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Strategies for operating and sizing low-carbon cloud data centers

March 22, 2024

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Cloud computing

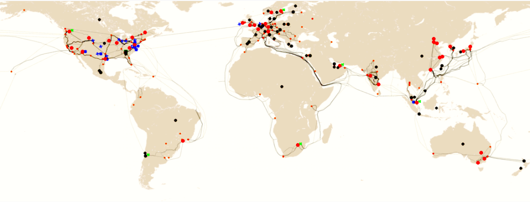

Figure 1: Azure cloud infrastructure.

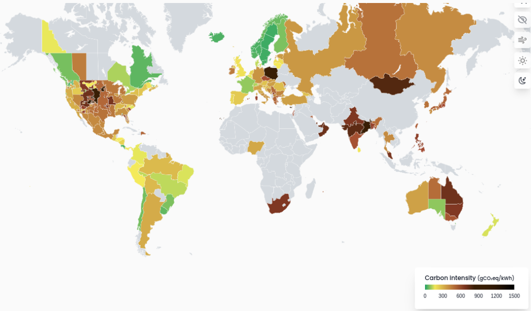

Figure 2: ElectricityMap.

- Computing resources on demand for most applications we use
- Cloud data centers (DCs) consumes ≈1% of the world's electricity[1]

[1] IEA. *Data Centres and Data Transmission Networks*. Tech. rep. IEA, Paris, 2022. URL: https://www.iea.org/energy-system/buildings/data-centres-and-data-transmission-networks.

Environmental impact of cloud computing

- Renewable energy in cloud DCs
  - Google avg 64%, up to 97%[a]
- Improvements in efficiency:
  - 6 $\times$ workload vs 6% energy (2010-2018)[b]
- The Green House Gas (GHG) Protocol:
  1. Direct GHG emissions
  2. Electricity indirect GHG emissions
  3. Other indirect GHG emissions: 74% from Google DCs total carbon footprint

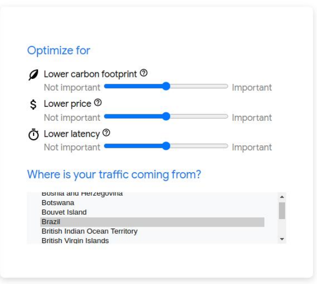

Figure 3: Google's Region picker tool.

[a] Google. *Environmental Report 2023*. `https://sustainability.google/reports/google-2023-environmental-report/`. Google, 2023.

[b] Eric Masanet et al. "Recalibrating global data center energy-use estimates." In: *Science* 367.6481 (2020), pp. 984–986.

Strategies for operating and sizing low-carbon cloud DCs

Low-carbon cloud DCs:

- Considering the 3 scopes of the GHG protocol
- CO_2-eq metric
  - Compare different GHG gases based in their Global Warming Potential (GWP)
  - R134a GWP is 1430: 1g R134a $=$ 1430g CO_2-eq

Carbon-responsive strategies:[2]

- follow-the-renewables
- sizing the renewable and IT infrastructure

[2] Dawn Nafus, Eve M. Schooler, and Karly Ann Burch. "Carbon-Responsive Computing: Changing the Nexus between Energy and Computing." In: *Energies* 14.21 (2021). ISSN: 1996-1073. DOI: 10.3390/en14216917. URL: https://www.mdpi.com/1996-1073/14/21/6917.

Strategies for operating and sizing low-carbon cloud DCs

Main contributions of this thesis:

- Analysis of the impact of adopting the follow-the-renewables approaches in both network congestion and energy consumption
- Modeling for sizing the renewable and IT infrastructure and operating the cloud data centers with follow-the-renewables using a Linear Program formulation

Analysis of the impact of follow-the-renewables in network congestion and energy consumption

Follow-the-renewables

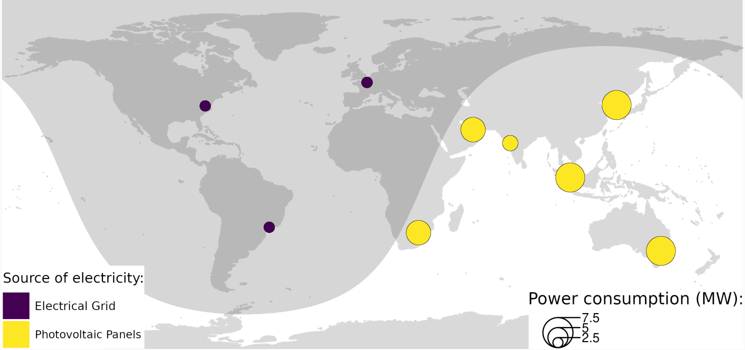

Figure 4: An example of a cloud federation that adopts the follow-the-renewables strategy.

- Allocates/Migrates the workload to the data centers (DCs) that have more renewable (green) power available
- Extra computations proportional to the migration duration
- What is the impact in network congestion and energy consumption?

Different usages of the follow-the-renewables

Table 1: Comparison between different approaches to adopt follow-the-renewables.

Algorithm	Allocation	Migration	Network
NEMESIS[3]	✓	✓	✓
FollowMe@S Intra[4]	✓	✓	✗
FollowMe@S Inter	✓	✓	✗
WSNB[5]	✓	✗	✗

[3] Benjamin Camus et al. "Network-Aware Energy-Efficient Virtual Machine Management in Distributed Cloud Infrastructures with On-Site Photovoltaic Production." In: *2018 30th International Symposium on Computer Architecture and High Performance Computing (SBAC-PAD)*. Lyon, France: IEEE, 2018, pp. 86–92.

[4] Hashim Ali et al. "FollowMe@LS: Electricity price and source aware resource management in geographically distributed heterogeneous datacenters." In: *Journal of Systems and Software* 175 (2021), p. 110907. ISSN: 0164-1212.

[5] Minxian Xu and Rajkumar Buyya. "Managing renewable energy and carbon footprint in multi-cloud computing environments." In: *Journal of Parallel and Distributed Computing* 135 (2020), pp. 191–202. ISSN: 0743-7315.

Computational simulations

- Simgrid: framework to simulate large scale distributed systems
  - Servers' power consumption: linear model based on CPU usage
  - Flow-level TCP modeling of the network
- Model of live-migration's power consumption:
  - one CPU core is used in the target host during the migration

Input: cloud infrastructure

- Based on a real example: Grid'5000
- 1035 homogeneous servers distributed among 9 DCs
  - 2 x Intel Xeon E5-2630 (6 CPU cores per processor)
  - 32 GB RAM
- Network:
  - 1Gbps links intra DC
  - 10Gbps links inter DC

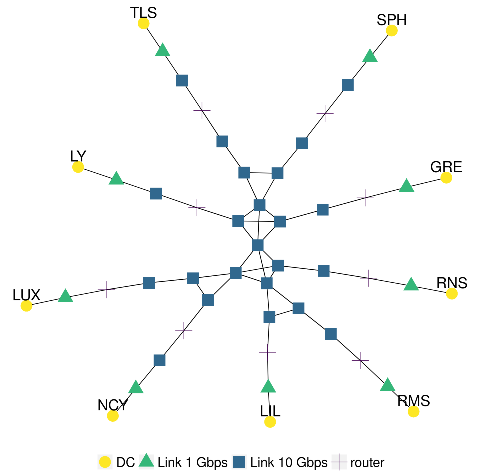

Figure 5: How the DCs are interconnected in the network.

Input: green energy traces

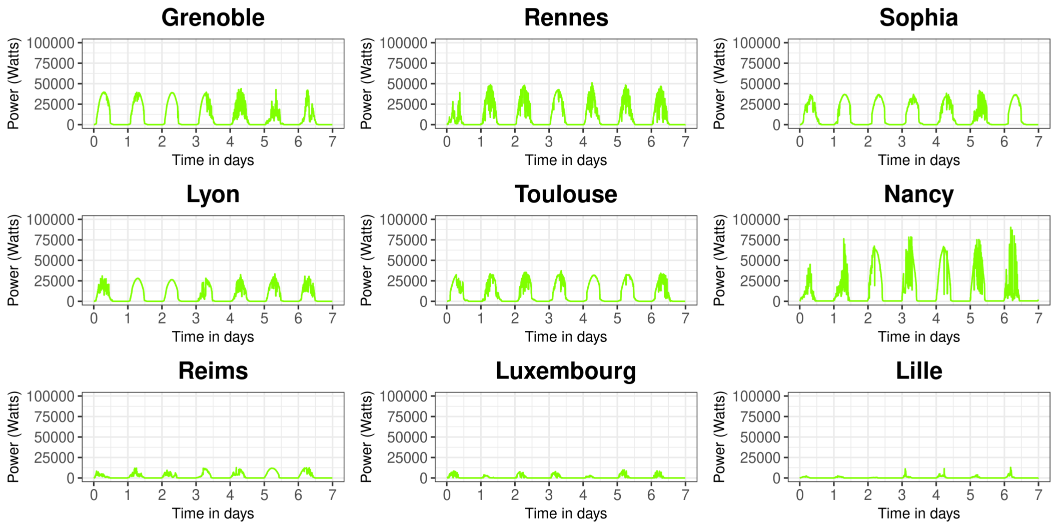

Figure 6: Green energy power production per DC - Source of data: Photovolta project.

Input: workloads

- Virtual machines
- Traces samples from real cloud providers:
  - Google (2011): 380k VMs
  - Azure (2020): 300k VMs
- Information extracted:
  - Submission time, CPU cores requested, runtime
- RAM = 2GB per CPU cores (t2.small)
- No network usage

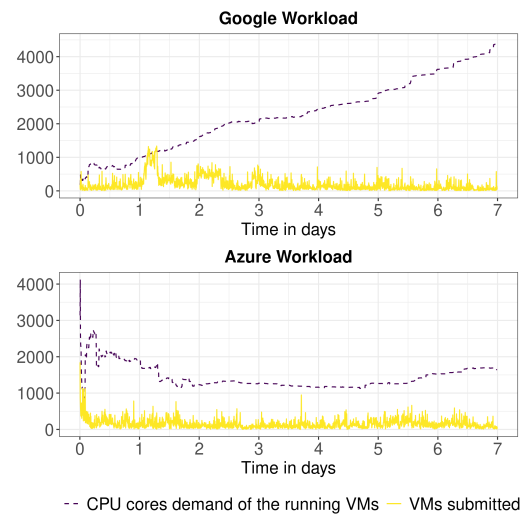

Figure 7: Workloads used for the simulations.

Total and brown energy consumption

Table 2: Comparison of energy consumption (MWh) for the Azure workload.

Algorithm	Total	Non-renewable
NEMESIS	30.43	21.21
FollowMe@S Inter	31.69	22.40
FollowMe@S Intra	31.69	22.41
WSNB	33.56	24.23

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- Impact of **network congestion** in the **energy consumption**?
- Using network information to plan the migrations without congestion

NEMESIS

"Network-aware Energy-efficient Management framework for distributEd cloudS Infrastructures with on-Site photovoltaic production"[6]

Main steps:

- Pre-allocation of incoming Virtual Machines (VMs)
- Revision of pre-allocations
- Migration of the running VMs
- Servers consolidation

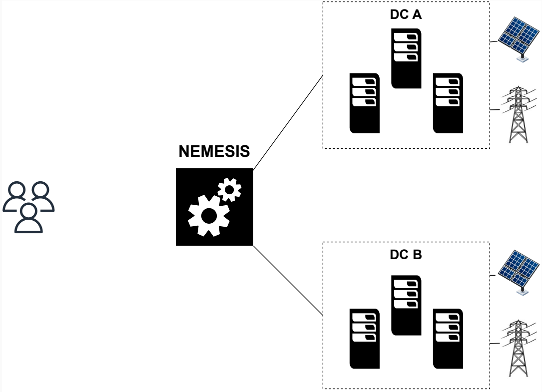

Figure 8: NEMESIS framework.

[6] Benjamin Camus et al. "Network-Aware Energy-Efficient Virtual Machine Management in Distributed Cloud Infrastructures with On-Site Photovoltaic Production." In: *2018 30th International Symposium on Computer Architecture and High Performance Computing (SBAC-PAD)*. Lyon, France: IEEE, 2018, pp. 86–92.

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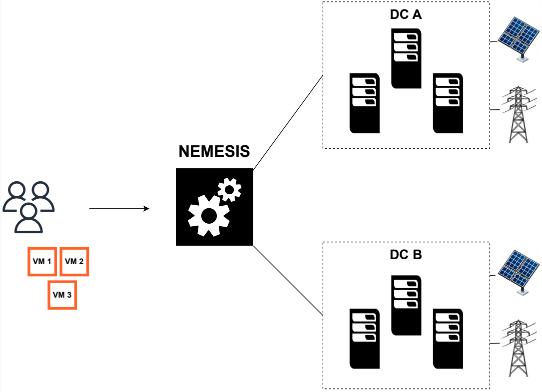

Figure 9: NEMESIS framework.

[7] Benjamin Camus et al. "Network-Aware Energy-Efficient Virtual Machine Management in Distributed Cloud Infrastructures with On-Site Photovoltaic Production." In: *2018 30th International Symposium on Computer Architecture and High Performance Computing (SBAC-PAD)*. Lyon, France: IEEE, 2018, pp. 86–92.

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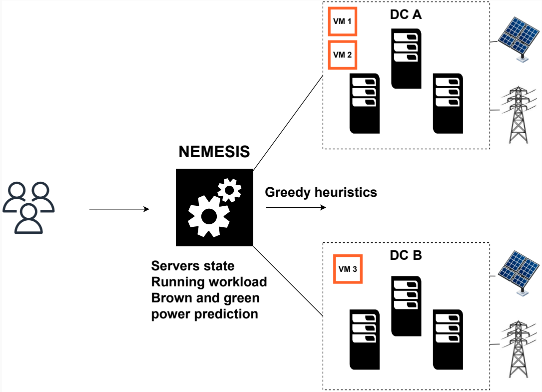

Figure 10: NEMESIS framework.

[8] Benjamin Camus et al. "Network-Aware Energy-Efficient Virtual Machine Management in Distributed Cloud Infrastructures with On-Site Photovoltaic Production." In: *2018 30th International Symposium on Computer Architecture and High Performance Computing (SBAC-PAD)*. Lyon, France: IEEE, 2018, pp. 86–92.

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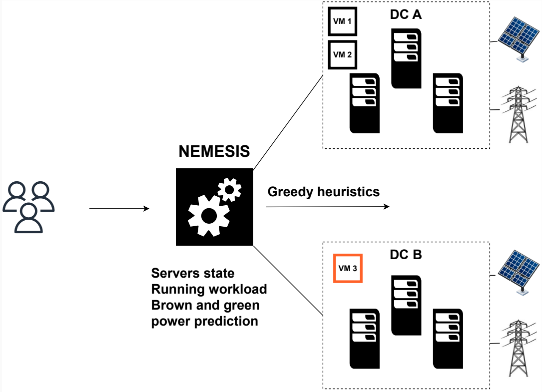

Figure 11: NEMESIS framework.

[9] Benjamin Camus et al. "Network-Aware Energy-Efficient Virtual Machine Management in Distributed Cloud Infrastructures with On-Site Photovoltaic Production." In: *2018 30th International Symposium on Computer Architecture and High Performance Computing (SBAC-PAD)*. Lyon, France: IEEE, 2018, pp. 86–92.

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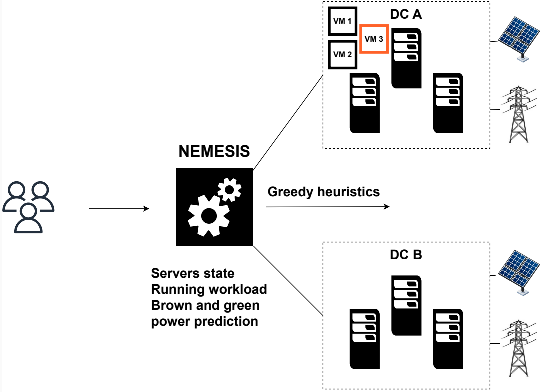

Figure 12: NEMESIS framework.

[10] Benjamin Camus et al. "Network-Aware Energy-Efficient Virtual Machine Management in Distributed Cloud Infrastructures with On-Site Photovoltaic Production." In: *2018 30th International Symposium on Computer Architecture and High Performance Computing (SBAC-PAD)*. Lyon, France: IEEE, 2018, pp. 86–92.

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- **Migration of the running VMs**
- Servers consolidation

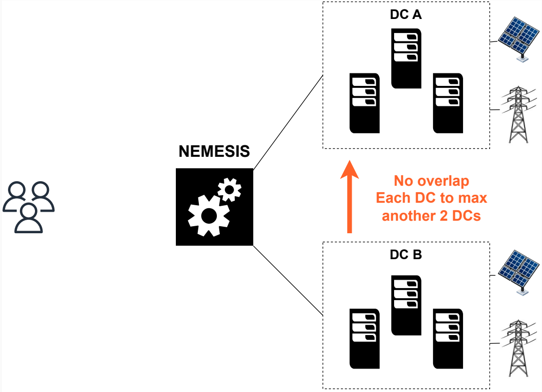

Figure 13: NEMESIS framework.

[11] Benjamin Camus et al. "Network-Aware Energy-Efficient Virtual Machine Management in Distributed Cloud Infrastructures with On-Site Photovoltaic Production." In: *2018 30th International Symposium on Computer Architecture and High Performance Computing (SBAC-PAD)*. Lyon, France: IEEE, 2018, pp. 86–92.

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- Revision of pre-allocations
- Migration of the running VMs
- **Servers consolidation**

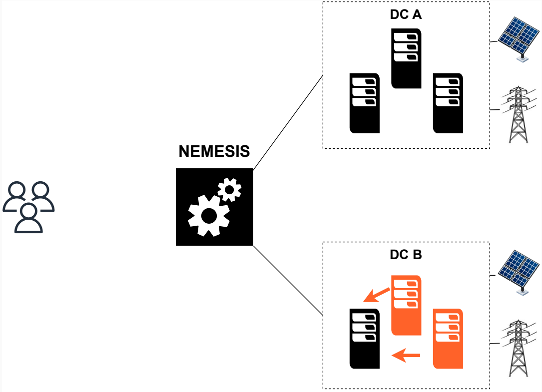

Figure 14: NEMESIS framework.

[12] Benjamin Camus et al. "Network-Aware Energy-Efficient Virtual Machine Management in Distributed Cloud Infrastructures with On-Site Photovoltaic Production." In: *2018 30th International Symposium on Computer Architecture and High Performance Computing (SBAC-PAD)*. Lyon, France: IEEE, 2018, pp. 86–92.

"Network-aware Energy-efficient Management framework for distributEd cloudS Infrastructures with on-Site photovoltaic production"[13]

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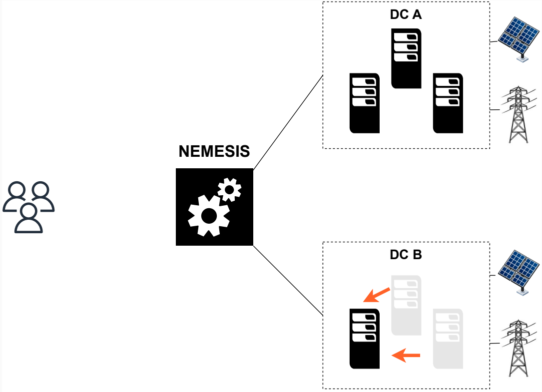

Figure 15: NEMESIS framework.

[13] Benjamin Camus et al. "Network-Aware Energy-Efficient Virtual Machine Management in Distributed Cloud Infrastructures with On-Site Photovoltaic Production." In: *2018 30th International Symposium on Computer Architecture and High Performance Computing (SBAC-PAD)*. Lyon, France: IEEE, 2018, pp. 86–92.

"Network-aware Energy-efficient Management framework for distributEd cloudS Infrastructures with on-Site photovoltaic production"[14]

Steps extended:

- Pre-allocation of incoming Virtual Machines (VMs)
- Revision of pre-allocations
- **Migration of the running VMs**
- **Servers consolidation**

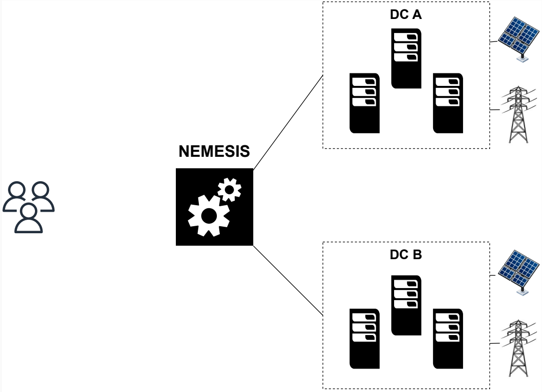

Figure 16: NEMESIS framework.

[14] Benjamin Camus et al. "Network-Aware Energy-Efficient Virtual Machine Management in Distributed Cloud Infrastructures with On-Site Photovoltaic Production." In: *2018 30th International Symposium on Computer Architecture and High Performance Computing (SBAC-PAD)*. Lyon, France: IEEE, 2018, pp. 86–92.

"Congestion and Network-aware Energy-efficient Management framework for distributEd cloudS Infrastructures with on-Site photovoltaic production"[15]

Modifications:

- Bandwidth and usage of links
- Network topology
- Migrations for server consolidation distributed in time (no overlap)

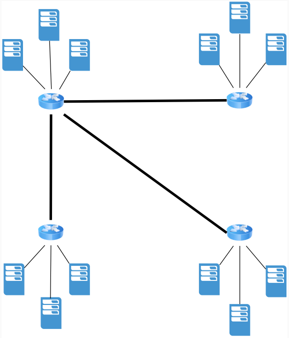

Figure 17: c-NEMESIS example.

[15] Miguel Vasconcelos., Daniel Cordeiro., and Fanny Dufossé. "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*. INSTICC. SciTePress, 2022, pp. 44–55. DOI: 10.5220/0011047000003203.

c-NEMESIS

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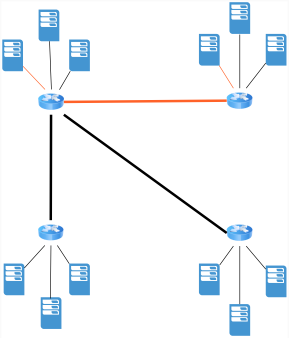

Figure 18: c-NEMESIS example.

[16] Miguel Vasconcelos., Daniel Cordeiro., and Fanny Dufossé. "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*. INSTICC. SciTePress, 2022, pp. 44–55. DOI: 10.5220/0011047000003203.

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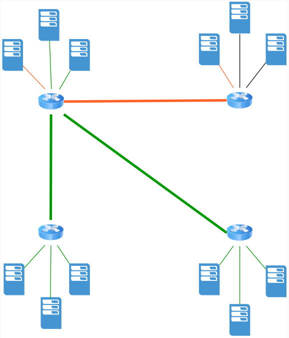

Figure 19: c-NEMESIS example.

[17] Miguel Vasconcelos., Daniel Cordeiro., and Fanny Dufossé. "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*. INSTICC. SciTePress, 2022, pp. 44–55. DOI: 10.5220/0011047000003203.

"Congestion and Network-aware Energy-efficient Management framework for distributEd cloudS Infrastructures with on-Site photovoltaic production"[18]

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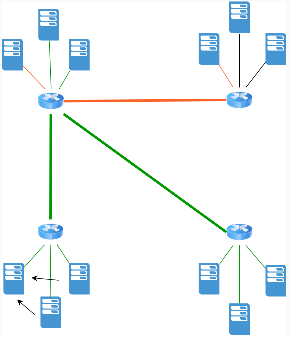

Figure 20: c-NEMESIS example.

[18] Miguel Vasconcelos., Daniel Cordeiro., and Fanny Dufossé. "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*. INSTICC. SciTePress, 2022, pp. 44–55. DOI: 10.5220/0011047000003203.

Assessing network congestion

- **"Perfect scenario"**:
  - full access to network resources
- Additional time the migration takes vs the perfect scenario
- Link under congestion: migration 10% longer vs "perfect scenario"

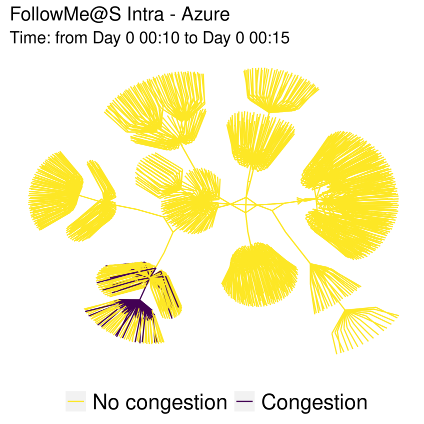

Figure 21: Example of links with congestion.

Network considered
Bandwidth, Usage
Topology
Duration:
avg=1.0, max=1.32

Network considered
No overlap, 1 DC
to max other 2 DCs
Duration:
avg=1.6, max=3.98

Network not considered
Duration:
avg=7.8, max=157.24

Network not considered
Duration:
avg=4.4, max=25.56

Wasted and non-renewable energy

- Wasted energy proportional to the extra time speding migrating in comparison to the perfect scenario
- 367 kWh of green energy was wasted in the case of the FollowMe@S Intra algorithm with the Google workload
- This energy could have powered the one of the DCs (38 servers at maximum capacity) for approximately 44 hours

Total and brown energy consumption

Table 3: Comparison of energy consumption (MWh) for the Azure workload.

Algorithm	Total	Non-renewable
c-NEMESIS	30.55	21.20
NEMESIS	30.43	21.21
FollowMe@S Inter	31.69	22.40
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Summary - first main contribution of this thesis

- Bad migration planning results in network congestion, waste of renewable energy (and increase in non-renewable energy consumption)
- Follow-the-renewables approaches need to consider all the workload execution, given the intermittent nature of renewables

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- Bad migration planning results in network congestion, waste of renewable energy (and increase in non-renewable energy consumption)
- Follow-the-renewables approaches need to consider all the workload execution, given the intermittent nature of renewables

Modern cloud DCs are geographically distributed all over the world, not all DCs have on-site renewable infrastructure, and some locations already have presence of renewable sources, how to reduce the carbon footprint in this scenario?

Model for sizing the renewable and IT infrastructure and operating the DCs

Sizing the renewable and IT infrastructure

- Defining:
  - Area of solar panels
  - Capacity of energy storage devices
- Considerations:
  - Climate conditions
  - Energy-mix
  - Carbon footprint of renewable sources

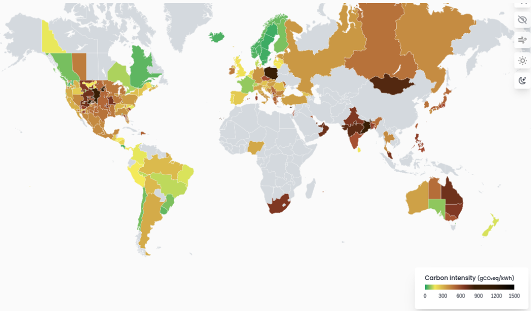

Figure 22: Electricitymap service.

Proposed solution

Linear program formulation to minimize the carbon emissions from the cloud federation operation (timespan of 1 year) [2]

- Scheduling and sizing modeled as single problem
  - Allocate workload to other DC or increase the **battery capacity** or **solar panels** (PV) area?
- Only real variables
  - Optimal solution in polynomial time

[2] M. Vasconcelos, D. Cordeiro, G. Da Costa, F. Dufossé, J.-M. Nicod, and V. Rehn-Sonigo, "Optimal sizing of a globally distributed low carbon cloud federation". *In: 2023 23nd IEEE International Symposium on Cluster, Cloud and Internet Computing (CCGrid), Bengaluru, India, 2023.*

Data centers modeling

- Infrastructure already built (servers, network)
- Homogeneous (regarding CPU cores)
- Server power consumption: idle and dynamic
- Intra-network power consumption: static
- Specific Power Usage Effectiveness (PUE) for each DC

Figure 23: Selected data centers location (inspired from Microsoft Azure)

Workload modeling

- All tasks must be scheduled and executed on time
- Batch tasks that can be executed in any of the DCs
- Task execution cannot be delayed
- No migration
    - High network links latency, migrating a VM with 12 GB of RAM takes: min. ≈ 4 min, avg. ≈ 14 min, max. ≈ 49 min

Renewables infrastructure modeling

- Batteries charge and discharge efficiency, Maximum Depth of Discharge
- PV panels efficiency
- Carbon emissions from manufacturing (PV: 250 kg CO_2-eq per m^2, bat: 59 kg CO_2-eq per kWh)
- Lifetime (PV: 30 years, bat: 10 years)

Local electricity grid modeling

- The energy mix is different at each location
- May have the presence of renewables or low carbon-intensive sources

Table 4: Carbon footprint of the regular grid at each location. Source for grid emissions: electricityMap, climate-transparency.org.

Location	**Emissions (g CO_2-eq per kWh)**
Johannesburg	900.6
Pune	702.8
Canberra	667.0
Dubai	530.0
Singapore	495.0
Seoul	415.6
Virginia	342.8
São Paulo	61.7
Paris	52.6

LP model - DC power consumption and supply

Data center power consumption (P_k^d):

$$P_k^d = PUE^d \times \left(Pintranet^d + Pidle^d + Pcore \times w_k^d\right) \tag{1}$$

Data center power supply:

$$P_k^d \leq Pre_k^d + Pgrid_k^d + Pdch_k^d - Pch_k^d \tag{2}$$

LP model - renewable infrastructure

Batteries level of energy (B_k^d):

$$B_k^d = B_{k-1}^d + Pch_{k-1}^d \times \eta_{ch} \times \Delta t - \frac{Pdch_{k-1}^d}{\eta_{dch}} \times \Delta t \tag{3}$$

Solar power production:

$$Pre_k^d = I_k^d \times Apv^d \times \eta_{pv} \tag{4}$$

Linear Program summary

Obj. function: Minimize the DC's operation CO_2 emissions (1 year 8760 time slots of 1 h)

$$\text{minimize} \sum_{k=0}^{K-1} \sum_{d=1}^{D} (FPgrid_k^d + FPpv_k^d) + \sum_{d=1}^{D} FPbat^d \quad (5)$$

- CO_2 comes from: grid power, manufacturing PV and batteries

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- CO_2 comes from: grid power, manufacturing PV and batteries

Input

- Power consumption of servers and network equipment
- 1 year of workload (Google trace)
- Renewable infrastructure specs (efficiency, manufacturing CO_2)
- For each DC:
  - Solar irradiation (1 year), Grid CO_2, PUE, CPU cores number

Linear Program summary

Obj. function: Minimize the DC's operation CO_2 emissions (1 year 8760 time slots of 1 h)

$$\text{minimize} \sum_{k=0}^{K-1} \sum_{d=1}^{D} (FPgrid_k^d + FPpv_k^d) + \sum_{d=1}^{D} FPbat^d \tag{5}$$

- CO_2 comes from: grid power, manufacturing PV and batteries

Input

- Power consumption of servers and network equipment
- 1 year of workload (Google trace)
- Renewable infrastructure specs (efficiency, manufacturing CO_2)
- For each DC:
  - Solar irradiation (1 year), Grid CO_2, PUE, CPU cores number

Output

- PVs area (m^2)
- Batteries capacity (kWh)
- Total CO_2 emissions
- Schedule of the workload

Results - CO_2 emissions

Table 5: 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

Results - CO_2 emissions

Table 5: 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

Reductions on carbon emissions:

- Grid vs DC renewable infra : $\simeq 5$ times

Results - CO_2 emissions

Table 5: 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

Reductions on carbon emissions:

- Grid vs DC renewable infra : $\simeq 5$ times
- Grid vs hybrid configuration (DC renewables and grid) : $\simeq 6$ times

Results - Sizing

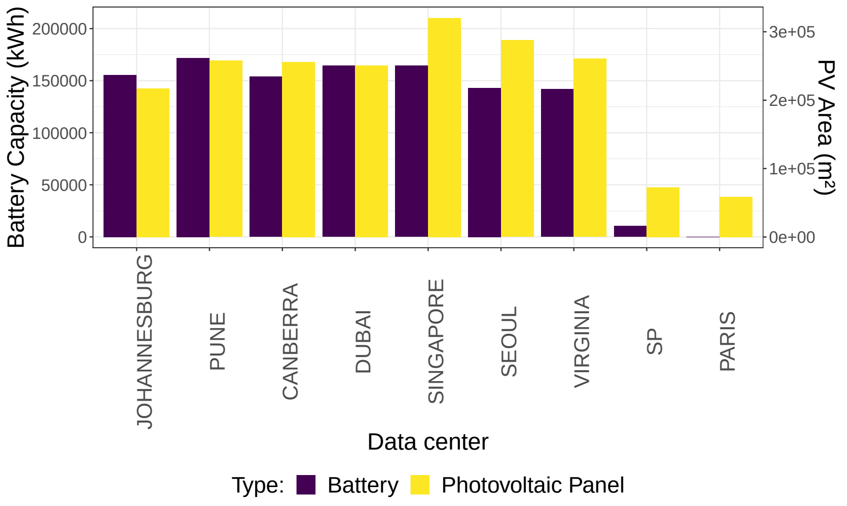


Figure 24: Optimal result for the area of PV panels and capacity of the batteries.

Visualization of DCs operation

- Each circle is a DC, and the radius is the power consumption (MW)
- The pizza graph represents the share of electricity source being used at that instant (PVs, batteries, or from the grid)
- The gray shadow represents the night
- Visualization for the first week of 2021

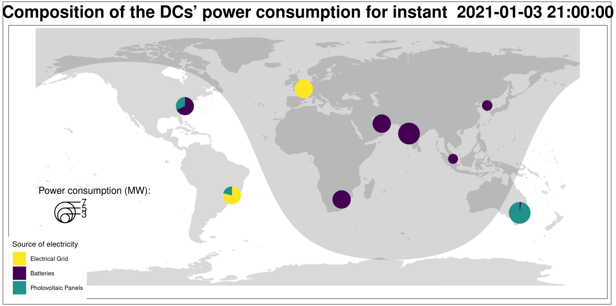


Figure 25: Example of data centers electricity source used.

Sizing for the long term

First modeling considering the short-term, but DCs have lifetime **longer than one decade**

- Manufacturing is only one of the phases of the life cycle of renewable infrastructure
- Workload keep increasing over time
- Hardware might be more power-efficient

What about?

- Wind power
- Delaying the workload
- Costs (dollars)

Sizing for the long term

First modeling considering the short-term, but DCs have lifetime longer than one decade

- Manufacturing is only one of the phases of the life cycle of renewable infrastructure
- **Workload keep increasing over time**
- **Hardware might be more power-efficient**

What about?

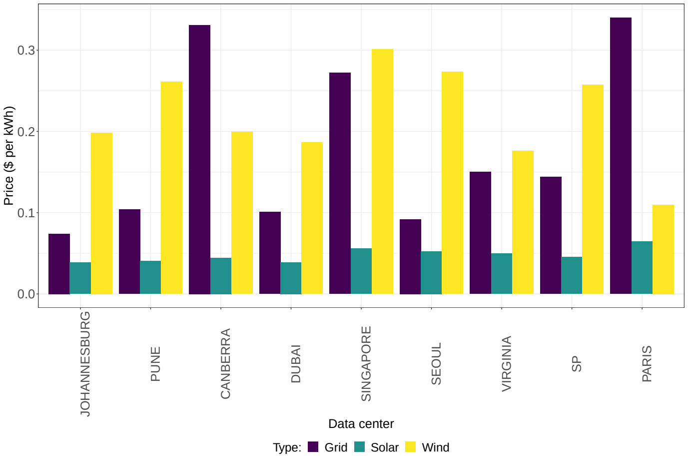
- Wind power
- Delaying the workload
- **Costs (dollars)**

Costs ($) of reducing the environmental impact

- How to measure the price of the renewable infrastructure?
  - **Levelized Cost of Energy (LCOE)**: Cost of manufacturing, operating, maintenance, related to the energy it can produce during the lifetime ($ per kWh)
  - **Levelized Cost of Storage (LCOS)**: Cost of manufacturing, operating, maintenance, related to the energy it is possible to discharge during the lifetime ($ per kWh)

Costs ($) of reducing the environmental impact

- Considered the Levelized Cost of Energy for the renewables
- Grid price is half at off-peak times (10 pm to 8 am)
- Battery price: 0.20 dollars per kWh of electricity delivered



Costs ($) of reducing the environmental impact

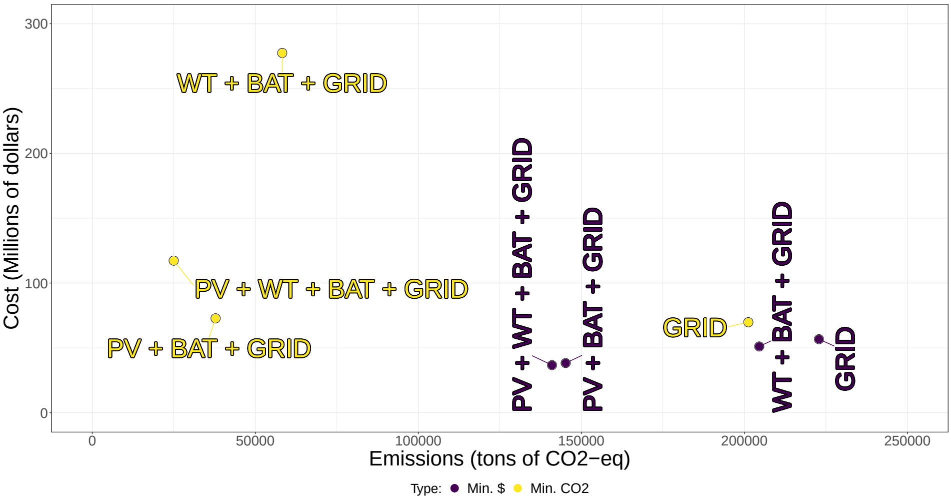


Figure 27: Costs vs CO_2 emissions for the different scenarios.

Costs ($) of reducing the environmental impact

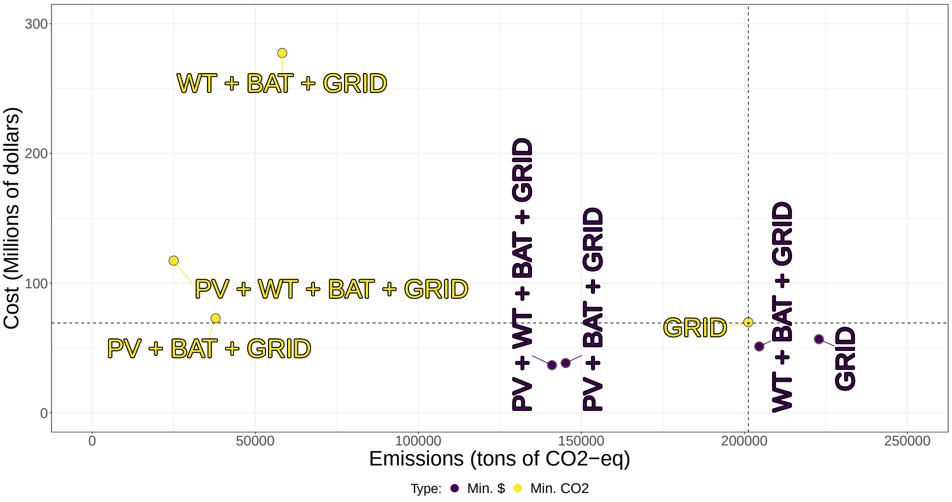


Figure 28: Costs vs CO_2 emissions for the different scenarios.

Costs ($) of reducing the environmental impact

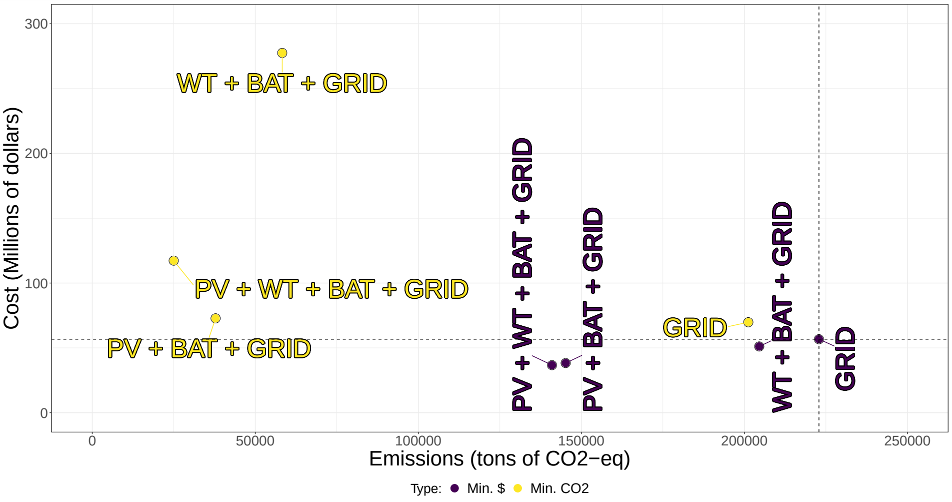


Figure 29: Costs vs CO_2 emissions for the different scenarios.

Costs ($) of reducing the environmental impact

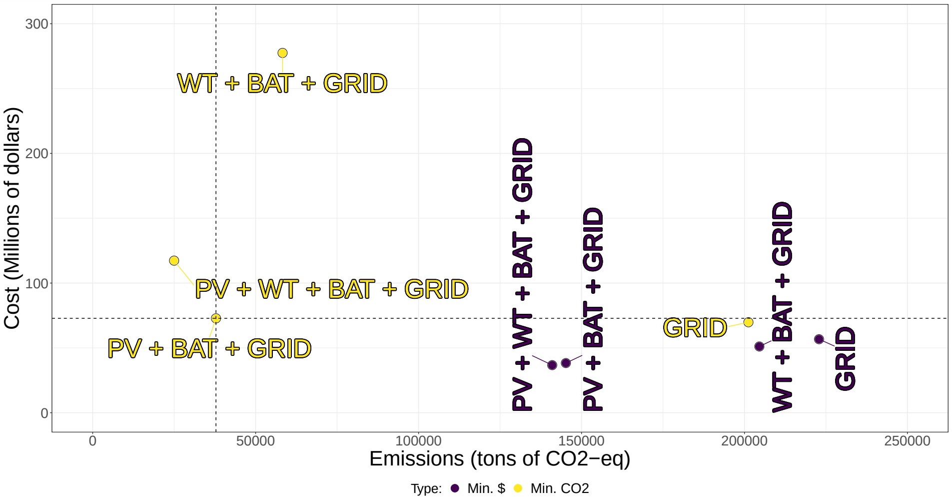


Figure 30: Costs vs CO_2 emissions for the different scenarios.

Sizing the IT part

Defining the number of servers needed for the operation

- Workload growth over time
- New hardware generations that may be more power-efficient
- **CO_2 from manufacturing the servers**

CO_2-eq computed based in the specifications of the integrated circuits[19]

- Dell R740: 4020 vs 688 kg CO_2-eq

[19] Udit Gupta et al. “ACT: Designing Sustainable Computer Systems with an Architectural Carbon Modeling Tool.” In: *Proceedings of the 49th Annual International Symposium on Computer Architecture*. ISCA ’22. New York, New York: Association for Computing Machinery, 2022, pp. 784–799. ISBN: 9781450386104. DOI: 10.1145/3470496.3527408.

Sizing the IT part

Is it worth to add/replace the servers every year?

- Decision made year by year (greedy approach)
- Optimal solution (all information is known in advance)

Settings:

- Workload increase 25% per year[20]
- Server expected lifetime of 4 years
- 5 years of operation

Table 6: Servers specifications for different generations.

Year	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

[20] Cisco. *Cisco Global Cloud Index: Forecast and Methodology, 2016-2021. White Paper.* Cisco, 2018.

Sizing the IT part

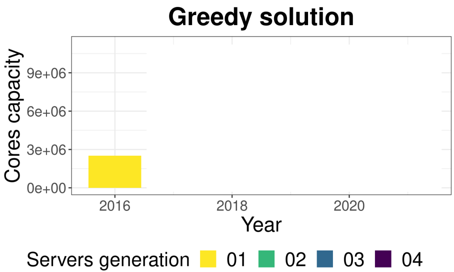


Figure 31: Comparison between the optimal and greedy approaches.

Table 7: Servers specifications for different generations.

Gen	Years	CPU	Cores	Pidle	Pcore	kg CO_2-eq
01	2016 <	Intel Xeon E5-2660 v2	20	52	7.5	-
02	2017, 2018	Intel Xeon Platinum 8180	56	48.9	6.68	578.6
03	2019, 2020	AMD EPYC 7742	64	66.1	2.71	587.2
04	2021	AMD EPYC 7763	128	75.6	3	590.3

Sizing the IT part

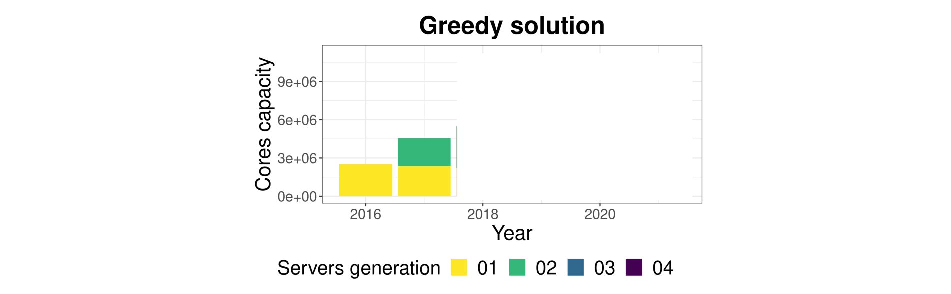


Figure 32: Comparison between the optimal and greedy approaches.

Table 8: Servers specifications for different generations.

Gen	Years	CPU	Cores	Pidle	Pcore	kg CO_2-eq
01	2016 $<$	Intel Xeon E5-2660 v2	20	52	7.5	-
02	2017, 2018	Intel Xeon Platinum 8180	56	48.9	6.68	578.6
03	2019, 2020	AMD EPYC 7742	64	66.1	2.71	587.2
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Sizing the IT part

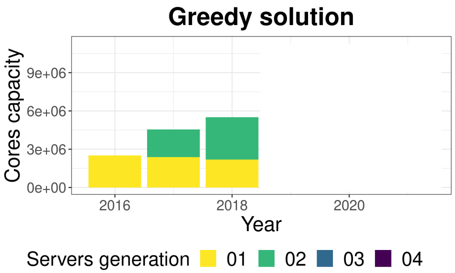

Figure 33: Comparison between the optimal and greedy approaches.

Table 9: Servers specifications for different generations.

Gen	Years	CPU	Cores	Pidle	Pcore	kg CO_2-eq
01	2016 <	Intel Xeon E5-2660 v2	20	52	7.5	-
02	2017, 2018	Intel Xeon Platinum 8180	56	48.9	6.68	578.6
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04	2021	AMD EPYC 7763	128	75.6	3	590.3

Sizing the IT part

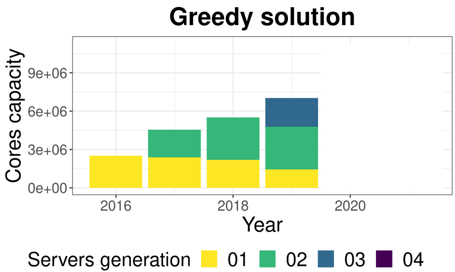

Figure 34: Comparison between the optimal and greedy approaches.

Table 10: Servers specifications for different generations.

Gen	Years	CPU	Cores	Pidle	Pcore	kg CO_2-eq
01	2016 <	Intel Xeon E5-2660 v2	20	52	7.5	-
02	2017, 2018	Intel Xeon Platinum 8180	56	48.9	6.68	578.6
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Sizing the IT part

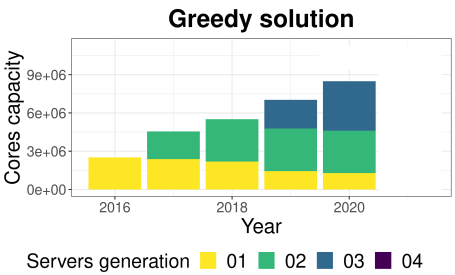

Figure 35: Comparison between the optimal and greedy approaches.

Table 11: Servers specifications for different generations.

Gen	Years	CPU	Cores	Pidle	Pcore	kg CO_2-eq
01	2016 <	Intel Xeon E5-2660 v2	20	52	7.5	-
02	2017, 2018	Intel Xeon Platinum 8180	56	48.9	6.68	578.6
03	2019, 2020	AMD EPYC 7742	64	66.1	2.71	587.2
04	2021	AMD EPYC 7763	128	75.6	3	590.3

Sizing the IT part

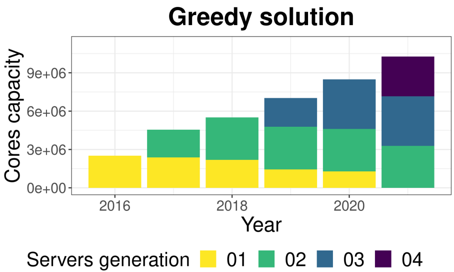

Figure 36: Comparison between the optimal and greedy approaches.

Table 12: Servers specifications for different generations.

Gen	Years	CPU	Cores	Pidle	Pcore	kg CO_2-eq
01	2016 <	Intel Xeon E5-2660 v2	20	52	7.5	-
02	2017, 2018	Intel Xeon Platinum 8180	56	48.9	6.68	578.6
03	2019, 2020	AMD EPYC 7742	64	66.1	2.71	587.2
04	2021	AMD EPYC 7763	128	75.6	3	590.3

Sizing the IT part

The optimal solution emits 13.4% less CO_2.

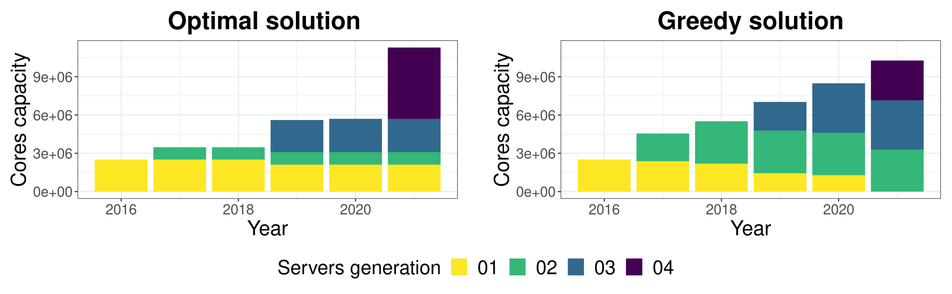

Figure 37: Comparison between the optimal and greedy approaches.

Table 13: Servers specifications for different generations.

Gen	Years	CPU	Cores	Pidle	Pcore	kg CO_2-eq
01	2016 <	Intel Xeon E5-2660 v2	20	52	7.5	-
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03	2019, 2020	AMD EPYC 7742	64	66.1	2.71	587.2
04	2021	AMD EPYC 7763	128	75.6	3	590.3

Summary - second main contribution

- Linear program formulation for **sizing** and **operating** DCs
  - renewable and IT infrastructure
- Characteristics of each region
  - climate conditions, energy mix
- Follow-the-renewables
- Flexible to evaluate many scenarios
- Solved in polynomial time

Future research directions

- Other types of environmental impact
- Migrating the workload
- Robustness
- Degradation of the infrastructure over the years
- Sizing new data centers (renewable and IT infrastructure)

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- LabEx PERSYVAL-Lab (“ANR-11-LABX-0025-01”)
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Thank you !

Thank you for your attention!

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Strategies for operating and sizing low-carbon cloud data centers

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Xu, Minxian and Rajkumar Buyya. “Managing renewable energy and carbon footprint in multi-cloud computing environments.” In: *Journal of Parallel and Distributed Computing* 135 (2020), pp. 191–202. ISSN: 0743-7315.

Baselines

WSNB (**W**orkload **s**hifting **n**on **b**rownout)[21]:

- Allocates the workload to the nearest DC that has available green power
- Follow-the-renewables strategy applied for the initial allocation
- Does not perform live-migrations
- Does not shutdown under-utilized servers

[21] Minxian Xu and Rajkumar Buyya. "Managing renewable energy and carbon footprint in multi-cloud computing environments." In: *Journal of Parallel and Distributed Computing* 135 (2020), pp. 191–202. ISSN: 0743-7315.

Baselines

FollowME@Source[22]:

- Allocation step: tries to allocate the incoming VMs to the greenest DC
- Migration step: Either only intra (origin = destination) or inter (origin != destination) DC
  - Intra DC: executed at each DC separately
  - Inter DC: tries to migrate the workload to the greenest DC
- Under-utilized servers are shut down (server consolidation)
- Do not consider network for migration planning

[22] Hashim Ali et al. "FollowMe@LS: Electricity price and source aware resource management in geographically distributed heterogeneous datacenters." In: *Journal of Systems and Software* 175 (2021), p. 110907. ISSN: 0164-1212.

Baselines

Follow-the-renewables strategy

- Only for the VM allocation
  - WSNB and FollowME@S Intra
- During the whole execution of the workload
  - NEMESIS, c-NEMESIS and FollowME@S Inter

Impact of adding wind turbines (WT)

- Can further reduce 34% the carbon emissions in comparison to only using PVs and batteries.
- However, requires larger land area (1 to 3 WT per km^2)

Table 14: Computed number of WT for each location.

Location	Number of WT
Johannesburg	59
Pune	26
Canberra	67
Dubai	79
Singapore	37
Seoul	109
Virginia	39
São Paulo	87
Paris	22

Impact of adding wind turbines (WT)

- Can further reduce 34% the carbon emissions in comparison to only using PVs and batteries.
- However, requires larger land area (1 to 3 WT per km^2)

Table 15: 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

Wasted energy

Table 16: Wasted energy in the migrations (Wh) for the Azure workload.

Algorithm	**Origin**	**Target**
NEMESIS	539.6	491.1
c-NEMESIS	39.3	24.1
FollowMe@S Intra	163 128.1	93 298.9
FollowMe@S Inter	175 086.3	105 528.8

Flexibility in the scheduling

What is the impact in carbon emissions of delaying α percent of the jobs up to β time slots (1h per time slot) ?

Table 17: Reductions in total carbon emissions (%) in comparison to the scenario where it is not possible to delay the workload.

α \ β	**1**	**24**	**48**	**72**	**96**	**120**	**144**	**168**
10	0.46	3.14	3.48	3.66	3.76	3.81	3.85	3.85
20	0.84	3.85	4.11	4.21	4.21	4.21	4.22	4.22
30	1.15	4.07	4.25	4.25	4.26	4.26	4.27	4.27
40	1.42	4.15	4.25	4.26	4.27	4.28	4.28	4.29
50	1.65	4.22	4.26	4.27	4.28	4.29	4.3	4.3

Network congestion

Table 18: Extra seconds during migrations compared to the case when there is no congestion for the Azure workload, where "avg." stands for the average of the observations, "max." for the maximum value, and "rel." for the relative value.

Algorithm	**avg. rel.**	**max. rel.**	**Total extra seconds**
NEMESIS	1.6	3.98	86 235.5
c-NEMESIS	1.0	1.32	4 224.4
FollowME@S Intra	4.4	25.56	16 384 188.8
FollowME@S Inter	7.8	157.24	18 531 893.3

Input: DCs irradiation used in second part

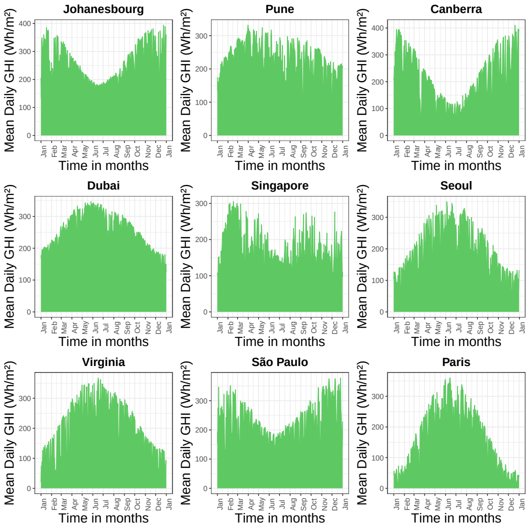

Figure 38: Solar Irradiation at different locations in 2021. Source: NASA's MERRA-2.

Performance of the migration planning algorithm

- Will all the network links be evaluated all the time?
- No. Using the "migration history" reduces the search space
- Planning is made between servers, if server a server already has a migration planed, it will not be evaluated anymore

What if my workload require ms to be scheduled?

- Allocation and migration steps could be executed in parallel
- Precomputations
- Azure uses parallel instances of the scheduler service, and cache mechanisms[23]

[23] Ori Hadary et al. "Protean: VM Allocation Service at Scale." In: *Proceedings of the 14th USENIX Conference on Operating Systems Design and Implementation*. OSDI'20. USA: USENIX Association, 2020. ISBN: 978-1-939133-19-9.

DCs all over the world for c-NEMESIS

- Multiple instances (for availability reasons, taking into account the energy consumption)
- 1 global controller
- N-regional controllers (Azure uses 1 instance to manage 10-100k machines)[24]
- Response-time and Quality-of-Service
  - Select DCs with acceptable latency
  - If workload is too restrictive: no migration

[24] Ori Hadary et al. "Protean: VM Allocation Service at Scale." In: *Proceedings of the 14th USENIX Conference on Operating Systems Design and Implementation*. OSDI'20. USA: USENIX Association, 2020. ISBN: 978-1-939133-19-9.

Changes or Failure in the network

- Cloud platforms have detection systems for failure or changes in the network
- Information can be incorporated to the controller

Incorporating other sources of environmental impact

- Multi-objective optimization
- Evaluate the trade-offs of optimizing one type of environmental impact regarding the others

Heterogeneous servers in c-NEMESIS

- Algorithm is agnostic to servers specification
- Different clusters with homogeneous servers
- Considered workload will execute for a fixed amount of time
- Does not invalidate the analysis of the impact in the network

Adopting the solutions

- All software is open source, documented, and reproducible
- Feedback from industry can help improve the assumptions

Duration of time slots

- MERRA-2 provide solar irradiation data as Short-wave irradiation (Wh/m2)
- Tested with shorter duration (5 min), small differences in the sizing
- Long-term sizing: changes between seasons (winter and summer) have higher impact

How to model migrations in the LP ?

- Possible modeling:
- Classify the workload into groups (regarding their response time requirements):
- workload of group $1 =$ can only be executed in DCs A and B
- workload of group $2 =$ can only be executed in DCs B and C

Why LP ?

- Using only linear variables allow for finding polynomial time solution:
  - $\approx$ 2 min for 1 year sizing (pv + bat + grid)
  - $\approx$ 40 min for 5 year sizing (IT sizing)
  - Important to compare multiple scenarios
- Most studies in the literature uses MILP
- Other example of strategies: iterative methods as Genetic Algorithms

Rebound effect

- Clouds will become low-carbon, will the usage increase ?
- Workloads keep increasing
- What really needs to be computed?
- Integration with social sciences, how to reeducate the users ?

Decision to choose new servers

- Couple of years instead of every year:
  - Model is flexible enough to analyze both scenarios
- Collaboration with industry to understand what are the requirements and constraints (logistic, money, installation...), to evaluate if it is necessary to extend the model

Different workloads impact the sizing

- Bigger workload = More servers = Higher power consumption = More renewable infrastructure
- We used a workload generated inspired in the statistic properties of the traces from Google (only 1 month)
- Most public available traces have short duration
- Workload is an input, the cloud provider can use more appropriated data
- Model needs to be updated if we consider other type of workloads, for example, workloads that require specific hardware (GPUs, FPGA, etc)

CO_2 from servers

Table 12: IC LCA and ACT comparison.

IC	Device	Actual HW node	LCA node	LCA CO_2	ACT node 1	ACT CO_2	ACT node 2	ACT CO_2
RAM	Dell R740	10nm DDR4	50nm DDR3	533 kg	50nm DDR3	329 kg	10nm DDR4	64 kg
	Fairphone 3	14nm LPDDR4	50nm DDR3	see Flash + RAM	50nm DDR3	2.9 kg	1Xnm DDR4	0.5 kg
Flash	Apple iPhone	iPhone 11 - 10nm CPU	-	0.56 kg	10nm NAND	0.6 kg	V3 TLC	0.48 kg
	Dell R740 31TB	10nm NAND 10nm DDR4	45nm NAND 50nm RAM	3373 kg	30nm NAND 50nm DDR3	1440 kg	V3 TLC	583 kg
	Dell R740 400GB	10nm NAND 10nm DDR4	45nm NAND 50nm RAM	67 kg	30nm NAND 50nm DDR3	63 kg	V3 TLC	14 kg
	Fairphone 3	10nm NAND	50nm	see Flash + RAM	30nm NAND	2.3 kg	3V3 TLC 1Xnm LPDDR4	0.9 kg
Flash + RAM	Fairphone 3	10nm NAND 14nm LPDDR4	50nm NAND 50nm RAM	11 kg	30nm NAND 50nm RAM	5.2 kg	V3 TLC 1Xnm LPDDR4	0.9 kg
CPU	Dell R740	14nm	32nm	47 kg	28nm	22 kg	14nm	27 kg
	Fairphone 3	14nm	32nm	1.07 kg	28nm	0.9 kg	14nm	1.1 kg
Other ICs	Fairphone 3	14nm	32nm	5.3 kg	28nm	5.6 kg	14nm	6.2 kg

Figure 39: Impact of old data in LCA analysis[25]

[25]Udit Gupta et al. "ACT: Designing Sustainable Computer Systems with an Architectural Carbon Modeling Tool." In: *Proceedings of the 49th Annual International Symposium on Computer Architecture*. ISCA '22. New York, New York: Association for Computing Machinery, 2022, pp. 784–799. ISBN: 9781450386104. DOI: 10.1145/3470496.3527408.