Life Cycle Assessment of Dell R740

On behalf of Dell

On behalf of thinkstep AG and its subsidiaries

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List of Acronyms

ANSI	American National Standards Institute
APJ	Asia Pacific including Japan
BGA	Ball Grid Array
BOM	Bill of Materials
CMC	Chassis Management Controller
CML	Centre of Environmental Science at Leiden
CPU	Central Processing Unit
DIMM	Dual Inline Memory Module
DVD	Digital Versatile Disk
ELCD	European Life Cycle Database
EoL	End of Life
EMEA	Europe, Middle East and Africa
EP	Eutrophication Potential
EPEAT	Electronic Product Environmental Assessment Tool
ESSA	Energy Smart Solution Advisor
EU	European Union
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GB	Gigabyte, unit of digital information
GHG	Greenhouse Gas
GWP	Global Warming Potential
IC	Integrated Circuit
ILCD	International Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
IOM	Input/Output Module
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MB	Mainboard / Motherboard

ODD	Optical Disk Drive
PCF	Product Carbon Footprint
PCI	Peripheral Component Interconnect
PERC	PowerEdge RAID Controller
PSU	Power Supply Unit
PWB	Printed Wiring Board
RAID	Redundant Array of Independent Disks
RAM	Random Access Memory
SSD	Solid-State Drive
TEC	Typical Energy Consumption
VOC	Volatile Organic Compound
WEEE	Waste Electrical and Electronic Equipment

Glossary

Life cycle

A view of a product system as “consecutive and interlinked stages … from raw material acquisition or generation from natural resources to final disposal” (ISO 14040:2006, section 3.1). This includes all material and energy inputs as well as emissions to air, land and water.

Life Cycle Assessment (LCA)

“Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO 14040:2006, section 3.2)

Life Cycle Inventory (LCI)

“Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle” (ISO 14040:2006, section 3.3)

Life Cycle Impact Assessment (LCIA)

“Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product” (ISO 14040:2006, section 3.4)

Life cycle interpretation

“Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations” (ISO 14040:2006, section 3.5)

Functional unit

“Quantified performance of a product system for use as a reference unit” (ISO 14040:2006, section 3.20)

Allocation

“Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems” (ISO 14040:2006, section 3.17)

Closed-loop and open-loop allocation of recycled material

“An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.”

“A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials.”

(ISO 14044:2006, section 4.3.4.3.3)

Foreground system

“Those processes of the system that are specific to it … and/or directly affected by decisions analysed in the study.” (JRC, 2010, p. 97) This typically includes first-tier suppliers, the manufacturer itself and any downstream life cycle stages where the manufacturer can exert significant influence. As a general rule, specific (primary) data should be used for the foreground system.

Background system

“Those processes, where due to the averaging effect across the suppliers, a homogenous market with average (or equivalent, generic data) can be assumed to appropriately represent the respective process … and/or those processes that are operated as part of the system but that are not under direct control or decisive influence of the producer of the good….” (JRC, 2010, pp. 97-98) As a general rule, secondary data are appropriate for the background system, particularly where primary data are difficult to collect.

Critical Review

“Process intended to ensure consistency between a life cycle assessment and the principles and requirements of the International Standards on life cycle assessment” (ISO 14044:2006, section 3.45).

Executive Summary

In order to meet EPEAT standard regulations and to understand how life cycle assessment (LCA) can be used to support the development and reporting of environmentally sustainable products, Dell commissioned thinkstep to carry out an LCA on the Dell PowerEdge R740 server. Goals for this ISO 14040/14044 compliant study include:

- Life Cycle Assessment (LCA) of a Dell R740 server across its full life cycle;
- Determine environmental hotspots over the product's life cycle with specific focus on material/part/product manufacturing and use;
- Generate results to answer customer enquiries;
- Gain public relations/marketing advantage by communicating results (online/offline) in white papers, sustainability reports, customer communications, and conferences;
- Meet the EPEAT standard regulations.

System boundaries of the study are from cradle-to-grave, accounting for all life cycle activities from extraction of raw materials and energy sources from the environment through to disposal and recycling of products at end of life. The functional unit used in the assessment, which can serve as the basis for comparisons to similar products, is the provision of computing services capable of handling very demanding workloads and applications, such as data warehouses, ecommerce, AI/Machine Learning, and high-performance computing (HPC) for four years for four years with the following load profile:

- 100% load mode: 10% of the time
- 50% load mode: 35% of the time
- 10% load mode: 30% of the time
- Idle mode: 25% of the time

The reference flow is one (1) Dell PowerEdge R740 server, including its power supply and packaging.

The Dell PowerEdge R740 is 2U, 2-socket platform and was evaluated with the following typical market configuration: 2x Intel Xeon 140W CPUs, 12x 32GB DIMMs, 1x 400GB SSD, 8x 3.84TB SDDs, and 2x 1100W PSUs. The Dell R740 with the given configuration weighs around 29.5 kg including packaging and the data was collected by using a combination of dimensioned photographs and a physical product teardown.

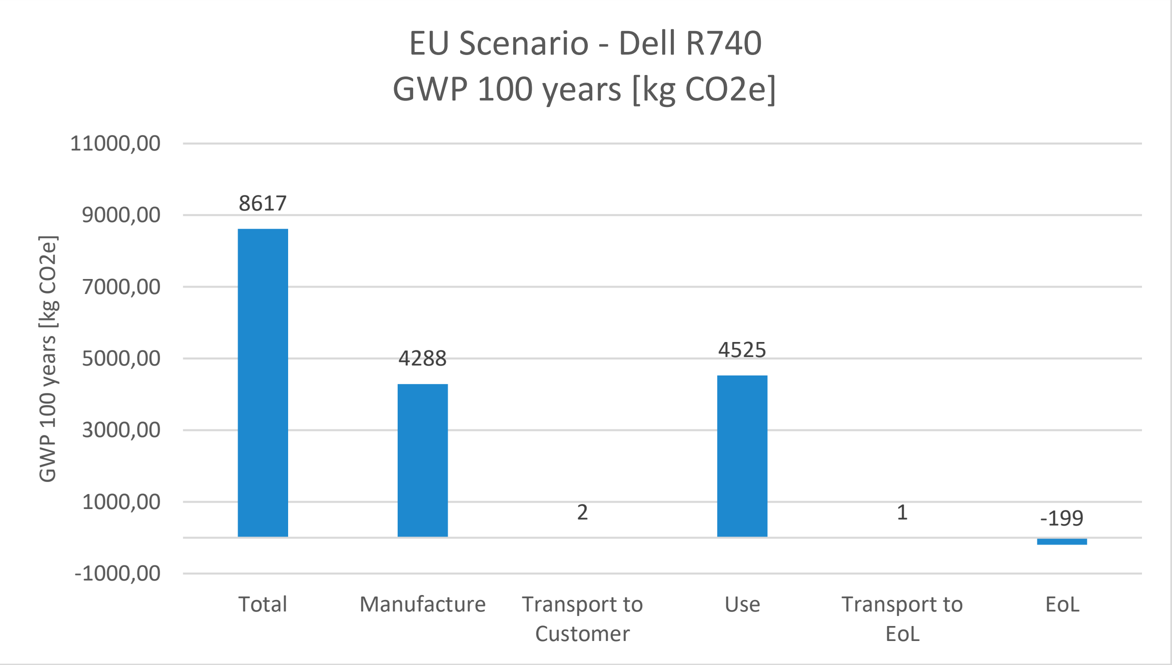
The intended time reference for the study is the 2017 calendar year and the geographical coverage considers both an EU and US in two scenarios.

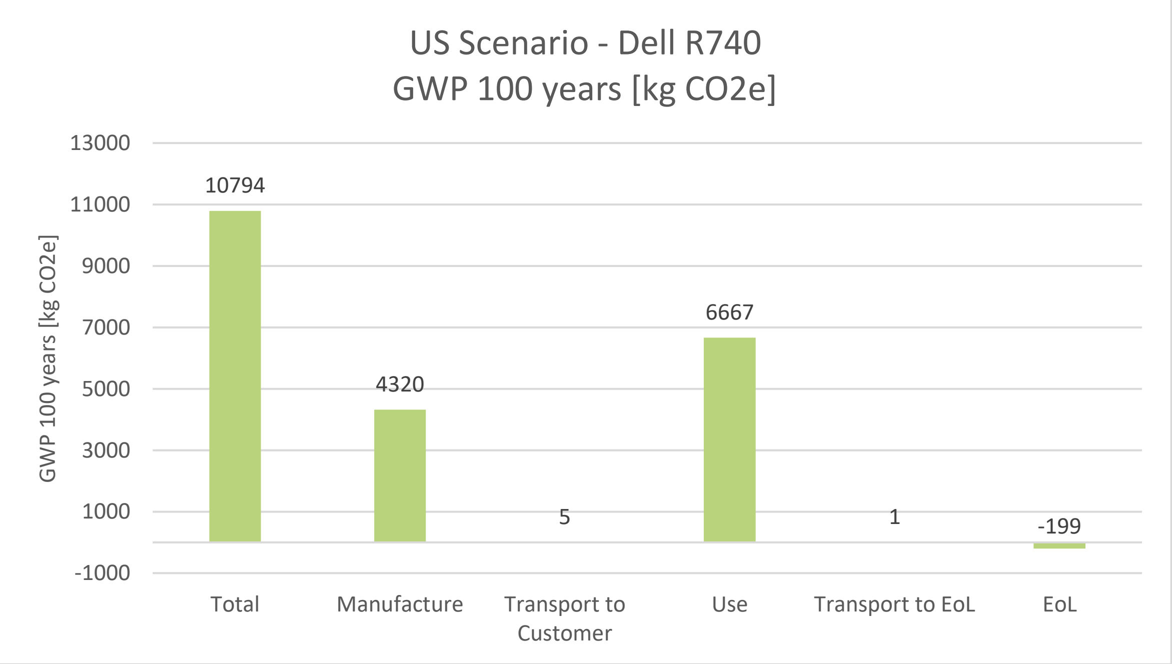
The following table summarizes the results of the study for all considered impact categories.

Impact Category	EU Scenario	US Scenario
Abiotic Depletion [MJ]	9,66E+04	1,30E+05
Acidification Potential [kg SO2 eq.]	3,01E+01	3,88E+01
Eutrophication Potential [kg Phosphate eq.]	2,43E+00	2,37E+00

Ozone Layer Depletion Potential [kg R11 eq.]	5,74E-08	4,67E-08
Photochem. Ozone Creation Potential [kg Ethene eq.]	1,96E+00	2,43E+00
Global Warming Potential 100 years incl. biogenic carbon [kg CO2 eq.]	8,62E+03	1,08E+04

As the overall conclusions remain valid also for the other impact categories and GWP is considered the most robust and widely used impact category, the following diagrams shows the results for GWP over all life cycle phases for the EU and US scenario.





Analysis results indicate that the major fraction of the impact – approximately 98% in both the EU and the US – derives from the manufacturing and the use phase of the Dell R740. The transport to end of life has a less relevant contribution in both cases and the end of life credits contribute to a reduction of about 2.3% and 1.8% of the life cycle impacts respectively. Overall, the US scenario has approximately 25% higher impact than the European one, due to the differences in the electricity grid mix and fuel used, as well as distances travelled

The majority of the part production impacts during manufacturing are from the components containing electronics, which account for only 30% of the total mass of the Dell R740, and especially the 400GB and 3.84TB SSDs. The biggest contribution of the SSDs comes from the NAND flash, for which several assumptions were made regarding package dimensions, die/package ratio and die stack per package to model these chips. Since the data for these parameters are based on the part number of the chips and publicly available data from Samsung (Gibb, 2016) (PC Watch, 2016), a scenario was calculated that considers different die/package ratios as this parameter is considered to be of the highest uncertainty and impact. The scenarios assume two different die/package ratios of 30% and 80% in addition to the default 60%. Results show that the overall manufacturing impacts of the Dell R740 are reduced by almost 40% if a die/package ratio of 30% is assumed for the nine SSDs built in.

Overall, the results of the present study exemplify that the configuration of a server can have a high impact on the environmental results within its lifetime. This leads to the recommendation to a) increase the data quality of considered components, by e.g. having access to BOMs and b) focus more on the manufacturing part of products and hence more on the supply chain of those components. Looking at this issue from a (post-)consumer perspective, the reuse (or refurbishment) of used SSDs from servers could potentially extend their designated lifetime. This would require an appropriate take-back system (if reused externally after use by the first customer) or an appropriate data erasure system (if reused internally).

1. Goal of the Study

This study was commissioned by Dell Technologies Inc. with the following main goals:

- Life Cycle Assessment (LCA) of a Dell R740 server across its full life cycle;
- Determine environmental hotspots over the product's life cycle with specific focus on material/part/product manufacturing and use;
- Generate results to answer customer enquiries;
- Gain public relations/marketing advantage by communicating results (online/offline) in white papers, sustainability reports, customer communications, and conferences; and
- Meet the EPEAT standard regulations.

This study meets the requirements of the international standards for Life Cycle Assessment (LCA) according to ISO 14040 (ISO, 2006) / ISO 14044 (ISO, 2006).

2. Scope of the Study

2.1. Product System(s)

The Dell PowerEdge R740 is a server that integrates accelerator cards, storage and computational resources in a 2U, 2-socket platform (i.e. 2 rack units). This study relates to the PowerEdge R740 with the following configuration: 2x Intel Xeon 140W CPUs, 12x 32GB DIMMs, 1x 400GB SSD, 8x 3.84TB SDDs, and 2x 1100W PSUs. This configuration is a typical configuration according to Dell sales and marketing figures and thus representative for this product category.

2.2. Product Functional Unit

The functional unit is 1 piece of general purpose rack server equipment and its provision of computing services capable of handling very demanding workloads and applications, such as data warehouses, ecommerce, AI/Machine Learning, and high-performance computing (HPC) for four years with the load profile specified in section 3.2.4. The target system under investigation is the Dell PowerEdge R740.

2.3. System Boundaries

The system boundary is defined in Table 2-1.

Table 2-1: System boundaries

Included	Excluded
✓ Extraction of raw materials ✓ Manufacture of parts ✓ Transport to assembly ✓ Assembly ✓ Transport to customers ✓ Use stage ✓ Transport to recycling ✓ End of life (disposal/recycling)	× Production of capital equipment (factories, tooling, etc.) × Employee travel / commuting × Additional air conditioning requirements × Network infrastructure outside of the product itself × Refurbishment/Reuse of parts

2.3.1. Time Coverage

The intended time reference for the study is the 2017 calendar year, which corresponds to the data provided for the assembly and recycling. Data collected from Dell relate to this year.

2.3.2. Technology Coverage

This study assesses the cradle-to-grave impacts of the product based on a global production and technology mix. Primary production data was gathered from Dell and its partners and included the physical product for disassembly, additional data on usage, recycling and transport, as well as data on additional configuration that was not part of the physical product received, e.g. additional solid-state drives and network cards.

2.3.3. Geographical Coverage

The geographical coverage of this study considers the following conditions:

The product is assembled in Lodz, Poland (representative for Dell server production in Europe). The components are mainly sourced from China. The use phase considers a European electricity grid mix (EU-28) and the recycling of the product takes place in Europe. A scenario that considers assembly in Mexico and use and recycling in the USA has also been considered as part of this report.

2.4. Allocation

2.4.1. Multi-output Allocation

There are no significant multi-output processes within the foreground system. As a result, all impacts from the foreground system are fully allocated to the product under study.

Allocation of background data (energy and materials) taken from the GaBi 2018 databases is documented online at http://www.gabi-software.com/support/gabi/gabi-database-2018-lci-documentation/.

2.4.2. End-of-Life Allocation

End-of-Life allocation generally follows the requirements of ISO 14044, section 4.3.4.3.

Material recycling (substitution approach): Open scrap inputs from the production stage are subtracted from scrap to be recycled at end of life to give the net scrap output from the product life cycle. This remaining net scrap is sent to material recycling. The original burden of the primary material input is allocated between the current and subsequent life cycle using the mass of recovered secondary material to scale the substituted primary material, i.e., applying a credit for the substitution of primary material so as to distribute burdens appropriately among the different product life cycles. These subsequent process steps are modelled using industry average inventories.

Energy recovery (substitution approach): In cases where materials are sent to waste incineration, they are linked to an inventory that accounts for waste composition and heating value as well as for regional efficiencies and heat-to-power output ratios. Credits are assigned for power and heat outputs using the regional grid mix and thermal energy from natural gas. The latter represents the cleanest fossil fuel and therefore results in a conservative estimate of the avoided burden.

Landfilling (substitution approach): In cases where materials are sent to landfills, they are linked to an inventory that accounts for waste composition, regional leakage rates, landfill gas capture as well as utilisation rates (flaring vs. power production). A credit is assigned for power output using the regional grid mix.

2.5. Cut-off Criteria

No cut-off criteria are defined for the product sample and data provided for this study. All available energy and material flow data have been included in the model. In cases where no matching life cycle inventories are available to represent a flow, proxy data have been applied based on conservative assumptions regarding environmental impacts.

Some data for upstream production chains, e.g. the packaging of electronic components that are populated onto the PWBs (tape-and-reel packaging), were not considered in this study due to a lack of available data and a high probability of very low environmental relevance.

2.6. Selection of LCIA Methodology and Impact Categories

The impact assessment categories and other metrics considered to be of high relevance to the goals of the project are shown in Table 2-2. Various impact assessment methodologies are applicable for use in the European context including e.g. CML, ReCiPe, and selected methods recommended by the ILCD. This assessment is predominantly based on the CML impact assessment methodology framework (CML 2001 update January 2016). CML characterisation factors are applicable to the European context, are widely used and respected within the LCA community, and required for Environmental Product Declarations under EN 15804.

Global warming potential and non-renewable primary energy demand (represented by ADP fossil) were chosen because of their relevance to climate change and energy efficiency, both of which are strongly interlinked, of high public and institutional interest, and deemed to be the most pressing environmental issues of our time. The global warming potential impact category is assessed based on the current IPCC characterisation factors taken from the 5th Assessment Report (IPCC, 2013) for a 100-year timeframe (GWP100) as this is currently the most commonly used metric.

The global warming potential results include the photosynthetically bound carbon (also called *biogenic carbon*) as well as the release of that carbon during the use or end-of-life phase as CO_2 and/or CH_4.

Eutrophication, acidification, and photochemical ozone creation potentials were chosen because they are closely connected to air, soil, and water quality and capture the environmental burdens associated with commonly regulated emissions such as NO_x, SO_2, VOC, and others.

Ozone depletion potential was chosen because of its high political relevance, which eventually led to the worldwide ban of more active ozone-depleting substances; the phase-out of less active substances is due to be completed by 2030. Current exceptions to this ban include the application of ozone depleting chemicals in nuclear fuel production. The indicator is therefore included for reasons of completeness; however, the few identifiable values in the background data do not necessarily reflect important considerations for the product under study.

Table 2-2: Impact category descriptions

Impact Category	Description	Unit	Reference
Global Warming Potential (GWP100)	A measure of greenhouse gas emissions, such as CO_2 and methane. These emissions are causing an increase in the	kg CO_2 equivalent	(IPCC, 2013)

	absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.		
Abiotic Resource Depletion (ADP fossil)	The consumption of non-renewable resources leads to a decrease in the future availability of the functions supplied by these resources. Depletion of non-renewable energy resources are reported separately.	MJ (net calorific value)	(van Oers, de Koning, Guinée, & Huppes, 2002)
Eutrophication Potential	Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.	kg PO_4^{3-} equivalent	(Guinée, et al., 2002)
Acidification Potential	A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H^+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials.	kg SO_2 equivalent	(Guinée, et al., 2002)
Photochemical Ozone Creation Potential (POCP)	A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone O_3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems and may also damage crops.	kg C_2H_4 equivalent	(Guinée, et al., 2002)
Ozone Depletion Potential (ODP)	A measure of air emissions that contribute to the depletion of the stratospheric ozone layer. Depletion of the ozone leads to higher levels of UVB ultraviolet rays reaching the	kg CFC-11 equivalent	(Guinée, et al., 2002)

	earth’s surface with detrimental effects on humans and plants.

It shall be noted that the above impact categories represent impact *potentials*, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) actually follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the functional unit (relative approach). LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

The selected impact categories fit the requirement of NSF/ANSI 426 – 2017 (NSF, 2017).

2.7. Interpretation to Be Used

The results of the LCI and LCIA were interpreted according to this Goal and Scope. The interpretation addresses the following topics:

- Identification of significant findings, such as the main process step(s), material(s), and/or emission(s) contributing to the overall results.
- Evaluation of completeness, sensitivity, and consistency to justify the exclusion of data from the system boundaries as well as the use of proxy data.
- Conclusions, limitations and recommendations.

2.8. Data Quality Requirements

The data used to create the inventory model shall be as precise, complete, consistent, and representative as possible with regards to the goal and scope of the study under given time and budget constraints.

- Measured primary data are considered to be of the highest precision, followed by calculated data, literature data, and estimated data.
- Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. The goal is to capture all relevant data in this regard.
- Consistency refers to modelling choices and data sources. The goal is to ensure that differences in results reflect actual differences between product systems and are not due to inconsistencies in modelling choices, data sources, emission factors, or other artefacts.
- Reproducibility expresses the degree to which third parties would be able to reproduce the results of the study based on the information contained in this report.
- Representativeness expresses the degree to which the data matches the geographical, temporal, and technological requirements defined in the study’s goal and scope.

An evaluation of the data quality with regard to these requirements is provided in Chapter 5 of this report.

2.9. Software and Database

The LCA model was created using the GaBi 8 Software system for life cycle engineering, developed by thinkstep AG. The GaBi 2018 LCI database provides the life cycle inventory data for the raw and process materials obtained from the background system.

2.10. Critical Review

A critical review according to ISO 14044, section 6.2 was performed by Colin Fitzpatrick, Department of Electronics and Computer Engineering, University of Limerick. The Critical Review Statement can be found in Annex D: .

3. Life Cycle Inventory Analysis

3.1. Data Collection Procedure

Primary data for the material content of the product were collected using a combination of dimensioned photographs and a physical product teardown, as no Bill of Materials (BOM) could be provided by Dell. During the product teardown, parts and materials were identified, weighed and measured. During photograph mapping, the same procedure was applied to high-resolution photos with a dimension reference, together with component datasheets and supporting information (see as an example Figure 3-1). The teardown was conducted on a mass-production version of the product provided by Dell.

Data on distribution, product use and end of life were collected and discussed though online communication and in regular project meetings.

If gaps, outliers, or other inconsistencies were found, thinkstep engaged with the Dell to resolve any open issues.

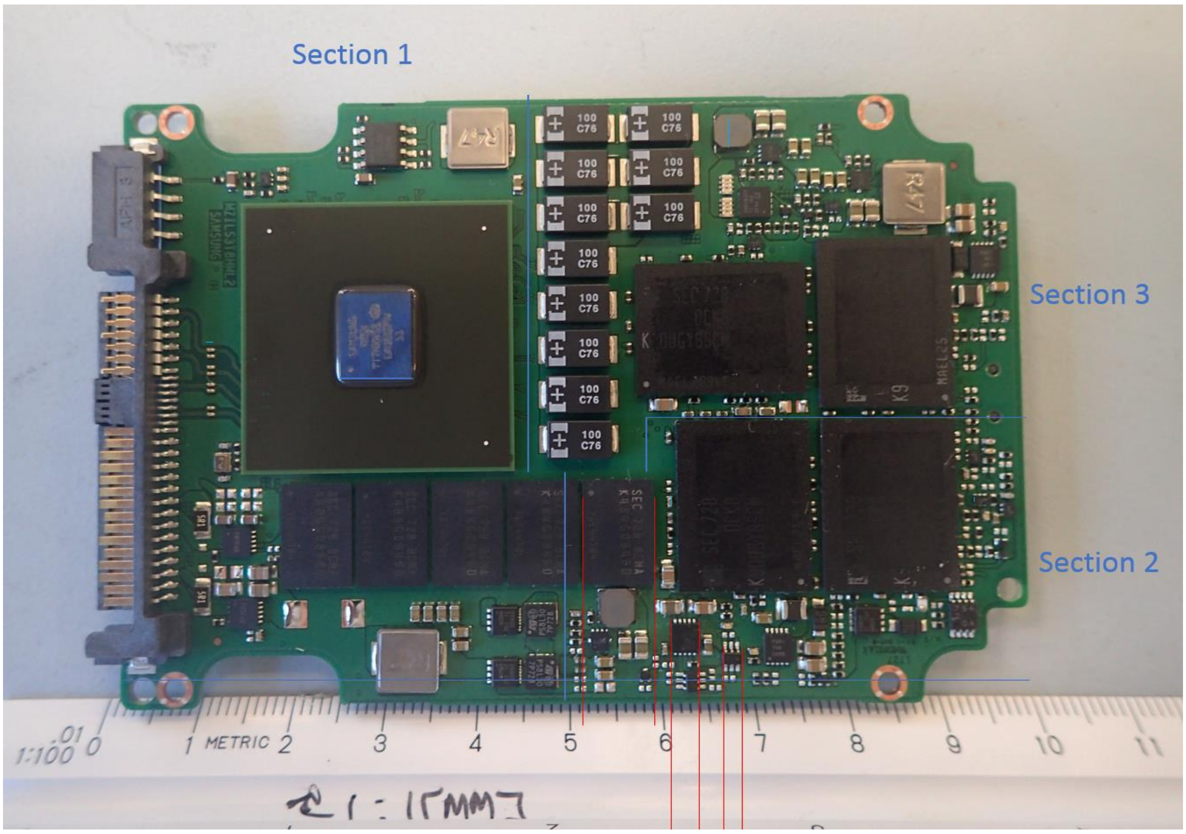


Figure 3-1: Example of component mapping from dimensioned photographs

3.2. Product System

3.2.1. Product Composition

Table 3-1 presents the main components of the product system considered in this study: the Dell R740.

Table 3-1: Part composition of the product system

Component	Weight (kg)
Chassis	11.50
SSDs	1.20
Motherboard, incl. CPU	2.65
PWB – mixed boards	2.43
PSU	2.99
Fans, incl. case	1.59
Packaging	7.11
Total weight	29.47

Table 3-2: Dell R740 main components data overview

Main components		Dell R740	Comments / Assumptions
Chassis	% of total server wt.	39,02%	calculated, including packaging
	weight (kg)	11.496	disassembled and weighted
Solid State Drives 400GB	units	1	data provided by Dell
	weight (kg)	0.132	data provided by Dell, estimated with pictures
Solid State Drives 3.84 TB	units	8	data provided by Dell
	weight (kg)	1.068	data provided by Dell, estimated with pictures
PWB - Mainboard (MB)	area (cm2)	1924.7	measured
	weight (kg)	2.649	weighed, incl. CPU, frame, heatsink
PWB - Mixed boards	area (cm2)	1452.1	measured with actual component or estimated with photos provided by Dell
	weight (kg)	2.434	data provided by Dell
PSU	units	2	counted
	weight (kg)	2.992	weighed
Fans	units	6	counted
	weight (kg)	1.590	weighed, including case
Packaging	units	1	measured
	weight (kg)	7.105	weighed
	TOTAL WEIGHT (kg)	**29.466**	

3.2.2. Manufacturing

Final assembly occurs in Poland. Components are largely sourced from East Asia. These components are described in more detail within this section.

Solid State Drives

Due to their number, capacity and complexity, the SSDs are separately listed in Table 3-3 below.

Table 3-3: Dell R740 SSD configuration and significant components

SSD	Area (mm2)	Pieces	Comments / Assumptions
SSD 3.84TB		8	
Memory Chip (DRAM)	85.42	5	per SSD
Memory Chip (Flash)	257.18	8	per SSD
SSD 400GB		1	
Memory Chip (DRAM)	85.42	5	per SSD
Memory Chip (Flash)	257.18	8	per SSD

Given their high capacity, the following table shows the parameter and assumptions taken for the NAND Flash of the 3.84TB SSDs

Table 3-4: 3.84TB SSD NAND Flash Parameter and Assumptions

	3.8 TB SSD - NAND Flash
Package dimension (mm x mm)	14 x 18.3
Die / package ratio	60%
Die stack per package	16
Chips per SSD	8
Total die area per chip (mm2)	2460
Total die area per SSD (mm2)	19676
Part number	K9DUGY8SCM

For the smaller printed wiring boards, e.g. RAM, riser cards or ethernet cards, either the physical component was evaluated via product teardown or high-resolution photographs were provided by Dell.

PWB Mixed

Table 3-5: Dell R740 printed wiring boards (mixed)

PWB Mixed	Area (cm2)	Pieces	Comments / Assumptions
RAM (32GB)	40.2	12	estimated via pictures and data provided by Dell
Riser card 1	114.3	1	measured, teardown
Riser card 2	127.5	1	measured, teardown
Riser card 3	117.3	1	measured, teardown
Ethernet card	102.3	1	measured, teardown
HDD Controller	107.0	1	measured, teardown
Q-logic	111.4	2	estimated via pictures and data provided by Dell
Intel Ethernet X710	178.2	1	estimated via pictures and data provided by Dell
Total Mixed PWBs	**1452.1**		

CPU

Two Intel Xeon Gold 6152 CPUs were included in the Dell R740. The CPU and all other active and passive electronic components were evaluated with the above described teardown and visual inspection method.

Table 3-6: Dell R740 CPU, heatsink and frame

Electro-mechanic components	Weight (g)	Pieces
CPU	107.2	2
Heatsink	330	2
Plastic mount	7.78	2
Thermal paste	0.7	2
CPU socket on mainboard		2
Stainless Steel	194.8	
Plastic	1.3	
Total weight (2 CPUs)	**1284**	

Table 3-7: Dell R740 CPU Details

CPU	Substrate (mm x mm)	Die (mm x mm)	Die area (mm2)	Tech node	Technology
Intel® Xeon® Gold 6152 2.1G,22C/44T,10.4GT/s 2UPI,30M Cache, Turbo, HT (140W)	**76 x 57**	**32 x 22**	**698**	**32nm**	**CMOS**

Packaging

Table 3-8: Dell R740 packaging

Packaging	Weight (kg)
Corrugated board	5.67
Expanded polyethylene	1.44
Total weight	**7.11**

The source of origin for all components is listed in Table 3-9.

Table 3-9: Source and production location of components

Component	Source
Chassis	Liteon - China
Fan	Liteon - China
Packaging	WWT, Expeditors, Ichain – Regional (US, EMEA, APJ)
Cables	3M, Avnet, Luxshare, Amphenol - China
HDD	Leveraged - China
ODD	Leveraged - China
SSD	Leveraged - China
Mainboard (incl. RAM, CPU)	IEC – China
Power Supply Unit	Delta, Lite On, Emerson, Artesyn, Flex - China

3.2.3. Distribution

Transport to customer in the United States and in Europe was included. It is assumed that Dell R740 produced in Europe supply customers in Europe and Dell R740 produced in Mexico supply customers in the US. Therefore:

- Transport to customer in Europe:
  - 100% truck transport from Poland to customer in Europe (1,200 km)
- Transport from Mexico assembly site to the hub location for finished goods in El Paso, US:
  - 10 % air transport (1,500 km)
  - 90% truck transport (1,200 km)

3.2.4. Use

For this study, the following four working modes were defined for the use stage:

- 100% load mode: full work mode when server is executing tasks with CPU loading of 100%
- 50% load mode
- 10% load mode
- Idle mode: state in which the server is not asleep but there is no application running

The power consumption at the 100%, 50%, 10% and idle load modes was provided by Dell for the typical configuration that is evaluated in this study and separately for light-medium and heavy workload. The light-medium workload is considered in this study as the baseline for evaluation, whereas the heavy workload is included as a scenario.

Dell provided the percentage of time at each load mode with light-medium workload as follows:

- 100% load mode: 10%
- 50% load mode: 35%
- 10% load mode: 30%
- Idle mode: 25%

It is assumed that the server is connected to the electricity supply 24 hours a day and 365 days of the year. Table 3-10 illustrates the different use phase parameters for the scenarios considered in the study.

The Typical Energy Consumption (E_{TEC}) formula represents annual energy consumption in kWh:

$$E_{TEC} = \frac{365}{1000} \times (P_x \times T_x)$$

In the above equation:

- P_x: power consumption in the various modes (W);
- T_x: ratio of time spent in the various modes (h).

Table 3-10: Use phase scenarios for the Dell R740 (light-medium workload)

	100% Load Mode	50% Load Mode	10% Load Mode	Idle Mode
T (h)	2.4	8.4	7.2	6
P (W)	510	369	261	201
Lifespan (yr)	4	4	4	4
Power (kWh/yr)	447	1131	686	440

As a sensitivity check, an additional heavy workload with the following parameters was considered (see Table 3-11):

- 100% load mode: 15%
- 50% load mode: 55%
- 10% load mode: 20%
- Idle mode: 10%

Table 3-11: Use phase scenarios for the Dell R740 (heavy workload)

	100% Load Mode	50% Load Mode	10% Load Mode	Idle Mode
T (r)	3.6	13.2	4.8	2.4
P (W)	510	369	261	201
Lifespan (yr)	4	4	4	4
Power (kWh/yr)	670	1778	457	176

3.2.5. End of Life

Assumptions for the End of Life (EoL) follow the primary data that was collected by Dell and the recycling contractor Wisetek.

Based on this primary data, weighted averages were calculated for the following materials:

Material	Recycling rate [%]	Energy recovery [%]	Landfill [%]
Electronics	82,32	0	17,68
Aluminium	100	0	0
Steel	100	0	0
Plastic	0	0	100
Paper Packaging	0	100	0
Plastic Packaging	0	100	0

The distance to EoL is 680 km. This value is the average distance from seven primary locations to one of the biggest recyclers for servers in Europe

3.3. Background Data

3.3.1. Fuels and Energy

National and regional averages for fuel inputs and electricity grid mixes were obtained from the GaBi 2018 databases. Table 3-12 shows the most relevant LCI datasets used in modelling the product systems. Electricity consumption was modelled using national and regional grid mixes that account for imports from neighbouring countries and regions.

Documentation for all GaBi datasets can be found at http://www.gabi-software.com/support/gabi/gabi-database-2018-lci-documentation/.

Table 3-12: Key energy datasets used in inventory analysis

Energy	Location	Dataset	Data Provider	Reference Year	Proxy?
Electricity	EU-28	EU-28: Electricity grid mix	thinkstep	2014	No
Electricity	US	US: Electricity grid mix	thinkstep	2014	No

3.3.2. Raw Materials and Processes

Data for upstream and downstream raw materials and unit processes were obtained from the GaBi 2018 database. Documentation for all GaBi datasets can be found at http://www.gabi-software.com/support/gabi/gabi-database-2018-lci-documentation/.

3.3.3. Transportation

Average transportation distances and modes of transport are included for the transport of the raw materials, operating materials, and auxiliary materials to production and assembly facilities (e.g. Table 3-13).

The GaBi 2018 database was used to model transportation. Truck transportation was modelled using GaBi global truck transportation datasets.

A list of all datasets can be found in Annex C:

3.4. Life Cycle Inventory

As shown in Figure 3-2, the GaBi LCI model consists of three main phases, each separated by a transport step: manufacture, use, and end-of-life. Each phase is described in more detail in the following sections.

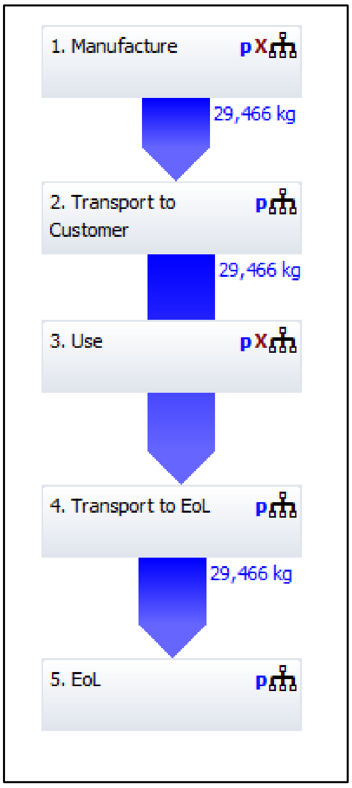


Figure 3-2: GaBi screenshot of the life cycle of the Dell R740

3.4.1. Manufacture phase and transport to customer

The manufacture of the product consists of two main modules – part production and assembly – as depicted in Figure 3-3.

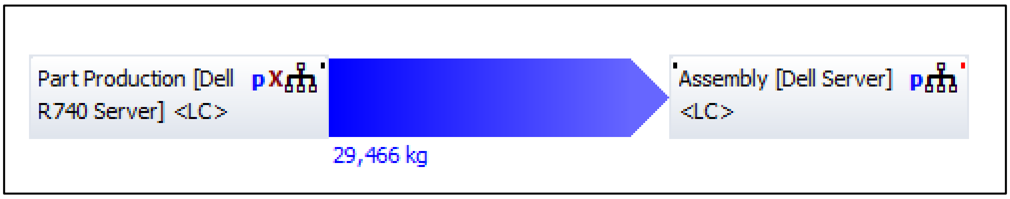


Figure 3-3: GaBi screenshot of the manufacture of the Dell R740

Part production includes the different components of the server grouped into 8 different plans, as depicted in Figure 3-4. Overall, the electronic components of the product consist of over 3500 capacitors, over 3000 resistors and over 220 single ICs.

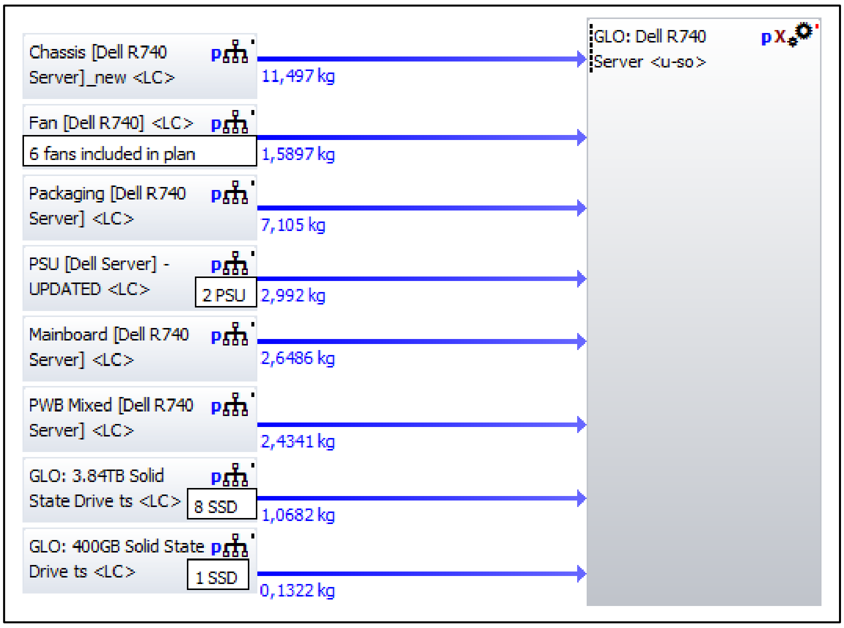


Figure 3-4: GaBi screenshot of the part production of the Dell R740

Inside each one of the 8 plans, there is a transport module built in, as shown in Figure 3-5, to represent the shipping of parts to the assembly site (transport to assembly). This module is parametric and adjusted according to the scenarios (transport distance and mode of transportation). Table 3-13 summarizes the distances of transport to assembly in the different scenarios considered.

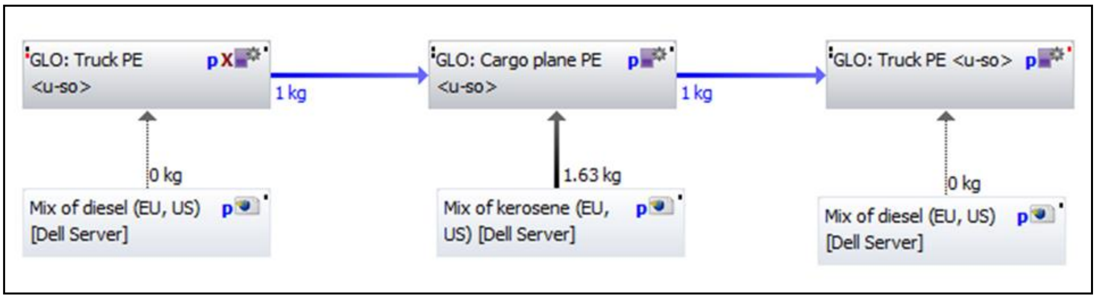


Figure 3-5: GaBi screenshot of the transport to assembly of the electronic components of Dell R740

Table 3-13: Transport to assembly scenarios for the Dell R740

Main Components	Poland			Mexico		
	Truck [km]	Plane [km]	Ship [km]	Truck [km]	Plane [km]	Ship [km]
Chassis	1200		18000	1000		14000
Fans						
Packaging						
PSU	140	8300		100	14000	
Mainboard						
PWB mixed						
SSDs						

3.4.2. Use phase

As described in section 3.2.4, the total consumption in the use phase is split between idle and different load modes. Figure 3-6 depicts the modelling approach on the top-level plan.

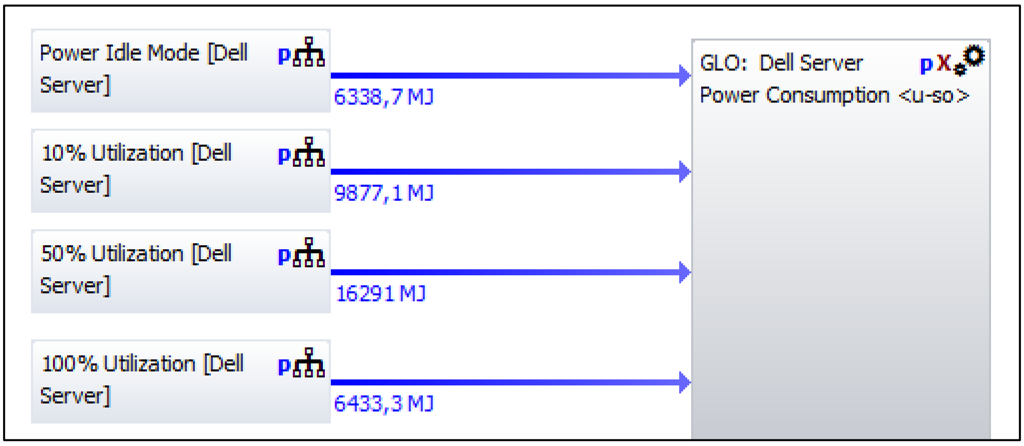


Figure 3-6: GaBi screenshot of the use phase of the Dell R740

The GaBi model can be adjusted to reflect the mix of customers from the US or EU, i.e. the proportion of electricity from each region's electricity grid mix. A screenshot of a power mode plan is depicted in Figure 3-7.

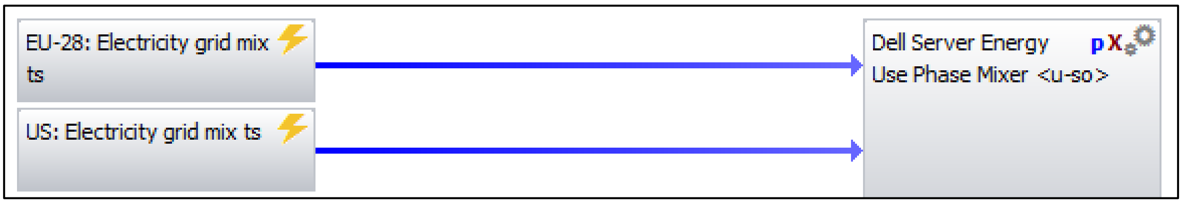


Figure 3-7: GaBi screenshot of a power mode plan of Dell R740

3.4.3. End of Life

End-of-life is modelled as described in chapter 3.2.5. For recycling, large mechanical parts are first separated manually. The remaining parts (electronics such as printed wiring boards and the electronic parts of the SSDs) are shredded and then further processed to recover copper and precious metals (see Figure 3-8).

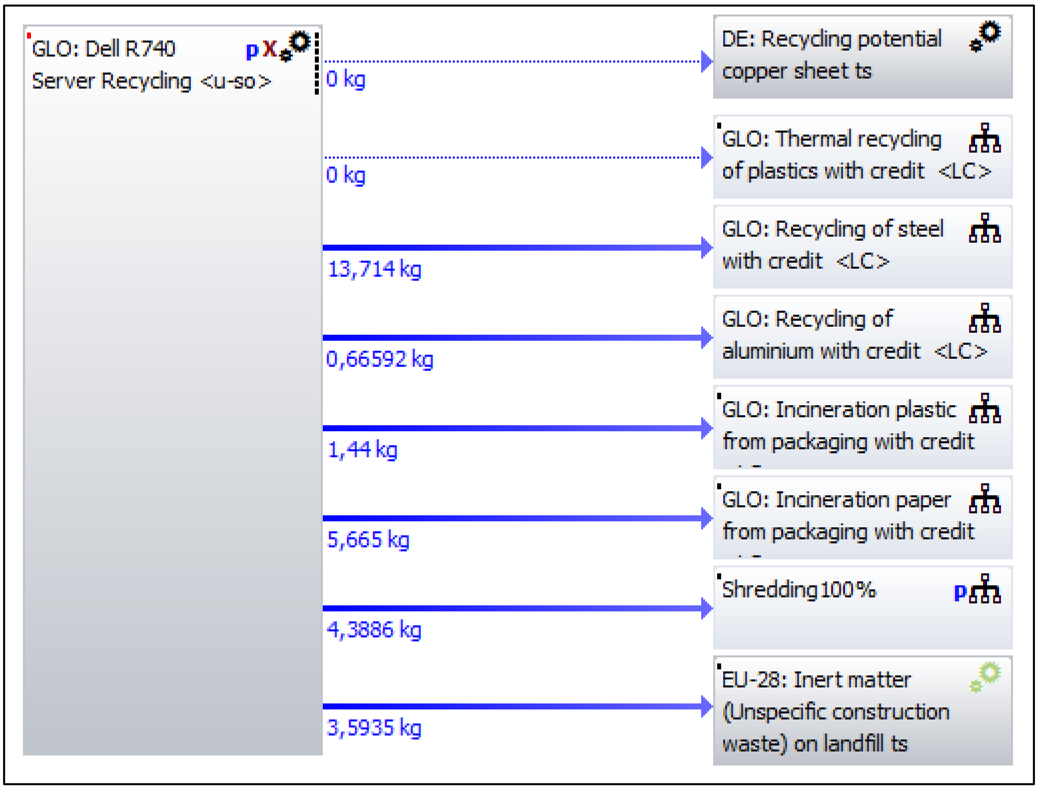


Figure 3-8: GaBi screenshot of the End of Life of the Dell R740

4. Results

This chapter contains the results of the LCA study. It shall be reiterated at this point that the reported impact categories represent impact potentials, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the chosen functional unit (relative approach).

LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

The results will be discussed for the impact category Global Warming Potential (GWP) in the following chapter, as the overall conclusions remain valid also for the other impact categories and GWP is considered the most robust and widely used impact category. A table summarizing all impact category results can be found below and diagrams in Annex B:

4.1. Overall Results

Two scenarios are defined given the two regions in which the Dell R740 is produced, sold, used, and sent to end of life:

- Europe; and
- United States of America.

The study made the following assumptions, which are based on information provided by Dell:

- Manufacturing of most components take place in China (see Table 3-9),
- Assembly of components take place in Poland and Mexico,
- Transportation to European and US customer, and
- Use stage takes place in the EU and in the US.

Table 4-1 shows the impact assessment results for all impact categories under consideration within this study.

Table 4-1: Overall results for the Dell R740

Impact Category	EU Scenario	US Scenario
Abiotic Depletion [MJ]	9,66E+04	1,30E+05
Acidification Potential [kg SO2 eq.]	3,01E+01	3,88E+01
Eutrophication Potential [kg Phosphate eq.]	2,43E+00	2,37E+00
Ozone Layer Depletion Potential [kg R11 eq.]	5,74E-08	4,67E-08
Photochem. Ozone Creation Potential [kg Ethene eq.]	1,96E+00	2,43E+00
Global Warming Potential 100 years incl. biogenic carbon [kg CO2 eq.]	8,62E+03	1,08E+04

For the life cycle of the Dell R740 in the United States, the GWP is ca. 25% higher than the GWP in Europe. The main reason for this is the use phase and hence the emissions associated with the production of electricity within the respective electricity grid mix.

In a detailed view of the carbon footprint of these two scenarios in Figure 4-1 and Figure 4-2, it is clear that the major fraction of the impact – approximately 98% in both the EU and the US – derives from the manufacturing and the use phase of the Dell R740. The production of the parts in the EU accounts for around 50% of the total GWP, whereas in the US the production accounts for little over 40% of the total impact. Transportation of each component to the assembly location is included in the manufacturing stage and accounts for less than 1% of the overall results. Regarding the transport to assembly, the impact is slightly higher in the US region due to the fuel mixes and the distances on some of the modules. Depending on the components, this can be local transport (~1200km) with a truck accompanied be either air transport from China (8300km and 14000km for EU and US assembly respectively) or ship transport (18000km and 14000km for EU and US assembly respectively). Concerning the assembly of the Dell R740, the associated carbon footprint is marginally higher in Europe as the Polish electricity mix was selected, which has a higher impact than the electricity mix in Mexico.

The lower impact of the transport to the customer in the EU can be mainly explained by the underlying assumptions of longer distances and different modes of transport. The transport to end of life has a less relevant contribution in both cases and the end of life credits contribute to a reduction of about 2.3% and 1.8% of the life cycle impacts respectively.

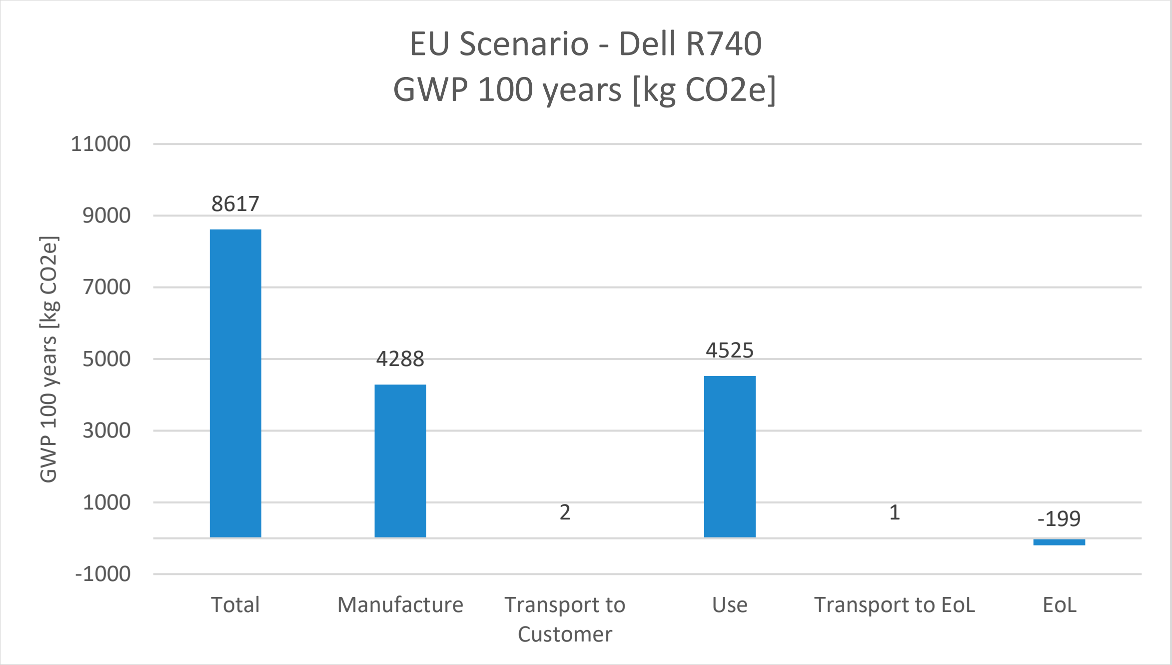


Figure 4-1: Contribution of the different stages of the life cycle to the global warming potential (GWP) of the Dell R740 in the EU

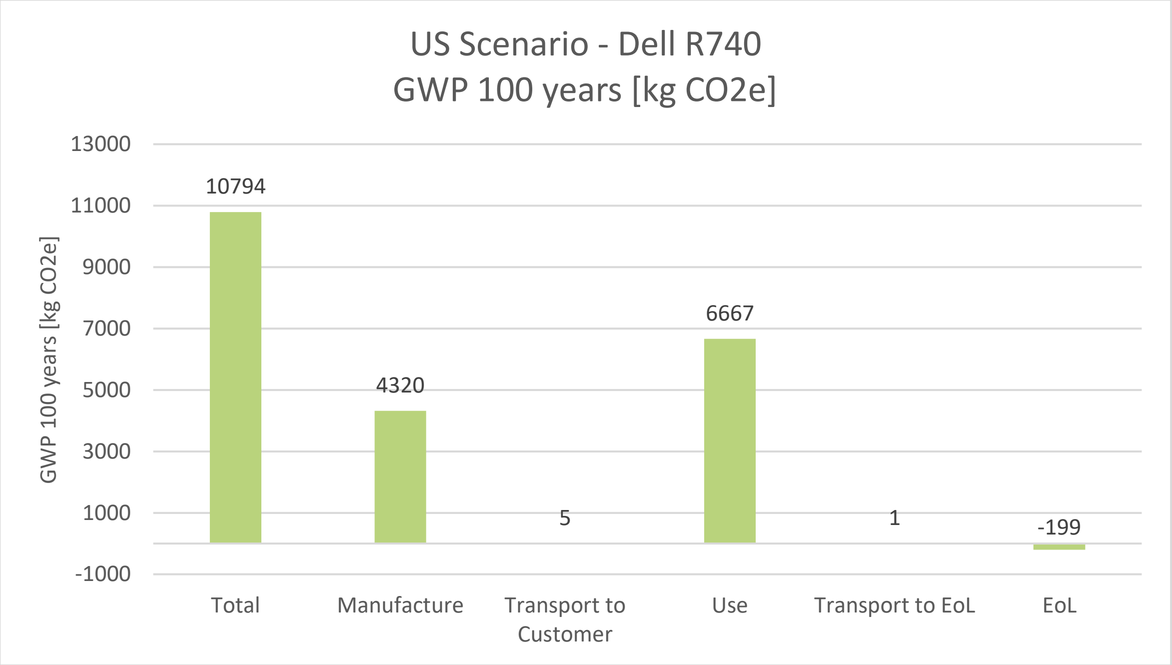


Figure 4-2: Contribution of the different stages of the life cycle to the global warming potential (GWP) of the Dell R740 in the US

4.2. Manufacturing of the Dell R740

4.2.1. General

In the previous section, it was shown that the manufacturing of the Dell R740 in the EU has a contribution of 4,288 kg CO_2e, contributing to approximately 50% to the total of the life cycle impact.

Figure 4-3 presents the contribution of the different parts to the total impact resulting from the part production, not including assembly.

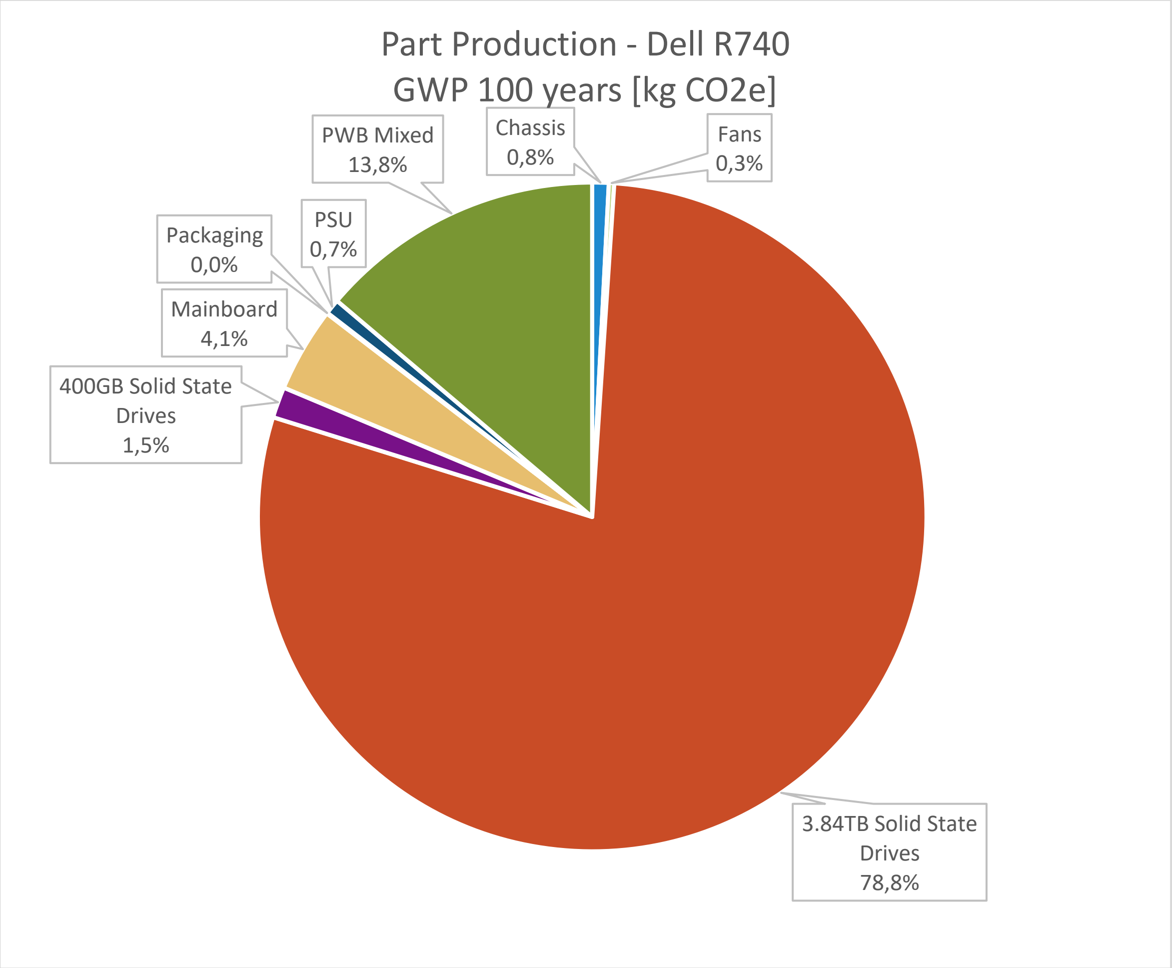


Figure 4-3: Contribution of the production of different modules to the global warming potential (GWP) of the Dell R740 – EU Scenario

It becomes very clear that the large majority of the part production impacts are from the components containing electronics and especially the eight 3.84TB SSDs. The results of the detailed assessment and sensitivity analyses for these will be shown in the next sections. In Table 4-2, the impact contribution of each component is shown in terms of kg CO_2e.

Table 4-2: Carbon footprint of main components of the Dell R740

Main Components	Global Warming Potential (GWP 100 years) [kg CO2e]
Chassis	34.1
Fans	11.1
3.84TB Solid State Drives	3373.5
400GB Solid State Drives	64.1
Mainboard	175.3
Packaging	1.9
PSU	31.3
PWB Mixed	591.8
Total	**4283.1**

It is interesting to understand the relation between the mass and the impact of each of the parts. Figure 4-4 illustrates the mass of the main components in comparison to their corresponding weight. As shown, over 99% of the part production impact comes from the components containing electronics which account for only 30% of the total weight of the Dell R740. The eight 3.84TB SSDs again are a significant outlier, accounting for approximately 80% of the total GWP while only accounting for 4% of the weight.

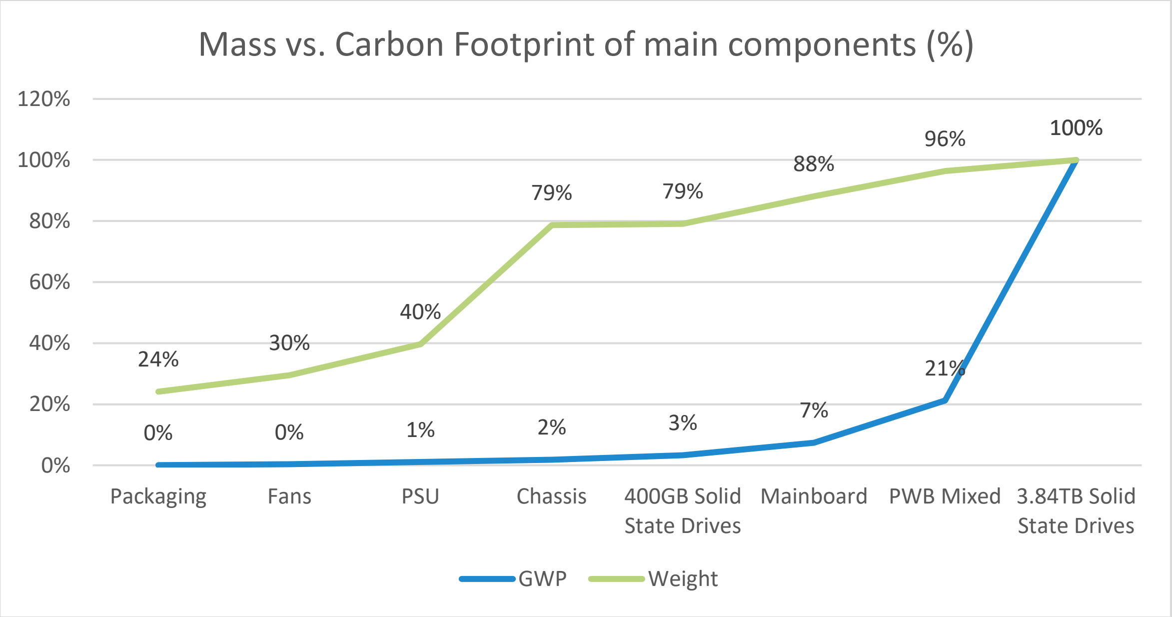


Figure 4-4: Comparison of masses and associated global warming potential (production) on the components in the Dell R740

It is thus possible to show that the global warming potential is not directly linked to mass. While the chassis dominates the mass of the product (39%), the impact of this component (GWP) per unit of mass is relatively low. By contrast, the SSDs, the mainboard and PWB mixed – which contain the RAMs and all other additional cards (see Table 3-5) – together contribute only 21% of the total mass, but their impact per unit mass is a large share (98%) of the total GWP of the parts. This is a typical phenomenon in electronic products where the energy consumption, waste, and emissions of electronics manufacturing processes far outweigh the regular metallurgical or plastic production processes of the chassis and packaging.

Packaging has the lowest impact per unit mass, since here the largest part of mass comes from paper, in which production – when compared with the processes in the other modules – is relatively less energy-consuming.

4.2.2. Solid State Drives

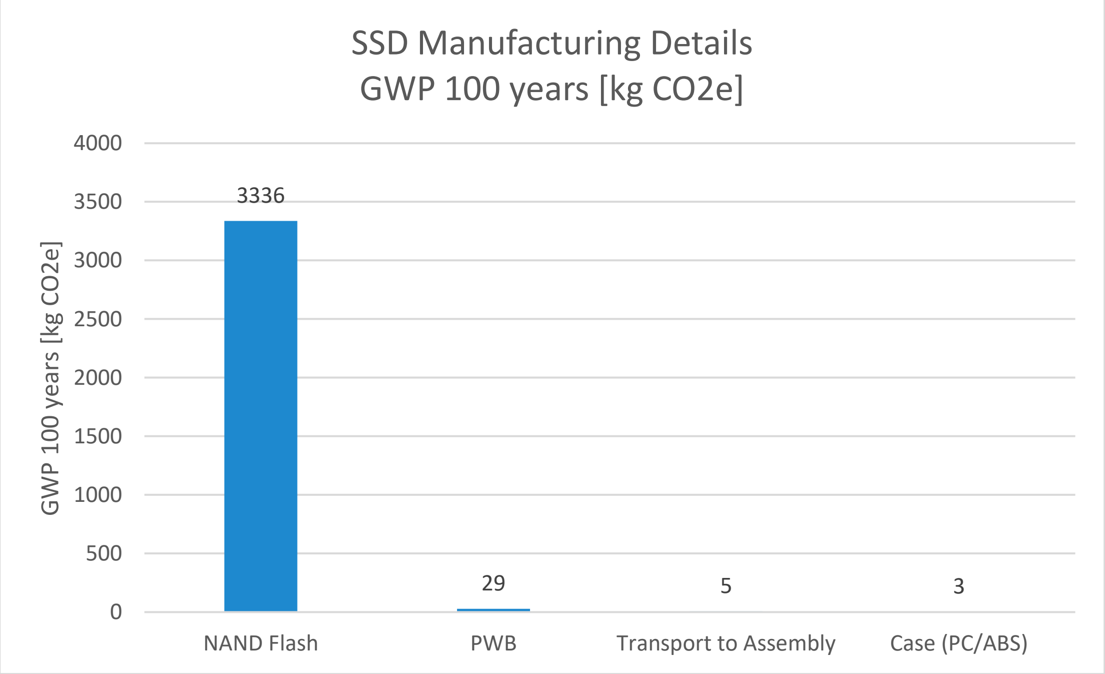


Figure 4-5: SSD manufacturing Impacts

The typical configuration evaluated in this study considers one 400GB SSD and eight 3.84TB SSDs. They represent, in total, the largest contribution to the overall impact of manufacturing the system and almost half of the overall impact of the product.

Figure 4-5 shows that the majority of the SSD impact of the 3.84TB SSDs comes from the NAND flash. As described in chapter 3.2.2, several assumptions were made regarding package dimensions, die/package ratio and die stack per package to model these chips. The data for these parameters are based on the part number of the chips and publicly available data from Samsung (Gibb, 2016) (PC Watch, 2016). To evaluate the impacts of those parameters, a scenario was calculated that considers different die/package ratios as this parameter is considered to be of the highest uncertainty and impact.

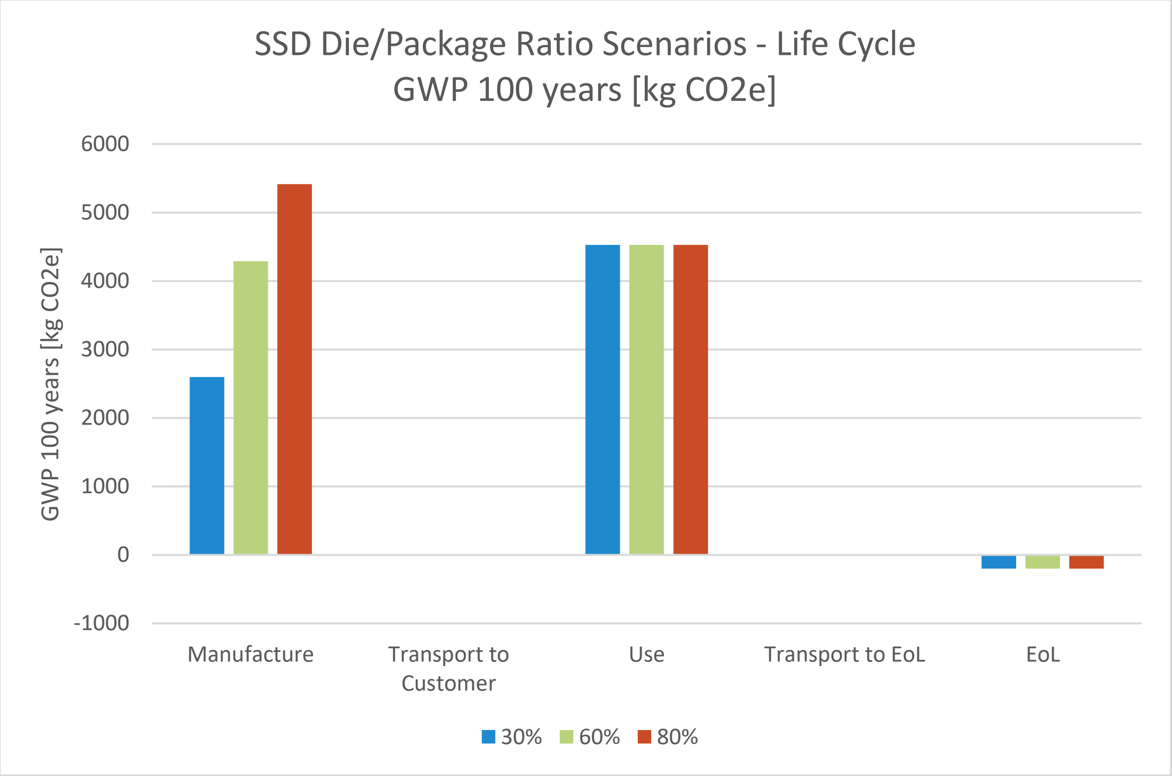
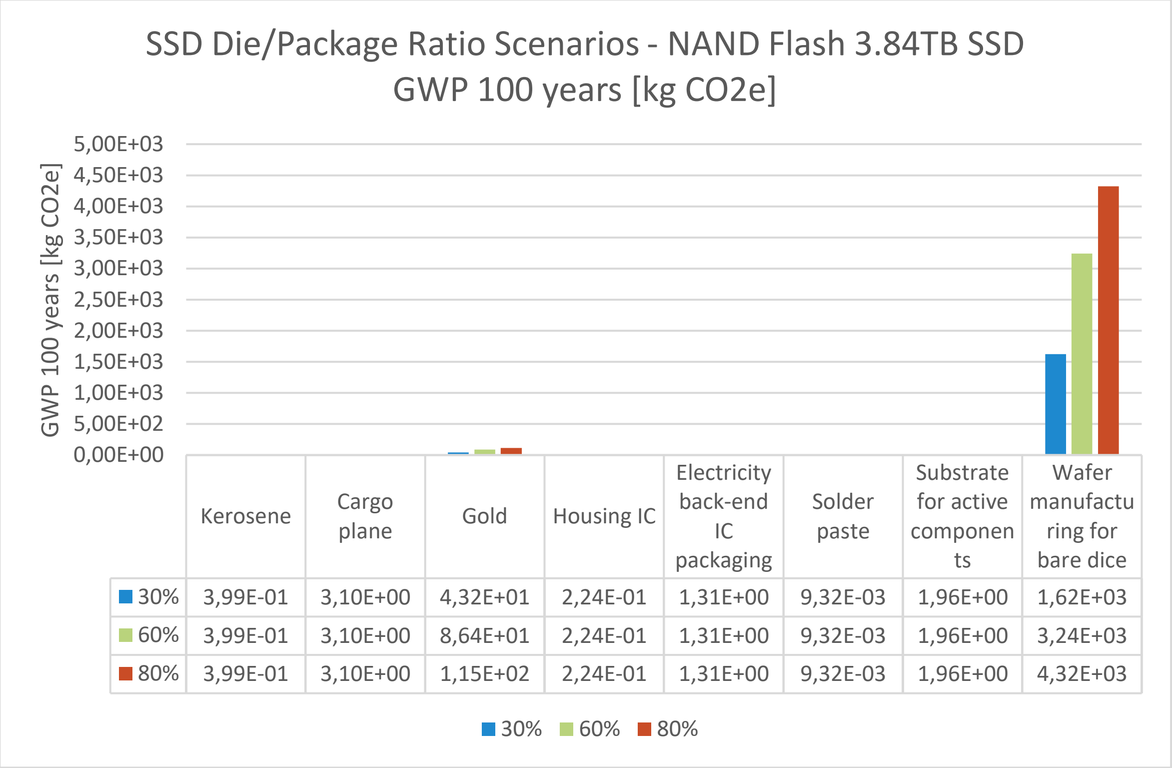


Figure 4-6: SSD Die/Package Ratio Scenarios - Life Cycle GWP

The scenarios assume two different die/package ratios of 30% and 80% in addition to the default 60%. Lab results from other NAND flash chips showed that those values are in a range typically found within the industry. Looking at the results of the sensitivity analysis, it shows how significant the influence of the die/package ratio on the GWP results are. The overall manufacturing impacts of the Dell R740 are reduced by almost 40% if a die/package ratio of 30% is assumed for the nine SSDs built in.

As the NAND flash chips are the main driver of the environmental impacts of the SSDs, Figure 4-7 shows the main impact drivers of the chips for all three scenarios. The two components/materials that are influenced by the different die/package ratio are the wafer manufacturing and gold and hence show the impact of assuming different ratios.



	Kerosene	Cargo plane	Gold	Housing IC	Electricity back-end IC packaging	Solder paste	Substrate for active components	Wafer manufacturing for bare dice
30%	3,99E-01	3,10E+00	4,32E+01	2,24E-01	1,31E+00	9,32E-03	1,96E+00	1,62E+03
60%	3,99E-01	3,10E+00	8,64E+01	2,24E-01	1,31E+00	9,32E-03	1,96E+00	3,24E+03
80%	3,99E-01	3,10E+00	1,15E+02	2,24E-01	1,31E+00	9,32E-03	1,96E+00	4,32E+03

Figure 4-7: NAND flash 3.84TB SSD - GWP results

4.2.3. Mainboard

Figure 4-8 depicts the contribution of the main elements in the mainboard and their respective contributions to the carbon footprint.

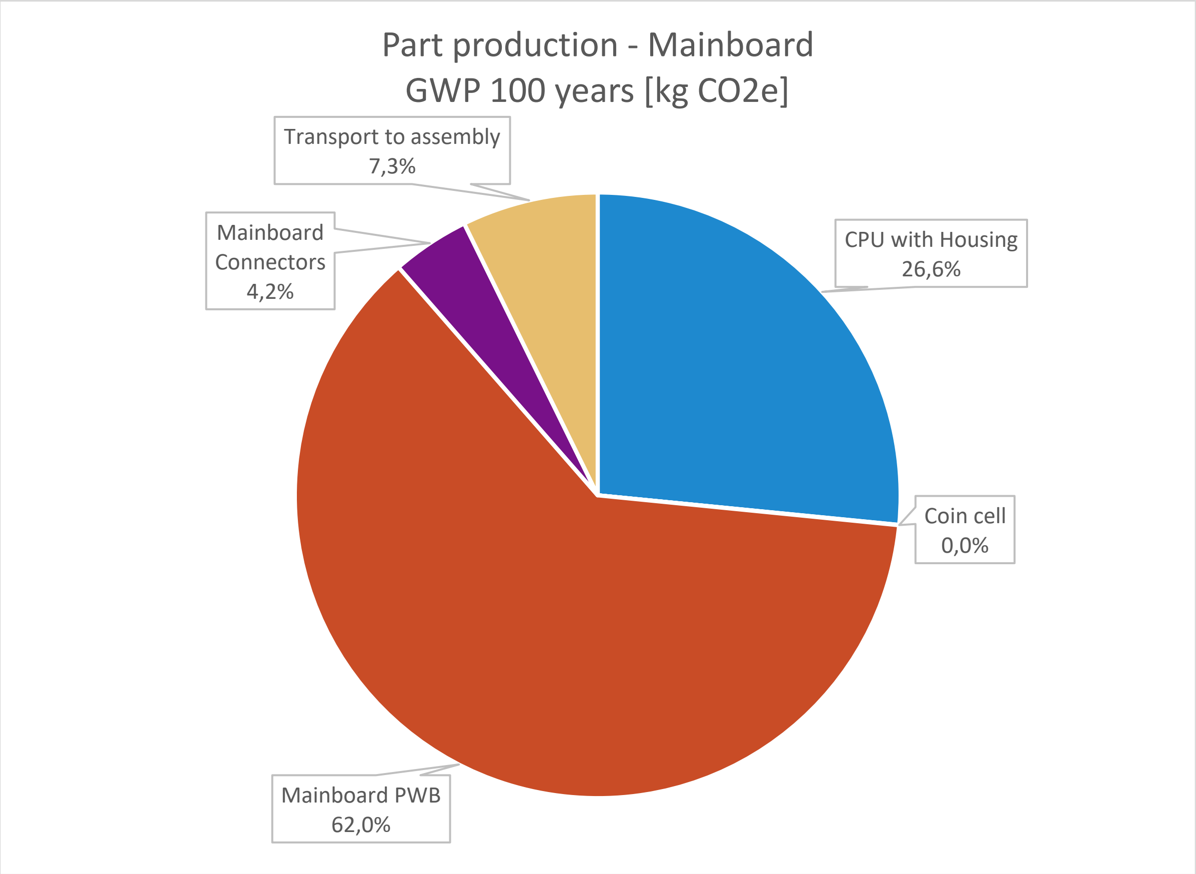


Figure 4-8: Contribution of the elements of the mainboard for the carbon footprint of this component of the Dell R740

Two main submodules generate almost all the impact from the mainboard:

- Production and assembly of the substrate assembly (62%, from which ~85% is directly related with the production of the printed wiring board itself). Physical dimensions (length, width, thickness) of the mainboard were measured. Since panel optimization drawings were not provided, mainboard area was calculated by multiplying widest and longest dimensions of the board as a conservative estimate to account for cutting losses. Number of layers and surface finish for the PWBs were estimated based on visual inspection. The mainboard was estimated to be 12-layer HASL, 1925 cm2 in area.
- Large and complex ICs (i.e. the CPUs) and the corresponding heatsink contribute with 27% for the total impact of the mainboard.

Due to the large number of rather small connectors used on the mainboard, they also account for around 4% of the total impact. Due to the assumption of the transport to assembly by plane, the emissions associated with this transport contribute to around 7% to the mainboard impacts.

The following characteristics help to explain this impact distribution and are true for all electronics discussed within this study:

- PWB manufacturing is a multi-step, highly energy intensive process with a significant amount of waste production and direct emissions. For Dell's circuit boards, some also require the use of gold which is a precious metal with very energy and emission intensive upstream production steps of extraction and processing.
- Active components (ICs, diodes and transistors) contain a semiconductor die which has a highly energy intensive manufacturing process, increasing in direct proportion with the area of the chips. In addition, active components often require gold or other precious metals. Therefore, large ICs such as memory chips, CPUs, and graphic cards etc., will have a high carbon footprint due to the energy demand of the production steps.
- Passive components do not contain a die, but can contain a small amount of precious metals. Large and massive passive components can therefore have a high contribution to environmental impacts, but small components are generally less relevant to the overall impact;
- Connectors can also contain gold and/or other precious metals in small amounts.

The Dell R740 mainboard analysed by thinkstep was a highly populated board on both sides with a significant amount of electronics. The number of ICs was high, reflecting the high functionality.

4.2.4. PWB Mixed

The PWB Mixed consolidate a variety of different components used within the Dell R740 (Table 3-5) and together account for around 14% of the total GWP impact. The twelve 32GB RAM bars used within the configuration account for around 33% of the total mass of the mixed PWB. But analogous to the mass vs. carbon footprint discussions in chapter 4.2.1, they account for over 90% of the total GWP impact of the PWB Mixed due to their high capacity per RAM bar and the associated complexity and density of the built-in chips and dies.

4.3. Use phase of the Dell R740

In this section, two distinct scenarios are presented based on a) the two regions where the current study considers that the Dell R740 is used and b) as well as a comparison of the standard light-medium workload with a heavy workload.

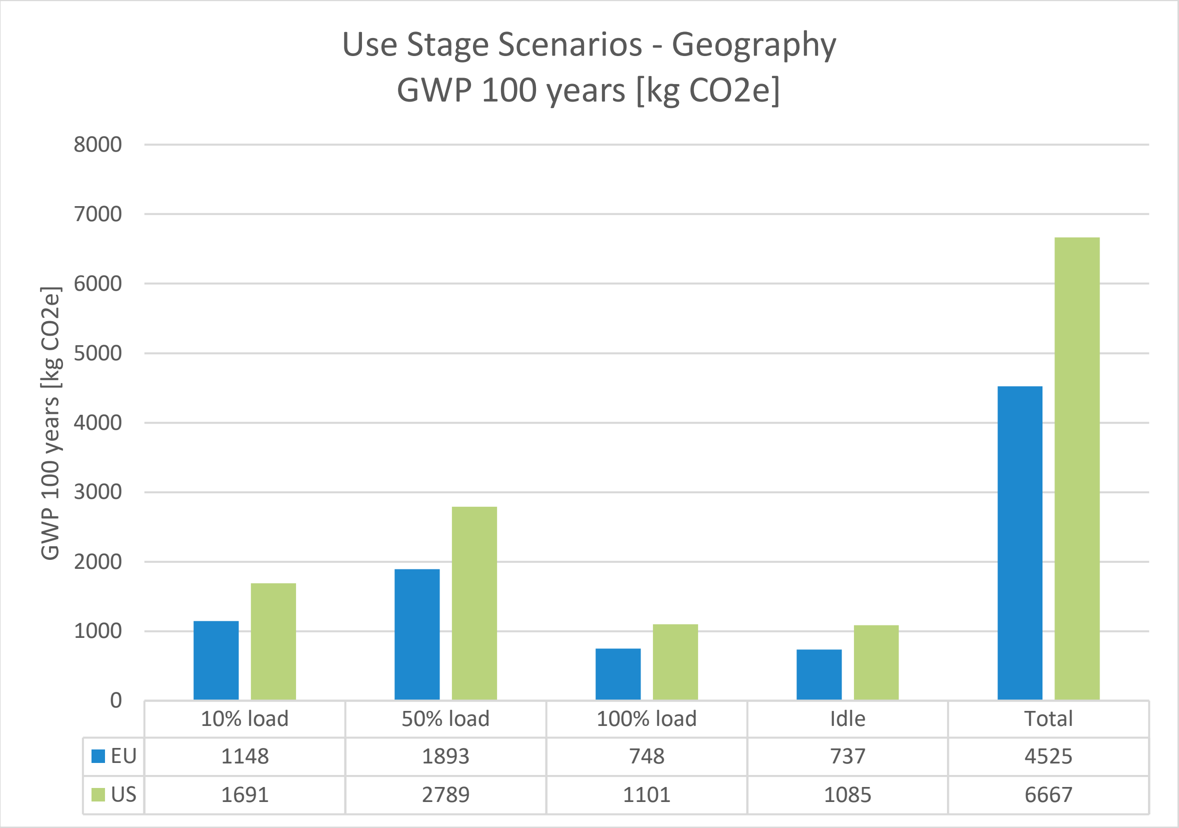
4.3.1. Regional Scenario

The following two locations are considered within this scenario and represent the two most typical cases for Dell products:

- The Dell R740 is used 100% in the US
- The Dell R740 is used 100% in the EU

The duty cycle of the server was the default light-medium workload described in chapter 3.2.4.

Figure 4-9 includes the carbon footprint results for the two scenarios based on the mode of the use phase and the region where it is used over the entire lifespan of the product.



	10% load	50% load	100% load	Idle	Total
🟦 EU	1148	1893	748	737	4525
🟩 US	1691	2789	1101	1085	6667

Figure 4-9: Global Warming Potential of the Dell R740's use stage in Europe and the USA

As expected, the Dell VRTX working at 50% load mode leads to the highest electricity consumption and therefore the highest carbon footprint, given the high share of this load mode. In idle mode, the platform is not asleep, but there are no applications running, and thus this mode corresponds to lower power consumption. The 100% workload mode, although consuming almost 2.5 times as much as the idle mode (510W vs. 201W), accounts for similar emissions due to difference in time the server is running in each mode.

Overall, the use of the Dell R740 in the USA shows higher GWP impacts compared to a usage in the EU. This can be associated with the different share of renewable and non-renewable energy carriers in the respective electricity grid mixes.

4.3.2. Workload Scenario

In addition to the default light-medium workload, which is considered by Dell to be the typical workload of the R740, a heavy workload was evaluated as sensitivity for the EU geography. The different load mode shares are shown in Table 4-3 and all other details about the scenarios can be found in chapter 3.2.4.

Table 4-3: Load mode share light-medium and heavy workload

Load mode	Light-medium workload [h/d]	Heavy workload [h/d]
100%	2.4	3.6
50%	8.4	13.2
10%	7.2	4.8
Idle	6	2.4

As expected, the heavy workload scenario increases the overall GWP impacts of the lifecycle and shifts the burden more towards the use phase of the product.

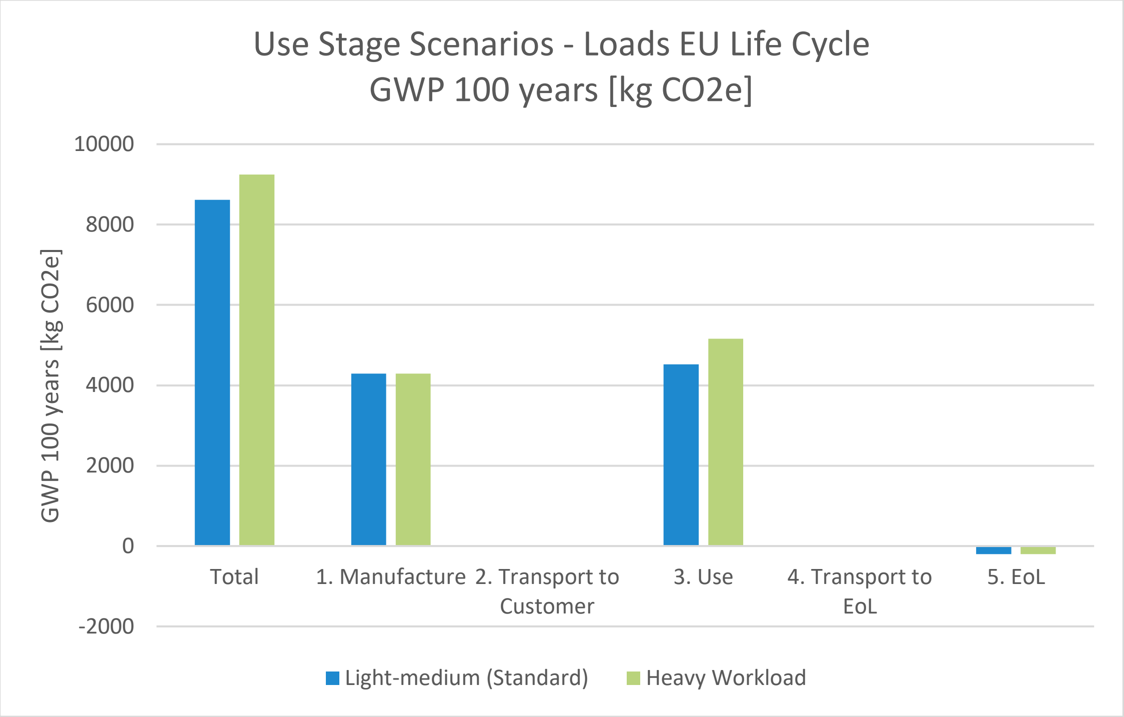
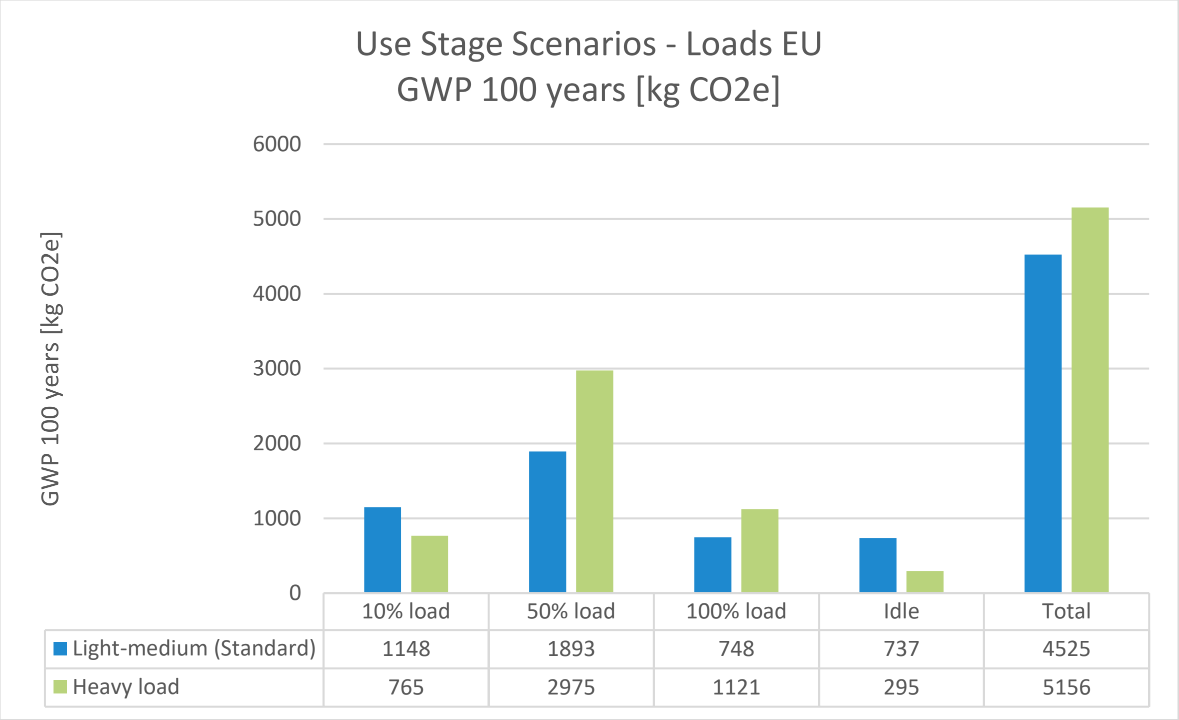


Figure 4-10: Global Warming Potential of the Dell R740 for the two considered workloads

The detailed evaluation of the use phase and its different load modes shows that the shares, as expected, correspond directly with the amount of time the server runs in the different modes.



	10% load	50% load	100% load	Idle	Total
🟦 Light-medium (Standard)	1148	1893	748	737	4525
🟩 Heavy load	765	2975	1121	295	5156

Figure 4-11: Global Warming Potential of use stage of the Dell R740 in the two considered workloads

4.4. End of Life (EoL) of the Dell R740

Recycling of the Dell R740 results in a credit of approximately 200 kg CO_2e to future product systems, corresponding to a reduction of ca. 1.8% of the total product's life cycle impact.

Table 4-4 shows the impacts and credits associated with the end of life treatment of the server assuming the values provided by Wisetek (chapter 3.2.5). Due to the data collection procedure undertaken within the study, it was possible to determine quite precisely the amounts of electronics and other materials used within the product.

Credits shall be understood as avoidance of impacts associated with primary production of the material which is sent to recycling. In cases where the recycled (secondary) material can be used directly to replace the primary material, the primary production of the same amount of material can be avoided and thus all environmental impacts associated with primary production are also avoided. Therefore, credits are displayed as having a *negative* impact.

In the case of aluminum and steel, the metal can be recycled (almost) completely and the secondary material can have the same value as the primary one, making metal recycling an economically, as well as environmentally, worthwhile enterprise.

Mechanical recycling, however, may not always be viable for non-metals, such as plastics and paper. In this model, packaging paper and plastic are incinerated yielding energy (thermal and electric), and this amount is credited much the same way as materials: the amount of energy that is yielded will not need to be produced elsewhere, and therefore the burdens associated with a given amount of energy production are avoided. Incineration, however, has the disadvantage of also producing emissions of greenhouse gases; therefore, the impacts in this case are higher than the generated credits.

After separating the mechanical parts, the electronic assemblies (e.g. the printed wiring boards and electronic parts of the SSDs) are shredded. This process requires energy (leading to an impact) but enables the subsequent separation and recycling of precious metals (e.g. gold, silver, etc.). In Figure 4-4 it is shown that the post-shredding mechanical recycling of these metals yields rather high credits, especially gold.

The landfilled portion of the product, i.e. the portion that is not recycled, produces some emissions, but these are minor, primarily due to the assumption that the waste is largely inert. Transport to recycling (680 km by truck) also has a very minor impact (see Figure 4-1).

Table 4-4: Net results of recycling the server constituent materials

		Net results (GWP 100 years) [kg CO2-Equiv.]
Mechanical Recycling	Aluminium	-5,30
	Steel	-21,10
Waste paper	Paper packaging	5,13
Thermal treatment	Thermal recycling, Plastic	1,71
Shredding	Power	0,70
Post-shredding mechanical recycling	Copper	-8,80
	Gold	-169,14
	Palladium	-2,62
	PWB	0,81
	Silver	-0,17
	Platinum	-0,08
Landfill	Emission from inert wastes	0,06

5. Interpretation

5.1. Identification of Relevant Findings

- The use phase contributes approximately 50% to the total the life cycle GWP of the server. During this phase the source of electricity determines the environmental impact, as the use pattern is considered identical in both the US and EU scenarios.
- The two regions differ in their contribution to the global life cycle. The US scenario has approximately 25% higher impact than the European one, due to the differences in the electricity grid mix and fuel used, as well as distances travelled.
- The manufacturing stage accounts for 50% (40% in US) of the product carbon footprint.
- The transport to assembly, depending on the components, can be local transport with a truck accompanied be either air transport from China or ship transport. Avoiding the transport of components or products by air is highly recommended, as air transport has much higher impact than ground or sea transport.
- Considering only the manufacturing stage, the electronic components have by far the highest impact (~99%) of all modules. largely dominated by the eight 3.84TB SSDs used within the configuration.
- 99% of the part production impact comes from the components containing electronics which account for only 30% of the total mass of the Dell R740. The chassis dominates the mass of the product (39%) but the impact per unit is relatively low (~1% of part production). By contrast, the 3.84TB SSDs contribute only ~4% to the total mass, but their impact per unit mass is very high. This is a typical phenomenon in electronic products where the energy consumption, wastes and emissions of electronics manufacturing far outweigh the regular metallurgical or plastic production processes. This is especially true for such high density and high capacity chips used for high capacity SSDs, as their PWB are highly populated.
- The Dell R740 configuration considered includes 12 RAM bars with 32GB each, resulting in a total memory configuration of 384GB. These are the highest PWB Mixed contributor, while only accounting for 33% of the total mass of all components within the mixed PWB. The PWBs of these RAM bars are highly populated, meaning that the impact of the semiconductors is dominant (~93.5%).
- The chassis is the highest non-electronic component contributing to GWP in the manufacturing stage, with 34.1 kg CO_2-equivalents. The contribution to the total mass and carbon footprint from this component demonstrate that steel production is not particularly high impact.
- Recycling given the primary data provided by Wisetek resulted in a net reduction of 200 kg CO_2-equivalents. This represents a reduction of the total impact by around 1.8%.

- Considering the net gains from recycling, the largest gain comes from the recycling of gold (~84%), followed by steel (~10% of the total net gain). The recycling benefit from aluminum is very high, but the aluminum content is lower than that of steel in the chassis (leading to ~2% of total net gain overall).

The high impact of the SSD within this typically and representatively configured Dell R740 exemplifies that the configuration of a server can have a high impact on the environmental results within its lifetime. Especially given that the price per GB of SSDs are and will become more competitive with traditional HDDs while offering superior performance. This will most probably increase the share of SSDs in sold products even more and thus increase the shift of the environmental burden from the use phase to the manufacturing stage that can already be observed in this study. This leads to the recommendation to a) increase the data quality of considered components, by e.g. having access to BOMs and b) focus more on the manufacturing part of products and hence more on the supply chain of those components. Looking at this issue from a (post-)consumer perspective, the reuse (or refurbishment) of used SSDs from servers could potentially extend their designated lifetime. This would require an appropriate take-back system (if reused externally after use by the first customer) or an appropriate data erasure system (if reused internally).

5.2. Data Quality Assessment

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied) and representativeness (geographical, temporal, and technological).

To cover these requirements and to ensure reliable results, first-hand industry data in combination with consistent background LCA information from the GaBi 2018 database were used. The LCI datasets from the GaBi 2018 database are widely distributed and used with the GaBi 8 Software. The datasets have been used in LCA models worldwide in industrial and scientific applications in internal as well as in many critically reviewed and published studies. In the process of providing these datasets they are cross-checked with other databases and values from industry and science.

5.2.1. Precision and Completeness

- ✓ **Precision:** As the majority of the relevant foreground data are based on primary measured data or calculated based on primary information sources of the owner of the technology, precision is considered to be good considering the goal and scope of this study. All background data are sourced from GaBi databases with the documented precision.
- ✓ **Completeness:** Each foreground process was checked for mass balance and completeness of the emission inventory. Only upstream component packaging was knowingly omitted. Completeness of foreground unit process data is considered to be high. All background data are sourced from GaBi databases with the documented completeness.

5.2.2. Consistency and Reproducibility

- ✓ **Consistency:** To ensure data consistency, all primary data were collected with the same level of detail, while all background data were sourced from the GaBi databases.

- ✓ **Reproducibility:** Reproducibility is supported as much as possible through the disclosure of input-output data, dataset choices, and modelling approaches in this report.

5.2.3. Representativeness

- ✓ **Temporal:** All primary data were collected for the year 2017. All secondary data come from the GaBi 2018 databases and are representative of the years 2010-2017. As the study intended the reference year 2017, temporal representativeness is considered to be high.
- ✓ **Geographical:** All primary and secondary data were collected specific to the countries or regions under study. Two scenarios (US and EU) were used to represent regional differences. Geographical representativeness is considered to be acceptable.
- ✓ **Technological:** All primary and secondary data were modelled to be specific to the technologies or technology mixes under study. Where technology-specific data were unavailable, proxy data were used. Technological representativeness is considered to be high.

5.3. Model Completeness and Consistency

5.3.1. Completeness

All relevant process steps for each product system were considered and modelled to represent each specific situation. The process chain is considered sufficiently complete and detailed with regards to the goal and scope of this study.

5.3.2. Consistency

All assumptions, methods and data are consistent with each other and with the study's goal and scope. Differences in background data quality were minimised by predominantly using LCI data from the GaBi 2018 databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

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Annex A: Manufacture of submodules as represented in GaBi 6

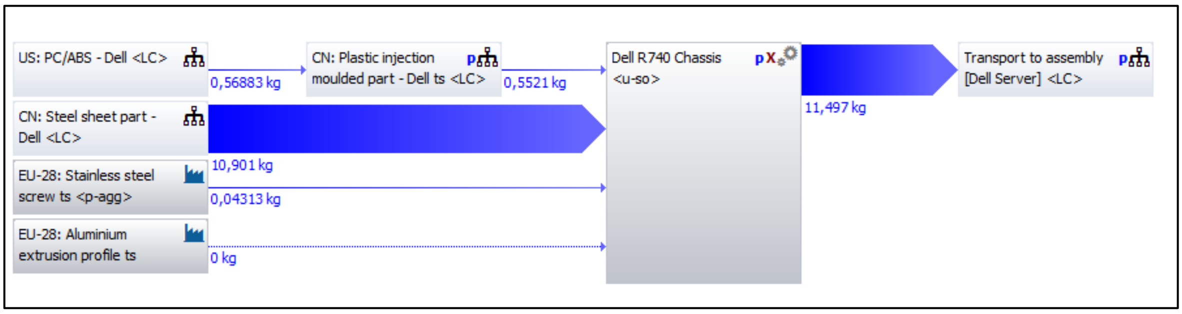

Figure A.5-1 Top-level chassis model for the Dell R740

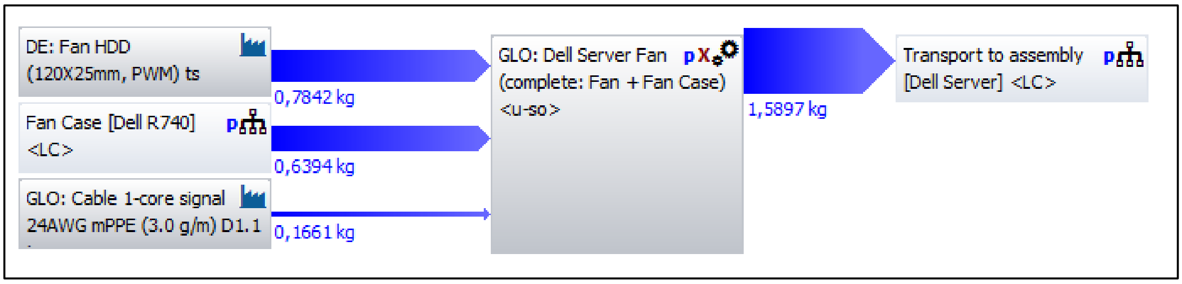

Figure A.5-2 Top-level fan model for the Dell R740

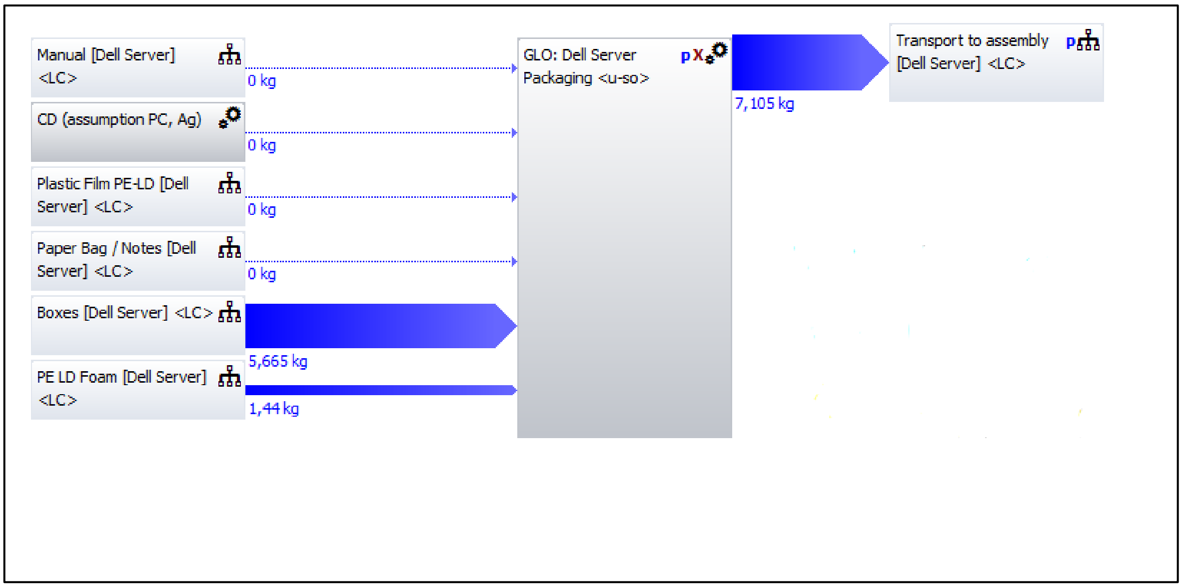

Figure A.5-3 Packaging model for the Dell R740

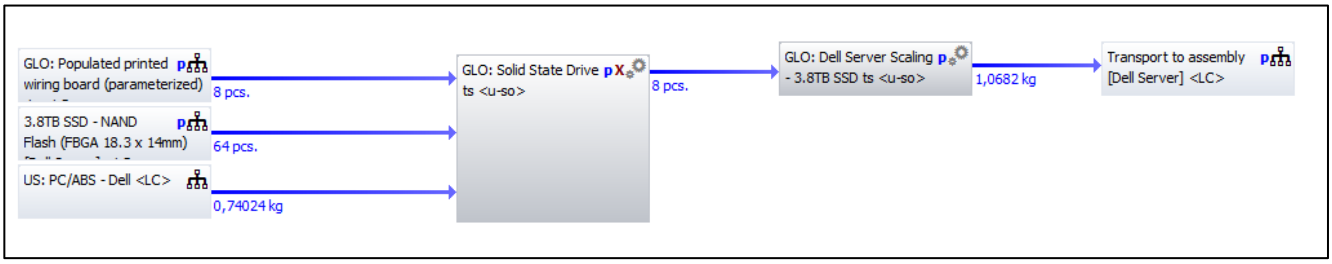

Figure A.5-4 Top level 3.84TB Solid State Drive for the Dell R740

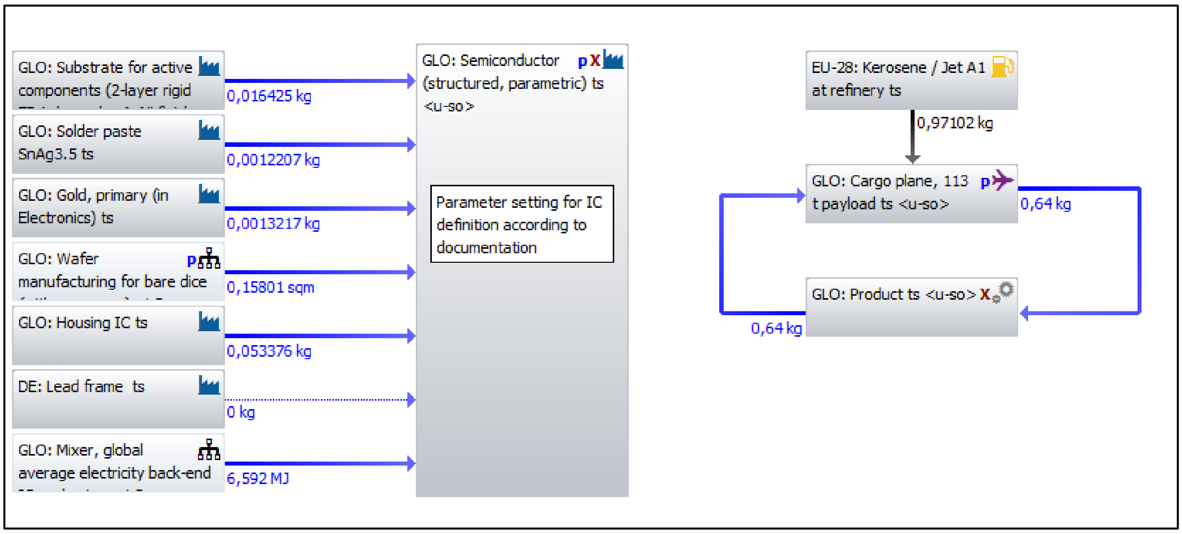

Figure A.5-5 NAND Flash for 3.84TB SSD for the Dell R740

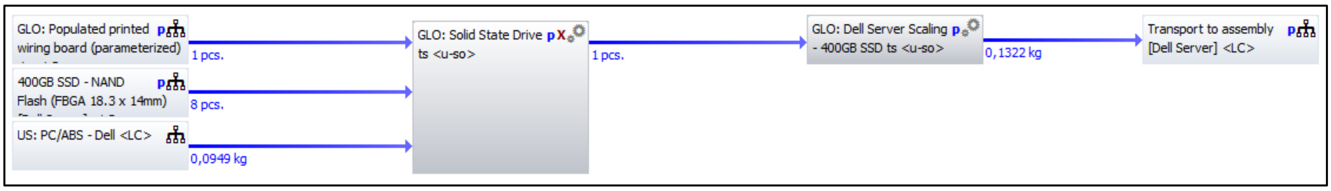

Figure A.5-6 Top level 400GB Solid State Drive for the Dell R740

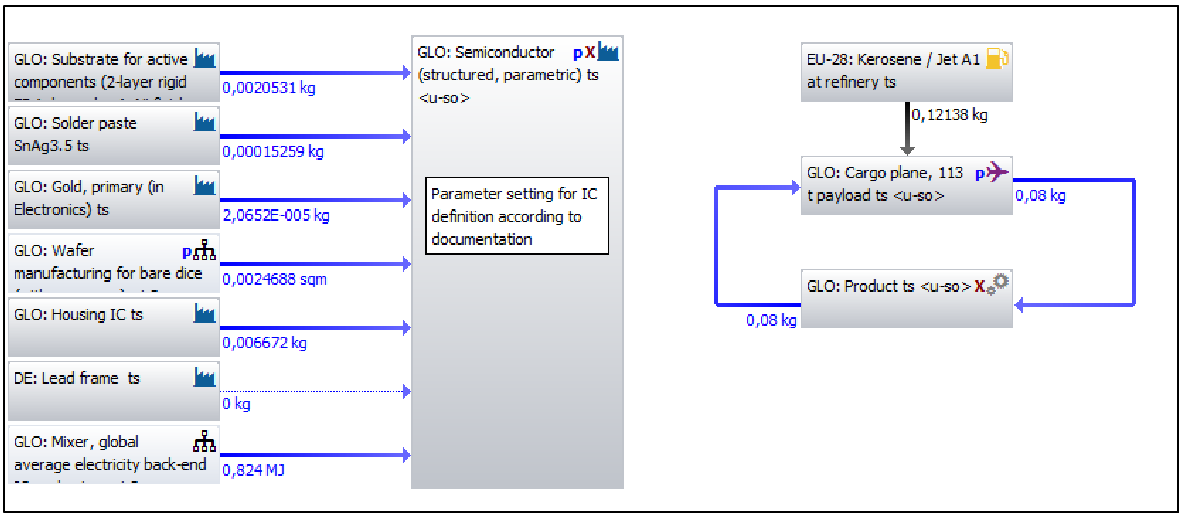

Figure A.5-7 NAND Flash for 400GB SSD for the Dell R740

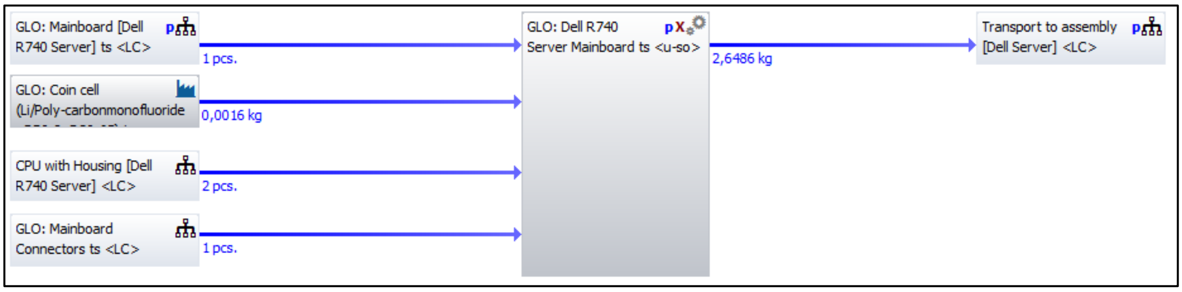

Figure A.5-8 Top level mainboard for the Dell R740

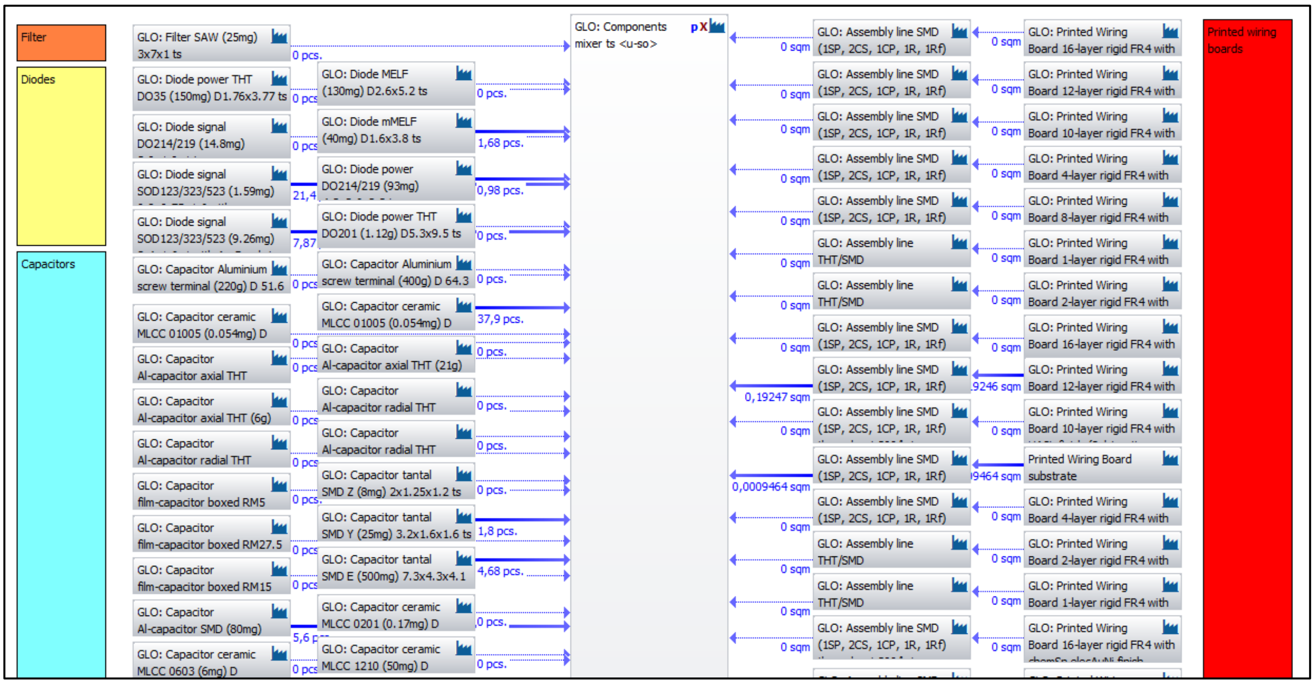

Figure A.5-9 Part of mainboard model for the Dell R740

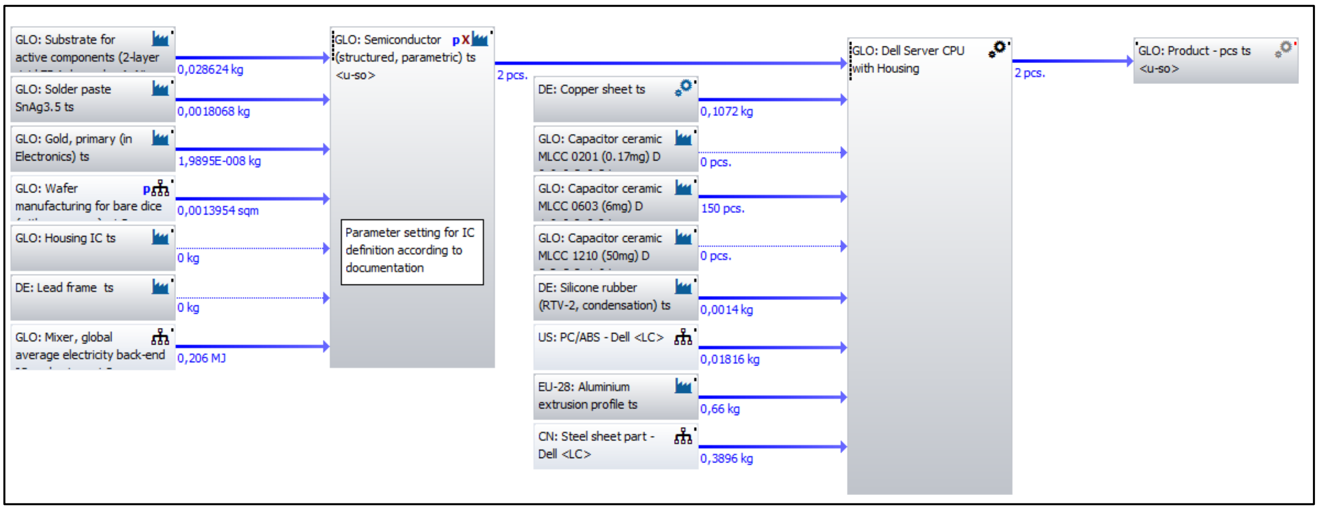

Figure A.5-10 CPU model for the Dell R740

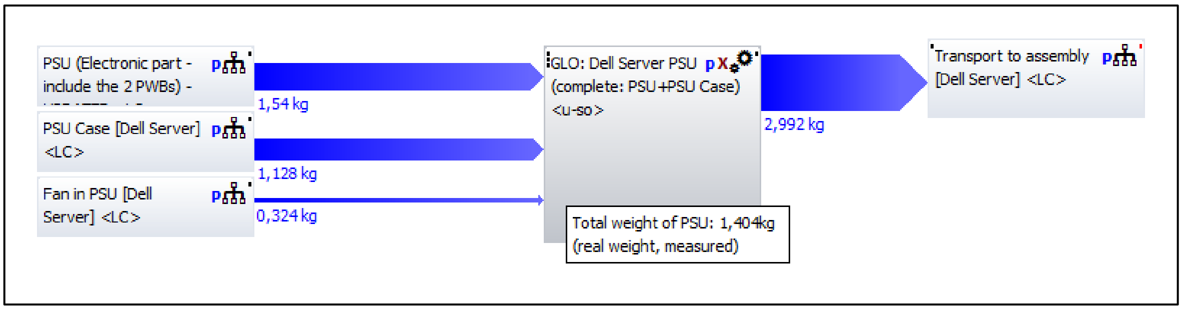

Figure A.5-11 Top-level PSU model for the Dell VRTX

Figure A.5-12 Top level of the PWB Mixed model for the Dell VRTX

Annex B: Result diagrams

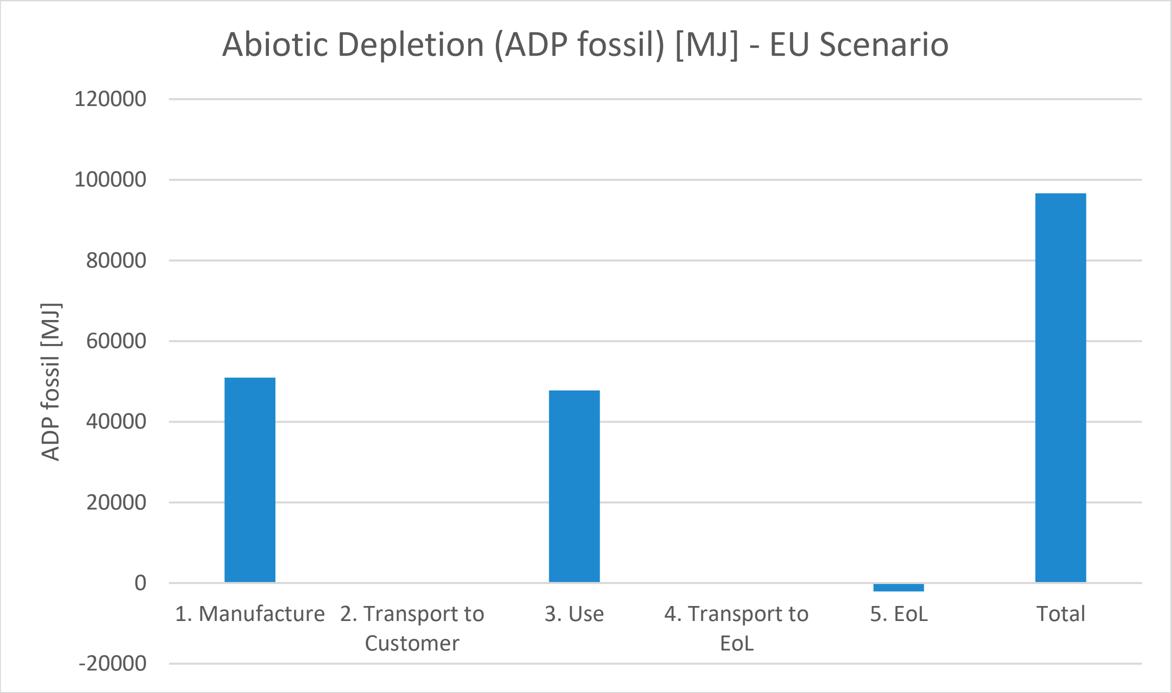

Figure B.5-13: Abiotic Depletion EU Scenario

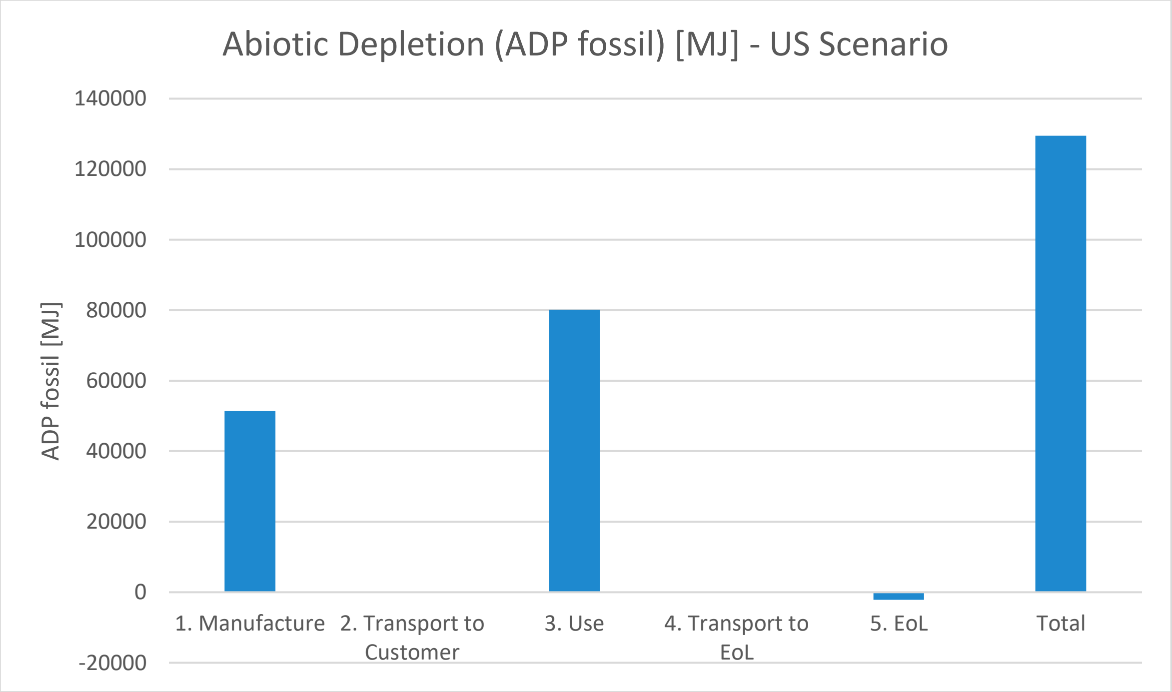

Figure B.5-14: Abiotic Depletion US Scenario

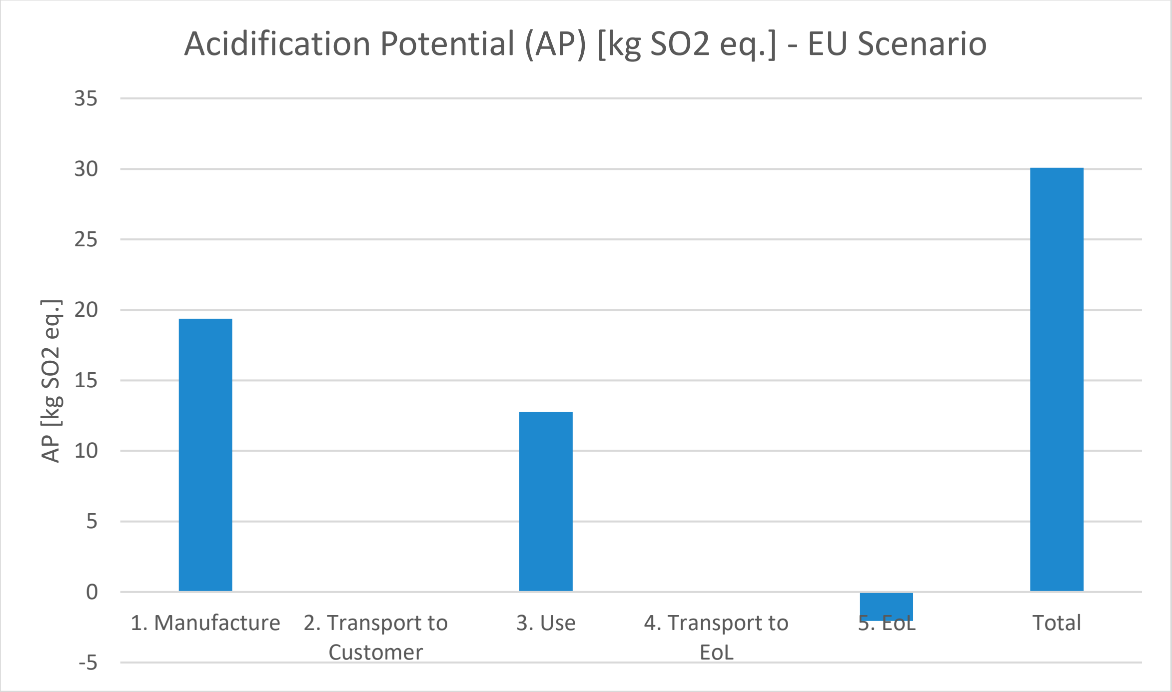

Figure B.5-15: Acidification Potential EU Scenario

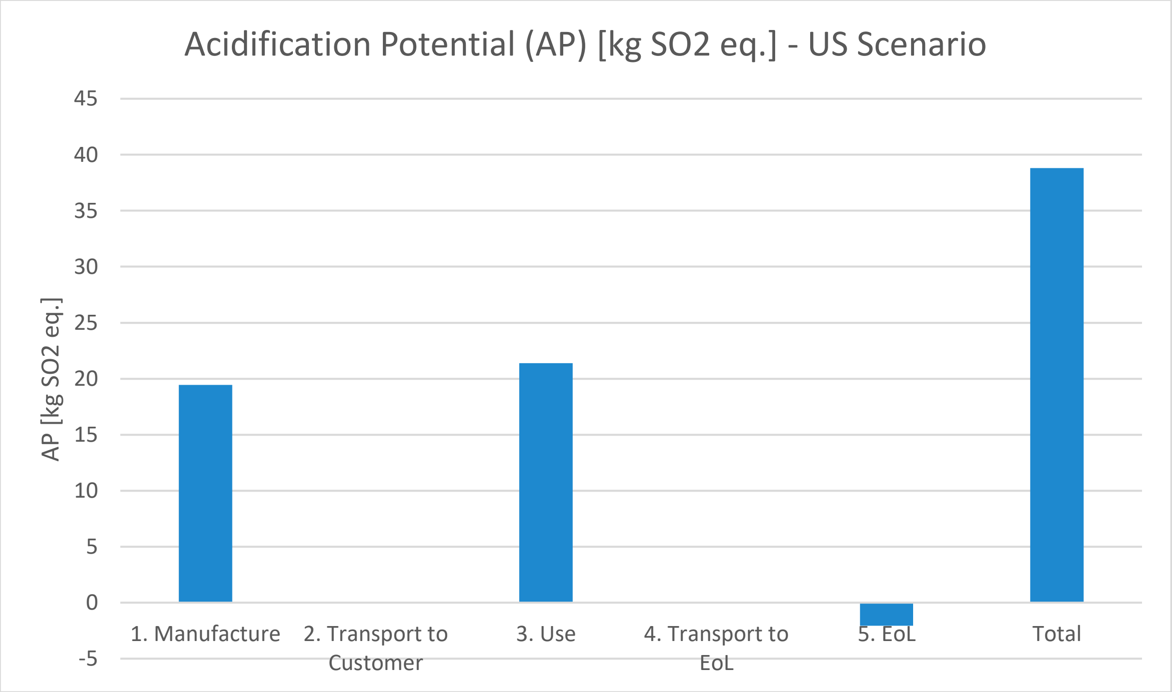

Figure B.5-16: Acidification Potential US Scenario

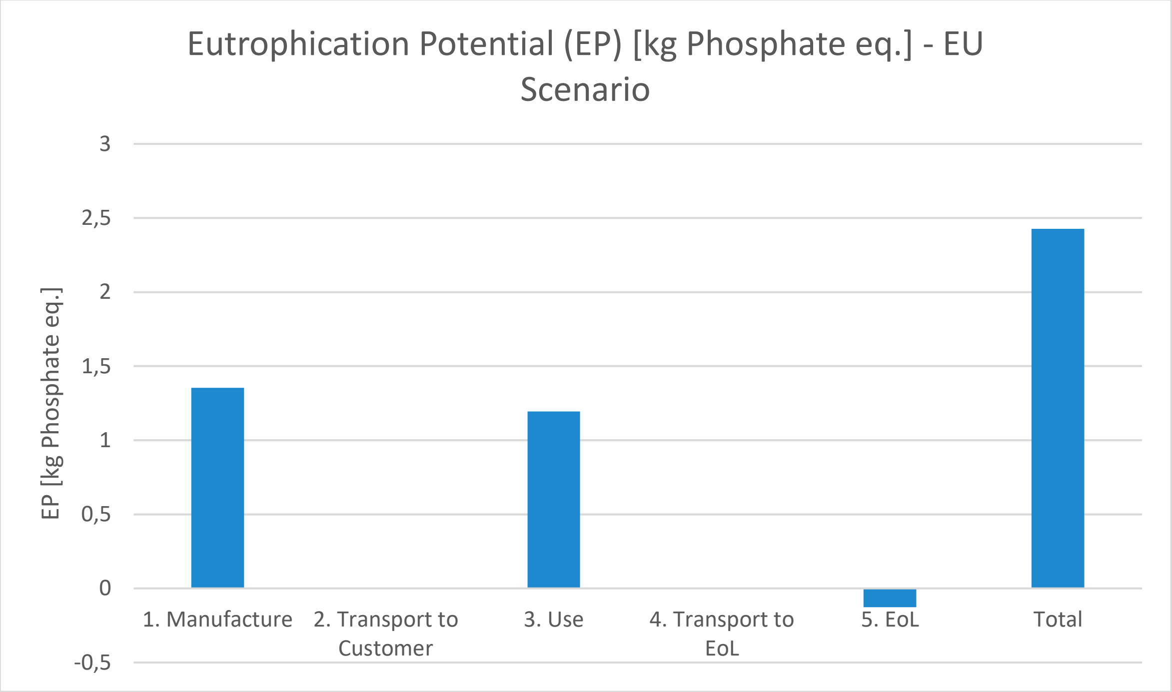

Figure B.5-17: Eutrophication Potential EU Scenario

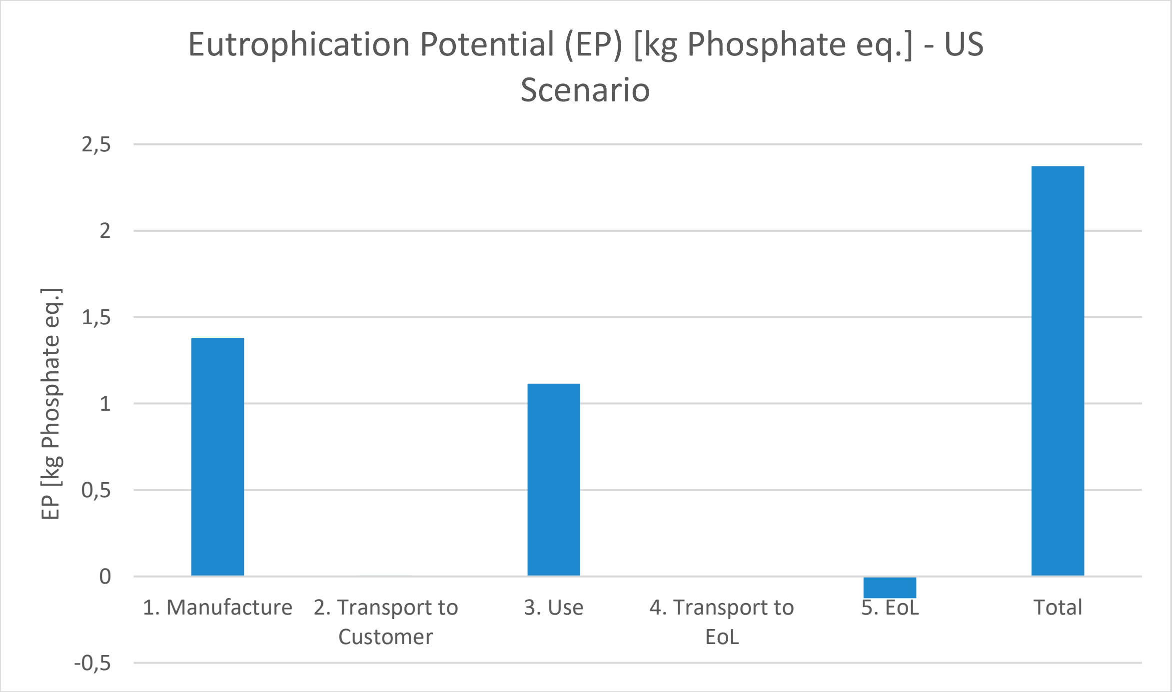

Figure B.5-18: Eutrophication Potential US Scenario

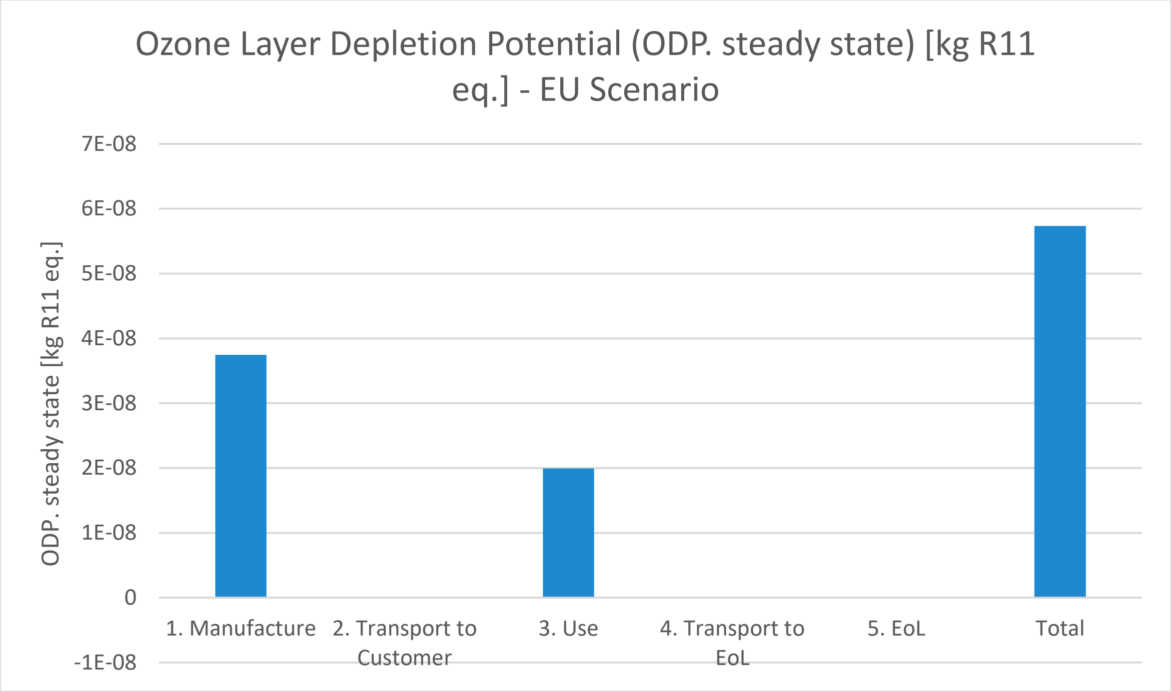

Figure B.5-19: Ozone Layer Depletion Potential EU Scenario

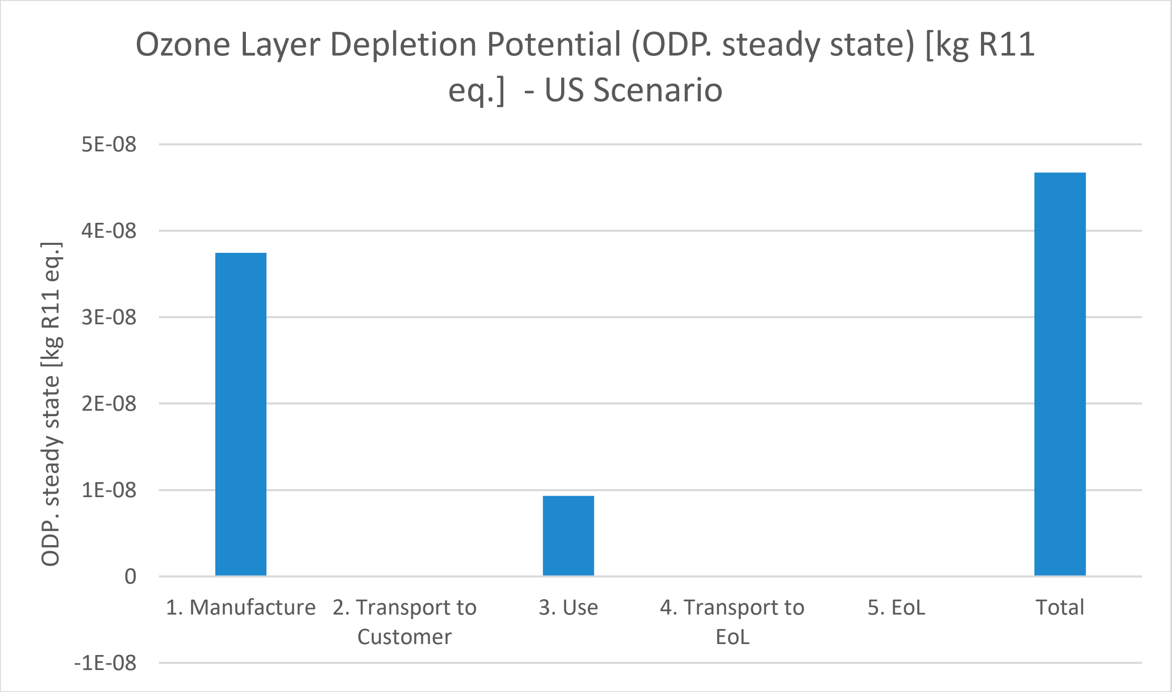

Figure B.5-20: Ozone Layer Depletion Potential US Scenario

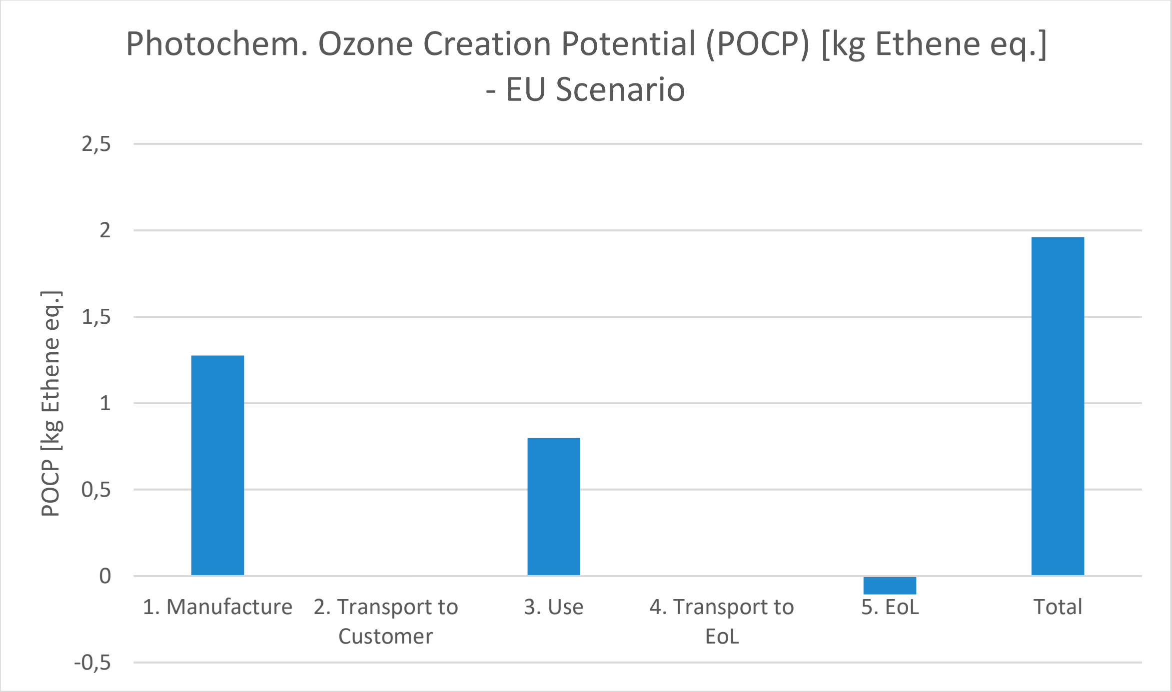

Figure B.5-21: Photochemical Ozone Creation Potential EU Scenario

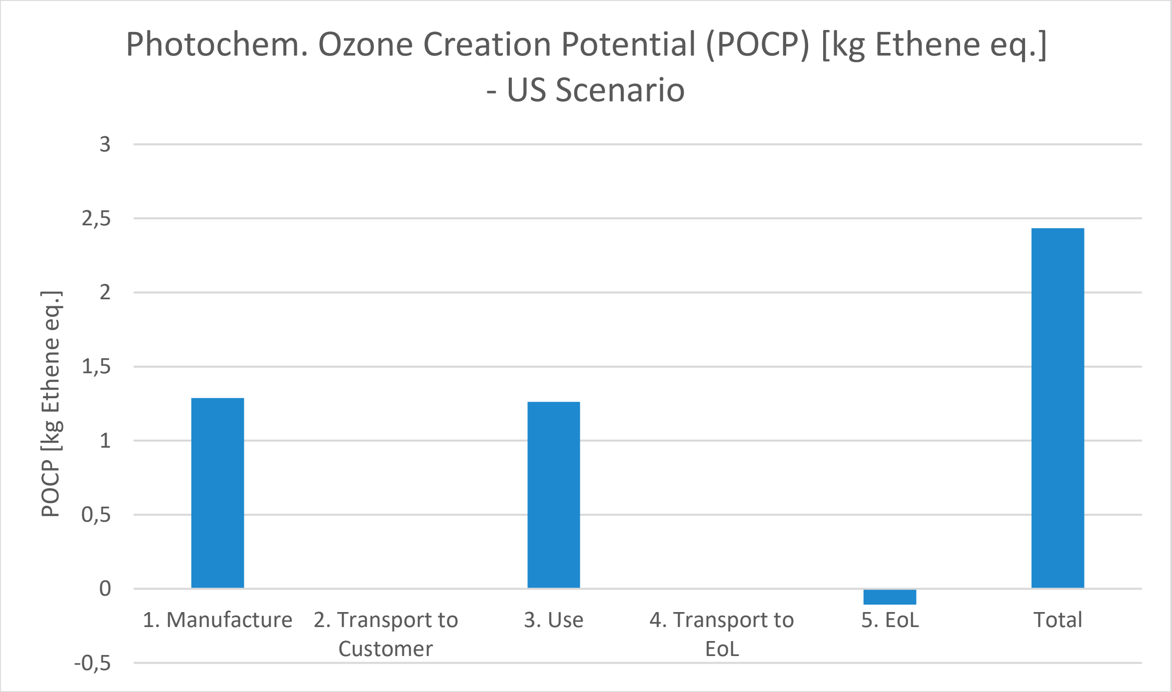

Figure B.5-22: Photochemical Ozone Creation Potential US Scenario

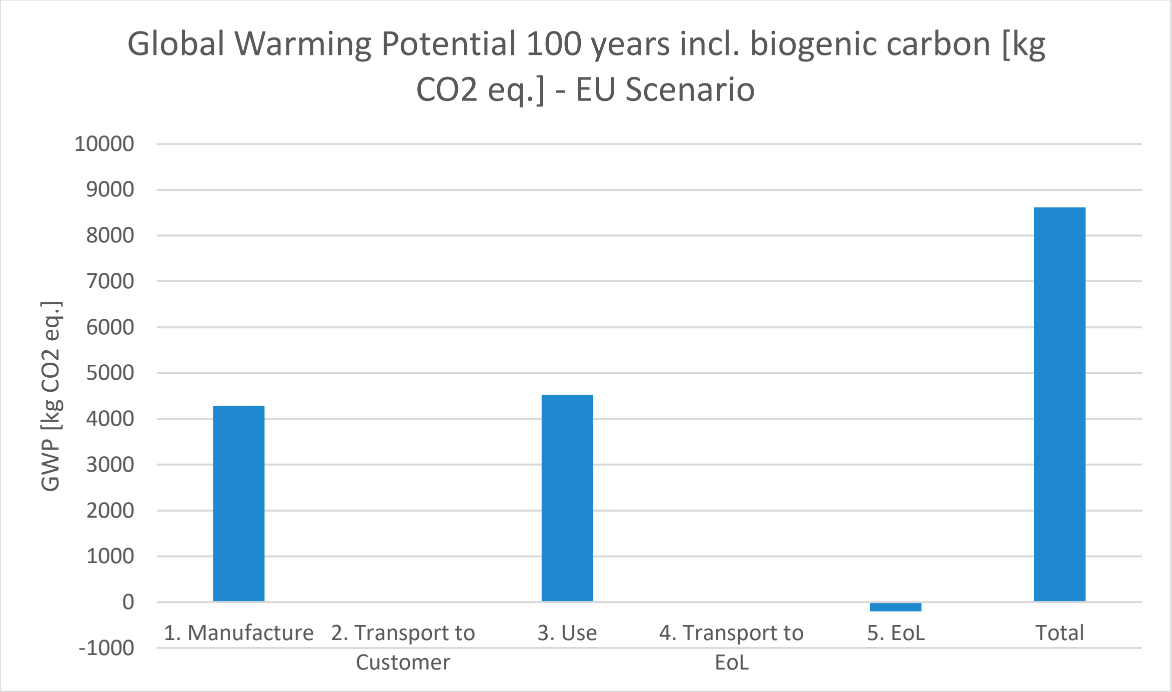

Figure B.5-23: Global Warming Potential EU Scenario

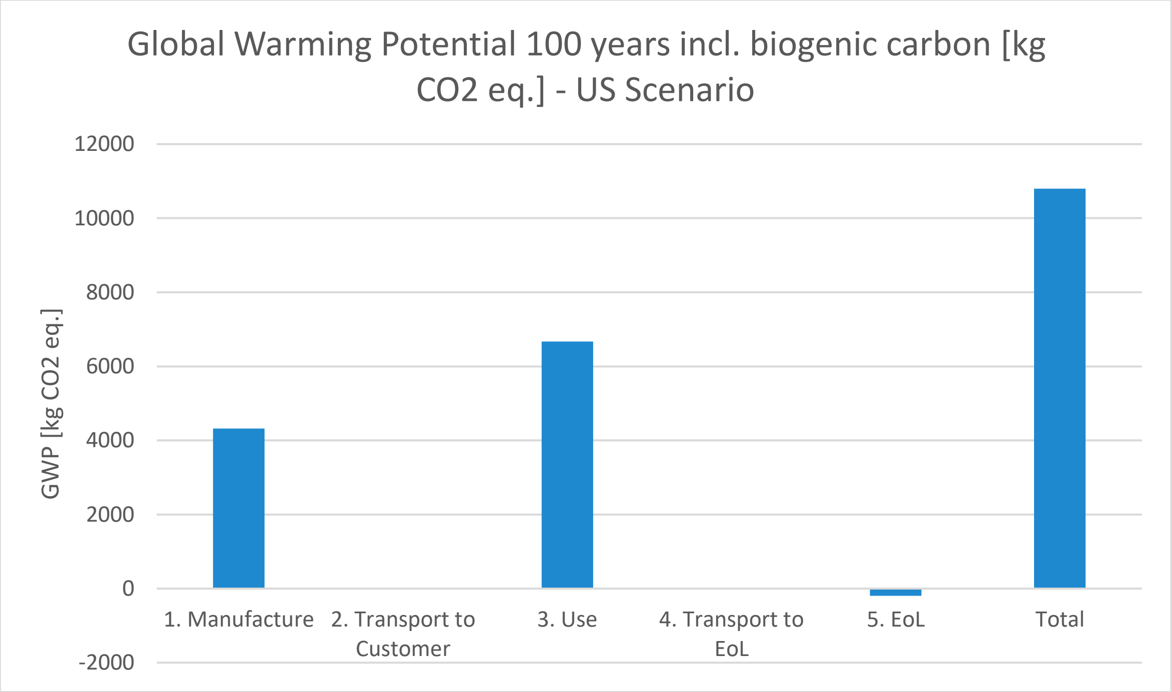

Figure B.5-24: Global Warming Potential US Scenario

Annex C: Background data

Table C.5-1: thinkstep GaBi background data used

Material	Geographic Reference	Dataset	Data provider	Reference Year
Back-end IC Electricity	KR	Electricity grid mix	ts	2017
	MX	Electricity grid mix	ts	2017
	MY	Electricity grid mix	ts	2017
	SG	Electricity grid mix	ts	2017
	TW	Electricity grid mix	ts	2017
Electronic	GLO	Assembly line SMD (1SP, 2CS, 1CP, 1R, 1Rf) throughput 300/h	ts	2017
	GLO	Assembly line SMD (1SP,1CS,1Rf) throughput 300/h	ts	2017
	GLO	Assembly line THT/SMD (1TP,1SP,1CS,1WO,1Rf) throughput 300/h	ts	2017
	GLO	Cable 1-core signal 24AWG PE (4.5 g/m) D1.4	ts	2017
	GLO	Cable 2-core audio headphone 32AWG PVC (2 g/m) D1.4	ts	2017
	GLO	Cable 4-core audio headphones with mic 32AWG PVC (4.7 g/m) D2.0	ts	2017
	GLO	Cable USB2.0 28AWG PE/PVC (18 g/m) D4.2	ts	2017
	GLO	Camera module (CMOS sensor)	ts	2017
	GLO	Capacitor Al-capacitor radial THT (110mg) D3x5	ts	2017
	GLO	Capacitor Al-capacitor radial THT (5.65g) D12.5x30	ts	2017
	GLO	Capacitor ceramic MLCC 01005 (0.054mg) D 0.4x0.2x0.22 (Base Metals)	ts	2017
	GLO	Capacitor ceramic MLCC 01005 (0.054mg) D 0.4x0.2x0.22	ts	2017
	GLO	Capacitor ceramic MLCC 0201 (0.17mg) D 0.6x0.3x0.3 (Base Metals)	ts	2017
	GLO	Capacitor ceramic MLCC 0201 (0.17mg) D 0.6x0.3x0.3	ts	2017

	GLO	Capacitor ceramic MLCC 0603 (6mg) D 1.6x0.8x0.8 (Base Metals)	ts	2017
	GLO	Capacitor ceramic MLCC 0603 (6mg) D 1.6x0.8x0.8	ts	2017
	GLO	Capacitor ceramic MLCC 1210 (50mg) D 3.2x1.6x1.6 (Base Metals)	ts	2017
	GLO	Capacitor film-capacitor unboxed RM15 (2.6g) 15x7x12	ts	2017
	GLO	Coil miniature wound SRR0804 (580mg) D10.5x3.8	ts	2017
	GLO	Coil multilayer chip 0402 (1mg) 1x0.5x0.5	ts	2017
	GLO	Connector board-to-board 0.4mm-pitch SMD 60-pin plug (25mg) 15x2.6x1.0mm	ts	2017
	GLO	Connector board-to-board 0.4mm-pitch SMD 60-pin socket (56mg) 15x2.6x1.0mm	ts	2017
	GLO	Connector coaxial micro-miniature W.FL SMD plug (18.6mg) 2.0x3.7x1.15mm	ts	2017
	GLO	Connector coaxial micro-miniature W.FL SMD socket (5.6mg) 1.7x1.7x0.85mm	ts	2017
	GLO	Connector SIM card mini THT/SMD socket (1.1g) 26x18x1.8mm	ts	2017
	GLO	Connector TRS 3,5 male (2,4 g, 1 pin)	ts	2017
	GLO	Connector USB micro (2,5 g, 4 pins, gold plated)	ts	2017
	GLO	Connector USB micro-AB THT/SMD 5-pin socket (260mg) 7.5x5.0x2.5mm	ts	2017
	GLO	Connector USB type A (1,6 g, 4 pins, gold plated)	ts	2017
	GLO	Connector USB Type-A 4-pin plug (9.2g) (gold-plated) 36x12x4.5mm	ts	2017
	GLO	Diode power THT DO201 (1.12g) D5.3x9.5	ts	2017
	GLO	Diode power THT DO35 (150mg) D1.76x3.77	ts	2017
	GLO	Diode signal SOD123/323/523 (1.59mg) 0.8x0.75x1.6 with Au-Bondwire	ts	2017
	GLO	Diode signal SOD123/323/523 (9.26mg) 2.4x1.6x1 with Au-Bondwire	ts	2017
	GLO	Filter SAW (25mg) 3x7x1	ts	2017
	GLO	IC BGA 48 (72mg) 8x6 mm MPU generic (130 nm node)	ts	2017
	GLO	IC SO 8 (76mg) 4.9x3.9 mm CMOS logic (90 nm node)	ts	2017
	GLO	IC SSOP 24 (123mg) 8.2x5.3 mm CMOS logic (65 nm node)	ts	2017

	GLO	IC TQFP 32 (146mg) 5x5 mm MPU generic (130 nm node)	ts	2017
	GLO	IC WLP CSP 49 (10.2mg) 3.17x3.17x0.55mm CMOS logic (14 nm node)	ts	2017
	GLO	IC WLP CSP 49 (10.2mg) 3.17x3.17x0.55mm CMOS logic (22 nm node)	ts	2017
	GLO	IC WLP CSP 49 (10.2mg) 3.17x3.17x0.55mm MPU generic (130 nm node)	ts	2017
	GLO	Key switch tact (242mg) 6.2x6.3x1.8	ts	2017
	GLO	LED SMD low-efficiency max 50mA (35mg) without Au 3.2x2.8x1.9	ts	2017
	GLO	Liquid Crystal Display (LCD), Panel Assembly LED TFT, mixed TN-IPS technology	ts	2017
	GLO	Lithium cobalt oxide cell (LiCoO2, LCO) - incl. housing, scaled up to 1 kg	ts	2017
	GLO	Micro Speaker (2g, dynamic, Nd magnet, SMD)	ts	2017
	GLO	Oscillator crystal (500mg) 11.05x4.65x2.5	ts	2017
	GLO	Phosphor bronze sheet part	ts	2017
	GLO	Printed Wiring Board 10-layer rigid FR4 with chem-elec AuNi finish (Subtractive method)	ts	2017
	GLO	Printed Wiring Board 1-layer rigid FR4 with chem-elec AuNi finish (Subtractive method)	ts	2017
	GLO	Printed Wiring Board 2-layer rigid FR4 with chem-elec AuNi finish (Subtractive method)	ts	2017
	GLO	Resistor flat chip 0603 (1.9mg)	ts	2017
	GLO	Resistor thick film flat chip 01005 (0.04mg)	ts	2017
	GLO	Resistor thick film flat chip 0201 (0.15mg)	ts	2017
	GLO	Resistor thick film flat chip 0402 (0.75mg)	ts	2017
	GLO	Resistor thick film flat chip 1206 (8.9mg)	ts	2017
	GLO	Ring Core Coil 8g (With housing)	ts	2017
	GLO	Thermistor SMD NTC 0402 (ca. 4mg)	ts	2017
	GLO	Thermistor SMD NTC 0603 (6mg)	ts	2017
	GLO	Thermistor THT NTC, Leaded Disk (120mg) D2.5x43	ts	2017
	GLO	Transistor power THT/SMD SOT93/TO218 3 leads (4.70g) 15.5x12.9x4.7	ts	2017
	GLO	Transistor signal SOT23 8 leads (18mg) 1.4x3x2	ts	2017

	GLO	Gold, primary (in Electronics)	ts	2017
	GLO	Housing IC	ts	2017
	DE	Lead frame	ts	2017
	GLO	Printed Wiring Board 2-layer rigid FR4 with chem-elec AuNi finish (Subtractive method)	ts	2017
	GLO	Semiconductor manufacturing CMOS logic 14 nm tech node	ts	2017
	GLO	Semiconductor manufacturing CMOS logic 45 nm tech node	ts	2017
	GLO	Semiconductor manufacturing DRAM 57 nm tech node	ts	2017
	GLO	Semiconductor manufacturing flash memory 45 nm tech node	ts	2017
	GLO	Solder paste SnAg3.5	ts	2017
Fabrication	GLO	Plastic extrusion profile	ts	2017
	GLO	Copper wire (0.6 mm)	ts	2017
	GLO	Plastic Film (PE, PP, PVC)	ts	2017
	GLO	Plastic injection moulding part (unspecific)	ts	2017
	GLO	Punching steel sheet small part ts <u-so>	ts	2017
	RER	Copper sheet rolling	ts	2017
	CN	Aluminium die cast part, machined	ts	2017
Metal	CN	Aluminum ingot	IAI/ts	2015
	CN	Copper Foil (11 µm) for 1 m2	ts	2017
	CN	Iron oxide (Fe_2O_3)	ts	2017
	CN	Magnet Nd-Fe-Dy-B	ts	2017
	DE	Fixing material screws stainless steel (EN15804 A1-A3)	ts	2017
	GLO	Copper mix (99,999% from electrolysis)	ts	2017
	GLO	Steel finished cold rolled coil	worldsteel	2014
Other	CN	Lubricants at refinery	ts	2017
	EU-28	Tap water	ts	2017
	EU-28	Water (desalinated; deionised)	ts	2017
	US	Laminated gorilla glass (0.7 x 0.76 x 0.7 mm)	ts	2017
Packaging	CN	Corrugated board (75% secondary content)	ts	2017
	CN	Corrugated board (paper and energy input open)	ts	2017

	CN	Kraftliner	ts	2017
	CN	Molded pulp loose from bagasse stand alone plant case (estimation)	ts	2017
	CN	Semichemical Fluting	ts/FEFCO	2015
	CN	Solid-Bleached sulfate (SBS) coated on one side (estimation)	ts	2017
	CN	Testliner	ts/FEFCO	2015
	DE	Oriented Polypropylene film (OPP)	ts	2017
	EU-28	Greyboard 50% RC	ts	2017
	EU-28	Kraft paper (EN15804 A1-A3)	ts	2017
	US	Paper waste on landfill, post-consumer	ts	2017
Plastic	CN	Polypropylene granulate (PP) (estimation)	ts	2017
	DE	Acrylonitrile-Butadiene-Styrene Granulate (ABS) Mix	ts	2017
	DE	Polybutylene Terephthalate Granulate (PBT)	ts	2017
	DE	Polycarbonate Granulate (PC)	ts	2017
	DE	Polyphenylene sulfide granulate (PPS)	ts	2017
	DE	Silicone rubber (RTV-2, condensation)	ts	2017
	DE	Toluene diisocyanate (TDI; Phosgenation)	ts	2017
	EU-28	Ethylene Propylene Diene Elastomer (EPDM)	ts	2017
	EU-28	Polyether polyol	ts	2017
	EU-28	Polyurethane foam (PU, flexible)	ts	2017
	CN	Polyethylene terephthalate granulate (PET via DMT)	ts	2017
Waste	EU-28	Inert matter (Aluminium) on landfill	ts	2017
	EU-28	Inert matter (Steel) on landfill	ts	2017
	EU-28	Inert matter (Unspecific construction waste) on landfill	ts	2017
	EU-28	Municipal waste water treatment (mix)	ts	2017
	EU-28	Plastic waste on landfill	ts	2017

Annex D: Critical Review Statement

Life Cycle Assessment of Dell R740 Rack Server

Commissioned by: Dell Computers

Conducted by: thinkstep AG

Reviewed by: Dr. Colin Fitzpatrick, University of Limerick, Ireland

Reference: ISO 14040 (2006): Environmental Management – Life Cycle Assessment- Principles and Framework

ISO 14044 (2006): Environmental Management – Life Cycle Assessment – Requirements and Guidelines

ISO/TS 14071 (2014): Environmental Management – Life Cycle Assessment- Critical Review Processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006

Scope of the critical review

The reviewer had the task to assess whether

- The methods used to carry out the LCA are consistent with the international standards ISO 14040 and ISO 14044
- The methods used to carry out the LCA are scientifically and technically valid
- The data used are appropriate and reasonable in relation to the goal of the study
- The interpretations reflect the limitations identified and the goal of the study
- The study report is transparent and consistent

The critical review was performed concurrently to the study as it is intended to be disclosed to the public and may be used to support comparisons with equivalent products.

The analysis and verification of individual datasets is outside the scope of this review.

The review process

The review process was co-ordinated by Dell between thinkstep and the critical reviewer. It began once the goal and scope definition had been finalised and commenced with a call on January 23rd 2019 where all parties involved in the assessment were introduced to the reviewer and the overall timeframe and process for the study and review were discussed and agreed. An early draft of the structure of the report was also provided at this time for comment and the reviewer submitted a first round of comments on January 28th 2019. A spreadsheet was used to log all comments including their exact location in the report, the comment and proposed change from the critical reviewer, and the action/answer to that comments when it was addressed. This ensured a systematic method of ensuring that every comment raised was satisfactorily addressed and concluded. Beginning the review process at this early stage provided the opportunity to highlight areas where particular attention was required to be paid to primary data collection in order to improve the data quality used. A draft final report was provided on April 10th 2019 and a further round of comments was provided by the critical reviewer on April 17th 2019. A video call was subsequently arranged for May 2nd 2019 to allow the critical reviewer to make direct queries about the GaBi models utilised. The final report was provided on May 24th 2019.

General Evaluation

This evaluation is based on the final report received on May 24th 2019. The goal and scope of the assessment are defined unambiguously. The functional unit is clearly defined and measurable. The system boundary appropriately includes all major life cycle stages from manufacture through to end of life and the chosen system configuration is representative of such server products being placed on the market. The team went to great lengths to itemise every single component included in the system for inclusion in the models. Any major assumptions which had a significant bearing on the results, including the die to package ratio and portion of time spent in different modes during the use phase, are well justified and a range of figures are used for both. It is also appropriate to include scenarios for both North America and Europe which considers the distances for shipping and energy mix in the use phase. The team also gathered important primary data about end-of-life treatment for such products directly from recyclers. The allocation procedures employed for recycling were appropriate. The life cycle impact assessment is performed to a high standard and includes all mandatory elements. The life cycle interpretation is comprehensive. One interesting finding is the very high burden during the manufacturing stage due to the Solid Stage Drives and the sensitivity of the results to the die to package ratio. The report correctly identifies this as an area that warrants further investigation. This finding also highlights the potential significance of data-wiping and reuse at end of life for the SSDs in these products and further work should be done to advance this area. The evaluation is comprehensive and includes considerate completeness, sensitivity and consistency checks. The report is prepared to a high standard.

The team was at all times very open and receptive to my comments and all were addressed to my full satisfaction. They were also very open in demonstrating all aspects of the models employed as part of the calculations.

Conclusion

The study has been carried out in conformity with ISO 14040 and ISO 14044. The critical reviewer found the overall quality and rigour of the methodology and its execution to be very adequate for the purposes of this study. The study is reported in a comprehensive manner and is transparent in its scope and methodologically choice.

Colin Fitzpatrick

27th May 2019