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Strategies for operating and sizing low-carbon cloud data centers

December 14, 2023

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Cloud computing

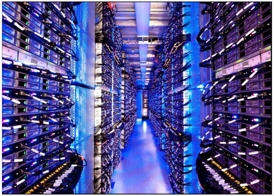


Figure 1: Inside a DC (Microsoft).

Figure 2: Microsoft's Azure DCs location.

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

Environmental impact of cloud computing

- Renewable energy in cloud DCs
  - Google avg 65%, up to 94% (hourly basis)
- Improvements in efficiency:
  - $6\times$ workload vs 6% energy (2010-2018)[a]
- The GHG Protocol:
  1. Direct GHG emissions
  2. Electricity indirect GHG emissions
  3. Other indirect GHG emissions: 74% from Google, and 99% from Meta DCs

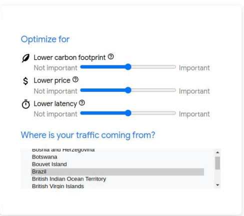


Figure 3: Google's Region picker tool.

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

This thesis

Strategies for operating and sizing low-carbon cloud DCs

This thesis

Strategies for operating and sizing 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)
  - methane (CH_4) GWP is 25
  - 1g CH_4 = 25g CO_2-eq

This thesis

Strategies for operating and sizing low-carbon cloud DCs

- Carbon-responsive strategies
  - follow-the-renewables
  - sizing the renewable and IT infrastructure

This thesis

Strategies for operating and sizing low-carbon cloud DCs

- Main contributions:
  - Analysis of the impact of adopting the follow-the-renewables approaches in both network congestion and energy consumption
  - Linear program formulation for sizing the renewable and IT infrastructure and operating the cloud data centers using follow-the-renewables

Follow-the-renewables

Follow-the-renewables

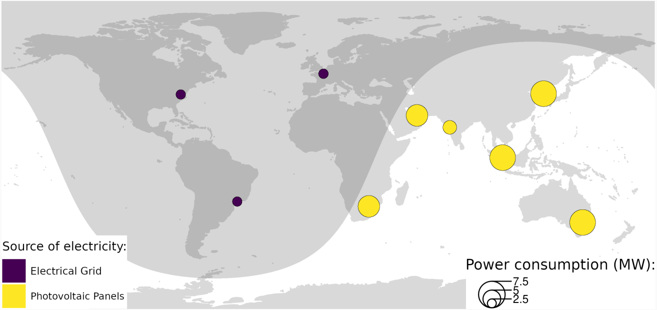
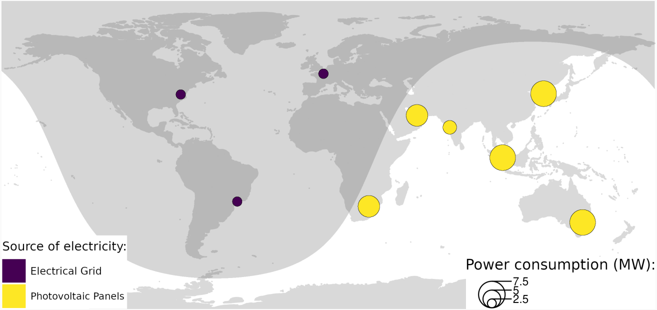


Figure 4: An example of a cloud federation that adopts the follow-the-renewable strategy.

- Allocates/Migrates the workload to the data centers (DCs) that have more renewable (green) power available

Follow-the-renewables



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- Allocates/Migrates the workload to the data centers (DCs) that have more renewable (green) power available
- Extra computations proportional to the migration duration

Follow-the-renewables

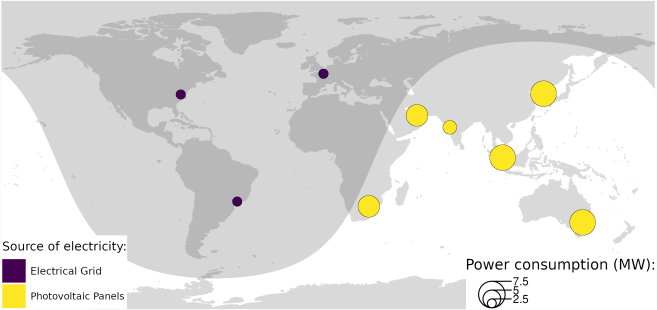

Figure 4: An example of a cloud federation that adopts the follow-the-renewable strategy.

- 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 ?

NEMESIS

"Network-aware Energy-efficient Management framework for distributEd cloudS Infrastructures with on-Site photovoltaic production"[1]

- Extended for this analysis
- Resource management framework with a central controller
- Stochastic green and brown power consumption prediction
- Greedy heuristics for the scheduling
- Follow-the-renewables for workload allocation and migration
- Servers consolidation

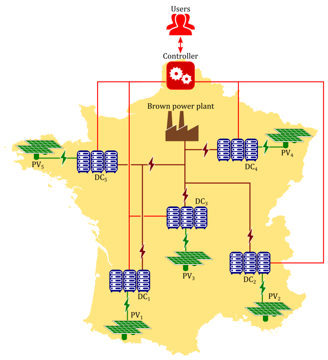

Figure 5: Cloud infrastructure.

[1] 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"[2]

- the bandwidth of the links, and the history of its usage is considered scheduling the migrations
- inter-DC migrations are performed in parallel between DCs
- intra-DC migrations do not execute simultaneously and are distributed in time (for each DC)
- the estimation algorithm for the duration of migrations considers the real number of links that interconnects the origin and the target server

[2] 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. ISBN: 978-989-758-572-2. DOI: 10.5220/0011047000003203.

Experimental validation

- Cloud platform (Grid'5000 Taurus), workload (Google and Azure), and renewable traces (Photovolta) inspired in real-world values
- Simgrid (3.28) framework and flow-level TCP model
- metrics: non-renewable energy consumption, time spent migrating the workload
- 1 week simulated

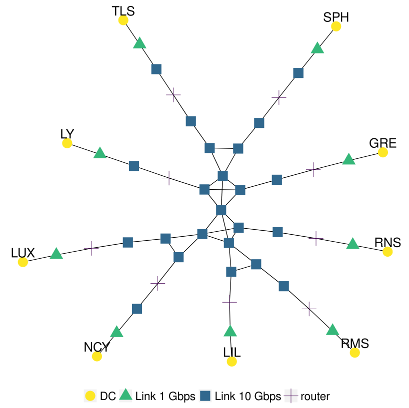

Figure 6: DCs and how they are connected in the network: links intra-DC with 1Gbps, and inter-DC with 10Gbps

Results

- Analysis of the live-migrations
  - Network congestion and wasted energy
- Total and non-renewable (brown) energy consumption
- Comparison with two baselines
  - WSNB[3]: Follow-the-renewables only at the allocation of the workload, no migration
  - FollowMe@Source[4]: Follow-the-renewables at the allocation and migration of the workload (either intra or inter DC)
  - Only have information of the current green energy availability
  - Network is not taken into account

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[3] 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. DOI: `https://doi.org/10.1016/j.jpdc.2019.09.015`. URL: `https://www.sciencedirect.com/science/article/pii/S0743731519303132`.

[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. DOI: `https://doi.org/10.1016/j.jss.2021.110907`. URL: `https://www.sciencedirect.com/science/article/pii/S0164121221000042`.

Assessing network congestion

- "Perfect scenario":
  - All migrations are executed again individually with full access to network resources
- Additional time the migration takes (when planned by the scheduling algorithms) in comparison with the perfect scenario
- Link under congestion if the migration takes 10% longer vs the "perfect scenario"

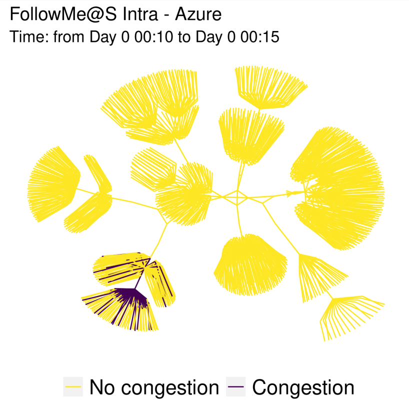

Figure 7: Example of links with congestion.

Visualizating network congestion

Comparison of the different algorithms

Wasted 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 Luxembourg DC (38 servers at maximum capacity) for approximately 44 hours

Total and brown energy consumption

Table 1: Comparison of energy consumption (MWh) for the Azure workload.

Algorithm	Total	Non renewable
NEMESIS	30.43	21.21
c-NEMESIS	30.55	21.20
FollowMe@S Intra	31.69	22.41
FollowMe@S Inter	31.69	22.40
WSNB	33.56	24.23

Summary

- 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

Sizing the renewable and IT infrastructure

- Defining:
  - Area of solar panels, capacity of energy storage devices, number of wind turbines
- Considerations:
  - Climate conditions, energy-mix, carbon footprint of renewable sources

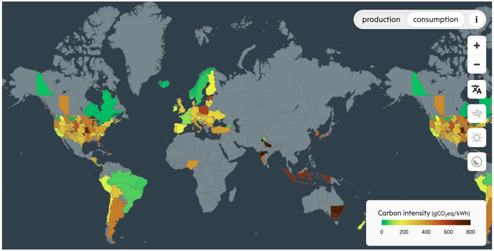

Figure 8: Electricitymap service.

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 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.*

Assumptions

Data centers:

- 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 9: Selected data centers location (inspired from Microsoft Azure)

Assumptions

Workload:

- 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

Assumptions

Workload:

- 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

Assumptions

Renewables infrastructure

- Batteries charge and discharge efficiency, Maximum Depth of Discharge
- PV panels efficiency
- Carbon emissions from manufacturing (PV: 250 kg CO_2 eq per m², bat: 59 kg CO_2 eq per kWh)
- Lifetime (PV: 30 years, bat: 10 years)

Assumptions

Local electricity grid

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

Table 2: Emissions (in gCO_2-eq/kWh) for using the regular grid. Source for grid emissions: electricityMap, climate-transparency.org.

Location	Emissions
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

What the LP looks like?

Data center power consumption (P_k^d):

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

where PUE^d is the cooling efficiency at data center d, $Pintranet^d$ is the power consumption of the network devices, $Pidle^d$ is the server static power consumption, $PCore$ the dynamic power consumption of using a CPU core, and w_k^d is the workload allocated on DC d at time slot k .

Data center power supply:

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

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.

What the LP looks like?

Batteries level of energy (B_k^d):

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

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

Solar power production:

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

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

Linear Program summary

Obj. function: Minimize the DC's operation CO_2 emissions (1 year)

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

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

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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)
  - CO_2 from electricity grid
  - PUE
  - CPU cores number

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- Renewable infrastructure specs (efficiency, manufacturing CO_2)
- For each DC:
    - Solar irradiation (1 year)
    - CO_2 from electricity grid
    - 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 3: 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

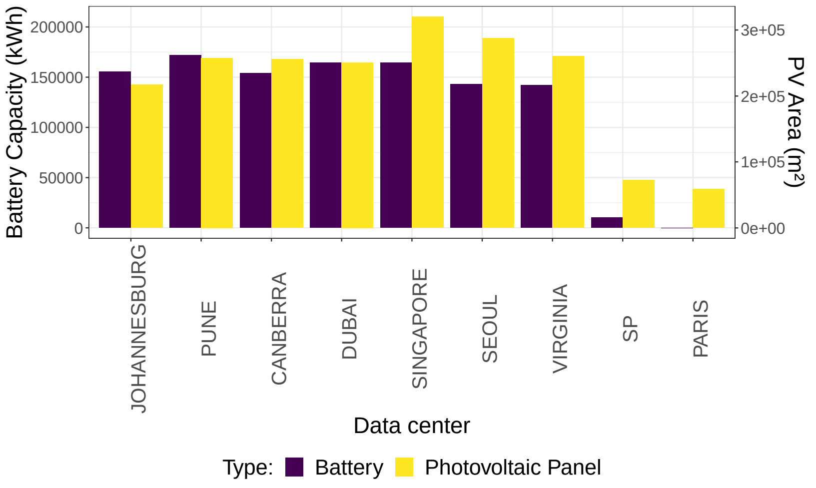

Figure 10: Optimal result for the area of PV panels and capacity of the batteries.

- 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

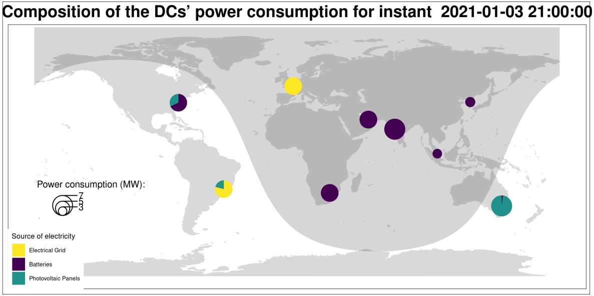

Figure 11: Example of data centers electricity source used.

Visualization of DCs operation

Example of DCs electricity source used.

Sizing for the long term:

DCs have life time of decades:

- 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)

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What about:

- Wind power
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- 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
- Values computed using models, and parameters from the NREL
- Battery price: 0.20 dolars per kWh of electricity delivered

Table 4: Price of different sources of energy (USD per kWh) at each location.

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

Costs ($) of reducing the environmental impact

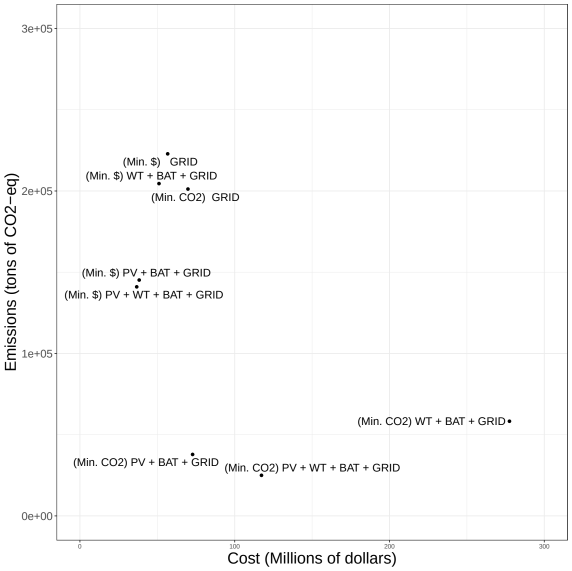

Figure 12: Costs vs CO_2 emissions for the different scenarios.

Sizing the IT part

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

Sizing the IT part

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

Based in the methodology proposed by Gupta et al. (2022)[5], emissions computed based in the specifications of the integrated circuits.

Using outdated data in LCA analysis:

- Dell R740: 4020 vs 688 kg CO_2-eq

[5] 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`. URL: `https://doi.org/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 know in advance)

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

Settings:

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

Table 5: 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

Sizing the IT part

The optimal solution emits 13.4% less CO_2.

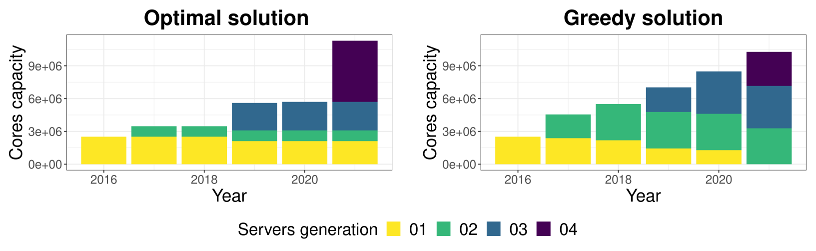

Figure 13: Comparison between the optimal and greedy approaches.

Table 6: Servers specifications for different generations.

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Summary

- 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)

Thank you !

Thank you for your attention!

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References

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Baselines

WSNB (Workload shifting non brownout)[6]:

- 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

[6] wsnb.

Simulations c-NEMESIS

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

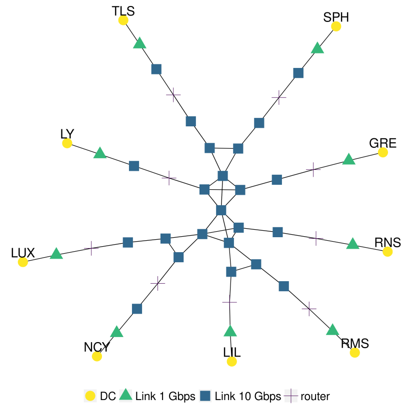

Figure 14: DCs and how they are connected in the network.

Green energy traces

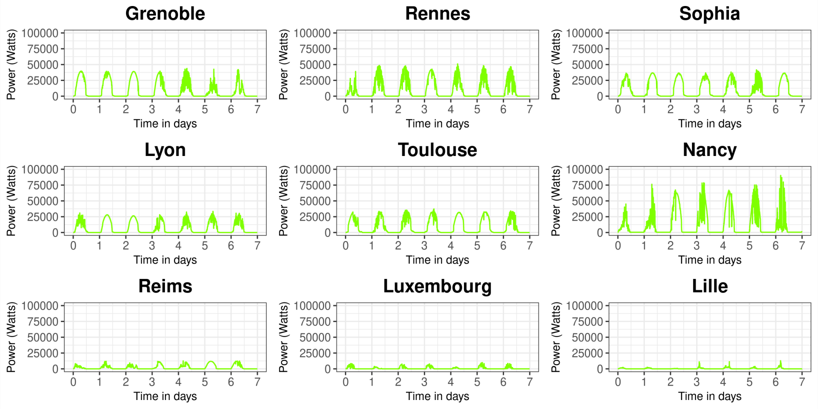

Figure 15: Green energy power production per DC - Source of data: Photovolta project.

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

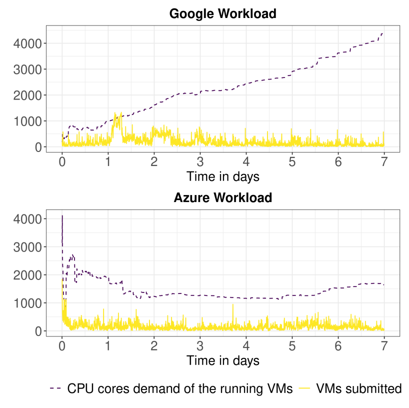

Figure 16: Workloads used for the simulations.

Results

Baselines

FollowME@Source[7]:

- 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

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[7] followme.

LP Overview

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 km²)

Table 7: 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 8: 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 9: 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 10: 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 11: 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

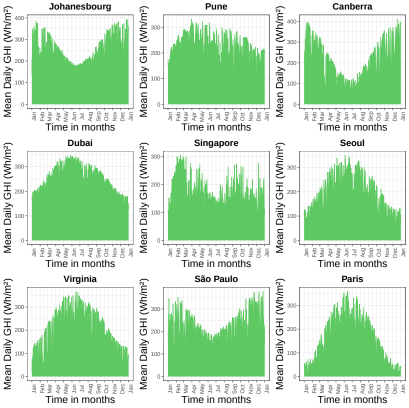

Figure 17: Solar Irradiation at different locations in 2021. Source: NASA's MERRA-2.

Table 12: 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