Towards Sustainable Low Carbon Emission Mini Data Centres

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Abstract
Mini data centres have become increasingly prevalent in diverse organizations in recent years. They can be easily deployed at large scale, with high resilience. They are also cost-effective and provide high-security protection. On the other hand, IT technologies have resulted in the development of ever more energy-efficient servers, leading to the periodic replacement of older-generation servers in mini data centres. However, the disposal of older servers has resulted in electronic waste that further aggravates the already critical e-waste problem. Furthermore, despite the shift towards more energy-efficient servers, many mini data centres still rely heavily on high-carbon energy sources. This contributes to data centres' overall carbon footprint. All these issues are concerns for sustainability. In order to address this sustainability issue, this paper proposes an approach to extend the lifespan of older-generation servers in mini data centres. This is made possible thanks to a novel solar-powered computing technology, named Genesis, that compensates for the energy overhead generated by older servers. As a result, electronic waste can be reduced while improving system sustainability by reusing functional server hardware. Moreover, Genesis does not require server cooling, which reduces energy and water requirements. Analytical reasoning is applied to compare the efficiency of typical conventional mini data centre designs against alternative Genesis-based designs, in terms of energy, carbon emissions and exploitation costs.

Keywors: Sustainability, mini data centre, renewable energy, server refresh, server consolidation, solar energy

1. Introduction

Recent advances have been made in information technology, particularly in data centres, which provide cloud services, e.g. the Internet of Things, streaming, etc. However, this sustained progress comes at a price, especially for the environment, including an increase in carbon dioxide (CO_2) emissions as a result of the production of electricity to answer the energy demand for data centres, which accounts for approximately 1% of worldwide global energy consumption, as indicated in [9]. Data centres commonly use non-green energy sources that contribute to significant CO_2 emissions [10], which account for 0.3% of the total CO_2 emissions on the planet. Besides CO_2 emissions, data centres are also concerned about water stress problems in some regions [15].

On the environmental impact of data centre equipment. Gupta *et al.* pointed out that data centre hardware and infrastructure also significantly contribute to the amount of CO_2 released [8]. Electronic waste is another pollution source. Indeed, hazardous substances may be present in metals and electronic components retrieved from data centre equipment and deposited in the environment. Within this category, there are two distinct types of equipment: data centre infrastructure that comprises mechanical and electrical components, including transformers, generators, air conditioners, racks, and cables; and computing components, such as servers. Equipment is periodically replaced to improve performance

* This project has partially received financial support from the CNRS through the MITI interdisciplinary programs.

and energy efficiency [1]. Infrastructure components are replaced every 10 to 15 years. In contrast, computing components are more frequently changed. A white paper from the SuperMicro Company [2] examines the server renewal cycle in data centres.

Problem statement and our contribution. Reusing servers in data centres has become a critical issue for modern businesses and organizations. It contributes to cost reduction and data centre sustainability. Additionally, it can help reduce environmental impact by reducing the need for new servers and limiting waste. However, server reuse should not compromise data centre security (such as hosted data confidentiality) or quality. Therefore, a careful balance should be found between security and environmental impacts due to server reuse. The aforementioned issues have been mostly studied on large data centres, but not on mini data centres which are widespread nowadays. Approximately 40% of all data centres in the United States are mini data centres [11]. Generally, a mini data centre consists of less than 1,000 square feet of space in which servers are located. It typically has fewer than twenty-five servers [11]. The server utilization rate of conventional data centres usually ranges from 6-12% [13].

The sustainability issue addressed in the present work concerns server lifetime extension in mini data centres. This is done while mitigating the associated energy efficiency penalty from server aging. Indeed, older servers tend to be less energy-efficient than newer ones. In order to resolve this issue, we adopt a novel computing technology, called Genesis [3, 6], which enables us to deploy mini data centres powered by solar energy in a similar way to smart grids. Using this free energy under favorable meteorological conditions can compensate for energy consumption due to old-generation servers kept in the system. Therefore, Genesis could help solve the problem of renewing servers, which generate electronic waste. Furthermore, it reduces data centre operating costs, e.g., electricity bills, with low-carbon emissions. We use an analytical method to show the potential benefits of Genesis against conventional mini data centre designs w.r.t. server renewal.

2. Related work

Numerous approaches have been explored to reduce the environmental impact of data centres. Consolidation of a limited number of powerful servers is an approach often adopted for reducing physical machines in data centres. It can reduce operational expenses. Qiu *et al.* proposed using a probabilistic request allocation problem to minimize the number of servers required to meet workload execution requirements without violating service level agreements [12]. Farahnakian *et al.* studied a virtual machine (VM) consolidation approach by considering a regression-based model that approximates the future CPU and memory utilization of VMs [5].

Doyle *et al.* [4] addressed the issue of finding the most appropriate periods for server renewal in mini data centres, so as to maximize the return on investment. They presented a comprehensive framework allowing to evaluate selected server deployment scenarios according to various hardware refresh options. In [1], Bashroush *et al.* rather focused on electronic waste using a different server refresh strategy. Instead of replacing the whole servers for upgrading the compute infrastructure, they advocate renewing only some components within servers. To better understand the server failure issue, a study has been carried out on over 290,000 hardware component failures recorded over the past four years in [18]. Data is collected from hundreds of thousands of servers in dozens of data centres.

Wang *et al.*[19] dealt with the reduction of CO_2 emissions by suggesting early actions during data centre building beyond the operational phase. So, they propose a novel manufacturing cost-aware server provisioning plan to mitigate the carbon footprint of the data centre construction phase.

Finally, Vasconcelos *et al.* [16] studied the size of renewable energy sources for geographically distributed data centres around the world. They take into account the carbon footprint caused by electricity consumption in regions where data centres are deployed. In addition, they consider the carbon footprint associated with solar panels and battery manufacturing.

3. The Genesis technology

We consider a novel computing technology, Genesis, recently implemented through a solar-powered mini data centre demonstrator [7, 3]. As illustrated in Figure 1, Genesis can be seen as a companion mini data centre typically deployed on the roof of a classical data centre building, in order to harvest the solar energy directly used in the system. Genesis is composed of modules or nodes that are interconnected. Each module can host computing resources and energy harvesting and storage facilities. Typically, it includes a solar panel, a battery, a server, and local power control logic for inter-node energy exchange. The modules can exchange energy and computational data, e.g., virtual machines. When a module lacks energy in its local battery to execute a workload, it can request energy from a remote module. Alternatively, it can send its local workload to another module having sufficient energy and compute capability for remote execution. At least, one module is connected to the utility grid in case all batteries are empty and one would like to execute some workload in Genesis. Figure 1 illustrates a typical deployment of Genesis. A brief technical description of Genesis design is provided in the appendix.

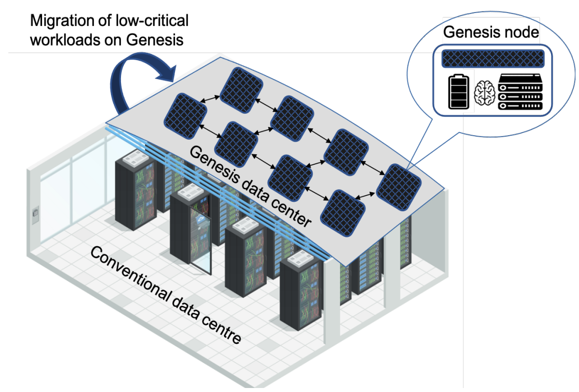


Figure 1: Integration of Genesis with conventional data centre for sustainable compute infrastructure (illustration partly based on macrovector / Freepik, see `https://fr.freepik.com/vecteurs-libre/composition-interieure-isometrique-du-cloud-computing-server-datacenter_4027518.htm`)

4. Evaluation of different strategies for sustainable data centres

We present a number of strategies for enabling sustainable mini data centres, under performance and energy-efficiency constraints. We start with a given mini data centre design corresponding to a typical system deployment scenario, C_{ref}. Then, we explore different evolution options for C_{ref} over time, by applying state-of-the-art solutions, including the Genesis-based approach.

Given N servers in a mini data centre DC, we define the global[2] energy consumed by DC as follows:

$$Energy^{DC} = \sum_{i=1}^{N} (P_i * T) + E_{cooling} \quad (1)$$

where P_i is the thermal design power (TDP) of each server i, T is the activity period of the servers during which some workloads are executed, and $E_{cooling}$ is the energy required for server cooling in the data centre.

On the other hand, we define the global computational capacity of a data centre composed of N servers as follows:

$$Compute\_capacity^{DC} = \sum_{i=1}^{N} Perf_i \quad (2)$$

where $Perf_i$ represents the performance of a server i, expressed in FLOPs. For the sake of simplicity, the analytical reasoning we apply in the next sections makes some strong assumptions: i) the server

[2] For simplicity, this is a rough definition, which does not include the energy consumption of all the other equipment of a data centre.

operation cost is reduced to that of its integrated processors, i.e., other relevant components such as memory, storage, or GPUs are deliberately neglected here; ii) regarding server operations, we assume an on-off execution modality, i.e., when a server executes a workload it operates at 100% of its maximum TDP, otherwise it consumes 0 W.

4.1. Hardware renewal approaches based on conventional server technologies

Table 1 summarizes different characteristics of Intel server processors for various processor generations, including the latest one in 2018 [4]. We can observe successive improvements in processor performance over time. This hardware evolution necessitates server renewal in data centres to achieve better energy efficiency and cost management. In the same table, we have included the respective prices of the processors based on the information available on Intel's website. Using the information from Table 1, we will analyze the performance of a mini data centre considering the advances in processor performance.

Year of Release	Processor type	TDP (W)	Performance per server (GFLOPs)	Energy efficiency (GFLOPs / watt)	Online prices from Intel ($)
2011	i7-2600	95	32.52	0.3423	135.40
2012	i7-3770	77	29.29	0.3804	189.15
2013	i7-4770	84	31.57	0.3758	137.74
2015	i7-6700	65	31.42	0.48334	311.86
2017	i7-7700	65	34.14	0.5252	343.33
2018	i7-8700	65	92.07	1.4165	287.80

Table 1: Performance of Intel Core i7 Processors [4] and server acquisition cost

Table 2 provides an overview of the configuration parameters for the analyzed mini data centre designs, highlighting the number and types of servers, as well as the inclusion of solar panels and batteries for each configuration. The initial mini data centre configuration C_{ref} consists of i7-2600 generation servers from 2011. As server renewal happens in general every 6 or 7 years in data centres [2], we will select the i7-7700 and i7-8700 server generations as candidates for replacing i7-2600 generation servers. They improve energy efficiency and performance.

System config.	# Servers	Processor type	# Solar panels	# Batteries	Power (kW)
C_{ref}	12	i7-2600	0	0	1.14
C_0	12	i7-7700	0	0	0.78
C_1	5	i7-8700	0	0	0.32
C_2	5	i7-8700	5	2kWh $\times 5$	0.42
C_3	14	i7-8700 $\times 5$ & i7-2600 $\times 9$	14	2kWh $\times 14$	1.46
C_4	7	i7-8700 $\times 5$ & i7-2600 $\times 2$	7	1kWh $\times 5$ & 2kWh $\times 2$	0.65
C_5	7	i7-8700 $\times 4$ & i7-2600 $\times 3$	7	1kWh $\times 4$ & 2kWh $\times 3$	0.68

Table 2: Configuration parameters of mini data centre

The energy consumption and computation capacity corresponding to C_{ref} are given in Table 3. Here, we assume that T is constant in equations (1) and (3) for the sake of simplicity in our analysis. This is based on the strong assumption that all servers operate during the same time interval T. However, a more detailed modeling would require dividing T into several distinct intervals to model the operation of each server. In our study, we assume the mini data centres execute daily during a same period of 10 hours. On the other hand, we consider the energy corresponding to data centre cooling to represent 7% of servers' energy consumption [4].

To improve the energy consumption and computation capacity of a mini data centre, the first solution consists in replacing each server with a more powerful server with a better TDP and possibly better energy efficiency per server. In the specific case of the above reference configuration, one can consider a data centre server renewal composed of twelve i7-7700 servers (configuration C_0). Then, the obtained

System config.	$Energy^{DC}$ (kWh)	$Compute\_capacity^{DC}$ (GFLOPs)
C_{ref}	12.19	390.24
C_0	8.34 (-31.58 %)	409.68 (+4.98 %)
C_1	3.47 (-71.53 %)	460.35 (+17.96 %)

Table 3: Reference configuration C_{ref} versus improved configuration C_0 and C_1

energy gain and computation capacity compared to C_{ref} are respectively 31.58 % and 4.98% (see Table 3). Considering the purchase price of i7-7700 servers from 2017, server renewal can be very expensive. Alternatively, one can apply a different server renewal approach consisting of consolidation [4] by using only 5 i7-8700 servers for the entire mini data centre (configuration C_1). Now, the observed energy and computation capacity gains compared to C_{ref} are respectively 71.53% and 17.96% (see Table 3). Overall, we observe that server consolidation as suggested in the configuration C_1 provides the highest outcome both in terms of energy and computation capacity. The same observation can be found in [4].

Server consolidation offers energy reductions and improved computation capacity, but its implementation requires mitigating cooling requirements due to increased heat dissipation. Cooling systems consume significant energy, and additional mechanisms may be needed to maintain temperature limits. For instance, Doyle *et al.* in [4] assume that the maximum allowable temperature in a consolidated mini data centre, based on the servers highlighted in Table 1 is 45°C. To ensure this, they considered a mechanism consuming 7% of server energy consumption. However, this approach may contribute to reduced server sustainability due to the high operating temperature and significant workload they experience. Moreover, the use of consolidation can lead to resource availability issues in the event of server failures. When services are consolidated onto a limited number of servers, if some of these servers experience failures and no replication measures have been implemented, some availability problems can occur.

4.2. Hardware renewal approaches based on the Genesis technology

Considering Genesis technology for data centre energy reduction and old server refresh issues, we explore previous hardware renewal issues. Given the specific characteristics of Genesis, the energy consumption definition of a data centre is slightly different from that of the formula (1), as follows:

$$Energy_{DC} = ((\sum_{i=1}^{N} P_i) + Overhead) * T \tag{3}$$

where N is the number of servers in the system; P_i is the thermal design power of a server i; T is the activity period of the servers; and $Overhead$ represents the power required for the operation of a power board in a Genesis module, excluding the power required for the operation of the server.The overhead, here, refers to the losses due to the conversion of battery energy to power the server, as well as the power required to operate the micro-controllers. The outdoor Genesis system benefits from passive cooling, so there is no cooling energy needed. In a module, it is possible to maintain the temperature below 50°C for 100% operation of its capacities. In our study, we assume that the temperature within a module can be maintained at an acceptable threshold for the proper functioning of the servers and batteries.

We do not consider the weather conditions to simplify the analysis, assuming that all module batteries have initially enough energy to power the servers during the operating duration. This is a pessimistic assumption as batteries can be simultaneously recharged by solar irradiation and discharged by servers activity. This leaves room for further workload execution using the residual solar energy. However, modeling sunlight is an important consideration in cases where solar energy is the main power source for our mini data centre.

In the following, we analyze new mini data centre configurations based on Genesis w.r.t. energy consumption and computation capacity. This is done when integrating old and new-generation servers into Genesis modules. We assume that each module can include a complete 2 kWh or 1 kWh lithium battery with usable energy of 1.7 kWh and 0.85 kWh per battery. In order to extend the lifespan of our batteries, we assume that they cannot be discharged beyond 85% of their maximum capacity. The

Genesis prototype's power overhead is around 20W. It corresponds to infrastructure power management logic.

Table 4 summarizes the outcomes from Genesis configurations compared with C_{ref}. Here, to determine the power consumption and computing capacity, we sum up the capacities of configurations (C_2 - C_5) which are composed of i7-2600 and i7-8700 servers. In configuration C_2, each module is charged with 2 kWh of solar energy, with 85% of the stored energy available for computing workloads. With five modules, there is initially 8.5 kWh of energy, which sufficiently covers the energy consumption of the five i7-8700 servers used for consolidation. The surplus green energy in the batteries allows for potential expansion of the computation capacity in the mini data centre. Configuration C_3 extends to 14 modules, further increasing the available green energy and computing capacity. It also enables the continued use of older servers alongside newer ones, extending their lifetime and reducing environmental impact.

System config.	$Energy^{DC}$ (kWh)	$Compute\_capacity^{DC}$ (GFLOPs)
C_{ref}	12.19	390.24
C_2	4.25	460.35
C_3	14.60	753.03
C_4	6.55	525.39
C_5	6.85	465.84

Table 4: Genesis with new servers C_2 versus Genesis with new and old servers

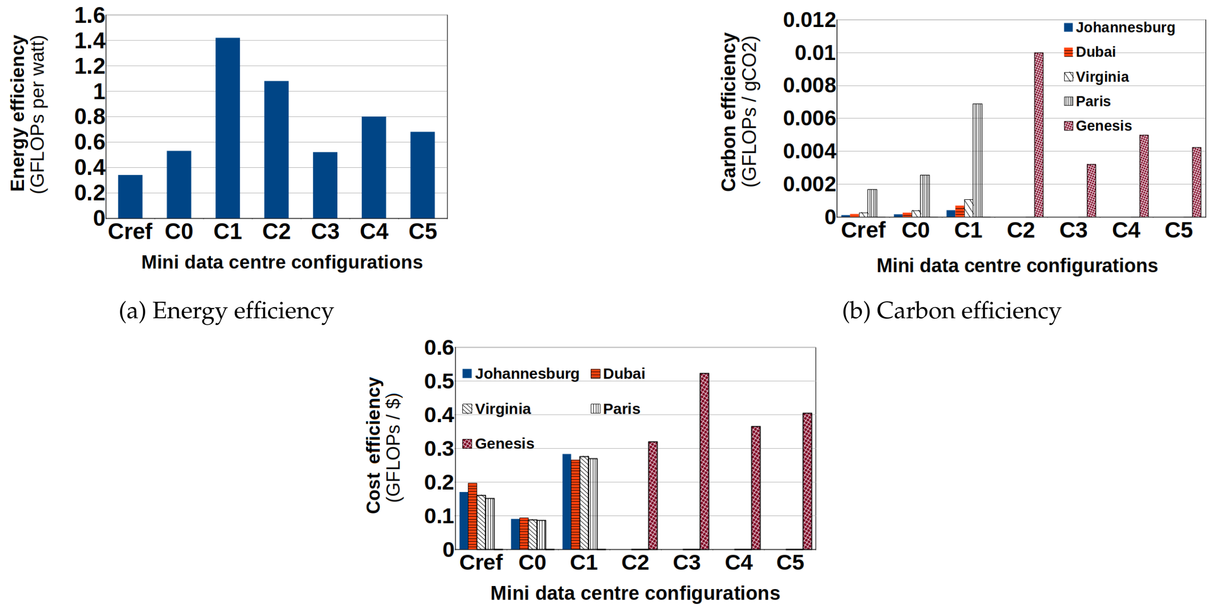
Note that C_3 can have a number of disadvantages. Due to the significant cost of purchasing several batteries modules, it is not cost-effective compared with C_4 and C_5. Moreover, in terms of sustainability, the large amount of minerals required for manufacturing these batteries can be a concern. Therefore, the C_3 configuration should be further optimized, as illustrated by C_4 and C_5 configurations, which preserve the performance of C_3 configuration.

In C_4, we have five Genesis modules including 1 kWh batteries for i7-8700 servers and 2 kWh batteries for older i7-2600 servers. This configuration provides a high computation capacity. In C_5 configuration, we slightly adjust the server distribution, but the computation capacity remains higher than the reference configuration C_{ref} and the energy consumption is covered by the available green energy in the batteries. The C_4 and C_5 configurations allow for modular server renewal, providing cost-saving options for owners of Genesis mini-data centres. The installation and purchase costs of module components are not included in this analysis.

5. Comparison of design efficiency: energy, carbon and cost

In the previous section, we evaluated different Genesis technology configurations, highlighting the opportunity to combine new and older generation servers for sustainability in mini data centres. Now, we compare these configurations based on three key metrics: energy efficiency, carbon efficiency, and execution cost efficiency. To assess the carbon efficiency and cost efficiency in our study, we considered the levels of CO_2 emissions and electricity prices in various major cities worldwide. Information regarding these parameters are provided in the appendix of the document.

Figure 2a shows the energy efficiency of different configurations, with C_1 being the most efficient overall. However, C_2 also exhibits high energy efficiency and utilizes green energy, unlike C_1. When assessing carbon efficiency, considering various deployment scenarios in different cities, C_1 performs best in Paris, but only slightly surpasses C_2 in terms of carbon efficiency. For the carbon and cost efficiency, we extended the analysis over one-year period to better illustrate the impacts in terms of carbon emissions and operational costs (Figures 2b and 2c). Genesis-based configurations generally outperform conventional data centre designs in carbon efficiency (see Figure 2b). Figure 2c compares the cost of the configurations, showing that Genesis configurations are more cost-effective due to the re-purposing of outdated servers and the associated cost savings. Overall, the Genesis approach proves suitable for extending server lifetimes in mini data centres while maintaining energy efficiency and achieving better carbon efficiency.



(a) Energy efficiency

(b) Carbon efficiency

(c) Cost efficiency

Figure 2: Three design efficiency metrics comparing classical server renewal w.r.t. Genesis approach

It should be noted that there are some important parameters that have not been taken into consideration and may have an impact on the results obtained. Our solution does not consider the power consumption of network equipment, and the environmental impact of manufacturing solar panels and batteries is not taken into account. These parameters will be addressed in future versions of the model.

6. Concluding remarks and perspectives

This work aimed to show how Genesis can reduce electronic waste emitted into the environment by data centres. During this analysis, we illustrated how data centres can positively evolve by integrating new servers and extending the lifetime of older servers in the system. Genesis' solar energy has less carbon impact on the environment than a large number of mini data centres that often rely on an energy mix inherent to the local utility grid, partly relying on fossil fuels such as coal. From a financial perspective, Genesis-oriented mini data centres can be configured to save money. We used analytical reasoning to show the potential benefits of Genesis over conventional mini data centre designs w.r.t. server renewal. Overall, thanks to all these interesting features, Genesis appears as an excellent candidate for mini data centre sustainability.

Further perspectives to this work-in-progress is to refine the considered analytical modeling by relaxing some strong assumptions and by integrating more realistic operational conditions, e.g., server execution costs beyond the processor components, a higher diversity of processor power dissipation levels according to executed load, analysis under various solar irradiation conditions, etc. We will also refine the analytical model by considering important parameters such as the power consumption of network equipment and the environmental impact of manufacturing solar panels and batteries. Scheduling policies will be investigated to address the battery energy constraint, aiming at avoiding task interruptions when power is no longer available.

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A. Appendix

To assess the carbon efficiency in our study, we considered various deployment scenarios of the mini data center in four cities: Johannesburg, Dubai, Virginia, and Paris. Carbon emissions for energy production vary from one city to another. So, we used data from [16], which quantifies carbon emissions according to city (see Table 5). According to the authors [14], solar energy sources emit 44 gCO_2/kWh. Regarding the electricity price, we used the statistics given by [17] in 2022 per country worldwide, as indicated in Table 5.

Location	Johannesburg	Dubai	Virginia	Paris
Emissions (gCO_2/kWh)	900.6	530.0	342.8	52.6
Price ($/kWh)	0.15	0.8	0.18	0.21

Table 5: CO_2 emission and energy cost numbers in the cities considered in our study

B. Genesis description

Using our lab prototype of Genesis, we evaluated the integration of two typical old-generation servers into modules: a server with an Intel Xeon processor E5-1620 v2 with 10M cache and operating at 3.70 GHz, and a Dell PowerEdge T20 server. The former server was used six years ago in the world-class supercomputer hosted by CINES in Montpellier, France (`https://www.cines.fr/en`). The latter belongs to an old Dell server generation. Genesis' benchmarked configuration comprises a 2 kWh Lithium Iron Phosphate (LiFePO4) battery and 300 W solar panel per module. Genesis modules are equipped with Ethernet ports enabling data communication via a router. Given these configurations, a node integrating the most powerful server can run for 10h and 6.5h at 50% and 100% CPU stress levels respectively. This is achieved by only using the associated battery budget. When considering the less powerful Dell server option, a node can run for 27h and 19h at 50% and 100% stress levels respectively. Under favorable solar irradiation conditions, such as July in Montpellier (south of France), an empty node battery can be fully charged in approximately 18 hours using a single solar panel.