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Strategies for operating and sizing low-carbon cloud data centers

December 19, 2023

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Cloud computing

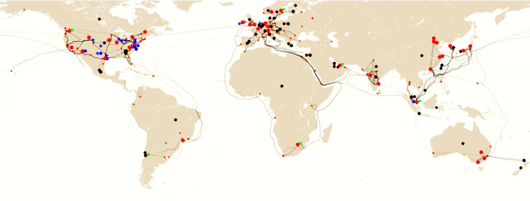

Figure 1: Azure DCs location.

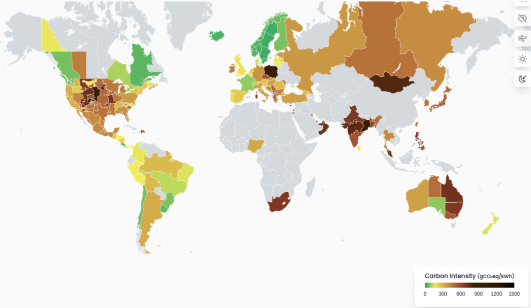

Figure 2: ElectricityMap.

- 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

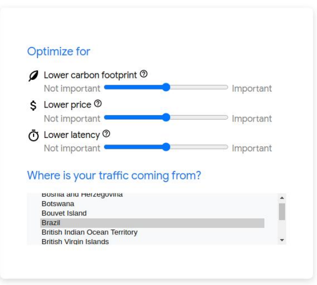

Figure 3: Google's Region picker tool.

[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

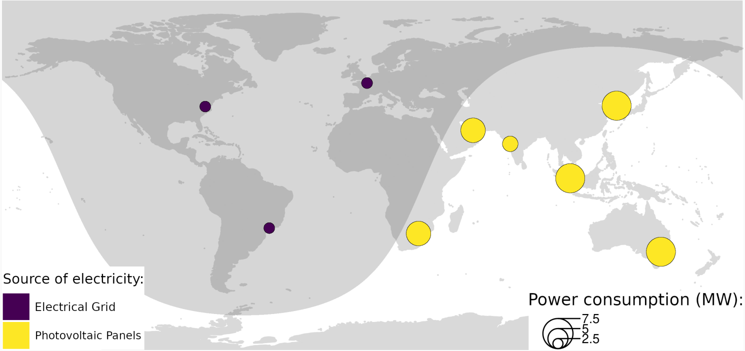

Figure 4: An example of a cloud federation that adopts the follow-the-renewables strategy.

- 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

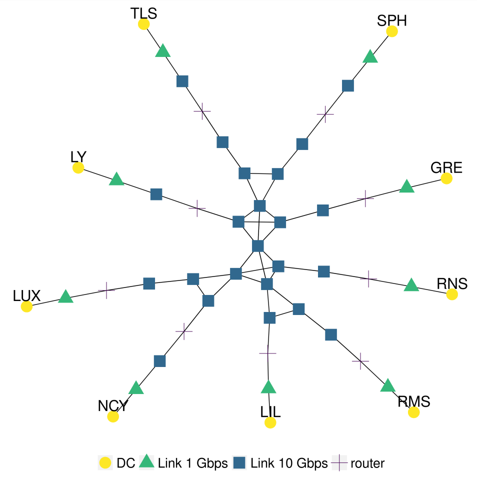

Figure 5: How the DCs are interconnected in the network.

Input: green energy traces

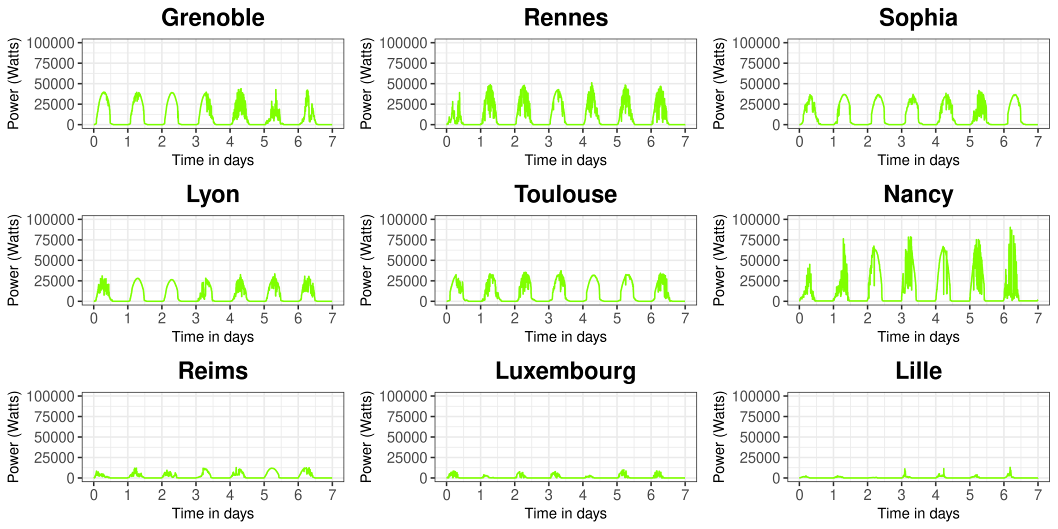

Figure 6: Green energy power production per DC - Source of data: Photovolta project.

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

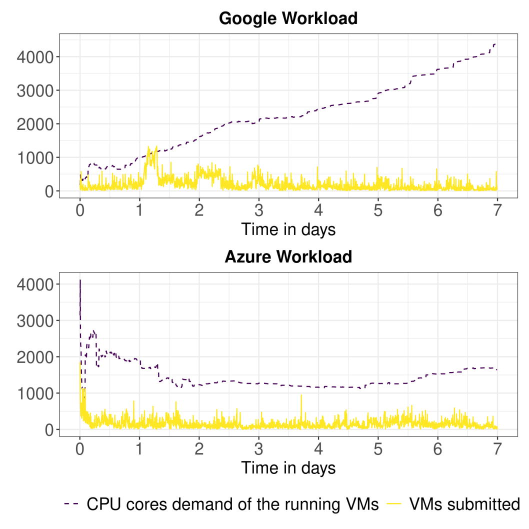

Figure 7: Workloads used for the simulations.

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

"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

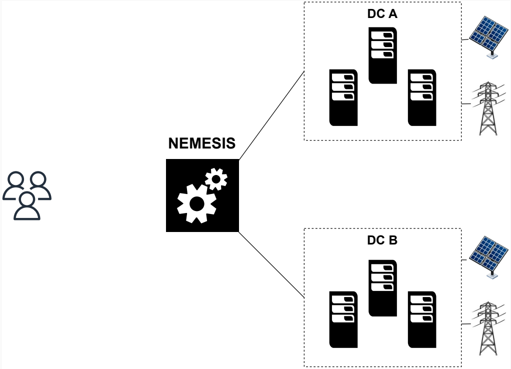

Figure 8: NEMESIS framework.

[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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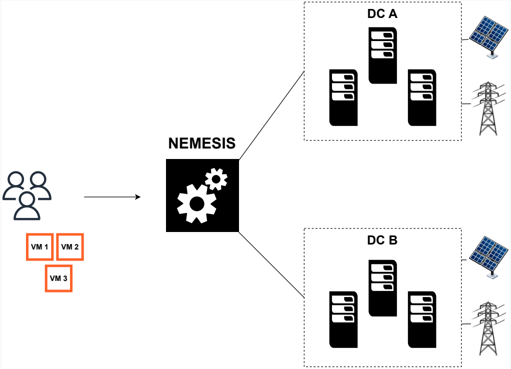

Figure 9: NEMESIS framework.

[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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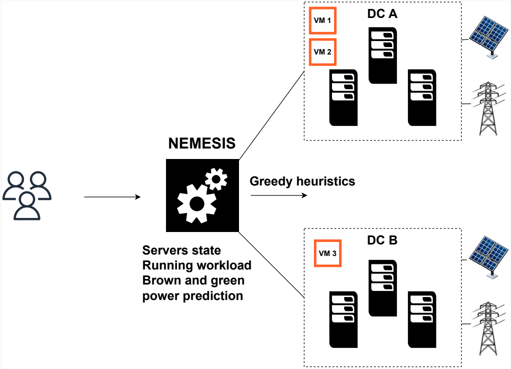

Figure 10: NEMESIS framework.

[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.

NEMESIS

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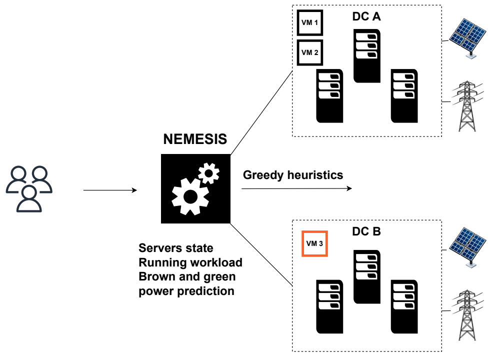

"Network-aware Energy-efficient Management framework for distributEd cloudS Infrastructures with on-Site photovoltaic production"[10]

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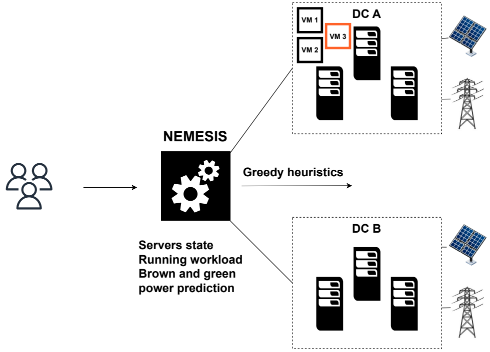

"Network-aware Energy-efficient Management framework for distributEd cloudS Infrastructures with on-Site photovoltaic production"[11]

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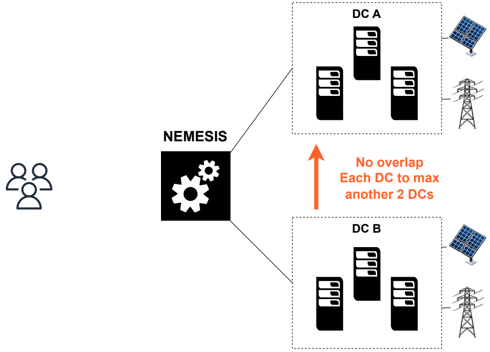

NEMESIS

"Network-aware Energy-efficient Management framework for distributEd cloudS Infrastructures with on-Site photovoltaic production"[12]

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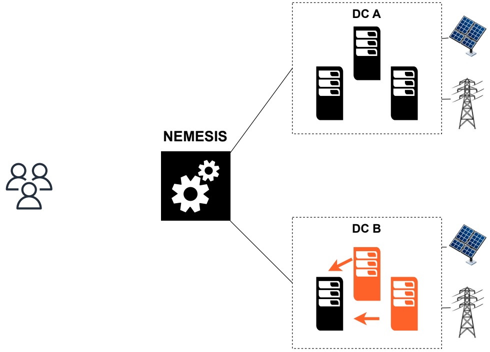

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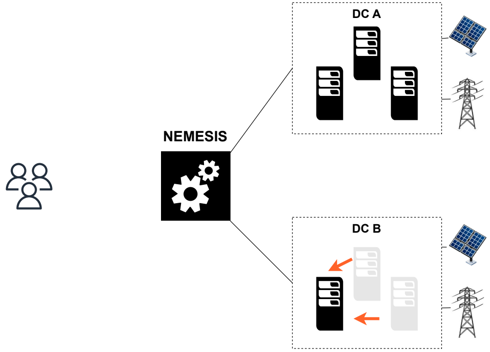

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"Congestion and Network-aware Energy-efficient Management framework for distributEd cloudS Infrastructures with on-Site photovoltaic production"[14]

Modifications:

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

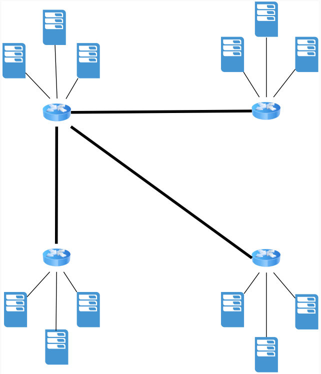

Figure 16: c-NEMESIS example.

[14] 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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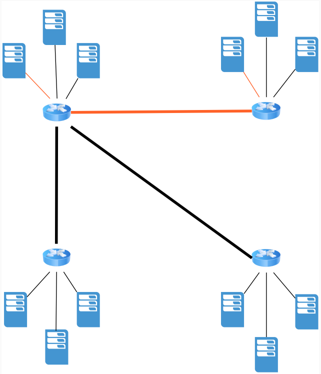

Figure 17: c-NEMESIS example.

[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.

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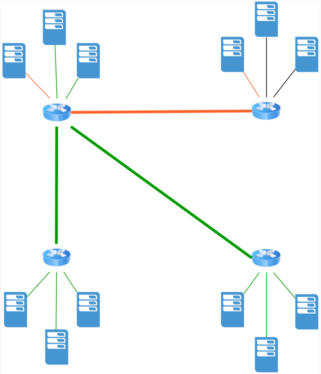

Figure 18: c-NEMESIS example.

[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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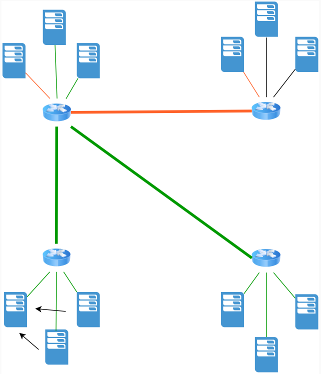

Figure 19: c-NEMESIS example.

[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.

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”

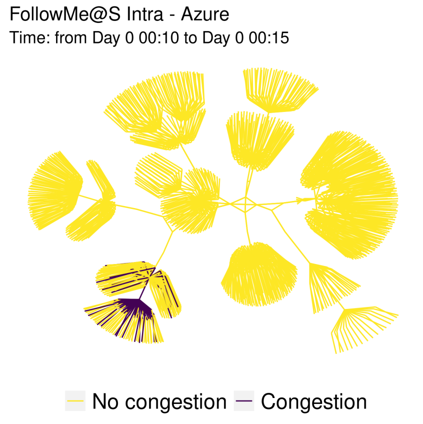

Figure 20: Example of links with congestion.

Network considered

Bandwidth, Usage

Topology

Duration:

avg=1.0, max=1.32

Network considered

No overlap

1 DC to 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
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Summary - first main contribution

- 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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Modern cloud DCs are geographically distributed all over the world, 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

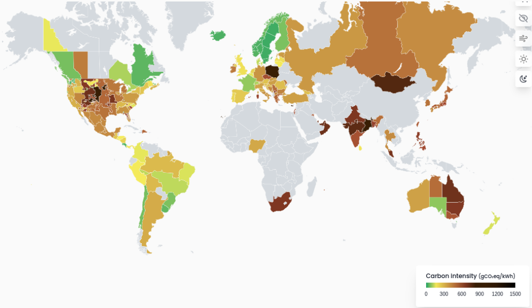

Figure 21: Electricitymap service.

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.*

- 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 22: 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):

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

Data center power supply:

$$P_k^d \leq Pre_k^d + Pgrid_k^d + Pdch_k^d - Pch_k^d \quad (2)$$

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)

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

- 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

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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.

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Reductions on carbon emissions:

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

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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

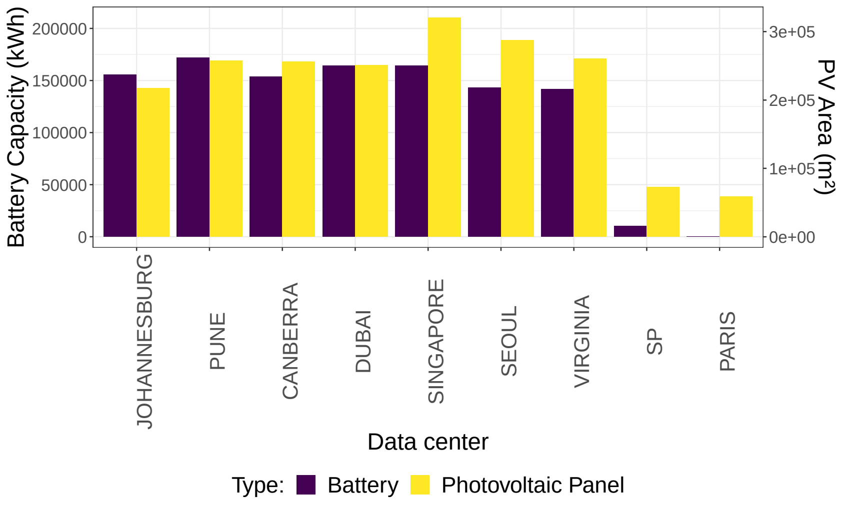


Figure 23: Optimal result for the area of PV panels and capacity of the batteries.

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

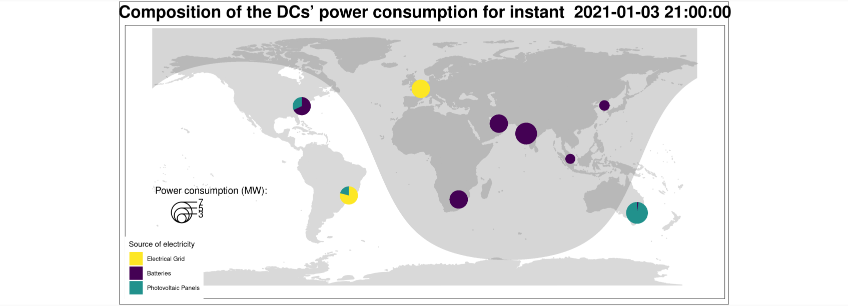


Figure 24: Example of data centers electricity source used.

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
- Hardware might be more power-efficient
- Workload keep increasing over time

What about?

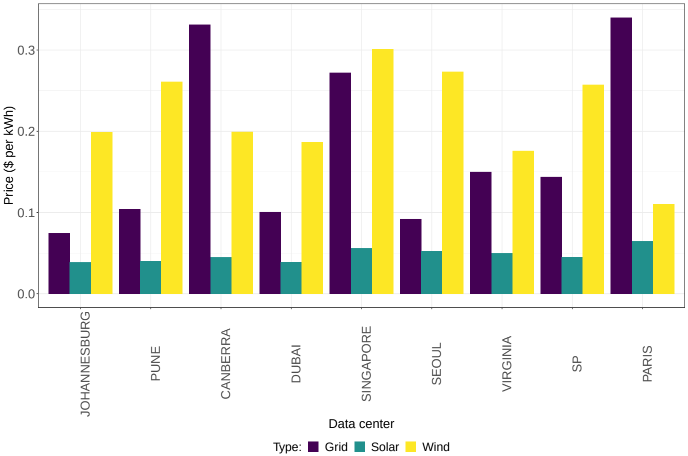
- Wind power
- Delaying the workload
- Costs (dollars)

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

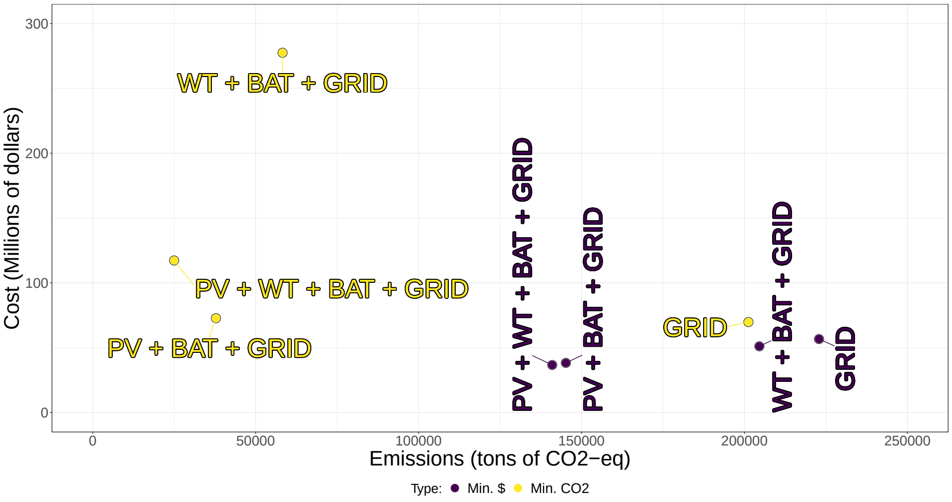


Figure 26: Costs vs CO_2 emissions for the different scenarios.

Costs ($) of reducing the environmental impact

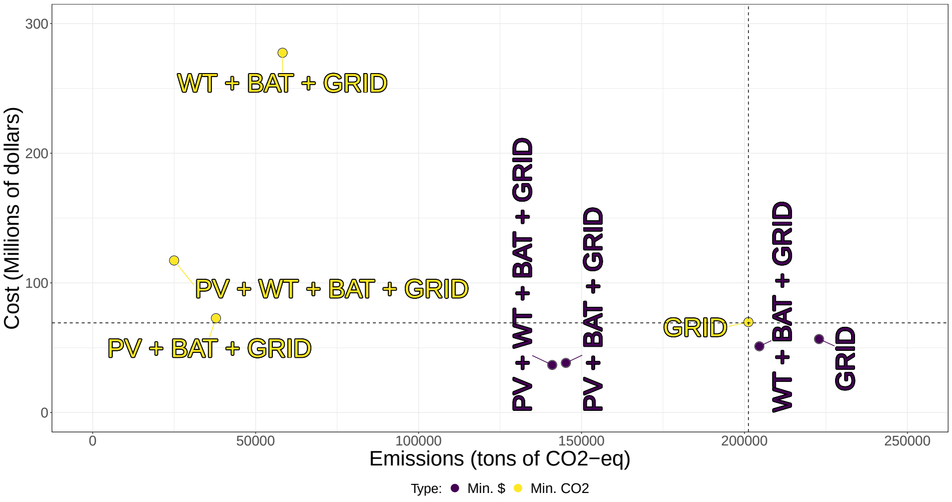


Figure 27: Costs vs CO_2 emissions for the different scenarios.

Costs ($) of reducing the environmental impact

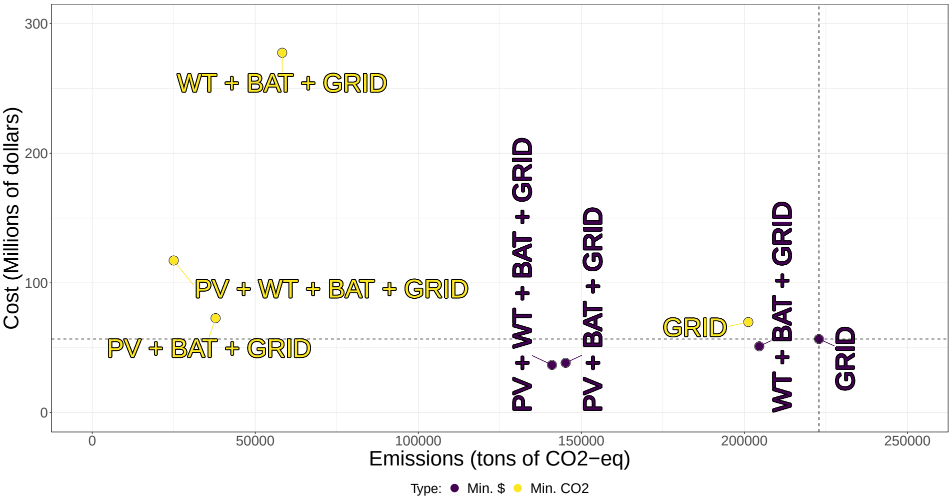


Figure 28: Costs vs CO_2 emissions for the different scenarios.

Costs ($) of reducing the environmental impact

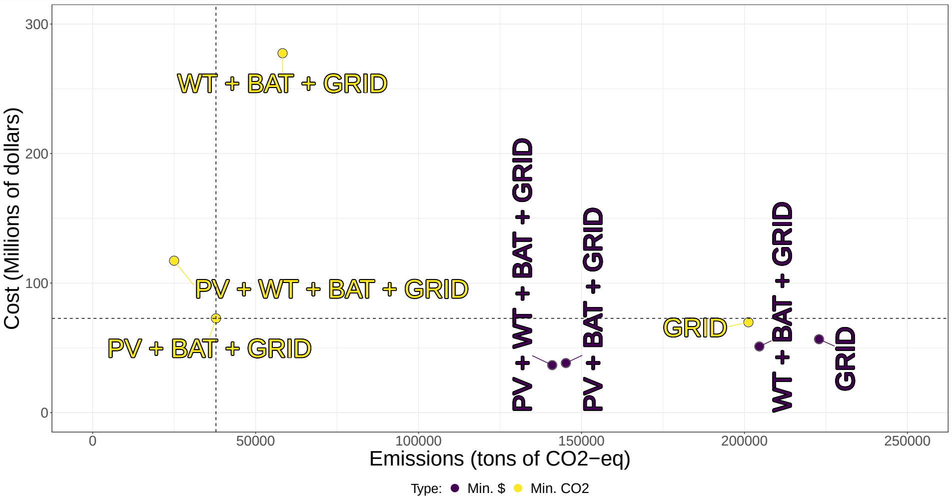


Figure 29: Costs vs CO_2 emissions for the different scenarios.

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[18]

- Dell R740: 4020 vs 688 kg CO_2-eq

[18] 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[19]
- 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

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

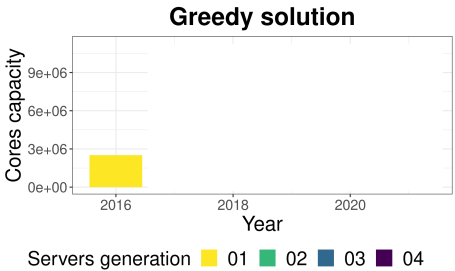


Figure 30: Comparison between the optimal and greedy approaches.

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

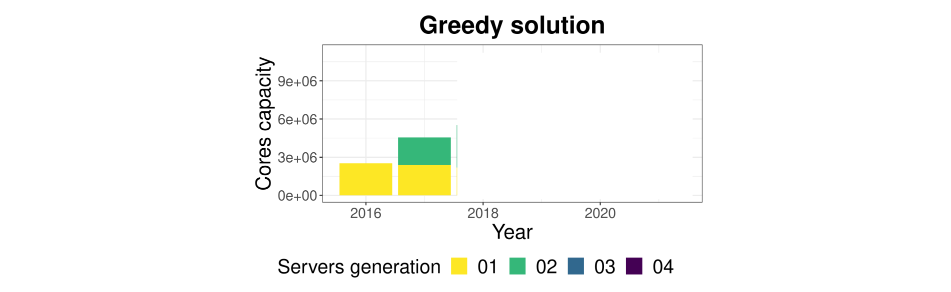


Figure 31: Comparison between the optimal and greedy approaches.

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
04	2021	AMD EPYC 7763	128	75.6	3	590.3

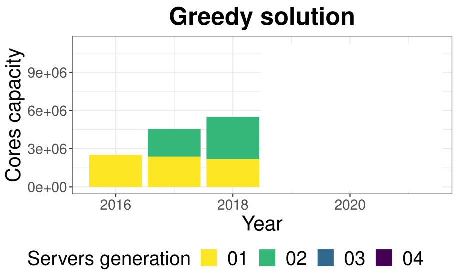


Figure 32: Comparison between the optimal and greedy approaches.

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
03	2019, 2020	AMD EPYC 7742	64	66.1	2.71	587.2
04	2021	AMD EPYC 7763	128	75.6	3	590.3

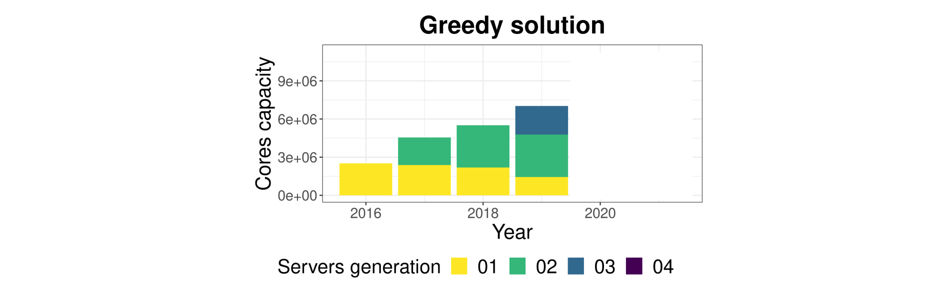


Figure 33: Comparison between the optimal and greedy approaches.

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
03	2019, 2020	AMD EPYC 7742	64	66.1	2.71	587.2
04	2021	AMD EPYC 7763	128	75.6	3	590.3

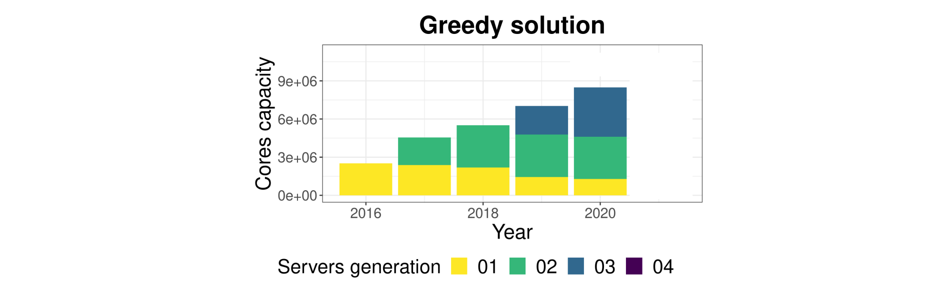


Figure 34: Comparison between the optimal and greedy approaches.

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

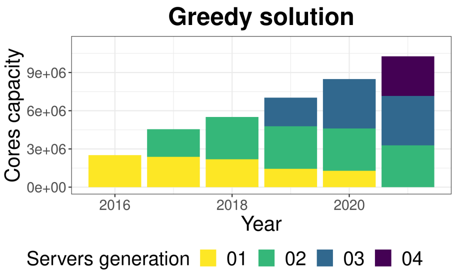


Figure 35: Comparison between the optimal and greedy approaches.

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.

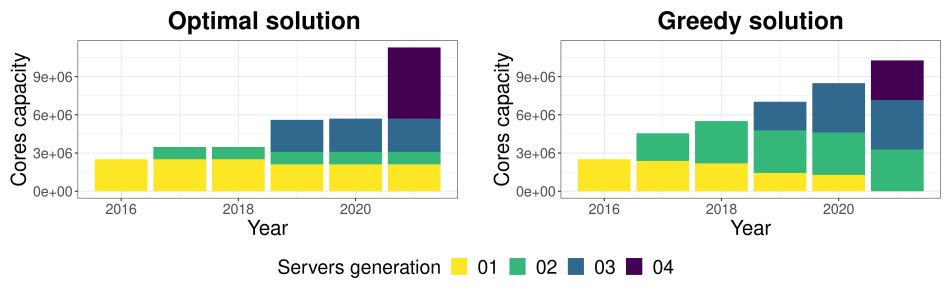


Figure 36: Comparison between the optimal and greedy approaches.

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	-
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

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 for your attention!

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Strategies for operating and sizing low-carbon cloud data centers

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Baselines

WSNB (Workload shifting non brownout)[20]:

- 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

[20] wsnb.

Framework

- Simgrid (3.28)
  - Well-validated by the scientific community (over 20 years of usage)
  - Servers' power consumption uses a linear model based on CPU usage
  - Flow-level TCP modeling of the network
- Modification for modeling live-migration power consumption:
  - one CPU core is used in the target host during the VM migration process

Cloud platform

- 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

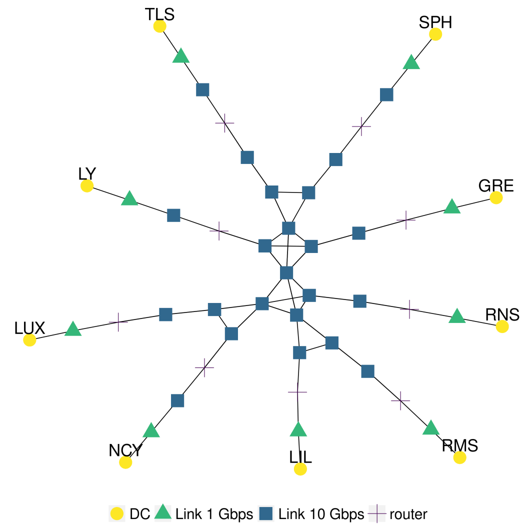

Figure 37: DCs and how they are connected in the network

Green energy traces

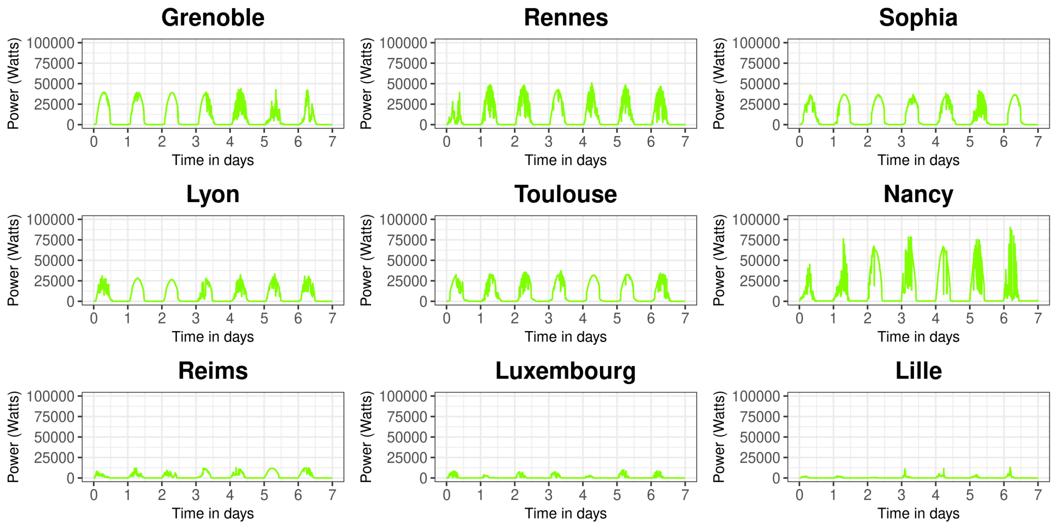

Figure 38: Green energy power production per DC - Source of data: Photovolta project.

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

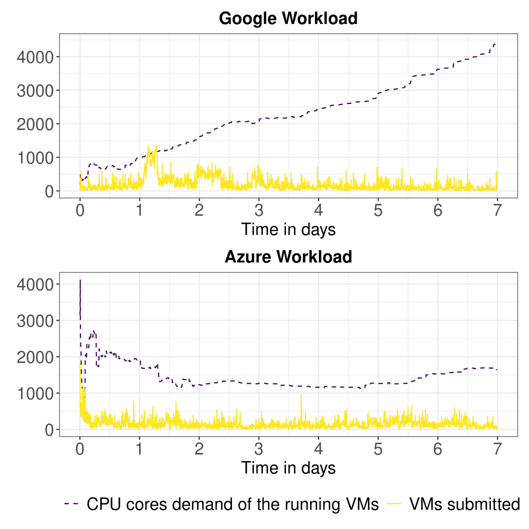

Figure 39: Workloads used for the simulations.

Baselines

FollowME@Source[21]:

- 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

[21] followme.

Data center power consumption:

$$P_k^d \leq Pre_k^d + Pgrid_k^d + Pdch_k^d - Pch_k^d \tag{6}$$

where Pch_k^d is the power to charge the battery at each time of time slot k on DC^d and $Pdch_k^d$ is the power to discharge the battery, Pre_k^d is the solar power produced, and $Pgrid_k^d$ is the power used from the local grid.

Workload:

$$w_k^d \leq C^d \tag{7}$$

where w_k^d is number of cores needed during the kth time slot on DC^d, and C^d is the number of cores within DC^d .

LP Overview

Batteries level of energy (B_k^d):

$$B_k^d = B_{k-1}^d + Pch_{k-1}^d \times \eta_{ch} \times \Delta t - \frac{Pdch_{k-1}^d}{\eta_{dch}} \times \Delta t \tag{8}$$

where η_{ch} is efficiency of the charge process and η_{dch} is the efficiency of the discharge process.

Solar power production:

$$Pre_k^d = I_k^d \times Apv^d \times \eta_{pv} \tag{9}$$

where I_k^d is the solar irradiance, Apv^d the PV panel area, and η_{pv} is the efficiency of PV module

LP Overview

Objective function:

$$\text{minimize} \sum_{k=0}^{K-1} \sum_{d=1}^{D} (FPgrid_k^d + FPpv_k^d) + \sum_{d=1}^{D} FPbat^d \tag{10}$$

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: 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 15: 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) ?

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 16: 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

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 17: 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

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

Experimental validation

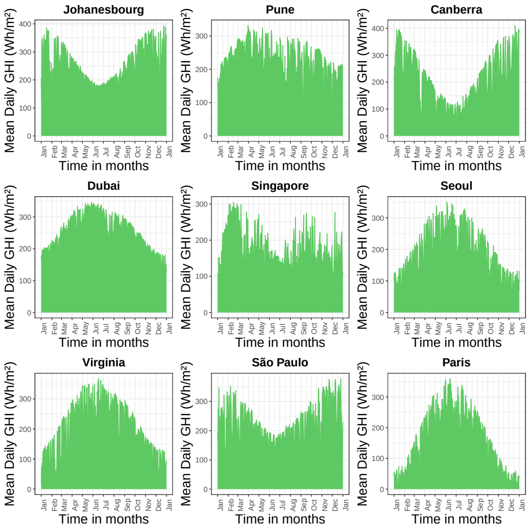

Figure 40: Solar Irradiation at different locations in 2021. Source: NASA's MERRA-2

Table 19: Grid carbon footprint per location

Location	CO_2-eq/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