CEE 226 PROJECT REPORT-GROUP 9

LIFE CYCLE ASSESSMENT FOR STANFORD INFORMATION TECHNOLOGY

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Industry Sponsor: Stanford Office of Sustainability

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Abstract

In 2021, Stanford University launched a Scope 3 Emissions Program, aiming to reduce, mitigate or offset university-related emissions to the maximum extent possible. The Scope 3 program analyzes and addresses indirect emissions from 15 categories purchased by the university, including building construction, products, services, etc. The purpose of this case study is to conduct a comprehensive life cycle assessment on the category of IT & Telecommunications in the Scope 3 Emissions Program and provide suggestions that may help Stanford to seek a more sustainable alternative for this category.

This analysis specifically focused on analyzing the emission and environmental impact from using on-premise servers (Stanford's Forsythe Data Center and Stanford Research Computing Facility) versus the cloud computing servers (Amazon AWS). Two server types selected for the analysis are Dell PowerEdge R610 for on-premise servers and Dell PowerEdge R720 for cloud computing. The scope of the analysis includes the production of the servers from raw materials, transportation to users, and their use phases, excluding the end of life of servers. Based on the data shared by our sponsor, the Stanford Office of Sustainability, Stanford University has a constant computation power demand at 141,325 ssj_ops, which is about 30% of PowerEdge's full potential. Therefore, although the R720 server is operating at high effectiveness, we would only account for 10.8% (141,325 ssj_ops/1,306,322 ssj_ops) of the total emissions caused by the cloud computing server during the production phase, transportation, and use phase.

SPECpower_ssj2008 is an industry benchmark that evaluates the power and performance characteristics of single server and multi-node servers. The processing load of servers is expressed as ssj_ops. We used this benchmark to set the functional unit as 1.78×10^{13} ssj_ops, which is equivalent to a typical server (PowerEdge R610) used by Stanford IT operating at 30% of the full performance for 4 years.

The result of our analysis shows that Stanford's Forsythe Data Center with R610 servers would have the most airborne emissions in CO_2 fossil, CO_2 biogenic, NO_X, SO_X, PM10, CO fossil, and CO biogenic, whereas the cloud computing servers would result in the least airborne emissions in the above categories. One exception is that cloud computing would result in the highest lead emission, but Forsythe has the least lead emission. Similarly, Stanford's Forsythe Data Center with R610 servers would result in the highest impact in all impact categories, versus the least impact with cloud computing. The total life cycle cost analysis indicates that an on-premise server with R610 at Stanford Research Computing Facility would have the highest cost of $24,126. On the other hand, if renting the cloud computing services, Stanford University would only need to pay $4,428 in total.

From both the environmental and economical points of view, renting cloud computing services from companies like Amazon is the best IT operation alternative for Stanford University because this option would result in the least airborne emissions, the lowest environmental impact, and is the cheapest option among all three scenarios. In the case that Stanford University needs to store some private data with its own servers, we recommend transferring all IT services to Stanford Research Computing Facility because this option would result in fewer airborne emissions and impacts than Stanford's Forsythe Data Center, though at a slightly higher total cost of $23,934. In addition, increasing the percentage load usage on servers helps to improve the performance-to-power ratio and the efficiency of the servers.

1 Introduction

1.1 Introduction of Data Centers

As living in the Data Era, people enjoy the connection and convenience served by the tech-linked world while some disturbing facts may have been ignored. The number of data centers reached its peak at 8.55 million around 2015 and cut down to nearly 8000 by 2021 (Daigle, 2021). There is never a contraction of data, but a transition from smaller data centers to “mega data centers.” U.S. accounts for the largest share of data centers, which consumed more than 2% of all U.S. electricity use in 2013 (Vargas, 2014). Generally, servers and cooling systems are responsible for 86% of direct electricity use in data centers (Masanet & Lei, 2020). Meanwhile, to operate these data centers, large amounts of water are flowing in and out, and types of emissions are produced as well. Stanford Forsythe data center and Stanford Research Computing Facility (SRCF) are two main data centers that contain on-premise servers to store and manage Stanford’s data.

1.2 On-Premise Server V.S. Cloud Computing

A server is designed as a piece of computer hardware or software that offers functionality for devices and systems. It provides various services, such as storing and managing network data. As for on-premise servers, they are servers that are stored and maintained in the physical office space. Thus, there is no need for an internet connection to access data. In our life cycle analysis of IT & Telecommunications, the on-premise servers are the servers located at Stanford’s Forsythe data center, which is on campus, and the SRCF at SLAC National Accelerator Laboratory. As for Cloud Computing, Stanford works with the major cloud providers and gets the services they need to manage data. Cloud-based servers are located online with all operations performed over an internet connection. They are accessed remotely and do not require on-premise facilities. In recent years, cloud computing has become more important, and the reason is that it provides flexibility, easy access, and little to no maintenance.

1.3 Problem Identification

As one of the most outstanding universities around the world, Stanford takes an active part in addressing global warming concerns and aims to reach at least net-zero emissions from its operation by 2050. In addition, Stanford’s on-campus energy will be 100% renewable starting in 2022. Among the 15 emissions intense categories addressed by Stanford University’s Scope 3 Emissions Program, IT & Telecommunications are gaining importance and consume greater amounts of energy with the rapid increase in data volume (Stanford University Office of Sustainability [Stanford], 2021). It is necessary to understand the emissions caused by the IT category, most notably the energy consumption of servers and their associated system, so we may make better eco-friendly decisions on what server service Stanford University should adopt.

2 Goal of the Study

The purpose of this study is to compare the environmental impacts of on-premise servers with those of cloud servers’ services provided by big tech companies through process-based Life Cycle Assessment. The study is, at the same time, designed to provide suggestions for the Stanford Office of Sustainability on whether to transmit data from on-premise servers to cloud servers. Thereby, we propose three scenarios for comparison.

- Scenario 1: A target server was purchased by Stanford and located in the SRCF. The SRCF is built particularly to house high-performance computing equipment for the campus research community. The building has a non-traditional and especially energy-efficient cooling system.
- Scenario 2: A target server was purchased by Stanford and located in Stanford’s Forsythe Data Center. The Forsythe data center houses Stanford’s administrative infrastructure or other items that do not qualify for the SRCF.
- Stanford purchases the cloud computing service from a cloud provider to access technology services, instead of purchasing, managing, and maintaining physical data centers and servers.

For purchased Stanford servers, the target custom server for Stanford under investigation is a general-purpose Dell PowerEdge R610 server. For the public cloud infrastructure like Amazon Web Services (AWS), we assume the service company uses the Dell PowerEdge R720 server with a higher utilization rate due to Cloud server sharing and higher energy efficiency of data centers due to regional aggravation. This assessment will trace the product's life cycle from the contributions from materials, manufacturing, distribution, use, and end-of-life management with a specific focus on the use stage.

3 Scope of the Study

3.1 Functional Unit

To calculate power consumption in relation to performance for customized load server-class computers, we use SPECpower_ssj2008 as a benchmark to generate an in-depth analysis of server efficiency. The SPEC Power benchmark is the first industry-standard benchmark that evaluates the power and performance characteristics of single server and multi-node servers. This benchmark is used to compare power and performance among different servers and serves as a toolset for use in improving server efficiency. According to the SPECpower_ssj2008 report, the processing load of servers with different performance levels (from 10% to 100% of the idle segment) is expressed as ssj_ops(Standard Performance Evaluation Corporation [SPEC], 2021c).

The function unit for this study is 1.78×10^{13} ssj_ops, equivalent to a typical server (PowerEdge R610) used by Stanford IT operating at 30% of the full performance for 4 years.

3.2 Process Flow Diagram & System Boundaries

The process flow diagram of our model is shown in Figure 1 is a detailed breakdown of our analysis using SimaPro. The assessment of raw material and energy consumption for these phases are analyzed using SimaPro by examining a list of physical components of the Dell PowerEdge R610 provided by the sponsor. After the first stage of manufacturing, the completed components will be shipped to a large assembly factory in Southeast Asia, where the final product, the server, is assembled together. The server will be shipped to customers across the world for their use. In our case, the server will be transported to the Stanford campus. After 4 to 5 years of usage phase, the server will probably be replaced and disposed of at a nearby landfill.

The boundary of our life cycle analysis was drawn to include the environmental impacts of the selected Dell R610 and R720 server across most of its full life cycle including the component manufacturing, transportation to assembly factory, component assembly, transportation to customer, and use phase. We purposely exclude the reuse and end-of-life phases because of the uncertainty in material recycling, the location of the landfill center, lack of supportive data from cloud service vendors, and insignificance compared to use phase energy consumption.

3.3 Server Comparison Assumptions

The core components of a data center that provides IT services are servers that process requests and deliver data to another computer over the internet or a local network. Due to the variety of needs, a data center may include different types of servers from different companies to meet the customized demands from the clients. Therefore, it is unrealistic for us to perform a comprehensive life cycle analysis at a data center. To simplify the problem, we picked Dell PowerEdge R610, the most common type of server that the Stanford IT department purchased in the past 3 to 5 years, as the baseline model. Dell PowerEdge R610 is capable of performing 468,471 ssj_ops at 100% load and 172 W (SPEC, 2021a). Based on the data shared by our sponsor, Stanford on average operates the on-campus server at 30% of its maximum capacity, that is 141,325 ssj_ops at 107 W (SPEC, 2021b) (see Figure 2). The more specific R610 server hardware configuration can be found in Figure 3. We assume that Stanford will use only the Dell PowerEdge R610 server for Stanford's on and off-campus data centers.

Unfortunately, there is very limited information on what type of server cloud computing service companies use because of their privacy policy. Considering the scale of industrialized data centers and the amount of data big data services like AWS would process every day, we assume that cloud computing data centers would use more powerful, higher operation capacity, more industrialized servers, such as Dell PowerEdge R720. Dell PowerEdge R720 is capable of performing 1,447,466 ssj_ops at 100% load and 230 W. Comparing to the low usage of server's full potential at Stanford data center, we assume that the percentage usage at cloud computing data center would be 90% because cloud computing companies would allocate most of the server's computing power to multiple customers so that they may maximize profit from providing such services. Based on our assumption, the cloud computing server is on average performing 1,306,322 ssj_ops at 199W (see Figure 4). The more specific R720 server hardware configuration can be found in Figure 5.

3.4 Production Phase Assumptions

The server is a unique category that has not been specifically captured by SimaPro as a searchable item. Carnegie Mellon's EIO-LCA database's description of the electronic computer manufacturing category, this category includes "manufacturing and/or assembling electronic computers, such as mainframes, personal computers, workstations, laptops, and computer servers" (Carnegie Mellon University Green Design Institute [CMU], 2010). Therefore, to simplify the problem, we used the laptop computer category on SimaPro to calculate the emissions caused by computer servers. The unit for the computer category is pieces instead of a weight unit. To improve the accuracy of the result, we account for the difference in server weights by converting the selected server weights to SimaPro equivalent pieces (see Table 1) (Lehmann, 2013). Then we compute the energy required and environmental impact of the production of the two servers by running SimaPro to draw the data related to the production of computer raw materials with the corresponding weight.

3.5 Transportation Assumptions

In this life cycle assessment, we assume that servers travel from raw material sources through pre-manufacturers, manufacturers, and finally data centers. The transportation of the disposal and recycling are not addressed since the reuse and end-of-life phases are not covered in the study. SimaPro's outputs involve transportation from raw material sources to pre-manufacturers, as well as transportation from pre-manufacturers to manufacturers. We assume that servers are sent from Dell's assembly plant in Austin, Texas, for transit from manufacturers to data centers (PlanetMagpie, 2019). Given the AWS infrastructure map, we assume that the AWS data center selected in Scenario 3 is situated in Portland, Oregon (Amazon, 2021). Because the number of servers acquired by either the SRCF or the Forsythe data center is modest at a time, we assume the delivery is made by a single-unit truck powered by diesel. Due to the bulk purchase, a freight train powered by diesel is employed to deliver servers to the AWS data center (see Tables 4 and 3 for transportation assumption summary).

3.6 Use phase assumptions

The use phase includes evaluating the environmental impacts of the 4-year span of usage in the three different scenarios. Although the entire data center may require multiple energy sources to remain functional, the main energy source that powers servers during the use phase is electricity. Therefore, we take the usage of electricity as the only criteria we need to consider for the emission produced by servers during their use phase. The hourly usage indicator is converted to kWh. Due to the essential function servers are providing, the servers are connected to power 24 hours a day and 365 days a year.

In addition, the final electricity a server used also depends on the effectiveness of the data center's cooling system, which determined the power usage effectiveness (PUE) of a data center. PUE is energy use efficiency which is used to determine energy efficiency metrics for specific data centers. The PUE is a ratio of the total power coming into the data center divided by the power used by the computing infrastructure running inside the data center. The more efficient the data center – the lower the PUE value. We cite a comprehensive performance PUE data of 1.10 for the 12 months period of Google data center (Google, 2021), which includes all its large-scale data centers, all seasons, and all indirect energy consumption for cloud computing energy usage. We import the PUE efficiency quantified by Stanford for the two data centers at Stanford: 1.52 for Stanford's Forsythe data center and 1.19 for SRCF (see Table 2 for use phase assumption summary). We also assumed no server components will need to be replaced during its use, that is, no additional emission from the production or shipping of components will be added during the use phase.

3.7 Emissions Allocation Assumptions

As mentioned in product selection, the R610 server is assumed to be operating at 30% of full capacity (141,325 ssj_ops) at 107W and the R720 server is operating at 90% of full capacity (1,306,322 ssj_ops) at 190W. The computing demand from Stanford University is constant and equals 30% of R610's full capacity at all times. Therefore, although the R720 server is operating at high effectiveness, we would only account for 10.8% (141,325 ssj_ops/1,306,322 ssj_ops) of the emissions caused by the cloud computing server during the production phase, transportation, and use phase.

4 Data Collection

The data relating to all on-premise servers is provided by our sponsor, which includes server models purchased by Stanford in the last 5 years, the PUE efficiency and electricity grid of the two on-premise data centers, and the workload of an average server running on-premise. Another important data used to analyze cloud computing services is the supplier list of the cloud computing service used by Stanford University, from which we chose Amazon Web Services and targeted a High-End Dell PowerEdge R720 Server as the object of our life cycle assessment analysis.

The data of the material content of the products we used came from the computer model in SimaPro because we did not have the Server BOM provided by Dell to apply. We communicated with the Sponsor and held regular project meetings through online data collection and discussion about product production and use.

5 Life Cycle Interpretation

5.1 Inventory and Impact Assessment

Production phase, use phase, and transportation from manufacturers to data centers are the three key portions of the life cycle inventory analysis and impact assessment. We abstract the commonly considered airborne pollutants from SimaPro's emissions outputs (some examples of SimaPro's outputs are shown in Figure 14 to Figure 17) and examine at the absolute values of emissions for three scenarios: Dell PowerEdge R610 at the SRCF and at Forsythe, and Dell PowerEdge R720 at AWS data center. In terms of each scenario, we also compare the relative percentages of production phase, use phase and transportation for each type of emission. The categories of emissions include CO_2 fossil, CO_2 biogenic, nitrogen oxides (NO_X), sulfur oxides (SO_X), PM10, Lead, CO fossil, and CO biogenic. Table 5 summarizes the numerical data for total airborne emissions from each scenario. See Table 6 to Table 8 for detailed emissions results for production phase, use phase and transportation in each scenario. Figure 6 to Figure 8 illustrates the emission characterizations for all of the cases. Most types of pollutants have a high proportion in the use phase (more than 99%), therefore the emissions in the production phase and during the transportation are negligible. For scenarios 1 and 2, however, lead emissions throughout the production process account for more than 10% of the total.

To conduct the impact assessment, we adopt the TRACI tool for the characterization factors, which include ozone depletion, global warming, smog, acidification, eutrophication, carcinogenics, non carcinogenics, respiratory effects, ecotoxicity, and fossil fuel depletion. Table 9 summarizes the numerical data for environmental impact from each scenario. Table 10 through Table 12 shows the quantifiable outcomes, whereas Figure 9 and Figure 11 show the comparison results for each scenario. The use phase appears to have a stronger impact, similar to the inventory analysis, but the production phase in all three scenarios has a higher ozone depletion impact.

In the production phase, both raw material acquisition and manufacturing process are considered. In general, because of its bigger bulk, R720 produces more emissions and so has a greater environmental effect than R610 at this stage. However, due to the differences in target loads and benchmarks between on premise and cloud servers, we only use roughly 10% of the R720 server's overall capacity for this analysis. As a result, we only account for about 10% of the emissions and impact during the production phase, which is significantly less than the impact of the entire R610 manufacture.

In the use phase, the energy consumption of servers and the building system, as well as various emission variables for different power grid systems, are taken into account. As a result, scenario 1 has the greatest emission for all kinds of airborne pollutants, with the exception of lead, which is highest in scenario 3. What's more, of the three situations, scenario 1 has the largest impact in all the impact categories.

During the transportation process, distance, weight, and transportation options are considered for each scenario. The transportation of R610 for scenarios 1 and 2 results in higher CO_2 fossil, CO_2 biogenic, PM10, and CO fossil emission. The NO_X, SO_X, Lead, and CO biogenic emissions that we account for in scenario 3 transportation are greater than those in scenario 1 and 2. The transportation of scenarios 1 and 2 has a larger impact in all impact categories except for ozone depletion.

The normalized emission comparison, Figure 12, demonstrates that R610 at Forsythe emits higher airborne pollutants than the identical server at the SRCF or R720 in cloud data center, except for R720 emitting more lead. Unsurprisingly, R720 in the cloud data center produces considerably fewer airborne emissions than R610 in on-premise data centers. The normalized impact comparison, Figure 13, shows that R610 at Forsythe has the highest overall impact for all impact categories, while the R720 for cloud server has significantly less impact for all impact categories than the other two scenarios.

5.2 Life Cycle Cost Analysis

The life cycle cost analysis is used to assess the overall cost of alternatives and to support decision-making by selecting the option with the lowest total cost while maintaining the same level of quality and function. Thus, we evaluate the cost of three data solutions for Stanford's data plan as described in the three scenarios.

The one-time expenditures for R610 servers at the SRCF and Forsythe include purchase, installation, and disposal. Energy expenses, maintenance costs, operating costs, and downtime costs are all included in the annual costs for the server's four-year lifetime. The electric bill determines the majority of the energy costs; for the SRCF and Forsythe, we use California electricity rates ($0.1689/kwh), and for an AWS cloud data center, we use Oregon electricity rates ($0.0881/kwh) (U.S. Energy Information Administration [EIA], 2020). Meanwhile, a salvage value of about $200 for R610 is deducted from the total cost (Corporate Finance Institute [CFI], 2021). For the cloud service, we primarily account for the annual service expenses of an equivalent server to R720, which is around $1,220 per year. To compare with the on-premise servers, we take into consideration the same parameters when calculating the life cycle cost of a cloud server, and multiply by roughly 10% to estimate the life cycle cost for consumers who use about 10% of the server's capacity. The complete data in this analysis can be found in Table 13.

Finally, we calculate the total cost in present value for each scenario using a nominal interest rate of 4%. The life cycle cost for an R610 at the SRCF is $23,934, $24,126 at Forsythe, and $4,428 for AWS cloud service with an R720 equivalency for 4-year use. For 10% utilization, the projected life cycle cost of an R720 in a cloud data center is $2,508. For comparable data computation and storage operations, the cloud service, as expected, offers the lowest life cycle cost.

5.3 Sensitivity Analysis

Our sensitivity analysis is based on the first scenario, where the server will be purchased by Stanford and installed in Forsythe. Since the impact from production phase and transportation only account for a small portion of environmental impact, we decide to perform the analysis focusing on the uncertainty in the electricity consumption in the use phase of the product with three uncertainty factors from our assumptions, the percentage load of the server, the power usage efficiency (PUE), and the active idle power of the server.

Among the uncertainty factors, the load percentage of the server will have the highest uncertainty. For the life cycle analysis, we assume the server to operate under 30% of the maximum workload, while the actual workload can vary according to the needs. In the sensitivity analysis, we assume the server workload to be 20% at lowest, resulting in a longer time to finish the one functional unit of operation at a lower power, and 50% at highest, resulting in a shorter time to finish the operation at a higher power. We also assume a 5% uncertainty for the power usage efficiency since the efficiency of cooling system and other electric usage in the data center can vary due to change in climate from year to year. There is also an 0.8% uncertainty in the measurement of active idle power, which will influence the actual power of the server. See Table 14 and Table 15 in Appendix E for more details of the sensitivity analysis.

The result of sensitivity analysis is shown in Figure 18. The uncertainty in load percentage of the server will have the largest influence on the electricity consumption of server to perform one functional unit of operation since the server's power efficiency varies a lot under different loading conditions.

6 Analysis and Strategies for Improvement

6.1 Data Hosting Location Recommendation

We find that scenario 3 has the lowest emission among all scenarios, except for lead emission, by generating the normalized emissions and normalized effects graphs in Figures 12 and 13 for three scenarios. Because of the differences in the power grid system and its emission factors, scenario 3 has the highest lead emission. In scenario3, we assume the cloud server is located in Portland, Oregon, where the grid emits more lead than California. Scenario 3 also has the least impacts across all TRACI impact categories.

Hence, if allowed, we recommend transferring data to a cloud data center to reduce Stanford's Scope 3 emissions and environmental impacts in the IT & Telecommunications category.

6.2 Sensitivity Analysis and Improvement

We conduct a sensitivity analysis for Scenario 2, concentrating on the server's usage phase, and observe that the loading percentage has a considerable impact on the energy consumption of performing one functional unit. This is because the server's performance to power ratio varies greatly depending on the load. According to the SPECpower_ssj2008 benchmark, the Dell R610 has the ideal performance to power ratio when loaded to 100% (SPEC, 2021a), while the Dell R720 reaches the best when loaded to 80% (SPEC, 2021b).

We are aware that not all the servers can be hosted in the cloud data center. In this instance, we propose that the on-premises servers run at a greater utilization rate to optimize the performance-to-power ratio and thereby reduce energy consumption for the same series of functions.

7 Discussion and Conclusions

The study is carried out in accordance with the ISO 14040 standard. This process-based life cycle assessment of Stanford's data hosting alternatives analyzes the environmental performance of server production, assembly, transportation, and use. The report was developed to support the Stanford Office of Sustainability make decisions on the university's data hosting plans in relation to the Scope 3 Emissions Program target. Because of the scarcity of information about cloud servers and other unknowns, several assumptions are made by necessity.

Given the current operation parameters, cloud servers have much fewer environmental impacts than on-premise servers situated in the SRCF and Forsythe data centers, according to the results of our study. The SRCF has superior environmental performance than the Forsythe data center of the two on-premise data centers. In terms of the major stages of the life cycle, the environmental impacts in the production phase are directly related to the weight of a server, whereas the environmental impacts in the use phase are determined by the energy effectiveness of the data center, as well as the target load and power of the server. The environmental performance exhibited in the transportation process is correlated to the shipping distance, server weight, and transit methods.

Nevertheless, our analysis has a few drawbacks. First, in the production stage, we simplify the SimaPro inputs by utilizing the "computer" category instead of multiple server components. Though this replacement is backed by the Carnegie Mellon's EIO-LCA database classification, the compositions of various servers differ from that of a computer. SimaPro's embedded data of transportation from raw material sources to manufacturers in a computer category might differ from that of a server as well. As a result, the analysis during the production process may be insufficiently precise. Second, while we assume a certain model of servers in the cloud data center, the models utilized by cloud providers might vary, potentially resulting in a variance in environmental impacts. Moreover, while the PUE we employ for the cloud data center is near to the ideal solution, the cloud data center may fall short of the desired environmental friendliness in practice. Third, the analysis excludes the end-of-life phase, which ignores both the substantial effects of reuse and recycling as well as the associated emissions in the disposal stage.

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Appendices

A Process Flow Diagram

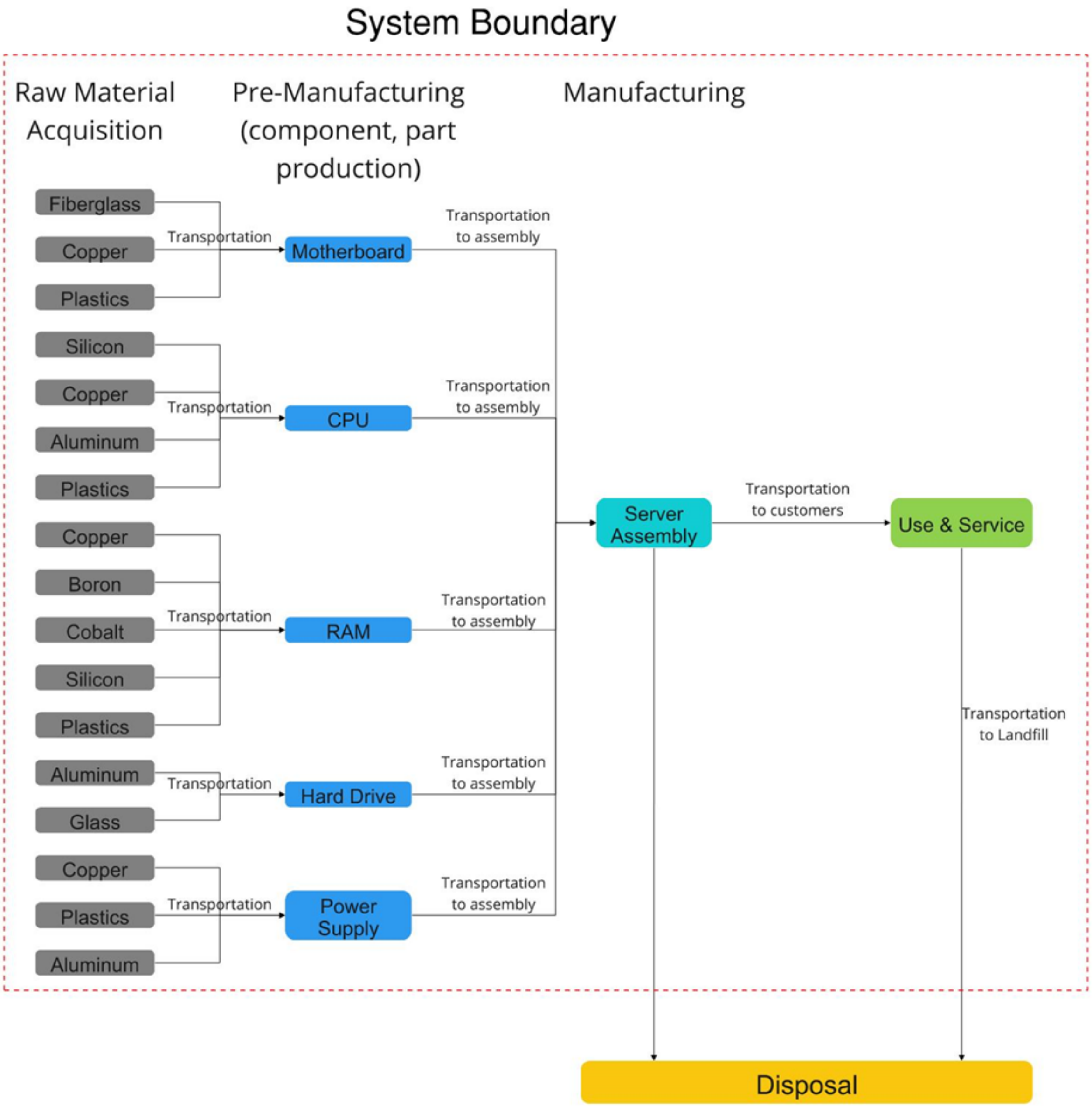
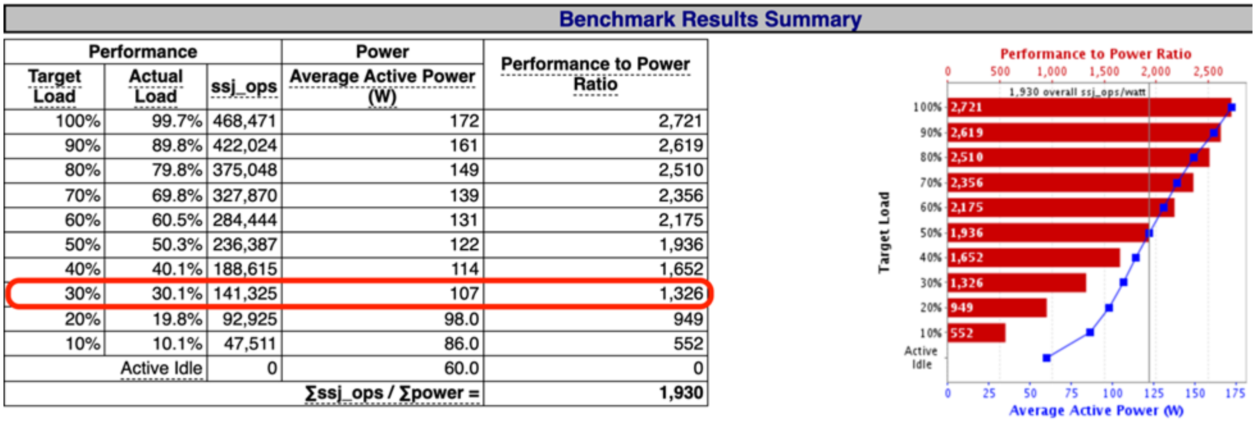


Figure 1: Process Flow Diagram

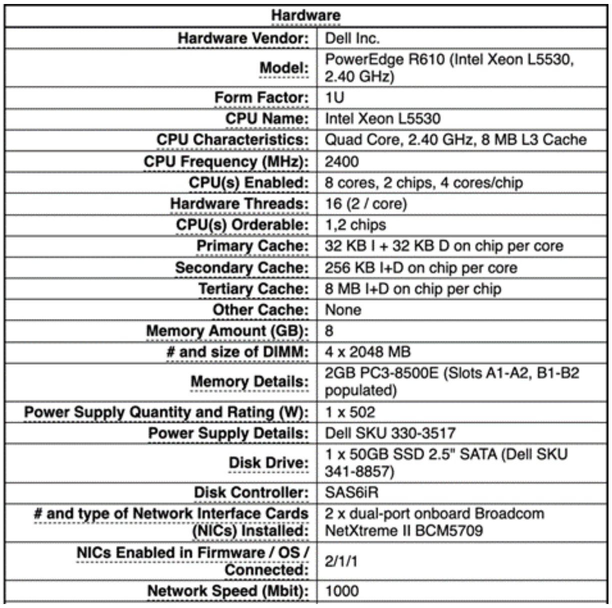
B Product Information



Benchmark Results Summary

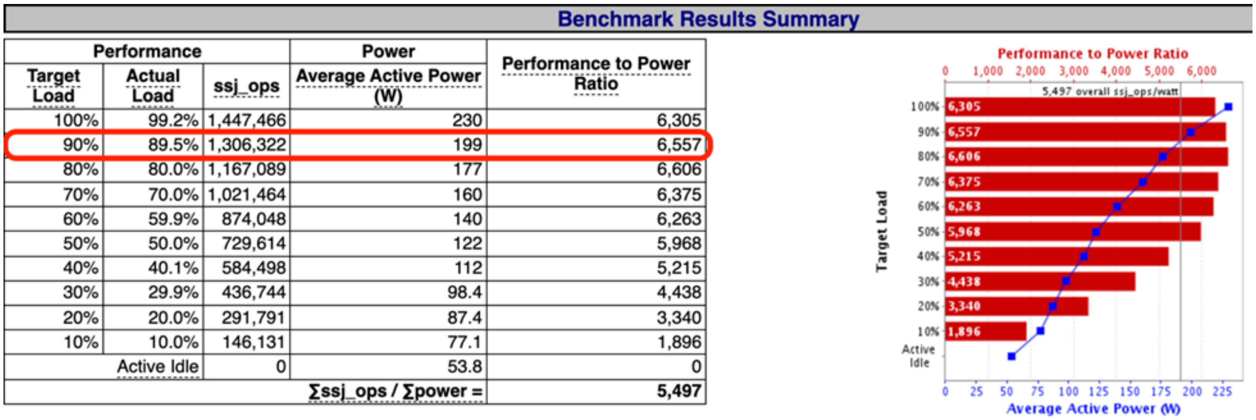
Performance			Power	
Target Load	Actual Load	ssj_ops	Average Active Power (W)	Performance to Power Ratio
100%	99.7%	468,471	172	2,721
90%	89.8%	422,024	161	2,619
80%	79.8%	375,048	149	2,510
70%	69.8%	327,870	139	2,356
60%	60.5%	284,444	131	2,175
50%	50.3%	236,387	122	1,936
40%	40.1%	188,615	114	1,652
30%	30.1%	141,325	107	1,326
20%	19.8%	92,925	98.0	949
10%	10.1%	47,511	86.0	552
	Active Idle	0	60.0	0
			∑ssj_ops / ∑power =	1,930

Figure 2: Benchmark results summary for Dell PowerEdge R610



Hardware	
Hardware Vendor:	Dell Inc.
Model:	PowerEdge R610 (Intel Xeon L5530, 2.40 GHz)
Form Factor:	1U
CPU Name:	Intel Xeon L5530
CPU Characteristics:	Quad Core, 2.40 GHz, 8 MB L3 Cache
CPU Frequency (MHz):	2400
CPU(s) Enabled:	8 cores, 2 chips, 4 cores/chip
Hardware Threads:	16 (2 / core)
CPU(s) Orderable:	1,2 chips
Primary Cache:	32 KB I + 32 KB D on chip per core
Secondary Cache:	256 KB I+D on chip per core
Tertiary Cache:	8 MB I+D on chip per chip
Other Cache:	None
Memory Amount (GB):	8
# and size of DIMM:	4 x 2048 MB
Memory Details:	2GB PC3-8500E (Slots A1-A2, B1-B2 populated)
Power Supply Quantity and Rating (W):	1 x 502
Power Supply Details:	Dell SKU 330-3517
Disk Drive:	1 x 50GB SSD 2.5" SATA (Dell SKU 341-8857)
Disk Controller:	SAS6iR
# and type of Network Interface Cards (NICs) Installed:	2 x dual-port onboard Broadcom NetXtreme II BCM5709
NICs Enabled in Firmware / OS / Connected:	2/1/1
Network Speed (Mbit):	1000

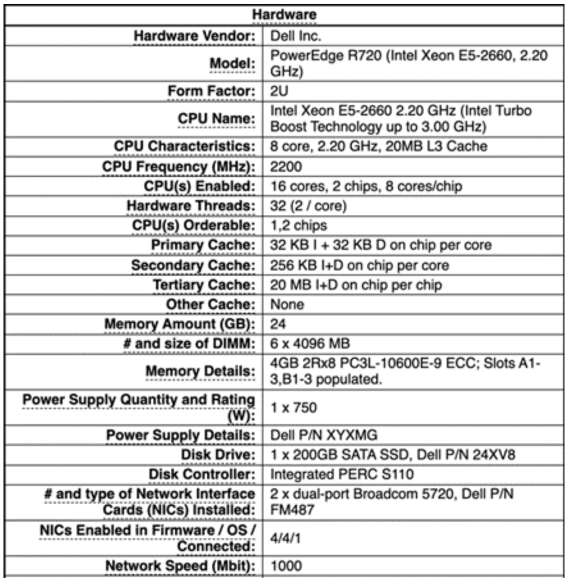
Figure 3: Dell PowerEdge R610 hardware configuration



Benchmark Results Summary

Performance			Power	Performance to Power Ratio
Target Load	Actual Load	ssj_ops	Average Active Power (W)	
100%	99.2%	1,447,466	230	6,305
90%	89.5%	1,306,322	199	6,557
80%	80.0%	1,167,089	177	6,606
70%	70.0%	1,021,464	160	6,375
60%	59.9%	874,048	140	6,263
50%	50.0%	729,614	122	5,968
40%	40.1%	584,498	112	5,215
30%	29.9%	436,744	98.4	4,438
20%	20.0%	291,791	87.4	3,340
10%	10.0%	146,131	77.1	1,896
	Active Idle	0	53.8	0
			∑ssj_ops / ∑power =	**5,497**

Figure 4: Benchmark results summary for Dell PowerEdge R720



Hardware	
Hardware Vendor:	Dell Inc.
Model:	PowerEdge R720 (Intel Xeon E5-2660, 2.20 GHz)
Form Factor:	2U
CPU Name:	Intel Xeon E5-2660 2.20 GHz (Intel Turbo Boost Technology up to 3.00 GHz)
CPU Characteristics:	8 core, 2.20 GHz, 20MB L3 Cache
CPU Frequency (MHz):	2200
CPU(s) Enabled:	16 cores, 2 chips, 8 cores/chip
Hardware Threads:	32 (2 / core)
CPU(s) Orderable:	1,2 chips
Primary Cache:	32 KB I + 32 KB D on chip per core
Secondary Cache:	256 KB I+D on chip per core
Tertiary Cache:	20 MB I+D on chip per chip
Other Cache:	None
Memory Amount (GB):	24
# and size of DIMM:	6 x 4096 MB
Memory Details:	4GB 2Rx8 PC3L-10600E-9 ECC; Slots A1-3,B1-3 populated.
Power Supply Quantity and Rating (W):	1 x 750
Power Supply Details:	Dell P/N XYXMG
Disk Drive:	1 x 200GB SATA SSD, Dell P/N 24XV8
Disk Controller:	Integrated PERC S110
# and type of Network Interface Cards (NICs) Installed:	2 x dual-port Broadcom 5720, Dell P/N FM487
NICs Enabled in Firmware / OS / Connected:	4/4/1
Network Speed (Mbit):	1000

Figure 5: Dell PowerEdge R720 hardware configuration

C Material Input Tables

Table 1: Server Weights to SimaPro Equiv. Piece

SimaPro Input Calculation			
Type	**Mass (kg)**	**Calculation**	**SimaPro Equiv. Piece**
SimaPro Computer	11.3	N/A	1
Dell PowerEdge R610	17.69	$\frac{17.69}{11.3} = 1.57$	1.57
Dell PowerEdge R720	28.1	$\frac{28.1}{11.3} = 2.49$	2.49

Table 2: Use Phase Assumptions

Use Phase Assumptions			
	R610 at SRCF	**R610 at Forsythe**	**R720 (Cloud)**
Target load	30%	30%	90%
ssj_ops	1.41E+05	1.41E+05	1.31E+06
Functional Unit of 4-year R610 operation (ssj_ops)	1.78E+13	1.78E+13	1.78E+13
Allocated ratio	100%	100%	10.82%
Power (W)	107	107	199
PUE	1.19	1.52	1.10

D Transportation Input Tables

Table 3: Transportation Choices

Transportation Choices			
	R610 at SRCF	**R610 at Forsythe**	**R720 (Cloud)**
SimaPro Choice	Transport, Single Unit Truck, Diesel-powered, US	Transport, Single Unit Truck, Diesel-powered, US	Freight train, Diesel powered
Start-Finish	Austin, TX - Stanford, CA	Austin, TX - Stanford, CA	Austin, TX - Portland, OR
Distance (miles)	1735	1736	2608
Weight (ton)	0.0177	0.0177	0.0281
Weight (Short ton)	0.016	0.016	0.0255
Short ton-miles	27.838	27.854	66.469

Table 4: Transportation Emission Unit Data

Transportation Emission Unit Data		
Airborne Emissions	**Single Unit Truck 1 Short Ton-Mile**	**Freight Train 1 Short Ton-Mile**
CO_2 Fossil (kg)	2.79E-01	8.48E-02
CO_2 Biogenic (kg)	1.90E-04	6.94E-04
NO_X (kg)	2.01E-03	9.81E-04
SO_X (kg)	3.98E-04	1.57E-04
PM_{10} (kg)	3.97E-05	2.81E-05
Lead (kg)	1.20E-09	5.56E-08
CO Fossil (kg)	1.42E-03	3.99E-04
CO Biogenic (kg)	4.88E-08	1.58E-06

E SimaPro Outputs

F Comparative Study Outputs

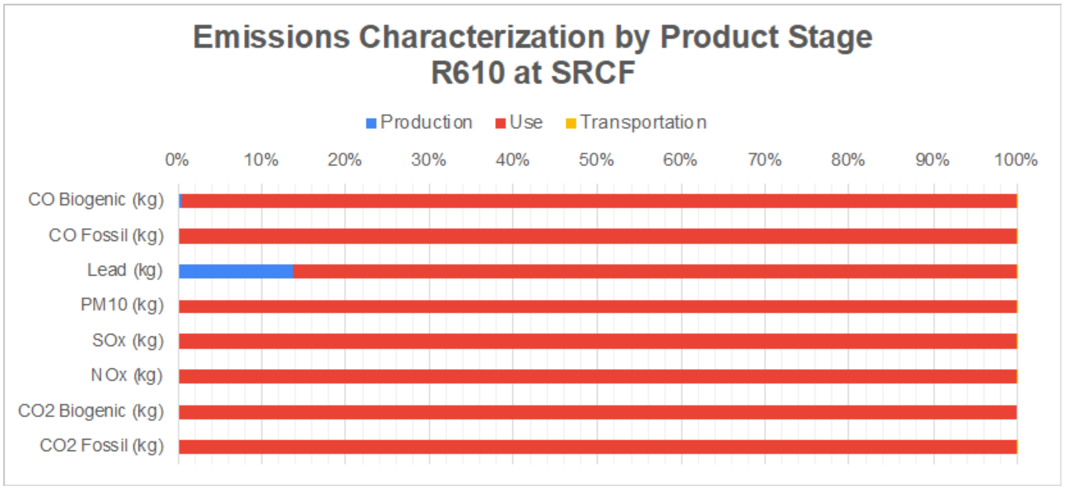


Figure 6: Scenario 1 Emission Characterization

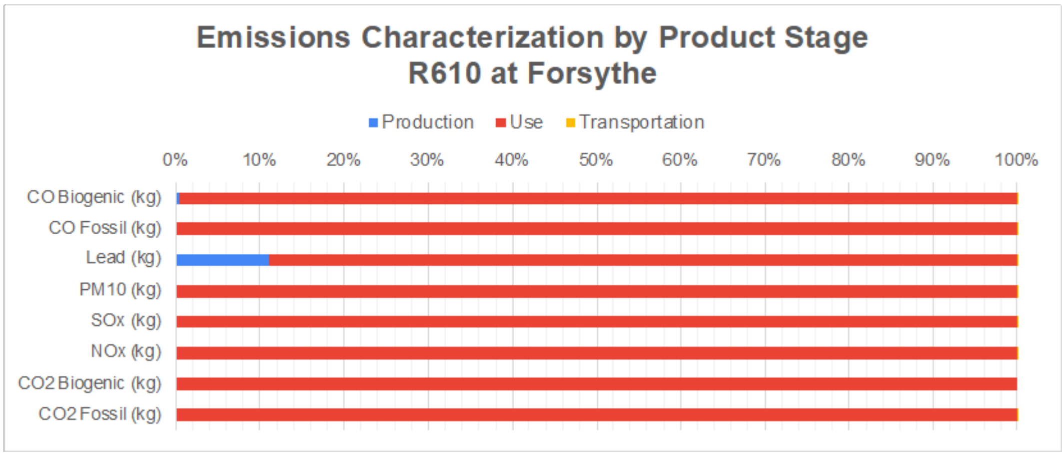


Figure 7: Scenario 2 Emission Characterization

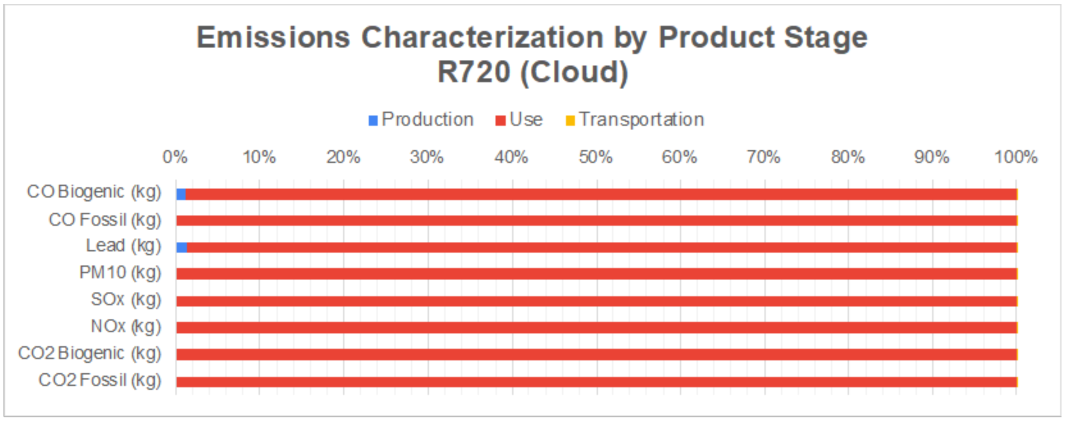


Figure 8: Scenario 3 Emission Characterization

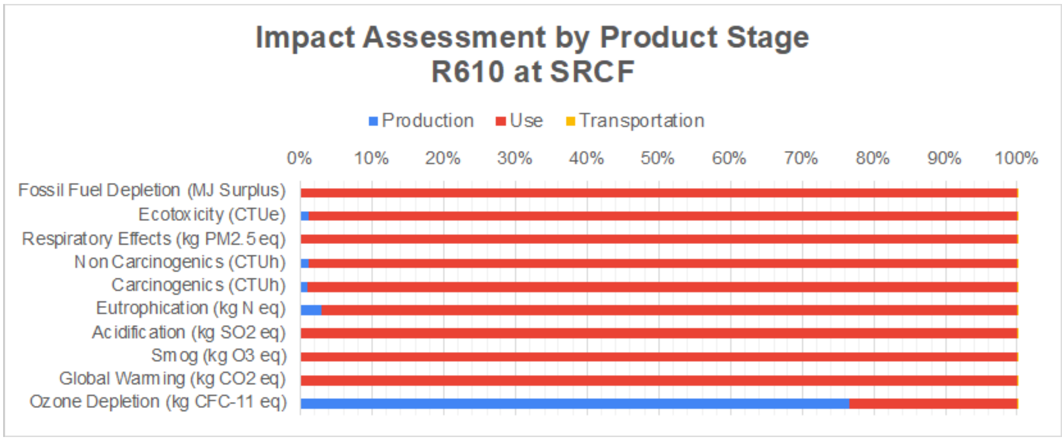


Figure 9: Scenario 1 Impact Assessment

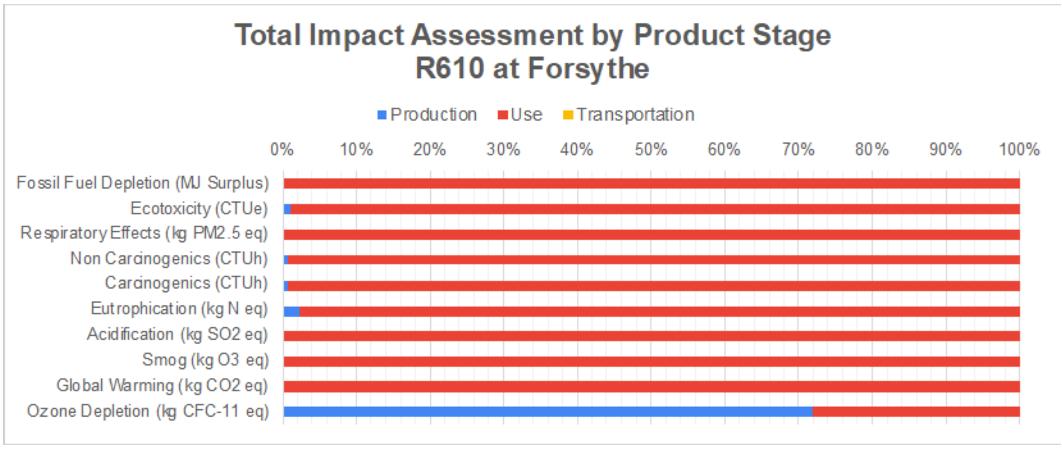


Figure 10: Scenario 2 Impact Assessment

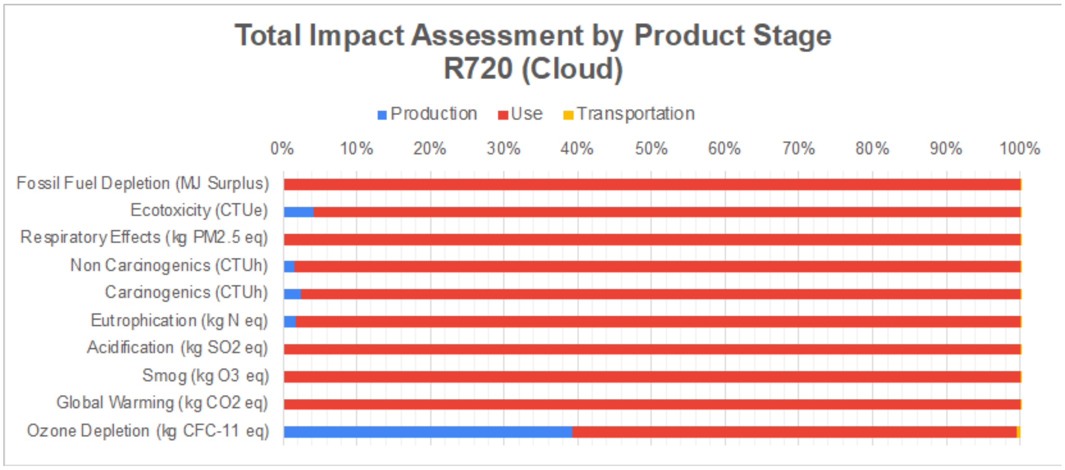


Figure 11: Scenario 3 Impact Assessment

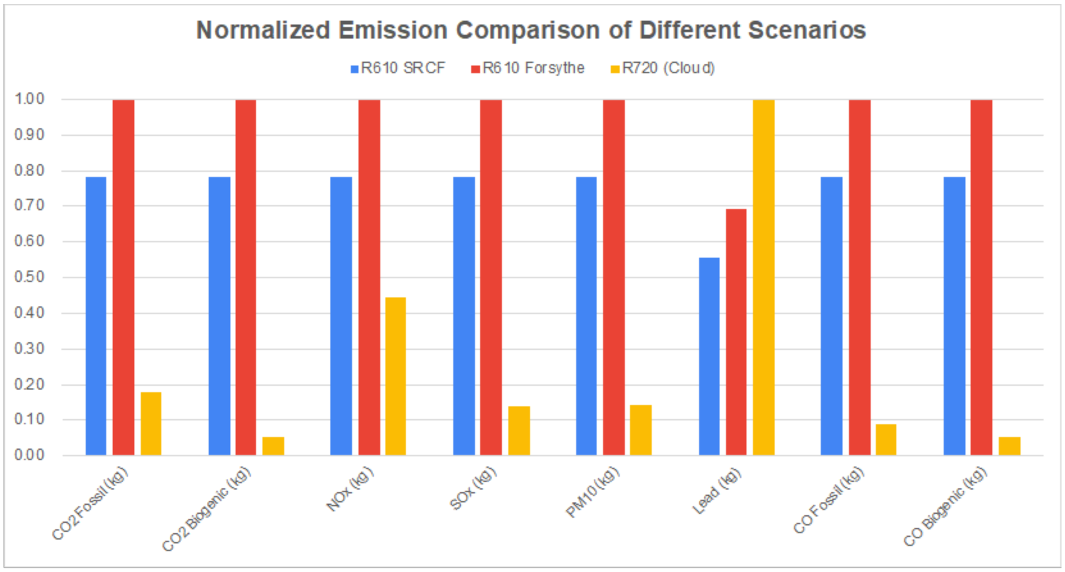


Figure 12: Normalized Emission Comparison of Different Scenarios

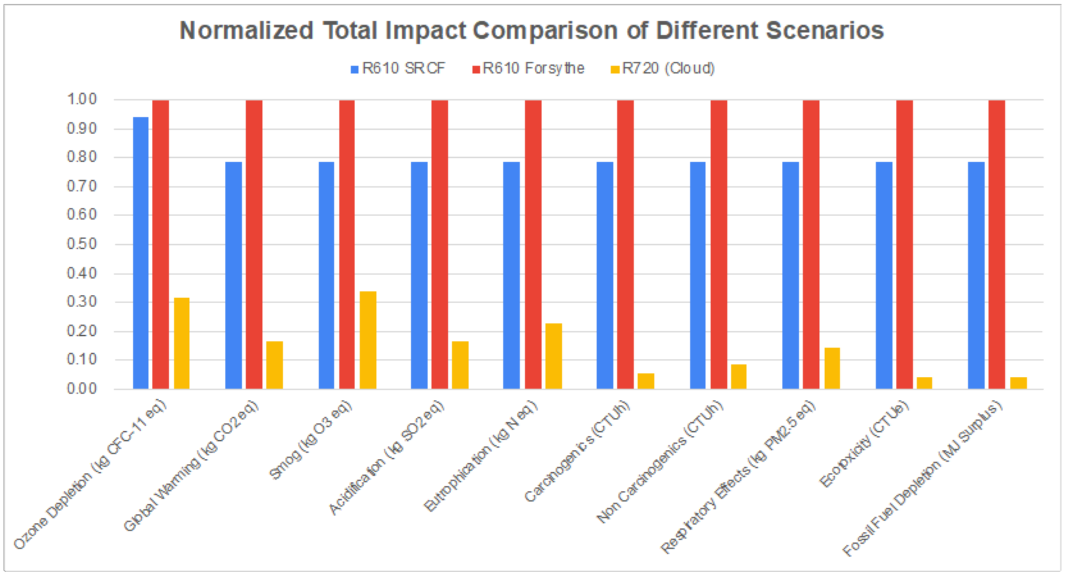


Figure 13: Normalized Impact Comparison of Different Scenarios

Table 5: SimaPro Outputs for Each Scenario's Total Airborne Emissions

Summary of Inventory Analysis			
Airborne Emissions	**R610 at SRCF**	**R610 at Forsythe**	**R720 (Cloud)**
CO_2 Fossil (kg)	1.74E+06	2.22E+06	3.91E+05
CO_2 Biogenic (kg)	5.76E+04	7.35E+04	3.86E+03
NO_X (kg)	1.79E+03	2.28E+03	1.02E+03
SO_X (kg)	1.56E+04	1.99E+04	2.77E+03
PM_{10} (kg)	1.07E+02	1.37E+02	1.99E+01
Lead (kg)	1.70E-02	2.11E-02	3.04E-02
CO Fossil (kg)	1.32E+03	1.69E+03	1.47E+02
CO Biogenic (kg)	4.93E+00	6.29E+00	3.36E-01

Table 6: SimaPro Outputs of Inventory Analysis for Scenario 1

Scenario 1: Inventory Analysis of R610 at SRCF			
Airborne Emissions	**Production**	**Use**	**Transportation**
CO_2 Fossil (kg)	2.88E+02	1.74E+06	7.77E+00
CO_2 Biogenic (kg)	8.97E+00	5.76E+04	5.29E-03
NO_X (kg)	1.08E+00	1.78E+03	5.60E-02
SO_X (kg)	6.84E-04	1.56E+04	1.11E-02
PM_{10} (kg)	1.26E-01	1.07E+02	1.11E-03
Lead (kg)	2.33E-03	1.47E-02	3.34E-08
CO Fossil (kg)	9.12E-01	1.32E+03	3.95E-02
CO Biogenic (kg)	2.41E-02	4.91E+00	1.36E-06

Table 7: SimaPro Outputs of Inventory Analysis for Scenario 2

Scenario 2: Inventory Analysis of R610 at Forsythe			
Airborne Emissions	**Production**	**Use**	**Transportation**
CO_2 Fossil (kg)	2.88E+02	2.22E+06	7.77E+00
CO_2 Biogenic (kg)	8.97E+00	7.35E+04	5.29E-03
NO_X (kg)	1.08E+00	2.28E+03	5.60E-02
SO_X (kg)	6.84E-04	1.99E+04	1.11E-02
PM_{10} (kg)	1.26E-01	1.37E+02	1.11E-03
Lead (kg)	2.33E-03	1.87E-02	3.34E-08
CO Fossil (kg)	9.12E-01	1.69E+03	3.96E-02
CO Biogenic (kg)	2.41E-02	6.27E+00	1.36E-06

Table 8: SimaPro Outputs of Inventory Analysis for Scenario 3

Scenario 3: Inventory Analysis of R720 (Cloud)			
Airborne Emissions	**Production**	**Use**	**Transportation**
CO_2 Fossil (kg)	4.94E+01	3.91E+05	6.10E-01
CO_2 Biogenic (kg)	1.54E+00	3.86E+03	4.99E-03
NO_X (kg)	1.86E-01	1.02E+03	7.06E-03
SO_X (kg)	1.17E-04	2.77E+03	1.13E-03
PM_{10} (kg)	2.17E-02	1.98E+01	2.02E-04
Lead (kg)	4.00E-04	3.00E-02	4.00E-07
CO Fossil (kg)	1.57E-01	1.47E+02	2.87E-03
CO Biogenic (kg)	4.13E-03	3.32E+01	1.14E-05

Table 9: SimaPro Outputs for Each Scenario's Impact Assessment

Summary of Impact Assessment			
Impact Categories	**R610 at SRCF**	**R610 at Forsythe**	**R720 (Cloud)**
Ozone Depletion (kg CFC-11 eq)	3.12E-05	3.32E-05	1.04E-05
Global Warming (kg CO_2 eq)	1.96E+06	2.51E+06	4.14E+05
Smog (kg O_3 eq)	6.16E+04	7.87E+04	2.66E+04
Acidification (kg SO_2 eq)	1.69E+04	2.15E+04	3.58E+03
Eutrophication (kg N eq)	1.75E+02	2.22E+02	5.03E+01
Carcinogenics (CTUh)	8.20E-03	1.05E-02	5.95E-04
Non Carcinogenics (CTUh)	1.07E-01	1.36E-01	1.16E-02
Respiratory Effects (kg $PM_{2.5}$ eq)	9.86E+02	1.26E+03	1.80E+02
Ecotoxicity (CTUe)	2.61E+06	3.32E+06	1.36E+05
Fossil Fuel Depletion (MJ Surplus)	4.46E+06	5.70E+06	2.35E+05

Table 10: SimaPro Outputs of Impact Assessment for Scenario 1

Scenario 1: Impact Assessment of R610 at SRCF			
Impact Categories	**Production**	**Use**	**Transportation**
Ozone Depletion (kg CFC-11 eq)	2.39E-05	7.27E-06	3.09E-10
Global Warming (kg CO_2 eq)	3.17E+02	1.96E+06	8.10E+00
Smog (kg O_3 eq)	2.73E+01	6.16E+04	1.40E+00
Acidification (kg SO_2 eq)	2.76E+00	1.69E+04	5.04E-02
Eutrophication (kg N eq)	5.09E+00	1.70E+02	2.84E-03
Carcinogenics (CTUh)	8.19E-05	8.12E-03	1.11E-07
Non Carcinogenics (CTUh)	1.14E-03	1.06E-01	1.07E-06
Respiratory Effects (kg $PM_{2.5}$ eq)	3.85E-01	9.86E+02	8.99E-04
Ecotoxicity (CTUe)	3.31E+04	2.57E+06	2.06E+01
Fossil Fuel Depletion (MJ Surplus)	2.75E+02	4.46E+06	1.46E+01

Table 11: SimaPro Outputs of Impact Assessment for Scenario 2

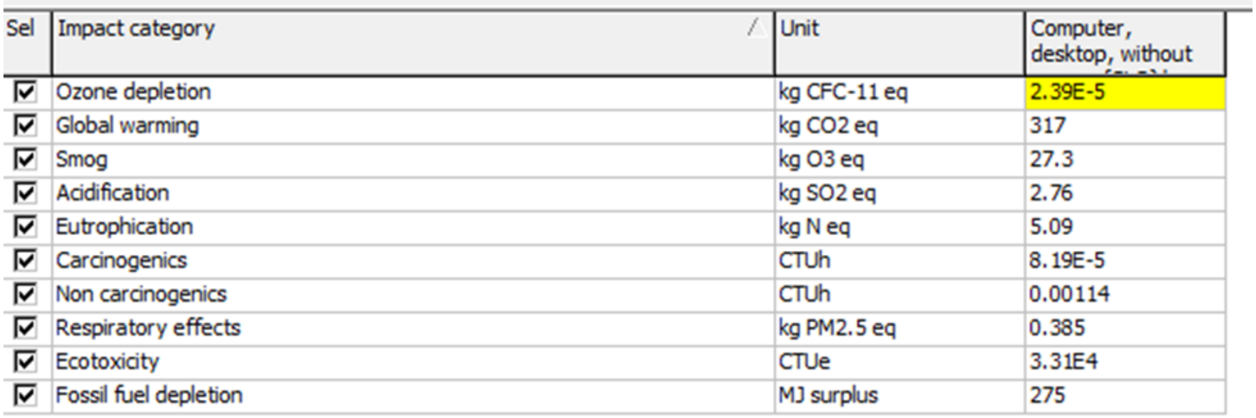
Scenario 2: Impact Assessment of R610 at Forsythe			
Impact Categories	**Production**	**Use**	**Transportation**
Ozone Depletion (kg CFC-11 eq)	2.39E-05	9.29E-06	3.09E-10
Global Warming (kg CO_2 eq)	3.17E+02	2.51E+06	8.11E+00
Smog (kg O_3 eq)	2.73E+01	7.86E+04	1.40E+00
Acidification (kg SO_2 eq)	2.76E+00	2.15E+04	5.04E-02
Eutrophication (kg N eq)	5.09E+00	2.17E+02	2.84E-03
Carcinogenics (CTUh)	8.19E-05	1.04E-02	1.11E-07
Non Carcinogenics (CTUh)	1.14E-03	1.35E-01	1.07E-06
Respiratory Effects (kg $PM_{2.5}$ eq)	3.85E-01	1.26E+03	9.00E-04
Ecotoxicity (CTUe)	3.31E+04	3.29E+06	2.06E+01
Fossil Fuel Depletion (MJ Surplus)	2.75E+02	5.70E+06	1.46E+01

Table 12: SimaPro Outputs of Impact Assessment for Scenario 3

Scenario 3: Impact Assessment of R720 (Cloud)			
Impact Categories	**Production**	**Use**	**Transportation**
Ozone Depletion (kg CFC-11 eq)	4.10E-06	6.30E-06	4.80E-08
Global Warming (kg CO_2 eq)	5.44E+01	4.14E+05	6.42E-01
Smog (kg O_3 eq)	4.67E+00	2.66E+04	1.75E-01
Acidification (kg SO_2 eq)	4.74E-01	3.58E+03	6.13E-03
Eutrophication (kg N eq)	8.74E-01	4.95E+01	1.03E-03
Carcinogenics (CTUh)	1.41E-05	5.81E-04	5.39E-08
Non Carcinogenics (CTUh)	1.95E-04	1.15E-02	1.00E-07
Respiratory Effects (kg $PM_{2.5}$ eq)	6.60E-02	1.80E+02	4.70E-04
Ecotoxicity (CTUe)	5.68E+03	1.30E+05	2.39E+00
Fossil Fuel Depletion (MJ Surplus)	4.72E+01	2.35E+05	1.03E+00

Table 13: Life Cycle Cost Comparison for Three Scenarios

Life Cycle Cost Analysis				
	On-Premise Servers		**Cloud Server**	**Cloud Service**
	SRCF	**Forsythe**	**(R720)**	**(R720 Equivalent)**
Useful Life (Years)	4	4	4	4
Purchase Price ($)	15,828	15,828	17,242	Service Price: $1,220/yr
Interest (%)	4	4	4	4
Installation Cost ($/server)	626	626	626	N/A
Replacement Cost ($/server)	N/A	N/A	N/A	N/A
Salvage Value ($/server)	200	200	218	N/A
Disposal Cost ($/server)	20	20	20	N/A
Energy Cost ($/yr.)	241	188	170	N/A
Maintenance Cost ($/yr.)	900	900	325	N/A
Operating Cost ($/yr.)	115	115	115	N/A
Downtime Cost ($/yr.)	900	900	900	N/A
Total Future Costs ($)	-180	-180	-198	N/A
Present Value of Future Costs ($)	-154	-154	-169	N/A
Total Annual Costs ($)	2,156	2,103	1,510	N/A
Present Value of Annual Costs	7,826	7,634	5,481	N/A
Total Life Cycle Cost in Present Value ($)	24,126	23,934	23,180	4,428
Allocated LCC in Present Value ($)	**24,126**	**23,934**	**2,508**	**4,428**



Sel	Impact category	Unit	Computer, desktop, without
☑	Ozone depletion	kg CFC-11 eq	2.39E-5
☑	Global warming	kg CO2 eq	317
☑	Smog	kg O3 eq	27.3
☑	Acidification	kg SO2 eq	2.76
☑	Eutrophication	kg N eq	5.09
☑	Carcinogenics	CTUh	8.19E-5
☑	Non carcinogenics	CTUh	0.00114
☑	Respiratory effects	kg PM2.5 eq	0.385
☑	Ecotoxicity	CTUe	3.31E4
☑	Fossil fuel depletion	MJ surplus	275

Figure 14: Dell R610 Production Phase TRACI Impact from SimaPro

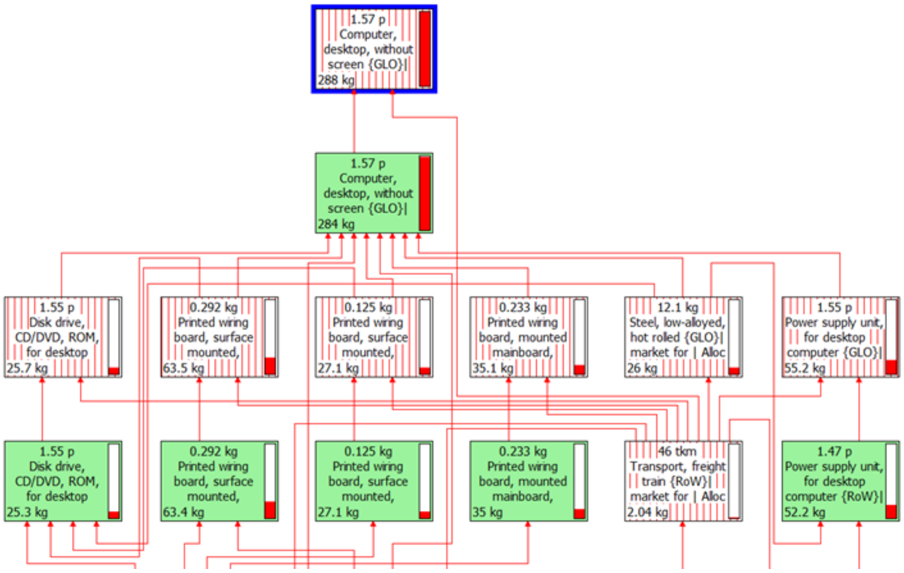


Figure 15: Dell R610 Production Phase CO_2 Fossil Emission from SimaPro

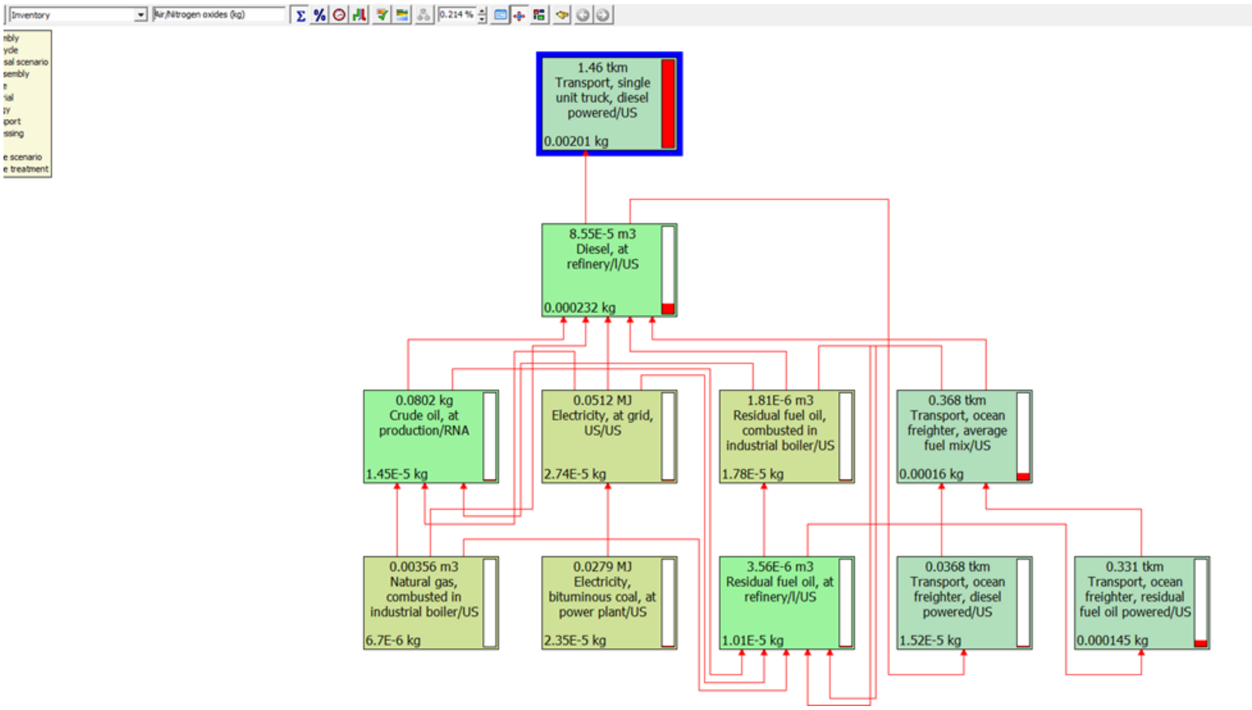
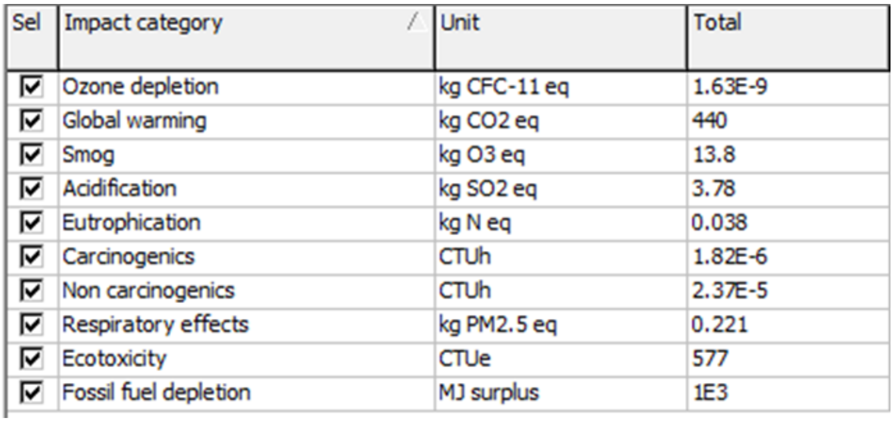


Figure 16: NO_X Emission of 1 Single Unit Truck per Shortton-Mile in Transportation Process



Sel	Impact category	Unit	Total
☑	Ozone depletion	kg CFC-11 eq	1.63E-9
☑	Global warming	kg CO2 eq	440
☑	Smog	kg O3 eq	13.8
☑	Acidification	kg SO2 eq	3.78
☑	Eutrophication	kg N eq	0.038
☑	Carcinogenics	CTUh	1.82E-6
☑	Non carcinogenics	CTUh	2.37E-5
☑	Respiratory effects	kg PM2.5 eq	0.221
☑	Ecotoxicity	CTUe	577
☑	Fossil fuel depletion	MJ surplus	1E3

Figure 17: Traci Impact of CAMX Electricity per 1000 kWh in Use Phase

G Sensitivity Analysis Outputs

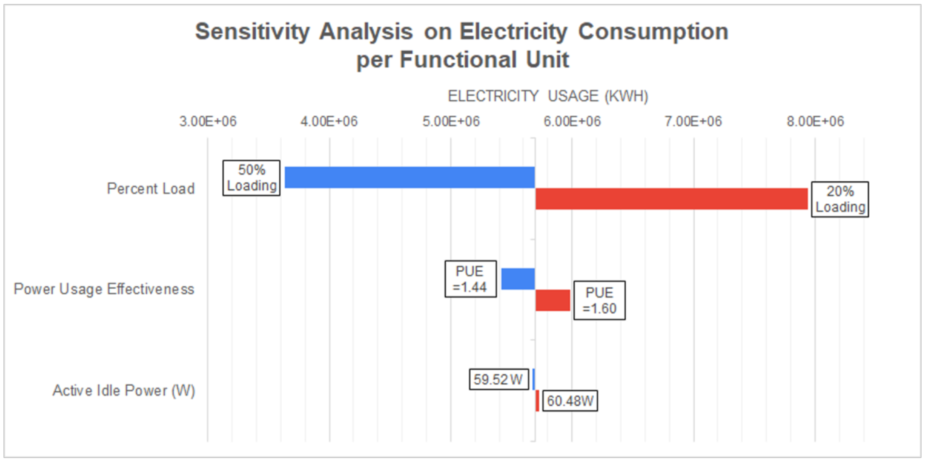


Figure 18: Use Phase Electricity Consumption Sensitivity Analysis Result

Table 14: Use Phase Electricity Consumption Uncertainty Events

Uncertainties Events		
Uncertainties Events	**Low-end**	**High-end**
Percent Load	50% of Maximum Load (Results in less electricity usage for one functional unit)	20% of Maximum Load (Results in more electricity usage for one functional unit)
Power usage effectiveness	5% less than current assumption: $1.52 \times 0.95 = 1.44$	5% more than current assumption: $1.52 \times 1.05 = 1.60$
Active Idle Power (W)	0.8% less than current assumption: $60 \times 0.992 = 59.52$	0.8% more than current assumption: $60 \times 1.008 = 60.48$

Table 15: Use Phase Electricity Consumption Sensitivity Analysis Results

Electricity (kWh)		
Uncertainties Events	**Low-end**	**High-end**
Percent Load	3.63E+06	7.94E+06
Power Usage Effectiveness	5.41E+06	5.98E+06
Active Idle Power (W)	5.67E+06	5.72E+06