THE FINANCIAL & SUSTAINABILITY CASE FOR CIRCULARITY

Maximize the life of your IT hardware and gain environmental and TCO benefits

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SUMMARY

This report presents a new way to think about the economic and environmental value of data center equipment. Based on research, interviews and ITRenew's market expertise, the report focuses on a Circular Data Center model that maximizes the economic life of hardware in the data center environment. The developed model shows clear benefits for primary and secondary equipment users that can be quantified with sustainability and financial metrics. The adoption of this business model by the global IT hardware industry can lower total cost of ownership (TCO) by 24% or more and decrease the greenhouse gas impact (measured in equivalent carbon dioxide, or CO2e) of the data center industry by as much as 24% or more.

24% LOWER
TCO AND GHG IMPACT

Impact of Global Circular Data Center Industry.

1. INTRODUCTION

The amount of data around the world has grown significantly in recent years and is projected to reach 175ZB in 2025 compared to 33ZB in 2018.[1] This growth is fueled by greater data collection and computation required for advanced analytics and machine learning (especially deep learning). One often overlooked consequence of this growth is the massive physical infrastructure that's required in the form of data centers to enable flow, storage and availability for all users of these highly connected and data-dependent services. This high concentration of compute power and data storage has led to an immense growth in the number of such hyperscale data center facilities.

967,107
METRIC TONS
OF WASTE

Additional waste from projected growth of data center market by 2023.

At the same time, the data center market is projected to be worth over $520bn by the end of 2023,[2] which is more than double the current market size. Alongside the massive growth, the market evolution is also projected to result in more than 46 million servers reaching end of life (EoL) in the world's data centers with 50 racks or more between 2019 and 2023.[3] The aforementioned growth will also further drive up consumption of 2% of the world's electricity to 8% by 2030[4], and generate an additional 967,107 metric tons of waste[5] that result from discarding servers at the end of their life.

When it comes to more sustainable data center practices, we have to emphasize that a lot is already being done to tackle these issues, especially in the Open Compute Project (OCP) community. This includes Power Usage Effectiveness (PUE), computational efficiency, utilization and power scaling, cooling, power efficiency, and use of renewables in data centers.[6] However, the embodied energy (the environmental burden caused by producing the equipment and sourcing the required materials), and to a lesser extent the post-use phase (end of life), are not yet accounted for.

OPEN Compute Project®

The Open Compute Project is already tackling many issues related to sustainable data center practices.

Quantifying the carbon footprint of these wasteful practices is time-consuming and expensive, due to a lack of extensive data sets[7] and complex and secretive supply chain practices. To overcome these barriers and help the industry to run better analyses in this space, we applied academic methods to collect, evaluate and use data for our model. Throughout our project, we consulted over 50 papers, more than 10 expert interviews, engaged a third-party to consult and review our processes, and used our own expertise, knowledge and data sets in the data center space.

Our expertise and research show that the data center industry is ready to tackle the wasteful practices mentioned above. In recent years, the "circular economy" has gained popularity and has found many early adopters across various industries. At its core, a circular economy aims to end our take-make-dispose economy, which is a very linear approach, and instead keep products at their highest possible value for as long as possible. Figure 1 shows how different systems can be designed for stock and renewables flow management, the latter being relevant to a Circular Data Center industry (see red circle).

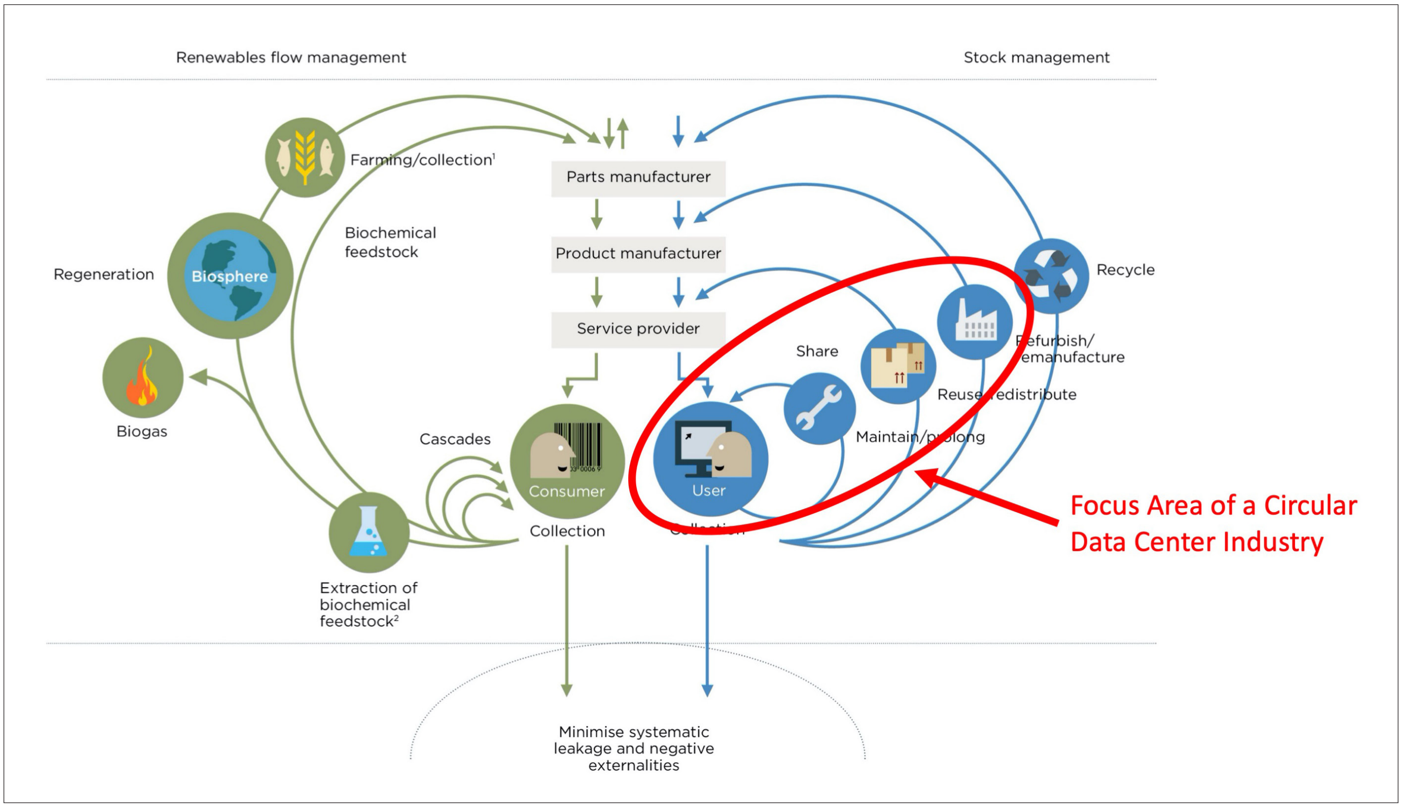

Figure 1: The concept of a circular economy, according to the Ellen MacArthur Foundation.
Source: Ellen MacArthur Foundation, SUN, and McKinsey Center for Business and Environment;
Drawing from Braungart & McDonough, Cradle to Cradle (C2C).

This approach is the guiding principle for the conceptualization of a Circular Data Center industry at ITRenew, which itself entered the data center industry in the early 2000s with IT asset decommissioning services and data sanitation. Since then, it has evolved with the data center ecosystem into a key enabler for a Circular Data Center industry, combining deep expertise, industry relations and a pole position in data center innovation (see Figure 2). With direct access to hyperscale data center operators, ITRenew is able to receive high-end data center equipment that had previously operated in the most pristine environments and then distribute the equipment through various channels into secondary markets (downstream partners).

A circular economy aims to end our take-make-dispose economy, which is a very linear approach, and instead keep products at their highest possible value for as long as possible.

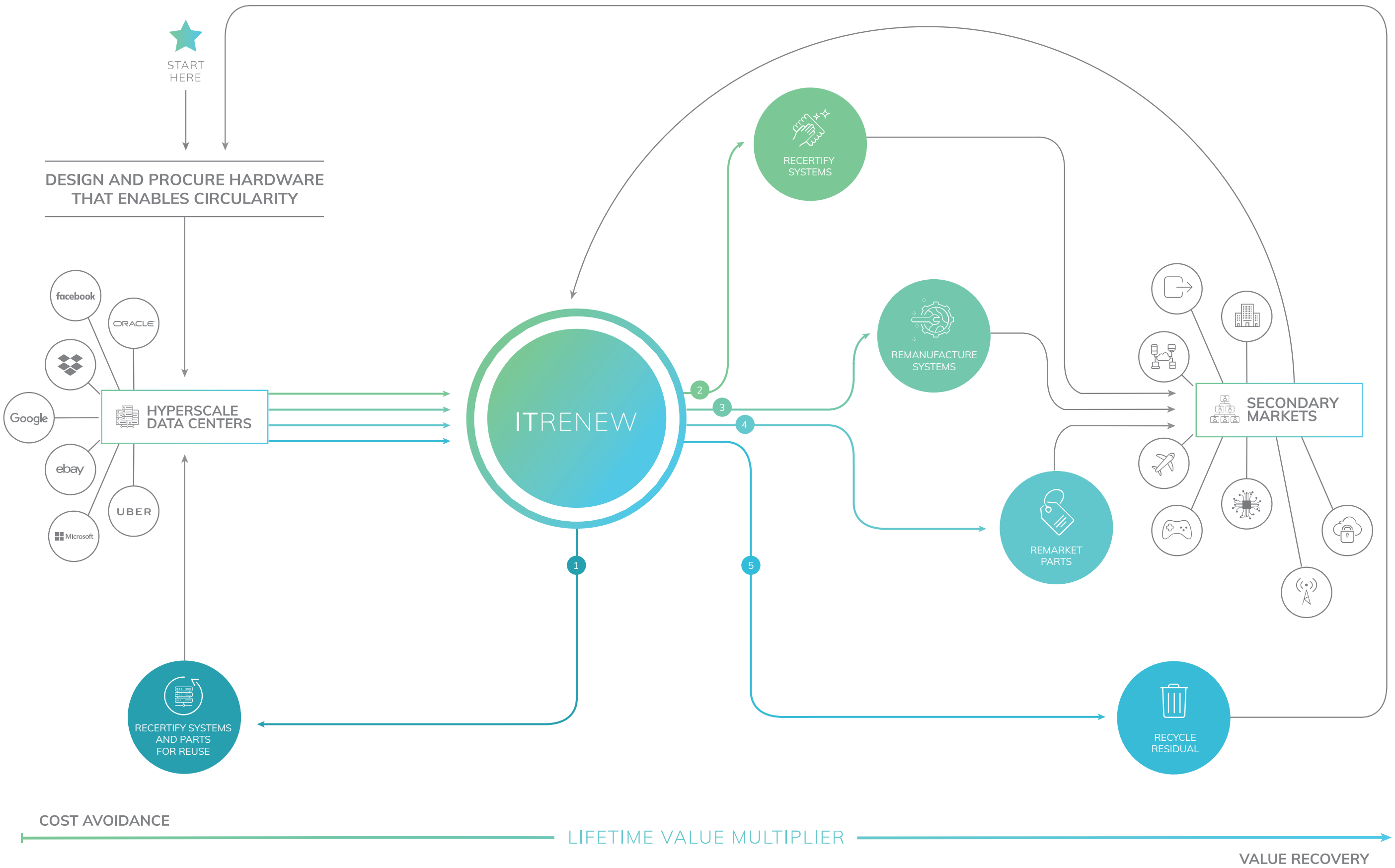

Figure 2: ITRenew at the center of a global circular IT hardware Industry through the (1) reuse, (2) recertification, (3) re-manufacturing, (4) re-marketing and (5) recycling of IT hardware

While high throughput and short refresh cycles of servers may be required in hyperscale environments, a different approach is needed to maximize the financial and sustainability value of the equipment in a circular system. While a hyperscale facility might not have optimal use for secondary equipment, there are many other data center operators in the market that can use it without compromise to performance and quality. This financially rewarding and sustainably necessary model makes these high-performing machines accessible to everyone for a secondary life.

Working in tandem, hyperscale (by providing hardware) and downstream markets (by implementing hardware) can benefit from a circular model. We will also examine the financial and environmental gains of this circular economy model achieved by extending the lifetime of data center equipment to its economically reasonable maximum.

Hyperscalers (by providing hardware) and downstream markets (by implementing hardware) can benefit from a circular model.

2. METHODOLOGY

We follow the main methodology of a life cycle assessment (LCA) by defining goal and scope, presenting key assumptions and the inventory, assessing the impacts, presenting the results, and limitations and future work. This report presents these steps in a chronological fashion (see Figure 3), but note that such steps require several iterations in practice. Also note that our impact assessment is limited to global warming potential (GWP), since we consider this the most critical and widely understood metric for measuring the life cycle impact. Global warming potential can be calculated for the main greenhouse gases through equating the greenhouse effects of that gas to carbon dioxide (see table 1).[8] Thus, we will express the global warming potential in the following in terms of carbon dioxide equivalents (CO2e).

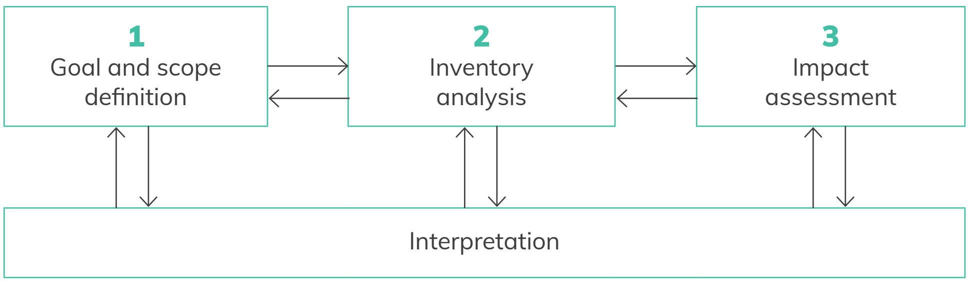

Figure 3: Life cycle assessment framework [9]

Gas	Global Warming Potential (EPA)
CO2	1 (independent of time scale, since reference gas)
Methane (CH4)	28 – 36 (for a 100 year time period)
Nitrous Oxide (N2O)	265 – 298 (for a 100 year timescale)

Table 1: Greenhouse warming potential

Our impact assessment focuses on Global Warming Potential (GWP) since we consider this the most critical and widely understood metric for measuring the life cycle impact.

3. GOAL AND SCOPE DEFINITION

The ITRenew model aims to capture the life cycle of a compute server in a simplified yet modular fashion that allows for efficient estimates and user-specific adjustments. The primary aim is to compare energy from use, pre-use, and post-use phases.

This starts by defining the basic rack and compute server setup and identifying its building blocks, choosing appropriate unit processes (e.g., 1 kg of steel). Figures 4 and 5 show the different inputs and outputs for each of these processes.

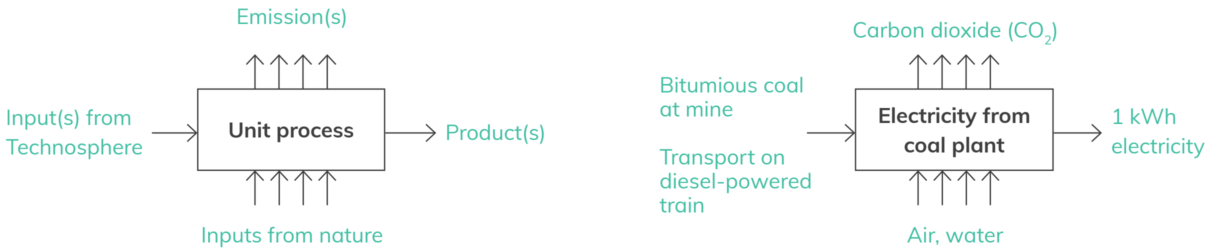

Figure 4: Generalized Unit Process Diagram, according to Matthews et al. (2014), p.103 [10]

Using unit processes then enables us to build a highly modular model that allows for adjustments at any time and lets the user verify assumptions at specific points.

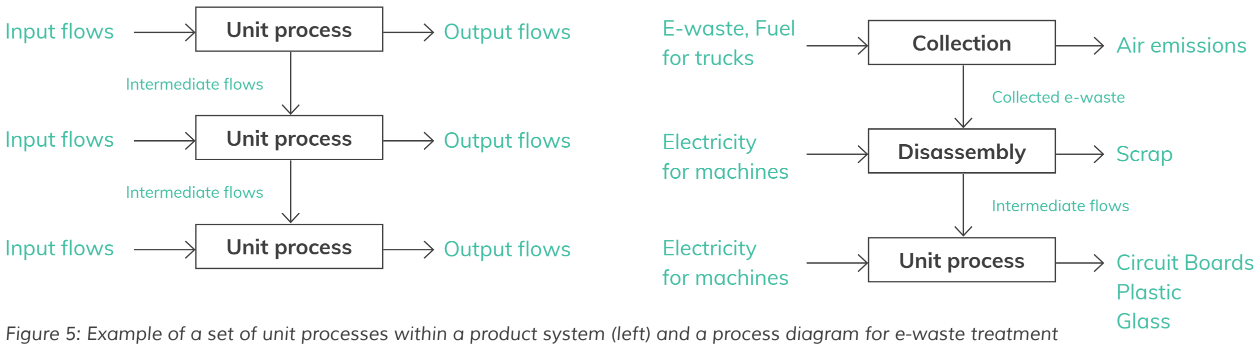

Figure 5: Example of a set of unit processes within a product system (left) and a process diagram for e-waste treatment (right) [11]

Before we can build our complete system, we need to apply the data collection and evaluation process as outlined in ISO 14044 (Figure 6).

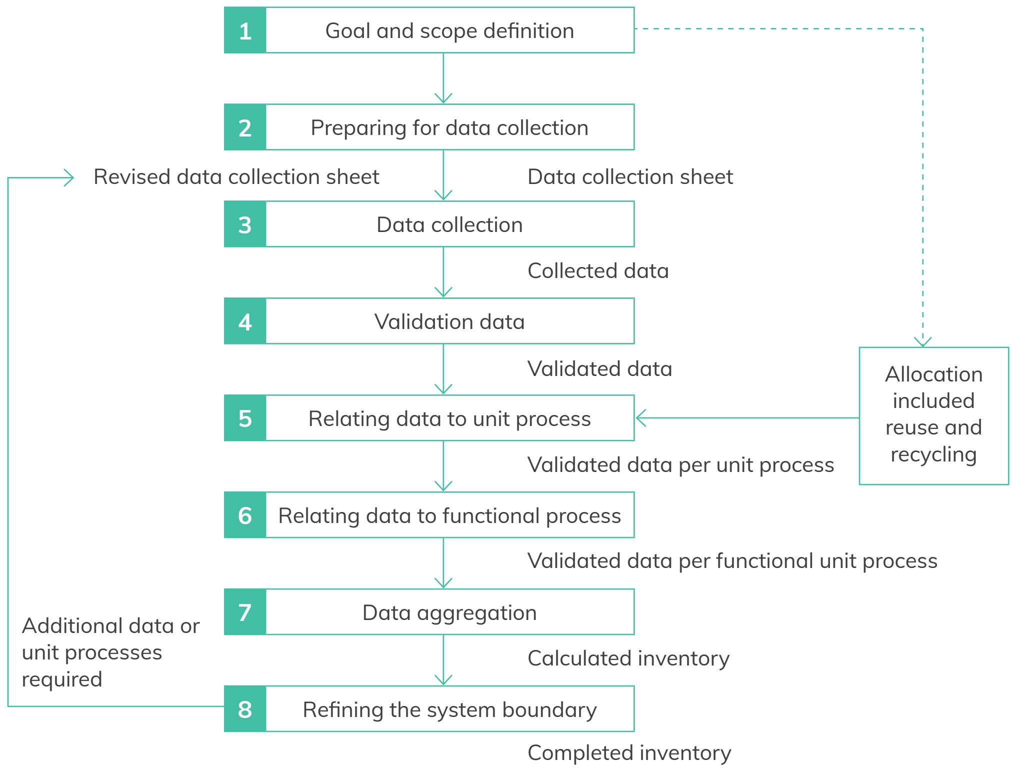

Figure 6: Data collection and evaluation process[12]

With goal and scope defined as above (1), we prepare for data collection (2) and ensure a combination of unit processes and product systems that describes our entire system. System boundaries might be adjusted where necessary.

For data collection (3), primary data sources (i.e., applying measurement equipment to own processes) are preferred, but not always available in a complicated, global and closed system of electronics supply chains. We use Microsoft Excel for data collection, visualization and computations. Mass and energy balances serve as a means to validate the inputted data (4).

Next, we relate the data to the aforementioned unit processes (e.g., normalize all data inputs to the production of 1 kg of steel) (5). These unit processes then need to be put into the larger system and linked to the other unit processes to allow a calculation of the total input based on the definition of a count and mass balances of examined racks and servers. Finally, the data is aggregated (7) to obtain a single result for the overall rack and server system. This highly iterative procedure then leads to refining system boundaries (8) and may also indicate a revision in the data collection strategy.

The model focuses on raw materials and energy as inputs and evaluates the impact in emissions and waste.

The resulting system shown in Figure 7 is a simplified life cycle model, as we cannot represent all inputs and outputs in detail. Instead, we focus on raw materials and energy as inputs and evaluate the impact in emissions and waste.

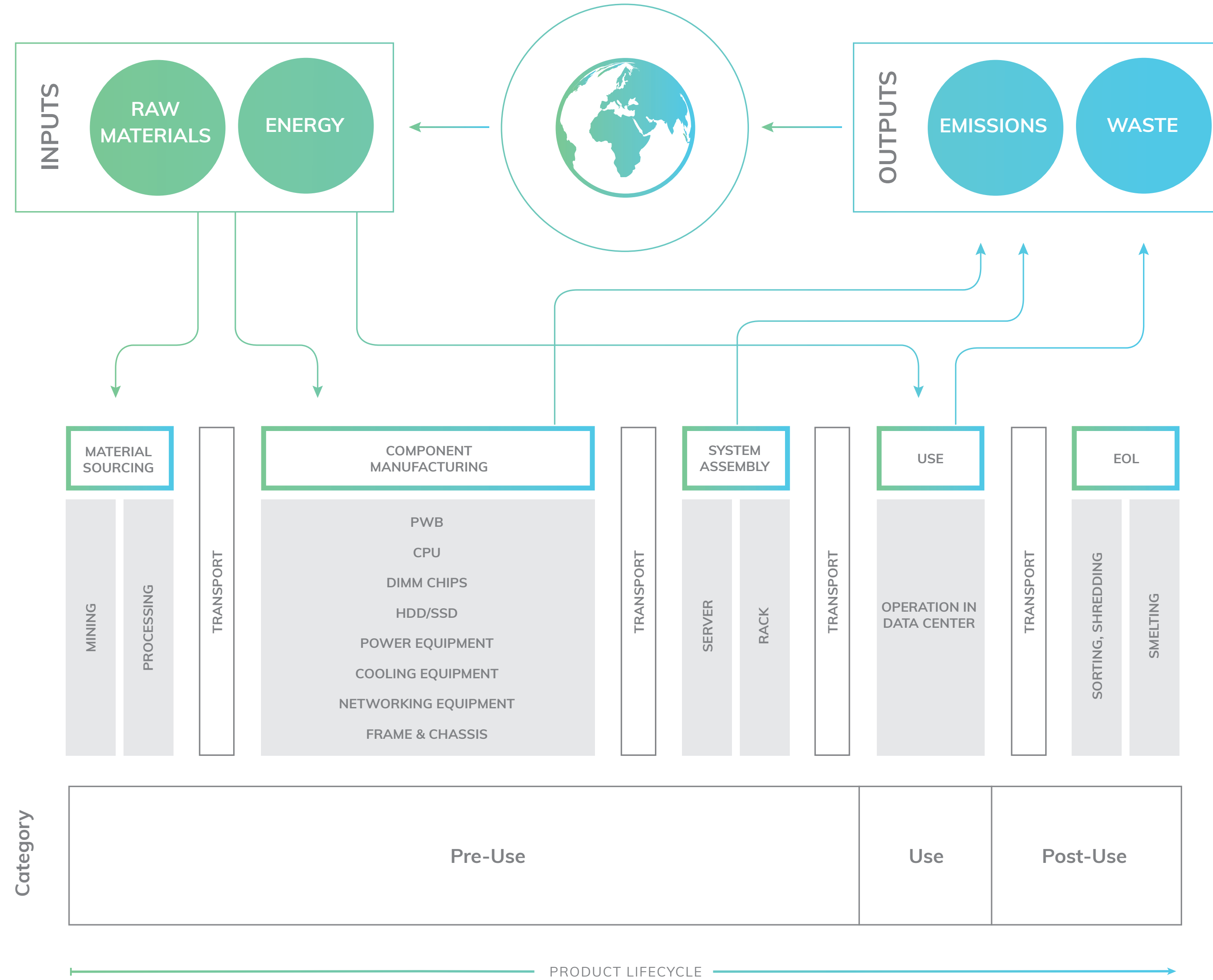

Figure 7: System boundaries of the ITRenew Circular Data Center Model

The product life cycle is divided into pre-use, use, and post-use phases. The pre-use phase includes all activities from raw material sourcing and mining to manufacturing and deployment of products. Energy from this phase is called embodied energy. Emissions from the operational phase include all those that occur while running the equipment in the data center. The post-use phase covers all recycling and end-of-life processes. Note that our model does not account for environmental effects of the data center facility, but both new and circular equipment require almost the same facility footprint and, thus, do not influence the comparison of the environmental footprint between new and circular equipment.

Energy from the pre-use and post-use phase is called embodied energy.

Based on our abstract model and considering our system boundaries (Figure 7), we are now able to construct a computational model (see Figure 8) that we implement in Microsoft Excel with a logic detailed in Figure 8.

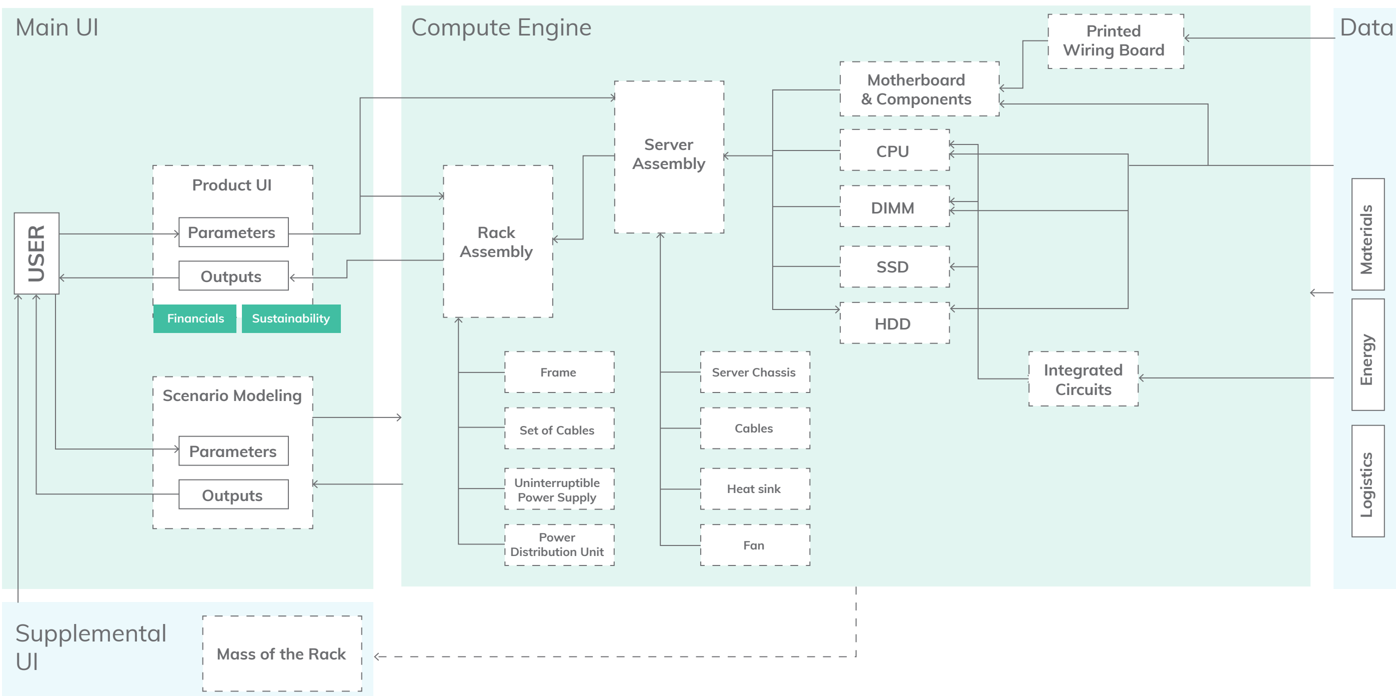

Figure 8: Computational model framework

4. INVENTORY ANALYSIS

This section presents the primary assumptions that we make for the pre-use, use, and post-use phases and sums up the total bill of materials (BoM).

ELECTRICITY SUPPLY

The main driver of emissions in the use phase is the electricity that's consumed by the servers. The carbon intensity of these electricity (grid) mixes depends on geography and the forms of energy that are used to generate electricity, as are the electricity prices costs (see Table 2). Also shown are carbon intensities for 100% renewable energy supplies to the world's largest data centers, which is a claim that is being made by an increasing share of the world's largest data center operators.[13, 14]

Data center location	Carbon intensity (kg CO2e / kWh)	Electricity costs ($ / kWh)
Quebec, Canada	0.0012[19]	0.0346[20]
Sweden	0.023[17]	0.056[18]
Virginia, United States	0.425[15]	0.0628[16]

Table 2: Location-specific electricity carbon intensities and electricity costs

We also look at different scenarios of electricity input by renewable energy sources.

Electricity source	Carbon intensity (kg CO2e / kWh)	Electricity costs ($ / kWh)
100% solar power	0.035[21]	Assume same rates as above, since mostly purchased through grid
100% wind power	0.007[22]	
100% hydropower	0.024[23]	
50% solar / 50% wind	0.021	

Table 3: Carbon intensity and costs of renewable energy sources

GREENER GRIDS

As mentioned earlier, huge progress has been made towards implementation of greener grids at many of the world's hyperscale data center facilities. Data centers that run on 100% renewable energy or employ comparable forms of low-carbon electricity provision make a great use case for further environmental benefits through the circular economy model. Thus, we will focus on how a Circular Data Center model brings significant reductions in terms of cost and environmental metrics with the example of Sweden, which shows a low carbon intensity in its electricity grid.

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EQUIPMENT

Figure 9 shows an overview of the parts that constituent one server unit and one server rack, respectively.

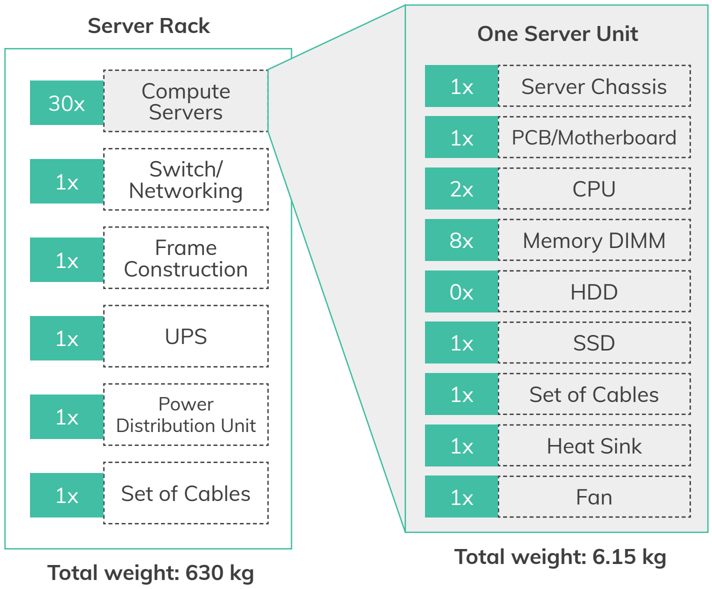

Figure 9: Component list on rack (left) and server level (right)

We research the materials that flow into each of the components outlined in Figure 9 and derive mass balances that inform us about the raw material need for these components (e.g. gold, copper, etc.). In a second step, we analyze the total energy and additional materials for each sourcing, production and distribution process along the supply chain. Following the methodology that we outlined earlier (see Figure 8), we obtain the component results as presented above. Assumptions for the components are available upon request for servers and racks respectively.

Note that, for simplification, we have assumed network peripherals to be similar to compute servers in terms of resource intensity and energy consumption, so we represent each one as the 31st server unit in our rack. Also note that the equipment is manufactured and assembled in different geographies based on the data center location. For data centers in Europe, our model assumes an assembly in the Czech Republic; servers for the North American market are assumed to be assembled in Guadalajara, Mexico.

MOORE'S LAW

Another big driver of energy costs and also the comparability of new and circular servers is the slowing down of Moore's Law, which we define as the improvement of compute per watt. To obtain a comparable measure for our model, we have measured and express improvements in compute and energy efficiency in a combined metric, which reflects the increases in compute power per installed watt of compute power. For general purpose machines, we see a clear downwards trend in recent years (this is independent from improvements that are made with accelerated units since they are customized to a specific application). To account for changes due to Moore's Law in our model, we have assumed a compound annual growth rate of the compute per watt of 12.8% per year over a 10 year horizon, with a declining curve annualized across the period.[24]

Another big driver of energy costs and also the comparability of new and circular servers is the slowing down of Moore's Law.

5. IMPACT ASSESSMENT

An impact assessment allows us to compare results from the data aggregation phase (that are measured in different metrics) and to value certain flows and quantify damages to the environment. Life cycle assessments look at a variety of different output metrics (see Appendix) – in this first version, we focus on global warming potential (CO2e emissions) and estimate the waste caused by the processes and products.

PRE-CONSIDERATION: THE JOURNEY TOWARDS GREENER GRIDS

Following the principles of life cycle assessments and calculating the share of individual life cycle phases, it's necessary to estimate the impact of operating servers under current data center conditions.

GLOBAL WARMING POTENTIAL

Phase in life cycle	Emission in phase		Share in total LCA emission
CO2e pre-use	657	kg CO2e	77%
Operational energy over lifetime (3 years)	188	kg CO2e	22%
CO2e post-use	11	kg CO2e	1%
Total	**856**	**kg CO2e**	

Table 4: Life cycle CO2e emissions for the Swedish example. The overall emissions over the life cycle for the Sweden case are presented in Table 4 and break down into different life cycle phases as outlined in Figure 10

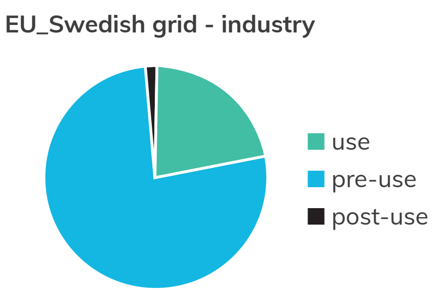

Figure 10: Greenhouse warming potential (GWP) of different life cycle phases for Swedish data centers

In our life cycle assessment, we focus on global warming potential (CO2e emissions) and estimate the waste caused by the processes and products.

WASTE

Table 5 below shows estimates for the mass balance of racks analyzed. These are only estimates for the product itself and do not consider process waste from pre-use phases.

Waste stream	**Mass**		**Description**
Rack steel allocation	11.67	kg	Steel frame
Rack electronics allocation	3.21	kg	Networking, power distribution unit, uninterruptable power supply, cables
Server	6.15	kg	Chassis, hardware components
Total	21.02	kg	

Table 5: Waste estimate per server

For all 46 million servers that will arrive at their end of life (EoL) by 2023 from data centers that have an average of 50 racks or more, this results into almost one million metric tons (967,107 metric tons) of waste that can be avoid by implementing a Circular Data Center ecosystem.

6. RESULTS AND INTERPRETATION

This section studies the results of the previous phases which enable us to make conclusions and recommendations.[25]

HIGH-LEVEL SUMMARY

In ideal conditions with green grids (as we see in Sweden and Quebec, Canada) or with a high usage of renewable energies, embodied energy makes up the majority of emissions over the life cycle. However, that situation changes when we consider carbon intensive grid mixes which we currently see in the U.S. (even in states like California that have a growing share of renewables in their electricity grids).

SENSITIVITY ANALYSES

We consider the renewable/Sweden scenario as the desired status of energy provision to green data centers. In the following, we study sensitivities in order to understand what happens when assumptions change, and show that the electricity grid mix has a huge influence on overall results.

	Absolute values (in kg CO2e)				**Relative values (share in total lifetime emissions)**		
	Pre-use phase	Operational phase (3yrs)	End of life	Total	Pre-use phase	Operational phase	Post-use phase
US (Virginia)	657	3468	13	4138	16%	84%	<1%
US (California)		2530		3200	21%	79%	<1%
Sweden		188		858	77%	22%	<2%
Montreal, QC		10		680	97%	1%	2%
Solar power		286		956	69%	30%	1%
Wind power		57		728	90%	8%	2%
Solar / wind mix		171		842	78%	20%	2%

Table 6: Results for life cycle assessments in different locations and various energy assumptions

Note that the location and energy mix have a major influence on the ratios between the pre-use and use phases. This emphasizes that the operational phase is the right entry point for a more sustainable data center, given a clean grid that is fed by renewable energy sources. It also shows that sustainable data center industry requires both clean grids and circular material flows.

To model EoL effects, we apply the cut-off system model; that is, we do not give any credit in our model for recovered material at the EoL. Also, waste itself brings numerous other hazardous effects for environmental and human health, which are correlated to waste handling practices (especially with ewaste).[26] These effects are hard to quantify.

The operational phase is the right entry point for a more sustainable data center, which then makes embodied energy more attractive as carbon intensity of the electricity grid mixes reduces.

Overall, the global warming potential (measured in CO2e emissions) of the end of life phase is relatively low, which is in line with what can be found in literature.[27] For this reason, we focus our discussion on the effects of the pre-use and use phase, neglecting the post-use phase for now.

SYSTEM-LEVEL APPROACH

To understand the overarching effects of a Circular Data Center industry, we chose to study a system of a hyperscale data center that releases hardware after primary use into the secondary market, whose participants we call "downstream partners" (Figure 11).

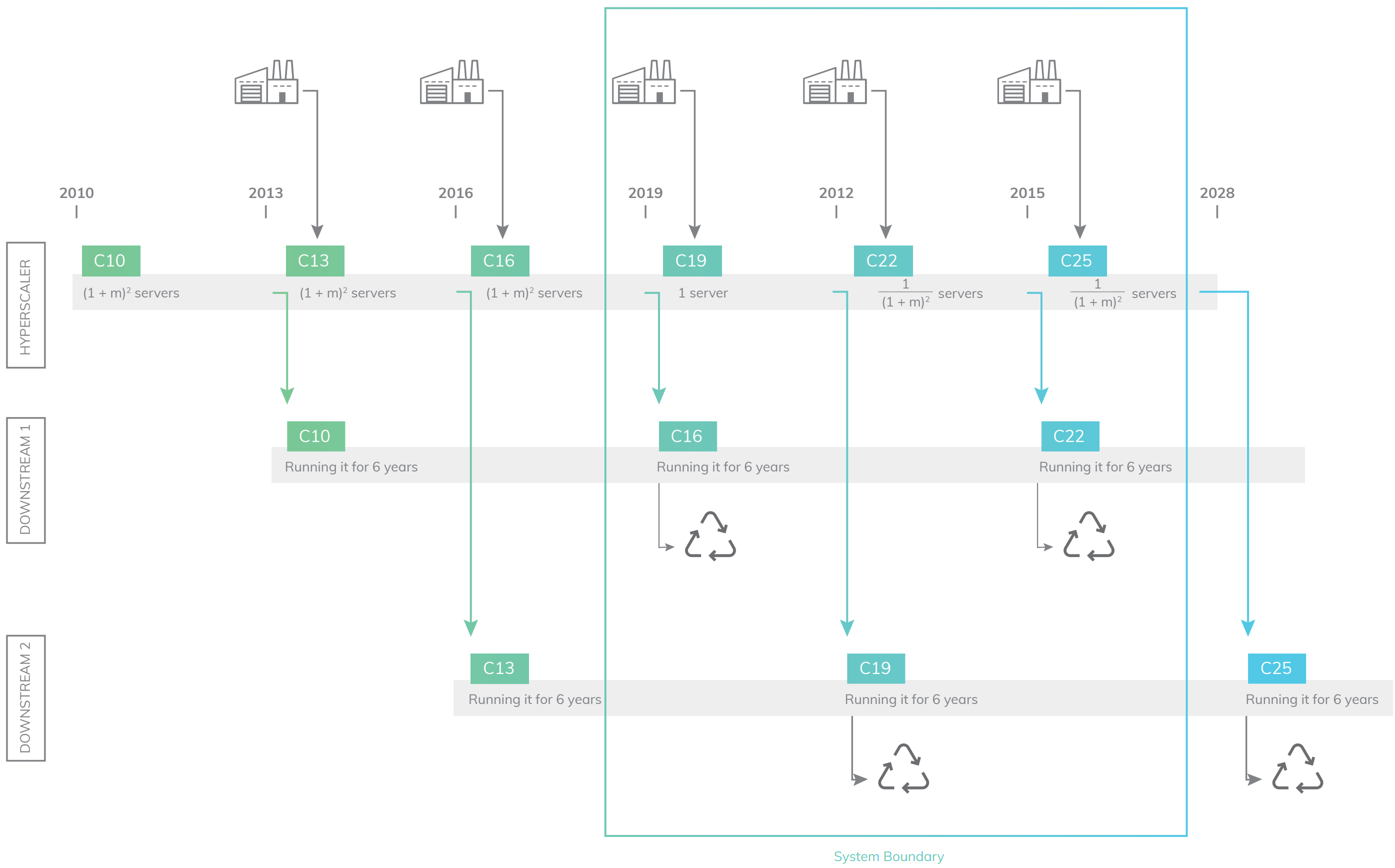

Figure 11: Comparing business as usual and circular economy scenarios on a system level

To measure the effects of a circular model on the overall data center ecosystem, we compare it against business as usual (BAU), where we assume that servers are initially employed for three years, whereas the average downstream user (a smaller data center) employs a server for nine years in its facility. For a circular economy (CE) case, we assume that the nine-year economic life of a server is split into three years of use in a hyperscale facility before being employed in a smaller downstream facility for 6 additional years. To generate an accurate comparison, we first normalize the server to its generation by the improvement of compute per watt and then study a new year "window" to see how a circular economy scenario plays out against a linear economy one.

Computing these scenarios for a complete system that hypothetically is run in Sweden by comparing BAU and CE scenario, we can see that a total savings of GHG emissions (in CO2e equivalents) of 24% occurs on the system level. We also note that, compared to the business-as-usual scenario, a system of primary and secondary equipment users in the Circular Data Center model requires manufacturing only roughly half the machine count to fulfill the same workload in both user groups, due to the circular model. This leads to additional environmental benefits that go beyond savings in CO2 emissions.

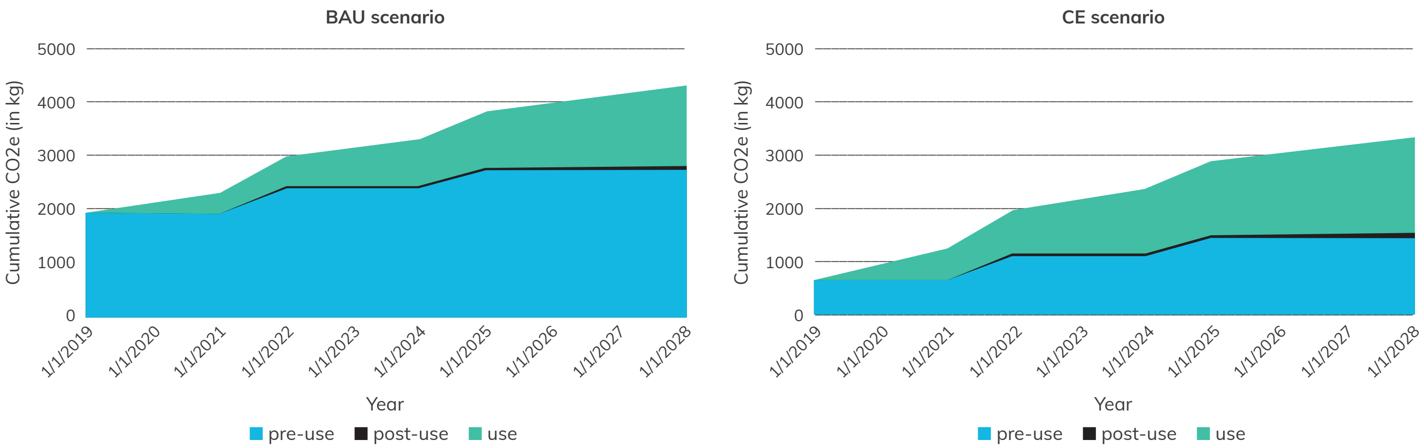

Figure 12: Comparing BAU with a CE scenario for a data center system run in Sweden

To understand more concretely, it helps to compare resulting emissions (Table 7) and waste numbers (Table 8) against real world examples.

Servers	Tons CO2e	Equivalent
15 million	10 million	3.9 million return trips from San Francisco to Amsterdam
46 million	31 million	6.7 million cars' annual emissions

Table 7: Comparing the potential CO2e savings to transportation equivalents

Servers	Tons of waste	Equivalent
46 million	967,107	Trucks loaded with waste stretching 2.2x the distance from Amsterdam to Brussels

Table 8: Visualizing the amount of waste that can be saved

FINANCIAL PERSPECTIVE

Significant financial benefits can also be achieved by the adopters of such a model, making sustainability affordable. Assuming a 12.8% compound annual growth rate over a 10 year horizon due to a declining Moore's curve annualized across the period, and a non-linear depreciation curve with annual depreciation of 60%, 30%, and 10% of the total server capital expenditure, we can calculate the following TCO savings[28] on a system level that can be achieved through transitioning from the business as usual case (BAU) to a circular economy (CE) case (see Figure 13).

While we see that the circular model can have a significant impact on net CO2e, we also see that we can achieve financial gains for all participants in the model.

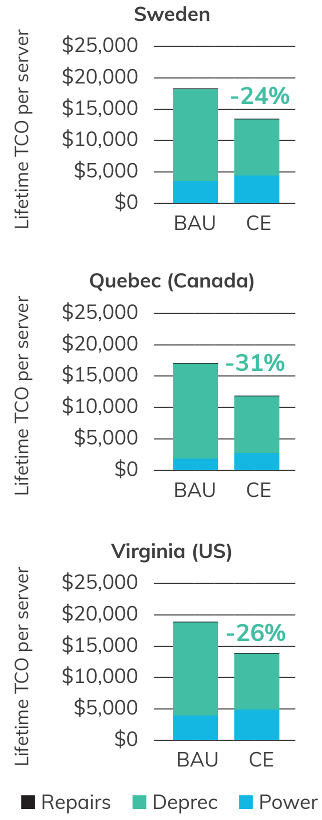

Figure 13: Realized savings in TCO in a model that is run in Sweden (top), Canada (middle) and the US (bottom)

ADDITIONAL REMARKS ON THE TECHNICAL FEASIBILITY

On the second-life server model, we identify two common considerations in relation to operating a Circular Data Center industry – these are the useful lifetime of a compute server and the space constraints that are connected with using servers for a secondary life.

Does this model work with the useful lifetime of a compute server?
Yes! Our model shows that compute servers show an expected economic useful life of 9.2 years.

Enough space available?
Yes! The required data center space is mainly driven by the business growth of the data center operator. If this growth exceeds the improvements in compute efficiencies, you need to refresh – no matter if you employ Sesame by ITRenew servers or new servers.

Assumptions
- Moore's law: 13% perf / watt / yr
- 150K sq. ft DC
- 20% compute and storage growth / year
- 10 year time horizon

New equipment, 3 year decom

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
40%	48%	54%	50%	53%	53%	49%	55%	61%	69%

50% recertified equipment

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029
40%	49%	56%	58%	63%	63%	59%	64%	70%	74%

- If Moore's Law is doubled, we still don't need more space.
- If you start at 60% full, you will need new space, in the same year.
- If you grow at 25% instead, you will need new space in year 8 instead of year 9.

Figure 14: Space requirements of new and re-certified equipment in a typical data center environment. Percentages reflect data center capacity.

7. LIMITATIONS AND FUTURE WORK

The approach presented in this report is a first model which aims to simplify the process of estimating the life cycle impacts of data center equipment. It is to be considered directionally robust and intended to drive future collaborations.

FAST-PACED CHANGES IN HARDWARE EQUIPMENT

The circular model works well for many workloads, given the alignment of total economic value with engineered technology treadmills. That said, there are certain workloads and new compute innovation domains for which this may not be optimal.

DATA SELECTION

This work is the result of an exhaustive literature review of industry and academic papers and ITRenew internal data. Quick advancements in electronics design and manufacturing, and a small number of researchers and institutions that dive into the data sets required to conduct extensive life cycle assessments, add numerous challenges to obtaining clean data signals. Overall, we consider the implemented data sources as good and the model outcomes as accurate, which was also confirmed by an independent, external expert analysis.

UNCERTAINTY ANALYSIS

Within our data selection and simplification process, we used confidence intervals and selection techniques, and verified our key assumptions with independent, external experts.

SYSTEM BOUNDARIES

As discussed earlier, system boundaries provide significant leverage to the user for model adjustment and changes. In general, our model estimates the lower boundaries for parts of our analysis, where we obtained ambiguous results from research and literature (i.e., when in doubt, we chose the data point that implied lower environmental impacts). Thus, we consider our results as a conservative estimate.

RECYCLING AT THE END-OF-LIFE

We acknowledge that our approach is extending the lifetime of equipment but is not dealing with the overall problem of end-of-life treatment of equipment. Recycling this equipment requires many more changes to evolve within the industry, which goes beyond the scope of this model. Again, this report focuses on the inner loop of the circular economy; that is, keeping the equipment in its original form and application for as long as possible. All these issues pose many different model challenges and business cases that we are aiming to explore within our own business and with partners from industry, academia, international business and public policy.

This report focuses on the inner loop of the circular economy; that is, keeping the equipment in its original form and application for as long as possible.

8. CONCLUSION

The model presented in this report proves that the benefits of the Circular Data Center are truly transformative. Circular Data Centers are the root of a circular IT hardware industry, opening up redeployment and reuse pathways that create unprecedented financial returns for hyperscalers, and unlock economic growth and new market opportunities that are otherwise blocked for everyone else. Because these pathways extend the productive lifetime of hardware by years, the model also maximizes sustainability for the entire industry.

If you already run a hyperscale facility, and employ open standard that drive greater efficiency, you can leverage this model to reduce your CO2 footprint and extract maximum value across the full lifetime of your assets.

If you run your own data facilities and are facing CapEx and resource constraints, adopting circular principles and solutions can give you access to the same technologies and opportunities as the hyperscalers and drastically lower your TCO. Products like our Sesame by ITRenew rack-scale servers are designed to help you do that and more as you scale to meet ever-increasing data and infrastructure demands.

The first movers are already realizing the significant economic and sustainability benefits of the Circular Data Center. As this model scales to become industry standard, we need you to join the discussion, partner with us on research and bring our enormous collective power to bear to enable the Circular Data Center model for all. Together we can revolutionize how IT hardware is manage and deployed around the world, unlocking major advances in access, sustainability and data center economics.

Figure 15: Sesame rack of re-certified equipment

ABOUT ITRENEW

ITRenew, the global leader in Circular Cloud and data center transformation, refuses to settle for a world that pits economic success against social good. By applying the core principles of the circular economy to IT hardware and the data center industry, the company has replaced outdated deploy-and-dispose paradigms with solutions that keep IT assets in their highest utility for as long as possible. These innovative products and services create new loops of life, from the cloud to the edge, that lower total cost of ownership while maximizing the lifetime value and sustainability potential of data center technology. The world's leading hyperscalers, service providers and enterprises work with ITRenew to create new markets, expand existing ones and revolutionize how their IT hardware is managed and deployed around the world.

To learn more about ITRenew's innovative circular economic models and comprehensive portfolio of decommissioning and data security services, edge and component products and rack-scale compute and storage solutions, visit www.itrenew.com and follow ITRenew on LinkedIn and Twitter @ITRenewinc.

9. APPENDIX

IMPACT METRICS

Impact Category	Scale	Examples of LCI Data (i.e., classification)
Global Warming	Global	Carbon Dioxide (CO2), Nitrous Oxide (N2O), Methane (CH4), Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), Methyl Bromide (CH3Br)
Stratospheric Ozone Depletion	Global	Chlorofluorocarbons (CFCs), Hydrochlorofluorocarbons (HCFCs), Halons, Methyl Bromide (CH3Br)
Acidification	Regional, Local	Sulfur Oxides (SOx), Nitrogen Oxides (NOx), Hydrochloric Acid (HCl), Hydrofluoric Acid (HF), Ammonia (NH4)
Eutrophication	Local	Phosphate (PO4), Nitrogen Oxide (NO), Nitrogen Dioxide (NO2), Nitrates, Ammonia (NH4)
Photochemical Smog	Local	Non-methane hydrocarbon (NMHC)
Terrestrial Toxicity	Local	Toxic chemicals with a reported lethal concentration to rodents
Aquatic Toxicity	Local	Toxic chemicals with a reported lethal concentration to fish
Human Health	Global, Regional, Local	Total releases to air, water, and soil.
Resource Depletion	Global, Regional, Local	Quantity of minerals used, Quantity of fossil fuels used
Land Use	Global, Regional, Local	Quantity disposed of in a landfill or other land modifications
Water Use	Regional, Local	Water used or consumed

Figure 16: Summary of Impact Categories [29]

10. ENDNOTES

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