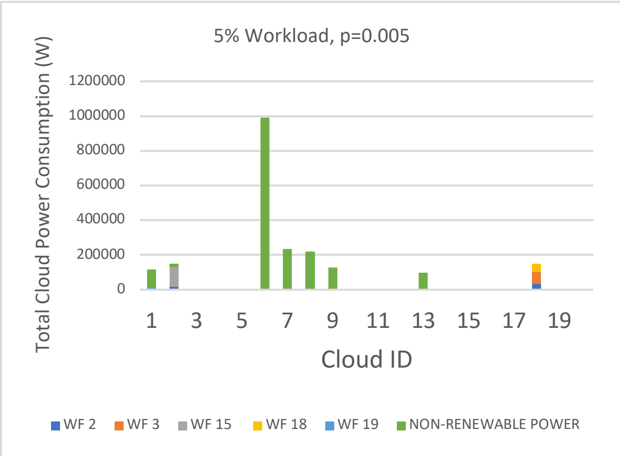

Figure 34 Graph Illustrating Total Cloud Power Consumption

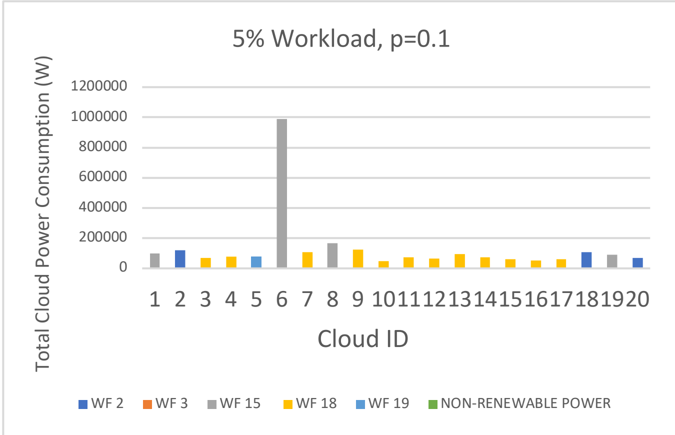

Figure 35 Graph Illustrating Total Cloud Power Consumption

When the workload is increased to 100%, the replication scheme is not so similar to approach 1 because when p=0.005, the model replicates to just two clouds (at nodes 6 and 8). Node 8 is no longer completely powered by non-renewable energy as it has some renewable energy coming from node 2. The wind farms supplying power to node 6 are the same wind farms supplying power when the transmission losses were still considered. However, when p=0.1, the replication scheme is very similar to what was attained in approach 1. Since transmission losses are not explicitly considered, the clouds at nodes 7 and 9 are supplied by wind farms farther from where these clouds are located.

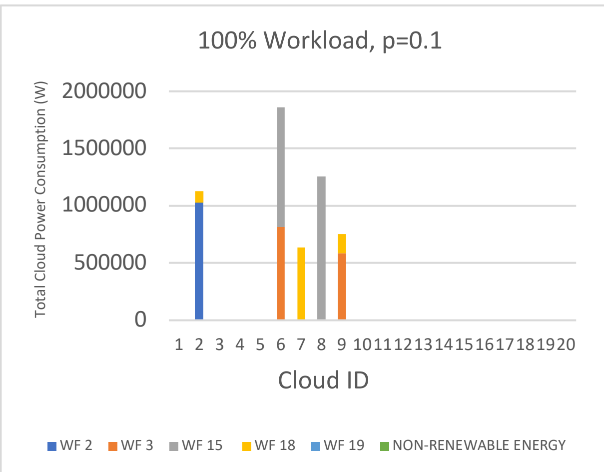

Figure 36 Graph Illustrating Total Cloud Power Consumption

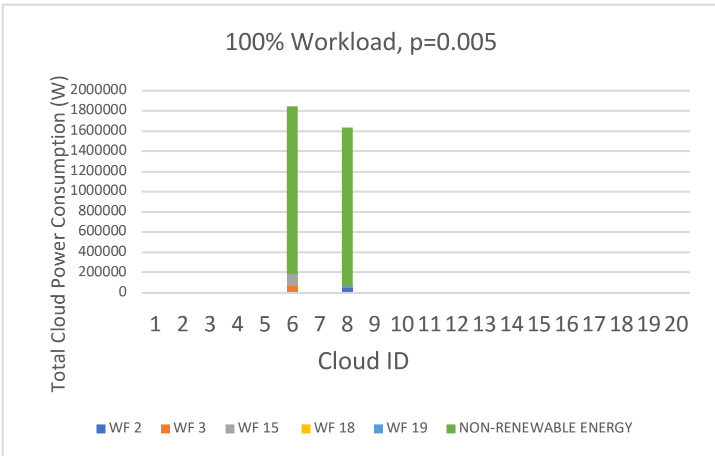

Figure 37 Graph Illustrating Total Cloud Power Consumption

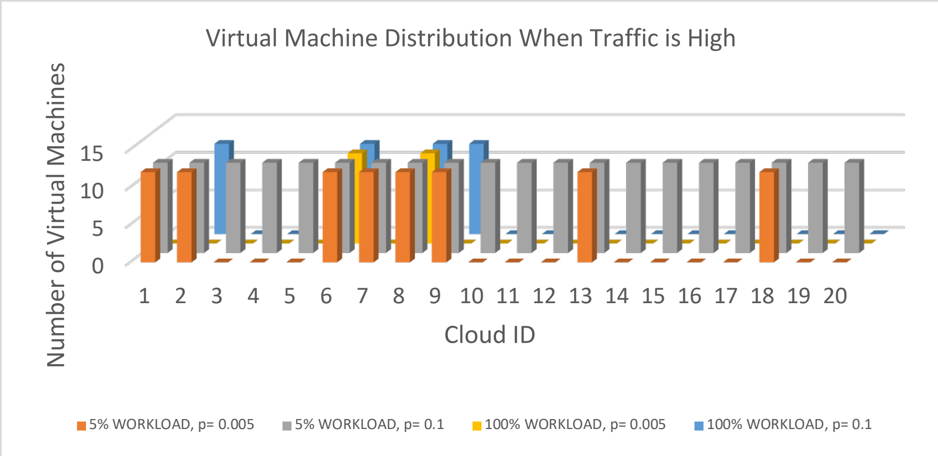

Figure 38 Virtual Machine Distribution

5.2.2.3 *Very High Traffic:*

At p=0.005, almost all the energy supplied to the clouds is non-renewable and when p=0.1, renewable energy is mainly supplied to clouds 2,6,8 and 19. It is useful to note that the wind farm placements and virtual machine placement is exactly how it was in the first approach. This is because although the transmission losses have been given a weight of 0, the electric power lost between wind farms and clouds is so small that it can be negligible. This makes wind farms to be able to supply renewable power to any cloud, regardless of location. This is the same case when the workload is increased to 100%.

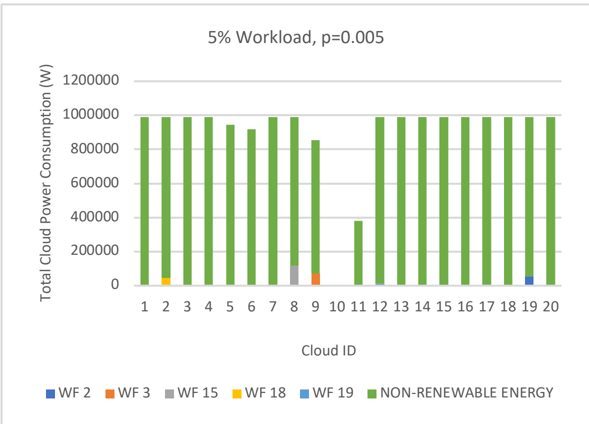

Figure 39 Graph Illustrating Total Cloud Power Consumption

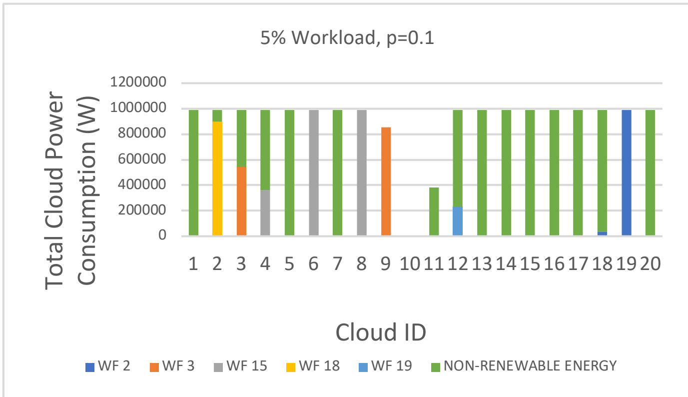

Figure 40 Graph Illustrating Total Cloud Power Consumption

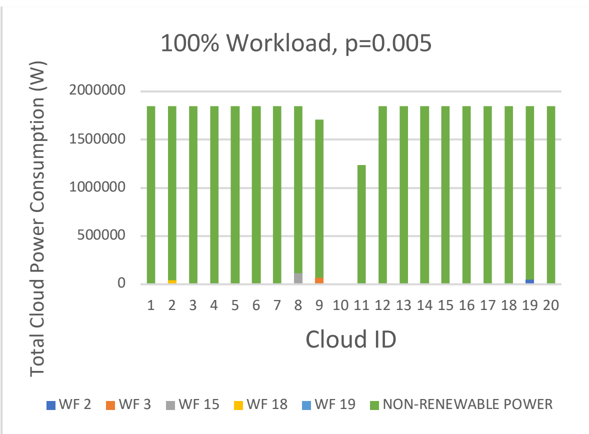

Figure 41 Graph Illustrating Total Cloud Power Consumption

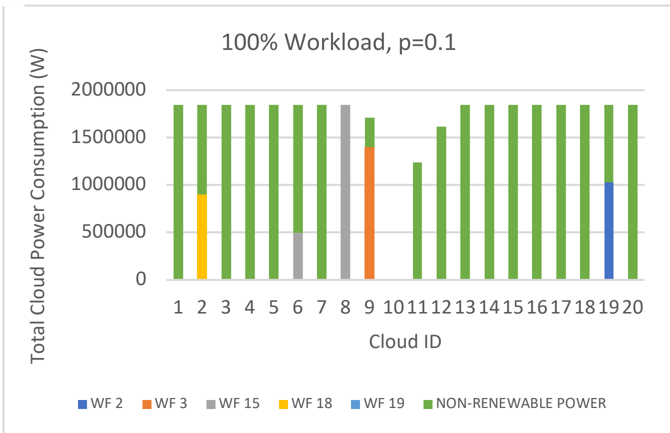

Figure 42 Graph Illustrating Total Cloud Power Consumption

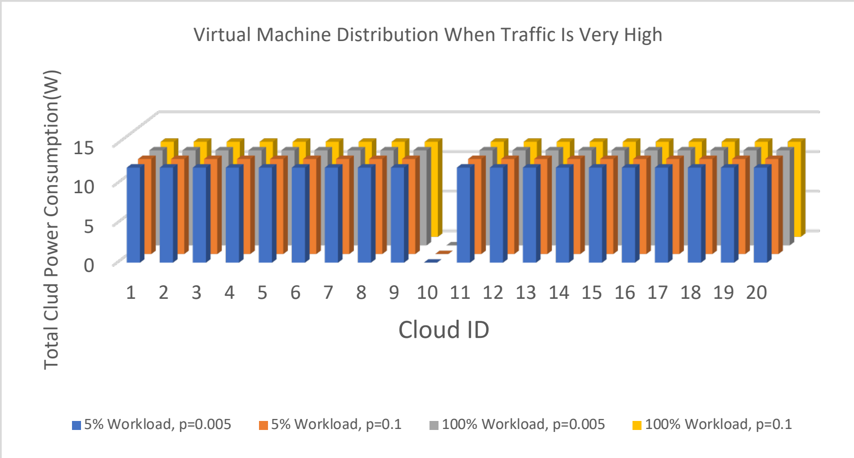

Figure 43 Virtual Machine Distribution Scheme

5.2.3 $\boldsymbol{Approach\ 3: \alpha = 100, \beta = 1\ and\ \gamma = 1}$

5.2.3.1 *Normal Traffic*

Here, the total network power consumption is given a weight of 100 while the transmission losses and the total cloud non-renewable power are given weights of one. At p=0.005, virtual machines are replicated to more clouds when compared to approach 1 and approach 2. Although, most of the power supplied to these clouds is non-renewable. When p=0.1, the virtual machine replication is pretty much the same with the two approaches but there are no transmission losses which gives this scenario an advantage when compared to previous approaches utilised.

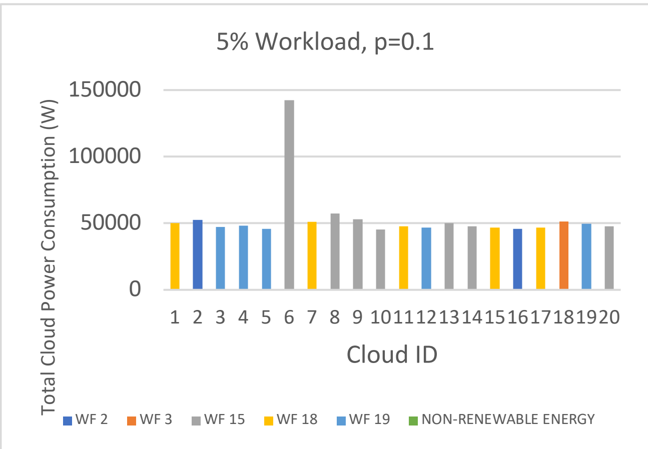

Figure 44 Graph Illustrating Total Cloud Power Consumption

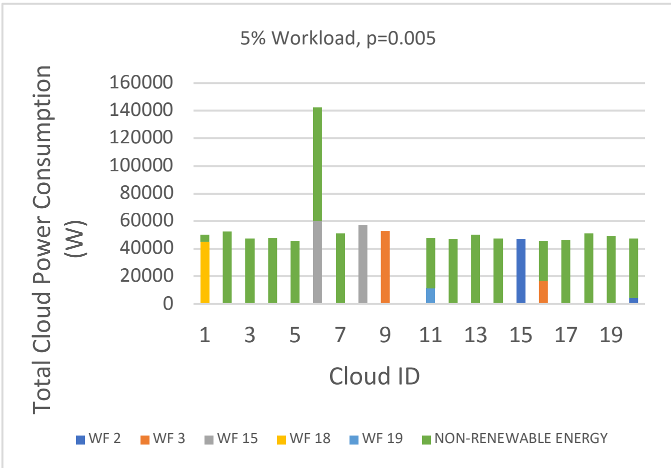

Figure 45 Graph Illustrating Total Cloud Power Consumption

When the workload is increased to 100%, the virtual machine placement scheme is somewhat similar to what was gotten in approach 1.

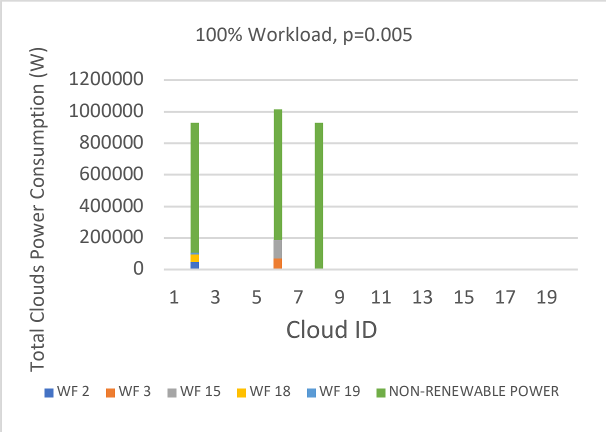

Figure 46 Graph Illustrating Total Cloud Power Consumption

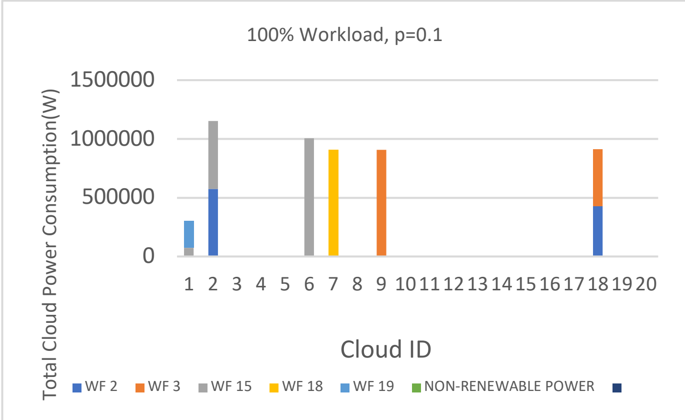

Figure 47 Graph Illustrating Total Cloud Power Consumption

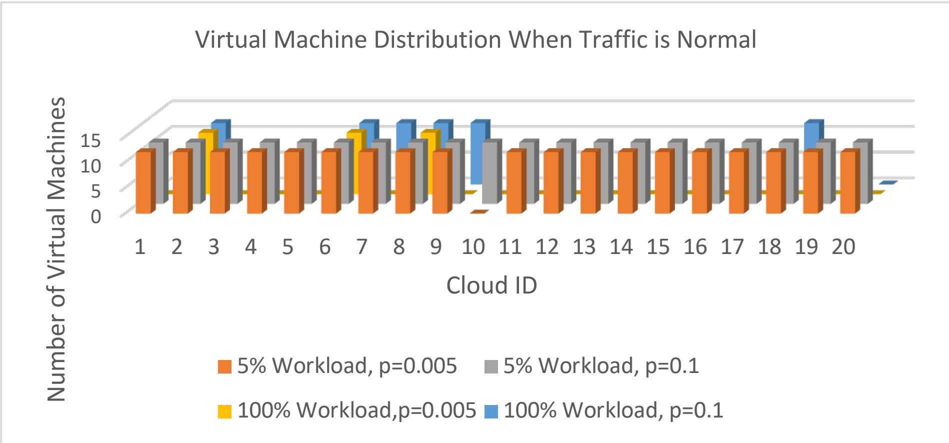

Figure 48 Virtual Machine Distribution Scheme

5.2.3.2 *High Traffic*

With low workloads and at p=0.005, most of the power supplied to the cloud is non-renewable and virtual machines are distributed in all nodes to reduce the network power consumption. However, when p=0.1, the virtual machine replication scheme is the same as approach 1 with most of the clouds being powered by either the wind farm in node 15 or the wind farm in node 2. The total clouds power consumption is also similar to that of approach 1.

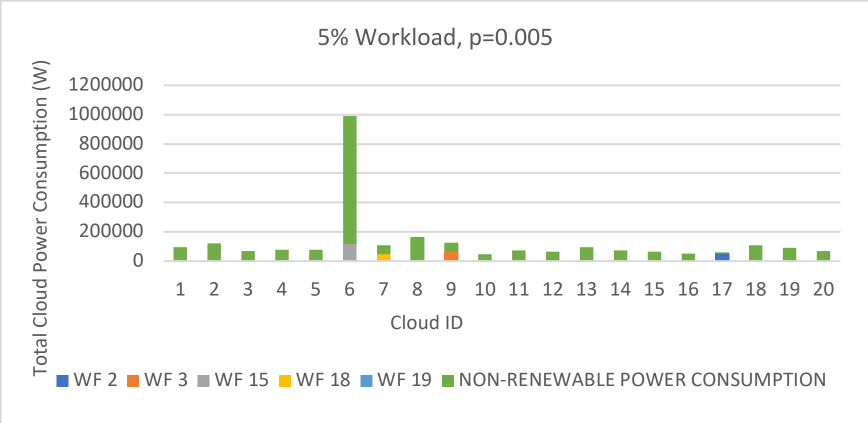

Figure 49 Graph Illustrating Total Cloud Power Consumption

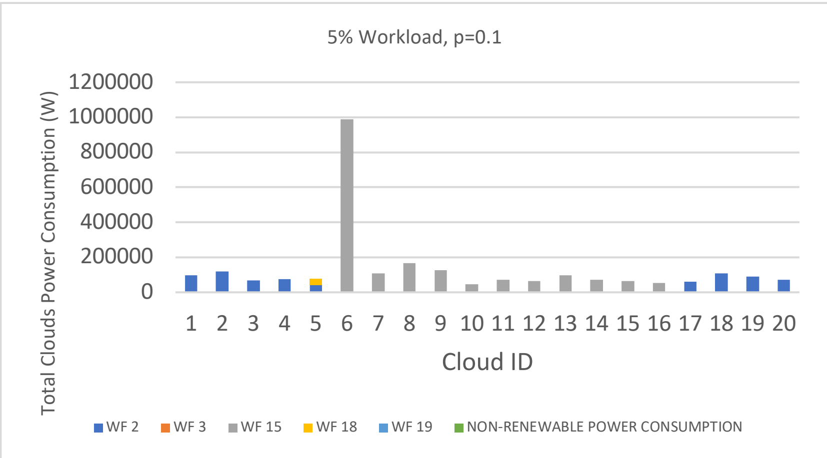

Figure 50 Graph Illustrating Total Cloud Power Consumption

When the workload is increased to 100% and at p=0.005, virtual machines are distributed in more nodes when compared to approached 1 and 2. When p=0.1, the virtual machine replication is still the same but most of the energy used to power the clouds is still non-renewable. The clouds located at nodes 1,6 and 19 seem to be the only clouds mainly powered by renewable energy.

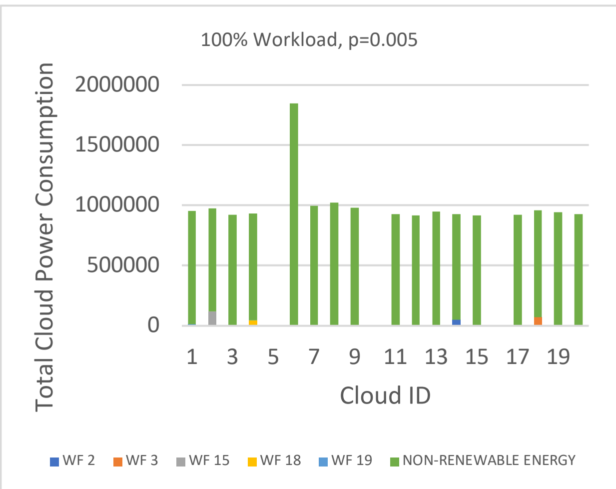

Figure 51 Graph Illustrating Total Cloud Power Consumption

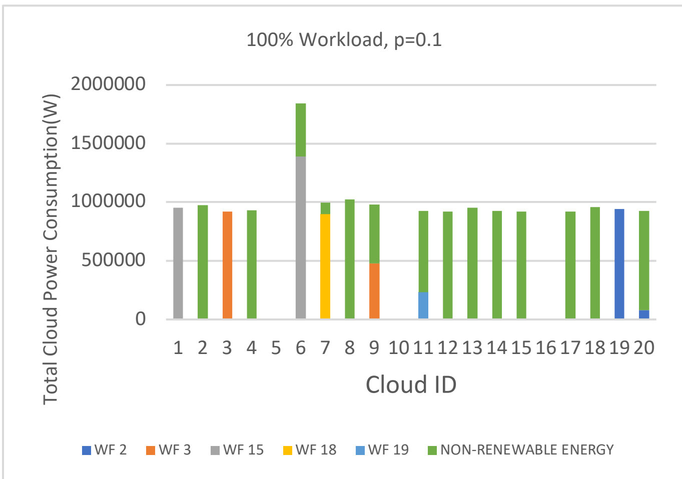

Figure 52 Graph Illustrating Total Cloud Power Consumption

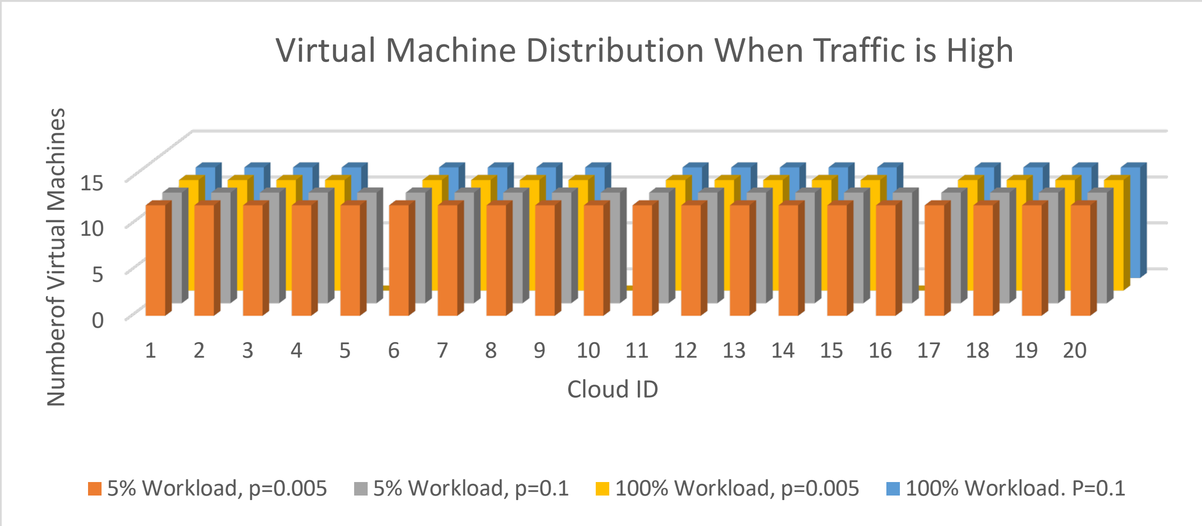

Figure 53 Virtual Machine Distribution Scheme

5.2.3.3 *Very High Traffic*

At p=0.005, the overall power consumption is about the same when compared to approach 1 and 2. Again most of the power supplied is non-renewable and the there are no transmission losses. At p=0.1, there is quite a noticeable increase in the amount of renewable energy which is about the same amount as the renewable energy supplied in approaches 1 and 2. When the workload is 100%, all the clouds have replicated virtual machines and the renewable energy supplied and the wind farm location of this renewable energy is the same with approaches 1 and 2.

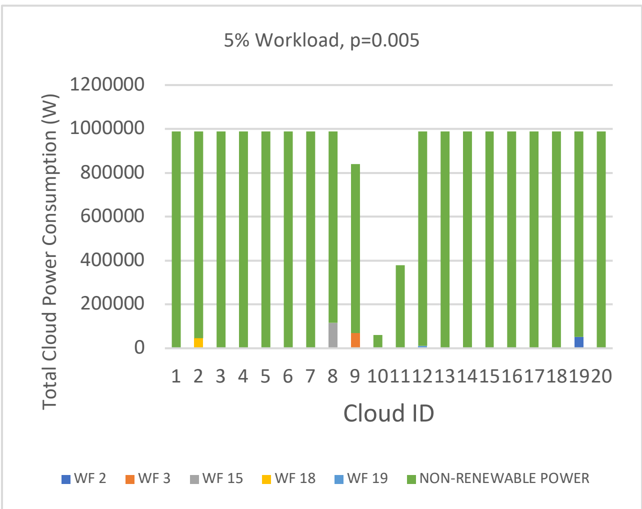

Figure 54 Graph Illustrating Total Cloud Power Consumption

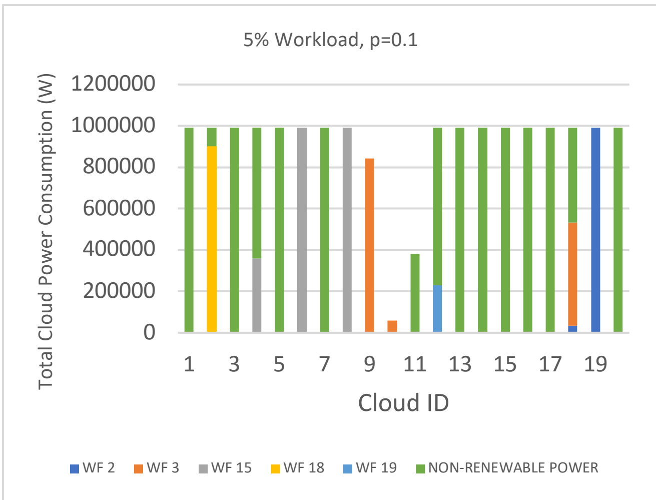

Figure 55 Graph Illustrating Total Cloud Power Consumption

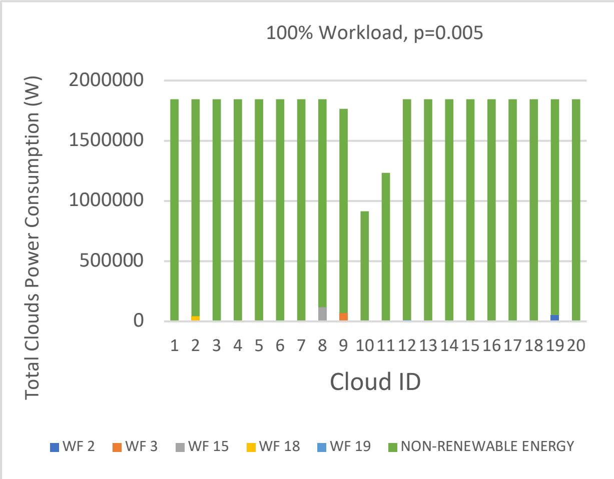

Figure 56 Graph Illustrating Total Cloud Power Consumption

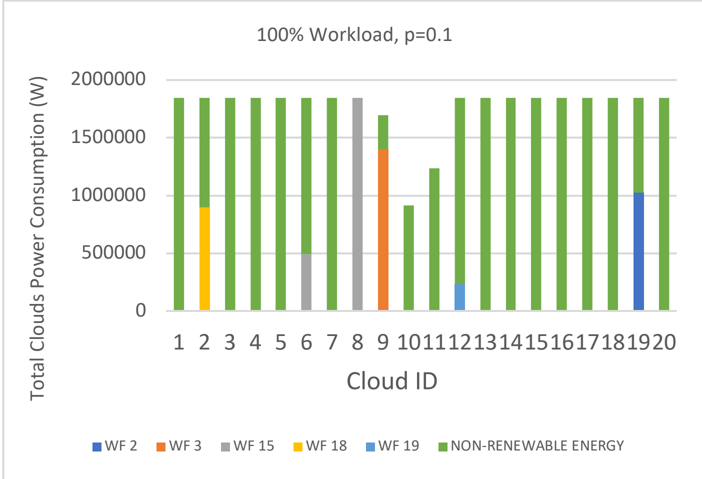

Figure 57 Graph Illustrating Total Cloud Power Consumption

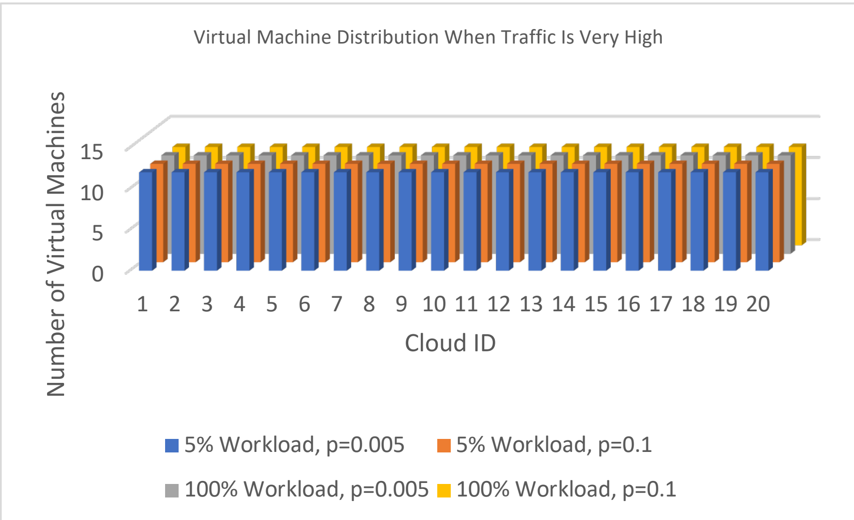

Figure 58 Virtual Machine Distribution

5.3 Virtual Machine Migration:

For this migration scheme only periods of normal and high traffic will be considered.

5.3.1 $\boldsymbol{Approach\ 1: \alpha = 1, \beta = 1\ and\ \gamma = 1}$

5.3.1.1.1 Normal Traffic:

Since this is the virtual machine migration scheme, all 12 virtual machines are placed in cloud 6. There are no copies to other clouds since the migration scheme does not permit more than one copy per virtual machine. At p=0.005, all the power supplied to the cloud at node 6 is renewable and this power is coming from three windfarms meanwhile when p=0.1, all the power supplied to that cloud comes from the wind farm located at node 6.

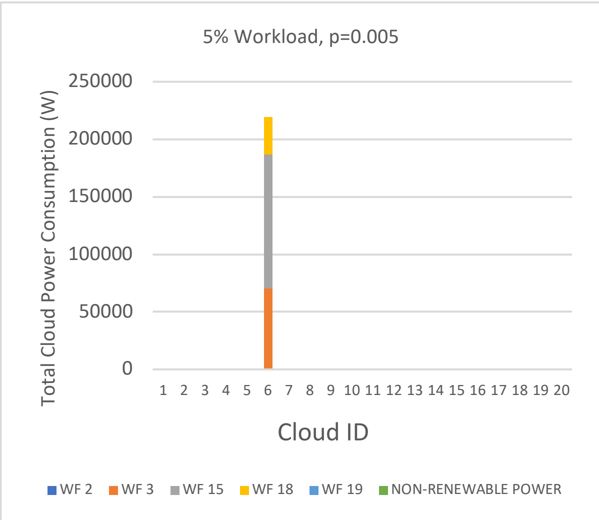

Figure 59 Graph Illustrating Total Cloud Power Consumption

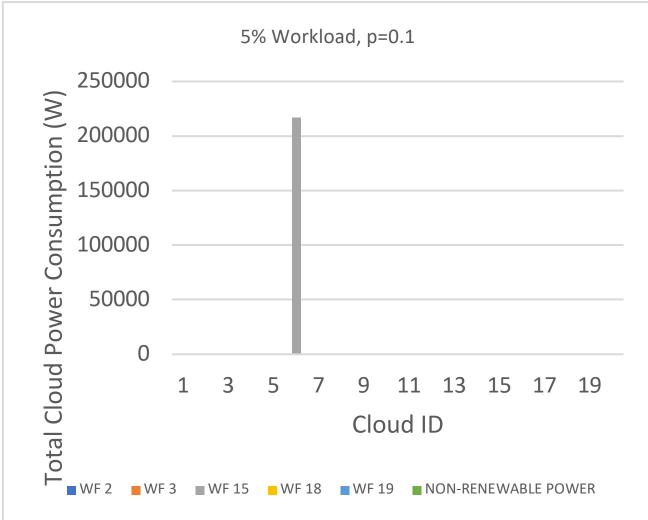

Figure 60 Graph Illustrating Total Cloud Power Consumption

With the workload now increased to 100%, when p=0.005, there is one virtual machine built in node 2 while the other eleven virtual machines are built in node 6. All the power supplied to node 2 is renewable while node 6 has more of non-renewable power supplied to it. As the workload has increased, the overall power consumption is also increased with approximately 1900W lost in transmission. When p=0.1, all the power supplied to cloud 6 is renewable and is supplied by the wind farm located in cloud 15. The wind farm located in cloud 15 always seems to be the preferable wind farm supplying power to cloud 6 because it has the highest capacity and cloud 6 serves the highest amount of users.

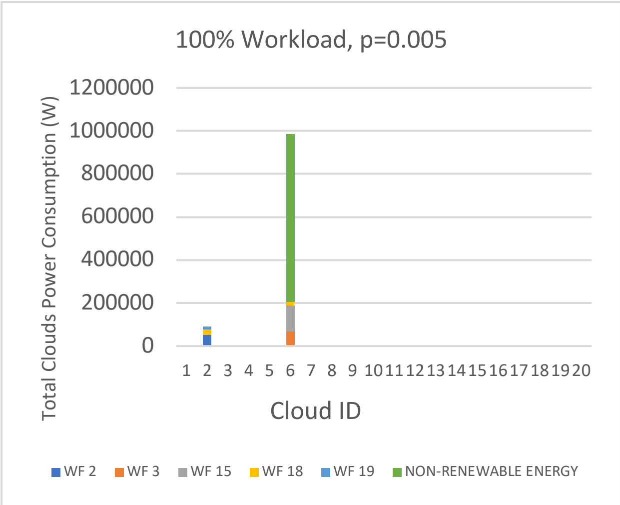

Figure 61 Graph Illustrating Total Cloud Power Consumption

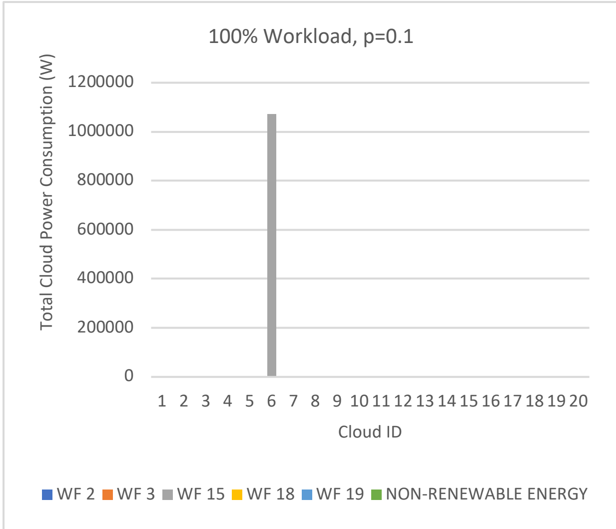

Figure 62 Graph Illustrating Total Cloud Power Consumption

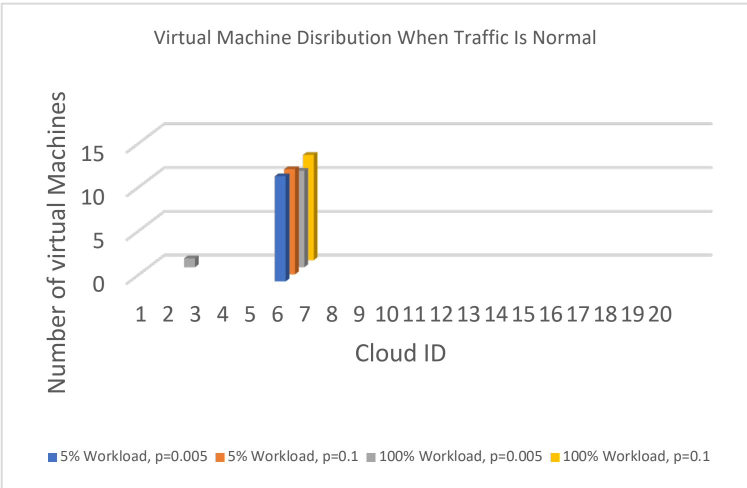

Figure 63 Virtual Machine Distribution

5.3.1.2 *High Traffic:*

At low workloads and when p=0.005, all 12 virtual machines are located in node 6 and most of the power supplied to the cloud is non-renewable and as expected since the traffic is high, the total cloud power consumption is higher than the total cloud power consumption that was gotten when the traffic was normal. When p=0.1, all the power supplied to the cloud is renewable and coming from the wind farm located in cloud 15. About 6600W of power is lost in transmission when p=0.005 but when p=0.1, there are no transmission losses.

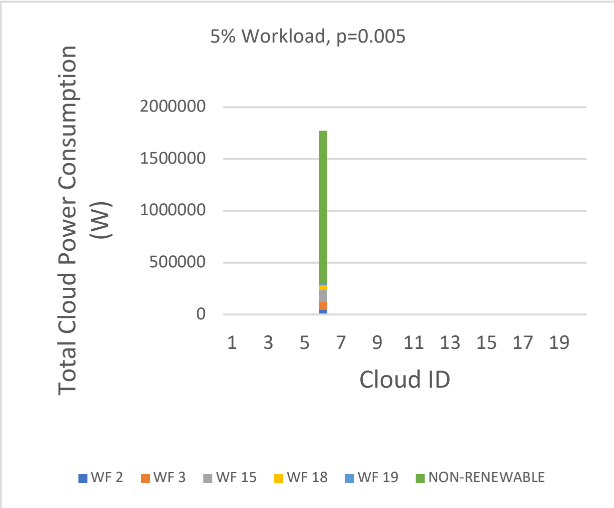

Figure 64 Graph Illustrating Total Cloud Power Consumption

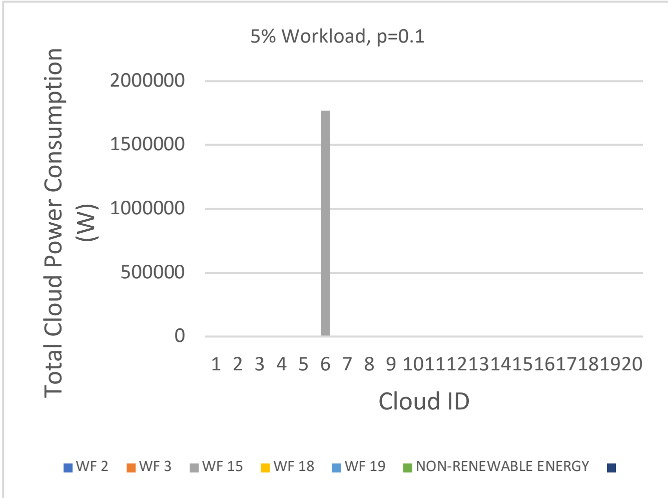

Figure 65 Graph Illustrating Total Cloud Power Consumption

When the workload increases to 100% and when p=0.005, the overall cloud power consumption is higher than the value gotten when the workload was low but the wind farms supplying power are exactly the same as before. Although when p=0.1, the renewable power is no longer supplied just from the wind farm in node 15 but also from the wind farm in node 3.

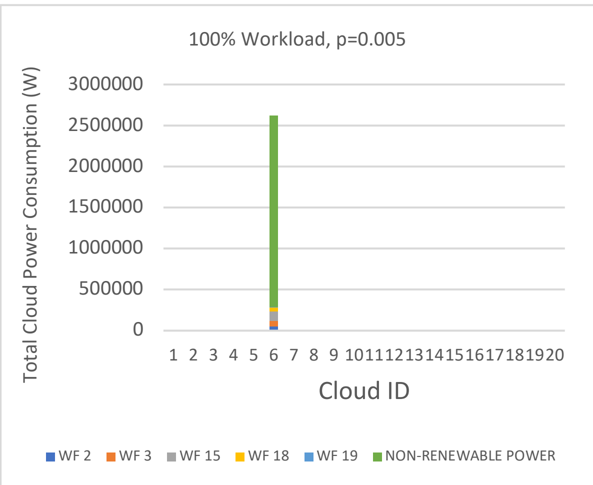

Figure 66 Graph Illustrating Total Cloud Power Consumption

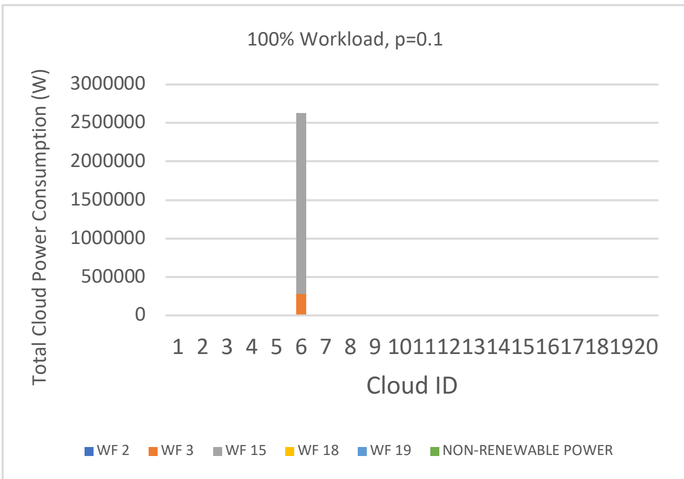

Figure 67 Graph Illustrating Total Cloud Power Consumption

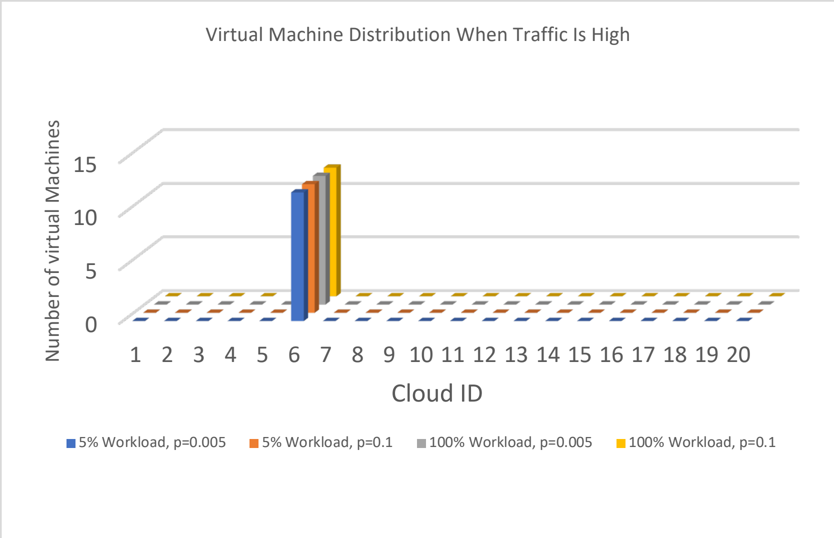

Figure 68 Virtual Machine Distribution

5.3.2 Approach 2: $\alpha = 1, \beta = 1$ and $\gamma = 0$

5.3.2.1 *Normal Traffic:*

At low workloads and when p=0.005, a comparison can be made with approach 1 for this same size of traffic. Here, all the wind farms are supplying power to cloud 6 but at the risk of an increase in transmission loss when compared to approach 1. When p=0.1, all the power is supplied from the wind farm located at node 2.

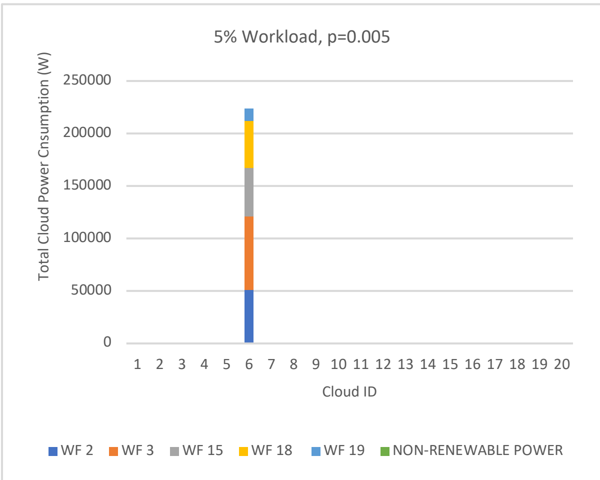

Figure 69 Graph Illustrating Total Cloud Power Consumption

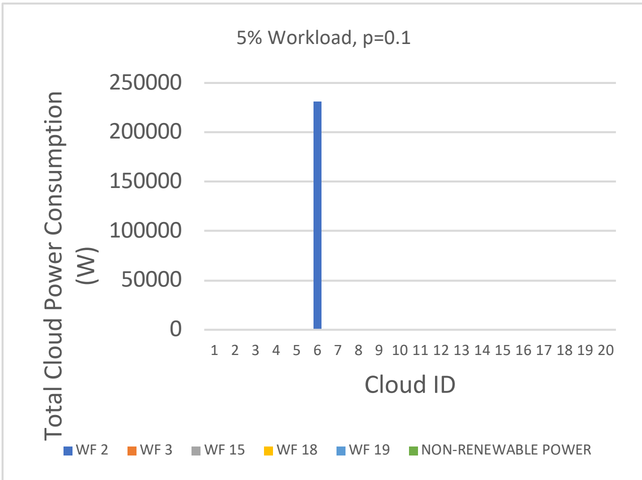

Figure 70 Graph Illustrating Total Cloud Power Consumption

When the workload is increased, and at p=0.005 all the Virtual Machines are located in node 6 unlike the first approach. The transmission losses have increased in this case when compared to what was attained in the first approach. When p is increased to 0.1, cloud 6 is being supplied renewable power from the wind farms at nodes 2 and 3. However an estimate of 65kW is lost in transmission unlike the previous approach that did not have any transmission losses.

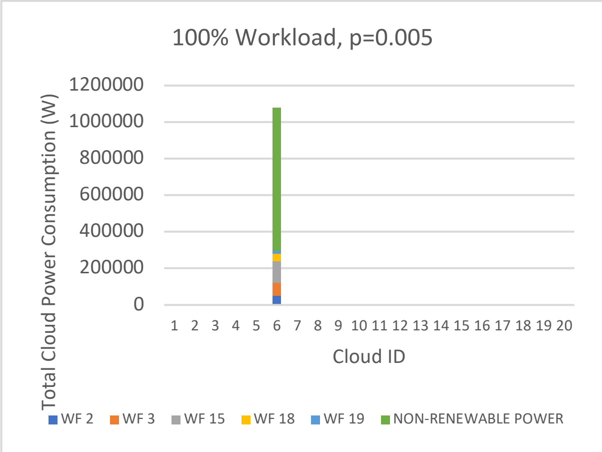

Figure 71 Graph Illustrating Total Cloud Power Consumption

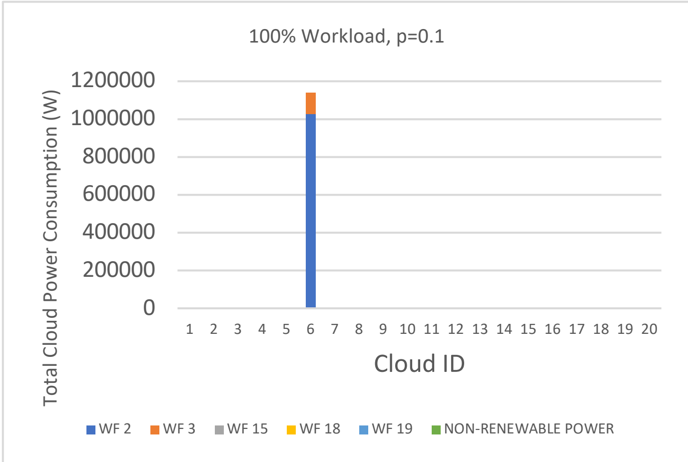

Figure 72 Graph Illustrating Total Cloud Power Consumption

5.3.2.2 *High Traffic:*

The wind farm placement gotten at low workloads when p=0.005 is similar to what was gotten in the first approach. The only difference here is that the non-renewable power available to power the cloud is lower than what was available in the previous approach. When p=0.1, exactly the same wind farm placement and overall cloud power consumption that was gotten in approach 1 is gotten in this scenario. Again, for all conditions here, all the virtual machines are placed in node 6.

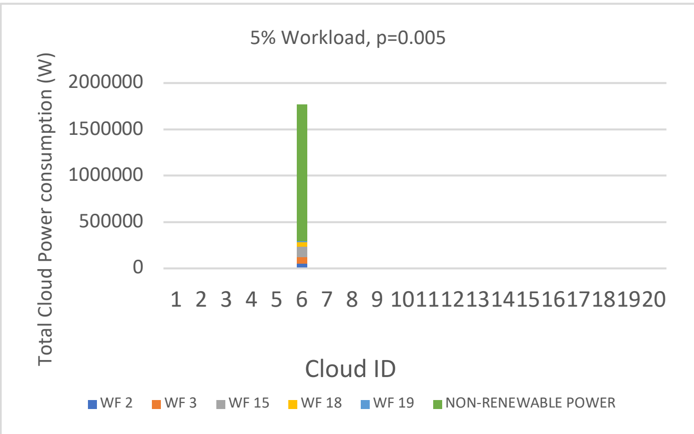

Figure 73 Graph Illustrating Total Cloud Power Consumption

When the workload is increased to 100% with little renewable energy available, scenario 1 is repeated for this case but when p=0.1, most of the power supplied to the cloud is coming from the wind farm located in node 3 and the transmission loss yielded here is 62kW higher than what was attained in the first scenario.

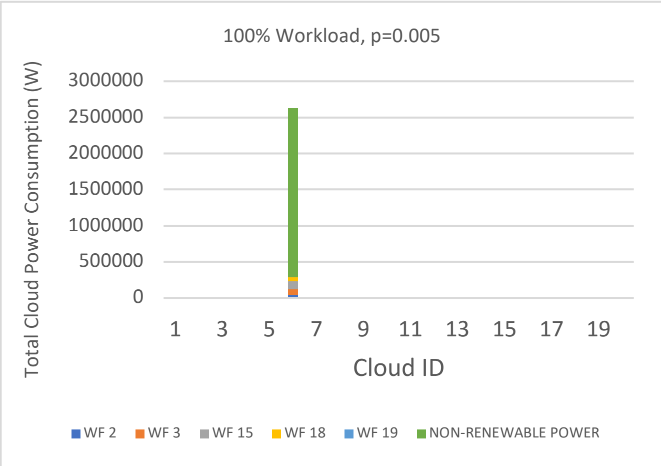

Figure 74 Graph Illustrating Total Cloud Power Consumption

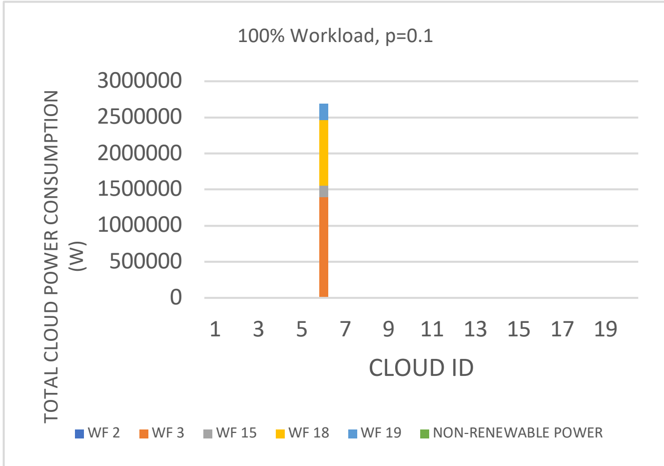

Figure 75 Graph Illustrating Total Cloud Power Consumption

5.3.3 Approach 3: $\alpha = 100, \beta = 1$ and $\gamma = 1$

5.3.3.1 *Normal Traffic:*

At low workloads and when p=0.005 and 0.1, the wind farms allocated to node 6 are the same as the first approach. They also get the same transmission losses. For all workloads in this scenario, all the virtual machines are placed in cloud 6.

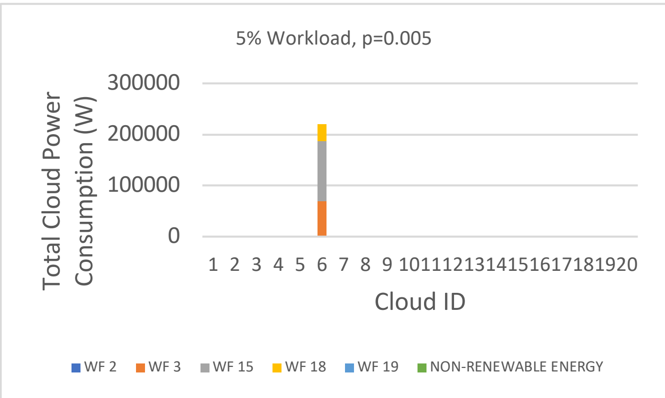

Figure 76 Graph Illustrating Total Cloud Power Consumption

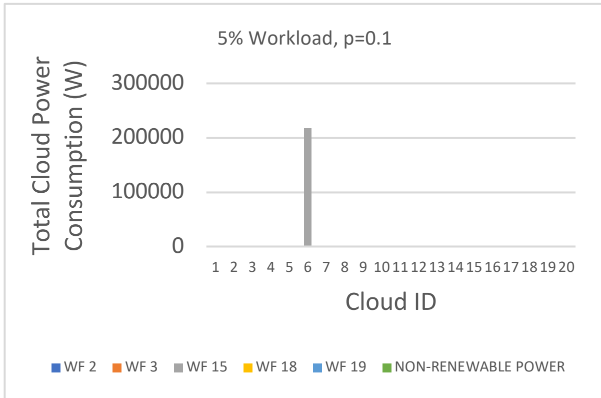

Figure 77 Graph Illustrating Total Cloud Power Consumption

However, when the workloads assigned to the virtual machines increase to 100% and p=0.005, the transmission loss gotten is higher than what was gotten in the first approach but equivalent to what was attained in the second approach. The network power consumption has also been saved by 7.9% when compared to the first approach. When p=0.1, the wind farm allocation and total power consumption is exactly the same as the first approach (no transmission losses).

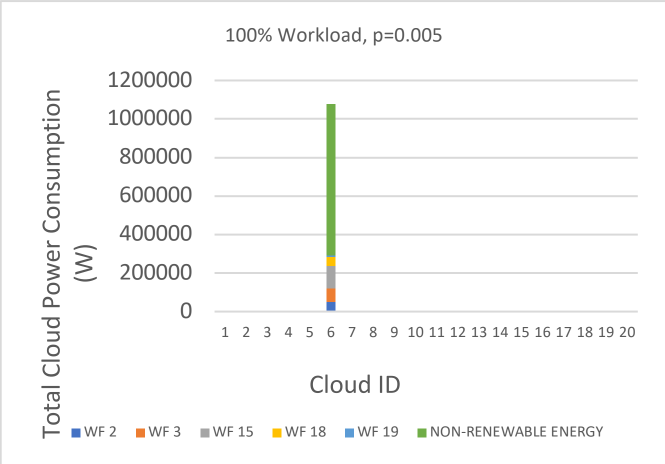

Figure 78 Graph Illustrating Total Cloud Power Consumption

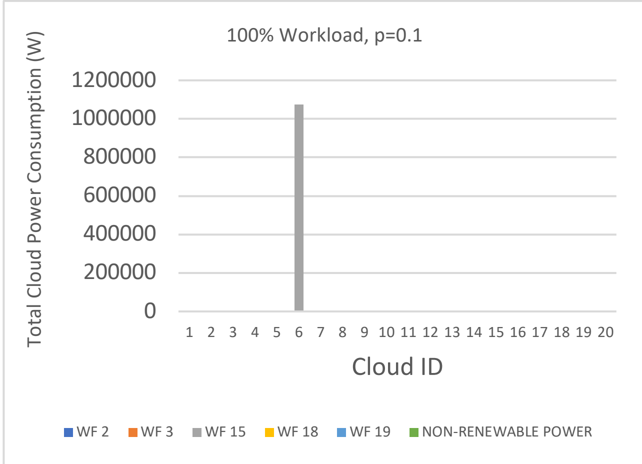

Figure 79 Graph Illustrating Total Cloud Power Consumption

5.3.3.2 *High Traffic:*

With the traffic increased, and at all workloads, for all values of p, this scenario imitates the first scenario but supplies more non-renewable power to the cloud when compared to the second scenario. All the virtual machines are placed in node 6 at all conditions.

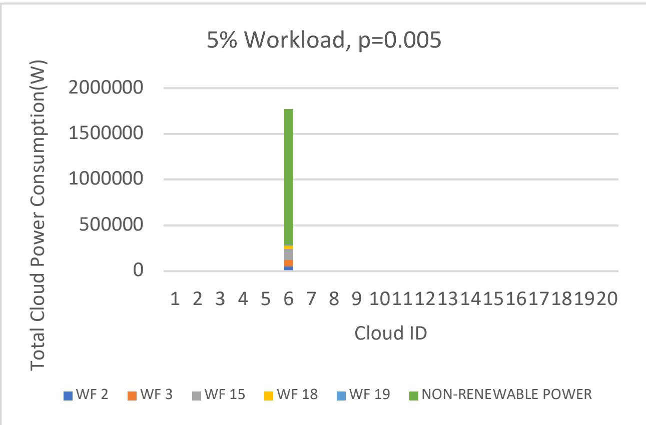

Figure 80 Graph Illustrating Total Cloud Power Consumption

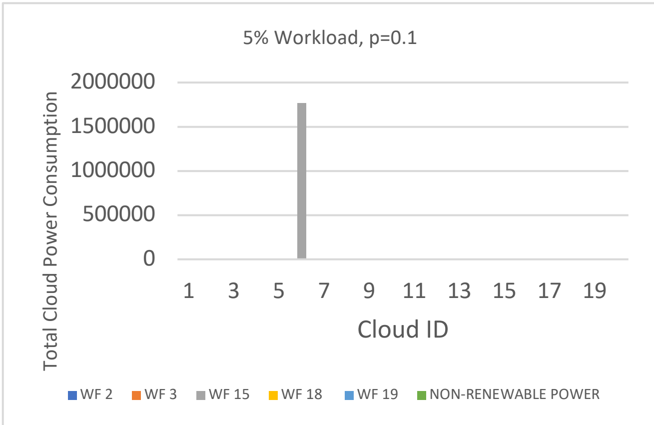

Figure 81 Graph Illustrating Total Cloud Power Consumption

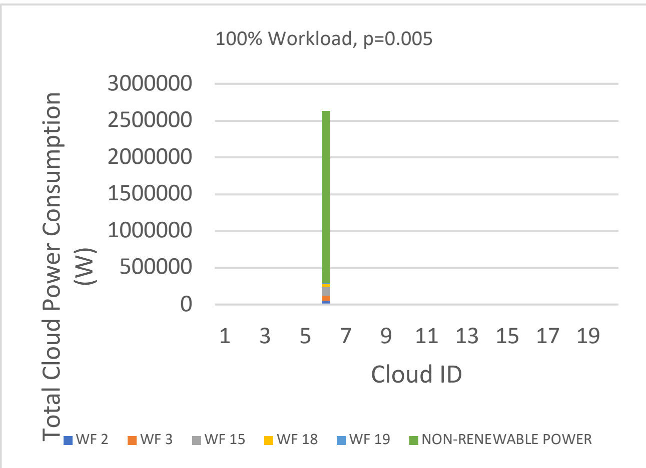

Figure 82 Graph Illustrating Total Cloud Power Consumption

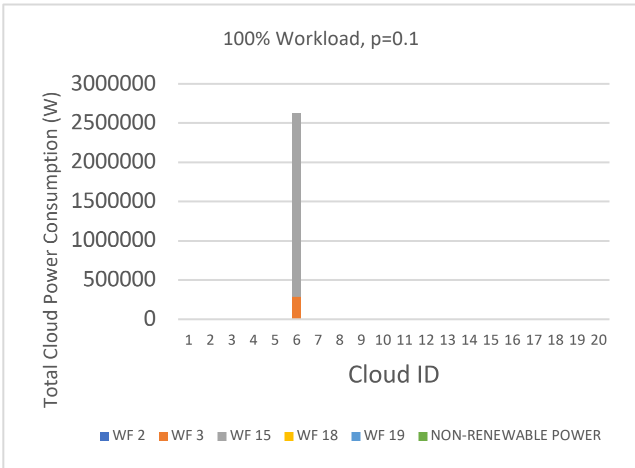

Figure 83 Graph Illustrating Total Cloud Power Consumption

6 Conclusion

This report has presented two models for the optimisation of virtual machines. One does not consider the availability of renewable energy while the other considers the availability of renewable energy. The main focus is the optimisation of these virtual machines considering the availability of renewable energy. Two virtual machine placement schemes have also been tested out with these models. Summaries of the best scenarios to use will be explained for periods of normal traffic and high traffic.

For the virtual machine replication, at periods of normal traffic and low workloads, approaches 1 and 3 are the best to use when there is sufficient renewable energy because there are no transmission losses and all the power available to power clouds is non-renewable hence reducing CO_2 emission. However, if approach 2 is used, 45kW of renewable power is lost as a result of transmitting this power from wind farm to clouds. All the approaches yield a low network power consumption of approximately 2kW. For periods of normal traffic with high workloads assigned to the virtual machines, approaches 1 and 3 are the best because they yield the lowest transmission losses when compared to the 2nd approach.

For the same virtual machine replication scenario but periods of high traffic and low workloads, approaches 1 and 2 are the best when the amount of renewable energy to power the clouds is not sufficient because 30% of total cloud non-renewable power is saved when compared to approach 3, but this comes at a risk of consuming a higher network power consumption than approach 3. However, when there is sufficient renewable power, all the approaches can be used because all the power available to the clouds is renewable, the network power consumption is low and there are no transmission losses. With high workloads, the 3rd approach uses up a lot of non-renewable power from the cloud but with no transmission loss. However, the 1st and 2nd approaches are preferable as they do not use any non-renewable power for the cloud, but this comes at a risk of high network power consumption (470kW) and high transmission loss of about 10kW for the first approach.

For the virtual machine migration scheme, most of the time all the virtual machines are placed in node 6 as can be seen from the results. The total cloud power consumption was always the same for all similar workloads but the first and third scenarios with low workloads and p=0.005 yields the lowest transmission loss for normal traffic. This also goes for when p=0.1. While for high workloads, the 1st and 3rd scenario yield no transmission losses when all the power being supplied to the cloud coming from renewable energy. For the 2nd scenario, these transmission losses are greater (65kW).

For the virtual machine replication scheme, it was noted that for the first scenario, transmission losses were considered to be minimised while for the second scenario, these transmission losses were nor considered to be minimised in the objective function. The results for the first scenario would expect the clouds with wind farms to power themselves while for the second scenario any wind farm from any node could power any cloud regardless of whether that cloud had a local wind farm or not. However, the results for the first and second scenario were very similar. They were similar in the sense that, the cloud at 19 could be powered by the wind farm in node 2 even though the cloud built in node 19 has a local wind farm. This is because, the distance between most of the nodes used in this project (link lengths) was very small hence the power loss matrix mainly consisted of very small power losses which could be negligible.

An extension to this project could be extending the model to include fog architecture. It could also involve analysing the Virtual Machine slicing scheme with the availability of renewable energy.

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