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Strategies for operating and sizing low-carbon cloud data centers

Miguel Felipe Silva Vasconcelos

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Stratégies pour l'opération et le dimensionnement des centres de données cloud à faible émission de carbone

Strategies for operating and sizing low-carbon cloud data centers

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Abstract

Cloud computing provides computational resources for most services and applications we use daily. Therefore, we must pay attention to the environmental impact, generated by the data centers' energy consumption (1% of the world's electricity demand) and the life cycle of the infrastructure.

Major cloud providers are integrating renewable electricity into the operations of their data centers to minimize their environmental impact. However, we need to consider the following factors when using renewable energy: its production varies over time; the renewable infrastructure presents an environmental impact during its life cycle; each geographic location has a different capacity for generating renewable power; and some locations in the world already have renewable sources in their energy mix.

In this thesis, we study how to reduce the environmental impact—in terms of carbon footprint—of operating and sizing cloud data centers. We explore carbon-responsive strategies—approaches that are aware of their environmental impacts and make informed decisions—to generate our proposed solutions.

The first main strategy explored is the follow-the-renewables, an approach that allocates and migrates the workload to the data centers with the highest availability of low-carbon-intensive power sources. We evaluated its impact on both the network and energy consumption, and proposed a scheduling algorithm that, by taking into account the network topology and usage, plans the migrations without generating network congestion and wasting energy.

The second main strategy explored is the sizing of the renewable and IT infrastructure: defining the required area of solar panels, number of wind turbines, capacity of batteries, and number of servers. We propose a Linear Program formulation that considers the carbon footprint of the renewable infrastructure and manufacturing

of the servers, as well as the specific characteristics of each geographic location: capacity for generating renewable power, cooling needs, and the energy mix.

Finally, the model employs only linear variables, which enables it to be optimally solved in polynomial time. The model is flexible enough to evaluate many scenarios. For example, we present an analysis of the potential carbon emissions' reduction by adopting servers from new generations. Decision-makers could use this model to guide their efforts to reduce the carbon emissions of cloud data centers.

Keywords: cloud computing; green computing; follow-the-renewables; sizing; carbon-aware; carbon-responsive computing.

Résumé

L'informatique en nuage fournit des ressources de calcul pour la plupart des services et applications que nous utilisons au quotidien. Par conséquent, nous devons prêter attention à l'impact environnemental généré par la consommation d'énergie des centres de données (représentant 1% de la demande mondiale d'électricité) et le cycle de vie de l'infrastructure.

Les principaux fournisseurs de services cloud intègrent l'électricité renouvelable dans le fonctionnement de leurs centres de données pour réduire leur impact environnemental. Cependant, plusieurs facteurs doivent être pris en compte lors de l'utilisation de l'énergie renouvelable : sa production varie dans le temps, l'infrastructure renouvelable présente un impact environnemental pendant son cycle de vie, chaque emplacement géographique a une capacité différente de production d'énergie renouvelable, et certains endroits dans le monde utilisent déjà des sources d'énergie renouvelable dans leur mix énergétique.

Dans cette thèse, nous étudions comment réduire l'impact environnemental, en termes d'empreinte carbone, de l'opération et du dimensionnement des centres de

données cloud. Nous explorons des stratégies “Carbon-responsive”, des approches qui sont conscientes de leurs impacts environnementaux et prennent des décisions éclairées pour élaborer nos solutions proposées.

La première stratégie principale que nous avons explorée est le suivi des énergies renouvelables, une approche qui alloue et migre la charge de travail vers les centres de données avec la plus grande disponibilité de sources d’énergie à faible teneur en carbone. Nous avons évalué son impact sur le réseau et la consommation d’énergie, et avons proposé un algorithme de planification qui, en tenant compte de la topologie du réseau et de l’utilisation, planifie les migrations sans générer de congestion du réseau ni de gaspillage d’énergie.

La deuxième stratégie principale que nous avons explorée est le dimensionnement de l’infrastructure renouvelable et informatique : la définition de la surface nécessaire pour les panneaux solaires, le nombre d’éoliennes, la capacité des batteries et le nombre de serveurs. Nous proposons une formulation de programme linéaire qui prend compte de l’empreinte carbone de l’infrastructure renouvelable et de la fabrication des serveurs, ainsi que des caractéristiques spécifiques de chaque emplacement géographique en termes de capacité de production d’énergie renouvelable, de besoins de refroidissement et de composition du mix énergétique.

Enfin, le modèle n’utilise que des variables linéaires, ce qui lui permet d’être résolu de manière optimale en temps polynomial. Le modèle est flexible pour évaluer de nombreux scénarios. Par exemple, nous présentons une analyse de la réduction potentielle des émissions de carbone grâce à l’adoption de serveurs de nouvelle génération. Les décideurs pourraient utiliser ce modèle pour orienter leurs efforts visant à réduire les émissions de carbone des centres de données cloud.

Mots-clés : l’informatique en nuage ; l’informatique verte ; follow-the-renewables ; dimensionnement ; carbon-aware ; carbon-responsive computing.

Resumo

A computação em nuvem fornece recursos computacionais para a maioria dos serviços e aplicações que usamos diariamente. Dada a sua importância, não podemos negligenciar o seu impacto ambiental, gerado pelo consumo de energia dos centros de dados (1% da demanda mundial de eletricidade) e pelo ciclo de vida da infraestrutura.

Grandes provedores de serviços em nuvem estão integrando eletricidade renovável nas operações de seus centros de dados para minimizar o impacto ambiental. No entanto, os seguintes fatores devem ser considerados quando usamos energia renovável: sua produção varia ao longo do tempo; a infraestrutura renovável também apresenta impacto ambiental ao longo de seu ciclo de vida; cada localização geográfica tem uma capacidade diferente de geração de energia renovável; e algumas regiões do mundo já têm a presença de fontes renováveis em sua matriz energética.

Nesta tese, estudamos como reduzir o impacto ambiental — em termos de pegada de carbono — da operação e dimensionamento de centros de dados em nuvem. Exploramos estratégias “carbon-responsive” — abordagens que são cientes de seus impactos ambientais e tomam decisões informadas — para desenvolver nossas soluções propostas.

A primeira estratégia principal explorada é o “follow-the-renewables”, uma abordagem que aloca e migra a carga de trabalho para os centros de dados com maior disponibilidade de fontes de energia renovável. Avaliamos seu impacto na rede e consumo de energia e propusemos um algoritmo de escalonamento que, considerando a topologia e o uso da rede, pode planejar as migrações sem gerar congestionamento de rede e desperdício de energia.

A segunda estratégia principal explorada é o dimensionamento da infraestrutura renovável e de TI necessária para minimizar a pegada de carbono dos centros de dados em nuvem: definir a área necessária para os painéis solares, o número de turbinas eólicas, a capacidade das baterias e o número de servidores. Propomos uma formulação de Programa Linear que leva em consideração o impacto ambiental da infraestrutura renovável e da fabricação dos servidores, assim como as características específicas de cada localização geográfica em termos de capacidade de geração de energia renovável, necessidades de resfriamento e composição da matriz energética.

Por fim, o modelo utiliza apenas variáveis lineares, o que permite que seja resolvido de forma ótima em tempo polinomial. O modelo é flexível para avaliar diversos cenários. Por exemplo, apresentamos uma análise do potencial de redução de emissões de carbono ao adotar servidores de uma nova geração. Os tomadores de decisão podem usar esse modelo para orientar seus esforços na redução das emissões de carbono dos centros de dados de plataformas de computação em nuvem.

Palavras-chave: computação em nuvem; computação verde; follow-the-renewables; dimensionamento; *carbon-aware*; computação *carbon-responsive*.

List of Figures

2.1	Geographic locations of Microsoft’s Azure DCs. Extracted from [16].	11
2.2	An example of a cloud federation that adopts the follow-the-renewable strategy. Each circle represents the data center locations: its area represents the total power consumption, and the color represents the source of electricity used to supply the DC power demand. The gray layer represents the day and night periods around the world.	16
3.1	Topology of the Cloud platform, where “GRE” is Grenoble, “LIL” is Lille, “LUX” is Luxembourg, “LY” is Lyon, “NCY” is Nancy, “RMS” is Reims, “RNS” is Rennes, “SPH” is Sophia, and “TLS” is Toulouse.	30
3.2	Workloads used as input for our simulations.	39
3.3	Green power production (in Watts) produced by DC during the simulated week.	41
4.1	Selected locations for the data centers.	69
4.2	Average daily solar irradiation per location throughout the year 2021.	70
4.3	Optimal result for the area of PV panels and capacity of the batteries.	72
4.4	Composition of the DCs’ daily energy consumption throughout the year considering the different sources of energy, where 1.0 is the DC’s total energy consumption.	82
4.5	Composition of the DCs’ hourly power consumption throughout the first day of the year. Time follows the Universal Time (UT) standard.	83
5.1	Average solar irradiation from 1980 to 2019 per location.	92

5.2	PV Area sizing when considering the carbon footprint of manufacturing vs. the whole life cycle.	93
5.3	Battery capacity sizing when considering the carbon footprint of manufacturing vs. the whole life cycle.	93
5.4	PV Area sizing when the WT are and are not included.	99
5.5	Battery capacity sizing when the WT are and are not included.	99
5.6	Different energy production for 1 PV panel at each location for the years 1980 to 2019.	100
5.7	Different energy production for 1 wind turbine at each location for the years 1980 to 2019.	101
5.8	São Paulo’s hour-by-hour grid emissions for the years 2018, 2019, 2020 and 2021.	105
5.9	Seoul’s hour-by-hour grid emissions for the years 2018, 2019, 2020 and 2021.	106
5.10	PV Area to minimize costs in comparison to minimizing carbon emissions.	117
5.11	Battery capacity to minimize costs in comparison to minimizing carbon emissions.	117
5.12	Number of wind turbines to minimize costs in comparison to minimizing carbon emissions.	117
5.13	Solution for scenario where the old servers are kept and it is only possible to add new servers.	128
5.14	Solution for scenario where it is possible to add new servers and also replace the servers from the old generation.	129
5.15	Comparison between the optimal and greedy approaches to decide manufacturing new servers in terms of total CPU cores of the cloud federation and the generation of servers.	131
5.16	Solution for the greedy approach to decide manufacture servers—when there is only access to information of the current year’s server.	139

5.17 Solution for the optimal approach to decide manufacture servers—when
there is only access to information of the servers off all the years in
advance. 140

List of Tables

1.1	Emissions (in g CO ₂ -eq) from different power sources per kWh of electricity produced [9].	3
3.1	Number of underestimated live migrations and the ratio of the overestimation, where “W” stands for “Workload”, “G” for Google, and “A” for Azure.	44
3.2	Accuracy measurements, where “W” stands for “Workload”, “G” for Google, and “A” for Azure. The M.A.P.E. value is in percentage (%), and the R.M.S.E. in seconds.	44
3.3	Number of VM live migrations performed, where “W” stands for “Workload”, “G” for Google, and “A” for Azure.	45
3.4	Comparison of energy consumption (MWh), where “W” stands for “Workload”, “G” for Google, and “A” for Azure.	46
3.5	Extra seconds during migrations compared to the case when there is no congestion, where “W” stands for “Workload”, “G” for Google and, “A” for Azure. “avg.” for the average of the observations, “max.” for the maximum value, “abs.” for the absolute value, and “rel.” for the relative value.	48
3.6	Wasted energy in the migrations (Wh) in comparison to the perfect scenario where the migration process has full access to the network links. In the table, “W” stands for “Workload”, “G” for Google, and “A” for Azure.	49

4.1	Main notations for the IT model for each DC^d ($1 \leq d \leq D$) during time slot k ($0 \leq k < K$)	57
4.2	Main notations for the Workload model for each DC^d ($1 \leq d \leq D$) during time slot k ($0 \leq k < K$)	58
4.3	Main notations for the Electrical model of each DC^d ($1 \leq d \leq D$) during each time step k ($0 \leq k < K$)	59
4.4	Main notations for the carbon footprint model of each DC^d ($1 \leq d \leq D$) during each time step k ($0 \leq k < K$)	63
4.5	Emissions (in $gCO_2\text{-}eq/kWh$) for both PV usage and using the regular grid. Source for grid emissions: electricityMap, climate-transparency.org.	71
4.6	Total emissions for the different scenarios.	73
4.7	Average DC load throughout the year	73
4.8	Results of the sustainability metrics for the experiments	74
4.9	Evaluating sizing for different years using the MAPE metric (values are in %).	75
5.1	New notations for the updated carbon footprint model for each DC^d ($1 \leq d \leq D$) during time slot k ($0 \leq k < K$)	90
5.2	Total emissions for the different scenarios.	92
5.3	New notations for the updated electrical and carbon footprint models for each DC^d ($1 \leq d \leq D$) during time slot k ($0 \leq k < K$)	95
5.4	Total emissions ($tCO_2\text{-}eq$) for different scenario.	97
5.5	Computed number of WT for each location.	97
5.6	Capacity Factor (in %) for solar panels and wind turbines at each location.	98
5.7	Comparison of local electricity grid information.	103
5.8	Average emissions (in $gCO_2\text{-}eq/kWh$) from using the regular grid at the different years.	104

5.9	Difference in total emissions (%) between the scenario where the sizing used the grid year's average value in comparison to using hourly information.	107
5.10	Emissions (in kilotons of CO ₂ -eq) for the different scenarios—renewable infra only have PV panels and batteries.	107
5.11	Emissions (in kilotons CO ₂ -eq) for the different scenarios—renewable infra only have wind turbines and batteries.	107
5.12	Emissions (in kilotons of CO ₂ -eq) for the different scenarios—renewable infra has PV panels, wind turbines and batteries.	108
5.13	New notations for the updated workload model for each DC^d ($1 \leq d \leq D$) during time slot k ($0 \leq k < K$)	109
5.14	Reductions in total carbon emissions (%) in comparison to the scenario where it is not possible to delay the workload. The α values represent how much of the workload can be delayed (in %) and the β values how long the workload can be delayed (in hours).	111
5.15	Main notations for the monetary costs model for each DC^d ($1 \leq d \leq D$) during time slot k ($0 \leq k < K$)	112
5.16	Parameters used in the LCOE PV calculator.	114
5.17	Price of different sources of energy (USD per kWh) at each location. Source for the grid electricity prices: Petrolprices.org.	116
5.18	Total costs (millions of \$), emissions (tCO_2 -eq) and how much energy was used from the grid to supply the DCs with the Grid Usage metric (G.U.) for the different scenarios.	116
5.19	New notations for the IT, electrical and footprint models for each DC^d ($1 \leq d \leq D$) during time slot k ($0 \leq k < K$)	119
5.20	Servers specifications for different generations. Values are inspired by results from the SpecPower benchmark [72, 73, 74, 75, 76].	126
5.21	CPU specifications in terms of die area and processor size. Values retrieved from x86guide.net [78, 79, 80].	127

5.22 Total emissions for the different approaches to manufacture new servers.129

5.23 Total emissions for the different approaches to manufacture new servers.131

A.1 Émissions (en g CO₂-eq) de différentes sources d'énergie par kWh
d'électricité produite [9]. A11

Contents

Contents	xix
1 Introduction	1
1.1 Structure of the thesis and contributions	4
2 Background and Related Work	9
2.1 Cloud computing	9
2.2 Measuring the environmental impact of cloud computing platforms .	11
2.3 Scheduling for cloud computing platforms	13
2.4 Carbon-Responsive Computing	14
2.4.1 Follow-the-renewables	15
2.4.2 Sizing the renewable infrastructure	19
2.5 Summary	24
3 Follow-the-renewables and their impact on the network and energy consumption	25
3.1 Introduction	25
3.2 The NEMESIS algorithm	27
3.2.1 Cloud Modeling	29
3.2.2 VM live migration model	31
3.3 The c-NEMESIS algorithm	31
3.3.1 Estimating the duration of the live migration	31
3.3.2 Planning the migrations	33

3.3.3	Energy cost of migrations	36
3.4	Experiments	37
3.4.1	Settings	38
3.4.1.1	Workload	38
3.4.1.2	Green energy traces	40
3.4.2	Baselines	41
3.4.3	Results	43
3.4.3.1	Accuracy of the estimation algorithm	43
3.4.3.2	Analysis of the VM live migrations performed	45
3.4.3.3	Total and brown energy consumption of the cloud platform	45
3.4.3.4	Wasted resources in the migrations	47
3.5	Summary	49
4	Sizing the renewable infrastructure of cloud data centers	51
4.1	Introduction	51
4.2	Problem statement	53
4.2.1	Addressed problem	54
4.2.2	Models and notations	56
4.2.2.1	IT model	56
4.2.2.2	Workload model	58
4.2.2.3	Electrical model	59
4.2.2.4	Carbon footprint model	61
4.2.3	Objective function	63
4.3	Optimal resolution	64
4.3.1	Constraints to address the workload	64
4.3.2	Constraints to reach the power demand	65
4.3.3	Constraints on batteries	65
4.3.4	Linear program	66

4.4	Experiments	67
4.4.1	Settings	67
4.4.1.1	Cloud infrastructure	67
4.4.1.2	Workload	68
4.4.1.3	Photovoltaic power production	69
4.4.1.4	Carbon footprint	69
4.4.1.5	Execution environment	71
4.4.2	Results	71
4.5	Analysis and Discussion	75
4.6	Summary	80
5	Long-term evaluation of sizing cloud data centers	85
5.1	Introduction	85
5.2	Life cycle of the renewable infrastructure	89
5.2.1	Updates in the model	89
5.2.2	Experiments	91
5.2.2.1	Settings	91
5.2.2.2	Results	92
5.3	Including wind turbines to the renewable infrastructure	94
5.3.1	Updates in the model	94
5.3.2	Experiments	96
5.3.2.1	Settings	96
5.3.2.2	Results	97
5.4	Sensibility of the LP to uncertainties	98
5.4.1	Updates in the model	101
5.4.1.1	Fine-grain values of grid emission data (hour by hour)	101
5.4.1.2	Intermittency of renewable sources	102
5.4.2	Experiments	102
5.4.2.1	Settings	102

5.4.2.2	Results	106
5.5	Scheduling flexibility to reduce CO ₂ emissions	108
5.5.1	Updates in the model	108
5.5.2	Experiments	110
5.5.2.1	Settings	110
5.5.2.2	Results	110
5.6	Monetary costs of reducing the carbon emissions	110
5.6.1	Updates in the model	111
5.6.2	Experiments	113
5.6.2.1	Settings	113
5.6.2.2	Results	115
5.7	Adding or replacing servers considering new hardware and future workload	118
5.7.1	Updates in the model	118
5.7.2	Experiments	124
5.7.2.1	Settings	125
5.7.2.2	Results	127
5.8	Discussion	131
5.9	Summary	137
6	General Discussion	141
6.1	Summary of contributions	141
6.2	Future Research Directions	145
6.3	Work Dissemination	146
	References	A1
A	Résumé étendu en français	A9
A.1	Introduction	A9
A.2	Contexte	A16

A.2.1	Cloud computing	A16
A.2.2	Mesurer l'impact environnemental des plateformes de cloud computing	A18
A.2.3	Ordonnancement pour les plateformes de cloud computing	A20
A.2.4	Carbon-Responsive Computing	A22
A.2.4.1	Follow-the-renewables	A22
A.2.4.2	Dimensionner l'infrastructure renouvelable	A23
A.3	Follow-the-renewables et leur impact sur le réseau et la consommation énergétique	A24
A.4	Dimensionnement de l'infrastructure renouvelable des centres de données cloud	A27
A.5	Évaluation à long terme du dimensionnement des centres de données cloud	A31
A.6	Discussion générale	A36

Cloud computing has revolutionized the industrial and academic world of Information Technology with its ability to provide large amounts of computing resources on demand. Most of the applications and services we use every day that feature more and more users, such as social networking, e-mail, video games, internet banking, health applications, and video streaming, are supported by cloud computing platforms.

Despite all its benefits, cloud data centers (DCs)—the facilities that host all the infrastructure needed for the cloud—have a significant power demand. The International Energy Agency (IEA) estimates that the data centers that host cloud computing platforms consumed between 240 and 320 TWh, or approximately 1% of the global final electricity generated in 2022 [1]. To put this energy consumption into perspective, it's enough to supply the annual energy demand of entire countries. In 2022, seven countries had an energy consumption similar to the DCs energy demand: Greece (316 TWh), Israel (304 TWh), Belarus (297 TWh), Switzerland (292 TWh), Hungary (266 TWh), Portugal (258 TWh), and Morocco (257 TWh) [2].

Efforts from both academia and industry alike are trying to reduce this gigantic energy consumption. An analysis of the global energy use by data centers performed by Masanet et al. [3] showed that during the period between 2010 and 2018, the DC's internet protocol traffic increased more than 10-fold, it is estimated that the DC's storage capacity increased by 25-fold, and the DCs workload and compute instances increased by 6-fold. On the other hand, the energy consumption only increased by 6% thanks to improvements in: i) virtualization, which allowed a 5-fold increase in the average number of compute instances per physical server; ii) more

energy-efficient servers (a decrease with a factor of 4 regarding the power used for computation and a factor of 9 in terms of watts per terabyte); and iii) energy-efficient infrastructures, in particular for the cooling needs and power supply.

It is uncertain if the improvements in efficiency in cloud computing will mitigate the power increase caused by the growing demand for computational resources in the long term. In the work of Koot and Wijnhoven [4], the authors developed a model for forecasting the energy consumption of data centers using the system dynamic models approach. Considering the period from 2016 to 2030, and the scenario with the end of Moore's law—that predicts that the number of components in the integrated circuits doubles every year [5]—and the rise of industrial Internet of Things applications, the energy demand of the data centers could reach 2.3% of the global electricity generation—it will double considering what was reported by the IEA for the year 2022 [1].

The electricity consumption of the DCs results in an environmental impact in terms of Greenhouse Gases (GHG) emissions. According to the International Energy Agency, 1% of the energy-related GHG emissions originate from data centers and data transmission networks [1]. The extent of this impact depends on the type of source used to produce the electricity. Table A.1 presents the emissions for the different types of power sources to produce 1 kWh of energy. The emissions are measured using the carbon dioxide equivalent (or CO₂-eq) metric. This metric is used to compare different GHGs in terms of their Global Warming Potential (GWP) using carbon dioxide as a base: methane (CH₄) has a GWP of 25, which means that emitting 1g of CH₄ in the atmosphere has the same environmental impact as emitting 25g of CO₂ [6]. It is possible to observe that producing power from coal emits 77 times more CO₂ than wind or nuclear. In 2019, approximately 70% of the internet's data traffic was processed by the DCs in the “Data Center Alley”, a region located in Virginia (United States of America), which was only supplied by less than 2% of renewable energy (green energy) [7].

In order to reduce their environmental impact, major cloud providers—such as Amazon AWS, Apple, Google, Meta (former Facebook), and Microsoft—made commitments to integrate low-carbon intensive electricity produced by renewable sources in the operations of their data centers, and some have already deployed their projects to reach the goal of minimizing the carbon footprint. In fact, Google reported that in 2022, 64 percent of the power used to supply its DCs on an hourly basis came from renewable sources [8], with some DCs reaching up to 97% of green energy usage.

Table 1.1. Emissions (in g CO₂-eq) from different power sources per kWh of electricity produced [9].

Generation technology	Emissions (g CO ₂ -eq/kWh)
Coal	1 010
Oil	840
Natural gas	486
Biomass	52
Photovoltaic	43
Hydropower	21
Nuclear	13
Wind	13

The cloud platforms are integrating renewable power into their operations in the following ways. One possibility is to buy green energy from the local electricity grid, although this makes them dependent on the grid’s energy mix, and not all locations in the world are supplied by low-carbon sources. Another possibility is to manufacture their own on-site renewable infrastructure. A critical aspect of producing electricity using renewable energy that must be considered for both possibilities, is their intermittent nature—their production fluctuates over time and is influenced by variables such as the time of day, climate, season, and geographic location. For example, photovoltaic panels (PVs) only produce power when the sun is shining, and during the winter, the solar irradiation is lower than in the summer. For hydropower, long periods without rain will affect power production.

The adoption of energy storage devices (ESDs) in DCs to store renewable energy [10] is an approach to dealing with intermittency. These devices are already used in DCs as a temporary backup for power outages. The green energy from the ESDs could

be used when there is no production of green power or when demand is greater than production. Nevertheless, this approach also presents some challenges for deciding when to use or recharge, given the characteristics of the ESDs, such as the self-discharge rate (they lose stored energy over time when not used), aging (their maximum capacity decreases over time), and limited charge and discharge rates (the maximum power that can be extracted or recharged).

In this thesis, we study how to reduce the environmental impact of cloud computing data centers, specifically in terms of CO₂ emissions. The usage of Carbon-Responsive strategies—approaches that are aware of their carbon footprint and use this information to make decisions [11]—is explored to reduce the CO₂ emissions in both operating and sizing the data centers—determining the required on-site renewable infrastructure (area of solar panels, number of wind turbines, capacity of ESDs). In terms of DC operations, we leverage the workload scheduling using “follow-the-renewables” approaches—strategies that migrate and allocate the workload to the locations with higher renewable energy availability [12]—and study their impact on both energy consumption and network congestion. Regarding sizing, we model our problem using a Linear Program (LP) formulation that considers the characteristics of each DC location in terms of cooling needs and local grid energy mix, as well as the fact that the renewable infrastructure generates an environmental impact. More details about the structure and contributions of this thesis are presented in the next section.

1.1 Structure of the thesis and contributions

This thesis is structured into six chapters, which include this introductory chapter. An overview of the content of each chapter and their respective contributions is described in what follows.

In Chapter 2, the reader is introduced to the concepts required to comprehend the research done in this thesis. In particular, the chapter contains a description of the general scenario of cloud computing, how one can measure the environmental impact of cloud platforms, an overview of scheduling algorithms in the context of cloud computing, and the definition of carbon-responsive strategies—in particular, the approaches explored in this thesis: “follow-the-renewables” and sizing. Finally, the related works used as inspiration or as baselines for our proposed solutions are presented in this chapter as well.

An analysis of adopting the carbon-aware strategy “follow-the-renewables” and its impact on energy consumption and network congestion is presented in Chapter 3. The proposed solution consists of an algorithm that considers the network topology and usage for scheduling the workload migration. Through computational experiments with real-world data for the workload, cloud infrastructure, and a simulator that uses realistic models validated by the scientific community for both energy consumption and network usage, the results show that the proposed solution outperforms the baselines considering energy consumption, non-renewable energy consumption and network congestion.

Chapter 4 introduces a carbon-responsive strategy that can be combined with follow-the-renewables to reduce the carbon footprint of operating cloud computing platforms: sizing the renewable infrastructure. This strategy involves determining the required area of on-site solar panels and the capacity of the batteries to supply the DCs power demand.

The proposed solution consists of a Linear Program formulation that addresses both the workload scheduling using follow-the-renewables and the sizing of the on-site renewable infrastructure. By modeling these two sub-problems as one problem, it is possible to evaluate whether it is more effective to execute the workload in other geographic locations or to increase the area of solar panels and capacity of the batteries to achieve the goal of reducing the CO₂ emissions. The model only uses

linear variables, enabling it to be optimally solved in polynomial time—essential for the scale of cloud computing platforms that have millions of servers and execute hundreds of millions of computational tasks daily. Other important aspects of the modeling are that it considers the characteristics of each DC geographic location in terms of cooling needs, the energy mix of the local electricity grid (which may have a share of renewable energy sources), and the fact that manufacturing solar panels and batteries has an environmental impact.

The results demonstrate that the hybrid configuration that combines both the on-site renewable infrastructure and the regular grid outperforms in terms of CO₂ emissions the strategies of having a DC only supplied by energy produced from its local renewable infrastructure—a reduction of approximately 30%—and only using power from the regular electrical grid—a reduction of approximately 85%.

The model introduced in Chapter 4 focuses on the short-term operation (one year). In Chapter 5, we extend the model to evaluate how to minimize the carbon emissions of cloud data center operations in the long term.

The following modifications and analysis were performed: the environmental impact of the whole life cycle of the renewable infrastructure (from manufacturing, operation and recycling) is taken into account to make the model closer to the real-world; an analysis of the benefits and challenges of including wind turbines in the on-site renewable infrastructure; an assessment of the model's sensitivity to the inputs, in particular climate conditions and grid emissions data; an analysis of how much the CO₂ emissions can be reduced by adopting the flexibility of delaying a part of the workload, which could be used to mitigate the impacts of over-sizing the renewable infrastructure; a discussion of the monetary costs (in dollars) associated with on-site renewable infrastructure, as well as the trade-offs between minimizing the carbon footprint and reducing the costs for the DCs; and deciding to manufacture new servers over the years that may be more energy-efficient, considering that manufac-

turing them also emits carbon. This modeling may be used to guide decision-makers in their efforts to reduce the carbon footprint of cloud data centers.

Finally, Chapter 6 presents a discussion of the main contributions of this thesis, as well as possible future research trajectories.

This chapter provides the foundational knowledge required for the reader to comprehend the subsequent chapters of this thesis. First, the general scenario of cloud computing is presented in Section 2.1. Section 2.2 presents how one can measure the environmental impact of cloud computing platforms. Then, an introduction to scheduling in the context of clouds is shown in Section 2.3. The existing approaches explored in this thesis to reduce the environmental impact of cloud computing platforms are discussed in Section 2.4, and the works used in this thesis as inspiration and baselines are presented as well. Finally, Section 2.5 summarizes this chapter.

2.1 Cloud computing

Cloud computing was introduced by the industry to address the most significant problems of e-commerce found at the time. Before the advent of cloud computing and its on-demand access to computational resources, users and companies had to purchase their own computational infrastructure to deploy their services or applications. In the event of a sudden surge in requests, it was often challenging to scale the computational infrastructure in time to handle the computational load demand. Despite its revolutionary aspects in information technology, cloud computing is not classified as a new paradigm in computer science research. As a matter of fact, it is the evolution of research into different fields of computer science, such as clusters, grids, autonomous computing, and ubiquitous computing.

One of the critical elements that enable cloud computing is virtualization technology, in which the computational resources of a physical machine are converted to virtual resources that can be shared among many users and applications—also known as multi-tenancy. The main ideas from virtualization originate from the late 1950's and beginning of the 1960's with the multiprogramming paradigm, and today, the research on virtual machines (VMs) and containers continues to investigate the compromises outlined in the literature of multiprogramming in terms of portability—allowing the virtual resource to execute on any hardware, performance—the impact of the additional virtual layer in the application execution in comparison to the gains regarding multi-tenancy, and security—how to isolate the interaction between different applications and the applications and the computational resources [13].

Cloud computing platforms generally support services in three distinct levels: IaaS (Infrastructure as a Service), PaaS (Platform as a Service), and SaaS (Software as a Service) [14]. In the first level, Infrastructure as a Service (IaaS), the platform grants users access to hardware resources (such as processing and storage) and charges them for their usage. Services such as Amazon EC2 (Elastic Cloud Computing) Service and Amazon S3 (Simple Storage Service) are examples of IaaS clouds. At the second level, Platform as a Service (PaaS), the provider supports a complete development, testing, and deployment environment for the application developer, which usually means that the developer will have to follow a specific fixed development model and accept restrictions on how to model the software in exchange for the scalability provided. An example is the Google App Engine. Finally, at the third level, Software as a Service (SaaS), specific applications are offered to users via the Internet, and the rate is proportional to the use of the application. We can cite the Google Docs office applications as examples.

Modern cloud computing platforms are composed of multiple data centers geographically distributed over the world—also denominated cloud federations or multi-clouds. Figure 2.1 illustrates the locations of the cloud data centers from

Microsoft's Azure that, in total, consist of millions of physical servers [15]. The need for such geographically distributed infrastructure comes from meeting the demand of the huge number of users and reducing the response time for their applications, as well as for security and redundancy reasons. For example, if a data center in a region goes down because of a power problem or hacking attack, another region could temporarily receive the computational load. Finally, this distributed infrastructure enables exploring different approaches to reduce the environmental impact of operating the data centers, and more details of these strategies are given in Section 2.4.

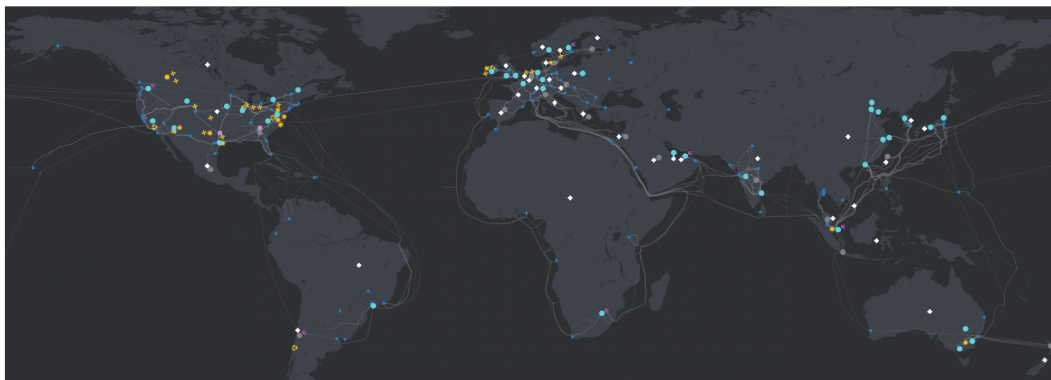


Figure 2.1. Geographic locations of Microsoft's Azure DCs. Extracted from [16].

2.2 Measuring the environmental impact of cloud computing platforms

The GHG protocol [17] was developed as a way to standardize the measurement and reporting of companies' environmental impact. It considers six types of Green Houses Gases (GHGs) of the Kyoto protocol: carbon dioxide (CO_2), methane (CH_4), sulfur hexafluoride (SF_6), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), and perfluorocarbons (PFCs).

The protocol has three scopes to quantify the direct and indirect emissions:

- **Scope 1 - Direct GHG emissions:** Takes into account the emissions generated by sources that the company owns or has control over. In the context of cloud computing, it could come from the electricity generated when there is a power surge, and generators should be used as a backup; the transportation of products, materials, and employees using the company vehicles; and the cooling of the data center infrastructure [18].
- **Scope 2 - Electricity indirect GHG emissions:** Takes into account the emissions generated from the electricity consumed.
- **Scope 3 - Other indirect GHG emissions:** This one is optional, and takes into account emissions from the production or extraction of materials and fuels bought, for example, IT equipment (such as servers and routers) as well as constructing the data center facilities. Emissions from transportation are also included in this scope if they come from vehicles not owned by the company.

Major cloud players already provide sustainability reports and use the GHG Protocol. In the 2023 sustainability report from Meta [19], it is estimated that 1% of the emissions came from Scope 1, less than 1% from Scope 2, and 99% from Scope 3. Additionally, it is stated that the operational emissions have been reduced by 94% in comparison to 2017 thanks to the renewable energy commitments. Another remarkable example is the Google environmental report from 2023 [8], where it is estimated that 1% of the emissions come from Scope 1, 24% from Scope 2, and 74% from Scope 3. Google also reports that most of the Scope 3 emissions come from manufacturing the hardware and capital goods they bought and constructing the data center facilities.

In this thesis, the environmental impact is only evaluated in terms of the carbon footprint—using the CO₂ equivalent metric (CO₂-eq). This decision was taken due to the lack of data for measuring other environmental impacts, such as water usage, and impacts caused by extracting raw minerals to fabricate the integrated circuits.

2.3 Scheduling for cloud computing platforms

Scheduling problems are combinatorial optimization problems where, given the description of the characteristics of a computational resource set (α) and a task set (β), the objective is to find an allocation (in time) of resources to tasks that minimize some optimization criteria (γ). These problems are denoted, generally, using the $\alpha | \beta | \gamma$ notation, introduced by Graham [20].

The most common criterion studied in problems of high-performance computing is called makespan (also denoted by C_{\max}), which indicates the time when the last task that makes up an application finishes its execution. When the available computational resources are identical and known previously, and we are interested in minimizing makespan—typically the case in scheduling problems in cluster and computational grids—the problem is strongly NP-hard [21]. This problem is denoted by $P || C_{\max}$ in Graham’s notation.

For the research problem explored in this thesis, α represents the computational resources (memory and CPU) from the servers of the data centers as well as their information about the availability of low-carbon-intensive power sources, β represents the VM requirements in terms of execution time, deadline, memory and CPU, and γ represents the reduction of carbon-intensive energy consumption.

It is known—from the work of Graham et al. [20] and Garey and Johnson [21]—that the class of greedy algorithms known as list algorithms provides fast and efficient heuristics for scheduling tasks on parallel computers. These algorithms have a $2 - 1/m$ approximation guarantee for the worst case, but are remarkably effective in practice, especially when the ratio of the number of tasks to the number of available computational resources is large. Among the most commonly used list algorithms are the Longest Processing Time first (LPT) and Shortest Processing Time first (SPT), for homogeneous platforms, and the Heterogeneous Earliest Finish Time (HEFT) algorithm, for heterogeneous platforms.

The VM consolidation strategy illustrates an example of a scheduling problem in cloud computing enabled by virtualization. It consists of using live migrations—migrating the VM between different machines while in execution, that is, without preemption—to reallocate the VMs in order to achieve the minimum number of physical machines used, and turning off the machines that became idle to save power. The reader can check the work from Dias et al. [22] for a systematic literature review on such techniques.

The greedy algorithms were adopted in some of the solutions proposed in this thesis, as well as most of the related works used as baselines and inspiration. The justification for such a decision is that despite not providing the optimal solution, they can provide an acceptable solution in a reasonable amount of time, which is important considering the workload size with millions of tasks and restrictions such as deadline, response time, and others. The following section presents these strategies to the reader.

2.4 Carbon-Responsive Computing

Many efforts from both academia and industry are being made to reduce the environmental impact of information technology. The term Carbon-Responsive Computing was created to describe the strategies that explore moving the computational workload both in time and spatial dimensions aiming to reduce the carbon footprint of the operation [11].

There are three levels of Carbon-Responsive computing. In the first, Carbon-aware computing, the system knows the carbon intensity of the electricity used by its workloads or IT equipment. In the second, Carbon-responsive computing, the information about the carbon intensity is taken into account to make decisions. The final stage, Carbon-resilient computing, studies how to manage and integrate

carbon-responsive elements and what modifications are needed in IT and power supply infrastructure to reduce the carbon footprint.

In this thesis, it is presented a study of the Carbon-Aware strategy follow-the-renewables—presented in Section 2.4.1, and the Carbon-Resilient computing strategy of sizing the renewable infrastructure—discussed in Section 2.4.2.

2.4.1 Follow-the-renewables

As we saw in Section 2.1, modern cloud computing platforms are geographically distributed across the globe, having data centers in many combinations of latitudes, longitudes, and time zones. Considering that each location has a different potential for generating renewable power, and that renewable energy is intermittent—the sun only shines during the day, and the wind does not blow all the time at speeds that are sufficient to turn the wind turbine propeller—the scheduling algorithms can use this characteristic to plan the execution of the workload in the locations that have more availability of green energy. In the literature, the term “follow-the-renewables” [12] describes this strategy. This strategy focuses on the Scope 2 of the GHG Protocol, as it schedules the workload to the location that uses less carbon-intensive power from renewable sources.

Figure 2.2 is an illustration of a cloud federation’s operation that adopts the follow-the-renewable strategy. The cloud federation is composed of nine data centers geographically distributed over the world, and each DC has on-site solar panels to produce green power and can also use power from the regular local electrical grid. The circles represent the locations of the data centers, and the area of the circle represents the power consumption of the DC at that instant of time. The power consumption is directly related to the amount of computational workload being executed by the DC, therefore the circle area also represents the ratio of workload allocated to the DCs. The color represents the electricity source used to supply the

DC. The gray layer in the picture represents the division between night and day periods over the globe. One can observe that a higher portion of the workload was allocated to the DCs where renewable energy is being produced: the DCs located where the sun is still shining. This figure was generated from the experiments performed in this thesis. More details can be found in Chapter 4.

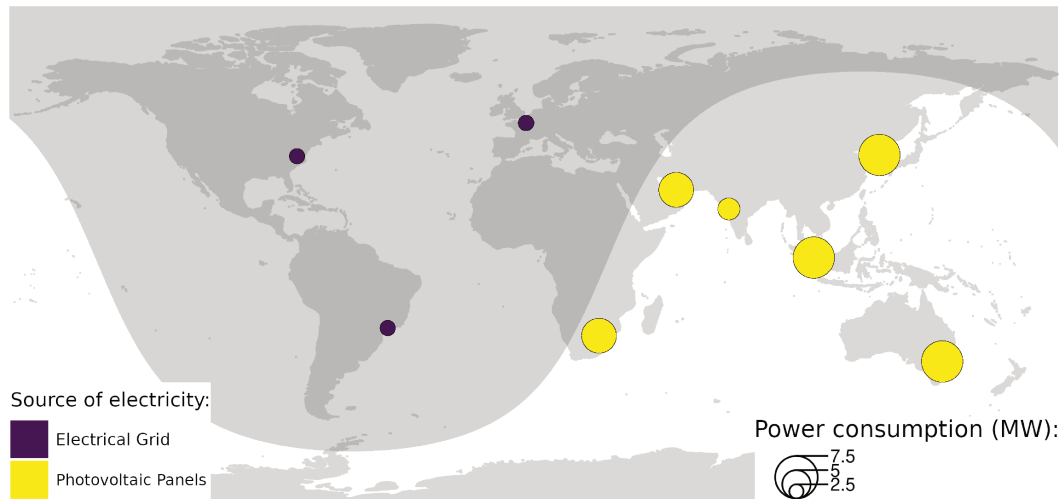


Figure 2.2. An example of a cloud federation that adopts the follow-the-renewable strategy. Each circle represents the data center locations: its area represents the total power consumption, and the color represents the source of electricity used to supply the DC power demand. The gray layer represents the day and night periods around the world.

The work from Xu and Buyya [23] provides a comprehensive overview of the classical strategies utilized to reduce data centers’ power consumption. Additionally, they present their scheduling algorithm that incorporates the “follow-the-renewables” to allocate the workload between the data centers located in different time zones. The optimization algorithm has the objective of minimizing the total carbon emissions of the operation while ensuring the average response time of the requests. The workload will be executed on the data centers they were allocated to, and during execution it is not possible to migrate to other DCs that may have a higher availability of green energy—no VM live migration nor VM consolidation to reduce the number of servers being used.

Reducing power consumption, the environmental impact generated by using carbon-intensive electricity, and monetary costs while not degrading workload performance

were studied by Ali et al. [24]. They proposed a distributed scheduling algorithm for geographically distributed DCs with heterogeneous hardware. The algorithm has two main steps that adopt greedy heuristics. The first consists of allocating the workload to the servers given a policy (lower energy price or carbon intensity). In the second step, it is possible either to apply server consolidation to the workload in execution to reduce the number of servers in utilization (by using intra-DC migrations) or the tasks can be shifted to other data centers (inter-DC migrations) in order to use cheaper or greener electricity. The algorithm also considers that the migration's destination server might be less powerful than the server where the tasks were originally in execution, which would degrade the performance of the workload.

Ruiz Duarte and Fan [25] studied the problem of operating data centers geographically distributed across the United States in terms of scheduling the workload and the power supply—that comes from the regular electrical grid, batteries, or on-site renewables. The proposed solution consisted of a Mixed Integer Linear Program (MILP) formulation that adopted follow-the-renewables for allocating and migrating the workload, and managed the decision of selecting which power source would be used. The objectives of the MILP are to minimize both costs—that originate from purchasing electricity from the grid, energy storage devices, or selling or buying carbon credits—and CO₂ emissions—that originate from using carbon-intensive electricity from the regular electrical grid.

In Khodayarsesht et al. [26], the authors study the workload scheduling problem to minimize energy consumption while avoiding violating the Service Level Agreements. The proposed solution used greedy heuristics to find the server that could run the tasks with the minimum increase in total energy consumption. If the algorithm found more than one server available, the criterion of the one that uses less carbon-intensive electricity was used to break the tie. Therefore, minimizing the emissions was the secondary objective of the algorithm, and the “follow-the-renewables” was only applied at this step. It is important to remind the reader that minimizing energy

consumption and carbon emissions are different problems. For example, suppose DC A uses power from a grid supplied by coal power plants. In that case, it will have a carbon footprint more than 20 times higher than a DC B that consumes the same amount of power and uses photovoltaic energy— 1001 g of CO₂-eq per kWh of electricity produced for coal power and 43 g of CO₂-eq per kWh for solar power [9].

The studies by Camus et al. [27, 28, 29] aim to optimize low-carbon-intensive energy usage in the context of data centers that have a power supply for both the regular electrical grid and locally installed solar panels. Also, these studies consider data centers that are geographically distributed, which allows for exploring “follow-the-renewables” strategies. The first study proposed the SAGITTA algorithm [27], which uses a stochastic approach to estimate renewable energy production and a greedy heuristic to allocate resources to meet the demand of virtual machines. The greedy heuristic chooses which servers in the data centers will receive the virtual machine workload considering their green energy availability and turns off those not selected to reduce the loss of renewable energy. After determining the servers to turn on or off, the algorithm tries to migrate the workload between servers in distinct data centers to use those with the most green energy availability.

The NEMESIS algorithm [28] is an evolution of the SAGITTA algorithm, and also uses a stochastic approach to estimate renewable energy production and greedy heuristics for VM allocation that select the servers from the data centers with the most available green energy. The main differences are that the proposed solution uses a consolidation algorithm to reduce the number of powered servers and a VM migration algorithm that considers network costs.

The SCORPIOUS algorithm [29] is an extension of the NEMESIS algorithm with a new approach: sharing excess renewable energy generated by geographically distributed data centers that have on-site solar panels installed. This approach uses SmartGrid’s collective self-consumption, and the excess of green energy can be used

by data centers that are not generating solar power, or when the demand is greater than the production.

Finally, “follow-the-renewables” approaches are feasible candidates for mitigating the intrinsic intermittent nature of renewable power, but one must not neglect its limitations. Chapter 3 presents a discussion of the impact of adopting such strategies, in particular on the network and energy consumption, a proposed solution that extends the work from Camus et al. [28], and the works of Xu and Buyya [23] and Ali et al. [24] were used as baselines to evaluate the solution.

2.4.2 Sizing the renewable infrastructure

There are two main options for supplying the cloud federation’s power demand with low-carbon-intensive electricity. The data center owner can purchase green power from the local electricity grid that has the integration of renewables—which makes them dependent on the grid, and not all locations provide this possibility—or it can install a local renewable infrastructure in the DCs. For the latter option, the main problem is deciding the dimensions of the renewable infrastructure needed, for example, the required area of solar panels, number of wind turbines, and capacity of the batteries (to store green power and use it when opportune) to supply the data center and minimize its carbon footprint. This problem is known as *sizing*, *dimensioning*, or *capacity planning* in the literature. Many factors need to be considered in the sizing decision: the costs of manufacturing and operating these devices, the potential of generating power given the climate conditions and the geographic location, and the fact that these devices also present an environmental impact during their lifetime cannot be neglected as well.

The strategy sizing of the renewable infrastructure considers the Scope 1, 2, and 3 of the GHG Protocol: the direct carbon emissions from generating electricity in the DC, emissions from consuming power from the regular electrical grid, and other indirect

GHG emissions that come from the manufacturing and life cycle of the renewable infrastructure and IT equipment.

Most of the scientific literature on the sizing problem for cloud data centers has focused on the scenario of a single DC. Two main approaches are investigated: i) the data center may be supplied by the regular electrical grid as a backup when the renewable power production is not sufficient, and ii) the DC is fully supplied by green energy from its on-site renewable infrastructure—which may require the adoption of energy storage devices.

The first approach—using the regular electrical grid as a backup—is adopted by the majority of works on sizing for clouds. To supply the power demand of fog DCs in a rural area in India, R and Rekha [30] proposed a solution that adopts a Particle Swarm Optimization strategy for sizing a smart microgrid. The optimization problem's objective is to minimize the monetary costs of buying solar panels, wind turbines, diesel generators, and batteries. Additionally, the authors propose a scheduling algorithm to maximize low-carbon-intensive energy utilization from its local renewable infrastructure.

Depending on the local electricity grid and the renewable infrastructure, more renewable power can be produced than what the electrical grid can receive. In this situation, there is a curtailment, a reduction in the energy delivered when the generation exceeds the demand or there are system conditions in the grid, such as transmission congestion, minimum generation levels of thermal generators or hydropower, or back-feeding in the distribution systems [31].

Niaz et al. [32] evaluated using curtailed green energy to supply the DCs power demand and provide hydrogen to hydrogen refueling stations. The proposed solution consisted of an optimization problem that used Mixed Integer Linear Programming (MILP) with the objective of minimizing the capital costs. The modeling included natural-gas-powered combined cooling, heating, power systems, electrolyzers, hy-

drogen fuel cells, heat pumps, hydrogen tanks, and battery energy storage systems. The study provided three interesting results: i) the worst scenario regarding both economic and environmental aspects was to only consume power from the regular electrical grid; ii) The scenario with the minimal monetary costs was the combination of using curtailed renewable energy and power from the grid; and iii) the best solution for the environment was to consume only renewable power, however, it resulted in the highest costs.

The second main approach—using only power from the on-site renewable infrastructure without accessing the grid—is becoming more and more explored in the literature, presenting promising results. A planning methodology for a net-zero energy system—an energy system that does not emit carbon dioxide to the atmosphere [33]—was discussed by Richter et al. [34], which assessed the potential for a net-zero energy DC in Germany through a qualitative study. The data center is considered net-zero because its power demand would only be supplied by electricity generated by the low-carbon-intensive on-site renewable infrastructure. Power from the regular electrical grid is assumed to be highly carbon-intensive and is only used in the case of failures of the green power infrastructure. The research concluded that the DC presented a large potential to operate as a net-zero energy system, taking into account the importance of selecting proper technologies for producing electricity, increasing energy efficiency, and optimal sizing of energy storage devices. Other secondary benefits are that the marketing image and economic value can increase when the DC operates as a net-zero energy system.

The DATAZERO [35] project explores the possibility of a single data center being operated exclusively from renewable energy and uses energy storage devices to try to smooth the short- and long-term intermittency. The work from Haddad et al. [36]—part of the DATAZERO project—evaluates the possibility of using the combination of solar panels and wind turbines for supplying the DC power demand and the usage of batteries and hydrogen storage—for short- and long-term storage,

respectively. The study discussed the impact of the geographic location and the computational workload that must be executed in the resulting sizing—number of servers, dimensions of the renewable power sources, and capacity of the energy storage devices.

Another work from the DATAZERO project evaluated how to reduce oversizing, that is, manufacturing more renewable infrastructure than needed, in DCs powered by green energy [37]. The classical sizing approaches are very sensitive to variations in the inputs, as there are a few days when there is a peak in computational demand for the workload or low renewable production. The proposed solution evaluated how to minimize the oversizing and the impact in terms of Quality of Service and on the dimensions of the renewable infrastructure. A binary search strategy was adopted to find the best relevant sizing, in contrast to the previous studies that used MILP approaches.

Other research areas explored in the scientific literature analyze the sizing of particular elements, such as the electrical infrastructure. Sheme et al. [38] investigated the usage of batteries as an energy storage device and their size to supply 50% of the DC's total energy demand using power from renewable sources. For the experiments, the authors developed a simulator that receives information on the PV area and capacity of the batteries as input, and different geographic locations were considered: Finland, Crete, and Nigeria. The results highlight the different potential of the geographic locations: Nigeria presented the smallest area of solar panels required: 17% less than Crete and 45% less than Finland. Additionally, Finland requires a battery with 39 times more capacity than Nigeria—even if it receives 15% less solar energy, and Crete needs a battery with a capacity 27% higher than Nigeria.

Most studies in the literature focus on dimensioning the renewable infrastructure for a single data center. A similar trend can be observed in the context of scheduling problems for DCs powered by green energy: a literature review on recent publi-

cations on the subject of DCs that are supplied by renewable energy was made by Song et al. [39], and the results show that over 100 publications, only around 25% considered geographically distributed data centers partially powered by renewable energy. Additionally, the authors reported that most research on integrating renewable sources in cloud data centers focuses on the scheduling of the workload, and few articles analyze the dimensioning of the renewable infrastructure.

The Carbon Explorer framework [40] explored sizing for multiple geographically distributed DCs. The study's objective is to supply DCs located in the United States exclusively with renewable power, and three strategies were used: i) only use green power; ii) use renewable power and energy storage devices; and iii) use green energy and workload scheduling. It is assumed that the DCs have access to low-carbon intensive power from the regular electrical grid—solar, wind, or both—and additional renewable infrastructure will be built—PV panels, wind turbines, and batteries, taking into account the emissions of manufacturing. The study performed an exhaustive search to evaluate the possible scenarios. In conclusion, the authors report that, when taking into account the scenario of geographically distributed data centers and the manufacturing carbon emissions of the renewable infrastructure, there may be better solutions than powering the cloud federation exclusively with green power. Finally, deciding the optimal solution is still an open research question for future work.

This thesis explored the dimensioning of geographically distributed data centers worldwide. The proposed solution combined both “follow-the-renewables” for scheduling the workload and sizing the renewable infrastructure to reduce the carbon footprint of a global cloud federation. Compared to the Carbon Explorer framework, our proposed solution considers the use of the local electrical grid when feasible, given that it may have the presence of low-carbon-intensive power sources. Finally, our model uses a linear program formulation, in contrast to most of the works in the literature that use MILP.

In Chapter 4, the reader is introduced to our initial modeling of the problem and the evaluation of the short-term scenario (1 year) for reducing the carbon footprint of operating a cloud federation. In Chapter 5, an extension of the modeling is presented, focusing on the long-term operation, taking into account the life-cycle of the renewable infrastructure, another source for renewable power, scheduling strategies to reduce the carbon footprint further, and manufacturing servers taking into account their carbon footprint. Additionally, one new dimension of the problem is explored: the monetary costs of reducing the environmental impact with on-site renewable infrastructure.

2.5 Summary

This chapter presented an overview of the context of cloud computing, how it is possible to measure the environmental impact of the cloud computing platforms using the GHG protocol, scheduling, and the concept of carbon-responsive computing to describe the strategies for reducing its environmental impact, in particular the follow-the-renewables and the sizing that are explored in this thesis. The content presented in this chapter should provide the reader with adequate information to comprehend the succeeding chapters of this thesis.

Follow-the-renewables and their impact on the network and energy consumption

3.1 Introduction

The “follow-the-renewables” approach (the reader may consult Chapter 2 for more details) is an interesting strategy for mitigating the intermittency of renewable energy availability without the need to use energy storage devices. For example, when it is night in the location where a DC A resides, the workload could be migrated to another DC B where the sun is still shining to use solar power—as seen in Figure 2.2.

Despite its benefits, one cannot neglect the limitations of the follow-the-renewables strategy. First, the process of migrating a VM between different DCs consumes energy itself: it uses network devices (such as switches and routers) and a computational task for the live migration process. The scheduling algorithm must consider this energy consumption before deciding if the migration is advantageous. Second, the network communications links that connect the servers inside the DC and the different DCs can suffer from congestion, which may increase migration duration. This results in unnecessary computation and energy consumption on both the origin and the target servers: the server that is sending the VM needs to wait for the migration process to finish to free its resources and receive additional VMs, or it could be turned off as well to save energy; the server that is receiving the VM will only start executing the new VM after the end of the migration process. An efficient

scheduling algorithm must consider those factors to decrease the carbon footprint of the DCs operations.

The work by Camus et al. [27, 28] studied the scheduling of the cloud workload, in the form of virtual machines (VMs), on geographically distributed DCs to minimize non-renewable energy consumption. It proposed different stochastic models to estimate renewable energy production and greedy heuristic algorithms to allocate tasks to servers. VMs are allowed to be migrated during execution to a computer within the same DC (intra-DC server consolidation) or to a computer in a DC located in another geographic location (“follow-the-renewables”). The scheduling algorithm considers the network cost of the migration.

This chapter presents an extension of this work with an analysis of the indirect impact of using the follow-the-renewables approach in energy consumption. This impact can be divided into two categories: direct and indirect. The network devices’ energy consumption causes the direct impact, and since the power consumption does not vary significantly based on the device usage [41], we assume the network devices’ power consumption to be static. For the indirect impact, it is generated by the live migration of the VMs, which uses the network to transfer all the data related to the task to the destination machine, as well as the computational task required to perform this live migration. More specifically, this chapter presents the following contributions:

- an analysis of the impact of not considering the network (bandwidth, latency, and topology) in both energy consumption and network congestion;
- an accurate estimation algorithm for the time it takes to migrate a virtual machine that takes into account the network topology, link bandwidth, and latency;

- a scheduling algorithm for the live migration of the VMs that uses the estimation algorithm and has the same or lower brown energy; consumption than the baselines, with no network congestion.

The work of this chapter resulted in the following publication: **Miguel Felipe Silva Vasconcelos, Daniel Cordeiro and Fanny**. “Indirect network impact on the energy consumption in multi-clouds for follow-the-renewables approaches”. In *Proceedings of the 11th International Conference on Smart Cities and Green ICT Systems — SMART-GREENS 2022*, pages 44–55. INSTICC, SciTePress. The text of the present chapter is an adaptation of this publication.

This chapter is organized as follows. In Section 3.2, the model of Camus et al. [28], the foundation of this work, is summarized. Section 3.3 details the new scheduling method for the migrations, while Section 3.4 is devoted to simulations parameters. Results are detailed in Section 3.4.3. Finally, Section 3.5 summarizes the chapter.

3.2 The NEMESIS algorithm

In this section, we describe the resource management framework NEMESIS [28], which was the foundation for the work presented in this chapter. The NEMESIS algorithm manages a multi-cloud composed of DCs geographically distributed across a country. The DCs power demand is supplied from the regular electrical grid and locally installed PVs. Given the intermittency of renewable energy, the NEMESIS algorithm uses the stochastic modeling of SAGITTA [27] to obtain the expected value of the renewable energy available at a given time to be used as input for the scheduling algorithms.

NEMESIS has a central controller, and the workload execution is scheduled in 5-minute time slots. The workload consists of heterogeneous VMs in terms of the number of CPU cores, RAM size, and requested execution time. The scheduling

decision uses greedy heuristics inspired by the Best-Fit algorithm. While it may not result in the optimal solution, greedy heuristics can provide an acceptable result in a reasonable amount of time, and these characteristics are relevant for the scenario of cloud computing, where millions of VMs are submitted per hour and a significant portion of these tasks have strict quality of service requirements and cannot be delayed. The scheduling algorithm has four main steps, detailed as follows.

In the first step of the algorithm (pre-allocation of the incoming VMs), the controller will search for servers to allocate the VMS received during the time slot. There are two restrictions for this scheduling algorithm: i) the server has available computational resources to host the VM; and ii) executing the VM in this server would result in the minimum increase in the expected brown energy consumption. The algorithm first sorts the VMs by their volume (a product of the number of CPU cores and the amount of RAM) in decreasing order and then performs the search for each of the VMs. If a server is found that respects the two restrictions, the algorithm makes a reservation (pre-allocation) for the VM being analyzed and goes to the next VM. On the other hand, if no server is found, the VM will be delayed to be processed in the next time slot.

The second step of the algorithm (revision of the pre-allocations) performs a revision of the reservations made by the previous step, given that the greedy heuristic used may not provide the optimal solution. The strategy is to move the reservation from the DCs expected to consume more brown energy to the DCs expected to have the most availability of green energy. There are two constraints for this algorithm: i) there exists a server in the DC being evaluated that can host the VM; and ii) the expected brown energy is reduced.

The availability of green energy may change during the execution of the VMs, and the third step of the algorithm (migration of the running VMs) aims to reduce brown energy consumption by migrating the running VMs. It uses the same strategy as the second step of the algorithm (moves the workload from DCs using more

brown power to DCs that have more green power available) and with the following restrictions: i) the migration needs to finish before the beginning of the next time slot; ii) the remaining execution time of the VM needs to be greater than the duration of the migration process; iii) one DC can only migrate to another 2 DCs during a time slot; and iv) the migrations from one DC are planned to execute one after another, that is, they cannot happen simultaneously in parallel. Restrictions (iii) and (iv) are simple heuristics to avoid network congestion with the load generated by the VM live migrations.

The power demand from the servers accounts for approximately half of a data center's overall energy consumption [42]. The last step of the algorithm (server consolidation) aims to minimize the number of active servers. In this process, the algorithm assesses if it can redistribute the running VMs (by executing live migrations within the data center, referred to as intra-DC migrations) to decrease the number of servers in use and shut down the servers that become idle.

3.2.1 Cloud Modeling

NEMESIS cloud modeling is based on a real cloud infrastructure: the Grid'5000 testbed¹. It is considered a subset of the original platform with 1035 servers distributed among 9 data centers in France and Luxembourg: 116 servers in Grenoble; 74 servers in Lille; 38 servers in Luxembourg; 103 servers in Lyon; 240 servers in Nancy; 44 servers in Reims; 129 servers in Rennes; 151 servers in Sophia Antipolis; and 140 servers in Toulouse. The servers are considered homogeneous in terms of memory, CPU, and energy consumption, and are based in the Taurus node of the Grid'5000, equipped with two Intel Xeon E5-2630 CPUs (6 cores per processor), and 32 GB RAM.

¹Grid'5000 testbed: <https://www.grid5000.fr>. Accessed on October 20, 2023.

The network is modeled both for the connection of the servers inside the DCs (network links with 1 Gbps of bandwidth) and the connection between the different DCs (network links with 10 Gbps bandwidth). Figure 3.1 depicts the cloud platform’s network topology (the DCs’ placement was not based on their geographic location, but to visualize the network links better). One can observe that multiple DCs share some network links, thus the migration planning needs to consider this information to avoid generating network congestion and the resulting waste of resources.

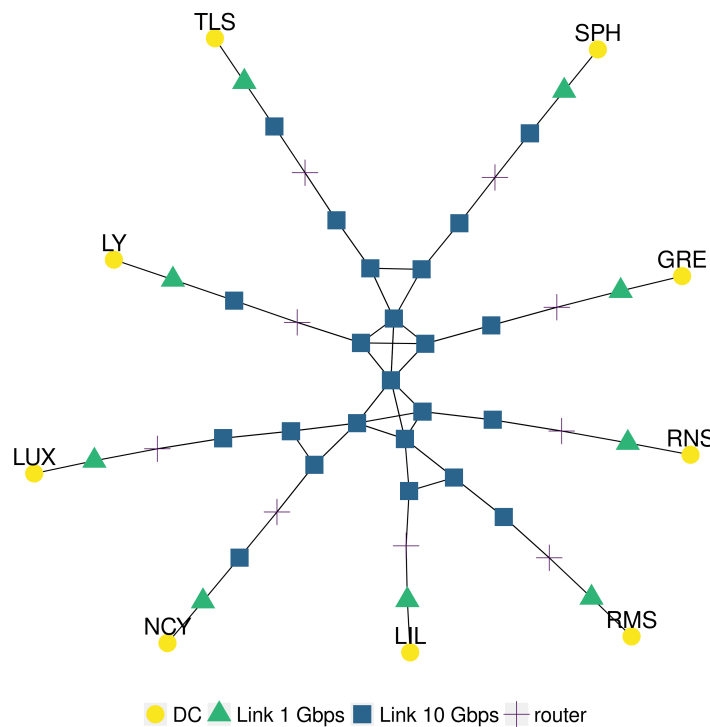


Figure 3.1. Topology of the Cloud platform, where “GRE” is Grenoble, “LIL” is Lille, “LUX” is Luxembourg, “LY” is Lyon, “NCY” is Nancy, “RMS” is Reims, “RNS” is Rennes, “SPH” is Sophia, and “TLS” is Toulouse.

Regarding the energy consumption of the servers, it is considered a linear model based on CPU usage, and the VMs always use 100% of the requested number of CPU cores. The server presents a fixed consumption for its IDLE state (97 W), and the power consumption based on core usage is as follows: 128 W for 1 core; 146.4 W for 2 cores; 164.8 W for 3 cores; 183.2 W for 4 cores; 201.6 W for 5 cores; and 220 W with 6 cores. Furthermore, the energy consumption of turning on a server

(127 W during 150 s), turning off a server (200 W for 10 s), and when the server is off (8 W) are modeled as well.

3.2.2 VM live migration model

The VM live migration model of NEMESIS has three phases. In the first phase, all the memory pages of the VM are transferred to the destination server. In the second, after completing the copy of all the memory pages, a message is sent to notify the end of the stop-and-copy step. Finally, in the last step, the commitment message is sent to the new host to inform them of the end of the migration process, and the VM will be destroyed on the server of origin and resumed on the destination host.

3.3 The c-NEMESIS algorithm

In this section, we present how we extended the NEMESIS algorithm to perform the analysis of the impact of the follow-the-renewables in both network and energy. The new algorithm is called c-NEMESIS, where the “c” stands for congestion and its full name is “Congestion and Network-aware Energy-efficient Management framework for distributEd cloudS Infrastructures with on-Site photovoltaic production”. Section 3.3.1 presents how the algorithm for estimating the duration of the migration process was updated, and Section 3.3.2 shows the modification in the migration scheduling algorithm. Finally, Section 3.3.3 presents how we model the energy consumption of the live migration process.

3.3.1 Estimating the duration of the live migration

The duration of the migration is essential information for the scheduling decision, as it can help avoid oversaturating the network links and generating network

congestion. Algorithm 1 is an extension of the NEMESIS algorithm, and it executes this estimation, where: $linkLatency$ is the latency of the link; $routeSize$ is the number of links that interconnects the host where the VM is originally running to the target host of the migration; $windowSize = 4,194,304$ Bytes, is the TCP maximum window size; $bandWidthRatio = 0.97$, represents the additional load caused by the headers of TCP/IP; $bandwidth$ = the minimum bandwidth among the links that interconnect the host of origin with the target host; $\alpha = 13.01$, simulates the TCP slow start factor, that is, not all the bandwidth is instantly available for the communication; and γ is used to represent the Bottleneck effect of the TCP protocol; the computation of the value $throughputL$ models the TCP flow control—high network latency values can impact the available bandwidth. The parameters and computations used in Algorithm 1 were based on the study from Velho et al. [43]. The algorithm is also inspired in the VM live-migration model of the Simgrid framework, which has three phases [44]—which justifies the constant 3 in the last line of the algorithm which computes the total time to migrate.

Algorithm 1 Estimation of the migration duration.

$$\begin{aligned}
theLatency &\leftarrow linkLatency \times routeSize \\
transferLat &\leftarrow theLatency + \frac{\gamma}{bandwidth} \\
throughputL &\leftarrow \frac{windowSize}{2 \times transferLat} \\
throughputB &\leftarrow bandwidth \\
throughput &\leftarrow \min(throughputL, throughputB) \\
throughput &\leftarrow throughput \times bandWidthRatio \\
timeToMigrate &\leftarrow 3 \times \alpha \times transferLat + \frac{vmRamSize}{throughput}
\end{aligned}$$

The difference between Algorithm 1 and NEMESIS is the $routeSize$ variable: NEMESIS used fixed values (5 for live migrations intra-DC, and 11 for live migrations inter-DC), and now it is assumed that the cloud operator has information about the network topology of his DCs, thus the real number of links that interconnect the two hosts is used.

3.3.2 Planning the migrations

Algorithms 2 and 3 plan the VM migrations considering the network topology and the bandwidth usage. They are inspired in the migration planning of NEMESIS, with the following modifications: i) the available bandwidth of the links is considered (it changes based on the number of migrations that use the same network link); ii) migrations can be performed in parallel between different DCs respecting the links' bandwidth constraint; iii) the intra-DC migrations (for the server consolidation) are sequentially distributed in time (do not execute simultaneously) ; iv) the real number of links that interconnect the origin and the target server is used as input for the estimation algorithm of the migration duration.

Algorithm 2 Migration planning at multi-cloud level.

```
DCs                                     ▷ Sorted by increasing ERGE
plannedTime ← 0
timeSlotDuration ← 300
linksHistory ← ∅
while plannedTime < timeSlotDuration do
  dc_tx ← first item of DCs
  while dc_tx ≠ last item of DCs do
    dc_rx ← last item of DCs
    if dc_tx has VMs that can be migrated then
      while dc_tx ≠ dc_rx do
        plan migrations between dc_tx and dc_rx using Alg. 3
        dc_rx ← previous DC of DCs
      end while
    end if
    dc_tx ← next DC of DCs
  end while
  if no VM migration was planed and no migration is in execution then
    exit
  end if
  plannedTime ← instant after the expected end of next migration
end while
```

Algorithm 2 is used to plan the migrations of the multi-cloud. Initially, the DCs are sorted by increasing order of expected remaining green energy (ERGE). Let *dc_tx* be the index of the position of the DC with the least available energy—initially at

Algorithm 3 Migration planning between two DCs.

Require: dc_tx, dc_rx
 $VMs \leftarrow$ list of VMs of dc_tx
for vm in VMs **do**
 $origin \leftarrow$ server where the vm is running
 $target \leftarrow$ server from dc_rx being evaluated that has available computational resources (CPU and RAM) to host the VM
 $worth \leftarrow brownMig < brownNotMig$
 $e_time \leftarrow$ estimate the migration time using Alg. 1
 $band_ok \leftarrow$ links between $origin$ and $target$ can receive the additional load of the migration
 if $worth$ and $band_ok$ **then**
 registers the planning of the migration and updates the link history
 end if
end for

the beginning of the list, and it will be the candidate to send VMS, and dc_rx the index of the position of the DC with the most green energy—initially at the end of the list, and it is the candidate to receive the VMs. The main idea of the algorithms is to migrate VMs from the DCs that are expected to use brown energy to the DCs that are expected to have green energy.

In order to evaluate if it is possible to migrate VMs from dc_tx to dc_rx and if it is worth—the brown energy consumption will be reduced—Algorithm 2 uses the Algorithm 3, which works as follows. First, the algorithm extracts the information about the running VMs (grouped by the servers) of the DC dc_tx . The planning starts at the beginning of the time slot. For each VM that can be migrated, the algorithm tries to find a server in the destination DC dc_rx with the following restrictions: i) it has available computational resources to host the VM (CPU and memory); ii) the links that interconnect the server of origin (where the VM is running) and the target server can receive the additional load of the migration without violating their bandwidth constraint; iii) the VM migration finishes during the current time slot (if the destination server is off, the time to turn the server on is taken into account); and iv) performing the migration reduces the expected brown energy consumption. The fourth restriction uses the original NEMESIS algorithm to compute the expected

brown energy consumption when performing the migration (*brownMig*) and the expected brown energy consumption if the VM remains executing in the same server (*brownNotMig*).

If all these restrictions are respected, the VM is planned to migrate, and the algorithm registers in the *linkHistory* that the links that connect these two servers will be used until the instant when the VM migration is expected to finish in order to compute the available bandwidth of the network links. If there are still remaining VMs that could be migrated from DC dc_{tx} , the algorithm will try to migrate them to DC $dc_{rx} - 1$, and so on, until all the VMs from DC dc_{tx} are planned to be migrated or all the DCs are processed. After finishing processing the DC dc_{tx} , the algorithm repeats the same process for the DC $dc_{tx} + 1$ until all the DCs are processed.

After evaluating all the possible migrations for the instant at the beginning of the time slot, the algorithm will use the link usage history to obtain information about when there will be available links in terms of bandwidth—at what instant of time t the next migration is expected to finish. If there are still VMs that could be migrated, the migration planning algorithm will be executed again using the availability of the bandwidth at the instant t . Then, the process repeats until there are no more VMs to migrate, or the evaluation time reaches the end of the time slot.

Regarding the server consolidation, there are two differences to the original NEMESIS algorithm: i) it will only be applied to the DCs that didn't have inter-DC migrations planned to avoid generating network congestion—given that the intra-DC migrations could use the same network links as the inter-DC migrations planned in the previous step; and ii) the migrations are distributed in time using the estimation computed with Algorithm 1 to avoid overlapping them.

The computational complexity of the Algorithm 3 is $O(n_{VMS} \times n_{servers} \times n_{links})$, where n_{VMS} is the number of running VMs on the DC that is sending the VM, $n_{servers}$ is the number of candidate servers that have the least possible amount

of free cores to run the VM on the destination host, and n_{links} represents the number of links that interconnect the VM's host of origin and the target host. For Algorithm 2, the computational complexity is given by $O(n_{DCs} \log n_{DCs} + n_{DCs}^2 \times n_{VMS} \times n_{servers} \times n_{links})$, where n_{DCs} is the number of DCs.

3.3.3 Energy cost of migrations

The energy consumption of a live VM migration is modeled in NEMESIS by a computation task executed on the target host. This task uses 100% of a single CPU core during the migration process. Suppose the migration is impacted by network congestion. In that case, its duration will increase, resulting in a waste of energy on the server where the VM was initially running as well as on the target server.

The wasted energy is proportional to the extra time migrating, that is, the difference between the duration of the migration process compared to the duration that it would take if there were no network congestion. A lower bound for the wasted energy can be computed with Algorithm 4 using as input this extra time migrating. Given that the migration planning uses a “follow-the-renewables” approach to move the workload from the DCs that are using brown power at that instant to the DCs that have more available green energy, the algorithm computes individually the wasted energy in the server that is sending the VM and in the server that is receiving the VM. For the server that is sending the VM, this extra energy consumed is brown(er), increasing the overall brown energy consumption of the cloud, since this server could be turned off to save energy. For the server that will receive the VM, this extra energy is green(er), but it is wasted because it was only available at that instant (no energy storage devices) and could have been used to execute the workload.

The value of $pCore$ is an estimate for the additional cost of executing a core, and is obtained as follows: the server consumes 220 W at full load and subtracting the power consumption of the IDLE state (97 W) it results in 123 W. Finally, this value

Algorithm 4 Extra energy consumption of migrating.

```
pCore ← 20.5
wastedOrigin ← 0
wastedTarget ← 0
for mig in Migrations do
  vmCores ← amount of cores of the VM being migrated
  extraTime ← mig.Time − mig.TimeNoCong
  if extraTime > 0 then
    wastedOrigin+ = extraTime · pCore · vmCores
    wastedTarget+ = extraTime · pCore
  end if
end for
```

is divided by the total number of cores on the server (6), resulting in 20.5 W. Notice that *pCore* is only multiplied by the number of cores of the VM for the server of origin, since it remains executing in the VM until the end of the migration, and on the destination server the computational task uses only a single CPU core.

3.4 Experiments

In this section, we describe the experiments performed to evaluate the impact of the follow-the-renewables approaches in both energy and network, considering one week of operating the multi-cloud. Section 3.4.1 presents the settings used to execute the experiments. To further evaluate the effectiveness of using “follow-the-renewables” approaches, we detail in Section 3.4.2 two other works that incorporate this approach in different ways and are used as baselines for the c-NEMESIS algorithm. Finally, Section 3.4.3 discusses the obtained results.

The results of the experiments are deterministic. Therefore, only results for a single execution of the simulations are presented. A public Git repository hosts all the simulation code, inputs, and the instructions to run and extract the results².

²Git repository with the c-NEMESIS reproducible artifact: <https://gitlab.com/migvasc/c-nemesis>. Accessed on October 20, 2023.

The experiments were performed using computational simulations. The Simgrid [45] framework (version 3.28) was used to develop the simulations because it allows modeling distributed computing experiments, such as cloud platforms, in particular: energy consumption of executing the tasks, turning on and off the servers, network usage by the live migration process, network topology and network congestion. Another relevant reason for choosing the Simgrid framework is the fact that it is well-validated by the scientific community, with over 20 years of usage. For the network, the default flow-level TCP modeling of Simgrid produces precise results for large distributed computing scenarios (as in our case with thousands of servers) in a reasonable amount of time. It is possible to use packet-level simulation, however, despite being more precise, it would result in a huge execution time for the simulations [43].

3.4.1 Settings

The cloud infrastructure is based on the adapted version of Grid'5000 (same as NEMESIS, see Section 3.2.1) for the network topology, server hardware specifications and power consumption.

3.4.1.1. Workload

Traces from real cloud providers were used to generate the workload for the experiments. The data extracted from the traces were the number of CPU cores requested, the instant of time when the task was submitted, and its duration. Regarding the requested RAM per VM, it is considered that each VM will consume 2 GB per core requested, similar to the `t2.small` instance of Amazon EC2³. It is also considered that the VMs execute with full CPU usage of the requested cores, the worst scenario for energy consumption.

³Amazon EC2 instance types: <https://aws.amazon.com/ec2/instance-types/>. Accessed on October 20, 2023.

The workloads are scaled to use a maximum of 80% of the computational resources of the cloud platform at any given simulated time. This decision ensures that the tasks will always be allocated to the servers, and that there will be some room for the servers to receive VMs from live migrations, thus allowing for the analysis of the different scheduling approaches. Furthermore, from the cloud traces, it is possible to observe that the DCs are not used 100% of their computational capacity. Figure 3.2 illustrates the number of VMs submitted during the week (in yellow), and the cumulative demand of CPU cores requested at a given time (in purple)—the total number of CPU cores used by the VMs in execution at that instant of time.

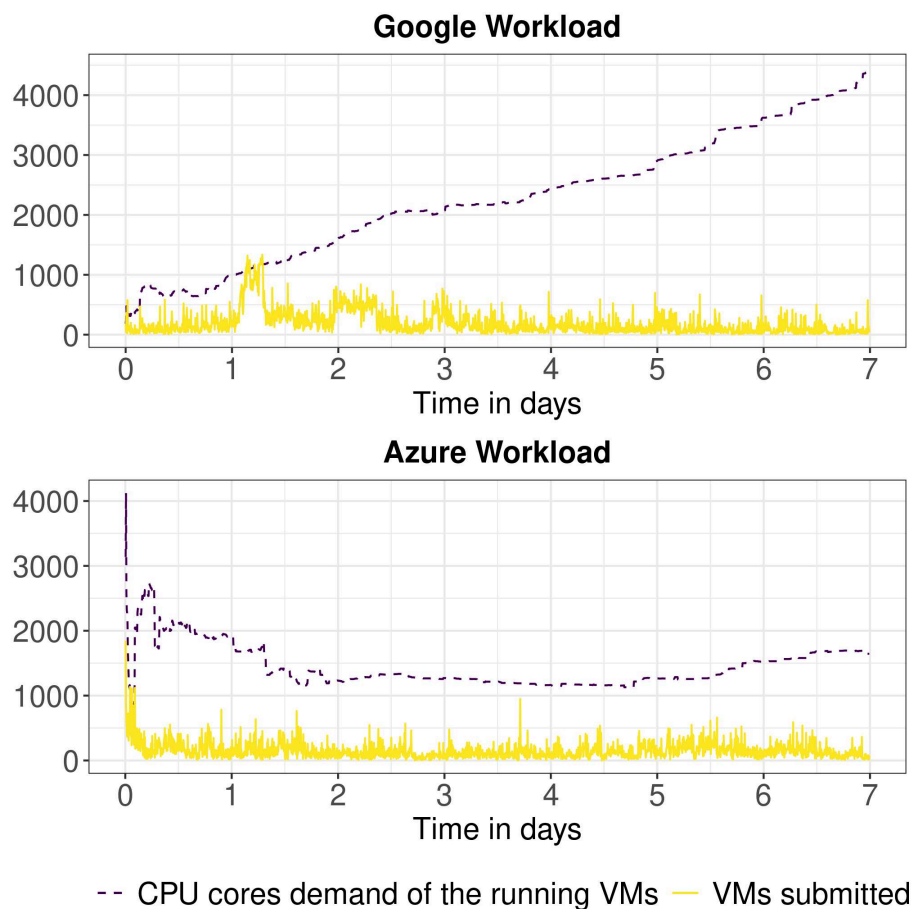


Figure 3.2. Workloads used as input for our simulations.

The first workload was generated using as a base the 2011 Google Cluster Workload traces [46], and it consists of over 380,000 VMs. In this workload, the VMs have a

long execution time, as can be seen in Figure 3.2, in which the value of the running VMs' CPU core demand keeps increasing throughout the week. The second workload was based on traces from Microsoft Azure [47], more specifically, the Azure Trace for Packing 2020, and contains over 304,000 VMs. This generated workload has a different behavior than the previous one: there is a peak in the VM submissions at the beginning of the week, and the VMs have a shorter execution time, as seen by the fact that the CPU core demand does not keep increasing during the week.

These traces do not provide data about the network usage of the tasks, which was not modeled in the simulations. The additional load on the network is generated only by the live migration of the VMs. Therefore, this work can be seen as a lower bound for the real-world scenario.

3.4.1.2. Green energy traces

The data for the energy produced by the solar panels were obtained from the Photovolta⁴ project by *Université de Nantes*. The data represents the power production of two arrays of 4 PVs each (Sanio HIP-240-HDE4) with a total nominal power production of 1920 Wc at intervals of 5 minutes. In order to simulate the different productions of the geographically distributed DCs, a different week of the production trace was used for each DC. Furthermore, each DC had three PV panels per server. The PVs installed in the DCs generated the following amount of energy during the simulated week: i) Grenoble: 1.58 MWh; ii) Lille: 0.07 MWh; iii) Luxembourg: 0.15 MWh; iv) Lyon: 1.19 MWh; v) Nancy: 2.16 MWh; vi) Reims: 0.38 MWh; vii) Rennes: 1.63 MWh; viii) Sophia: 1.75 MWh; and ix) Toulouse: 1.53 MWh. In total, around 10.5 MWh of green power was produced in the simulated week. Figure 3.3 shows the green power production per DC during the simulated week.

⁴Photovolta project: <http://photovolta.univ-nantes.fr/>. Accessed on October 20, 2023.

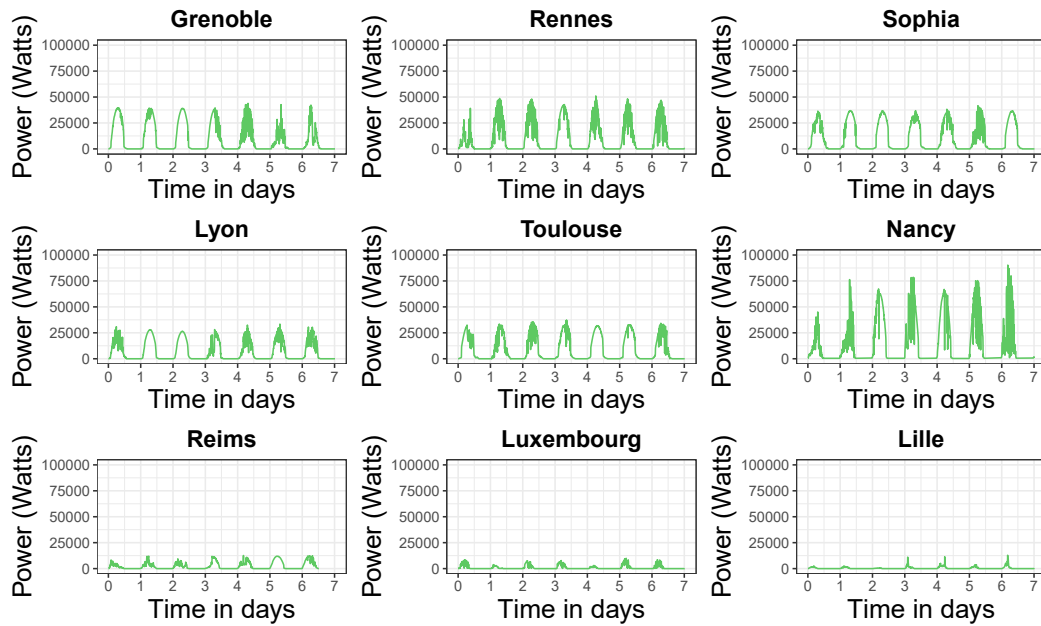


Figure 3.3. Green power production (in Watts) produced by DC during the simulated week.

3.4.2 Baselines

The first baseline is the Workload shifting non brownout (WSNB) algorithm [23]. The algorithm works as follows. Initially, the VM is allocated to the nearest DC (aiming to reduce the response time) and to the server that will increase the energy consumption by the least (a server that is already on and its available computational resources are equal to or slightly greater than the requirements of the requested VM). Then, suppose this initial DC does not have available renewable power to execute the VM. In that case, the algorithm will evaluate another DC (the DCs are sorted by available green energy) that matches this demand and does not exceed a threshold for the response time. If another DC is found, the VM will be reallocated to it. The algorithm does not perform server consolidation with live migrations, it tries to use the minimum number of servers during this allocation.

To adapt this baseline for the experiments, the response time restriction was removed from the algorithm, that is, we consider that all the DCs are homogeneous in terms

of latency for the VM request, since the used workloads do not have this data, and this modification does not change the behavior of the algorithm.

The second work used as a baseline is the FollowMe@Source (or FollowMe@S) algorithm [24] that has two variants: i) FollowMe@S Intra, which only performs VM migrations inside the same DC (intra-DC migrations); and ii) FollowMe@S Inter, that only performs VM migrations between different DCs (inter-DC migrations). Both algorithms have the same general steps, described as follows.

The FollowMe@S algorithm has two main steps: allocation and migrations. The allocation step begins by sorting the DCs by the availability of green energy. Then, the algorithm will search for a server that can host the VM, respecting the sorted list of DCs. If no server is found after searching through all DCs, the VM will be processed in the next scheduling round. The process will be executed again for all the other VMs to be scheduled.

In the migration step, either exclusively intra-DC or inter-DC migrations are performed. First, the algorithm obtains a list of all the VMs that are in execution at that instant of time. Then, it evaluates the usage of the servers to identify the underutilized hosts (less than 20% of CPU usage) and marks them to be turned off. The running VMs of these underutilized hosts will be removed using live migrations in order to turn them off and save energy. In the intra-DC case (FollowMe@S Intra), the algorithm will run in each DC separately. For each VM, it will try to find a server with available computational resources to host it, and the migration is performed if a server is found. In the inter-DC case (FollowMe@S Inter), for each VM that can be migrated, the algorithm will evaluate the DCs sorted by the availability of green energy, and migrate the VM to the server of the first DC that can host the VM. One important point to notice is that FollowMe@S does not consider the network when scheduling its migrations.

The following modifications were performed to the algorithm to adapt it for the experiments: i) it is not considered the network costs of a distributed algorithm, since NEMESIS, c-NEMESIS, and WSNB are centralized algorithms; ii) the workload degradation of performance by migrating the VM—for example, migrating to a server with a less efficient CPU—is not modeled as a homogeneous platform is used.

The baselines adopt the “follow-the-renewables” approaches in different ways. The algorithms WSNB and FollowMe@S Intra only use “follow-the-renewables” for the initial scheduling, and the VMs are not migrated to other DCs during their execution. On the other hand, the algorithm FollowMe@S Inter performs VM migrations to other DCs—the same strategy adopted by NEMESIS and c-NEMESIS.

3.4.3 Results

In this section, we present the results of the simulations. First, Section 3.4.3.1 shows an analysis of the accuracy of an essential component of NEMESIS and c-NEMESIS algorithms: the algorithm for the duration of migration (Algorithm 1). Then, Section 3.4.3.2 provides an overview of the live migrations performed. Results from the energy consumption—total and brown—of the multi-cloud platform are shown in Section 3.4.3.3. Finally, Section 3.4.3.4 discusses the impact of live migrations on network congestion and waste of energy.

3.4.3.1. Accuracy of the estimation algorithm

We define an *underestimated migration* as a VM live migration process with a longer duration than estimated. Table 3.1 presents the number of live migrations that were underestimated by NEMESIS and c-NEMESIS, and the percentage value that is based on the total number of migrations (that can be found in Table 3.3). For both workloads, c-NEMESIS presented almost no underestimation for the migrations

compared to NEMESIS. Furthermore, it is interesting to notice that virtually all the intra-DC migrations were underestimated in NEMESIS because they started simultaneously, resulting in network congestion.

Table 3.1. Number of underestimated live migrations and the ratio of the overestimation, where “W” stands for “Workload”, “G” for Google, and “A” for Azure.

Algorithm	W	Inter	Intra
NEMESIS	G	245 (4.4%)	3 393 (95.7%)
c-NEMESIS	G	0 (0%)	61 (2.9%)
NEMESIS	A	140 (3.6%)	3 324 (94.1%)
c-NEMESIS	A	24 (0.1%)	49 (3.8%)

In order to evaluate the estimation algorithm for the duration of the migrations, two metrics are used to assess its accuracy: the Mean Absolute Percentage Error (M.A.P.E.) and the Root Mean Square Error (R.M.S.E.). The M.A.P.E. is defined by: $\frac{1}{n} \sum_{i=1}^n \frac{|R_i - F_i|}{R_i}$, where n represents the amount of values being considered, i the index of the value being considered, R_i the real duration of migration, and F_i the estimated duration. The result of the M.A.P.E. is a percentage value, and it represents the relative value of the estimation errors compared to the original value, thus it is an easy-to-understand metric. The R.M.S.E. is defined by: $\sqrt{\frac{1}{n} \sum_{i=1}^n (R_i - F_i)^2}$. The R.M.S.E. is a metric similar to the standard deviation, and it allows us to validate how far the estimation was from the original value.

Table 3.2. Accuracy measurements, where “W” stands for “Workload”, “G” for Google, and “A” for Azure. The M.A.P.E. value is in percentage (%), and the R.M.S.E. in seconds.

Algorithm	W	M.A.P.E.	R.M.S.E.
NEMESIS	G	32.895	18.56
c-NEMESIS	G	0.70	0.395
NEMESIS	A	34.01	20.03
c-NEMESIS	A	0.649	0.432

Table 3.2 presents the results for the accuracy measurements. It is possible to observe that c-NEMESIS is accurate with low error values. Two points justify the improvement in the precision of the estimation algorithm: i) the new algorithm has full information on the network topology and uses the actual number of links that interconnect the servers involved in the migration process; ii) since it is more

precise, the migration planning results in less network congestion, which affects the duration of the migration.

3.4.3.2. Analysis of the VM live migrations performed

Table 3.3 presents the number of live migrations performed during the simulated week. NEMESIS performed the lowest number of inter-DC migrations for both workloads, since its migration planning does not allow for parallel migrations leaving or arriving at the same DC. The c-NEMESIS algorithm executed more inter-DC migrations than NEMESIS, as it takes into account the network topology and allows for migrations in parallel. c-NEMESIS had the lowest number of intra-DC migrations for two reasons: i) the server consolidation step is only executed for the DCs that do not have inter-DC migrations planned in a time slot; and ii) intra-DC migrations are distributed in time. The FollowME@S algorithm had the highest number of inter- and intra-DC migrations because the planning does not consider network usage.

Table 3.3. Number of VM live migrations performed, where “W” stands for “Workload”, “G” for Google, and “A” for Azure.

Algorithm	W	Inter	Intra
NEMESIS	G	5 617	3 545
c-NEMESIS	G	18 056	2 074
FollowMe@S Intra	G	0	560 862
FollowMe@S Inter	G	96 464	0
NEMESIS	A	3 863	3 532
c-NEMESIS	A	17 479	1 300
FollowMe@S Intra	A	0	177 086
FollowMe@S Inter	A	93 388	0

3.4.3.3. Total and brown energy consumption of the cloud platform

Table 3.4 presents the cloud platform’s total and brown energy consumption for the simulated week. The c-NEMESIS algorithm performed better in terms of brown en-

ergy usage, having the lowest consumption among the other evaluated algorithms—except for NEMESIS using the Azure workload, in which the consumption was the same. Regarding the total energy, c-NEMESIS consumed more than NEMESIS because it performed more migrations. On the other hand, more green energy was harnessed, since the brown energy consumed was the same or lower. Regarding the FollowME@S algorithm, both inter- and intra-DC versions had similar brown energy consumption, but the inter-DC approach had a marginally lower brown energy consumption than the intra-DC (around 0.3% for the Google workload and 0.04% for the Azure workload). The WSNB algorithm had the highest consumption of both total and brown energy.

Table 3.4. Comparison of energy consumption (MWh), where “W” stands for “Workload”, “G” for Google, and “A” for Azure.

Algorithm	W	Total	Brown
NEMESIS	G	25.46	17.23
c-NEMESIS	G	25.56	17.18
FollowMe@S Intra	G	27.56	19.13
FollowMe@S Inter	G	27.59	19.07
WSNB	G	29.49	20.89
NEMESIS	A	30.43	21.21
c-NEMESIS	A	30.55	21.20
FollowMe@S Intra	A	31.69	22.41
FollowMe@S Inter	A	31.69	22.40
WSNB	A	33.56	24.23

The difference between the total and brown energy consumed, and the green energy generated in the simulated week (10.5 MWh) is compared to obtain the green energy usage of the algorithms. For the Google workload, the usage of green energy was: c-NEMESIS = 80%, NEMESIS = 79%, FollowMe@S Intra = 80%, FollowMe@S Inter = 81%, and WSNB = 82%. Regarding the Azure workload, the usage was: c-NEMESIS = 89%, NEMESIS = 88%, FollowMe@S Intra = 89%, FollowMe@S Inter = 89%, and WSNB = 89%.

The scheduling policies and how the algorithms adopt the “follow-the-renewables” strategy justify the difference between total and brown energy consumption, and the

relative value of renewable energy used. The algorithms WSNB and FollowMe@S Intra that presented the highest brown energy consumption applied “follow-the-renewables” at the initial scheduling of the workload and didn’t migrate the VMs in execution to other DCs as the green energy availability changed over time—as done by the algorithms FollowMe@S Inter, NEMESIS and c-NEMESIS. The next section analyzes the live migrations’ impact on total and brown energy consumption to further understand the difference in these results.

3.4.3.4. Wasted resources in the migrations

To evaluate the wastage of resources in terms of network and energy, all the live migrations performed in the algorithms are compared with a perfect scenario: all the migrations are performed individually and isolated, having full access to the network.

Table 3.5 presents statistics about the extra time (in seconds) it took to migrate the VMs in the simulations in comparison with the perfect scenario. The absolute value is the absolute difference in seconds. For example, on average, the live migrations performed by the NEMESIS algorithm were 10.11 seconds longer compared to the perfect scenario for the Google workload. The relative value is the ratio of the difference. For example, in the FollowMe@S Inter with the Google workload, the migration duration was more than ten times longer in comparison with the perfect scenario.

The c-NEMESIS algorithm had the best performance in terms of extra seconds spent migrating for both workloads, with values close to the perfect scenario: the average relative difference (avg. rel.) was approximately 1. The NEMESIS algorithm had good performance as well, with low extra seconds values, and the duration of the migrations was, on average, about 1.5 times longer than in the perfect scenario. The migrations performed by FollowME@S, both intra- and inter-DC cases, had

Table 3.5. Extra seconds during migrations compared to the case when there is no congestion, where “W” stands for “Workload”, “G” for Google and, “A” for Azure. “avg.” for the average of the observations, “max.” for the maximum value, “abs.” for the absolute value, and “rel.” for the relative value.

Algorithm	W	avg. abs.	max. abs.	avg. rel.	max. rel.	Total sec.
NEMESIS	G	10.11	56.98	1.53	3.98	92 915
c-NEMESIS	G	0.22	0.88	1.0	1.05	4 331
FollowMe@S Intra	G	113.94	1 028.51	6.37	40.82	64 525 098
FollowMe@S Inter	G	215.18	4 875.8	10.67	155.5	22 058 949
NEMESIS	A	11.62	62.96	1.59	3.98	86 235
c-NEMESIS	A	0.23	6.14	1.0	1.32	4 224
FollowMe@S Intra	A	91.08	938.48	4.39	25.56	16 384 188
FollowMe@S Inter	A	186.56	8 047.89	7.8	157.24	18 531 893

the worst performance: the duration took, on average, from 4 to 10 times longer than the perfect scenario. These results highlight the importance of considering the network for migration scheduling, since c-NEMESIS and NEMESIS presented the lowest wastage of resources.

Using the extra seconds spent in the migrations, a lower bound for the wasted energy is computed using Algorithm 4 for both the servers that sent the VM (origin)—that represents the brown(er) energy consumption—and the servers that received the VMs (target)—that represents the green(er) energy waste. Table 3.6 presents the results. The algorithm FollowMe@S (both inter- and intra-DC versions) was the one that wasted the most energy. The c-NEMESIS algorithm had the lowest wastage of energy overall, despite performing more migrations than NEMESIS (the second best in wastage of energy).

These results are justified by the fact that wasted energy is directly proportional to the duration of the migrations, thus bad planning will congest the network and, as a consequence, increase the total energy consumption. Finally, it is important to notice that the wasted green energy is not negligible and can be used to power the cloud. For example, in the FollowMe@S intra-DC with the Google workload, the wasted green energy could have powered the Luxembourg DC for approximately 44 hours (at 100% computational performance).

Table 3.6. Wasted energy in the migrations (Wh) in comparison to the perfect scenario where the migration process has full access to the network links. In the table, “W” stands for “Workload”, “G” for Google, and “A” for Azure.

Algorithm	W	Origin	Target
NEMESIS	G	545.1	529.1
c-NEMESIS	G	35.42	24.67
FollowMe@S Intra	G	473 971.6	367 434.6
FollowMe@S Inter	G	153 829.96	125 613.5
NEMESIS	A	539.59	491.06
c-NEMESIS	A	39.31	24.06
FollowMe@S Intra	A	163 128.14	93 298.9
FollowMe@S Inter	A	175 086.3	105 528.8

3.5 Summary

Reducing the environmental impact of the operation of cloud computing platforms, particularly the carbon footprint generated from their gigantic energy consumption, is a complex and challenging problem currently being addressed from multiple angles. In this chapter, we focus on the strategy “follow-the-renewables” and study the indirect impact on energy consumption caused by the additional load generated in the network. The experiments were based on real-world data for the cloud infrastructure, workloads, and photovoltaic power production.

This chapter demonstrates that the indirect network impact on the energy consumption in multi-clouds for “follow-the-renewables” approaches is generated by bad scheduling policies for the migrations, which results in network congestion — as the live migrations compete for the available bandwidth of the network links, affecting not only the applications that are running inside the VMs, but also the duration of the migration process. Given that migrating a VM also consumes energy — proportional to its duration — and that the workload will be sent to the DCs using green(er) energy (“follow-the-renewables”), the extra energy consumption is in reality wasted energy that could be used to power the cloud platform. Furthermore, the adoption of the “follow-the-renewables” strategy needs to consider the whole execution of the workload: the state-of-the-art algorithms that only used the green energy informa-

tion for the initial scheduling and didn't migrate the workload as the availability of renewable energy changed had the highest brown energy consumption.

The proposed estimation algorithm for the duration of the live migrations that uses as input information about the communication network of the data centers (network link latency, bandwidth and topology) is accurate. By using this estimation algorithm and using as input the network characteristics of the cloud, the migration planning of c-NEMESIS was able to increase the number of migrations by at least 3-fold without network congestion, while maintaining or reducing the brown energy consumption in comparison to other state-of-the-art works.

Sizing the renewable infrastructure of cloud data centers

4.1 Introduction

In the previous chapter, we saw the adoption of the carbon-aware technique follow-the-renewables applied to a multi-cloud distributed over a country and its drawbacks, such as network congestion and extra energy consumption, if not used properly. Now, the reader is introduced to a carbon-responsive strategy that can be combined with follow-the-renewables in our quest to reduce the carbon footprint of operating cloud federations: sizing (or dimensioning) the renewable infrastructure. This strategy consists of defining how much investment needs to be made, for example, by defining the area of solar panels (when considering solar power), the number of wind turbines, and the capacity of the energy storage devices (such as lithium-ion batteries) that need to be manufactured.

The scenario considered has some differences to better represent modern cloud providers. First, it is considered that the DCs are geographically distributed worldwide, representing real cloud providers such as Google and Microsoft (as seen in Figure 2.1). Many reasons justify the need for geographically distributed DCs: i) meet the demand for the ever-increasing number of users; ii) redundancy, for example, if there is a problem in some region, the workload can be shifted to another location; iii) reduce the latency or response time for the users. This geographic distribution also allows for a better harvest of renewable sources, since there are

more variable climate conditions, solar irradiation levels are different between the countries, as are the speed and frequency of the wind. Second, many locations in the world have the presence of low-carbon-intensive sources in their local electricity grid, therefore in reality, there is not only a green and brown classification (as seen in the previous chapter). The classification into brown and green made sense in the previous scenario since it was considered only a single country, and renewable energy was less carbon-intensive than the local electricity grid. Finally, energy storage devices can be used to store the overproduction of renewable energy and use it when opportune.

One point that cannot be neglected is that manufacturing renewable infrastructure also presents an environmental impact: batteries have an ideal level of charge that can improve their lifetime, which can reduce the replacement frequency, but on the other hand, it causes them to be oversized [48], and their recycling rates still need to improve [49]; and considering the current state-of-the-art PVs, if they produce 40% of the global electricity by 2050, they will consume about 5% of today's CO₂ budget [50].

In this chapter, we explore the adoption of both strategies, sizing the PVs and batteries and scheduling with follow-the-renewables to reduce the carbon footprint of operating existing cloud platforms. More specifically, this chapter presents the following contributions:

- the two subproblems—PVs and batteries sizing, and workload scheduling—are modeled as a single problem, which allows evaluating scenarios such as: should the battery capacity or the PV area be increased, or should the workload be scheduled in a data center located in another part of the world?
- we propose a model that uses a linear programming approach (LP) with real variables, allowing us to optimally solve the problem we address in polynomial time using classical LP solvers. This allows a large number of

scenarios to be evaluated over broad time horizons (i.e., one year) to take the seasonal behavior of renewable energy production into account. This model can be extended to multiple scenarios, and it may help decision-makers evaluate which regions need more investment to reduce the cloud operation's environmental impact.

The work of this chapter was done in collaboration with the following members of the DATAZERO[35] research team: Georges Da Costa, Jean-Marc Nicod and Veronika Rehn-Sonigo, and it resulted in the following publication: **Miguel Felipe Silva Vasconcelos**, Daniel Cordeiro, Georges Da Costa, Fanny Dufossé, Jean-Marc Nicod, and Veronika Rehn-Sonigo. “Optimal sizing of a globally distributed low carbon cloud federation”. In *2023 IEEE/ACM 23rd International Symposium on Cluster, Cloud and Internet Computing (CCGrid), Bangalore, India, 2023*, pp. 203-215. The text of the present chapter is an adaptation of this publication.

The remainder of the chapter is organized as follows: Section 4.2 defines the problem addressed, the assumptions, the models, and the objective function. Details about the problem constraints and how to optimally solve the problem are given in Section 4.3. The experiments are presented in Section 4.4, and their results are discussed in Section 4.5. Finally, Section 4.6 concludes the chapter.

4.2 Problem statement

This section describes the problem addressed and the hypothesis. The following two sections further detail the modeling, notations, and optimal approach to solving the decision problem we investigate in this chapter.

4.2.1 Addressed problem

As mentioned earlier, the goal is to reduce the carbon footprint of an existing cloud platform, both in its operation and sizing the renewable infrastructure. The cloud platform consists of several data centers spread worldwide, in both hemispheres and on all continents. The proposed solution aims to design an additional solar-based power supply infrastructure to the classical power grid connection and to define an optimal way to operate the global IT cloud platform by scheduling its workload. To green the cloud infrastructure and reduce its carbon footprint, we must reduce the use of high-carbon-intensive energy to operate the data centers. Using renewable energy is a promising option. However, the carbon footprint of manufacturing needs to be taken into account.

Another problem is that the location where the DC is installed determines how sustainable it can be. First, the carbon intensity of the energy consumed from the local electricity grid depends on how it is produced: natural gas, coal combustion, hydraulic or nuclear energy. Second, each location has different climate conditions, and renewable power production will also have different efficiency. For example, solar power will be higher in locations that receive more solar irradiation, depending on whether the location is near or far from the tropics. Therefore, powering the cloud federation is a balance or mix between using low-carbon electricity from the local grid and using its solar panels, with the understanding that batteries are mandatory to mitigate intrinsic solar power intermittency.

The current decision problem aims to define an additional renewable power supply architecture from solar energy to reduce the carbon footprint of the global cloud infrastructure. It is assumed that: i) the data centers are already in operation, and the sizing will only define the area of PV panels and the capacity of the batteries; ii) the DCs can be supplied from the power of the local electricity grid, power from the PV panels or power stored in the batteries; iii) task submission is centralized; iv)

100% of the tasks must be completed in time (no delay); v) no migration of tasks; vi) tasks can be executed in any of the data centers; vii) cloud platform is homogeneous regarding the IT part (number and hardware characteristics of servers, CPU cores, and network equipment), but the total power consumption of the DCs is different because of the power used for cooling the DCs at each geographic location. Finally, the following inputs are considered:

- specifications of the cloud infrastructure:
 - number of servers, CPU cores per server, network switches;
 - power consumption of the servers (static and dynamic) and network equipment;
 - Power Usage Effectiveness (PUE) to represent cooling needs;
- specifications of the renewable infrastructure:
 - manufacturing carbon footprint;
 - technical parameters: batteries charge/discharge ratio and Max Depth of Discharge, PV efficiency to convert solar irradiation to power;
- weather conditions (solar irradiation) in areas where each data center operates for the federation (time series of 1 year with one value for every hour);
- carbon intensity of the local electricity grid in g CO₂-eq per kWh for each DC;
- the workload computing demand from clients (time series of 1 year with one value for every hour).

The decision not to include migration of the workload between the data centers might seem counter-intuitive to the reader, considering that in Chapter 3 we saw that migrating the workload as the availability of green power changes over time can significantly contribute to reducing the carbon emissions of the cloud operation. The justification for this decision is that when considering geographically distributed data

centers worldwide, there is another challenge: the high latency between the network links that interconnect these DCs. Therefore, for our initial modeling, we decided not to include the migrations because, as we saw in the previous chapter, bad planning generates network congestion and wastes low-carbon-intensive energy.

Now, the models and notations are introduced before the objective function to optimize.

4.2.2 Models and notations

In this section, we introduce how we modeled the optimization problem of reducing the carbon footprint of operating a cloud federation. The IT model is presented in Section 4.2.2.1, and it includes the cloud infrastructure in terms of the set of data centers, the computational capacity of the DCs (number of servers and CPU cores); and the DCs power consumption that originates from the servers (both when idle and when performing computations), network equipment and cooling needs. Section 4.2.2.2 shows how we modeled the workload in terms of the properties of the computational tasks—such as the computational resources requirement—that will be executed. The electrical model is described in Section 4.2.2.3, and it includes the power supply from the regular electrical grid, the power generation from the on-site renewable source, as well as the usage of the batteries. Finally, Section 4.2.2.4 presents how we modeled the carbon footprint, which originates from consuming power from the grid and manufacturing the renewable infrastructure.

4.2.2.1. IT model

Let \mathcal{H} be the decision horizon where task scheduling decisions can be taken. To do so, we propose discretizing \mathcal{H} into K indivisible time slots with a duration of Δt such that $\mathcal{H} = K \times \Delta t$. To simplify the notations, we consider $\Delta t = 1u.t.$ (unit of time). In our experiments, we will assume that $\Delta t = 1h$ such that $K = 8760h$

Table 4.1. Main notations for the IT model for each DC^d ($1 \leq d \leq D$) during time slot k ($0 \leq k < K$)

Δt	time slot's time duration in the unit of time [<i>u.t.</i>]
\mathcal{H}	decision horizon $\mathcal{H} = K\Delta t$
K	number of time slots $\Delta t = 1 \text{ h} = 1 \text{ u.t.}$
k	time slot between dates $k\Delta t$ and $(k+1)\Delta t$ excluded
DC^d	a specific data center d of the cloud federation
\mathcal{DC}	the set of all data centers $\{DC^d \mid d = 1, \dots, D\}$
C^d	number of CPU cores within DC^d
P_{core}	dynamic power consumption of one CPU core at 100% of utilization
P_{idle}^d	static power consumption of all the servers of DC^d
$P_{intranet}^d$	power consumption of network devices of the DC^d
P_k^d	the power demand to perform tasks on DC^d during time slot k
PUE^d	Power Usage Effectiveness of the data center d

with $\mathcal{H} = 1$ year. Let k be the time slot index that addresses any instant t such that $k\Delta t \leq t < (k+1)\Delta t$ with $0 \leq k < K$.

Let $\mathcal{DC} = \{DC^d \mid d = 1, \dots, D\}$ be the set of data centers in the cloud federation. Considering a given data center DC^d , let C^d be its number of CPU cores and P_{core} the energy used to power one core.

The power consumption of a cloud data center can be classified as static or dynamic [51]. For the static part, the current model considers the idle power consumption P_{idle}^d of the servers, the Power Usage Effectiveness (PUE) to represent the power consumption used to cool the DC infrastructure, and the power consumption of the network switches $P_{intranet}^d$ that interconnect the servers in each data center DC^d . Regarding the latter, cloud data centers usually adopt the fat-tree topology to interconnect servers in the DC [51]. In this topology, one can compute the number of network switches needed to match the number of servers. The power consumption of the network switches is considered to be static based on actual measurements, which have shown that the consumption does not change significantly with device us-

Table 4.2. Main notations for the Workload model for each DC^d ($1 \leq d \leq D$) during time slot k ($0 \leq k < K$)

\mathcal{T}	the workload to execute ($= \{T_i \mid 1 \leq i \leq N\}$)
T_i	task i of the workload \mathcal{T} ($1 \leq i \leq N$)
r_i	release date of tasks T_i
p_i	processing time of tasks T_i
c_i	number of CPU cores needed to execute task T_i
w_k	number of required CPU cores to execute all the tasks during the k th time slot
w_k^d	number of CPU cores needed to execute all the tasks during the k th time slot on DC^d

age [52]. Moreover, each geographic location has different cooling needs, therefore each DC has a specific PUE^d value.

Finally, the dynamic part of the power consumption is represented by the additional power demand generated by using the CPU cores in each data center to execute the workload that requires w_k^d CPU cores assigned to the DC d at time slot k . Equation (4.1) represents the power consumption of each DC for each step k ($0 \leq k < K$). Table 4.1 summarizes the main notations of the IT model.

$$P_k^d = PUE^d \times (P_{idle}^d + P_{intranet}^d + P_{core} \times w_k^d) \quad (4.1)$$

4.2.2.2. Workload model

Considering the workload that needs to be executed, let $\mathcal{T} = \{T_i \mid i = 1, \dots, N\}$ be the set of N tasks that have to be finished in time during the time horizon \mathcal{H} . Each task T_i has the following properties: i) release date r_i ; ii) processing time p_i ; and iii) it needs c_i CPU cores at 100% of usage to be executed. Let w_k be the total number of CPU cores needed to compute tasks during the time slot k in order to complete the workload in time. At each time step, w_k is the sum of all cores required by the tasks executed in time slot k , and given that the tasks will be scheduled to the DCs,

Table 4.3. Main notations for the Electrical model of each DC^d ($1 \leq d \leq D$) during each time step k ($0 \leq k < K$)

I_k^d	solar irradiation at time slot k [Wh/m^2]
$Appv^d$	surface area of photovoltaic panels of DC DC^d [m^2]
η_{pv}	PV efficiency (in %) in converting solar irradiation to power
$Pgrid_k^d$	power consumed from the grid at time slot k [W]
Pre_k^d	power generated from the PVs during the time slot k [W]
BAT^d	battery capacity installed in DC^d [Wh]
B_k^d	battery level of energy at the time $k \times \Delta t$ [Wh]
Pch_k^d	power charged in the batteries during the time slot k [W]
$Pdch_k^d$	power discharged from the batteries during the time slot k [W]
η_{ch}	efficiency of the charging process
η_{dch}	efficiency of the discharging process

w_k^d is the sum of the number of cores used to execute the allocated workload in DC (with $1 \leq d \leq D$) and $0 \leq k < K$) as shown by Equation (4.2). Table 4.2 summarizes the notations of the workload model.

$$w_k = \sum_{T_i | r_i \leq k\Delta t < r_i + p_i} c_i = \sum_d w_k^d \quad (4.2)$$

4.2.2.3. Electrical model

The power supply of the whole cloud platform DC has three sources: i) the renewable energy generated by the solar panels (PVs) installed on each DC^d site; ii) the classical electrical grid $Pgrid_k^d$ of each country on which $DC^d \in \mathcal{D}$ is hosted—used as backup when the power from the renewable infrastructure is not enough; and iii) energy discharged from the energy storage devices. The storage devices are mandatory to mitigate the intermittency of solar power by storing the overproduction when the sun shines to provide energy during the night when the solar panels do not produce power. Lithium-Ion batteries have been chosen to play this role because of their good efficiency in terms of costs, power and energy density, charge and discharge rates,

and self-discharge [10]. To model the fact that the cloud platform will not sell back energy to the grid, there is the constraint that the power from the grid ($P_{grid_k^d}$) is always positive. Table 4.4 summarizes the main notations of the electrical model.

Equation (4.3) models the on-site renewable power production, it depends on the solar irradiation I_k^d received at the location of DC^d during the time slot k , on the surface area of the solar panels Apv^d and on the efficiency η_{pv} of the PVs.

$$Pre_k^d = I_k^d \times Apv^d \times \eta_{pv} \quad (4.3)$$

Batteries are systematically installed next to the PVs for the reasons mentioned above. Let B_k^d be the battery level of energy, that is, the amount of energy (in Wh) at time $k \times \Delta t$ —the instant of time at the beginning of the time slot k —stored in batteries of capacity BAT^d installed in DC^d ($B_0^d = B_{init}^d$ being the amount of energy at the beginning the time horizon \mathcal{H}). The variable Pch_k^d represents the power charged in the batteries of DC d during the time slot k (and $Pdch_k^d$ is the power discharged from the batteries). It is not possible to charge and discharge simultaneously: if Pch_k^d is greater than zero, $Pdch_k^d$ equals zero and vice versa. Regarding the battery modeling, the charging and discharging processes have an efficiency η_{ch} and η_{dch} less than 1. Lithium-Ion batteries have a low value for daily self-discharge (0.5 % per day) [10], thus this property was not modeled. Finally, to increase the battery's lifetime, it cannot be discharged more than its Maximum Depth of Discharge.

Equation (4.4) models the battery in terms of the level of energy:

$$B_k^d = B_{k-1}^d + Pch_{k-1}^d \times \eta_{ch} \times \Delta t - \frac{Pdch_{k-1}^d}{\eta_{dch}} \times \Delta t \quad (4.4)$$

with $0.2 \times BAT^d \leq B_k^d \leq 0.8 \times BAT^d$ for any time slot k and DC^d ($0 \leq k < K$ and $1 \leq d \leq D$)—this last restriction models the Max Depth of Discharge property to

increase the battery lifespan. The modeling of the batteries and PVs is based on the work from Haddad et al. [53].

4.2.2.4. Carbon footprint model

In the current model, carbon emissions from operating the cloud platform originate from three sources: (i) consuming power from the regular electrical grid and manufacturing both (ii) the photovoltaic panels and (iii) the batteries. Equation (4.5) models the carbon footprint of the regular local electrical grid, defined by the carbon intensity of the power grid $gridCO2^d$ in the region of the data center DC^d times the amount of energy used during the time slot k .

$$FPgrid_k^d = Pgrid_k^d \times \Delta t \times gridCO2^d \quad (4.5)$$

It is considered that the power from the local electricity grid may originate from multiple sources, and the $gridCO2^d$ is an input that represents its average carbon intensity during the year: the value will be low if it is supplied by solar, wind, hydroelectric or nuclear power. On the other hand, the value will be higher if it is supplied by coal, oil, biomass, or natural gas.

For the carbon footprint of the PVs, to account for the different climate conditions in each region, in particular the solar irradiation received, one must also consider the expected power output that PVs can produce over their lifetime, as using a single year may cause over- or under-sizing of the PV infrastructure. Therefore, the carbon footprint of PVs is also related to the location of each data center. Equation (4.6) models the carbon footprint for PVs:

$$pvCO2^d = \frac{FPpv_{1m2}}{expectedE_{pv}^d} \quad (4.6)$$

where $FPpv_{1m^2}$ is the emissions of manufacturing $1 m^2$ PV in $g CO_2\text{-eq}$, and $expectedE_{pv}^d$ is the expected energy production in kWh that $1 m^2$ of the PV during its lifetime at the location of DC^d . As a result, the unit of this metric is expressed in $g CO_2\text{-eq}/kWh$, and so, the total emissions from the PVs are related to their power production, as shown in Equation (4.7).

$$FPpv_k^d = pvCO2^d \times Pre_k^d \times \Delta t \quad (4.7)$$

Regarding the batteries' carbon footprint $FPbat^d$ of the DC^d , it is computed based on their capacity BAT^d (kWh) and the carbon emissions of the manufacturing process $batCO2$ in $g CO_2\text{-eq}$, as seen in Equation (4.8). To be consistent with the calculation of $FPpv_k^d$, $batCO2$ is the share of the carbon footprint of the battery type chosen for a capacity of $1 kWh$ over the time horizon of \mathcal{H} , assuming a battery has a lifetime of 10 years. Thus, given that we are considering one year of cloud operation, $batCO2$ is the tenth of the total carbon footprint of the considered battery. It is considered that the battery carbon footprint is homogeneous for all the locations, as the climate conditions do not influence it.

$$FPbat^d = BAT^d \times batCO2 \quad (4.8)$$

These modifications regarding the lifetime of PVs and batteries were necessary because we are considering only one year of cloud operation. Suppose we use the total carbon emissions for manufacturing the PVs (lifetime of 30 years) and batteries (lifetime of 10 years) in our scenario of one year of operation. In that case, the solver will find a solution where there is little to no PV or batteries because using the regular electrical grid would be less carbon-intensive.

Table 4.4. Main notations for the carbon footprint model of each DC^d ($1 \leq d \leq D$) during each time step k ($0 \leq k < K$)

$gridCO_2^d$	Carbon intensity of the electricity grid in the region of the DC d (in grams of CO ₂ -eq per kWh)
$FPgrid_k^d$	Carbon emissions (in grams of CO ₂ -eq) of consuming $Pgrid_k^d \times \Delta t$ kWh from the local electricity grid of the DC d
$FPpv_{1m^2}$	Carbon emissions (in grams of CO ₂ -eq) of manufacturing 1 m^2 solar panel
$expectedE_{pv}^d$	Expected energy production that 1 m^2 solar panel will produce during its lifetime at the location of DC d
$pvCO_2^d$	Carbon intensity of producing power at the location of DC d (in grams of CO ₂ -eq per kWh)
$FPpv_k^d$	Carbon emissions (in grams of CO ₂ -eq) of generating $Pre_k^d \times \Delta t$ kWh from the solar panels at the DC d
$batCO_2$	Carbon emissions (in grams of CO ₂ -eq) of manufacturing a battery with 1 kWh capacity
$FPbat^d$	Carbon emissions (in grams of CO ₂ -eq) of manufacturing a battery with capacity of Bat^d

4.2.3 Objective function

Now that the reader has been introduced to the modeling of the problem, the objective function can be defined (see Equation (4.9)). It consists of minimizing the carbon footprint of the globally distributed cloud federation to reduce as much as possible the carbon emissions, which come from both the consumption of electricity from the power grid, and from the manufacturing of photovoltaic panels and batteries, with k and d defined as follows: $0 \leq k < K$ and $1 \leq d \leq D$.

$$\text{minimize } \sum_{k=0}^{K-1} \sum_{d=1}^D (FPgrid_k^d + FPpv_k^d) + \sum_{d=1}^D FPbat^d \quad (4.9)$$

4.3 Optimal resolution

In this section, we show that linear expressions can be used to express the constraints governing the operation of a globally distributed cloud platform. This is a mandatory step, since all the models presented in the previous section are linear equations.

New real variables and constraints are introduced to finish building the linear program that needs to be solved to achieve the targeted objective (see Equation (4.9)). The solution obtained after solving the linear program is optimal in nature and computed in polynomial time, as the model uses only real variables. Polynomial time is mandatory if we consider the number of variables needed for a time horizon \mathcal{H} as long as one year (with time slots of 1 hour).

We assume real positive values for all variables, even if variables denote discrete objects like cores. Indeed, w_k^d is the number of cores needed to run tasks on DC^d during time slot k . Considering the size of modern cloud data centers with thousands of servers and millions of cores, the decimal part of each w_k^d can be neglected. Having the solution with more or less than a core on a given DC keeps the order of magnitude for the PV and battery sizing process the same. Finally, some constraints are explicit, and others are implicit to avoid the addition of integer variables, which would transform this LP into a MILP whose solving process would not scale at all.

4.3.1 Constraints to address the workload

The workload to be executed must respect each data center's computational capabilities C^d (number of available CPU cores). Equation (4.10) expresses that the number of cores that will be allocated to execute the tasks of the workload (w_k^d) does not exceed the existing number of cores of DC^d :

$$w_k^d \leq C^d \quad (4.10)$$

4.3.2 Constraints to reach the power demand

The electric part of each DC has to supply the DC power demand using local renewable energy from its PV panels (Pre_k^d), from batteries ($Pdch_k^d$ and Pch_k^d) and/or from the classical electrical grid ($Pgrid_k^d$). Equation (4.11) presents the restriction for the power consumption.

$$P_k^d \leq Pre_k^d + Pgrid_k^d + Pdch_k^d - Pch_k^d \quad (4.11)$$

4.3.3 Constraints on batteries

The batteries are defined by their capacity (BAT^d in kWh), and each data center can have a different size of batteries depending on how the intermittency of the renewable energies is managed on each site. For example, if the local electricity grid is high-carbon intensive, the battery will need a higher capacity in order to store solar power during the day and use it at night, otherwise if the local electricity grid has the presence of low-carbon intensive sources, the battery will have a smaller capacity. Equation (4.12) models the Max Depth of Discharge property, that is, the range that the battery needs to operate in order to increase its lifetime. In addition, the power to charge or discharge a battery is also limited by the level of energy remaining in the associated battery, so it is not possible to reach a forbidden energy level. Equations (4.13) and (4.14) express these constraints.

$$0.2 \times BAT^d \leq B_k^d \leq 0.8 \times BAT^d \quad (4.12)$$

$$Pch_k^d \times \Delta t \times \eta_{ch} \leq 0.8 \times BAT^d - B_{k-1}^d \quad (4.13)$$

$$Pdch_k^d \times \Delta t / \eta_{dch} \leq B_{k-1}^d - 0.2 \times BAT^d \quad (4.14)$$

The reader may notice the absence of restrictions for charging and discharging simultaneously in the modeling. Such restrictions would impose the use of binary variables, which would significantly increase the required computational time to find the optimal solution to the problem. We performed experiments with a shorter duration (around one month), and the sizing results were the same between both versions: using and not using binary variables. Furthermore, given a solution for the linear program, it is possible to calculate an alternative optimal solution to the LP where there would be no charge and discharge at the same time slot and with the same sizing results—the differences between the solutions would be the values of the variables Pch_k^d and $Pdch_k^d$.

4.3.4 Linear program

The following linear program (LP) summarizes what has been described in the current section concerning the model to solve the problem explored. After solving the LP, the values of the variables are used to define both the renewable power supply part completely—variables BAT^d for the battery capacity and Apv^d for the area of the solar panels at each DC^d —and the core operating process of the distributed low carbon cloud federation with details of the way each DC is used time slot by time slot for one year on the considered weather conditions—variables w_k^d that represents the workload scheduled and Pch_k^d (and $Pdch_k^d$) for the power charged into (and discharged from) the batteries of each DC^d at each time slot k . Comprehensive experiments have been conducted to highlight the pertinence of the approach. These experiments are shown in the next section, and a discussion is proposed in Section 4.5.

$$(LP) \left\{ \begin{array}{l} \text{minimize } \sum_{k=0}^{K-1} \sum_{d=1}^D (FPgrid_k^d + FPpv_k^d) + \sum_{d=1}^D FPbat^d \\ \text{s.t. } \quad (4.1) (4.3) (4.4) (4.5) (4.7) (4.8) (4.10) (4.11) (4.12) (4.13) (4.14) \end{array} \right.$$

where all variables are positive real variables.

4.4 Experiments

In this section, we present the experiments' settings and results. More details for reproducing the experiments can be found in the publicly available software artifact [54].

4.4.1 Settings

4.4.1.1. Cloud infrastructure

The servers are homogeneous and based on equipment from real cloud infrastructure: the Taurus server of the Grid'5000 testbed¹. The servers are equipped with two Intel Xeon E2630 CPUs, for a total of 12 CPU cores. For modeling the power consumption of the servers, values from real measurements conducted in the study from Ahvar et al. [51] were considered: in the idle state, each server consumes 97 W, and their maximum power consumption (when using 100% of the 12 cores) is 220 W. The value of Pcore is 10.25 W, and it was obtained by linear interpolation between the power consumption of the idle and the fully used states.

¹Taurus server of the Grid'5000: <https://www.grid5000.fr/w/Lyon:Hardware#taurus>. Accessed on October 20, 2023

Each data center is equipped with 23,200 servers (and a total of 278,400 cores). This number represents what can be seen in the production data centers of major cloud players: Microsoft operates over 4 million servers distributed over 200 DCs [15]. The total power consumption from the servers of each data center when idle is 2.25 MW, and their maximum power consumption is 5.1 MW.

For the current experiments, we considered a network with a 48-ary fat-tree topology for the interconnection of the servers inside the DCs, that is, the network switches have 48 ports, and the total number of switches is 2,880. The power consumption of the switches was based on real measurements by Hlavacs et al. [52]: the HP ProCurve 2810-48G was selected, with 48 ports and approximately 52W per device. In total, the network equipment power consumption is 149.76 kW for each DC.

The locations of the data centers were based on the real cloud infrastructure of Microsoft Azure², and different regions in different continents, hemispheres, and time zones were selected. Figure 4.1 presents the details of the locations.

In order to represent the fact that each geographic region has different cooling needs, we used values for the PUE inspired by real data from Microsoft Azure for each site: for the Americas, the PUE is 1.17 (DCs São Paulo and Virginia), Asia Pacific has a PUE of 1.405 (DCs Pune, Canberra, Singapore, and Seoul), and for the Europe region, Middle East, and Africa, the PUE is 1.185 (DCs Johannesburg, Dubai, and Paris) [55].

4.4.1.2. Workload

The workload used was created using the Grog generator³, a workload generator tool based on analysis of properties of the execution trace made available by Google in 2011 [56]. For reproducibility purposes, the parameters regarding the number of

²Azure global infrastructure: <https://infrastructuremap.microsoft.com/>. Accessed on October 20, 2023.

³Grog generator: <https://pypi.org/project/grog/>. Accessed on October 20, 2023.

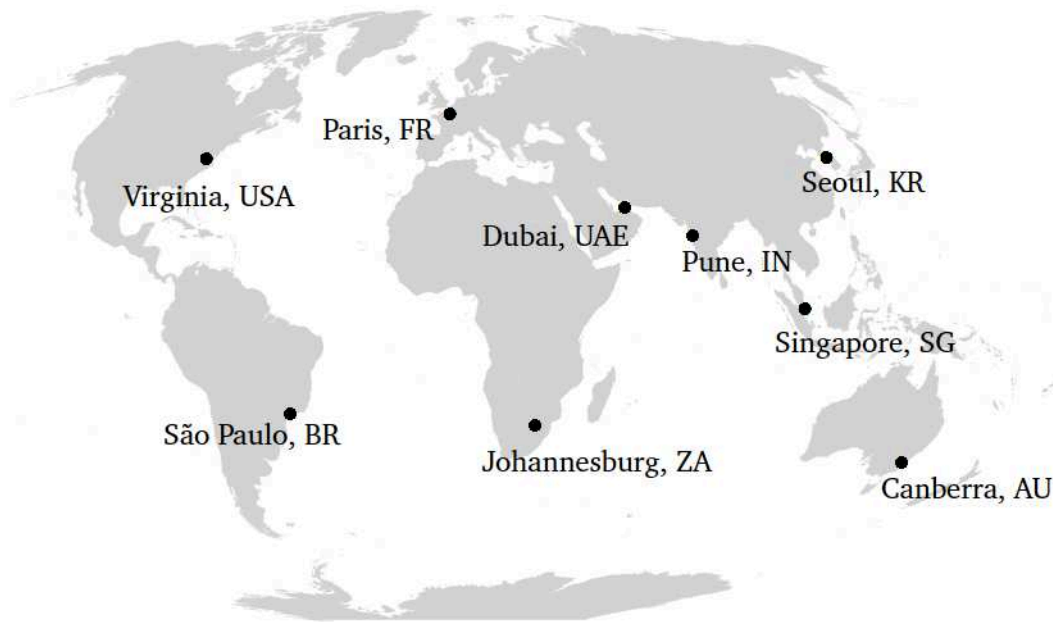


Figure 4.1. Selected locations for the data centers.

tasks were set to 350,000, and the duration was 30 days. The workload generator was run 12 times—1 per month. Finally, the tasks have a duration of one hour.

4.4.1.3. Photovoltaic power production

The data for simulating the solar power production—Global Solar Horizontal Irradiation (in Wh/m^2)—was collected from the MERRA-2 project [57], since it provides information for anywhere on earth. Figure 4.2 illustrates the average solar irradiation of each location throughout the year 2021.

4.4.1.4. Carbon footprint

For PV panels, it is considered a lifetime of 30 years, and manufacturing 1 m^2 emits 250 kg of $\text{CO}_2\text{-eq}$, inspired by real measurements [58]. To compute the emissions in

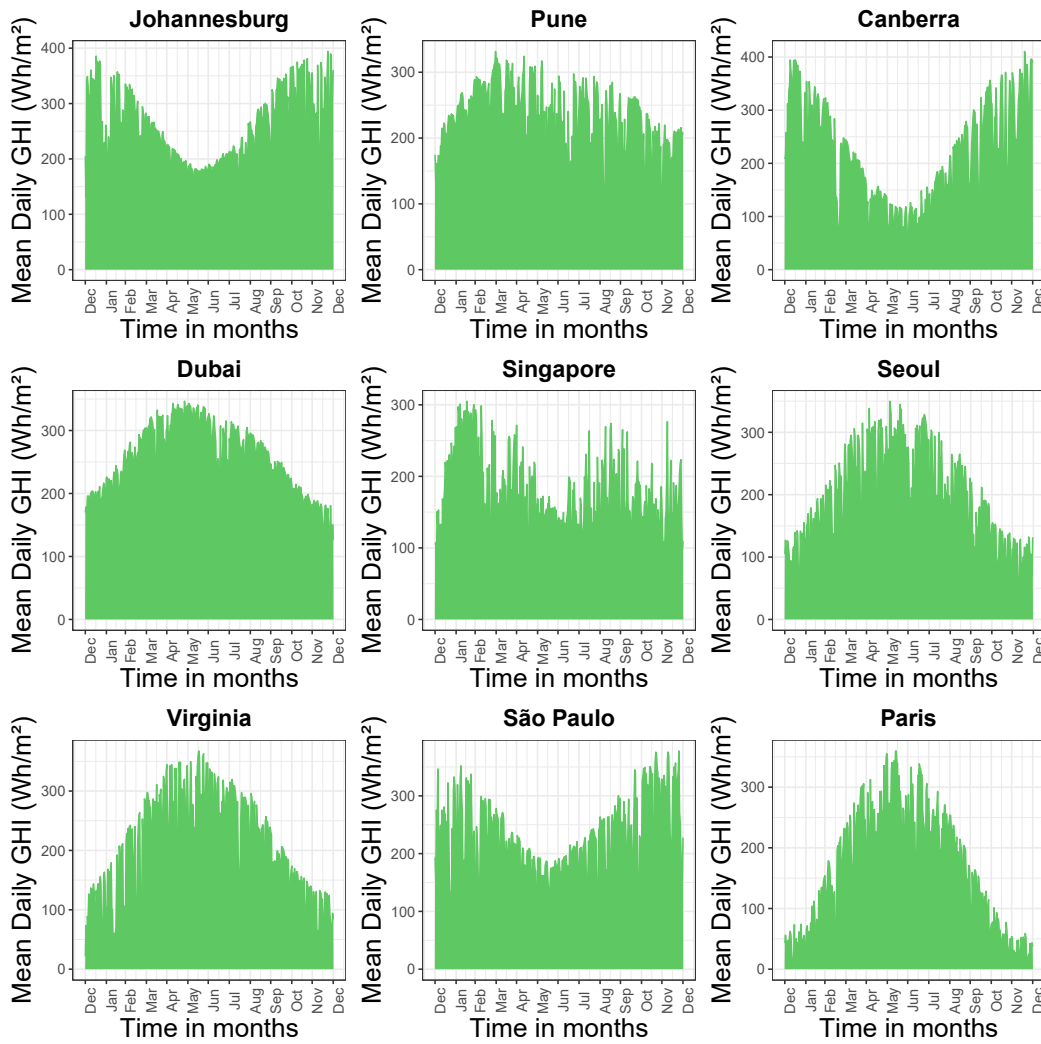


Figure 4.2. Average daily solar irradiation per location throughout the year 2021.

the form of $gCO_2\text{-eq}/kWh$ as stated in Section 4.2.2.4, we considered the total solar irradiation that was produced during the year 2021 multiplied by 30 (to account for the PV module lifetime of 30 years). For the electrical grid, we also considered the real-world data of the carbon footprint ($gCO_2\text{-eq}/kWh$). Table 4.5 lists the carbon emission values for each region.

Regarding the batteries, the emissions are only considered for the manufacturing step— 59 kg of $CO_2\text{-eq}$ per kWh and are the same for all the DCs locations. In our experiments, the considered lifetime of the batteries was ten years. Therefore, the input used is equal to 5.9 kg of $CO_2\text{-eq}$ per kWh, given that we simulated one year.

Table 4.5. Emissions (in $g\text{CO}_2\text{-eq}/kWh$) for both PV usage and using the regular grid. Source for grid emissions: electricityMap, climate-transparency.org.

Location	Grid	PV
Johannesburg	900.6	24.90
Pune	702.8	27.96
Canberra	667.0	29.71
Dubai	530.0	24.84
Singapore	495.0	36.19
Seoul	415.6	34.00
Virginia	342.8	31.71
São Paulo	61.7	27.99
Paris	52.6	39.93

4.4.1.5. Execution environment

The experiments were executed on a machine with the following configurations: an Intel i9-11950H CPU, and 32 GB of RAM. The solver program used for solving the LP was the Gurobi Optimizer (version 9.5.2). The execution time for solving the LP with the inputs listed in the previous sections—which resulted in a total of 394,263 variables—was on the order of 30 seconds.

4.4.2 Results

In this section, we present the results in terms of the computed optimal area of the PVs and capacity of the batteries, the origin of energy used to supply the DCs operation (from the electrical grid, batteries, or PV panels), and the total emissions of the cloud operation, generated from both manufacturing PVs and batteries, and power consumption of the regular electrical grid. Furthermore, to assess the solution computed by the LP, we compare it with two other scenarios: i) DCs can only be supplied using power from the regular electrical grid—representing most of the DCs in operation, and ii) only power generated from the PV panels, and stored and discharged from the batteries is used to supply the DCs—represent green DCs that

are fully autonomous from the power grid. Finally, we present an evaluation using metrics to assess the environmental impact of the results.

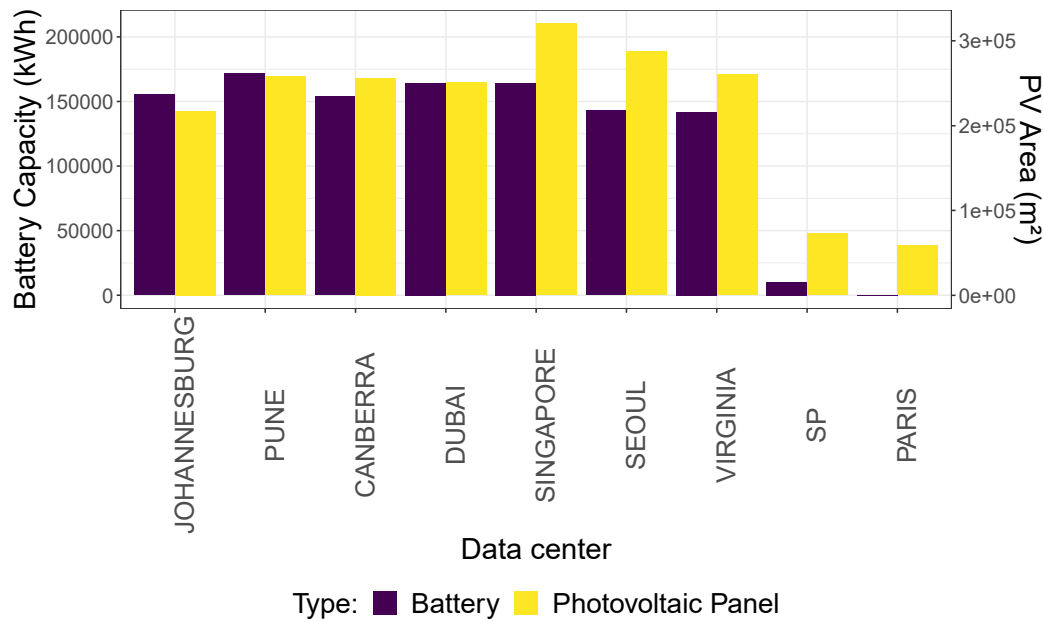


Figure 4.3. Optimal result for the area of PV panels and capacity of the batteries.

Figure 4.3 illustrates the optimal area of the photovoltaic panels and the capacity of the batteries computed from the LP using the inputs described in Section 4.4.

To analyze the sources of energy that supplied the DCs operation, we present in Figure 4.4 the percentage that each source (grid, renewable, and batteries) was used to daily supply the DCs throughout the year. Figure 4.5 is a fine-grain visualization of the DC operation regarding the power consumed or produced for one day (January 1st, 2021): it illustrates hour-by-hour the DC total power demand, how much power was consumed from the grid, discharged from the batteries, and produced by the PV panels.

Table 4.6 presents the total CO₂ emissions of the cloud operation using our approach and the two other scenarios—only using the on-site renewable infrastructure and exclusively using power from the grid. In comparison with the first scenario (only grid power), the reduction in the CO₂ emissions was approximately 85%, and it was approximately 30% for the second scenario (only renewable power).

Table 4.6. Total emissions for the different scenarios.

Scenarios	Emissions (t CO ₂ -eq)
Electrical grid	201 211.3
PV and batteries	42 370.6
PV, batteries, and grid	29 600.6

To further evaluate these scenarios, we present in Table 4.7 results in terms of the average load each DC executed throughout the year (Data Center Utilization metric), and Equation (4.15) represents how this metric was computed for each DC d . One may notice that the Johannesburg DC received no load in the scenario where only grid power is used. This is justified by two reasons: i) there is no restriction to the amount of workload the data centers need to receive in our initial modeling; and ii) Johannesburg has the most carbon-intensive electrical grid, so the LP decided to use all the DCs in all the other locations to minimize the carbon footprint of the global cloud operation.

$$DCU = \frac{\sum_k w_k^d}{C^d \times K} \quad (4.15)$$

Table 4.7. Average DC load throughout the year

Location	Grid	PV + Bat	PV + Bat + Grid
Johannesburg	0	79.31	86.20
Pune	10.25	82.07	89.34
Canberra	99.72	66.62	67.95
Dubai	99.97	93.93	95.11
Singapore	99.93	72.6	85.18
Seoul	99.99	81.87	65.39
Virginia	100.0	88.54	75.51
São Paulo	100.0	63.67	59.06
Paris	100.0	81.24	86.11

To analyze the environmental impact of the solution, we used metrics inspired by the work from Reddy et al. [59], which proposed a taxonomy of metrics for evaluating sustainable data centers. The first metric, the Green Energy Coefficient (or GEC), is the ratio between the total renewable energy generated and the DC

total energy consumption, and it can illustrate the oversizing of the green power supply infrastructure, that is, values above 1 indicate that more green energy is being produced than what the DCs are consuming. The second metric is the CO₂ savings, which represent the emissions' reduction after DC equipment upgrades or flexibility mechanisms. CO₂ savings is computed as seen in Equation 4.16, where: $CO2_{current}$ represents the system studied after the modifications—the DCs with PV area and battery capacity values computed from the LP—and $CO2_{baseline}$ the system in its original state. Here, it was considered that $CO2_{baseline}$ has the same workload allocation of $CO2_{current}$; the difference between the two is that $CO2_{baseline}$ does not have PVs and batteries, and thus only consumes power from the local grid. Table 4.8 shows the computed values for both metrics.

$$CO2_{savings} = \left(1 - \frac{CO2_{current}}{CO2_{baseline}}\right) \times 100 \quad (4.16)$$

Table 4.8. Results of the sustainability metrics for the experiments

Location	GEC	CO ₂ savings (%)
Johannesburg	1.47	93.93
Pune	1.45	91.5
Canberra	1.57	89.59
Dubai	1.59	89.1
Singapore	1.42	85.75
Seoul	1.53	82.51
Virginia	1.46	75.99
São Paulo	0.5	20.05
Paris	0.24	5.25

In order to assess the robustness of the sizing process for the area of PV panels and the capacity of the batteries, it is necessary to take into account the variability of meteorological conditions, given that the DCs will operate for decades and not only for one year. The metric selected is the Mean Absolute Percentage Error (MAPE) defined by: $\frac{1}{n} \sum_{i=1}^n \frac{|R_i - F_i|}{R_i}$, where n represents the number of values being considered, i the index of the value being considered, R_i the real value for the year, and F_i the estimated value (in this case, the computed sizing for the year 2021 that

was used in the experiments). Table 4.9 presents the results of the MAPE for both the area of PV and the capacity of the batteries when we solve the LP using as input the solar irradiation for the years 2018, 2019, and 2020. Results indicate a variation of less than 10% in the different DCs over the years.

Table 4.9. Evaluating sizing for different years using the MAPE metric (values are in %)

Location	PV Area	Battery Capacity
Johannesburg	1.72	1.64
Pune	3.72	0.76
Canberra	8.62	4.25
Dubai	2.31	2.88
Singapore	7.22	0.34
Seoul	3.15	1.11
Virginia	2.2	0.87
São Paulo	5.81	8.05
Paris	2.76	0

4.5 Analysis and Discussion

The results presented in the previous section enable us to evaluate the carbon footprint impact of different electricity supply policies for operating cloud data centers. On the one hand, as shown in Table 4.6, there is a significant reduction in carbon emissions—a 5-fold decrease in our experiments—to be obtained by including renewable energy in the electricity sources of DCs. Many Cloud providers have committed to using 100% renewable energy supplies for their DCs in the following years, and some have already started this process by buying renewable energy generated elsewhere or installing renewable infrastructure. On the other hand, this objective of 100% renewable is, in our opinion, more ideological than pragmatic, and there is more benefit to be obtained by combining grid and renewable electricity. We observe in our experiments a further reduction of a fourth in the optimal solution compared to the 100% renewable scenario. This study thus gives further insight into the debate over energy sources in modern clouds.

The data center locations used allow us to benefit from the diversity of latitudes, hemispheres, and climates. As shown in Figure 4.1, the model includes 3 DCs in the Southern Hemisphere, 5 in the Northern Hemisphere, and Singapore almost on the equator. Considering the longitudes, two DCs are on the American continent, two on the African and European continents, while the four last ones are geographically distributed on the Asian and Australian continents. This variety of longitudes and hemispheres permits mitigation of the impact of seasonal and daily variations of solar irradiation on electricity production and always has at least some DCs with good PV production, as shown in Figure 4.2. The diversity of climates is highlighted by the case of Singapore's solar production, which is the second lowest with Paris, while its location close to the equator could permit better irradiation.

As indicated in Table 4.5, we observe significant heterogeneity in the carbon footprint of grid electricity of the different DCs: Paris and São Paulo have the lowest electricity footprint, close to 50 g CO₂-eq/kWh, four DCs have a grid footprint between 300 and 600 g CO₂-eq/kWh (Virginia, Seoul, Singapore, and Dubai), Pune has just over 700 g CO₂-eq/kWh and the most carbon-intensive grid electricity is in Johannesburg with more than 900 g CO₂-eq/kWh. This heterogeneity results in two categories for the optimal solution: i) Paris and São Paulo, DCs with a reduced number of PVs and batteries (no battery in Paris), and ii) the other locations have quite similar sizes of PVs and batteries.

For the first category, we see the carbon footprint of solar panels and energy storage devices compared to the one of grid electricity: as the grid is low-carbon intensive for both locations, it can be used to supply the DCs. This justifies the low area for the PVs, and since there will be virtually no solar power overproduction, the battery capacity will be low as well.

In the second category, the larger PV area is mainly associated with low solar irradiation. It might appear counter-intuitive to allocate more PVs to locations with lower solar production, but this is more comprehensive considering the static part

of the power consumption of DCs—from the idle consumption of servers and the interconnection network, as referred to in Equation (4.1). This static electricity consumption implies either using the carbon-intensive grid or sizing PV and batteries to match the demand, even during winter days of low PV production. This results in a large PV and battery sizing—the PVs are producing up to 1.6 times the total DC energy consumption as seen in Table 4.8—and, as shown in Figure 4.4, the grid energy consumption of these DCs is very low.

The detail of hourly electricity consumption and renewable production is highlighted in Figure 4.5. The workload is allocated to DCs with solar power production. If all this power production is used, or the corresponding DCs are full (in terms of available CPU cores), then the allocation is driven by the battery level of energy, and when none of these possibilities are available, the allocation is for the DC with the lowest grid electricity footprint. For example, in the last few hours, the electricity consumption of the different DCs was supplied by power discharged from the batteries, and the remaining was allocated to the DCs of Paris, São Paulo, and Virginia. Thus, the DC of Virginia consumes grid electricity in two cases: either when Paris and São Paulo DCs are full and cannot receive more work (from hours 10 to 24), or when the DC is empty and only local electricity can be used (hours 3, 5, and 6 in Figure 4.5).

The follow-the-sun approach can be partially observed in Figure 4.5 between hours 7 and 8, when Seoul PV power production decreases, and the workload is transferred to Paris, with grid consumption. Then, at hour 10, the same happens between PV production in Singapore and grid electricity in São Paulo, and at hour 11, between Pune and Virginia. The figure also shows the impact of location, season, and PV sizing on the solar production between Pune and Canberra, large PV production in the best hours—summer in the Southern Hemisphere, and tiny production in Paris—winter in the Northern Hemisphere).

Table 4.7 presents the impact of the different scenarios for energy sources on the computational load of the different DCs using the Data Center Utilization (DCU) metric, that is, the average usage of the DCs total computational capacity in CPU cores being used during the year, which can also be used to infer how much workload is scheduled for the DCs. In the first scenario (electrical grid only), the single most important piece of information available for the allocation decision of the workload is the grid electricity footprint. Thus, one could expect the DCU values of the DCs to be sorted in the same order as the grid footprint order per kWh. However, the energy consumption does not only depend on the workload execution but also on the PUE of the different DCs—the power needed for cooling. We can thus observe a higher workload in Dubai compared to Singapore, considering that Dubai has electricity with a slightly higher footprint but the lowest PUE.

The second scenario considers a model supplied only by the local renewable infrastructure. The allocation is surprisingly distinct from the solar irradiation of the different DCs. For example, the DC of Paris has the lowest yearly irradiation but the median DCU in this scenario. Its DCU is higher than the one in Johannesburg, which has the second-highest yearly irradiation and is on a similar longitude. The workload allocation is thus not only driven by yearly irradiation. The extremely low PV production in Paris during winter, associated with the static part of the electricity consumption in each data center (network devices and idle consumption of the servers), implies a high sizing of PV and battery, which leads to a high solar power production during the other seasons that make it an interesting candidate for receiving the workload. In Johannesburg, the seasonal variation is lower, so the static power consumption does not influence the PV sizing.

Another surprising result is that the DCs with the lowest DCU in this scenario are the four in the Southern Hemisphere (including Singapore). This contradicts the intuition of “follow-the-summer” allocation. The cases of São Paulo and Canberra could be similar to those of Johannesburg and Paris, considering the minimal daily

production in Virginia and Seoul during the winter. The largest DCU concerns DCs with the most stable production (Dubai and Pune) and the lowest minimum daily production (Virginia, Paris, and Seoul).

For the last scenario—hybrid configuration with power from the electrical grid and DC’s renewable infrastructure, the DCs with the largest DCU are the three that receive the largest solar irradiation during the year (Dubai, Pune, and Johannesburg), followed by Paris with the lowest grid electricity footprint. The two surprises are: i) the DCU of São Paulo, which is low considering its low grid electricity footprint and high solar irradiation; and ii) the DCU of Singapore, which is high considering its low PV production. Concerning São Paulo, this could be explained by the fact that it has the second-lowest grid footprint. This implies a low PV sizing (and a low battery sizing as a consequence), and finally, it mainly receives workload only when no more DC can provide electricity from PV or battery discharge, and when the DC of Paris is full, which results in many constraints. Considering Singapore, it is probably due to its position close to the equator, which implies no “winter” season, and its large PV sizing.

We use the CO₂ savings metric to analyze the reduction of the carbon footprint of each DC between the hybrid scenario (PV + bat + grid) and the scenario where power comes exclusively from the regular grid, and the results are shown in Table 4.8. It is possible to observe a small decrease in Paris and São Paulo—since there are already low-carbon sources in the local electricity grid, and a large decrease in the other locations, correlated to the electricity footprint. This information could be used by the decision-maker to prioritize investments in the locations that would result in the highest reduction of the carbon footprint.

4.6 Summary

In this chapter, we studied the problem of lowering the carbon footprint of operating a cloud federation composed of geographically distributed cloud data centers. The IT part of the cloud platform already exists—servers and network devices, and the idea is to add renewable infrastructure equipment on site to introduce low-carbon-intensive energy in the DC power supply, as the local electrical grid may be high-carbon-intensive.

Given that the sun is shining everywhere on earth, we have proposed photovoltaic panels (PVs) to produce renewable energy and batteries as energy storage devices to mitigate the intrinsic intermittency of this energy during the day and for night computations. The question is how to size the PV array area (m^2) and associated battery capacity (kWh), given an existing federation of DCs distributed around the earth, without neglecting the fact that manufacturing PVs and batteries also presents an environmental impact.

We have provided a formulation of the problem as a linear program. The particularity of our formulation is that the modeling uses only real variables, given our objective function and the context of the problem. As a result, the linear program allows one to optimally solve large problem sizes in polynomial time, e.g., minimizing the carbon footprint of a nine-site federation, each with its own weather conditions, over a one-year horizon, hour by hour.

We have demonstrated that our program is able to calculate the optimal sizing for PVs and batteries in just a few minutes. Numerous experiments have brought forward results that we have analyzed and discussed, explaining what these results express. As an example, an interesting result, depending on the DC locations considered, is that the optimal solution to reduce the carbon footprint is to maintain an energy mix through a hybrid configuration including both PVs and a classical grid where the

production is low carbon instead of proposing an all-renewable platform. Moreover, batteries are not always mandatory in each location (as in the case of Paris DC).

Finally, our model has the flexibility to be extended to assess other scenarios (more DCs, other locations, values for carbon emissions, or workloads) and it may help decision-makers build their strategy to reduce the environmental impact of the cloud operation.

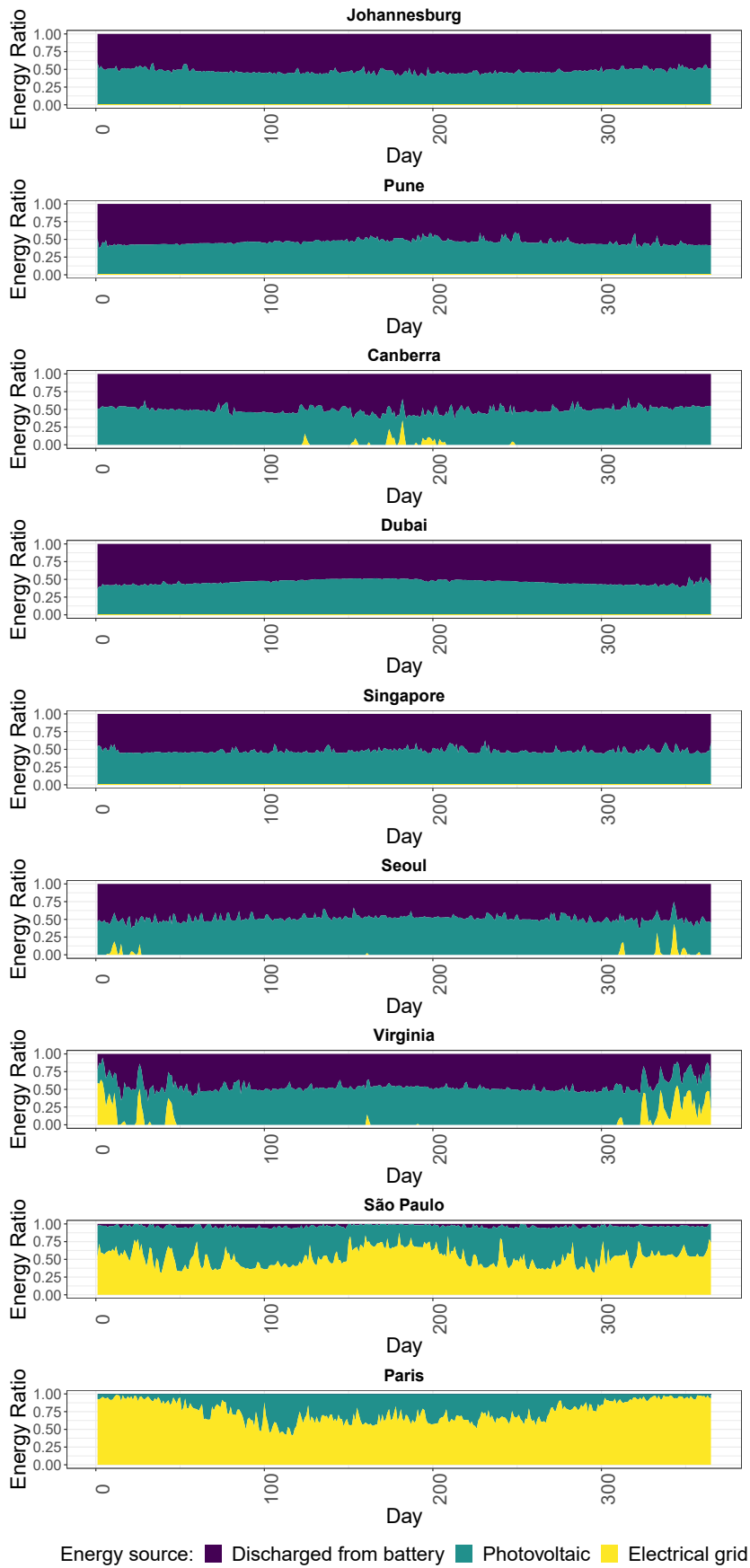


Figure 4.4. Composition of the DCs' daily energy consumption throughout the year considering the different sources of energy, where 1.0 is the DC's total energy consumption.

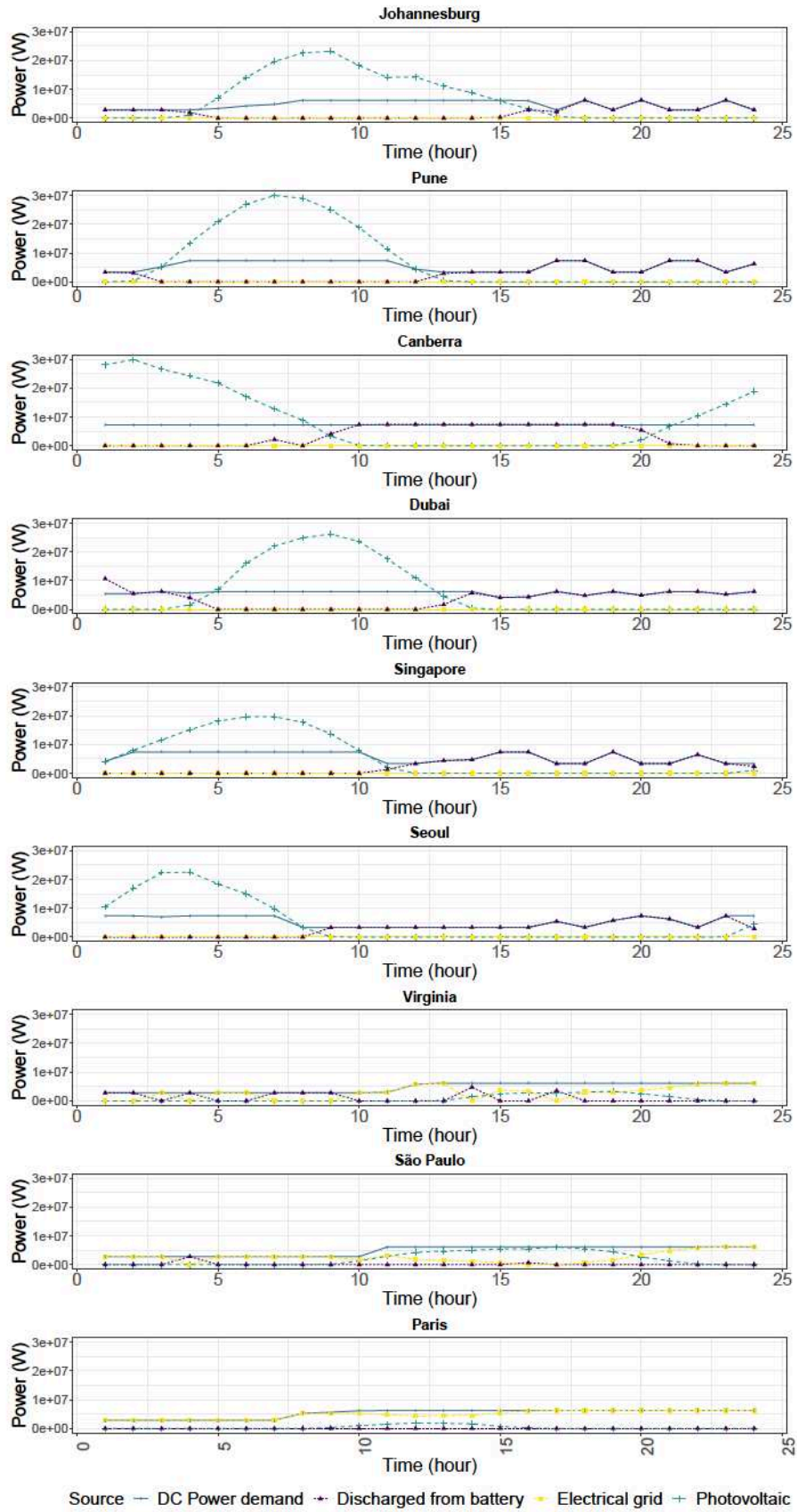


Figure 4.5. Composition of the DCs' hourly power consumption throughout the first day of the year. Time follows the Universal Time (UT) standard.

Long-term evaluation of sizing cloud data centers

5.1 Introduction

In the previous chapter, we presented an initial model to reduce the carbon emissions of operating a cloud federation for the short term (one year) by sizing its renewable infrastructure, that is, defining the area of solar panels and the capacity of the batteries for each data center. Given that the cloud federation will operate for the long term, the decision-maker needs to be sure of the investments that will be made to avoid wasting money and generating environmental impact with a bad strategy. Furthermore, a planning process is subject to many uncertainties that, if not considered, will decrease the validity and credibility of the solution.

This chapter presents an extension of the model, focusing on the long-term operation of the cloud DCs and the uncertainties that this sizing process is subject to. In our context, the uncertainty comes mainly from the intermittency of renewable sources. Therefore, the reader is introduced to an analysis of the sensitivity of the modeling to the climate conditions. Another input that may affect the sizing process is the value of the local electricity grid emissions. In our initial modeling, we used the average value of the year, given that not all locations provide this value with shorter intervals—hour-by-hour variation, for example. The reader is presented with an analysis of the impact of using the fine-grain information of the grid emissions in comparison to the year's average on the sizing process and the resulting total carbon footprint.

Given that the focus is now on long-term operation, it is essential to consider the entire life cycle of the renewable infrastructure. In the previous chapter, we made the modeling considering only the environmental impact of manufacturing solar panels and lithium-ion batteries. This decision was made because of the available data we found while studying the problem. However, the environmental impact is also present in the other phases of the lifetime of these devices—operation, discarding, and recycling. Therefore, the modeling was updated to account for the emissions from the life cycle of the renewable infrastructure.

Reducing carbon emissions by using solar panels is limited because they only generate power when the sun is shining. Therefore, they need to supply the operations of the cloud during the day and charge the batteries for night operations. In this chapter, we evaluate if using wind turbines could further reduce the carbon emissions of the cloud operation and the sizing of both the PV panels and batteries—considering that the wind may also be available at night.

One must also take into account that once built, the renewable infrastructure cannot be reduced—this would imply destroying or discarding PV panels, batteries, and wind turbines. Therefore, another strategy is necessary to deal with the oversizing that the intermittency of renewable sources might cause. Thankfully, another part can be managed to reduce the impact of bad sizing: the scheduling of the workload. On the cloud platform, a significant part of the workload consists of tasks that do not have a high priority and whose execution can be delayed over time, the so-called batch tasks. At Meta, 7.5% of the workload are offline tasks [40] and low-priority tasks consume on average 20% of the computational resources (CPU and memory) of Google’s clusters [60]. We show an analysis of the viability of delaying α % of the tasks up to β time slots (each time slot has 1 hour of duration) to reduce the carbon footprint.

Another important aspect to consider is that the demand for cloud computing resources grows year by year—to deal with the increasing number of users and

requests for applications. During the years 2010 to 2018, Cisco provided forecasts for workload growth for the following five years, updating the forecast every year. The last report—for the period from 2017 to 2021—predicted that the workload growth rate would be 22% on average per year for cloud data centers [61]. Additionally, new server generations are launched that have more computationally powerful hardware that may be more energy efficient. As said in Chapter 1, the analysis from Masanet et al. [3] showed that from 2010 to 2018, the DC workload increased six times; however, the increase in energy consumption was only 6% thanks to efficiency improvements in both hardware and software. On the other hand, manufacturing servers also emits carbon, which cannot be neglected. Furthermore, given the increasing integration of renewable infrastructures in cloud data centers, most of the carbon emissions are shifting from the power consumption of the DC operation to the manufacturing of IT equipment [18].

Until now, we only explored the environmental impact aspect—in terms of carbon emissions—of the cloud federation operation. Another dimension of high importance for the decision-maker is the monetary cost since the business will only survive if it generates profit. The reader is also presented with an analysis of how expensive it is to reduce the carbon footprint of the multi-cloud operation by using on-site renewable infrastructure. Similar to the environmental impact analysis, we consider the costs of the whole life of the solar panels, wind turbines, and batteries.

More specifically, the chapter presents the following contributions:

- we extend the modeling to account for all the life cycle emissions of the renewable infrastructure—from manufacturing to discarding/recycling (Section 5.2);
- we present an evaluation of how much the carbon footprint could be reduced if wind turbines were also included in the renewable infrastructure (Section 5.3);
- we show an evaluation regarding the sensitivity of the LP to the inputs: i) uncertainties caused by the intermittency of solar irradiation and wind speed,

and what needs to be considered in the modeling to avoid over or under-sizing of the renewable infrastructure; ii) some locations have data sources with grid carbon footprint at time intervals of one hour, and we show an analysis of whether this fine-grain value would affect the renewable infrastructure sizing (Section 5.4);

- we present an analysis of how much we can reduce the carbon footprint using the flexibility of the scheduling—delaying batch tasks (Section 5.5);
- we present an analysis of when it is viable to add new servers (that may replace servers from older generations) in terms of carbon footprint (Section 5.6).
- we show an analysis of how expensive (in dollars) it is to reduce the cloud federation footprint and the gains in both monetary and emissions savings (Section 5.7).

The remainder of the chapter is organized as follows. Considering that we are extending the model of the previous chapter to evaluate different scenarios, each scenario has its own Section—Sections 5.2, 5.3, 5.4, 5.5, 5.6, and 5.7, and in each section, the reader is presented with the necessary modifications in the modeling, the experiments performed and the results of the experiments. After presenting the evaluated scenarios, we show the discussion at Section 5.8. Finally, Section 5.9 concludes the chapter.

The work of this chapter is a direct extension of the work of Chapter 4, and it was also done in collaboration with the following members of the DATAZERO[35] research team: Georges da Costa, Jean-Marc Nicod and Veronika Rehn-Sonigo. Preliminary results were presented in the form of a short presentation: *Vasconcelos, M., Cordeiro, D., Costa, G. D., Dufossé, F., Nicod, J.-M., and Rehn-Sonigo, V. (2023). Long-term evaluation for sizing low-carbon cloud data centers. In CompAS 2023 Conférence francophone en informatique, Jul 2023, Annecy, France.* The results will

be submitted to a scientific journal—the publication was in the writing phase at the time this thesis was written.

5.2 Life cycle of the renewable infrastructure

In this section, we present how we can model the carbon footprint from the whole life cycle—from manufacturing to recycling or discarding—of the renewable infrastructure, a mandatory step to make the model more realistic, in particular when focusing on the long-term operation of the cloud federation.

5.2.1 Updates in the model

The carbon footprint model (presented in Section 4.2.2.4) needs to be updated to model the CO₂ emissions from the whole life cycle of the renewable infrastructure, and Table 5.1 presents the new notations used in the updated model. The previous model only considered the CO₂ emissions from the manufacturing phase, and now we use the emissions of the energy produced (or delivered in the case of batteries) in $gCO_2 - eq.Wh/kWh$ during the whole life cycle—which includes operation and recycling or discarding. Equation (5.1) models the new footprint for the PV panels, and the main difference is the $pvCO2LC$ input that represents the life-cycle emissions ($gCO_2 - eq/kWh$).

$$FPpv_k^d = pvCO2LC \times Pre_k^d \times \Delta t \quad (5.1)$$

For the batteries, the initial modeling considered the emissions of manufacturing related to their capacity. Now, to account for all the life cycle, the emissions relate to the energy delivered (discharged) by the batteries. Equation (5.2) models the

Table 5.1. New notations for the updated carbon footprint model for each DC^d ($1 \leq d \leq D$) during time slot k ($0 \leq k < K$)

$pvCO2LC$	Carbon footprint (in grams of CO ₂ -eq) to produce 1 kWh from a photovoltaic panel considering all the phases of its life cycle
$batCO2LC$	Carbon footprint (in grams of CO ₂ -eq) to deliver (or discharge) 1 kWh from a lithium-ion battery considering all the phases of its life cycle
$SUNRISE^d$	A set with all the instants of time when the sun starts shining throughout the year (1 value per day) in the location of data center d considering its time zone.
$FPbat_k^d$	Carbon emissions (in grams of CO ₂ -eq) of discharging energy from the battery of DC d during time slot k

new footprint for batteries, where $batCO2LC$ represents the life-cycle emissions ($g\text{ CO}_2\text{-eq/kWh}$).

$$FPbat_k^d = Pch_k^d \times batCO2LC \times \Delta t \quad (5.2)$$

Considering that now the information used for computing the batteries' emissions is the power discharged, we need to add a restriction for the batteries being used only for night computations, otherwise the solver may compute a solution where the batteries will be oversized to store all the excess renewable energy during summer to supply during winter, resulting in GWh of capacity—which is a problem considering the other environmental impact of batteries as their recycling rates need to improve [48]. Equation (5.3) models this restriction, where $SUNRISE^d$ is the set with all the instants of times when the sun starts shining throughout the year in each location considering its time zone.

$$\forall t \in SUNRISE^d : B_t^d = 0.2 \times Bat^d \quad (5.3)$$

Finally, the objective function also needs to be modified in order to include the new life-cycle emissions of the batteries. Equation 5.4 models the new objective function.

$$\text{minimize } \sum_{k=0}^{K-1} \sum_{d=1}^D (FP_{grid_k^d} + FP_{pv_k^d} + FP_{bat_k^d}) \quad (5.4)$$

5.2.2 Experiments

To evaluate the impact of taking into account the emissions from the whole life cycle in terms of carbon footprint and dimensions of the renewable infrastructure, we perform the sizing and use the previous model—which considered only the emissions from manufacturing—as a baseline.

5.2.2.1. Settings

The cloud infrastructure, the workload, grid emissions, and the execution environment are the same as in Section 4.4.1. For the photovoltaic power production, we use the average of the irradiation from the years 1980 to 2019, and Figure 5.1 illustrates the values for the different DCs locations. This modification was to consider the variations between the years, as using a single year is not enough: it may be the case of a year with the lowest or highest solar irradiation. More details on choosing the average irradiation value are given in the next section.

For the life-cycle CO₂ emissions of the batteries and PVs, we used values from the National Laboratory of Renewable Energy (NREL) of the United States that performed an analysis with over 3000 published studies on the life cycle of renewable infrastructures [9]: 43 *gCO₂-eq/kWh* for the PVs and 33 *gCO₂-eq/kWh* for the Lithium-Ion batteries.

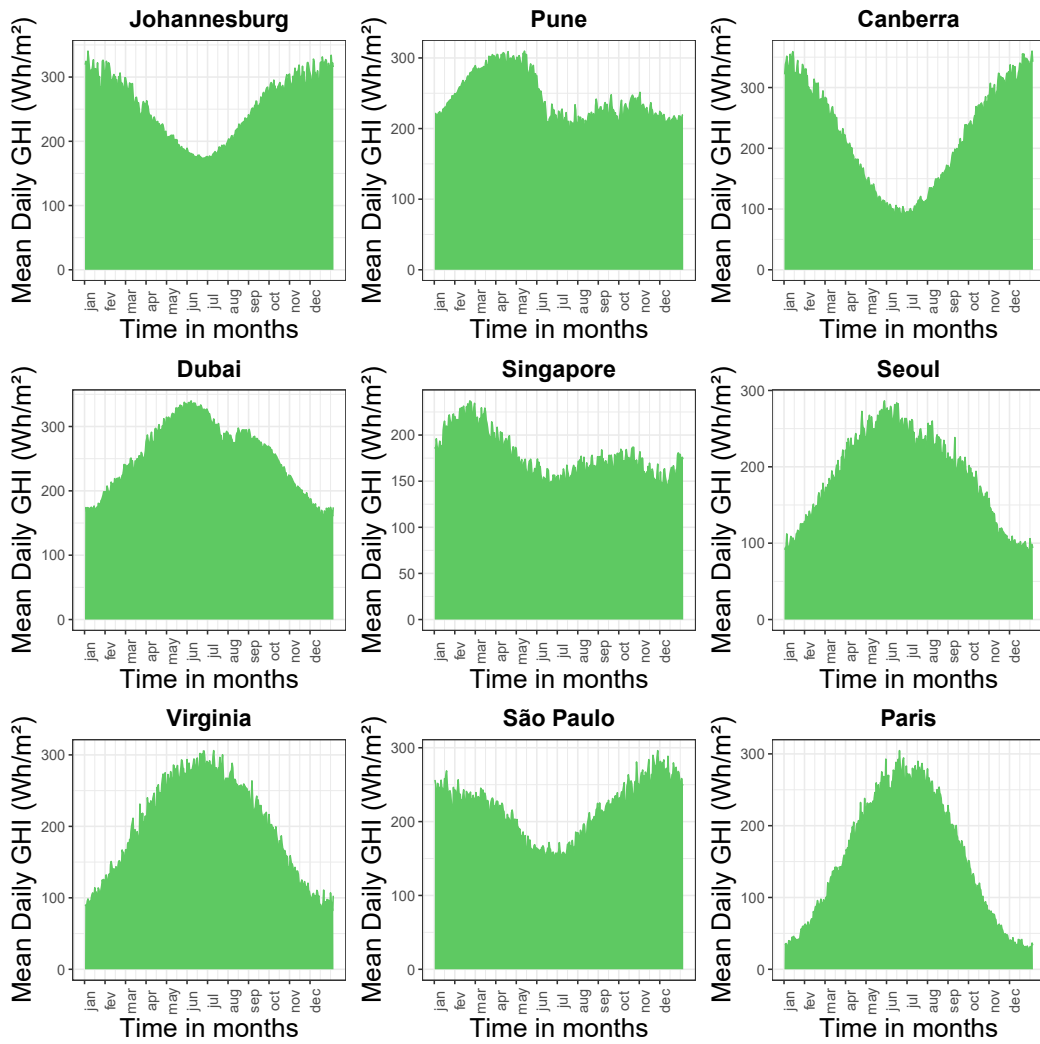


Figure 5.1. Average solar irradiation from 1980 to 2019 per location.

5.2.2.2. Results

Table 5.2 presents the CO₂ emissions considering the whole life cycle, compared to considering only the one from manufacturing. As expected, the total CO₂ emissions are higher (around 8% increase) since the whole life cycle of the renewable infrastructure is now taken into account.

Table 5.2. Total emissions for the different scenarios.

Scenarios	Emissions (t CO ₂ -eq)
CO ₂ from manufacturing	34 559.03
CO ₂ from the whole life cycle	37 828.49

Finally, to better assess the impact of considering the emissions from the whole life cycle of the sizing process, we compare its results with those of the sizing process that only considers the emissions from the manufacturing phase—Figures 5.2 and

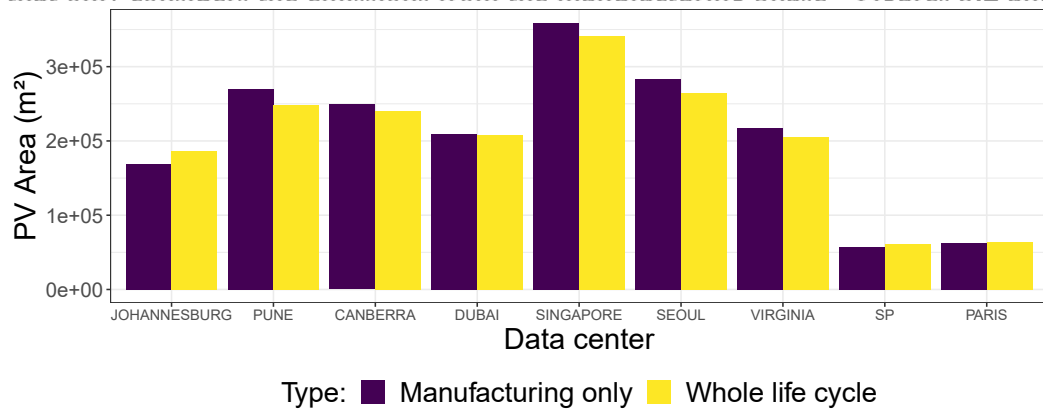


Figure 5.2. PV Area sizing when considering the carbon footprint of manufacturing vs. the whole life cycle.

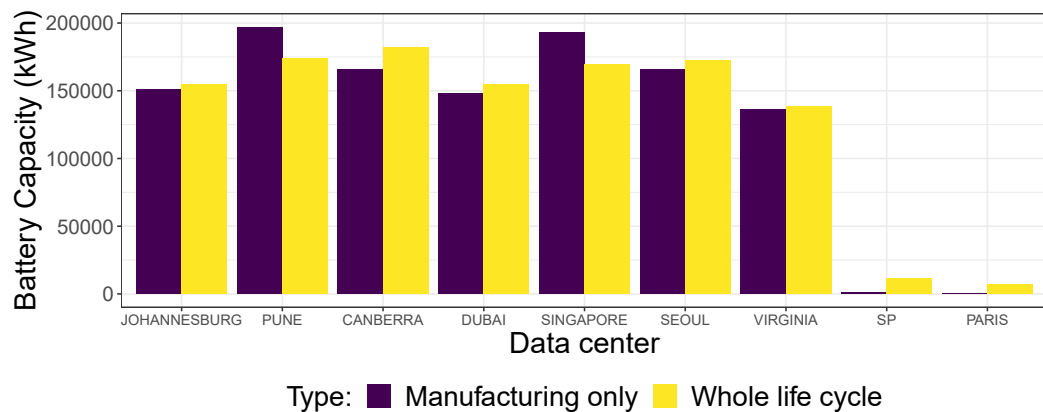


Figure 5.3. Battery capacity sizing when considering the carbon footprint of manufacturing vs. the whole life cycle.

5.3 Including wind turbines to the renewable infrastructure

In this section, we evaluate the impact on the carbon footprint of adding wind turbines (WT) as a power source to the on-site renewable infrastructure. Wind turbines may complement the photovoltaic power production to reduce the total emissions of the cloud federation operation, in particular during the night and seasons with lower solar irradiation, such as the winter. On the other hand, solar irradiation presents a lower variance than wind speed [62].

5.3.1 Updates in the model

The electrical model (see 4.2.2.3) needs to be updated to include the new renewable infrastructure, and we show in Table 5.15 the new notations used in the updated model. We consider a new variable WT^d representing how many wind turbines will be built at each DC location. The number of wind turbines (WT) is an integer number (we cannot produce 1.2 WT for example). However, to avoid increasing the computational complexity of the LP by including integer variables, we made a relaxation in our modeling to allow the WT variable to be linear.

The power production of the WT^d wind turbines at the location of the data center d at instant k (Pwt_k^d) is modeled by Equation 5.5, where V_k^d is the wind speed at location of the data center d at instant k ; V_{ici} is the *cut in* wind speed, that is, the wind turbines start producing power when the wind speed is greater or equal to V_{ici} ; V_{co} is the *cut out* wind speed, that is, the wind turbines stop producing power when the wind speed is greater than V_{co} ; Pr is the rated power production in Watts of the wind turbine; and V_r is the speed where the WT starts producing Pr power. This model is based on [36].

Table 5.3. New notations for the updated electrical and carbon footprint models for each DC^d ($1 \leq d \leq D$) during time slot k ($0 \leq k < K$)

WT^d	Number of Wind Turbines at DC d
Pwt_k^d	Power generated from the wind turbines at DC d during time slot k
V_k^d	Wind speed (m/s) at the location of DC d during time slot k
$Vici$	Cut in wind speed (m/s), in which the WT starts producing power
Vco	Cut out wind speed (m/s), in which the WT does not generate more power
Pr	Rated power of the WT (in Watts)
$wtCO2LC^d$	Carbon emissions (in grams of CO ₂ -eq) of producing 1 kWh of energy from wind turbines taking into account all their life cycle
$FPwt_k^d$	Carbon emissions (in grams of CO ₂ -eq) of producing power from the wind turbines of DC d during time slot k

$$Pwt_k^d = WT^d \times \begin{cases} 0 & \text{if } V_k^d \leq Vici \\ Pr \times \frac{V_k^d - Vici}{Vr - Vici} & \text{if } Vici < V_k^d \leq Vr \\ Pr & \text{if } Vr < V_k^d \leq Vco \\ 0 & \text{if } Vco < V_k^d \end{cases} \quad (5.5)$$

Given that we are using additional renewable power infrastructure, it is also necessary to update the model of the renewable power production on DC d at instant k . Equation (5.6) models that renewable power can originate from both PVs and WT.

$$Pre_k^d = Ppv_k^d + Pwt_k^d \quad (5.6)$$

To model the carbon footprint of the wind turbines, their whole life cycle also needs to be taken into account. Equation (5.7) models the footprint of using the WT at the location of the data center d at instant k , where $wtCO2LC$ is the input that represents its emissions for the life cycle (in $gCO_2\text{-eq}/kWh$).

$$FPwt_k^d = wtCO2LC^d \times Pwt_k^d \times \Delta t \quad (5.7)$$

Finally, the objective function also needs to be modified in order to include the carbon emissions from using WTs. Equation 5.8 models the new objective function.

$$\text{minimize } \sum_{k=0}^{K-1} \sum_{d=1}^D (FP_{grid_k^d} + FP_{pv_k^d} + FP_{wt_k^d} + FP_{bat_k^d}) \quad (5.8)$$

5.3.2 Experiments

In order to analyze the impact of including wind turbines in the renewable infrastructure in terms of carbon footprint and dimensions of the solar panels and batteries, we perform the sizing and use the previous model—which considered only the PV and batteries—as a baseline.

5.3.2.1. Settings

The cloud infrastructure, the workload, grid emissions, and the execution environment are the same as in Section 4.4.1. The solar irradiation values and emissions from PV panels and batteries are the same as Section 5.2.2. For the CO₂ emissions of the wind turbines, it is considered that they emit 13 gCO_{2-eq/kWh}, taking into account its life cycle. The source for this value was the same as in Section 5.2.2, the analysis from NREL that evaluated more than 3000 studies about life cycle emissions from renewable infrastructures.

For the wind speed data, we used values from the ERA5 data source [63]—an average of the years 1980 to 2019. The data source contains values for the 100 m v-component of wind (air horizontal speed towards the east) and the 100 m u-component of wind (air horizontal speed towards the north)—both values are at 100 m of height. To transform these values into wind speed, we need to execute the following computation using Pitagora’s theorem: $w_s = \sqrt{v^2 + u^2}$, where w_s is the wind speed, u the value of the u-component, and v the value of the v-component.

5.3.2.2. Results

To evaluate the impact of including WT, we compare the sizing for using only PVs and batteries and using PV, batteries and WT. Table 5.4 presents the results in terms of total emissions. When also considering the wind as a renewable power source, we observe a reduction of approximately 34% in comparison with the scenario where no WT is used and green energy is only produced by the PVs.

Table 5.4. Total emissions ($t\text{CO}_2\text{-eq}$) for different scenario.

Scenario	Total emissions ($t\text{CO}_2\text{-eq}$)
PV + Bat + WT + Grid	24 977.89
PV + Bat + Grid	37 828.49

Table 5.5 presents the optimal number of WTs manufactured at each data center location. As said in Section 5.3.1, we use a linear number for the wind turbines to avoid increasing the computational complexity of the problem. The decision-maker could decide whether to round the value up or down based on its budget constraints.

Table 5.5. Computed number of WT for each location.

Location	Number of WT
Johannesburg	58.11
Pune	25.77
Canberra	66.56
Dubai	79.09
Singapore	36.93
Seoul	109.56
Virginia	39.16
São Paulo	86.53
Paris	22.15

The Capacity Factor metric can be used to better analyze the potential of a location to generate renewable power. This metric measures a ratio of the real energy produced by the device in comparison to its maximum energy output [64]. In our experiments, we used the rated power of 150 W for a 1 square meter solar panel, and we used

climate conditions from 1980 to 2019 to estimate the Capacity Factor. Table 5.6 presents the results for both the PV and wind turbines.

Table 5.6. Capacity Factor (in %) for solar panels and wind turbines at each location.

Location	PV	WT
Johannesburg	25.55	12.96
Pune	24.26	10.04
Canberra	22.08	12.97
Dubai	25.28	13.98
Singapore	17.68	8.58
Seoul	18.81	9.41
Virginia	19.83	14.68
São Paulo	21.74	10.06
Paris	15.37	23.51

Finally, to assess the impact of including the WT regarding the sizing of both PV and batteries, we present in Figure 5.4 and Figure 5.5 the dimensioning for both equipment considering and not considering manufacturing WT. It is possible to observe that the inclusion of wind turbines has a significant reduction in the total solar panel area, and for some locations—such as São Paulo and Paris—the optimal is to use only wind turbines. The batteries are also reduced, given that the wind can blow at night as well, so no extra energy needs to be charged in the batteries from the solar panels to be used for night computations.

5.4 Sensibility of the LP to uncertainties

To assess the sensibility of the linear program to the inputs, we evaluate it considering different scenarios in terms of grid emissions data, solar irradiation, and wind speed.

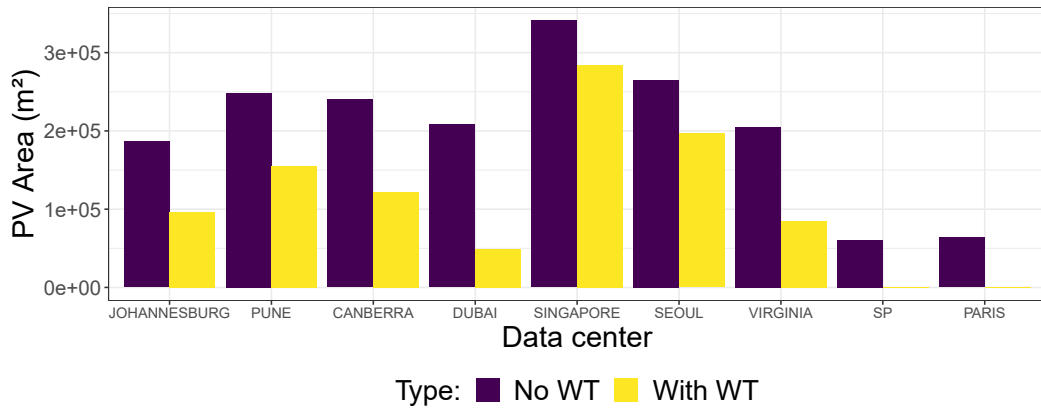


Figure 5.4. PV Area sizing when the WT are and are not included.

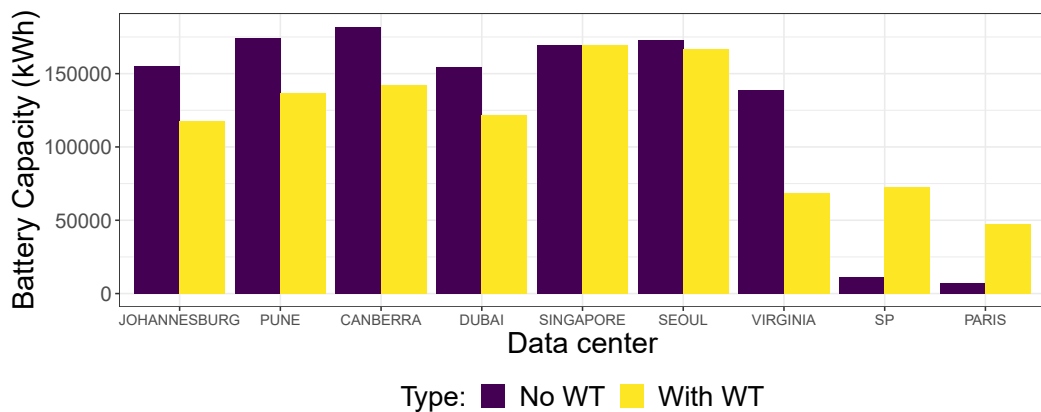


Figure 5.5. Battery capacity sizing when the WT are and are not included.

The renewable sources are intermittent by nature, and this variation can impact the sizing process, resulting in an over- or under-sizing of the renewable infrastructure.

Given the presence of low-carbon-intensive power sources in some countries, the emissions of the local electricity grid are not static all year. For example, regions with access to solar energy have a lower grid footprint during the day. Some countries provide access to fine-grain information about their electricity mix in real-time or historical data in the form of time series. However, obtaining data for all the locations is not an easy process: not all the locations provide this information, or they provide different time granularity (day, hour, month), historical data with different durations (for example, only the last six months), or only real-time values.

For modeling the variation in grid emissions, it is necessary to update the model, and in the next section, we present the modifications.

In order to illustrate the intermittency of both wind speed and solar irradiation, we present in Figure 5.6 the total energy one solar panel produced per year during the years 1980 to 2019, and in Figure 5.7 for a single wind turbine. Those figures show the intermittency of renewable power production over the years, and one may also observe the potential for using one source or another: for example, Paris has the lowest solar power production considering one solar panel, and on the other hand, it has the highest wind power production.

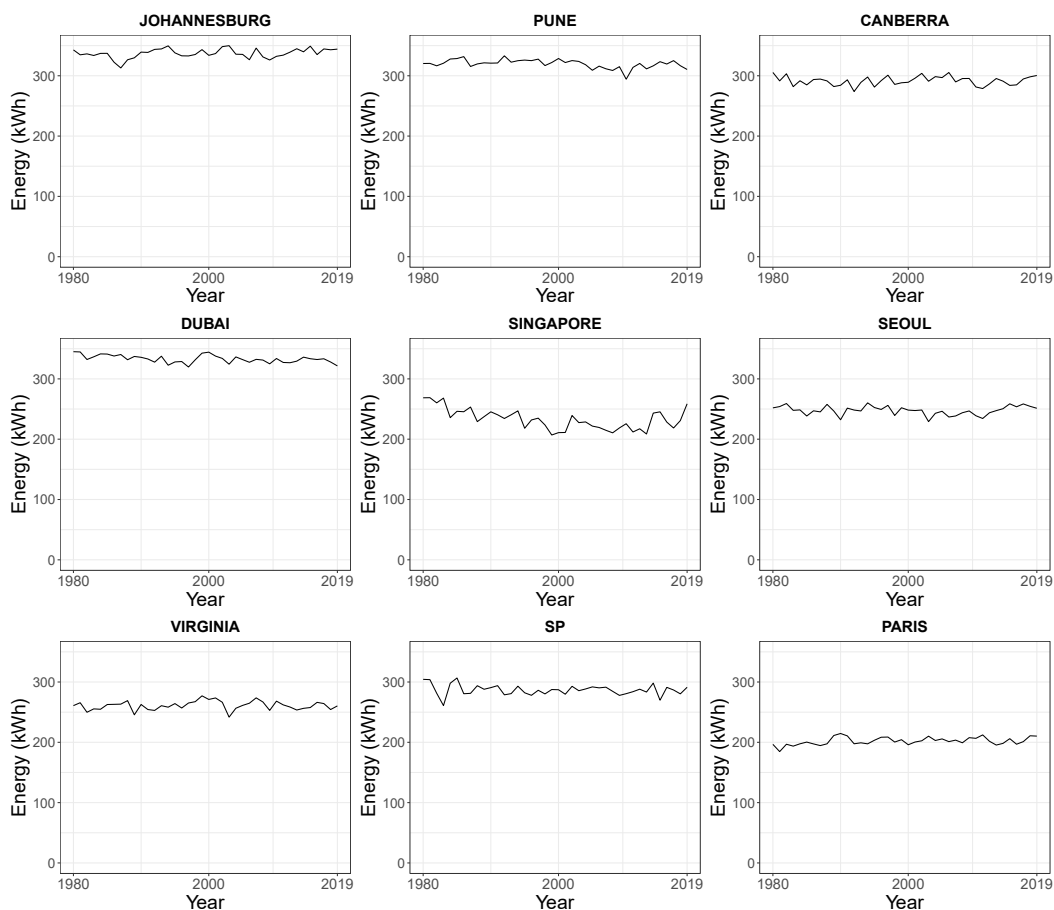


Figure 5.6. Different energy production for 1 PV panel at each location for the years 1980 to 2019.

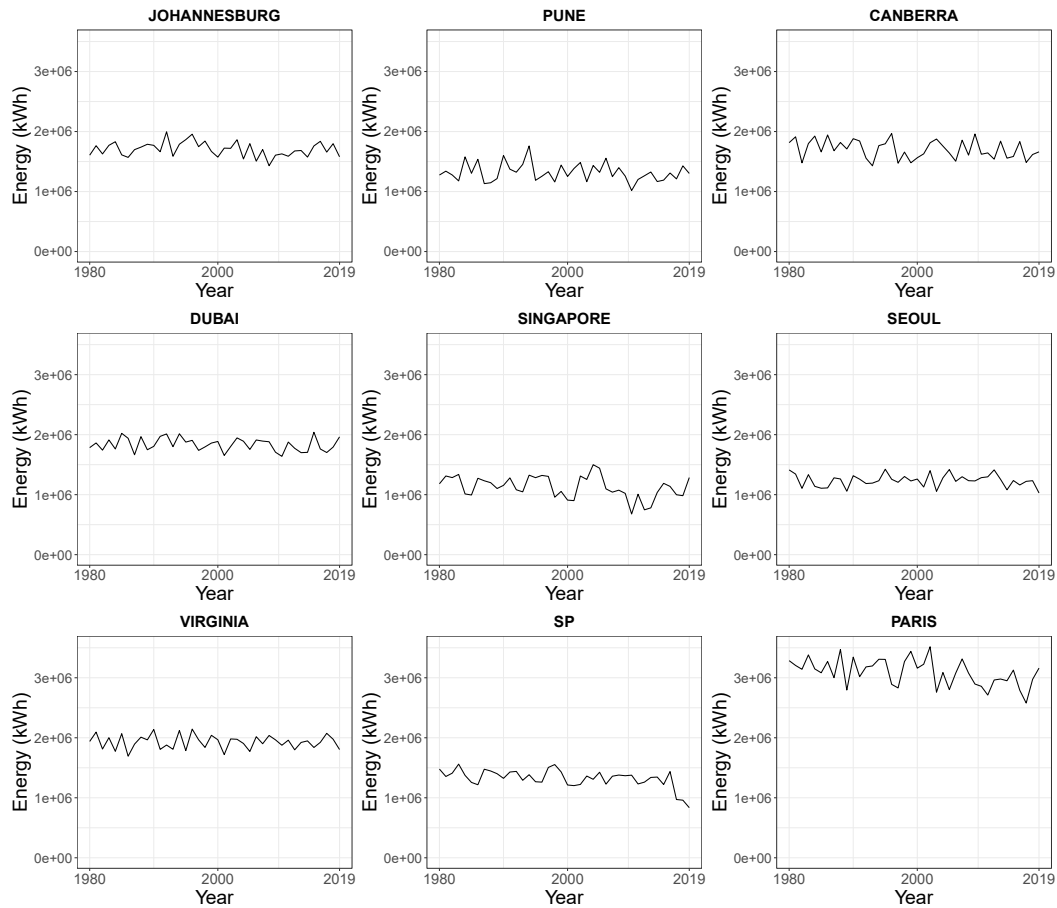


Figure 5.7. Different energy production for 1 wind turbine at each location for the years 1980 to 2019.

5.4.1 Updates in the model

5.4.1.1. Fine-grain values of grid emission data (hour by hour)

To model the change in the electricity grid emissions over time, we need to modify the carbon footprint model (presented in Section 4.2.2.4). We introduce the input $gridCO_2_k^d$, which is a time series with CO_2 emissions values of producing 1 kWh of energy at the location of DC d at time slot k . For locations where data is not available hourly, pre-processing of the data is needed. For example, if the region only provides daily data, one can assume that for the 24 hours of the day, the value of grid emissions will be the same. Equation (5.9) presents the modification where

$gridCO2_k^d$ is the new input for the grid emissions with one value for each time slot k at the location of the data center d .

$$FP_{grid_k^d} = P_{grid_k^d} \times \Delta t \times gridCO2_k^d \quad (5.9)$$

5.4.1.2. Intermittency of renewable sources

Regarding the intermittency of solar irradiation and wind speed, there are no necessary modifications to be made in the modeling itself, as the impact is generated by the input data that will be used for the sizing process.

5.4.2 Experiments

To assess the sensitivity of the model to the inputs of climate conditions and grid emissions, we conducted a series of experiments. For the climate conditions, we evaluate if using forecasts that are not computationally expensive—using the average and median values—provides precise results and the impact on the carbon footprint considering the future operation—10 years, and the baseline is the optimal scenario where the climate conditions are known in advance. For the grid emissions, we evaluate the impact on the carbon footprint by using the fine-grain information—hourly—and the average year value.

5.4.2.1. Settings

For both scenarios, the cloud infrastructure, the workload, and the execution environment are the same as in Section 4.4.1.

5.4.2.1.1. Fine-grain values of grid emission data (hour by hour) In order to evaluate the impact of using a fixed value for the grid emissions (an average of the year) or a fine grain value (hourly time series), we perform the sizing with these two scenarios and compare them in terms of CO₂ emissions and dimensions of the renewable infrastructure for the years 2018, 2019, 2020 and 2021.

For the scenario of hourly grid emissions, we used data sources provided by Electricity Map. For the locations: Pune, Canberra, Seoul, Virginia, São Paulo, and Paris, the data source provides CO₂ intensity of the grid hour by hour for the duration of 1 year. For the Johannesburg and Singapore regions, the information on CO₂ emissions was in the granularity of months. Therefore, we generated a time series with a total duration of one year and the same value of CO₂ per hour for each corresponding month. For Dubai, we only found data for the year’s average grid CO₂ emissions, and we generated a time series in which the grid emissions are fixed for every hour of the year.

Table 5.7 presents the sources of the data, the time span, and the granularity for the grid emissions of each data center location, and Table 5.8 presents the average CO₂ emissions of the year for these data sources—the value used is the average of the time series of each location for the evaluated years.

Table 5.7. Comparison of local electricity grid information.

Location	Granularity	Span	Source
Johannesburg	month	year	ElectricityMaps
Pune	hour	year	ElectricityMaps
Canberra	hour	year	ElectricityMaps
Dubai	year	year	1.5°C national pathway explorer
Singapore	month	year	ElectricityMaps
Seoul	hour	year	ElectricityMaps
Virginia	hour	year	ElectricityMaps
São Paulo	hour	year	ElectricityMaps
Paris	hour	year	ElectricityMaps

To illustrate the variations of the grid emission over time, we present two scenarios to the reader: one with a significant presence of renewables in the local electricity

Table 5.8. Average emissions (in $g\text{CO}_2\text{-eq}/kWh$) from using the regular grid at the different years.

Location	2021	2020	2019	2018
Johannesburg	700.66	700.66	700.66	700.66
Pune	728.15	724.04	726.43	723.83
Canberra	655.36	692.23	712.43	728.21
Dubai	530.00	530.00	530.00	530.00
Singapore	491.01	491.01	491.01	491.01
Seoul	490.60	490.15	490.73	490.90
Virginia	435.25	415.14	447.98	453.40
São Paulo	172.54	103.47	108.95	105.21
Paris	63.48	62.99	61.62	60.00

grid (São Paulo) and another with a low presence (Seoul). It will be possible to observe the differences between day and night, seasons, and years.

Figure 5.8 illustrates the local electricity grid emissions over time for São Paulo, and each subplot represents one quarter of the year (3 months). The differences between day and night might be justified by using solar energy and the differences between seasons. However, it is also possible to observe a difference among the years—2021 is the year in which the grid had the highest carbon footprint. The higher emissions of the year 2021 are justified by the hydric crisis that occurred during that period—the greatest of the previous 91 years—and since a large share of São Paulo’s electricity demand is supplied by hydroelectric power, coal power plants were used to meet the power demand [65].

The scenario of Seoul—illustrated in Figure 5.9—represents a location with a low presence of renewables: most of the electricity demand is supplied by carbon-intensive sources such as coal and gas. The usage of PV panels can justify the small variation between the hours, as when the sun starts shining, they produce power and the emissions are reduced.

5.4.2.1.2. Intermittency of renewable sources To evaluate the sensibility of the sizing process considering the uncertainty of the production of renewable sources, we compare—in terms of CO_2 emissions—the operation of the cloud federation

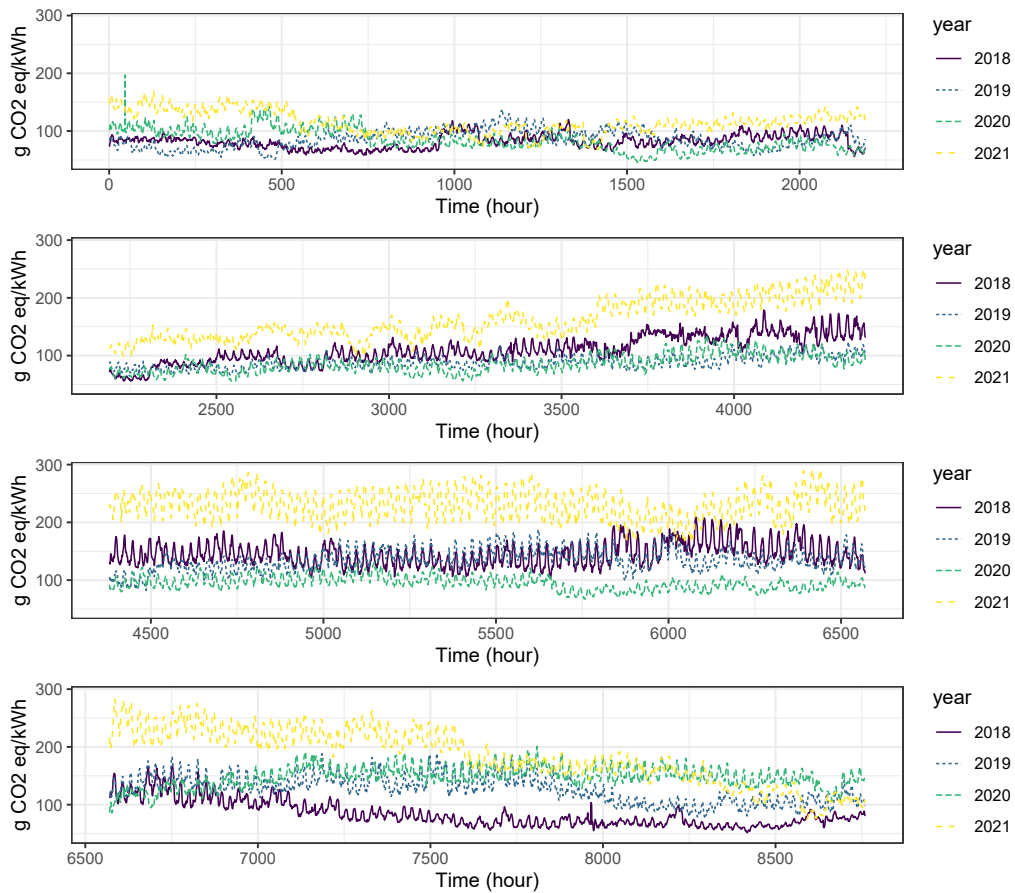


Figure 5.8. São Paulo's hour-by-hour grid emissions for the years 2018, 2019, 2020 and 2021.

using the optimal renewable infrastructure (where all the climate conditions are known in advance) with a renewable infrastructure dimensioned using simple forecasting techniques (average and median from the past). The scenarios are described as follows. First, we collected average and median solar irradiation and wind speed values per time slot from 1980 to 2009 to create inputs for the sizing process. Second, we executed the sizing process using the climate conditions generated in the previous step. Then, the cloud was operated for ten years (2010 to 2019) using the dimensions (PV area, number of wind turbines, and capacity of batteries) computed by the sizing process step, but with the climate conditions of each respective year. Finally, the results in terms of CO₂ emissions were compared to the optimal renewable infrastructure from 2010 to 2019.

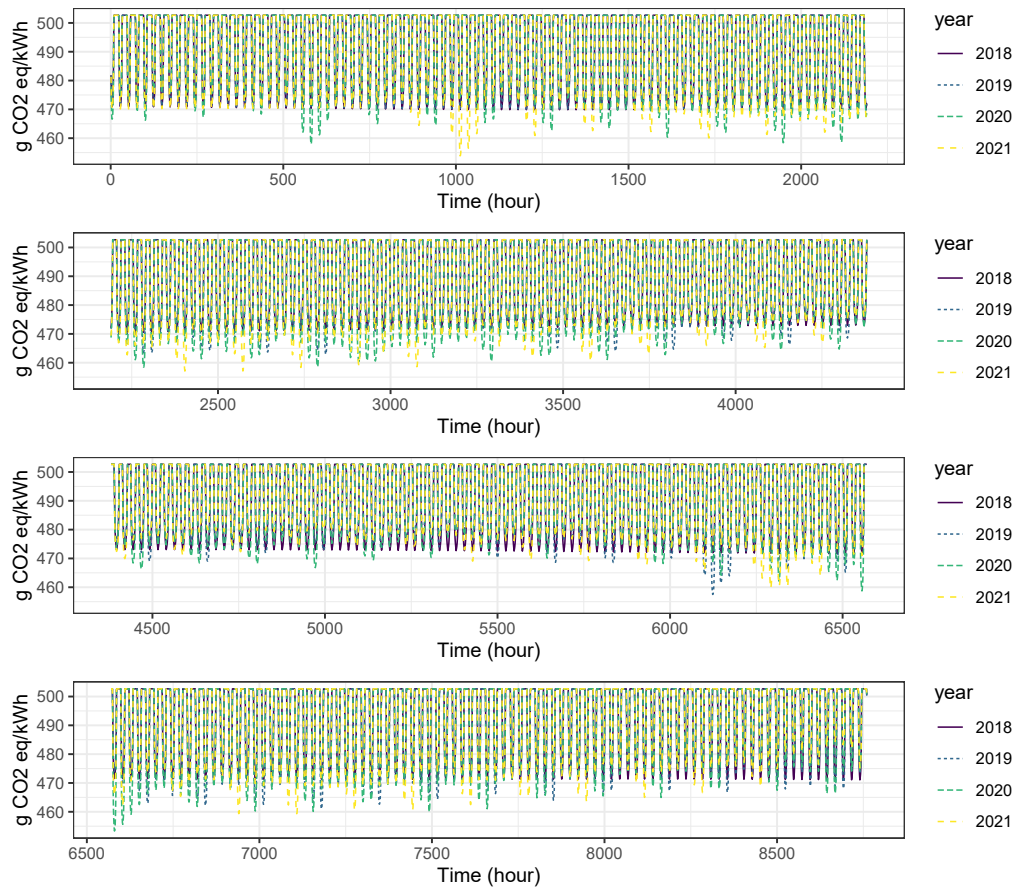


Figure 5.9. Seoul's hour-by-hour grid emissions for the years 2018, 2019, 2020 and 2021.

We also evaluate the adoption of PV only and WT only in the sizing, to assess which impacts the sizing process more. The evaluation follows the same steps described in the previous paragraph.

The data for the solar irradiation was collected from the MERRA-2 project [57], and for the wind speed from the ERA5 data-source [63].

5.4.2.2. Results

5.4.2.2.1. Fine-grain values of grid emission data (hourly) Table 5.9 presents the increase in CO₂ emissions (relative value in percent) of not having access to the fine-grain value of CO₂ emissions (as hourly values).

Table 5.9. Difference in total emissions (%) between the scenario where the sizing used the grid year’s average value in comparison to using hourly information.

Year	Difference (%) in CO ₂ emissions
2018	0.34
2019	0.59
2020	0.18
2021	0.74

5.4.2.2.2. Intermittency of renewable sources Table 5.12 presents the results in terms of CO₂ emissions for the renewable infrastructure that included both PV panels and wind turbines, and in Table 5.10 only PV panels are considered.

Table 5.10. Emissions (in kilotons of CO₂-eq) for the different scenarios—renewable infra only have PV panels and batteries.

Sizing Scenario	Emissions	Diff. to baseline (%)
Optimal sizing 2010-2019	408.767	-
Average irradiation 1980-2009	414.956	1.49
Median irradiation 1980-2009	422.928	3.35

Table 5.11. Emissions (in kilotons CO₂-eq) for the different scenarios—renewable infra only have wind turbines and batteries.

Sizing Scenario	Emissions	Diff. to baseline (%)
Optimal sizing 2010 - 2019	710.351	-
Average wind speed 1980 - 2009	777.957	9.5
Median wind speed 1980 - 2009	770.891	8.5

Table 5.12. Emissions (in kilotons of CO₂-eq) for the different scenarios—renewable infra has PV panels, wind turbines and batteries.

Sizing Scenario	Emissions	Diff. to baseline (%)
Optimal sizing 2010-2019	301.931	-
Average irrad. and wind speed 1980-2009	342.584	11.9
Median irrad. and wind speed 1980-2009	340.784	11.4

5.5 Scheduling flexibility to reduce CO₂ emissions

One of the challenges in the sizing process is that once built, the dimensions of the renewable infrastructure cannot be reduced—this would imply destroying them, resulting in an environmental impact and a waste of money. The intermittency of renewable sources could generate this oversizing of the infrastructure. In this section, we evaluate how workload scheduling may mitigate the effects of a bad-sizing process and, in particular, what the gains are in reducing carbon emissions if we delay the execution of the workload to handle renewable power fluctuations.

5.5.1 Updates in the model

We need to update the workload model (see 4.2.2.2) to evaluate the reduction in carbon emissions by delaying α percent of the workload up to β time slots. We introduce two new variables to model this new feature. Let $alloc_k^d$ represent the required number of CPU cores to execute the workload allocated to the data center d at the time slot k and $delay_{k,i}^d$ be the required number of CPU cores to execute the workload of the data center d that can be delayed from time slot k up to β time slots (i is the index of the list of size β for the delayed workload).

Table 5.13. New notations for the updated workload model for each DC^d ($1 \leq d \leq D$) during time slot k ($0 \leq k < K$)

α	Ratio of the total workload that can be delayed (in percentage)
β	Number of time slots in which the execution of the workload can be delayed (the workload can be delayed up to β time slots)
$alloc_k^d$	Number of CPU cores required to execute the workload that was not delayed at the location of DC d during time slot k
$delay_{k,i}^d$	Number of CPU cores required to execute the workload that was delayed at the location of DC d from the time slot k ($1 \leq i \leq \beta$)

This feature also requires new restrictions. Equation (5.10) models the flexibility of allowing α percent of the workload to be delayed, where W_k is the input that represents the total CPU core demand to execute the workload at time slot k .

$$\sum_{d=1}^D \sum_{i=1}^{\beta} delay_{k,i}^d \leq \alpha \times W_k \quad (5.10)$$

Equation (5.11) models the flexibility to delay the workload up to the next β time slots and ensure that all the workload will be executed:

$$\sum_{d=1}^D (alloc_k^d + \sum_{i=1}^{\beta} delay_{k,i}^d) = W_k \quad (5.11)$$

The allocated workload at a time slot k , and the delayed workloads from the previous $k - \beta$ time slots need to respect the data center servers's CPU core capacity. Equation (5.12) models this restriction.

$$\sum_{d=1}^D (alloc_k^d + \sum_{i=k-\beta}^{k-1} delay_{i,k-i}^d) \leq C_d \quad (5.12)$$

5.5.2 Experiments

To assess the reductions in carbon footprint we can achieve by delaying the workload, we perform a series of experiments with different combinations for the values of α —how much of the workload it is possible to delay—and β —how long it is possible to delay the workload—and compare them with the scenario where it is not possible to delay the workload.

5.5.2.1. Settings

The cloud infrastructure, the workload, grid emissions, and the execution environment are the same as in Section 4.4.1. In order to evaluate only the impact of the flexibility of the scheduling on reducing carbon emissions, all the other parameters are fixed: workload, solar irradiation (average from 1980 to 2019), wind speed (average from 1989 to 2019), area of PV panels and the capacity of the batteries, number of wind turbines, power consumption of servers and network devices, and so on. We present an evaluation for delaying 10% up to 50% of the workload— α values of 0.1, 0.2, 0.3, 0.4, and 0.5—for the period of one hour up to one week— β values of 1 h, 12 h, 24 h, 48 h, 96 h, 120 h, 144 h and 168 h.

5.5.2.2. Results

The results of the experiments in terms of reduction of CO₂ emissions are presented in Table 5.14.

5.6 Monetary costs of reducing the carbon emissions

In the previous sections, we showed the results only in terms of the environmental impact of the cloud operation, now we present the results in terms of the monetary

Table 5.14. Reductions in total carbon emissions (%) in comparison to the scenario where it is not possible to delay the workload. The α values represent how much of the workload can be delayed (in %) and the β values how long the workload can be delayed (in hours).

$\alpha \backslash \beta$	1	12	24	48	72	96	120	144	168
10	0.46	2.59	3.14	3.48	3.66	3.76	3.81	3.85	3.85
20	0.84	3.4	3.85	4.11	4.21	4.21	4.21	4.22	4.22
30	1.15	3.71	4.07	4.25	4.25	4.26	4.26	4.27	4.27
40	1.42	3.89	4.15	4.25	4.26	4.27	4.28	4.28	4.29
50	1.65	4.01	4.22	4.26	4.27	4.28	4.29	4.3	4.3

costs (in dollars) of operating the cloud platform and how much it would cost for the DC operator to reduce their environmental impact. This is also an important aspect, as the decision-makers want their business to be lucrative.

5.6.1 Updates in the model

To perform this new analysis, we will introduce a new model: the monetary cost model. The first aspect modeled regards buying electricity from the regular grid, and it is modeled by Equation (5.13), where $costGrid_k^d$ is an input that represents the costs of buying electricity at each location (in dollars per kWh) at time slot k .

$$PriceGrid_k^d = Pgrid_k^d \times costGrid_k^d \quad (5.13)$$

To measure the price of electricity from renewable sources, we can use the metric Levelized Cost of Energy (LCOE) [66]. This metric compares the total costs of manufacturing and operating the electricity infrastructure (for example, the PV panel) with the total energy it can deliver in its lifetime, and the metric is in the form of costs per unit of electricity generated—\$ per kWh.

Similar to the CO₂ emissions of renewable sources, the price will also differ per location, as the total amount of irradiation and wind speed differ.

Table 5.15. Main notations for the monetary costs model for each DC^d ($1 \leq d \leq D$) during time slot k ($0 \leq k < K$)

$PriceGrid_k^d$	Total price of the electricity consumed from the grid of DC d during time slot k
$costGrid_k^d$	Price of buying electricity (in dollars per kWh) from the local electricity grid of DC d during time slot k
$PricePV_k^d$	Total price of the electricity consumed from the solar panels of DC d during time slot k
$PVLCOE^d$	Price of producing electricity (in dollars per kWh) from the solar panels of DC d considering their Levelized Cost of Energy (LCOE)
$PriceWT_k^d$	Total price of the electricity consumed from the wind turbines of DC d during time slot k
$WTLCOE^d$	Price of producing electricity (in dollars per kWh) from the wind turbines of DC d considering their Levelized Cost of Energy (LCOE)
$PriceBat_k^d$	Total price of the electricity discharged from the batteries of DC d during time slot k
$BatLCOS^d$	Price of discharging energy (in dollars per kWh) from the batteries of DC d considering their Levelized Cost of Storage (LCOS)

Equation (5.14) models the costs of consuming energy from the solar panels, where $PVLCOE^d$ represents the specific LCOE at the location of the data center d (in dollars per kWh).

$$PricePV_k^d = PPV_k^d \times PVLCOE^d \quad (5.14)$$

For the wind turbines, we also use the LCOE to compute its price, and Equation (5.15) models the costs of using energy from the WT, where $WTLCOE^d$ represents the specific LCOE at the location of the data center d (in dollars per kWh).

$$PriceWT_k^d = PWT_k^d \times WTLCOE^d \quad (5.15)$$

For the batteries, the metric Levelized Cost of Storage (LCOS) is similar to the LCOE, and it represents the cost per unit of energy discharged (dollars per kWh or MWh) that takes into account its whole life cycle: calendar and cycle life, Max

Depth of Discharge limitations, and costs from operation and maintenance [67]. Equation (5.16) models the costs of the energy used from the batteries using its LCOS as input ($BatLCOS$ in dollars per kWh of electricity discharged). To avoid oversizing the batteries, the restriction of Equation (5.3) that makes the battery starts empty at the beginning of the day is also used in this scenario.

$$PriceBat_k^d = Pdch_k^d \times BatLCOS \quad (5.16)$$

We also introduce a new objective function to minimize the price of operating the cloud platform instead of its environmental impact, and Equation (5.17) models this new objective.

$$\text{minimize } \sum_{k=0}^{K-1} \sum_{d=1}^D PriceGrid_k^d + PriceBat_k^d + PricePV^d + PriceWT_k^d \quad (5.17)$$

5.6.2 Experiments

To analyze the monetary costs of operating the cloud federation, we present results in terms of price (millions of dollars) and carbon footprint (tons of CO₂-eq) for a series of experiments with both the objective of minimizing the monetary costs and the carbon emissions. Additionally, the reader is presented with a comparison of the dimensions of renewable infrastructure between the solutions of minimal monetary costs and minimal carbon footprint.

5.6.2.1. Settings

The cloud infrastructure, the workload, and the execution environment are the same as in Section 4.4.1. In this scenario, since the objective is to minimize costs, the

carbon footprint from the grid and renewable infrastructure is not considered for the experiments.

For the price of solar panel electricity, we use the tool “Comparative Photovoltaic Levelized Cost of Energy Calculator” from the National Renewable Energy Laboratory of the USA [68]—version 2.0.0 of August 2021. This tool provides a detailed cost model for many parts of the PV panel, with adequate default values. For reproducibility purposes, Table 5.16 lists the values of the parameters used, and the only differences between the default values were for the parameters Service life, Performance Efficiency, and the Energy yield (that depends on the location where the PV module is installed). For the latter, the following values were considered: 1934.03 for Canberra; 1648.08 for Seoul; 1346.32 for Paris; 1737.38 for Virginia; 2215.17 for Dubai; 1549.23 for Singapore; 2125.62 for Pune; 2238.52 for Johannesburg; and 1904.66 for São Paulo.

Table 5.16. Parameters used in the LCOE PV calculator.

Parameter name	Value
Cell technology	mono-SI
Package type	glass-polymer backsheet
System type	fixed tilt, utility scale
Inverter loading ration	1.5
Front layer cost (USD/m ²)	3.5
Cell cost (USD/m ²)	22.20
Back layer cost (USD/m ²)	2.40
Non-cell module cost (USD/m ²)	13.60
Extra component cost (USD/m ²)	0
Operations and Maintenance cost (USD/kWDC/year)	3.5
Balance of system cost,power-scaling (USD/W)	0.2
Balance of system cost,area-scaling (USD/m ²)	53.38
Performance Efficiency (%)	15.0
Energy yield (kWh/kWDC)	specific per location
System degradation rate (%/year)	1.0
Service life (years)	30
Discount rate	6.3

For computing wind turbines’ LCOE (dollars per MWh), we also used the modeling from NREL [69]. Equation (5.18) represents how to calculate the LCOE for WT,

where CapEx is the capital expenditures (dollars per kilowatt)—represents the initial investment cost in the infrastructure, OpEx is the operation expenditures (dollars per kilowatt per year), FCR is the fixed charge rate (%)—the amount of revenue per dollar of investment that must be collected annually from customers to pay the carrying charges on that investment, such as return on debt and equity, income and property tax, book depreciation and insurance [66]. We used the default values for a Distributed Single-Turbine (Large): Capex = 3540; Fcr = 5.42; OpEx = 35. For the net annual energy production (in MWh/MW/year), it also depends on the location where the wind turbine is installed: 1138.5 for Canberra; 829.57 for Seoul; 2065.38 for Paris; 1289.12 for Virginia; 1217.64 for Dubai; 754.0 for Singapore; 869.19 for Pune; 1143.32 for Johannesburg; and 881.95 for São Paulo.

$$LCOE_{wt} = \frac{(CapEx \times FCR) + OpEx}{\frac{AEP_{net}}{1000}} \quad (5.18)$$

For the batteries, we used values from a technical report of the US Department of Energy [67], where each kilowatt-hour of energy discharged (LCOS) has a price of 20 cents.

Finally, Table 5.17 presents the cost in dollars per kWh of using the electrical grid, PV panels and wind turbines. For the grid, to simulate the variation in price, it is considered that during off-peak times—from 22 h to 8 h—the value is half of the total, as in the work of Khodayarsesht et al. [26].

5.6.2.2. Results

Table 5.18 illustrates the cloud operation's total costs (in dollars), environmental impact (CO₂ emissions), and how much energy from the grid (in relation to the total energy consumed by the cloud federation) was used to supply the cloud federation operation considering multiple scenarios. The *Minimum Costs* scenario

Table 5.17. Price of different sources of energy (USD per kWh) at each location. Source for the grid electricity prices: Petrolprices.org.

Location	Grid	PV	WT
Johannesburg	0.074	0.0385	0.1984
Pune	0.104	0.0406	0.2610
Canberra	0.331	0.0445	0.1993
Dubai	0.101	0.0390	0.1863
Singapore	0.272	0.0557	0.3009
Seoul	0.092	0.0525	0.2735
Virginia	0.150	0.0498	0.1760
São Paulo	0.144	0.0453	0.2572
Paris	0.340	0.0643	0.1098

refers to solving the LP using the objective of Equation (5.17)—minimizing the monetary costs; the *Minimum CO₂* refers to solving the LP using the objective of Equation (4.9)—minimize the carbon footprint, and for both cases, the configuration of the renewable infrastructure used is written inside parenthesis; and *Only grid* represents the case where there is no on-site renewable infrastructure in the DCs, and they only use power from the local electricity grid.

Table 5.18. Total costs (millions of \$), emissions (*t CO₂-eq*) and how much energy was used from the grid to supply the DCs with the Grid Usage metric (G.U.) for the different scenarios.

Scenario	Millions of \$	t CO ₂ -eq	G.U. (%)
Min. cost (PV + WT + Bat + grid)	36.76	141 001.67	55.5
Min. cost (PV + Bat + grid)	38.34	145 193.64	59.69
Min. cost (WT + Bat + grid)	51.08	204 568.07	87.79
Min. CO ₂ (PV + Bat + grid)	72.8	37 828.49	16.90
Min. CO ₂ (WT + Bat + grid)	277.52	58 263.38	22.43
Min. CO ₂ (PV +WT+ Bat + grid)	117.31	24 977.89	5.83
Only grid	56.66	222 876.62	100.00

Finally, Figures 5.10, 5.11, and 5.12, show the difference in the renewable infrastructure sizing when the objective function is to minimize the costs and the carbon emissions of the cloud federation operation.

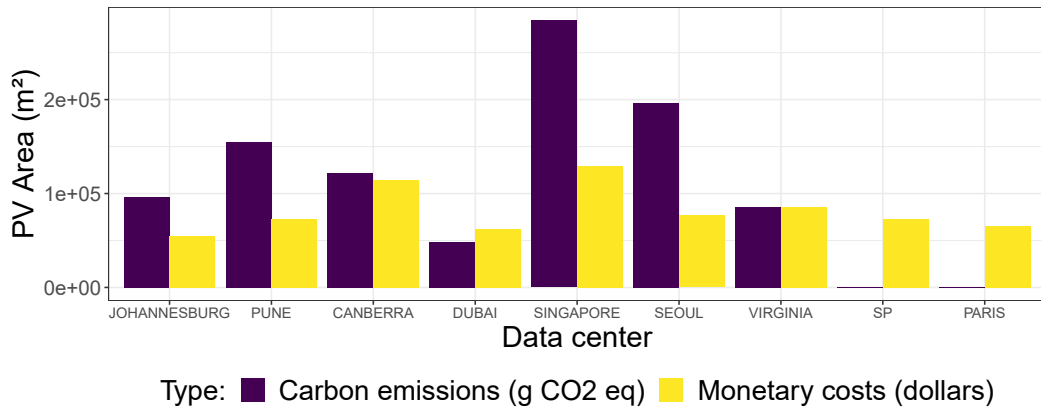


Figure 5.10. PV Area to minimize costs in comparison to minimizing carbon emissions.

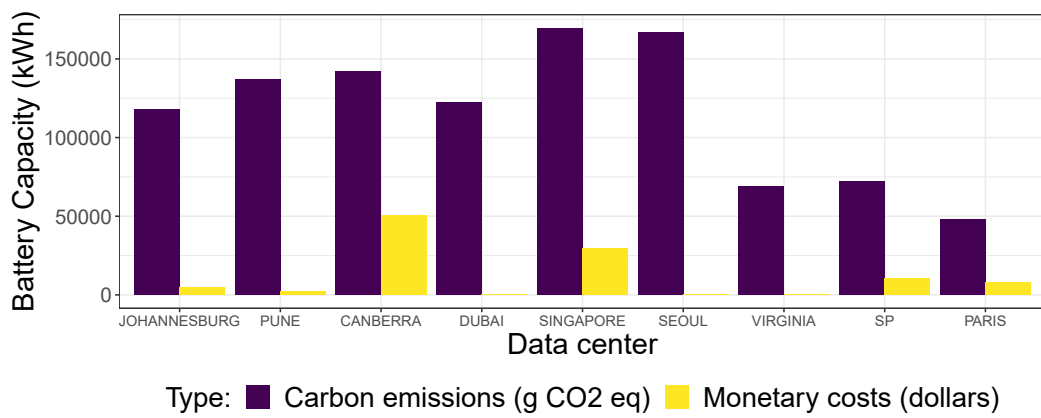


Figure 5.11. Battery capacity to minimize costs in comparison to minimizing carbon emissions.

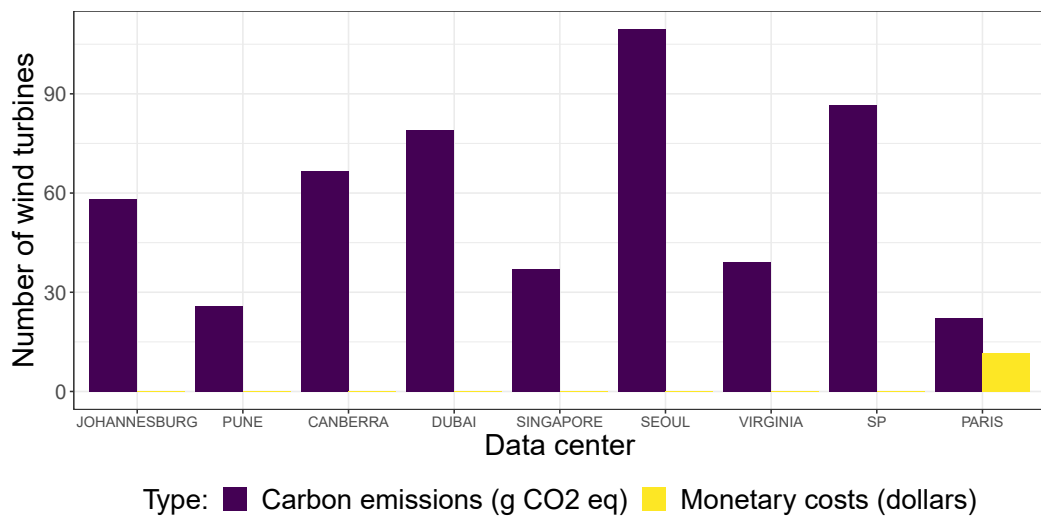


Figure 5.12. Number of wind turbines to minimize costs in comparison to minimizing carbon emissions.

5.7 Adding or replacing servers considering new hardware and future workload

In this section, we show the necessary modifications in our modeling to evaluate the decision to manufacture servers from new generations to match the cloud workload demand that increases year by year, considering that the servers also emit CO₂ during their lifetime. Table 5.19 presents the new notations used in the updated models. It is assumed that the cloud federation will operate for the long term and that new servers will be launched during the lifetime of the cloud data centers. The decision-maker of the cloud federation will determine whether to add new servers to operate with the older ones from previous generations or to replace them, and can use forecasts of the cloud workload growth demand to guide the decision process.

5.7.1 Updates in the model

To model this approach, the following modifications were performed in the IT model (see 4.2.2.1). Two new variables were created: NS^d , which represents the number of new servers to manufacture at the data center d ; and REP_{gen}^d , the number of servers of the generation gen to replace at the data center d . For replacing the servers from previous generations, it is considered that the data center computational capacity in the number of CPU cores cannot decrease, that is, the total number of CPU cores of the new servers needs to be greater or equal to the total number of CPU cores from the servers replaced. This constraint is modeled by Equation (5.19).

$$NS^d \times cpucore_{newgen} \geq \sum_{oldgen} REP_{oldgen}^d \times cpucore_{oldgen} \quad (5.19)$$

The number of servers replaced by a generation cannot be greater than the number of servers of this generation that exist in the DC (ES_{gen}^d). The value of ES_{gen}^d

is extracted from the solution of the previous year. Equation (5.20) models this constraint.

$$REP_{gen}^d \leq ES_{gen}^d \quad (5.20)$$

Table 5.19. New notations for the IT, electrical and footprint models for each DC^d ($1 \leq d \leq D$) during time slot k ($0 \leq k < K$)

NS^d	Number of new servers to be manufactured at DC d
REP_{gen}^d	Number of servers from generation gen to be replaced at DC d
ES_{gen}^d	Number of servers from generation gen that are in operation at DC d
$cpucore_{gen}$	Number of CPU cores of the server from generation gen
$w_{k,gen}^d$	Number of CPU cores allocated to the generation gen servers to execute the workload of DC d during the time slot k
γ	Represents the ratio of the tasks that are service ($0 \leq \gamma \leq 1$) (and remaining $1 - \gamma$ that are batch type)
$FPns^d$	Carbon footprint (in kilograms of CO ₂ -eq) of manufacturing new servers at DC d
$FPrep^d$	Carbon footprint (in kilograms of CO ₂ -eq) of replacing servers at DC d
$FPes^d$	Carbon footprint (in kilograms of CO ₂ -eq) of the existing servers in operation at DC d
ϵ^d	Ratio of CO ₂ -eq emitted by year considering the server lifetime ($0 \leq \epsilon \leq 1$)
$serversCO2$	Carbon footprint (in kilograms of CO ₂ -eq) of manufacturing one new server
age_{gen}	Age of the generation gen servers in years
μ	Ratio of the workload that will be executed in the servers of old generations ($0 \leq \mu \leq 1$)
$lowboundbat^d$	Capacity of the batteries (in kWh) of DC d that is fixed during the sizing process
$lowboundpv^d$	Area of the solar panels (in m ²) of DC d that is fixed during the sizing process
$lowboundwt^d$	Number of wind turbines of DC d that is fixed during the sizing process

Given that a data center may have servers of different generations, it is also necessary to update the models regarding workload execution and power consumption. Now, we have a variable $w_{k,gen}^d$ that represents the workload that is executed on the

servers of a generation gen at the data center d during a time slot k . We have two constraints for this variable: one for the servers that already exist in the DC, and another for the new servers that will be manufactured in the DC. Equation (5.21) models this constraint.

$$w_{k,gen}^d \leq \begin{cases} (ES_{gen}^d - REP_{gen}^d) \times cpucore_{gen} & \text{if server from older generation} \\ NS^d \times cpucore_{gen} & \text{if server from new generation} \end{cases} \quad (5.21)$$

The workload model (see 4.2.2.2) also needs to be updated. Equation (5.22) models the constraint that all the workload must be executed, and that it can be run on any generation of the servers.

$$w_k = \sum_{T_i | r_i \leq k \Delta t < r_i + p_i} c_i = \sum_d \sum_{gen} w_{k,gen}^d \quad (5.22)$$

We also assume that the workload is classified into two categories: services that are mandatory tasks that execute in the DCs, and batch tasks that can execute in any of the DCs. This assumption represents the modern workload of cloud platforms and also avoids allocating all the workload to the DC with the lowest carbon-intensive grid and only adding and replacing servers on this DC. To model the classification of the workload into two categories, we need a new parameter γ that represents the ratio of tasks that are of the service type (and remaining $1 - \gamma$ tasks are of the batch type) executed at each data center d . Equation (5.23) models this restriction.

$$\sum_{gen} w_{k,gen}^d \geq w_k \times \gamma^d \quad (5.23)$$

Equation (5.24) presents the new modeling of the power consumption for all the servers of different generations at a DC d , and Equation (5.25) models the power

consumption of the DC (including the costs of the intra-network equipment and the cooling devices).

$$P_{Servers}^d = \left(\sum_{gen} ES_{gen}^d \times P_{idle}_{gen}^d + w_{k,gen}^d \times P_{core}_{gen} \right) \quad (5.24)$$

$$P_k^d = PUE^d \times (P_{intranet}^d + P_{Servers}^d) \quad (5.25)$$

Now we present the modifications applied to the carbon footprint model (see 4.2.2.4). Regarding the carbon footprint of the servers, it is assumed that it is amortized over the server lifetime, and the LP considers the annual value. For example, if manufacturing a server emits 800 kg of CO₂-eq and its expected lifetime is 4 years, 25% (200 kg of CO₂-eq) of its manufacturing emissions will be accounted for in the 1st year of operation, the other 25% in the second year, and so on. After the fourth year, the server can still remain on the cloud platform, and its carbon emissions will come only from power consumption—all the carbon emissions from manufacturing have been amortized. On the other hand, if the server is replaced in the second year of operation, the remaining 75% of its emissions from manufacturing will also be taken into account.

Equation (5.26) illustrates the footprint of building additional servers at a given data center d , where $serversCO2$ is an input with the total CO₂ emitted from manufacturing the server (in gCO₂-eq), and ϵ the share of the emissions by year— ϵ is equal to 0.25 on the previous example.

$$FPns^d = NS^d \times (serversCO2 \times \epsilon) \quad (5.26)$$

Equation (5.27) illustrates the footprint of replacing servers from previous generations at a given data center d , where $repCO2_{gen}$ is the emissions (in kg of CO₂-eq)

from replacing the old servers that depend on the server age (age_{gen}) in years. The function that computes the value of $repCO2_{gen}$ is defined in Equation (5.28).

$$FP_{rep}^d = \sum_{gen} REP_{gen}^d \times repCO2_{gen} \quad (5.27)$$

$$repCO2_{gen} = \begin{cases} (1 - (age_{gen} * \epsilon)) \times serverCO2 & \text{if } age_{gen} < \text{expected lifetime} \\ 0 & \text{otherwise} \end{cases} \quad (5.28)$$

We also have the carbon footprint of the servers that were manufactured in previous years. Equation (5.29) illustrates the emissions of the existing servers where $esCO2_{gen}$ represents the emissions of operating the server of the generation gen during that year (in gCO_2-eq) and its value is computed by the function in Equation (5.30).

$$FP_{es}^d = \sum_{gen} (ES_{gen}^d - REP_{gen}^d) \times esCO2_{gen} \quad (5.29)$$

$$esCO2_{gen} = \begin{cases} \epsilon \times serverCO2 & \text{if } age_{gen} < \text{expected lifetime} \\ 0 & \text{otherwise} \end{cases} \quad (5.30)$$

It is assumed that the renewable infrastructure stays the same from one year to another. Equations (5.31), (5.32) and (5.33) model these constraints, where $lowboundbat^d$, $lowboundpv^d$ and $lowboundwt^d$ are the capacity of batteries, area of PVs and number of wind turbines, respectively, obtained from the sizing process.

$$Bat^d = lowboundbat^d \quad (5.31)$$

$$A^d = \text{lowboundpv}^d \quad (5.32)$$

$$WT^d = \text{lowboundwt}^d \quad (5.33)$$

In order to evaluate the CO₂ reduction by adding and replacing servers, we need a baseline for comparison. We assume the baseline to be the cloud infrastructure with the servers from the current generations, and new servers are only added if the cloud cannot compute the workload—as it grows year by year, and no server is replaced.

We need to add a new constraint to our LP to have the baseline. This constraint uses a metric similar to the Data Center Utilization presented in the previous chapter (see Section 4.4.2), and gives priority to the old servers to receive the workload, which ensures that they will be used and only manufacture new servers if necessary—the total amount of CPU cores from the old servers is smaller than the required number of CPU cores to execute the tasks of the workload.

Equation (5.34) models this new constraint, where w_{k,old_gen}^d represents the number of CPU cores from the servers of the old generation that will be used to execute the workload at instant k and DC d , $C_{old_gen}^d$ is the computational capacity—total number of CPU cores—of the servers from the old generation, K is the total number of time slots, and μ is an input that represents the utilization rate of the servers from the previous generations. We modeled using the μ parameter to provide the flexibility to evaluate many scenarios with different usage levels of the old servers. To ensure that no server is replaced, we use the constraint modeled in Equation (5.35).

$$\sum_k w_{k,old_gen}^d \geq \mu \times C_{old_gen}^d \times K \quad (5.34)$$

$$REP_{old_gen}^d = 0 \quad (5.35)$$

Finally, Equation (5.36) presents the new objective function of operating the cloud platform, considering that new servers can be manufactured and servers from previous generations can be replaced.

$$\text{minimize } \sum_{k=0}^{K-1} \sum_{d=1}^D (FPgrid_k^d + FPpv_k^d + FPbat_k^d) + \sum_{d=1}^D FPns^d + FPrep^d + FPes^d \quad (5.36)$$

5.7.2 Experiments

Three scenarios are considered in the experiments to assess the impact of the decision to manufacture new servers in terms of CO₂ emissions.

In the first scenario, the model is used to assess the CO₂ reduction by adding servers from a new generation. Two experiments are performed in this scenario: i) the sizing where the cloud infrastructure has few modifications, as it keeps the old servers and only adds new servers if required by the workload demand—Equations (5.34) and (5.35) are included in the LP; and ii) the cloud infrastructure can add new servers and replace servers from old generations—the LP does not include the constraints from Equations (5.34) and (5.35).

The second and third scenarios will consider five years of operation and the new servers launched during this period. In the second scenario, the LP is solved only by having information on the current year's servers and the cloud workload growth forecast. This will generate a plan for the expected server lifetime—to consider all the carbon emissions from manufacturing. In other words, the LP is solved for four years – starting from the year x —considering that it is only possible to

manufacture the server of the current year that will be used together with the existing computational infrastructure or to replace older servers.

Suppose a new, more computationally powerful, and energy-efficient server is launched in the next year ($x + 1$), or a new forecast for the workload growth for the following years is published. In that case, the initial plan of the previous year (year x) can be modified to consider information about the new server or a forecast of the workload growth. This will generate a new plan for the years $x + 1$ to $x + 5$. After the LP is solved for the year x , the results in terms of new servers manufactured and older ones replaced will be used as input for the year $x + 1$.

The five years of operation are solved in the third scenario. Therefore, the LP has access to all the information about future workloads, and server configurations. The second scenario represents an approach more realistic that has the potential to be taken by the decision maker, considering that it is hard to have accurate values for workload and server configurations in the long term, and the third scenario is only used as a baseline—it represents the optimal solution. The two approaches—the greedy from the second scenario and the optimal from the third scenario—are compared using the metric total carbon emissions that originated from manufacturing the servers, the life cycle of the renewable infrastructure, and the power consumed from the local grid.

5.7.2.1. Settings

For the workload growth, we assumed 22% per year as reported by Cisco for the period 2017 to 2021 [61]—for each year, we use an input where the number of requested CPU cores per time slot to execute the workload is 22% higher than the previous year.

Regarding the server configuration, for each year from 2017 to 2021, we selected the server with the highest score in the SPEC Power benchmark [70]—a benchmark

that assesses servers regarding both performance and energy—to represent the state-of-the-art. Table 5.20 lists the differences in hardware characteristics, power consumption, and the carbon footprint of manufacturing each server for the different generations. It is worth noting that in some cases, the same CPU was used in the servers with the highest score for multiple years (such as the Intel Xeon Platinum 8180 and the AMD EPYC 7742). For the CO₂ of manufacturing the servers, the methodology from the work of Gupta et al. [71] is used, which presents how to compute the carbon footprint of servers considering the integrated circuits of RAM, storage (HD and SSDs), and CPU.

The first scenario of the experiments evaluates four years of cloud operation (2017 to 2020) and only considers two generations of servers: servers with the Intel Xeon E5-2660 v2 CPU, which represents the old generation, and servers with the Intel Xeon Platinum 8180 CPU, which represents the new generation. Additionally, the value of μ —that defines a lower bound for the usage of servers from old generations—is equal to 0.99 in the first scenario. The second and third scenarios of the experiments evaluate five years of cloud operation (2017 to 2021) and consider all the generations of servers listed in Table 5.20.

Table 5.20. Servers specifications for different generations. Values are inspired by results from the SpecPower benchmark [72, 73, 74, 75, 76].

Years	CPU	Cores	Pidle	Pcore	kg CO ₂ -eq
< 2016	Intel Xeon E5-2660 v2	20	52	7.5	-
2017, 2018	Intel Xeon Platinum 8180	56	48.9	6.68	578.6
2019, 2020	AMD EPYC 7742	64	66.1	2.71	587.2
2021	AMD EPYC 7763	128	75.6	3	590.3

All the servers are based on the Dell R740 for the HD and SSD values (HD with 3.84 TB and SSD with 400GB), with the same values for CO₂ as in the work from Gupta et al. [71], and they have 256 GB of RAM (16 modules of 16 GB DDR4 10 nm). For the CPU, the CO₂ depends on the die area size, the processor size (in nanometers), and the number of chips in the server. Table 5.21 presents the specifications of the

CPUs used to compute their carbon footprint, and it is assumed that each server has two chips.

For the servers of the first generation (year 2013), it is considered that they have been used more than their expected lifetime, and all their CO₂ footprint has been paid. Finally, according to Barroso et al. [77], the typical lifespan of servers is three to four years. Therefore, we consider the server’s expected lifetime to be four years.

Table 5.21. CPU specifications in terms of die area and processor size. Values retrieved from x86guide.net [78, 79, 80].

Model	CPU die area (cm ²)	Processor size (nm)
Intel Xeon Platinum 8180	6.94	14
AMD EPYC 7742	5.92	7
AMD EPYC 7763	6.45	7

To obtain the area of solar panels, the capacity of batteries, and the number of wind turbines, the sizing process was realized using the average irradiation and wind speed from 1980 to 2019, as in Section 5.3.2.1, and the server configurations of the year 1. For the remaining five years of operation, the wind speed data and solar irradiation used are from 2013 to 2017.

5.7.2.2. Results

In this section, we present the results from the three scenarios of the experiments described in Section 5.7.2 in terms of carbon emissions and the resulting cloud infrastructure—the number of CPU cores from the different generations of servers at each DC over time—after applying the different decisions to manufacture new servers and to replace servers from previous generations.

5.7.2.2.1. Scenario 1: evaluating the CO₂ reductions by adopting servers from a new generation In the first experiment, we assessed the reductions in carbon emissions that could be achieved by adopting servers from a new generation. Figure 5.13

presents the result for the baseline—the current cloud infrastructure keeps the old servers, and only adds new servers because it is required to execute the workload—and Figure 5.14 presents the resulting cloud federation when it is possible to add new servers and replace the old ones.

Each bar in the figures represents the computational capacity of the cloud federation—the total number of CPU cores in the data centers. The colors denote the server generation of the CPU cores (more recent generations have darker colors). One can also observe that when new servers are added—the bar’s height of the corresponding generation increases—and when servers from older generations are replaced with newer ones—the bar’s height of the corresponding generation decreases.

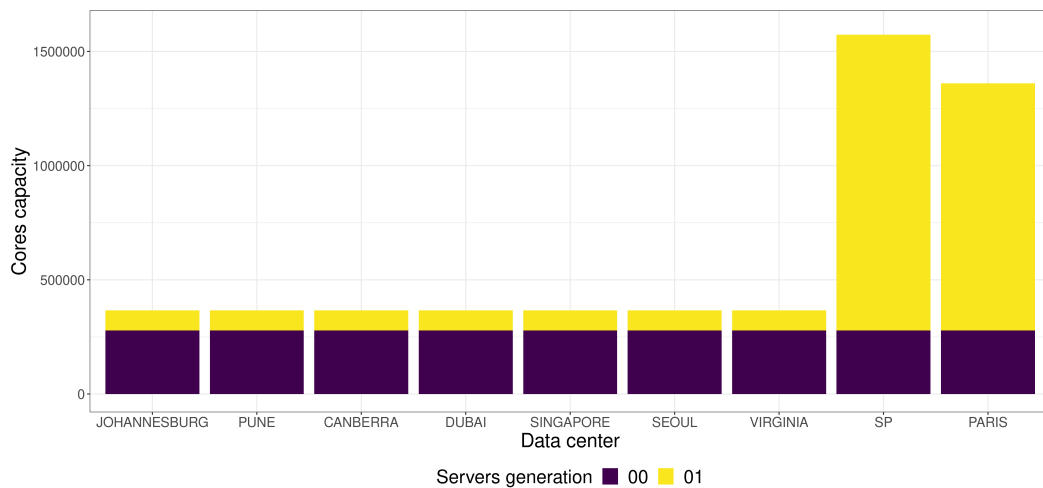


Figure 5.13. Solution for scenario where the old servers are kept and it is only possible to add new servers.

For the baseline (Figure 5.13, we observe that, except for the Paris and São Paulo data centers, all the DCs manufactured the same amount of new servers. The division of tasks can explain this result: all DCs must execute tasks of the service type, and as the workload increased over the four years of operation, it was necessary to add new servers in the DCs to supply the computational demand. The DCs of São Paulo and Paris probably received the batch tasks, since they are the DCs with the lowest carbon-intensive grid, therefore, it was necessary to add more servers to be able to execute the mandatory service tasks and the batch tasks.

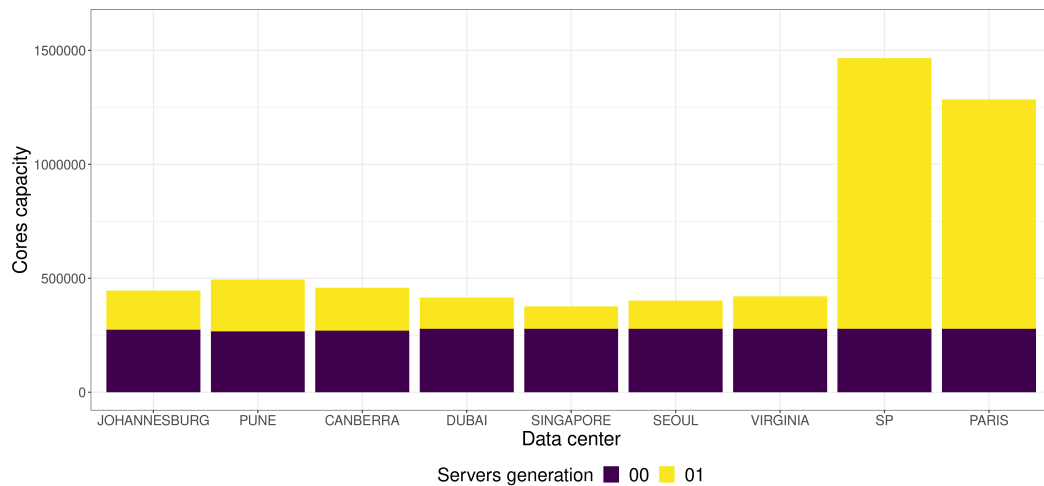


Figure 5.14. Solution for scenario where it is possible to add new servers and also replace the servers from the old generation.

We observe that the number of servers replaced was low in the scenario where it was possible to add and replace servers (Figure 5.14), and this can be justified by the fact that manufacturing a new server emits CO₂ and the old servers only emit carbon from the operation, as they are being used over their lifetime. This scenario also manufactured more servers than the baseline: 8.8% more new servers.

In terms of carbon emissions, the scenario where it is possible to add new servers and replace old ones had a reduction of approximately 10% in comparison to the baseline, as can be seen in Table 5.22. This result is justified by the fact that the new servers are more power-efficient for both idle and dynamic power consumption, and also computationally powerful: the new servers have almost three times the number of CPU cores as the servers of the old generation. This means that by replacing servers of the old generation, we also reduce the static power consumption of the servers of the DC, as one server from the new generation is almost equivalent to three servers of the previous generation regarding computational capacity.

Table 5.22. Total emissions for the different approaches to manufacture new servers.

Scenarios	Emissions (t CO ₂ -eq)
Keep old servers and only add new if needed	492 231.90
Add new servers and replace old ones	443 804.38

5.7.2.2.2. Scenarios 2 and 3: evaluating many servers generations over the years

In the previous section, we analyzed the possibility of reducing carbon emissions by adopting a new generation of servers, and we saw that by allowing the addition of new servers and also replacing servers from the previous generation, we obtained a better result than in the scenario where we kept the old servers and only added new servers if required. Now we extend this analysis to five years of operation, and four generations of new servers. We present the results for the greedy approach—in which the decision is made year by year only having access to the information of the server specifications of the current year—and the optimal solution—in which all server generations are known in advance.

Figure 5.15 provides a comparison of both approaches—greedy and optimal methods—to deciding to manufacture new servers. This comparison assesses the evolution of the cloud federation infrastructure in terms of computational power and which server generations are being used. The year 2016 represents the initial state of the cloud federation, which exclusively contains servers from the first generation. These servers had been in operation for a duration sufficient to offset all the carbon emissions associated with their manufacturing. The years 2017 to 2021 represent the five years of operation during which the two approaches for deciding whether to manufacture new servers are applied. We also present the results of the decision to manufacture new servers for each DC in Figure 5.16—for the greedy approach—and Figure 5.17—the optimal solution.

We observe that the optimal solution makes very few changes to the servers because it knows in advance when the right moment is to add or replace them and how. However, in real life, the first approach, where the decision is made year by year, is closer to what the cloud-federation operator would do. Finally, in terms of total CO₂ emissions, the optimal solution is 13.4% better than the solution that only has information about the current year, as can be seen in Table 5.23.

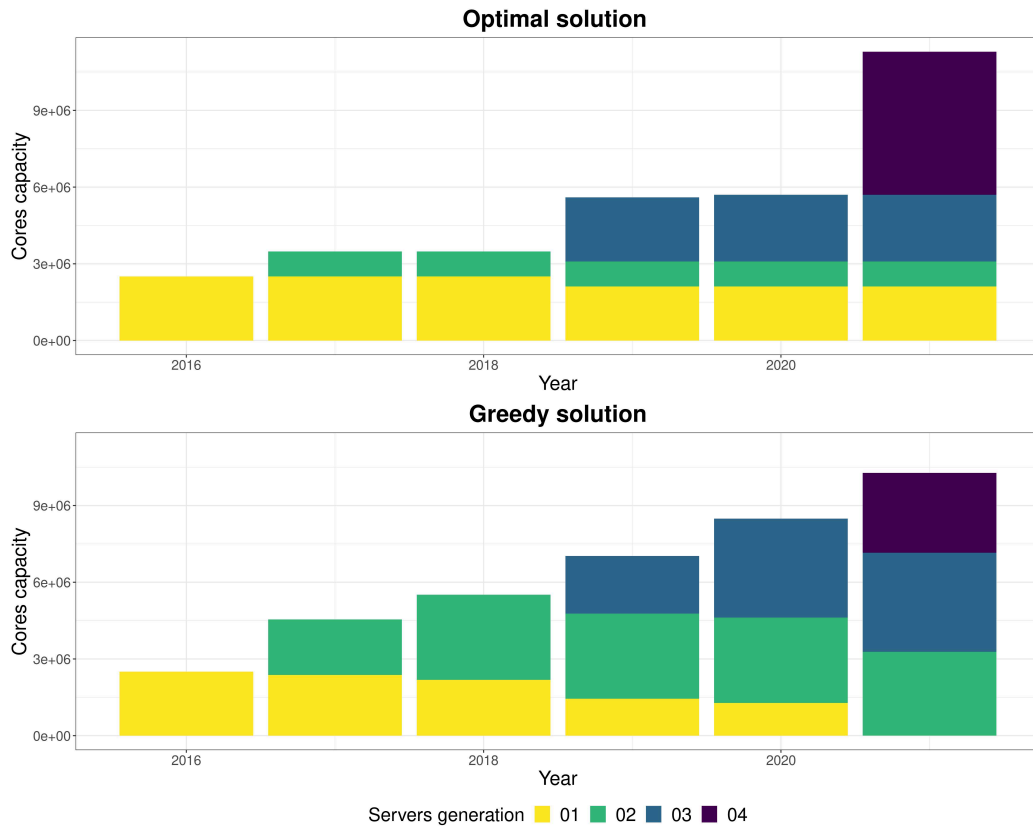


Figure 5.15. Comparison between the optimal and greedy approaches to decide manufacturing new servers in terms of total CPU cores of the cloud federation and the generation of servers.

Table 5.23. Total emissions for the different approaches to manufacture new servers.

Scenarios	Emissions (t CO ₂ -eq)
Optimal solution	213 730.59
Greedy approach	246 867.03

5.8 Discussion

This section presents the reader with an analysis of the experiments and their results. The scope of the study in this chapter is how to reduce the environmental impact that comes from the long-term operation of a cloud federation—in terms of CO₂ emissions—by adding locally installed renewable infrastructure: solar panels, wind turbines, and batteries (to deal with intermittency). One must pay attention to the fact that renewable infrastructure also emits carbon throughout its lifetime.

We made the modifications in our modeling—that initially only considered emissions from manufacturing—and, as expected, there was an increase in the total emissions—around 8%. It is also possible to observe that the area of PVs was reduced in most of the locations—Figure 5.2, except for Johannesburg. This could be explained by the fact that Johannesburg is the location that receives the most solar irradiation throughout the year, so it could compensate for the decrease in PV area in the other locations. Regarding the batteries, the reduction in Pune, Seoul, and Singapore could be justified by the smaller PV area, as there will be less energy to store.

Finally, including the life cycle aspect makes our modeling more realistic, and the emissions are still better than the scenario where only power from the local electricity grid is used in terms of carbon footprint—81% in the scenario with PV and batteries.

Regarding the wind turbines, we saw that including them in the renewable infrastructure has a significant positive impact on the carbon footprint of operating the cloud federation: a 34% reduction in CO₂ emissions in comparison to only using solar panels and batteries. This reduction could be justified by the fact that renewable power is produced even when the sun is not shining and throughout the whole year, which results in a reduction in the required PV area and battery capacity that can be observed in Figures 5.4 and 5.5—in the previous chapter, we saw the dimensions of PV and batteries needed to deal with the low solar irradiation during winter.

Nevertheless, the number of necessary wind turbines to manufacture is quite high, which is a problem considering the land area requirements of wind turbines. One study from NREL that evaluated the land area requirements in the United States reports that the average capacity density (relation between wind power production and required land area) is 3.0 ± 1.7 MW/km² [81]. Considering that in our experiments, we considered wind turbines with a rated power of 1.5MW, which implies that for each square kilometer, it is possible to install from one to three wind turbines. This would not be possible for data centers located in urban centers that

are highly populated. For example, in the case of Paris—the one with the lowest number of wind turbines—we would need from 7 to 23 km², and in the case of Seoul—the one with the highest number of wind turbines—it would require 36 to 110 km².

In comparison to solar panels, we observe that for all the evaluated locations—except Paris—the wind turbines have a lower potential for power generation—as seen in the Capacity Factor values of Table 5.6. Taking into account these points, it may be more interesting for the cloud federation operator to buy power from wind farms located near its data centers than to install wind turbines on them.

As said in Section 5.3, solar irradiation has a lower variance than wind speed, impacting the sizing process's quality. We saw that in the comparison of the optimal scenario for the renewable infrastructure that only considered PV panels and batteries, the sizing process that used simple estimation techniques (average and median values) had precise results, being up to 3% worse than the optimal scenario (Table 5.10). On the other hand, the scenario that only considers wind turbines and batteries as the green power infrastructure (Table 5.11) was significantly worse when compared with the optimal solution—around 11%—and presented more than two times the carbon emissions of only using solar panels—which can be justified by the lower potential to generate wind power on the selected locations as seen in Table 5.6.

For the scenario with a hybrid configuration of solar panels and batteries, it is possible to observe in Table 5.10 that it became less precise—up to 12% worse than the optimal—as it is affected by the uncertainties of solar irradiation and wind speed. Nevertheless, even in the worst case, the reduction in total CO₂ emissions by using the hybrid configuration with PVs and WTs is significant: the worst scenario for PV + WT + Bat has a 17% lower carbon footprint than the scenario with PV + Bat.

In what concerns the sensitivity of the model to the grid emissions input, we saw that the initial modeling that uses the average value of the year is robust: using the hourly value reduces the total CO₂ emissions by less than 1%—as seen on Table 5.9. This result presents a positive outcome, considering that not every location provides a fine-grain value of the carbon intensity of its electricity grid.

On the topic of exploring the flexibility in the scheduling of the workload to reduce carbon emissions, it is possible to extract the following information from the results. The first is that the reduction of the carbon footprint seems to have a limit (around 4%). This can be justified by the fact that there is little difference in the climate conditions during the interval of one week or that the DC, which would reduce carbon emissions, is already at peak capacity and cannot receive more workload.

The second interesting observation is that by delaying a small portion of the workload (for example, 10% to 20%), the reduction is already close to the maximum possible reduction value. Finally, this approach can be used to reduce the impact of renewable sources' intermittency in the sizing process—as we saw differences from 1% to 12% in comparison to the optimal scenario on Section 5.4—and in the context of cloud federations that emit from tens to hundreds of kilotons of CO₂-eq, a reduction of 4% is not negligible.

Concerning the costs of reducing the environmental impact of the cloud operation—one of the most important variables for the decision-makers—we see in Table 5.18 that the hybrid configuration that uses solar panels and wind turbines is the cheapest—around 35% cheaper and emits 37% less CO₂ in comparison with using only the grid. On the other hand, the solution that results in the lowest environmental impact (*Minimum CO₂ PV + WT + Bat + grid*) is the second most expensive: it presents a reduction of a factor of 9 in CO₂ emissions compared to the grid only scenario, but it costs double.

The results allow for comparing the benefits of using exclusively wind turbines or solar panels as well. We observe that only using wind power as a renewable source (*Min. CO₂ (WT + Bat + grid)*) results in the most expensive scenario and the third best in terms of environmental impact—in comparison with only using power from the grid, it is almost five times more expensive and emits 73% less. The scenario where the renewable infrastructure is only composed of PV panels (*Min. CO₂ (PV + Bat + grid)*) is the best in terms of costs and environmental impact: it has a price close to the grid-only scenario—22% more expensive—and has a reduction of 81% in CO₂ emissions. One can also observe that, in terms of minimizing the operation's monetary costs, the cloud federation will be less independent of the grid: using from 55% to 88% of grid power to supply its energy demand. In contrast, when the objective is to minimize the environmental impact, the cloud federation will be more autonomous, consuming from 6% to 22% of grid power.

When considering the long-term operation of cloud data centers, the evolution of the technology and hardware and the increase in computational workload are of significant concern as well. Furthermore, these two variables increase the uncertainty of the problem: the data centers usually have a lifetime longer than one decade [77], how power-efficient will the servers be, or how much will the workload increase during this period?

We demonstrated through our experiments that our model can be applied to assess the carbon reduction obtained in the cloud federation's operation by adopting servers from a new generation. One can expect the servers from new generations to be more power-efficient and computationally powerful, but we must pay attention to the environmental impact of manufacturing the servers. Furthermore, with the increase of low-carbon-intensive power supplies in the DCs, most of the environmental impact is shifting to Scope 3 of the GHG protocol—which includes manufacturing the IT infrastructure [18].

The results in Section 5.7.2.2.1 evaluated the carbon reductions that can be achieved by adopting one new generation of servers, and we saw that in the scenario in which it is possible to add new servers and also replace the old ones, we can reduce approximately 10% of the total carbon emissions in comparison to the baseline—the scenario where it is not possible to replace old servers, and we only add new servers to match the workload demand. This result is justified by the new servers being more power-efficient and computationally powerful (more CPU cores), which reduces the carbon footprint from the power consumption of the DCs operation. It is also interesting to note that more servers were manufactured in the scenario where it is possible to add servers from a new generation and replace servers from the old generation compared to the baseline—approximately 9%, resulting in a higher carbon footprint in manufacturing the servers. However, this new generation, in particular, had enough improvements in power efficiency to mitigate the emissions from manufacturing the new servers.

We also showed that our model is flexible enough to evaluate the scenario with many generations of servers in Section 5.7.2.2.2. The approach presented in this section, where the choice of manufacturing new servers is made year by year using input predictions from the growth of the workload—a greedy strategy, is closer to what could be adopted by the decision-makers of cloud federations, and it presented good results: in comparison to the optimal scenario—unlikely to be achieved as it needs all the information of future hardware characteristics and workload for five years—it is 13.4% worse.

We see in Figure 5.15 that the optimal solution is to manufacture most of the servers from the last generation—the year 2021. This decision was made because it knew in advance that this was the best server. In contrast, the greedy solution did not have access to this information and decided to manufacture servers in the previous years. As a result, it would be too expensive in terms of carbon footprint to discard the servers from the previous years and manufacture the servers for the year 2021.

Additionally, we observe in Figure 5.16 and Figure 5.17 that the LP decided to place most of the new servers of the last generation in the DCs of São Paulo and Paris. These data centers are connected to the local electricity grids with the lowest carbon intensity, allowing them to offset the additional emissions generated by the power consumption of these new servers. Furthermore, we see that in the optimal solution, the servers are being used way more than the expected lifetime of 4 years: except for the Pune DC, the first-generation servers are still being used nine years after their expected lifetime. This is interesting to motivate extending the lifetime of servers, as they are computationally powerful, and discarding them presents other environmental impacts than carbon emissions. Furthermore, extending the lifetime of the servers and waiting longer to replace them increases the chance of having a new-generation server that is significantly more power-efficient and computationally powerful.

Finally, all the modifications in the modeling do not change its computational complexity, we still use only linear variables, and it can be solved optimally in polynomial time.

5.9 Summary

In this chapter, we studied the problem of reducing the long-term environmental impact of cloud federations by integrating local renewable infrastructure at the sites where the data centers reside. We extended our initial modeling, presented in Chapter 4 in the following points:

- considered the whole life cycle of the renewable infrastructure;
- integrated wind turbines in the model to further reduce the environmental impact, in particular when the sun is not shining;

- evaluated how sensible the model is to the inputs of solar irradiation, wind speed and grid emission values;
- showed that allowing the workload to be delayed can reduce the carbon footprint of the cloud operation, and partially mitigate the error of the sizing process caused by the intermittency of renewables, which is important given that once built it is not feasible to reduce the dimensions of the renewable infrastructure;
- conducted an analysis of the monetary costs of minimizing the cloud's environmental impact, and illustrated that the renewable infrastructure can indeed reduce costs for the cloud operators;
- included the IT sizing in the model, to evaluate to what extent adopting servers from new generations can reduce the carbon footprint, as they might be more power-efficient, but manufacturing them also emits carbon.

These modifications were carefully made to use linear variables and restrictions, therefore the problem remains optimally solved in polynomial time.

All these scenarios may further help the decision-makers in their quest to reduce the environmental impact of their cloud federation. For example, we saw that the renewable infrastructure that included wind turbines had the lowest environmental impact, however, in comparison to PV panels, wind turbines require a large land area—PVs could be installed on the rooftops—and are more expensive, therefore their adoption needs to be thoroughly examined—in particular if the data centers reside in large urban areas.

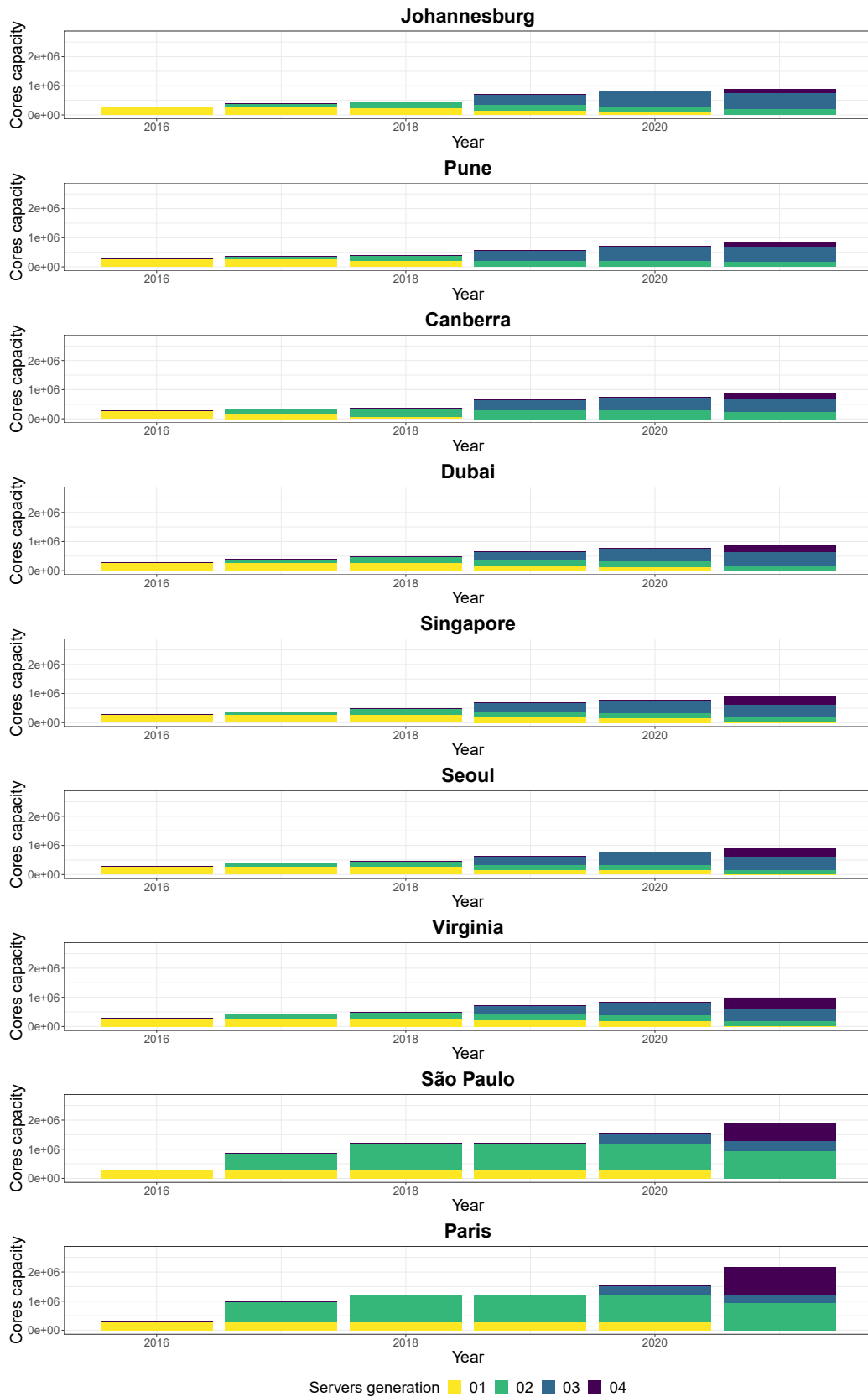


Figure 5.16. Solution for the greedy approach to decide manufacture servers—when there is only access to information of the current year’s server.

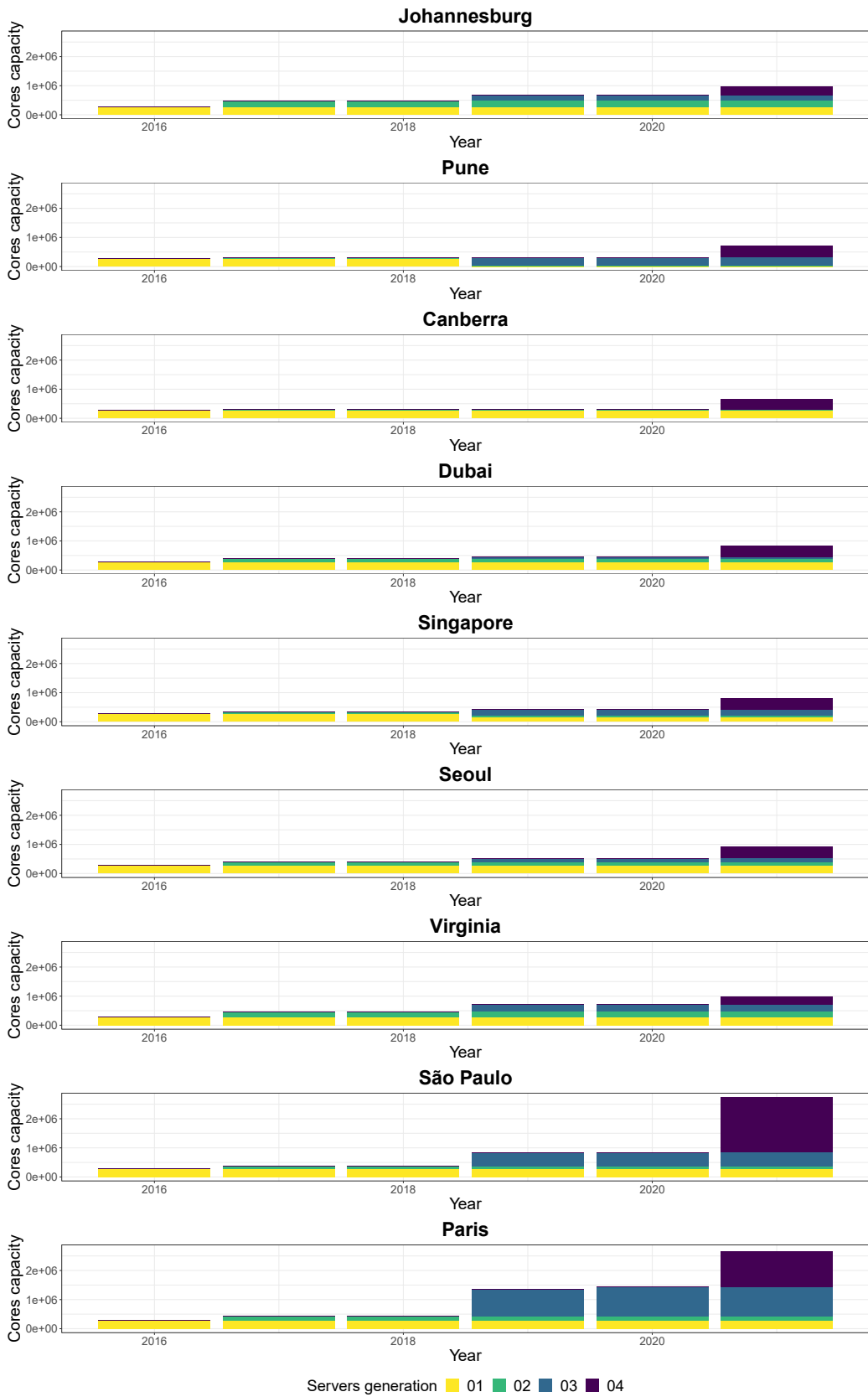


Figure 5.17. Solution for the optimal approach to decide manufacture servers—when there is only access to information of the servers off all the years in advance.

Cloud computing is an essential component of our modern digital society, given that it supports the majority of services and applications we use. On the other hand, one cannot neglect the environmental impact it presents, which originates both from the energy consumption of its operation—higher than the electricity demand of entire countries—and the life cycle of its infrastructure.

In this thesis, we studied strategies to reduce the environmental impact—in terms of carbon footprint—of operating and sizing cloud federations with data centers geographically distributed worldwide. More specifically, we explored two carbon-responsive strategies: “follow-the-renewables” and the sizing of the renewable infrastructure and IT equipment.

This chapter begins by providing an overview of the main contributions made in this thesis, as detailed in Section 6.1. Then, we discuss in Section 6.2 potential opportunities for future research directions that build upon the insights derived from the work presented in this thesis. Finally, Section 6.3 presents the various ways in which our work has been disseminated, including a list of scientific publications that have emerged from the research conducted in this thesis.

6.1 Summary of contributions

The first main contribution of this thesis is the analysis of the impact of the follow-the-renewables strategy on both energy consumption and network—presented in

Chapter 3. This approach is an interesting solution to exploit the geographic distribution of cloud data centers all over the world to reduce high-carbon-intensive electricity consumption. However, the decision to migrate the workload needs to consider the resources involved in this operation, particularly the network.

We conducted computational experiments to investigate the impact of the follow-the-renewables strategies. These experiments used real-world data for workload, climate conditions, models validated by the scientific community for energy consumption and network usage, and different adaptations of the follow-the-renewables.

The results demonstrated that migration planning without taking into account the network—in particular, the network topology and usage—will result in network congestion and waste of energy. As seen in Section 3.4.3.4, the energy wasted could be used to power the servers of cloud data centers, and it also contributes to increasing the environmental impact of the cloud operation. We proposed an algorithm for migration planning that can reduce non-renewable energy consumption while not impacting the network, compared to works from the literature that schedule the workload migration without considering the network.

The second main contribution of this thesis is the model to both size the renewable and IT infrastructure and operate cloud federations with the objective of reducing the carbon footprint—presented in Chapter 4 and Chapter 5.

The initial model proposed in Chapter 4 focused on the operation for the short term with one year of duration and the possibility of manufacturing on-site solar panels and lithium-ion batteries to generate renewable power and store it to deal with the intermittency of green power.

The first key aspect of the proposed solution is that it solves both subproblems—sizing and operating—as a single problem, allowing us to evaluate decisions such as increasing the on-site renewable infrastructure dimensions of a data center or

scheduling the workload to different geographic locations using the follow-the-renewables approach.

Another key aspect of the model is that it considers the specific characteristics of the geographic locations of the DCs in terms of climate conditions—the capacity to generate renewable power, cooling needs, and the local grid electricity supply—that may already incorporate low-carbon-intensive power sources. Lastly, the proposed solution does not neglect that manufacturing the renewable infrastructure also presents an environmental impact.

Through experiments using real-world data for workload, climate conditions, server specifications, location of data centers, and grid energy mix, we demonstrated that the hybrid solution, which combines the on-site renewable infrastructure and can use power from the local grid, is better in terms of carbon footprint than only operating the DCs using power from the local electricity grid or exclusively power from the on-site renewable infrastructure.

We then extended our modeling for the long term in Chapter 5—which is mandatory given that data centers have operational lifetimes spanning over a decade. We started by improving the modeling to consider the carbon footprint of the entire life cycle of the renewable infrastructure—from manufacturing to discarding or recycling—which provides more accurate information on the environmental impact and reduces oversizing.

Furthermore, we also evaluated including wind power as an on-site renewable source. Our experiments demonstrated that despite further reducing the carbon footprint, it might not be adequate for on-site renewable production given its requirements in terms of land area, the fact that it increases the uncertainty of the sizing process, and the higher monetary costs for wind power production. Therefore, the best candidates for the on-site renewable infrastructure are solar panels to generate

power and lithium-ion batteries to store power to supply at night or during periods with low irradiance.

We also showed that workload scheduling can mitigate a part of the impact of the errors in the sizing process—caused by the uncertainty of the climate conditions.

In terms of costs, we showed that adopting on-site renewable infrastructure is cheaper than operating the DCs exclusively with power from the local electricity grid. Additionally, the solution with solar panels and batteries is the best in both environmental and monetary aspects for the cloud operators.

Our model also enables us to assess the potential carbon reduction by adopting servers from new generations that may be more power-efficient, while also considering the carbon footprint of manufacturing the servers. The model is flexible enough to compare one generation of servers to another or determine what would be the optimal solution given many generations of servers. In the optimal solution, the servers are used over their expected lifetime. This fact can be used as inspiration for extending real-life server usage, since they are computationally powerful, discarding them results in environmental impact, and waiting to replace the servers increases the chance of having a server generation that is more power-efficient and computationally powerful.

Finally, the model was thoughtfully designed to exclusively employ linear variables. This enables the model to be solved optimally in polynomial time and evaluate long-term scenarios in a reasonable amount of time. This efficiency reduces the energy consumption and associated carbon footprint of the sizing process itself. Decision-makers could adopt this model to guide their efforts to reduce the environmental impact of cloud computing platforms.

6.2 Future Research Directions

As discussed in Section 3.5, to further assess the impact of the follow-the-renewables strategies, we also need to take into account the network usage by the workload—that reduces the available bandwidth for the migration process. Additionally, the model can be analyzed for container virtualization technology. Since containers are typically smaller than virtual machines, their migration time is faster. This can result in more tasks being migrated or allow migration to data centers located farther away.

We saw in Chapter 3 that applying follow-the-renewables has significant potential for reducing the carbon emissions of the cloud operation. We didn't include it in our modeling for sizing and operating the globally distributed cloud data centers, given the high latency between the network links that connect these data centers, which would result in a long migration time. This analysis needs to be made to evaluate the potential of migrating the workload, given that the DCs located farther away might have more availability of low-carbon intensive sources. One possibility is to have a threshold for the migration time, or migrate only tasks with low priority as batch tasks.

Regarding our proposed approach for sizing and operating cloud federations, one crucial point for the long term is the degradation of the renewable and IT infrastructure and the failure of IT equipment. For the decision to manufacture new servers, the model can be extended to a fine grain at the level of the IT equipment (for example, replacing only a disc that failed). The monetary cost analysis can also be applied to the decision to manufacture or replace new servers, provided that data on the hardware price is accessible. Additionally, it is possible to formulate a multi-objective optimization problem between the costs in dollars and the carbon footprint—for both the renewable infrastructure and the IT part. Another possibility is to analyze the sizing process considering the usage of other types of hardware

for computations, particularly graphical processors (GPUs) that are widely used for artificial intelligence applications.

We explored the sizing decision for existing cloud federations. Our proposed solution could also be extended to evaluate the placement of new data centers with the objective of minimizing the carbon footprint. For example, given a set of options for locations, their respective characteristics in terms of potential for generating renewable power, climate conditions, cooling needs, workload demand, and server specifications and their associated carbon footprint, it would be possible to perform a comparative analysis of the carbon footprint of each location. The results could be used to guide the decision on the location of the new data center.

Finally, there are other types of environmental impacts other than carbon emissions. For example, cloud computing platforms present impacts in terms of water usage for cooling, resource extraction for manufacturing the integrated circuits and the data center infrastructure, and improper disposal of the IT equipment, which could result in toxic substances being released into the environment. In the first moment, it is necessary to model these types of environmental impacts to generate metrics that will permit us to measure them. Similar to how there are metrics to assess the quality of service, it would be interesting to have metrics to evaluate the environmental impact of these services and applications. In the second step, it will be possible to propose solutions to reduce the environmental impact. For example, these metrics could be incorporated into multi-objective workload scheduling algorithms or included in the sizing process to minimize them.

6.3 Work Dissemination

The following two main publications emerged from the work performed during this thesis—both in the format of full papers:

- **Miguel Felipe Silva Vasconcelos**, Daniel Cordeiro, Georges Da Costa, Fanny Dufossé, Jean-Marc Nicod, and Veronika Rehn-Sonigo. “Optimal sizing of a globally distributed low carbon cloud federation”. In *2023 IEEE/ACM 23rd International Symposium on Cluster, Cloud and Internet Computing (CCGrid)*, Bangalore, India, 2023, pp. 203-215. DOI: 10.1109/CCGrid57682.2023.00028.
- **Miguel Felipe Silva Vasconcelos**, Daniel Cordeiro and Fanny. “Indirect network impact on the energy consumption in multi-clouds for follow-the-renewables approaches”. In *Proceedings of the 11th International Conference on Smart Cities and Green ICT Systems — SMARTGREENS 2022*, pages 44–55. INSTICC, SciTePress. DOI: 10.5220/0011047000003203. Candidate for the best paper award.

The work was also disseminated in the form of short summaries and presentations with partial results to receive initial feedback at the following events:

- **Miguel Felipe Silva Vasconcelos**, Daniel Cordeiro, Georges Da Costa, Fanny Dufossé, Jean-Marc Nicod, and Veronika Rehn-Sonigo. “Long-term evaluation for sizing low-carbon cloud data centers”. In *ComPAS 2023 Conférence francophone en informatique*, Jul 2023, Annecy, France
- **Miguel Felipe Silva Vasconcelos**. “Towards low-carbon globally distributed clouds”. In *GreenDays 2023*, ENS Lyon.
- **Miguel Felipe Silva Vasconcelos**, Daniel Cordeiro and Fanny Dufossé. “Dimensioning of multi-clouds with follow-the-renewable approaches for environmental impact minimization”. In *23ème congrès annuel de la Société Française de Recherche Opérationnelle et d’Aide à la Décision (ROADEF 2022)*, INSA Lyon.
- **Miguel Felipe Silva Vasconcelos**. “Towards greener multi-clouds: scheduling with follow-the-renewables and dimensioning of solar panels and batteries”. In *5th Workshop of the InterSCity Project (INCT of the Future Internet for Smart Cities)*, São Paulo, 2022.

Finally, the work presented in Chapter 5 will be submitted to a scientific journal—the publication was in the writing phase at the time this thesis was written.

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A.1 Introduction

Cloud computing (ou l'informatique en nuage) a révolutionné le monde industriel et académique de la technologie de l'information avec sa capacité à fournir de grandes quantités de ressources informatiques à la demande. La plupart des applications et des services que nous utilisons quotidiennement, qui comptent de plus en plus d'utilisateurs, tels que les réseaux sociaux, le courrier électronique, les jeux vidéo, la banque en ligne, les applications de santé et la diffusion vidéo, sont pris en charge par des plates-formes de cloud computing.

Malgré tous ses avantages, les centres de données en nuage (DC), les installations qui hébergent toute l'infrastructure nécessaire au cloud, ont une demande énergétique significative. L'Agence internationale de l'énergie (AIE) estime que les centres de données qui hébergent les plateformes de cloud computing ont consommé entre 240 et 320 TWh, soit environ 1% de l'électricité finale mondiale générée en 2022 [1]. Pour mettre cette consommation d'énergie en perspective, cela suffit à fournir la demande énergétique annuelle de pays entiers. En 2022, sept pays avaient une consommation énergétique similaire à la demande énergétique des DC : la Grèce (316 TWh), Israël (304 TWh), la Biélorussie (297 TWh), la Suisse (292 TWh), la Hongrie (266 TWh), le Portugal (258 TWh) et le Maroc (257 TWh) [2].

Les efforts à la fois de la communauté académique et de l'industrie tentent de réduire cette gigantesque consommation d'énergie. Une analyse de l'utilisation mondiale de l'énergie par les centres de données réalisée par Masanet et al. [3] a montré que pendant la période entre 2010 et 2018, le trafic Internet des DC a augmenté de plus

de 10 fois, on estime que la capacité de stockage des DC a augmenté de 25 fois, et la charge de travail et le nombre d'instances de calcul des DC ont augmenté de 6 fois. D'autre part, la consommation d'énergie n'a augmenté que de 6% grâce aux améliorations suivantes : i) la virtualisation, qui a permis une augmentation de 5 fois du nombre moyen d'instances de calcul par serveur physique ; ii) des serveurs plus économes en énergie (une diminution d'un facteur de 4 en ce qui concerne la puissance utilisée pour le calcul et un facteur de 9 en termes de watts par téraoctet) ; et iii) des infrastructures économes en énergie, en particulier pour les besoins de refroidissement et d'alimentation électrique.

Il est incertain si les améliorations de l'efficacité dans le cloud computing permettront de compenser l'augmentation de la consommation électrique causée par la demande croissante en ressources informatiques à long terme. Dans le travail de Koot and Wijnhoven [4], les auteurs ont développé un modèle de prévision de la consommation d'énergie des centres de données en utilisant l'approche des modèles dynamiques de système. En considérant la période de 2016 à 2030, et le scénario avec la fin de la loi de Moore, qui prédit que le nombre de composants dans les circuits intégrés double chaque année [5], et la montée des applications industrielles de l'Internet des objets, la demande énergétique des centres de données pourrait atteindre 2,3% de la génération mondiale d'électricité, elle doublera par rapport à ce qui a été rapporté par l'AIE pour l'année 2022 [1].

La consommation d'électricité des centres de données a un impact environnemental en termes d'émissions de gaz à effet de serre (GES). Selon l'Agence internationale de l'énergie, 1% des émissions de GES liées à l'énergie proviennent des centres de données et des réseaux de transmission de données [1]. L'ampleur de cet impact dépend du type de source utilisé pour produire l'électricité. Le tableau A.1 présente les émissions pour les différents types de sources d'énergie pour produire 1 kWh d'énergie. Les émissions sont mesurées en utilisant le métrique de l'équivalent en dioxyde de carbone (ou CO₂-eq). Cette métrique est utilisée pour comparer différents

GES en termes de leur potentiel de réchauffement global (PRG) en utilisant le dioxyde de carbone comme base : le méthane (CH₄) a un PRG de 25, ce qui signifie que l'émission de 1 g de CH₄ dans l'atmosphère a le même impact environnemental que l'émission de 25 g de CO₂[6]. On peut observer que la production d'électricité à partir du charbon émet 77 fois plus de CO₂ que l'éolien ou le nucléaire. En 2019, environ 70% du trafic de données d'Internet était traité par les centres de données dans l'« Allée des centres de données », une région située en Virginie (États-Unis d'Amérique), qui était alimentée par moins de 2% d'énergie renouvelable (énergie verte)[7].

Afin de réduire leur impact environnemental, les principaux fournisseurs de cloud, tels qu'Amazon AWS, Apple, Google, Meta (anciennement Facebook) et Microsoft, se sont engagés à intégrer dans leurs opérations des centres de données une électricité à faible intensité carbonée produite par des sources renouvelables, et certains ont déjà déployé leurs projets pour atteindre l'objectif de minimiser l'empreinte carbone. En effet, Google a rapporté qu'en 2022, 64% de l'électricité utilisée pour alimenter ses centres de données sur une base horaire provenait de sources renouvelables [8], certains centres de données atteignant même jusqu'à 97% d'utilisation d'énergie verte.

Table A.1. Émissions (en g CO₂-eq) de différentes sources d'énergie par kWh d'électricité produite [9].

Technologie de génération	Émissions (g CO ₂ -eq/kWh)
Charbon	1 010
Pétrole	840
Gaz naturel	486
Biomasse	52
Photovoltaïque	43
Hydraulique	21
Nucléaire	13
Éolien	13

Les plateformes cloud intègrent l'énergie renouvelable dans leurs opérations de différentes manières. Une possibilité est d'acheter de l'énergie verte auprès du

réseau électrique local, bien que cela les rende dépendantes du mix énergétique du réseau, et toutes les régions du monde ne sont pas alimentées par des sources à faible émission de carbone. Une autre possibilité est de fabriquer leur propre infrastructure renouvelable sur site. Un aspect critique de la production d'électricité à partir d'énergies renouvelables qui doit être pris en compte pour ces deux possibilités est leur caractère intermittent : leur production fluctue dans le temps et est influencée par des variables telles que l'heure de la journée, le climat, la saison et la localisation géographique. Par exemple, les panneaux photovoltaïques ne produisent de l'énergie que lorsque le soleil brille, et pendant l'hiver, l'irradiation solaire est plus faible que durant l'été. Pour l'hydroélectricité, de longues périodes sans pluie affecteront la production d'énergie.

L'adoption de dispositifs de stockage d'énergie (DSE) dans les centres de données pour stocker l'énergie renouvelable [10] est une approche pour faire face à l'intermittence. Ces dispositifs sont déjà utilisés dans les centres de données comme sauvegarde temporaire en cas de pannes de courant. L'énergie verte provenant des DSE pourrait être utilisée lorsqu'il n'y a pas de production d'énergie verte ou lorsque la demande est supérieure à la production. Néanmoins, cette approche présente également certains défis pour décider quand utiliser ou recharger, étant donné les caractéristiques des DSE, telles que le taux d'autodécharge (ils perdent de l'énergie stockée avec le temps lorsqu'ils ne sont pas utilisés), le vieillissement (leur capacité maximale diminue avec le temps) et les taux de charge et de décharge limités (la puissance maximale pouvant être extraite ou rechargée).

Dans cette thèse, nous étudions comment réduire l'impact environnemental des centres de données de cloud computing, notamment en termes d'émissions de CO₂. L'utilisation de stratégies sensibles au carbone - des approches conscientes de leur empreinte carbone et utilisant ces informations pour prendre des décisions [11] - est explorée pour réduire les émissions de CO₂ à la fois dans l'exploitation et dans le dimensionnement des centres de données - en déterminant l'infrastructure

renouvelable nécessaire sur site (surface des panneaux solaires, nombre d'éoliennes, capacité des DSE). En ce qui concerne les opérations des centres de données, nous exploitons la planification de la charge de travail en utilisant des approches follow-the-renewables - des stratégies qui migrent et allouent la charge de travail aux emplacements avec une disponibilité d'énergie renouvelable plus élevée [12] - et étudions leur impact à la fois sur la consommation d'énergie et la congestion du réseau. En ce qui concerne le dimensionnement, nous modélisons notre problème en utilisant une formulation de programme linéaire (PL) qui prend en compte les caractéristiques de chaque emplacement de centre de données en termes de besoins de refroidissement et de mix énergétique local du réseau, ainsi que le fait que l'infrastructure renouvelable génère un impact environnemental. Plus de détails sur la structure et les contributions de cette thèse sont présentés dans la section suivante.

Cette thèse est structurée en six chapitres, comprenant ce chapitre introductif. Une vue d'ensemble du contenu de chaque chapitre et de leurs contributions respectives est décrite ci-après.

Dans le Chapitre 2, le lecteur est introduit aux concepts nécessaires pour comprendre la recherche réalisée dans cette thèse. En particulier, le chapitre contient une description du scénario général du cloud computing, comment on peut mesurer l'impact environnemental des plateformes cloud, un aperçu des algorithmes d'ordonnancement dans le contexte du cloud computing, et la définition des stratégies sensibles au carbone - particulièrement, les approches explorées dans cette thèse : follow-the-renewables et le dimensionnement. Enfin, les travaux connexes utilisés comme inspiration ou comme bases pour nos solutions proposées sont également présentés dans ce chapitre.

Une analyse de l'adoption de la stratégie sensible au carbone follow-the-renewables et son impact sur la consommation d'énergie et la congestion du réseau est présentée dans le Chapitre 3. La solution proposée consiste en un algorithme qui prend en

compte la topologie et l'utilisation du réseau pour planifier la migration de la charge de travail. À travers des expériences computationnelles avec des données du monde réel pour la charge de travail, l'infrastructure cloud, et un simulateur qui utilise des modèles réalistes validés par la communauté scientifique pour la consommation d'énergie et l'utilisation du réseau, les résultats montrent que la solution proposée surpasse les références en termes de consommation d'énergie, de consommation d'énergie non renouvelable et de congestion du réseau.

Le Chapitre 4 introduit une stratégie sensible au carbone qui peut être combinée avec le suivi des renouvelables pour réduire l'empreinte carbone des plateformes de cloud computing en exploitation : le dimensionnement de l'infrastructure renouvelable. Cette stratégie consiste à déterminer la surface requise des panneaux solaires sur site et la capacité des batteries pour fournir la demande d'énergie des centres de données.

La solution proposée consiste en une formulation de Programme Linéaire qui aborde à la fois la planification de la charge de travail en utilisant le suivi des renouvelables et le dimensionnement de l'infrastructure renouvelable sur site. En modélisant ces deux sous-problèmes comme un seul problème, il est possible d'évaluer s'il est plus efficace d'exécuter la charge de travail dans d'autres emplacements géographiques ou d'augmenter la surface des panneaux solaires et la capacité des batteries pour atteindre l'objectif de réduction des émissions de CO₂. Le modèle n'utilise que des variables linéaires, ce qui lui permet d'être résolu de manière optimale en temps polynomial, ce qui est essentiel à l'échelle des plateformes de cloud computing qui comptent des millions de serveurs et exécutent des centaines de millions de tâches computationnelles chaque jour. D'autres aspects importants de la modélisation sont qu'elle prend en compte les caractéristiques de chaque emplacement géographique des centres de données en termes de besoins de refroidissement, le mix énergétique du réseau électrique local (qui peut avoir une part de sources d'énergie renouve-

lable), et le fait que la fabrication de panneaux solaires et de batteries a un impact environnemental.

Les résultats démontrent que la configuration hybride qui combine à la fois l'infrastructure renouvelable sur site et le réseau électrique régulier surpasse en termes d'émissions de CO₂ les stratégies ayant un centre de données uniquement alimenté par l'énergie produite par son infrastructure renouvelable locale, avec une réduction d'environ 30%, et n'utilisant que l'énergie du réseau électrique régulier, avec une réduction d'environ 85%.

Le modèle introduit au Chapitre 4 se concentre sur l'exploitation à court terme (une année). Dans le Chapitre 5, nous étendons le modèle pour évaluer comment minimiser les émissions de carbone des opérations des centres de données cloud à long terme.

Les modifications et analyses suivantes ont été réalisées : l'impact environnemental de tout le cycle de vie de l'infrastructure renouvelable (de la fabrication, de l'exploitation et du recyclage) est pris en compte pour rendre le modèle plus proche du monde réel ; une analyse des avantages et des défis liés à l'inclusion de turbines éoliennes dans l'infrastructure renouvelable sur site ; une évaluation de la sensibilité du modèle aux entrées, en particulier les conditions climatiques et les données sur les émissions du réseau ; une analyse de la réduction possible des émissions de CO₂ en adoptant la flexibilité de retarder une partie de la charge de travail, ce qui pourrait être utilisé pour atténuer les impacts du surdimensionnement de l'infrastructure renouvelable ; une discussion des coûts monétaires (en dollars) associés à l'infrastructure renouvelable sur site, ainsi que des compromis entre la minimisation de l'empreinte carbone et la réduction des coûts pour les centres de données ; et décider de fabriquer de nouveaux serveurs au fil des ans qui peuvent être plus économes en énergie, en considérant que leur fabrication émet également du carbone. Cette modélisation peut être utilisée pour guider les décideurs dans leurs efforts pour réduire l'empreinte carbone des centres de données cloud.

Enfin, le Chapitre 6 présente une discussion des principales contributions de cette thèse, ainsi que des trajectoires de recherche futures possibles.

Dans ce qui suit, nous présentons un résumé des principales contributions de chaque chapitre. Le lecteur peut consulter le manuscrit original (en anglais) pour avoir accès à plus de détails.

A.2 Contexte

Cette section fournit les connaissances fondamentales nécessaires au lecteur pour comprendre les chapitres suivants de cette thèse. Tout d'abord, le scénario général de l'informatique en nuage est présenté dans la Section A.2.1. La Section A.2.2 présente comment on peut mesurer l'impact environnemental des plateformes de cloud computing. Ensuite, une introduction à l'ordonnancement dans le contexte des clouds est présentée dans la Section A.2.3. Les approches existantes explorées dans cette thèse pour réduire l'impact environnemental des plateformes de cloud computing sont discutées dans la Section A.2.4, et les travaux utilisés dans cette thèse comme inspiration et références sont également présentés. Enfin, la Section ?? résume cette section.

A.2.1 Cloud computing

Le cloud computing a été introduit par l'industrie pour résoudre les problèmes les plus importants du commerce électronique de l'époque. Avant l'avènement du cloud computing et de son accès à la demande aux ressources informatiques, les utilisateurs et les entreprises devaient acheter leur propre infrastructure informatique pour déployer leurs services ou applications. En cas de pic soudain de demandes, il était souvent difficile de mettre à l'échelle l'infrastructure informatique à temps pour gérer la demande de charge informatique. Malgré ses aspects révolutionnaires

en technologie de l'information, le cloud computing n'est pas classé comme un nouveau paradigme dans la recherche en informatique. En fait, c'est l'évolution de la recherche dans différents domaines de l'informatique, tels que les clusters, les grilles, l'informatique autonome et l'informatique ubiquitaire.

L'un des éléments critiques qui permettent le cloud computing est la technologie de virtualisation, dans laquelle les ressources informatiques d'une machine physique sont converties en ressources virtuelles pouvant être partagées entre de nombreux utilisateurs et applications, également connue sous le nom de multi-tier. Les principales idées de la virtualisation proviennent de la fin des années 1950 et du début des années 1960 avec le paradigme de multiprogrammation, et aujourd'hui, la recherche sur les machines virtuelles (VM) et les containers continuent d'étudier les compromis décrits dans la littérature de la multiprogrammation en termes de portabilité, de performance et de sécurité [13].

Les plateformes de cloud computing prennent généralement en charge des services à trois niveaux distincts : IaaS (Infrastructure en tant que Service), PaaS (Plateforme en tant que Service) et SaaS (Logiciel en tant que Service) [14]. Au premier niveau, Infrastructure en tant que Service (IaaS), la plateforme accorde aux utilisateurs l'accès aux ressources matérielles (telles que le traitement et le stockage) et leur facture leur utilisation. Des services tels qu'Amazon EC2 (Elastic Cloud Computing) Service et Amazon S3 (Simple Storage Service) sont des exemples de clouds IaaS. Au deuxième niveau, Plateforme en tant que Service (PaaS), le fournisseur prend en charge un environnement complet de développement, de test et de déploiement pour le développeur d'applications, ce qui signifie habituellement que le développeur devra suivre un modèle de développement spécifique et accepter des restrictions sur la manière de modéliser le logiciel en échange de la scalabilité fournie. Un exemple est le Google App Engine. Enfin, au troisième niveau, Logiciel en tant que Service (SaaS), des applications spécifiques sont proposées aux utilisateurs via Internet,

et le tarif est proportionnel à l'utilisation de l'application. Nous pouvons citer les applications de bureautique Google Docs comme exemples.

Les plates-formes de cloud computing modernes sont composées de plusieurs centres de données répartis géographiquement dans le monde entier, également appelés fédérations de cloud ou multi-clouds. La figure 2.1 illustre les emplacements des centres de données cloud de Microsoft Azure qui, au total, sont composés de millions de serveurs physiques [15]. Le besoin d'une infrastructure géographiquement distribuée provient de la nécessité de répondre à la demande du grand nombre d'utilisateurs et de réduire le temps de réponse pour leurs applications, ainsi que pour des raisons de sécurité et de redondance. Par exemple, si un centre de données dans une région tombe en panne en raison d'un problème d'alimentation ou d'une attaque de piratage, une autre région pourrait temporairement recevoir la charge de calcul. Enfin, cette infrastructure distribuée permet d'explorer différentes approches pour réduire l'impact environnemental de l'exploitation des centres de données, et plus de détails sur ces stratégies sont donnés dans la section A.2.4.

A.2.2 Mesurer l'impact environnemental des platesformes de cloud computing

Le protocole GHG [17] a été développé comme moyen de standardiser la mesure et la déclaration de l'impact environnemental des entreprises. Il prend en compte six types de gaz à effet de serre (GES) du protocole de Kyoto : le dioxyde de carbone (CO_2), le méthane (CH_4), l'hexafluorure de soufre (SF_6), le protoxyde d'azote (N_2O), les hydrofluorocarbures (HFC) et les perfluorocarbures (PFC).

Le protocole comporte trois domaines pour quantifier les émissions directes et indirectes :

- **Scope 1 - Émissions directes de GES** : prend en compte les émissions générées par les sources que l'entreprise possède ou contrôle. Dans le contexte du cloud computing, cela pourrait provenir de l'électricité générée lors d'une surtension, et des générateurs devraient être utilisés comme solution de secours ; le transport des produits, des matériaux et des employés à l'aide des véhicules de l'entreprise ; et le refroidissement de l'infrastructure du centre de données [18].
- **Scope 2 - Émissions indirectes de GES liées à l'électricité** : prend en compte les émissions générées par l'électricité consommée.
- **Scope 3 - Autres émissions indirectes de GES** : Ce domaine est facultatif et prend en compte les émissions issues de la production ou de l'extraction des matériaux et des combustibles achetés, par exemple, les équipements informatiques (tels que les serveurs et les routeurs) ainsi que la construction des installations du centre de données. Les émissions liées au transport sont également incluses dans ce domaine si elles proviennent de véhicules non possédés par l'entreprise.

Les principaux acteurs du cloud fournissent déjà des rapports de durabilité et utilisent le Protocole GHG. Dans le rapport de durabilité de Meta pour 2023 [19], il est estimé que 1% des émissions proviennent du Scope 1, moins de 1% du Scope 2 et 99% du Scope 3. De plus, il est indiqué que les émissions opérationnelles ont été réduites de 94% par rapport à 2017 grâce aux engagements en matière d'énergie renouvelable. Un autre exemple remarquable est le rapport environnemental de Google pour 2023 [8], où il est estimé que 1% des émissions proviennent du Scope 1, 24% du Scope 2 et 74% du Scope 3. Google indique également que la majeure partie des émissions du Scope 3 proviennent de la fabrication du matériel et des biens d'équipement qu'ils ont achetés et de la construction des installations de centres de données.

Dans cette thèse, l'impact environnemental est uniquement évalué en termes d'empreinte carbone, en utilisant la métrique équivalente en CO₂ (CO₂-eq). Cette décision a été prise en raison du manque de données pour mesurer d'autres impacts environnementaux, tels que l'utilisation de l'eau, et les impacts causés par l'extraction de minéraux bruts pour fabriquer les circuits intégrés.

A.2.3 Ordonnement pour les plateformes de cloud computing

Les problèmes d'ordonnement sont des problèmes d'optimisation combinatoire où, étant donné la description des caractéristiques d'un ensemble de ressources informatiques (α) et d'un ensemble de tâches (β), l'objectif est de trouver une allocation (dans le temps) des ressources aux tâches qui minimise certains critères d'optimisation (γ). Ces problèmes sont généralement désignés en utilisant la notation $\alpha | \beta | \gamma$, introduite par Graham [20].

Le critère le plus couramment étudié dans les problèmes de calcul haute performance est appelé makespan (également noté par C_{\max}), qui indique le moment où la dernière tâche composant une application termine son exécution. Lorsque les ressources informatiques disponibles sont identiques et connues à l'avance, et que nous cherchons à minimiser le makespan, typiquement le cas dans les problèmes d'ordonnement dans les grappes et les grilles de calcul, le problème est fortement NP-difficile [21]. Ce problème est désigné par $P, |, |, C_{\max}$ dans la notation de Graham.

Pour le problème de recherche exploré dans cette thèse, α représente les ressources informatiques (mémoire et CPU) des serveurs des centres de données ainsi que leurs informations sur la disponibilité de sources d'alimentation à faible intensité carbonique, β représente les exigences des machines virtuelles en termes de temps d'exécution, de délai, de mémoire et de CPU, et γ représente la réduction de la consommation d'énergie carbonée.

Il est connu, d'après les travaux de Graham et al. [20] et Garey and Johnson [21], que la classe d'algorithmes gloutons connus sous le nom d'algorithmes de liste fournit des heuristiques rapides et efficaces pour l'ordonnancement des tâches sur des ordinateurs parallèles. Ces algorithmes ont une garantie d'approximation de $2 - 1/m$ dans le pire des cas, mais sont remarquablement efficaces en pratique, surtout lorsque le rapport entre le nombre de tâches et le nombre de ressources informatiques disponibles est élevé. Parmi les algorithmes de liste les plus couramment utilisés, on trouve le Longest Processing Time first (LPT) et le Shortest Processing Time first (SPT), pour les plateformes homogènes, et l'algorithme Heterogeneous Earliest Finish Time (HEFT), pour les plateformes hétérogènes.

La stratégie de consolidation des machines virtuelles illustre un exemple de problème d'ordonnancement dans le cloud computing rendu possible par la virtualisation. Elle consiste à utiliser des migrations en direct, migrer la VM entre différentes machines tout en étant en cours d'exécution, c'est-à-dire sans préemption, pour réallouer les VM afin d'atteindre le nombre minimum de machines physiques utilisées, et éteindre les machines devenues inactives pour économiser de l'énergie. Le lecteur peut consulter le travail de Dias et al. [22] pour une revue systématique de la littérature sur de telles techniques.

Les algorithmes gloutons ont été adoptés dans certaines des solutions proposées dans cette thèse, ainsi que dans la plupart des travaux connexes utilisés comme bases et sources d'inspiration. La justification de cette décision est que, bien qu'ils ne fournissent pas la solution optimale, ils peuvent fournir une solution acceptable dans un laps de temps raisonnable, ce qui est important compte tenu de la taille de la charge de travail avec des millions de tâches et des restrictions telles que la date limite, le temps de réponse, et autres. La section suivante présente ces stratégies au lecteur.

A.2.4 Carbon-Responsive Computing

De nombreux efforts, tant de la part du milieu universitaire que de l'industrie, sont déployés pour réduire l'impact environnemental des technologies de l'information. Le terme «Carbon-Responsive Computing» a été créé pour décrire les stratégies qui explorent le déplacement de la charge de travail informatique à la fois dans le temps et dans l'espace dans le but de réduire l'empreinte carbone de l'opération [11].

Il existe trois niveaux de Carbon-Responsive computing. Dans le premier, Carbon-aware computing, le système connaît l'intensité carbone de l'électricité utilisée par ses charges de travail ou son équipement informatique. Dans le second, carbon-responsive computing, les informations sur l'intensité carbone sont prises en compte pour prendre des décisions. La dernière étape, carbon-resilient computing, étudie comment gérer et intégrer des éléments réactifs au carbone et quelles modifications sont nécessaires dans l'informatique et l'infrastructure d'alimentation pour réduire l'empreinte carbone.

Dans cette thèse, une étude de la stratégie carbon-aware follow-the-renewables est présentée (Section A.2.4.1), ainsi que la stratégie carbon-resilient de dimensionner l'infrastructure renouvelable (Section A.2.4.2).

A.2.4.1. Follow-the-renewables

Comme nous l'avons vu dans la Section A.2.1, les plates-formes de cloud computing modernes sont réparties géographiquement à travers le monde, ayant des centres de données dans de nombreuses combinaisons de latitudes, de longitudes et de fuseaux horaires. Étant donné que chaque emplacement a un potentiel différent pour générer de l'énergie renouvelable, et que l'énergie renouvelable est intermittente - le soleil ne brille que pendant la journée, et le vent ne souffle pas tout le temps à des vitesses suffisantes pour faire tourner les pales des éoliennes - les algorithmes de planification peuvent utiliser cette caractéristique pour planifier l'exécution de

la charge de travail dans les endroits où il y a plus de disponibilité d'énergie verte. Dans la littérature, le terme «follow-the-renewables» [12] describes this strategy. Cette stratégie se concentre sur le Scope 2 du Protocole GHG, car elle planifie la charge de travail à l'emplacement qui utilise moins d'énergie intensive en carbone provenant de sources renouvelables.

A.2.4.2. Dimensionner l'infrastructure renouvelable

Il existe deux options principales pour répondre à la demande d'électricité à faible intensité en carbone de la fédération cloud. Le propriétaire du centre de données peut acheter de l'électricité verte auprès du réseau électrique local intégrant les énergies renouvelables, ce qui les rend dépendants du réseau, et toutes les localisations ne permettent pas cette possibilité, ou il peut installer une infrastructure renouvelable locale dans les centres de données. Pour cette dernière option, le principal problème est de décider des dimensions de l'infrastructure renouvelable nécessaire, par exemple, la surface requise des panneaux solaires, le nombre d'éoliennes et la capacité des batteries (pour stocker l'énergie verte et l'utiliser lorsque c'est opportun) pour alimenter le centre de données et minimiser son empreinte carbone. Ce problème est connu sous le nom de dimensionnement ou de planification de la capacité dans la littérature (sizing, dimensioning ou capacity planning en anglais). De nombreux facteurs doivent être pris en compte dans la décision de dimensionnement : les coûts de fabrication et d'exploitation de ces appareils, le potentiel de production d'énergie compte tenu des conditions climatiques et de la localisation géographique, et le fait que ces appareils présentent également un impact environnemental tout au long de leur cycle de vie ne peut être négligé.

La stratégie de dimensionnement de l'infrastructure renouvelable prend en compte les Scopes 1, 2 et 3 du Protocole GHG : les émissions de carbone directes de la production d'électricité dans le centre de données, les émissions liées à la consommation d'électricité du réseau électrique ordinaire, et les autres émissions de GES indirectes

provenant de la fabrication et du cycle de vie de l'infrastructure renouvelable et de l'équipement informatique.

A.3 Follow-the-renewables et leur impact sur le réseau et la consommation énergétique

L'approche «follow-the-renewables»(le lecteur peut consulter le Chapitre 2 pour plus de détails) est une stratégie intéressante pour atténuer l'intermittence de la disponibilité de l'énergie renouvelable sans avoir besoin d'utiliser des dispositifs de stockage d'énergie. Par exemple, lorsque c'est la nuit dans l'emplacement où se trouve un centre de données A, la charge de travail pourrait être migrée vers un autre centre de données B où le soleil brille encore pour utiliser l'énergie solaire, comme illustré dans la Figure 2.2.

Malgré ses avantages, on ne peut négliger les limitations de la stratégie follow-the-renewables. Tout d'abord, le processus de migration d'une machine virtuelle entre différents centres de données consomme lui-même de l'énergie : il utilise des dispositifs réseau (comme des commutateurs et des routeurs) et une tâche informatique pour le processus de migration en direct. L'algorithme de planification doit prendre en compte cette consommation d'énergie avant de décider si la migration est avantageuse. Deuxièmement, les liens de communication réseau qui connectent les serveurs à l'intérieur du centre de données et les différents centres de données peuvent souffrir de congestion, ce qui peut augmenter la durée de la migration. Cela entraîne une computation et une consommation d'énergie inutiles à la fois sur les serveurs d'origine et de destination : le serveur qui envoie la machine virtuelle doit attendre la fin du processus de migration pour libérer ses ressources et recevoir des machines virtuelles supplémentaires, ou il pourrait également être éteint pour économiser de l'énergie ; le serveur qui reçoit la machine virtuelle ne commencera

à exécuter la nouvelle machine virtuelle qu'après la fin du processus de migration. Un algorithme de planification efficace doit prendre en compte ces facteurs pour réduire l'empreinte carbone des opérations des centres de données.

Le travail de Camus et al. [27, 28] a étudié la planification de la charge de travail en nuage, sous forme de machines virtuelles (virtual machine ou VM en anglais), sur des centres de données géographiquement répartis afin de minimiser la consommation d'énergie non renouvelable. Il a proposé différents modèles stochastiques pour estimer la production d'énergie renouvelable et des algorithmes heuristiques gloutons pour allouer des tâches aux serveurs. Les VM peuvent être migrées pendant leur exécution vers un ordinateur situé dans le même centre de données (consolidation des serveurs intra-DC) ou vers un ordinateur dans un centre de données situé dans un autre emplacement géographique («follow-the-renewables»). L'algorithme de planification prend en compte le coût réseau de la migration.

Le Chapitre 3 présente une extension de ce travail avec une analyse de l'impact indirect de l'utilisation de l'approche «follow-the-renewables» sur la consommation d'énergie. Cet impact peut être divisé en deux catégories : direct et indirect. La consommation d'énergie des dispositifs réseau entraîne l'impact direct, et comme la consommation d'énergie ne varie pas significativement en fonction de l'utilisation du dispositif [41], nous supposons que la consommation d'énergie des dispositifs réseau est statique. Pour l'impact indirect, il est généré par la migration en direct des VM, qui utilise le réseau pour transférer toutes les données liées à la tâche vers la machine de destination, ainsi que la tâche de calcul nécessaire pour effectuer cette migration en direct. Plus précisément, ce chapitre présente les contributions suivantes :

- une analyse de l'impact de ne pas prendre en compte le réseau (bande passante, latence et topologie) à la fois dans la consommation d'énergie et la congestion du réseau ;

- un algorithme d'estimation précis pour le temps nécessaire à la migration d'une machine virtuelle qui prend en compte la topologie du réseau, la bande passante du lien et la latence ;
- un algorithme d'ordonnancement pour la migration en direct des VM qui utilise l'algorithme d'estimation et a la même consommation d'énergie brute ou inférieure aux références, sans congestion du réseau.

Le chapitre 3 est organisé comme suit. Dans la Section 3.2, le modèle de Camus et al. [28], fondement de ce travail, est résumé. La Section 3.3 détaille la nouvelle méthode de planification pour les migrations, tandis que la Section 3.4 est consacrée aux paramètres de simulation. Les résultats sont détaillés dans la Section 3.4.3. Enfin, la Section 3.5 résume le chapitre.

Dans ce qui suit, nous présentons la discussion générale du chapitre 3. Réduire l'impact environnemental de l'exploitation des plates-formes de cloud computing, en particulier l'empreinte carbone générée par leur consommation énergétique gigantesque, est un problème complexe et difficile actuellement abordé sous différents angles. Dans ce chapitre, nous nous concentrons sur la stratégie *follow-the-renewables* et étudions l'impact indirect sur la consommation d'énergie causé par la charge supplémentaire générée dans le réseau. Les expériences étaient basées sur des données du monde réel pour l'infrastructure cloud, les charges de travail et la production d'énergie photovoltaïque.

Ce chapitre démontre que l'impact indirect sur le réseau de la consommation d'énergie dans les multi-clouds pour les approches «*follow-the-renewables*» est généré par de mauvaises politiques de planification pour les migrations, ce qui entraîne une congestion du réseau. En effet, les migrations en direct rivalisent pour la bande passante disponible des liens du réseau, affectant non seulement les applications qui s'exécutent à l'intérieur des machines virtuelles, mais aussi la durée du processus de migration. Étant donné que la migration d'une machine virtuelle consomme

également de l'énergie, proportionnellement à sa durée, et que la charge de travail sera envoyée aux centres de données en utilisant de l'énergie plus verte («follow-the-renewables»), la consommation d'énergie supplémentaire est en réalité une énergie gaspillée qui pourrait être utilisée pour alimenter la plate-forme cloud. De plus, l'adoption de la stratégie «follow-the-renewables» doit prendre en compte l'ensemble de l'exécution de la charge de travail : les algorithmes de pointe qui n'utilisaient que les informations sur l'énergie verte pour la planification initiale et ne migraient pas la charge de travail lorsque la disponibilité de l'énergie renouvelable changeait avaient la plus forte consommation d'énergie non renouvelable.

L'algorithme d'estimation proposé pour la durée des migrations en direct, qui utilise en entrée des informations sur le réseau de communication des centres de données (latence des liens réseau, bande passante et topologie), est précis. En utilisant cet algorithme d'estimation et en utilisant les caractéristiques du réseau du cloud en entrée, la planification des migrations de c-NEMESIS a pu augmenter le nombre de migrations d'au moins trois fois sans congestion réseau, tout en maintenant ou en réduisant la consommation d'énergie non renouvelable par rapport à d'autres travaux de l'état de l'art.

A.4 Dimensionnement de l'infrastructure renouvelable des centres de données cloud

Dans le chapitre 3, nous avons vu l'adoption de la technique carbon-aware follow-the-renewables appliquée à un multi-cloud distribué sur un pays et ses inconvénients, tels que la congestion du réseau et la consommation d'énergie supplémentaire, si elle n'est pas utilisée correctement. Maintenant, le lecteur est introduit à une stratégie réactive au carbone qui peut être combinée avec «follow-the-renewables» dans notre quête de réduction de l'empreinte carbone de l'exploitation des fédérations cloud

: le dimensionnement de l'infrastructure renouvelable. Cette stratégie consiste à définir combien d'investissement doit être réalisé, par exemple, en définissant la superficie des panneaux solaires (lorsque l'on considère l'énergie solaire), le nombre d'éoliennes et la capacité des dispositifs de stockage d'énergie (comme les batteries lithium-ion) qui doivent être fabriqués.

Le scénario considéré dans le chapitre 4 présente quelques différences pour mieux représenter les fournisseurs de cloud modernes. Tout d'abord, il est considéré que les centres de données (DC) sont répartis géographiquement dans le monde entier, représentant ainsi de véritables fournisseurs de cloud tels que Google et Microsoft (comme on peut le voir dans la Figure 2.1). De nombreuses raisons justifient la nécessité de centres de données géographiquement distribués : i) répondre à la demande croissante en nombre d'utilisateurs ; ii) redondance, par exemple, en cas de problème dans une région, la charge de travail peut être déplacée vers un autre emplacement ; iii) réduire la latence ou le temps de réponse pour les utilisateurs. Cette distribution géographique permet également une meilleure exploitation des sources renouvelables, car il existe des conditions climatiques variables, les niveaux d'irradiation solaire diffèrent entre les pays, tout comme la vitesse et la fréquence du vent. Deuxièmement, de nombreux endroits dans le monde ont la présence de sources à faible intensité de carbone dans leur réseau électrique local, donc en réalité, il n'y a pas seulement une classification en vert et marron (comme on l'a vu dans le chapitre précédent). La classification en vert et marron avait du sens dans le scénario précédent, car seul un pays était considéré, et l'énergie renouvelable était moins carbonée que le réseau électrique local. Enfin, des dispositifs de stockage d'énergie peuvent être utilisés pour stocker la surproduction d'énergie renouvelable et l'utiliser lorsque c'est opportun.

Un point qui ne peut être négligé est que la fabrication de l'infrastructure renouvelable présente également un impact environnemental : les batteries ont un niveau de charge idéal qui peut améliorer leur durée de vie, ce qui peut réduire la fréquence

de remplacement, mais d'autre part, cela les rend surdimensionnées[48], et leurs taux de recyclage doivent encore s'améliorer[49]; et en considérant l'état actuel de l'art des panneaux solaires, s'ils produisent 40% de l'électricité mondiale d'ici à 2050, ils consommeront environ 5% du budget actuel de CO₂ [50].

Dans le chapitre 4, nous explorons l'adoption des deux stratégies, dimensionner les panneaux solaires et les batteries et planifier avec follow-the-renewables pour réduire l'empreinte carbone de l'exploitation des plates-formes cloud existantes. Plus précisément, le chapitre présente les contributions suivantes :

- les deux sous-problèmes, le dimensionnement des panneaux solaires et des batteries, et la planification de la charge de travail, sont modélisés comme un seul problème, ce qui permet d'évaluer des scénarios tels que : faut-il augmenter la capacité de la batterie ou la surface des panneaux solaires, ou faut-il planifier la charge de travail dans un centre de données situé dans une autre partie du monde ?
- nous proposons un modèle qui utilise une approche de programmation linéaire (linear programming ou LP en anglais) avec des variables réelles, nous permettant de résoudre de manière optimale le problème que nous abordons en temps polynomial en utilisant des solveurs LP classiques. Cela permet d'évaluer un grand nombre de scénarios sur de larges horizons temporels (c'est-à-dire un an) pour prendre en compte le comportement saisonnier de la production d'énergie renouvelable. Ce modèle peut être étendu à plusieurs scénarios, et il peut aider les décideurs à évaluer quelles régions nécessitent plus d'investissement pour réduire l'impact environnemental de l'opération du cloud.

Le chapitre 4 est organisé comme suit : La Section 4.2 définit le problème abordé, les hypothèses, les modèles et la fonction objective. Les détails sur les contraintes du problème et la façon de le résoudre de manière optimale sont donnés dans la

Section 4.3. Les expériences sont présentées dans la Section 4.4, et leurs résultats sont discutés dans la Section 4.5. Enfin, la Section 4.6 conclut le chapitre.

Dans ce qui suit, nous présentons la discussion générale du chapitre 4. Nous avons étudié le problème de réduire l’empreinte carbone de l’exploitation d’une fédération de cloud composée de centres de données cloud répartis géographiquement. La partie informatique de la plateforme cloud existe déjà, serveurs et équipements réseau, et l’idée est d’ajouter des équipements d’infrastructure renouvelable sur site pour introduire de l’énergie à faible intensité de carbone dans l’alimentation électrique des centres de données, car le réseau électrique local peut être à forte intensité de carbone.

Étant donné que le soleil brille partout sur terre, nous avons proposé des panneaux photovoltaïques (PV) pour produire de l’énergie renouvelable et des batteries comme dispositifs de stockage d’énergie pour atténuer l’intermittence intrinsèque de cette énergie pendant la journée et pour les calculs nocturnes. La question est de savoir comment dimensionner la surface de la zone des panneaux photovoltaïques (m^2) et la capacité des batteries associées (kWh), compte tenu d’une fédération existante de centres de données distribués autour de la terre, sans négliger le fait que la fabrication de PV et de batteries présente également un impact environnemental.

Nous avons fourni une formulation du problème sous forme de programme linéaire. La particularité de notre formulation est que la modélisation utilise uniquement des variables réelles, compte tenu de notre fonction objective et du contexte du problème. Par conséquent, le programme linéaire permet de résoudre de manière optimale des problèmes de grande taille en temps polynomial, par exemple, en minimisant l’empreinte carbone d’une fédération de neuf sites, chacun avec ses propres conditions météorologiques, sur une période d’un an, heure par heure.

Nous avons démontré que notre programme est capable de calculer le dimensionnement optimal des panneaux solaires et des batteries en seulement quelques min-

utes. De nombreuses expériences ont donné des résultats que nous avons analysés et discutés, expliquant ce que ces résultats expriment. Par exemple, un résultat intéressant, en fonction des emplacements des centres de données considérés, est que la solution optimale pour réduire l’empreinte carbone est de maintenir un mix énergétique grâce à une configuration hybride comprenant à la fois des panneaux solaires et un réseau classique où la production est faible en carbone, au lieu de proposer une plateforme entièrement renouvelable. De plus, les batteries ne sont pas toujours obligatoires dans chaque emplacement (comme dans le cas du DC de Paris).

Enfin, notre modèle a la flexibilité d’être étendu pour évaluer d’autres scénarios (plus de centres de données, d’autres emplacements, des valeurs d’émissions de carbone différentes ou des charges de travail différentes) et il peut aider les décideurs à élaborer leur stratégie pour réduire l’impact environnemental de l’exploitation du cloud.

A.5 Évaluation à long terme du dimensionnement des centres de données cloud

Dans le chapitre 4, nous avons présenté un modèle initial pour réduire les émissions de carbone de l’exploitation d’une fédération de cloud à court terme (un an) en dimensionnant son infrastructure renouvelable, c’est-à-dire en définissant la surface des panneaux solaires et la capacité des batteries pour chaque centre de données. Étant donné que la fédération de cloud fonctionnera à long terme, le décideur doit être certain des investissements qui seront réalisés pour éviter de gaspiller de l’argent et de générer un impact environnemental avec une mauvaise stratégie. De plus, un processus de planification est soumis à de nombreuses incertitudes qui, si elles ne sont pas prises en compte, diminueront la validité et la crédibilité de la solution.

Le chapitre 5 présente une extension du modèle, en se concentrant sur l'exploitation à long terme des centres de données cloud et les incertitudes auxquelles ce processus de dimensionnement est soumis. Dans notre contexte, l'incertitude provient principalement de l'intermittence des sources renouvelables. Par conséquent, le lecteur est introduit à une analyse de la sensibilité de la modélisation aux conditions climatiques. Une autre donnée qui peut influencer le processus de dimensionnement est la valeur des émissions du réseau électrique local. Dans notre modélisation initiale, nous avons utilisé la valeur moyenne de l'année, étant donné que toutes les localisations ne fournissent pas cette valeur avec des intervalles plus courts, variation heure par heure, par exemple. Le lecteur est présenté avec une analyse de l'impact de l'utilisation des informations granulaires des émissions du réseau par rapport à la moyenne annuelle sur le processus de dimensionnement et l'empreinte carbone totale résultante.

Étant donné que l'accent est désormais mis sur l'exploitation à long terme, il est essentiel de considérer l'ensemble du cycle de vie de l'infrastructure renouvelable. Dans le chapitre précédent, nous avons effectué la modélisation en ne tenant compte que de l'impact environnemental de la fabrication des panneaux solaires et des batteries lithium-ion. Cette décision a été prise en raison des données disponibles que nous avons trouvées lors de l'étude du problème. Cependant, l'impact environnemental est également présent dans les autres phases de la durée de vie de ces dispositifs, exploitation, mise au rebut et recyclage. Par conséquent, la modélisation a été mise à jour pour prendre en compte les émissions du cycle de vie de l'infrastructure renouvelable.

Réduire les émissions de carbone en utilisant des panneaux solaires est limité, car ils ne génèrent de l'énergie que lorsque le soleil brille. Par conséquent, ils doivent fournir les opérations du cloud pendant la journée et charger les batteries pour les opérations nocturnes. Dans ce chapitre, nous évaluons si l'utilisation d'éoliennes pourrait encore réduire les émissions de carbone de l'exploitation cloud

et le dimensionnement à la fois des panneaux solaires et des batteries, en considérant que le vent peut également être disponible la nuit.

Il est également nécessaire de prendre en compte le fait que, une fois construite, l'infrastructure renouvelable ne peut pas être réduite, cela impliquerait de détruire ou de jeter des panneaux solaires, des batteries et des éoliennes. Par conséquent, une autre stratégie est nécessaire pour faire face au surdimensionnement que l'intermittence des sources renouvelables pourrait causer. Heureusement, une autre partie peut être gérée pour réduire l'impact d'un mauvais dimensionnement : la planification de la charge de travail. Sur la plateforme cloud, une partie importante de la charge de travail est constituée de tâches qui n'ont pas une priorité élevée et dont l'exécution peut être retardée dans le temps, les tâches dites de lot. Chez Meta, 7,5% de la charge de travail sont des tâches hors ligne [40] et les tâches de faible priorité consomment en moyenne 20% des ressources informatiques (CPU et mémoire) des clusters de Google [60]. Nous présentons une analyse de la viabilité du retard de $\alpha\%$ des tâches jusqu'à β créneaux horaires (chaque créneau horaire dure 1 heure) pour réduire l'empreinte carbone.

Un autre aspect important à considérer est que la demande de ressources informatiques cloud augmente d'année en année, pour faire face au nombre croissant d'utilisateurs et de demandes d'applications. De 2010 à 2018, Cisco a fourni des prévisions de croissance de la charge de travail pour les cinq années suivantes, mettant à jour les prévisions chaque année. Le dernier rapport, pour la période de 2017 à 2021, prévoyait que le taux de croissance de la charge de travail serait en moyenne de 22% par an pour les centres de données cloud [61]. De plus, de nouvelles générations de serveurs sont lancées avec un matériel informatique plus puissant qui peut être plus économe en énergie. Comme indiqué dans le chapitre 1, l'analyse de Masanet et al. [3] a montré que de 2010 à 2018, la charge de travail des centres de données a augmenté six fois; cependant, l'augmentation de la consommation d'énergie n'a été que de 6% grâce aux améliorations d'efficacité à la fois du

matériel et du logiciel. D'autre part, la fabrication de serveurs émet également du carbone, ce qui ne peut être négligé. En outre, étant donné l'intégration croissante des infrastructures renouvelables dans les centres de données cloud, la plupart des émissions de carbone se déplacent de la consommation d'énergie de l'exploitation du centre de données à la fabrication de l'équipement informatique [18].

Jusqu'à présent, nous avons exploré uniquement l'aspect de l'impact environnemental, en termes d'émissions de carbone, de l'exploitation de la fédération de cloud. Une autre dimension d'une importance élevée pour le décideur est le coût monétaire, car l'entreprise ne survivra que si elle génère des bénéfices. Le lecteur se voit également présenter une analyse du coût pour réduire l'empreinte carbone de l'exploitation multi-cloud en utilisant une infrastructure renouvelable sur site. Tout comme l'analyse de l'impact environnemental, nous considérons les coûts de toute la durée de vie des panneaux solaires, des éoliennes et des batteries.

Plus spécifiquement, le chapitre 5 présente les contributions suivantes:

- nous étendons la modélisation pour prendre en compte toutes les émissions du cycle de vie de l'infrastructure renouvelable, de la fabrication à la mise au rebut/recyclage (Section 5.2);
- nous présentons une évaluation de la réduction possible de l'empreinte carbone si des éoliennes étaient également incluses dans l'infrastructure renouvelable (Section 5.3);
- nous montrons une évaluation concernant la sensibilité du LP aux entrées : i) les incertitudes causées par l'intermittence du rayonnement solaire et de la vitesse du vent, et ce qui doit être pris en compte dans la modélisation pour éviter un sur ou un sous-dimensionnement de l'infrastructure renouvelable ; ii) certaines localités disposent de sources de données avec l'empreinte carbone du réseau à des intervalles de temps d'une heure, et nous montrons une

analyse de savoir si cette valeur granulaire affecterait le dimensionnement de l'infrastructure renouvelable (Section 5.4);

- nous présentons une analyse de la réduction possible de l'empreinte carbone en utilisant la flexibilité de la planification, en retardant les tâches par lots (Section 5.5);
- nous présentons une analyse du moment où il est viable d'ajouter de nouveaux serveurs (qui peuvent remplacer des serveurs de générations plus anciennes) en termes d'empreinte carbone (Section 5.6);
- nous montrons une analyse de combien il est coûteux (en dollars) de réduire l'empreinte de la fédération de cloud et les gains en termes d'économies monétaires et d'émissions (Section 5.7).

Le chapitre 5 est organisé comme suit. Étant donné que nous étendons le modèle du chapitre 4 pour évaluer différents scénarios, chaque scénario a sa propre section, Sections 5.2, 5.3, 5.4, 5.5, 5.6, et 5.7, et dans chaque section, le lecteur est présenté avec les modifications nécessaires dans la modélisation, les expériences réalisées et les résultats des expériences. Après avoir présenté les scénarios évalués, nous montrons la discussion à la Section 5.8. Enfin, la Section 5.9 conclut le chapitre.

Dans ce qui suit, nous présentons la discussion générale du chapitre 5. Nous avons étudié le problème de réduire l'impact environnemental à long terme des fédérations de cloud en intégrant une infrastructure renouvelable locale sur les sites où se trouvent les centres de données. Nous avons étendu notre modélisation initiale, présentée dans le chapitre 4, selon les points suivants :

- nous avons pris en compte l'ensemble du cycle de vie de l'infrastructure renouvelable ;
- nous avons intégré des éoliennes dans le modèle pour réduire davantage l'impact environnemental, en particulier lorsque le soleil ne brille pas ;

- nous avons évalué la sensibilité du modèle aux données d'entrée telles que le rayonnement solaire, la vitesse du vent et les valeurs d'émission du réseau ;
- nous avons montré que permettre le retardement de la charge de travail peut réduire l'empreinte carbone de l'exploitation cloud et atténuer partiellement l'erreur du processus de dimensionnement causée par l'intermittence des énergies renouvelables, ce qui est important car une fois construite, il n'est pas possible de réduire les dimensions de l'infrastructure renouvelable ;
- nous avons mené une analyse des coûts monétaires de la minimisation de l'impact environnemental du cloud, et illustré que l'infrastructure renouvelable peut effectivement réduire les coûts pour les opérateurs cloud ;
- nous avons inclus le dimensionnement des équipements informatiques dans le modèle, pour évaluer dans quelle mesure l'adoption de serveurs de nouvelles générations peut réduire l'empreinte carbone, car ils pourraient être plus économes en énergie, mais leur fabrication émet également du carbone.

Ces modifications ont été soigneusement apportées pour utiliser des variables et des contraintes linéaires, de sorte que le problème reste résolu de manière optimale en temps polynomial.

A.6 Discussion générale

Le cloud computing est un composant essentiel de notre société numérique moderne, étant donné qu'il prend en charge la majorité des services et des applications que nous utilisons. D'un autre côté, on ne peut négliger l'impact environnemental qu'il présente, qui provient à la fois de la consommation énergétique de son fonctionnement, supérieure à la demande d'électricité de pays entiers, et du cycle de vie de son infrastructure.

Dans cette thèse, nous avons étudié des stratégies visant à réduire l'impact environnemental, en termes d'empreinte carbone, de l'exploitation et du dimensionnement des fédérations de cloud avec des centres de données répartis géographiquement dans le monde entier. Plus précisément, nous avons exploré deux stratégies sensibles au carbone: «follow-the-renewables»et le dimensionnement de l'infrastructure renouvelable et des équipements informatiques.

Cette section commence par fournir un aperçu des principales contributions apportées dans cette thèse. Ensuite, nous discutons des opportunités potentielles pour les futures directions de recherche qui s'appuient sur les enseignements tirés du travail présenté dans cette thèse. Enfin, nous présentons les différentes façons dont notre travail a été diffusé, y compris une liste de publications scientifiques qui ont émergé de la recherche menée dans cette thèse.

La première contribution principale de cette thèse est l'analyse de l'impact de la stratégie follow-the-renewables sur à la fois la consommation d'énergie et le réseau, présentée dans le chapitre 3. Cette approche est une solution intéressante pour exploiter la distribution géographique des centres de données cloud à travers le monde afin de réduire la consommation élevée d'électricité à forte intensité carbonée. Cependant, la décision de migrer la charge de travail doit prendre en compte les ressources impliquées dans cette opération, en particulier le réseau.

Nous avons mené des expériences computationnelles pour étudier l'impact des stratégies de follow-the-renewables. Ces expériences ont utilisé des données du monde réel pour la charge de travail, les conditions climatiques, des modèles validés par la communauté scientifique pour la consommation d'énergie et l'utilisation du réseau, ainsi que différentes adaptations du follow-the-renewables.

Les résultats ont démontré que la planification des migrations sans tenir compte du réseau, en particulier, la topologie et l'utilisation du réseau, entraînera une congestion du réseau et un gaspillage d'énergie. Comme vu dans la Section 3.4.3.4,

l'énergie gaspillée pourrait être utilisée pour alimenter les serveurs des centres de données cloud, et elle contribue également à augmenter l'impact environnemental de l'exploitation du cloud. Nous avons proposé un algorithme de planification des migrations qui peut réduire la consommation d'énergie non renouvelable sans impact sur le réseau, par rapport aux travaux de la littérature qui planifient la migration de la charge de travail sans tenir compte du réseau.

La deuxième contribution principale de cette thèse est le modèle permettant de dimensionner à la fois l'infrastructure renouvelable et informatique et de faire fonctionner les fédérations de cloud dans le but de réduire l'empreinte carbone, présenté dans les chapitres 4 et 5.

Le modèle initial proposé dans le chapitre 4 était axé sur l'exploitation à court terme sur une durée d'un an et la possibilité de fabriquer sur place des panneaux solaires et des batteries lithium-ion pour générer de l'énergie renouvelable et la stocker afin de faire face à l'intermittence de l'énergie verte.

Le premier aspect clé de la solution proposée est qu'elle résout à la fois les sous-problèmes de dimensionnement et d'exploitation comme un seul problème, ce qui nous permet d'évaluer des décisions telles que l'augmentation des dimensions de l'infrastructure renouvelable sur site d'un centre de données ou la planification de la charge de travail vers différents emplacements géographiques en utilisant l'approche du follow-the-renewables.

Un autre aspect clé du modèle est qu'il prend en compte les caractéristiques spécifiques des emplacements géographiques des centres de données en termes de conditions climatiques, la capacité à générer de l'énergie renouvelable, les besoins en refroidissement et l'approvisionnement en électricité du réseau local, qui peuvent déjà incorporer des sources d'énergie à faible intensité carbonée. Enfin, la solution proposée ne néglige pas que la fabrication de l'infrastructure renouvelable présente également un impact environnemental.

À travers des expériences computationnelles utilisant des données du monde réel pour la charge de travail, les conditions climatiques, les spécifications des serveurs, l'emplacement des centres de données et le mix énergétique du réseau, nous avons démontré que la solution hybride, qui combine l'infrastructure renouvelable sur site et peut utiliser l'électricité du réseau local, est meilleure en termes d'empreinte carbone que le simple fonctionnement des centres de données en utilisant l'électricité du réseau local ou exclusivement l'électricité de l'infrastructure renouvelable sur site.

Nous avons ensuite étendu notre modélisation pour le long terme dans le chapitre 5, ce qui est obligatoire étant donné que les centres de données ont des durées de vie opérationnelles s'étendant sur plus d'une décennie. Nous avons commencé par améliorer la modélisation pour tenir compte de l'empreinte carbone de l'ensemble du cycle de vie de l'infrastructure renouvelable, de la fabrication au rejet ou au recyclage, ce qui fournit des informations plus précises sur l'impact environnemental et réduit le surdimensionnement.

De plus, nous avons également évalué l'inclusion de l'énergie éolienne comme source renouvelable sur site. Nos expériences ont démontré que malgré la réduction supplémentaire de l'empreinte carbone, cela pourrait ne pas être adéquat pour la production renouvelable sur site en raison de ses exigences en termes de surface terrestre, du fait qu'il augmente l'incertitude du processus de dimensionnement et des coûts monétaires plus élevés pour la production d'énergie éolienne. Par conséquent, les meilleurs candidats pour l'infrastructure renouvelable sur site sont les panneaux solaires pour générer de l'énergie et les batteries lithium-ion pour stocker l'énergie afin de la fournir la nuit ou pendant les périodes de faible irradiance.

Nous avons également montré que la planification de la charge de travail peut atténuer une partie de l'impact des erreurs dans le processus de dimensionnement, causées par l'incertitude des conditions climatiques.

En termes de coûts, nous avons montré que l'adoption d'une infrastructure renouvelable sur site est moins chère que le fonctionnement exclusif des centres de données avec de l'électricité provenant uniquement du réseau électrique local. De plus, la solution avec des panneaux solaires et des batteries est la meilleure à la fois en termes environnementaux et monétaires pour les opérateurs de cloud.

Notre modèle nous permet également d'évaluer la réduction potentielle des émissions de carbone en adoptant des serveurs de nouvelles générations qui pourraient être plus économes en énergie, tout en tenant compte de l'empreinte carbone de la fabrication des serveurs. Le modèle est suffisamment flexible pour comparer une génération de serveurs à une autre ou déterminer quelle serait la solution optimale compte tenu de nombreuses générations de serveurs. Dans la solution optimale, les serveurs sont utilisés pendant leur durée de vie prévue. Ce fait peut servir d'inspiration pour prolonger l'utilisation réelle des serveurs, car ils sont puissants en termes de calcul, les mettre au rebut entraîne un impact environnemental et attendre de remplacer les serveurs augmente la probabilité d'avoir une génération de serveurs plus économe en énergie et plus puissante en termes de calcul.

Enfin, le modèle a été soigneusement conçu pour n'utiliser que des variables linéaires. Cela permet au modèle d'être résolu de manière optimale en temps polynomial et d'évaluer les scénarios à long terme en un temps raisonnable. Cette efficacité réduit la consommation d'énergie et l'empreinte carbone associée du processus de dimensionnement lui-même. Les décideurs pourraient adopter ce modèle pour guider leurs efforts visant à réduire l'impact environnemental des plates-formes de cloud computing.

Comme discuté dans la Section 3.5, pour évaluer davantage l'impact des stratégies follow-the-renewables, nous devons également prendre en compte l'utilisation du réseau par la charge de travail, ce qui réduit la bande passante disponible pour le processus de migration. De plus, le modèle peut être analysé pour la technologie de virtualisation de conteneurs. Étant donné que les conteneurs sont généralement

plus petits que les machines virtuelles, leur temps de migration est plus rapide. Cela peut entraîner la migration de plus de tâches ou permettre la migration vers des centres de données situés plus loin.

Nous avons vu dans le chapitre 3 que l'application de la stratégie follow-the-renewables a un potentiel significatif pour réduire les émissions de carbone de l'opération de cloud. Nous ne l'avons pas inclus dans notre modélisation pour le dimensionnement et le fonctionnement des centres de données cloud distribués à l'échelle mondiale, étant donné la latence élevée entre les liens réseau qui connectent ces centres de données, ce qui entraînerait un temps de migration long. Cette analyse doit être réalisée pour évaluer le potentiel de migration de la charge de travail, étant donné que les centres de données situés plus loin pourraient avoir plus de disponibilité en sources à faible intensité de carbone. Une possibilité est d'avoir un seuil pour le temps de migration, ou de migrer uniquement les tâches à faible priorité en tant que tâches en lot.

En ce qui concerne notre approche proposée pour le dimensionnement et le fonctionnement des fédérations de cloud, un point crucial pour le long terme est la dégradation de l'infrastructure renouvelable et informatique et la défaillance de l'équipement informatique. Pour la décision de fabriquer de nouveaux serveurs, le modèle peut être étendu à un niveau de granularité fine au niveau de l'équipement informatique (par exemple, en remplaçant uniquement un disque défaillant). L'analyse des coûts monétaires peut également être appliquée à la décision de fabriquer ou de remplacer de nouveaux serveurs, à condition que les données sur le prix du matériel soient accessibles. De plus, il est possible de formuler un problème d'optimisation multi-objectif entre les coûts en dollars et l'empreinte carbone, tant pour l'infrastructure renouvelable que pour la partie informatique. Une autre possibilité est d'analyser le processus de dimensionnement en tenant compte de l'utilisation d'autres types de matériel pour les calculs, en particulier les processeurs graphiques (GPU) largement utilisés pour les applications d'intelligence artificielle.

Nous avons exploré la décision de dimensionnement pour les fédérations de cloud existantes. Notre solution proposée pourrait également être étendue pour évaluer le placement de nouveaux centres de données dans le but de minimiser l'empreinte carbone. Par exemple, étant donné un ensemble d'options de localisation, leurs caractéristiques respectives en termes de potentiel de génération d'énergie renouvelable, conditions climatiques, besoins en refroidissement, demande de charge de travail, spécifications des serveurs et leur empreinte carbone associée, il serait possible d'effectuer une analyse comparative de l'empreinte carbone de chaque emplacement. Les résultats pourraient être utilisés pour orienter la décision sur l'emplacement du nouveau centre de données.

Enfin, il existe d'autres types d'impact environnemental autres que les émissions de carbone. Par exemple, les plateformes de cloud computing présentent des impacts en termes d'utilisation de l'eau pour le refroidissement, d'extraction des ressources pour la fabrication des circuits intégrés et de l'infrastructure des centres de données, et d'élimination inappropriée de l'équipement informatique, ce qui pourrait entraîner la libération de substances toxiques dans l'environnement. Dans un premier temps, il est nécessaire de modéliser ces types d'impacts environnementaux pour générer des métriques qui nous permettront de les mesurer. Tout comme il existe des métriques pour évaluer la qualité de service, il serait intéressant d'avoir des métriques pour évaluer l'impact environnemental de ces services et applications. Dans un deuxième temps, il sera possible de proposer des solutions pour réduire l'impact environnemental. Par exemple, ces métriques pourraient être incorporées dans des algorithmes d'ordonnancement de charges de travail multi-objectifs ou incluses dans le processus de dimensionnement pour les minimiser.