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Life Cycle Energy Assessment Methodology, Tool and Case Studies for Additive Manufacturing

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PREFACE

The purpose of this guidebook is to define a methodology and associated tool to consistently calculate the lifecycle energy consumption and savings for research, demonstration and development (RD&D) projects in additive manufacturing. The intended users are researchers, funding agencies, and technical staff working in the additive manufacturing industry. This guidebook supports a tool that can help evaluate when additive manufacturing is a more advantageous manufacturing method than conventional manufacturing, or to compare to different additive manufacturing methods. When used in conjunction with scenario analysis, the methodology can help estimate impacts of R&D for improvements in additive manufacturing technologies.

Chapter 1 (Introduction) covers the life cycle assessment concept, background on Additive Manufacturing (AM), sustainable benefits of AM processes, the need for a consistent methodology to calculate life cycle energy consumption and savings for RD&D projects in AM, and previous work on AM Energy Use and Life Cycle Assessment.

Chapter 2 (Overview) introduces the life cycle phases and the life cycle assessment methodology, including identifying and setting boundaries for life cycle phases, and the calculation of embodied energy of materials, processes, and transportation modes.

Chapter 3 (Tool) provides an outline of the Excel based Additive Manufacturing Energy Impacts Assessment Tool. It provides detailed instructions for the Excel based calculator tool including the general calculation process and the typical information that is needed at each step to do the calculations.

Chapter 4 (Case Studies) provides a walkthrough of four specific case studies as examples using the AM Energy Impacts Assessment Tool. The two life cycle energy case studies for aircraft brackets compare 1) the same metal part made by additive manufacturing to the conventional process; and 2) an optimized metal part designed for additive manufacturing to the conventionally designed and produced part are discussed in detail. The third case study covers the Aircraft Ventilation Nozzle manufactured by the Fused Deposition Modelling process. The fourth case study is based on a Hat Section Mold manufactured by the Fused Deposition Modelling process.

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ABBREVIATIONS, ACRONYMS, AND INITIALISMS

AM	Additive Manufacturing
AMO	Advanced Manufacturing Office
BBtu	Billion Btu (10^9 Btu)
Btu	British Thermal Units
CO_2	Carbon dioxide
DOE	Department of Energy
EERE	Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
EPA	Environmental Protection Agency
EPACT	Energy Policy Act
ITP	Industrial Technologies Program
MECS	Manufacturing Energy Consumption Survey
MER	Monthly Energy Review
MMBtu	Million Btu (10^6 Btu)
$MMTCO_2$	Million metric tons of carbon dioxide
ORNL	Oak Ridge National Laboratory
RECS	Residential Energy Consumption Survey
TBtu	Trillion Btu (10^{12} Btu)

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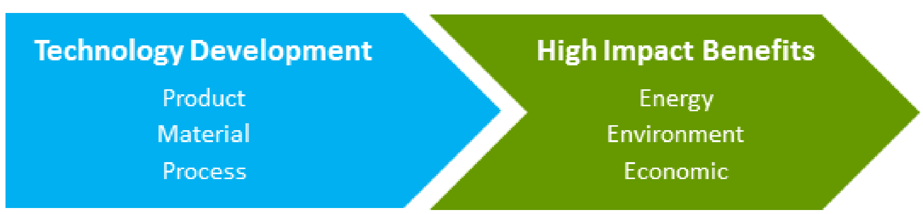
CHAPTER 1 - INTRODUCTION

Background

The U.S. Department of Energy's Advanced Manufacturing Office (AMO) supports research, development and demonstration (or deployment) (RD&D) in Additive Manufacturing (AM) at a number of venues, including the Oak Ridge National Laboratory (ORNL) Manufacturing Demonstration Facility (MDF) in Oak Ridge, TN and America Makes, the National Additive Manufacturing Innovation Institute in Youngstown, OH. Evaluating new products, materials, and processes (Figure 1) using the traditional energy analysis methods tends to evaluate technologies narrowly, where impacts are assessed at the plant level or perhaps on an industry sub-sector basis. A more comprehensive assessment of the energy impacts considers energy requirements from all phases (cradle-to-grave/cradle), which requires an accurate accounting at each phase. When considering the entire life cycle energy demands, the AM process and the products manufactured using the AM process have the potential to reduce energy over a product's entire lifespan. Hence, there is a need for a consistent methodology to calculate life cycle energy consumption and savings for RD&D projects in AM to capture the impact of the program investments as well as AM as a foundational technology. AMO is engaged in the development of several analytical methodologies and associated tools such as the Materials Flow through Industry (MFI) tool as well as the **L**ife Cycle **I**ndustry **GH**gas, **T**echnology and **E**nergy through the **U**se **P**hase (LIGHTEn-UP) tool can provide a cross-sector perspective on the energy impacts resulting from innovations in materials and manufacturing technologies. These tools form the foundation for the life cycle assessment methodology work presented in this report.

Figure 1: AMO Technology Focus [DOE AMO]



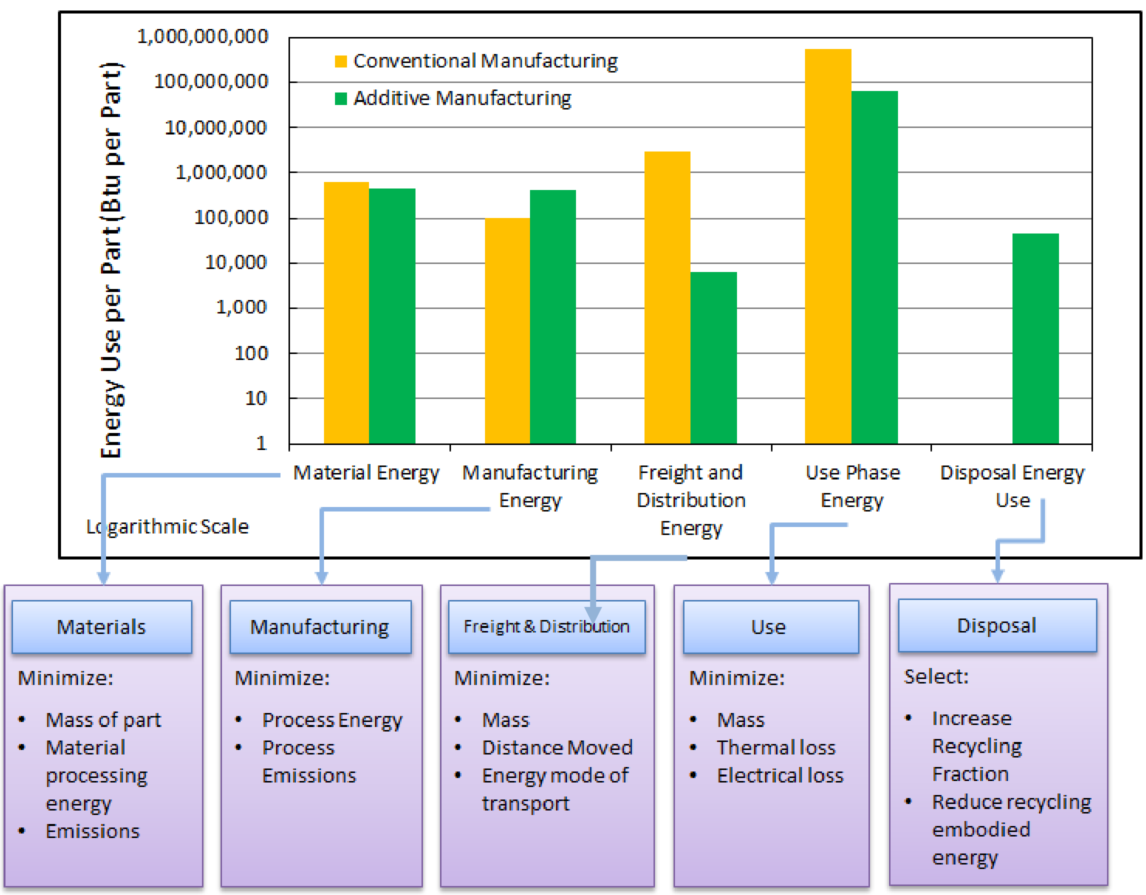
The overall goal of this report is to define a methodology to consistently calculate the life cycle energy consumption and savings for RD&D projects in AM. The approach is to define and calculate the energy requirements at each step of the AM process - drawing in part from the wide range of primary data available from subject matter experts as well as scientific literature. ORNL has developed an AM life cycle specific methodology, basic tool with guidance and has provided some case studies in this report to inform RD&D researchers on how to perform these calculations. Many of the funding agencies, practitioners and researchers in AM might not be familiar with life cycle energy assessment and therefore providing a consistent methodology to express the energy impacts will serve this community to better understand the complete energy footprint of AM products, as well the potential impact of AM RD&D activities. Further effort to create a library of material and process data may be used to refine the tool and methodology.

Life Cycle Assessment Concept

Life Cycle Assessment (LCA) is a methodology that considers all the resources and emissions associated with a product or process over its entire life cycle. Cumulative energy content – or embodied energy – of a product over the life of the product can be calculated using LCA. We will consider the product lifecycle using five phases: 1. Material, 2. Manufacturing, 3 Freight & Distribution, 4. Use, and 5. Disposal (Figure 2). The methodology for the tool is derived from the work of numerous LCA researchers, including Michael Ashby [M. ASHBY], B. W. Vigon [VIGON 1992], Martin Baumers [BAUMERS 2013], Geert Bergsma [BERGSMA 2013], and other important references listed in the reference chapter.

1. Material Phase: The material phase includes all the energy required to process a material (or materials) into a form that can be used to fabricate a particular product. The materials used in conventional as well as additive manufacturing processes may come in different forms and shapes. For example: metal ingots vs. metal powders, polymer pellets vs. extruded filaments, etc. The material phase includes all the energy required to process materials from mines to the manufacturing facility gate. This energy consumption is also called the embodied energy of the material. Please note – embodied energy of metal powder includes embodied energy of raw metal and additional energy required in the atomization process (metal to metal powder). Similarly, embodied energy of extruded polymer wires include embodied energy of polymer pellets and additional energy required in the extrusion process.

Figure 2: Reduced product life-cycle energy consumption through AM



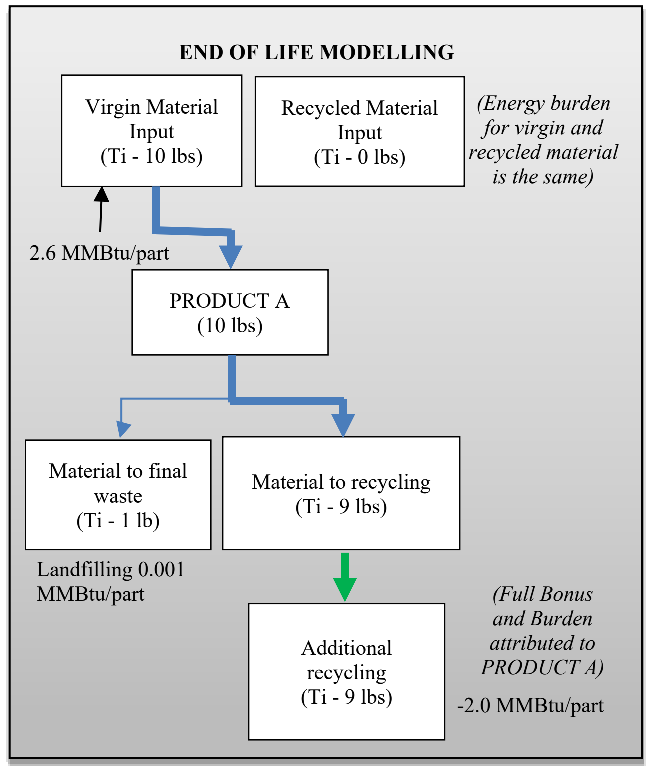
2. Manufacturing Phase: This phase includes product fabrication steps and the energy required to fabricate a product (using subtractive or additive process) from manufactured materials. The total energy consumed in manufacturing phase can be divided into three parts: i. Energy consumed by primary, secondary, and tertiary shaping and finishing processes; ii. Energy consumed in post-machining processes such as heat treating, stress relieving, brazing, HIP, inspection, etc.; and iii. Embodied energy of tooling and machine tools used in the manufacturing process.

3. Freight and Distribution Phase: This phase includes stepsthat prepare the final product for shipment, and the transport of the products from one location to the next. Energy use is a function of the transport mode(s), and weight of the component part, and distance the part travels through the supply chain.

4. Use Phase: Begins after the distribution of products or materials for intended use and includes any activity in which the product or package may be reconditioned, maintained, or serviced to extend its useful life. For example - parts used on the aircrafts, components mounted on vehicles, etc. In the case of part use, for static products, impact on energy use may be negligible. However, for transport related products, such as aerospace and automotive components, energy use is a function of the parts weight, its working life cycle on the vehicle, and the type of vehicle into which the component parts is integrated.

5. Disposal or End of Life Phase: Begins after the product has served its intended purpose and either will enter a new system through recycling (open-loop recycling or closed-loop recycling) or waste management (landfill, combustion or incineration, or composting). In open-loop recycling, products are recycled into new products that are eventually disposed. In closed-loop recycling, products are recycled again and again into the same product. There are multiple methods available for accounting energy use in the disposal or end of life phase. While selecting the energy accounting method, it is important to consider multiple factors such as promotion of the collection of secondary materials as well as question of fairness (who pays for recycling and who gets benefits?). The AM Energy Impacts tool uses "End of Life (EOL)" method [Bergsma, 2013] as it promotes recycling and rewards recycling effort (see Figure 3). The EOL method uses the following approach:
    a. Secondary or recycled materials that are INPUT to a process have the same attached environmental burden as virgin materials;
    b. Secondary materials on the OUTPUT side leave the product system causing extra environmental burden (energy use for melting and transport for collection, sorting) as well as an environmental bonus (avoided burden virgin material production); and
    c. The benefit of recycling goes entirely to product under consideration (e.g. Product A, Figure 3).

Figure 3: End of Life Method [BERGSMA 2013]



As shown in Figure 3, Product A is manufactured using 10 lbs of virgin Titanium (Ti) material. Assuming embodied energy of Ti equal to 263,328 Btu/lb, energy consumed per part in the material phase is 2.6 MMBtu/part. In the disposal phase, 9 lbs of Ti are recycled and 1 lb is wasted or land-filled. By assuming embodied energy of recycled Ti equal to 37,403 Btu/lb, avoided energy burden for virgin Ti is -2.0 MMBtu/part (0.3 - 2.4 MMBtu/part). By assuming landfilling energy intensity equal to 1000 lbs/lb, amount of energy wasted to landfill 1 lb of wasted Ti is 0.001 MMBtu/part. Hence total disposal energy per part using the EOL approach is -2.0 MMBtu/part.

Previous Work on Additive Manufacturing Energy Use and Life-Cycle Assessment

Conventional manufacturing (subtractive) processes, such as machining, form an important comparison technology to metallic AM and injection molding (IM) forms an important comparison technology for polymer AM. Significant amount of research and number of studies are conducted assessing the relationship between energy inputs and process parameters and life cycle energy use for subtractive processes and other processes like IM. On the other hand, a negligible amount of research has been conducted in evaluating the life cycle energy of products made using AM processes to date. When assessing the life cycle energy of an AM product, it is vital to consider the material, manufacture, freight and distribution, use, and the part disposal phase. Although AM processes may use more energy than conventional processes per unit mass of material processed, they do enable the production of parts with optimized shapes and geometric features that reduce raw materials and component weight. For example, in aircraft parts, the primary environmental and energy efficiency benefit of AM is during the use phase of the part. By enabling optimized part manufacture, significant weight savings can be realized, which can greatly reduce the fuel consumption of aircraft. In addition, localized production enabled by additive manufacturing could lead to a reduction in the energy used in freight and distribution of final products.

Summary of Literature Review

In 2013, Florent Bourhis and Olivier Kerbrat of *Institut de Recherche en Communications et Cybernétique de Nantes, France* [IJAMT 2013] presented a methodology to evaluate AM where all flows consumed (material, fluids, and electricity) are considered in the environmental impact assessment. Their article presented a life cycle framework to evaluate the energy consumption in the AM machine. They modeled each feature of the machine such as electricity, material, and fluid consumption. Their study excluded some parameters like powder production, inert gas production, hydraulic fluid production, and compressed air production and consumption. In addition, their approach didn't include powder recycling, material and energy used to manufacture the machine tools, parts recycling, machine tool recycling, etc.

In June 2013, Martin Baumers of the University of Nottingham (Baumers, 2013) investigated in their Journal of Industrial Ecology article whether the adoption of AM technology can be used to reach transparency in terms of energy and financial inputs to manufacturing operations. As per Baumers, the parallel character of AM (allowing the contemporaneous production of multiple parts) poses previously unconsidered problems in the estimation of manufacturing energy consumption. Their research discusses the implementation of a tool for the estimation of process energy flows and costs occurring in the AM technology variant direct metal laser sintering. They demonstrated that accurate predictions of manufacturing energy consumption per part can be made for the production of a basket of sample parts. The AM Energy Impacts Assessment tool uses the manufacturing phase energy estimation methodology discussed in Baumers' article.

Components for Energy Efficiency in Transport by Additive Manufacturing (CEEAM) project [CEEAM 2012] is funded by the Transport iNet (part of the East Midlands Development Agency, UK). The CEEAM project tackles issues preventing the growth of AM in the high-performance engineering sector, with a specific focus on the space industry. At present, it is not possible to exploit the advantages of AM due to concerns with respect to the integrity of the parts. One of the primary concerns is that every layer must be processed correctly otherwise part integrity is jeopardized. Moreover, before a new manufacturing process or material can be used for demanding space applications, a qualification process must be undertaken. The project also produced lightweight satellite components. The current launch cost of a satellite is about $13,800 per lb of load, so it showed clear economic and environmental benefits to reducing weight. Within this project, only the final part weight was considered and not the energy implications of either the raw material used or the manufacturing efficiencies of AM.

Led by Loughborough University in UK, the Atkins project [Atkins 2011] was set out to understand and quantify the energy efficiency and environmental benefits of using the AM process for the production of components within the aerospace and automotive supply chain. Aircraft TV monitor arms were redesigned using topological optimization software to significantly reduce mass while maintaining strength and stiffness. The parts were then manufactured using laser sintering or selective laser melting (SLM). These AM processes were found to consume between 10 and 100 times more energy per lb of material processed than computer numerical control (CNC) machines but reducing the weight by 5.25 lb/arm for these parts. Despite increasing the direct energy required to manufacture the part, the AM process reduces manufacturing sector energy through the reduction of aluminum requirements. However, these savings are relatively minor compared to the use-phase energy savings that lighter aircraft parts allow if deployed into airline fleets.

The research work at The University of Texas at Austin [UT Austin 2010] quantified the material and energy use of Selective Laser Sintering (SLS) nylon parts and compared these estimates with Injection Molding (IM) parts. The results indicated that SLS nylon parts are not as energy efficient as IM parts when considering nylon material and energy consumed during the material and part production process. They didn't take into consideration freight and distribution, use phase, and end of life phases in their research work. Supply chain effects such as reduced freight and distribution and infrastructure costs could make SLS more favorable. Additionally, one of the advantages of SLS is its ability to produce parts that cannot be manufactured using IM. These parts, with optimized geometries, have the opportunity to increase the efficiency of end-use applications.

The SAVING project (**S**ustainable product development via design optimization and **A**dditi**V**e manufactur**ING**) was established in September 2009 [SAVING 2009] and funded by the Technology Strategy Board in the United Kingdom. The SAVINGS project focused on design and process optimization, applied to AM, with the objective of creating innovative designs that could be manufactured or used more efficiently than with conventional practices. Design optimization and analysis of hollow and cellular structures was investigated, and parts were manufactured using the EOS Direct Metal Laser Sintering (DMLS) process. Through a series of case studies from the aerospace and automotive industries (cylinder head, heat exchanger, airline buckle, etc.), the project demonstrated that DMLS can be used to reduce the energy impact of vehicles by designing and manufacturing parts that weigh less.

In 2004, Jeffrey Dahmus and Timothy Gutowski with Massachusetts Institute of Technology [MIT 2004] presented a system-level environmental analysis of conventional machining process in their ASME paper. The analysis presented considers not only the environmental impact of the conventional material removal process, but also the impact of associated processes such as material preparation and cutting fluid preparation. This larger system view results in a more complete assessment of machining. Energy analyses show that the energy requirements of actual material removal can be quite small when compared to the total energy associated with machine tool operation. Also, depending on the energy intensity of the materials being machined, the energy of material production can, in some cases, far exceed the energy required for machine tool operation. This work can be used to do similar kind of analysis on AM processes.

Conclusions

The literature review indicates that while previous studies have advanced the practice of LCA assessment for additive manufacturing, none have been sufficiently comprehensive - either not covering the full life cycle (i.e. lacking raw material inputs, or end of life inputs) of a product, or based on a limited to a narrow set of additive processes. A tool and approach to cover the complete life cycle of a product and account for the range of additive processes and materials was lacking – which this methodology and the AM tool seek to address.

It was also noted from the literature review that there are significant inconsistencies in the energy intensity data for additive manufacturing processes. Compared to the traditional manufacturing processes (machining, casting, forging, etc.), process energy intensity data for relatively new additive manufacturing processes is very limited. Detailed data about MJ/kg (or Btu/lb) for AM processes and for different materials is often lacking. The energy experiments conducted by other researchers so far (see literature summary) were incomplete; the work did not include a full range of power measurements on different additive machines using a range of materials nor have previous studies identify power levels in different operating modes. In general, previous work was focused on specific technologies (e.g. EBM machines) rather than covering all technology platforms (EBM, SLM, FDM, etc.).

Within the LCA framework, there are areas where the integration of additional data can improve the energy estimates. There is a need to design and conduct experimental studies on energy, production time, and consumables (compressed air, nitrogen, argon, helium, etc.) and to develop process energy intensity (Btu/lb) and machine productivity (lb/hr) databases for various additive manufacturing platforms and materials. Experimental studies could provide detailed data on energy intensities for the most common AM processes and for different materials. The methodology and tool have been designed to be adaptable to new data and information that can expand the fidelity of the energy estimates. The data from additional experimental studies could be used to validated the AM tool and be directly used in the AM tool to make it more valuable, accurate, and consistent.

CHAPTER 2 – OVERVIEW OF LIFE-CYCLE ASSESSMENT METHODOLOGY

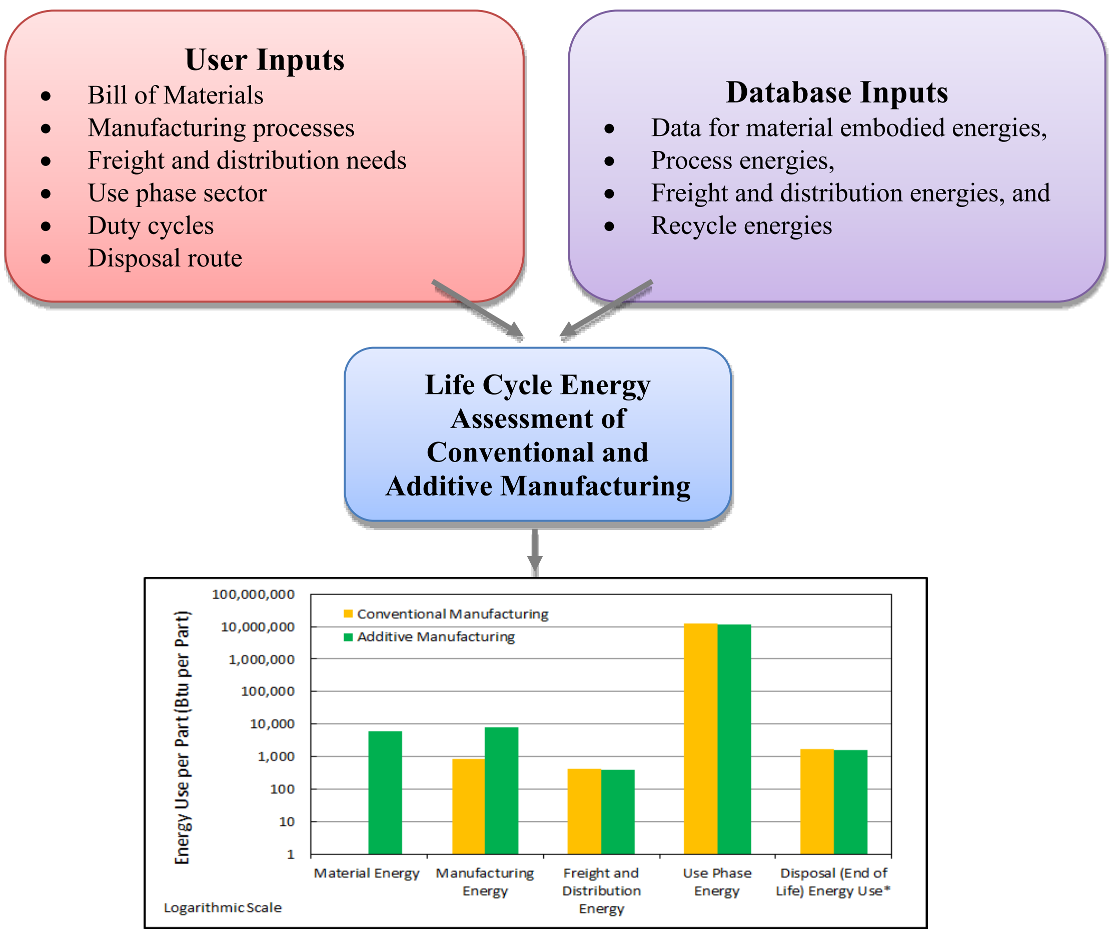
Figure 4 shows the procedure and associated inputs required and outputs generated for life-cycle energy assessment of a product manufactured either by conventional or additive manufacturing process. The **inputs** to the calculator are of two types: **i. User Inputs** and **ii. Database Inputs**.

User Inputs are shown in the top left of the flow diagram and include:

- Bill of materials,
- Manufacturing process choice,
- Freight and distribution requirements,
- Use phase sector,
- Duty cycle (the details of the energy and intensity of use), and
- Disposal route

Figure 4: Overview of life-cycle assessment methodology.

User inputs are combined with the data drawn from databases of embodied energy of materials, processes, freight and distribution energies and energy conversion efficiencies to create the energy use breakdown.



Database Inputs are shown in the top left of the flow diagram and include:

- Data for material embodied energies,
- Process energies,
- Freight and distribution energies, and
- Recycle energies – energy conversion efficiencies that are drawn from look-up tables stored in other tabs.

The Outputs are the energy footprint of each phase of life, represented as bar charts and in tabular form. The results also provide energy savings per part of each phase of life and overall energy savings with respect to conventional manufacturing process.

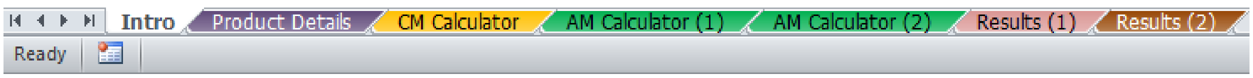
The procedure is explained in detail in chapter 3 and illustrated by case studies in chapter 4.

CHAPTER 3 – AM ENERGY IMPACTS ASSESSMENT TOOL

Outline of the Tool

This section provides guidance on how to use the Excel based tool and utilize the built-in life cycle framework. The tool is also referred as the calculator in this report.

The AM Energy Impacts Assessment Tool includes the following seven major tabs:

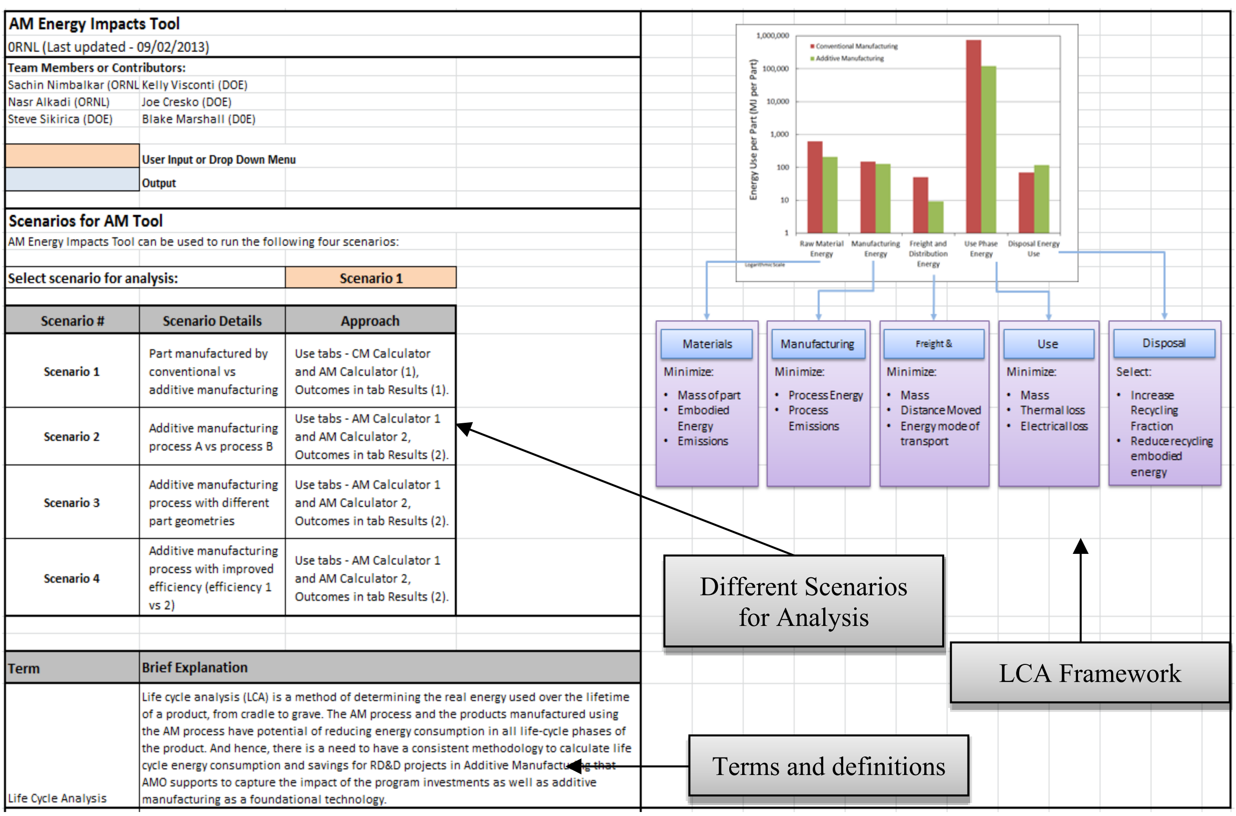


- Intro Tab
- Product Details Tab
- CM Calculator Tab (CM – Conventional Manufacturing)
- AM Calculator Tabs 1 and 2 (AM – Additive Manufacturing)
- Results Tabs 1 and 2

Intro

All users are recommended to start their analysis with the Intro Tab (see Figure 5). The Intro tab provides a drop down menu of different LCA scenarios for analysis. It also explains the LCA framework and defines various LCA terms used in the analysis.

Figure 5: AM Energy Impacts Assessment Tool - Intro Tab



The AM Energy Impacts Assessment tool can be used to run four different scenarios which are described in Table 1. The user selects a specific scenario for analysis using the drop-down menu. Based on the user's selection some tabs are automatically hidden or made visible. For example – if user selects scenario 1, tabs CM Calculator, AM Calculator (1), and Results (1) are shown but AM Calculator (2) and Results (2) are kept hidden. The Table 1 provides more information.

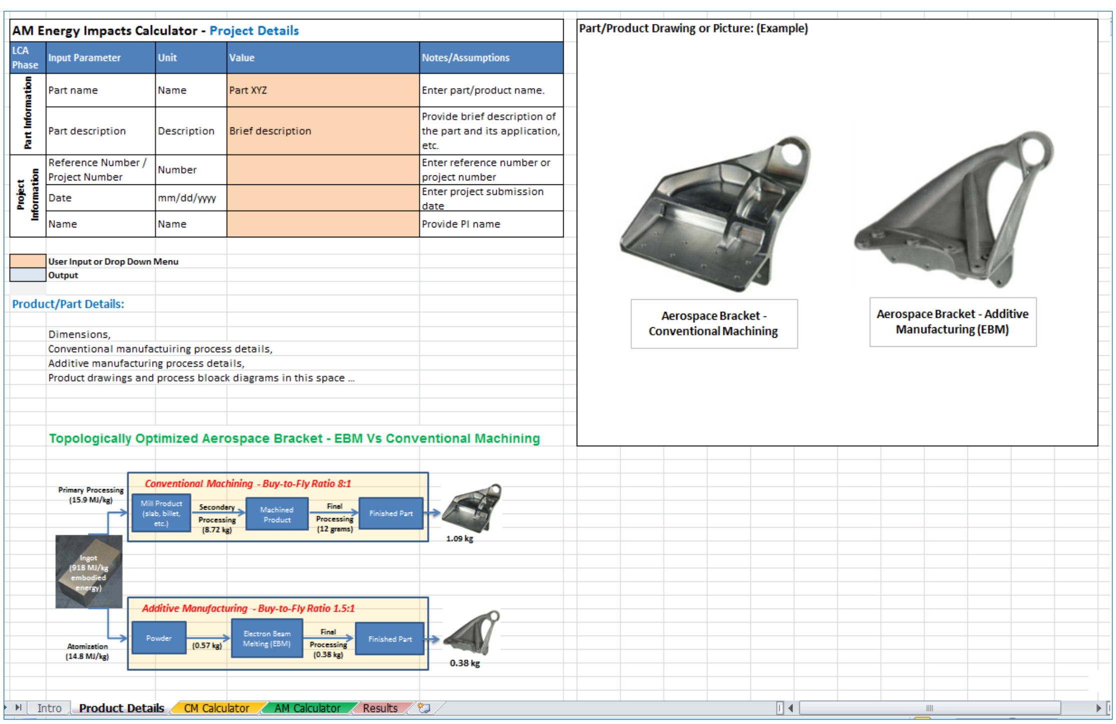
Table 1: Different scenarios for the AM Energy Impacts Assessment Tool

Scenario #	Scenario Details	Approach
Scenario 1	Part manufactured by conventional vs. additive manufacturing	Use tabs - CM Calculator and AM Calculator (1), Outcomes in tab Results (1).
Scenario 2	Additive manufacturing process A vs. process B	Use tabs - AM Calculator 1 and AM Calculator 2, Outcomes in tab Results (2).
Scenario 3	Additive manufacturing process with different part geometries	Use tabs - AM Calculator 1 and AM Calculator 2, Outcomes in tab Results (2).
Scenario 4	Additive manufacturing process with improved efficiency (efficiency 1 vs. 2)	Use tabs - AM Calculator 1 and AM Calculator 2, Outcomes in tab Results (2).

Product Details

The Product Details tab provides space for users to capture and document part details, part dimensions, conventional and additive manufacturing process details, process diagrams, and product diagrams. Figure 6 shows an example of optimized Titanium alloy bracket manufacturing using conventional and additive manufacturing processes.

Figure 6: Product Details Tab



CM Calculator

CM stands for Conventional Manufacturing. CM Calculator Tab covers life cycle assessment for conventional manufacturing process to determine energy used over the lifetime of a product, from cradle to grave.

When using the CM Calculator Tab, use the following color codes. The light orange color cells are user input cells where data is either entered by the user or selected from a drop down menu. Light blue color cells indicate outputs from calculations programmed in the tool. Cells with white background include labels, instructions, notes and formulae. No inputs are needed from the users in these white background cells.

(light orange)	User input or Drop Down Menu
(light blue)	Outputs from Calculations
(gray)	Energy Output

The CM calculator tab begins with the part information. Once user provides this information in the CM calculator tab, the same information is copied to the AM calculator tab and results section.

Part Information:

AM Energy Impacts Assessment Tool - Conventional Manufacturing Process				
LCA Phase	**Input Parameter**	**Unit**	**Value**	**Tool Guidance**
Part Information	Part name	Name	*Part XYZ*	Enter part/product name manufactured by the conventional manufacturing process under consideration.
	Part description	Description	*Brief Description*	Provide brief description of the part and its application, etc.

The CM lifecycle assessment calculator covers all five lifecycle phases, described here for energy.

Material Phase Energy Analysis:

In this step, the user is asked to draw up a bill of materials and provide the mass of each component used in the product and the material of which it is made. As described in Chapter 1, the materials used in conventional as well as additive manufacturing processes may come in different forms and shapes (For example: metal ingots vs. metal powders, polymer pellets vs. extruded wires, etc.). At present, the tool can only handle parts made from two materials. User provides data for material # 1 first. If material # 1 amount in the product is < 100% (this means the product is produced using more than one material), the tool brings up options for a second material. The tool's ability to handle parts made from more than two materials will be added in subsequent revisions. Data for the embodied energy (Btu/lb) per unit mass for each material is retrieved from the database. Please note – embodied energy of metal powder includes embodied energy of raw metal and additional energy required in the atomization process (metal to metal powder). Similarly, embodied energy of extruded polymer wires include embodied energy of polymer pellets and additional energy required in the extrusion process. Multiplying the mass of each component by its embodied energy and summing give the total material energy – the first bar of the bar chart in Figure 2.

Conventional Manufacturing Process				
LCA Phase	**Input Parameter**	**Unit/Part**	**Value** (Note – these terms are used in the formulae below)	**Tool Guidance**
Typical life-span of the product manufactured using conventional method		Years	LS_{CM}	Enter product life in terms of # of cycles, years, months, or days.
Material	Material # 1 consumed to produce final part	Select	M_1	Select material # 1 name from the drop-down list. The current version of the tool allows only two input materials.
	Material # 1 amount - % of total initial mass	%	$M_{1,\%}$	Enter material # 1 amount as a % of total initial mass. If material # 1 amount is < 100%, tools brings up a second material option.
	Total input material initial mass	Lb/part	$M_{initial,CM}$	Enter input material initial mass - this should include scrap, waste, and material loss during the manufacturing process.
	Final part mass	Lb/part	$M_{final,CM}$	Enter final mass of the component/part after going through all the manufacturing and post-manufacturing processes.
	Ratio between initial material used and the weight of the final product - Conventional Manufacturing Process	Ratio	$M_{initial,CM}/M_{final,CM}$	The weight ratio between initial input material used for a component and the weight of the final component itself.
	Total engineered scrap or waste generated onsite while producing final part	Lb/part	Escrap	This is the difference between total input material initial mass and final part mass.
	Percent of engineered scrap recovered and recycled onsite	%	$Escrap_{\%,recycle}$	User provides a percent of total engineered scrap recovered and recycled on-site. This is different from the recycled material after end of life.
	Material # 1 embodied energy (primary or virgin)	Btu/lb	$EEp_{M,1}$	Embodied Energy for input Material # 1 (primary or virgin) - pulled from the "Embodied Energy - Material" tab.
	Material # 1 embodied energy (recycled engineered scrap)	Btu/lb	$EEs_{M,1}$	Embodied Energy for input Material # 1 (recycled engineered scrap) - pulled from the "Embodied Energy - Material" tab.
	Material Phase Energy Use per Part	**Btu/part**	**M_EU_CM**	**The total material energy per part – the first bar of the bar chart (Figure 2).**

Equations:

For parts built with single material:

$$M\_EU\_CM = (M_{1,\%} * M_{initial,CM} - M_{1,\%} *(Escrap_{\%,recycle} * Escrap)) * EEp_{M,1} + (M_{1,\%} *(Escrap_{\%,recycle} * Escrap) * EEs_{M,1})$$

For parts built with two materials:

$$M\_EU\_CM = (M_{1,\%} * M_{initial,CM} - M_{1,\%} *(Escrap_{\%,recycle} * Escrap)) * EEp_{M,1} + (M_{1,\%} *(Escrap_{\%,recycle} * Escrap) * EEs_{M,1}) + (M_{2,\%} * M_{initial,CM} - M_{2,\%} *(Escrap_{\%,recycle} * Escrap)) * EEp_{M,2} + (M_{2,\%} *(Escrap_{\%,recycle} * Escrap) * EEs_{M,2})$$

Manufacturing Phase Energy Analysis:

Manufacturing phase energy analysis is done in three steps: Step A, B, and C.

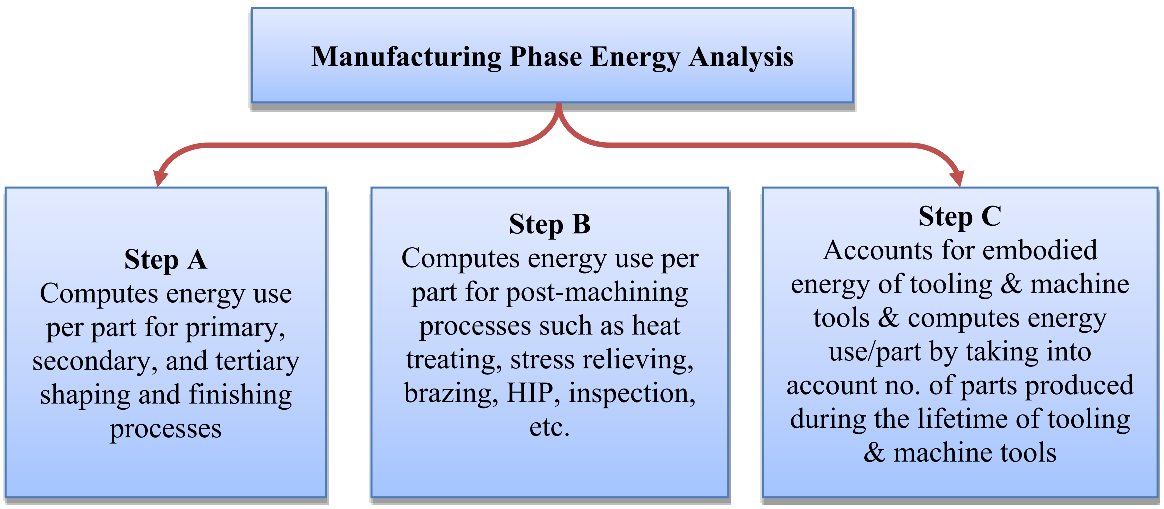


Figure 7: Manufacturing Phase Energy Analysis Steps

It is possible that there might be a few additional manufacturing steps that don't fit into steps A, B, and C. The AM tool assumes that those additional manufacturing steps are common between conventional and additive manufacturing processes and hence could be ignored. The "infrastructure" energy requirements (like lighting, heating, ventilation, and air conditioning) are also assumed to be equal for CM and AM processes. In reality, AM process could increase or decrease the infrastructure energy requirements.

Manufacturing Phase Energy Analysis – Step A:

Step A of the manufacturing analysis focuses on primary, secondary, and tertiary shaping and finishing processes since they are generally the most energy-intensive steps of conventional manufacturing. The process energy intensities per unit mass are retrieved from the database, as in Appendix 3. Multiplying the mass of each component by its primary, secondary, and tertiary shaping energy intensities and summing give an estimate of the total manufacturing energy in Step A.

LCA Phase	Input Parameter	Unit	Value	Tool Guidance

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
Manufacturing – Step A	**Conventional Manufacturing Process Steps (Step A):**			
	Primary Shaping Process	Select	CM_PP	Select primary mode of material processing. Metals, typically, are cast, rolled, or forged. Polymers are molded or extruded.
	Primary Shaping Process Energy Intensity	Btu/lb	EI_{CM_PP}	Energy intensity per lb of initial material for the primary shaping process - pulled from the "Embodied Energy - Process" tab.
	Secondary Process (machining/joining/finishing)	Select	CM_SP	Select secondary mode of material processing. Secondary processes take a shaped part and add features, join, and finish it.
	Secondary Process Energy Intensity	Btu/lb	EI_{CM_SP}	Energy intensity per lb of material removed by the secondary process - pulled from the "Embodied Energy - Process" tab.
	% of material removed by secondary process	%	$M_{CM\_SP,\%}$	Calculated. $M_{CM\_SP,\%} = 0.9*((M_{initial,CM} - M_{final,CM})/M_{initial,CM})$. It is assumed that 90% of the total mass difference is removed by secondary process.
	Tertiary Process (machining/joining/finishing)	Select	CM_TP	Select tertiary mode of material processing. Tertiary processes mainly include finishing operations like grinding.
	Tertiary Process Energy Intensity	Btu/lb	EI_{CM_TP}	Energy intensity per lb of material removed by the tertiary process - pulled from the "Embodied Energy - Process" tab.
	% of material removed by tertiary process	%	$M_{CM\_TP,\%}$	Calculated. $M_{CM\_TP,\%} = 0.1*((M_{initial,CM} - M_{final,CM})/M_{initial,CM})$. It is assumed that 10% of the total mass difference is removed by tertiary process.

Manufacturing Phase Energy Analysis – Step B:

Step B of the manufacturing energy analysis computes energy use per part for post-machining process or processes. Post-machining processes include heat treatment, stress relieving, brazing, Hot Isostatic Pressing (HIP), inspection, etc. Multiplying the mass of material per part going through post-machining processes with post-machining process energy intensity gives an estimate of manufacturing energy Step B.

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
Manufacturing – Step B	**Accounting for Post-machining process or processes (Part B):**			
	Enter post-machining process or processes (heat treating, stress relieving, brazing, HIP, inspection, etc.)	User defined	CM_PostM	Manually enter post-machining processes. Post-machining processes include heat treating, stress relieving, brazing, HIP, etc.). Care should be taken when the energy content of a secondary process is calculated based on batch processing. When the batch size changes there can be a significant change in the energy intensity per part.

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
	Enter post-machining process or processes Energy Intensity	Btu/lb	EI_{CM_PostM}	Provide post-machining process energy intensity. If more than one post-machining processes are involved, calculate combined energy intensity.
	% of material going through post-machining processes (heat treating, stress relieving, brazing, HIP, inspection, etc.)	%	$M_{CM\_PostM,\%}$	Provide % of material going through the post-machining processes. Typically, this number is going to be 100% of the final mass.

Manufacturing Phase Energy Analysis – Step C:
Step C of the manufacturing energy analysis accounts for embodied energy of tooling and machine tools used in the conventional manufacturing process.
While tooling plays a major role in the conventional machining process, the direct energy impact of tooling is limited [DAHMUS 200]. Due to their relatively long life, the energy cost of tools and tool maintenance is often amortized over numerous products, thereby making the energy impact relatively insignificant on a per part basis. This is true if parts are manufactured in high volume, but at low volumes, tooling can be a high part of the energy footprint (see Table 2). And hence AM process can have advantages for low volume applications. For example, producing carbide tools does require some energy intensive materials and processes. Tungsten, with an embodied energy of approximately 172,000 Btu/lb, comprises most of the mass of carbide cutters. Some of the manufacturing steps, including sintering, which are used to form the carbide tool, and physical vapor deposition (PVD) or chemical vapor deposition (CVD), which is used to coat the carbide, are also quite energy intensive, with estimates on the order of 947 to 1,894 Btu (1 to 2 MJ) per process per cutting insert. While these energy values are not trivial, the fact that carbide cutting tools can be used numerous times on multiple surfaces means that this energy investment is distributed over numerous parts.

Table 2: Tooling Energy Intensity for a Range of Parts Manufactured
(Material embodied energies – [DAHMUS 2004], [AZOM], and [M. ASHBY]).

Tooling Material	Material Embodied Energy (Btu/lb)	Tooling Embodied Energy per Part (Btu/lb per part)				
		10 parts	100 parts	1000 parts	10,000 parts	100,000 parts
Carbon tool steels	13,972	1,397	140	14	1.4	0.1
High speed steel (HSS)	36,328	3,633	363	36	3.6	0.4
Cast cobalt alloys	80,611	8,061	806	81	8.1	0.8
Cemented carbide	429,923	42,992	4,299	430	43.0	4.3
Ceramics (alumina, silicon nitride, silicon carbide)	429,923	42,992	4,299	430	43.0	4.3
Cubic Boron Nitride (CBN)	107,481	10,748	1,075	107	10.7	1.1
Tungsten Carbide (WC)	171,969	17,197	1,720	172	17.2	1.7

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
Manufacturing – Step C	**Accounting for Tooling and Machine Tools (Step C):**			
	Material used for tooling or machine tools	Select	M_{tool}	Please select material (e.g. tungsten carbide, high speed steel, etc.) used for tooling or machine tools from the drop-down menu.
	Embodied Energy per lb of tooling material	Btu/lb of tooling material	$EE_{M,tool}$	Embodied energy per lb of tooling material - pulled from the "Embodied Energy - Material" tab. Producing carbide tools requires energy intensive materials and processes.
	Number of tooling or machine tools needed	No. of tools	No_{tool}	Enter total number of tooling and machine tools needed during all the manufacturing steps.
	Average mass of tooling and machine tools	lb/tool	AM_{tool}	Provide average mass of tooling and machine tools used in the process.
	Tooling manufacturing energy intensity per lb of tool (includes sintering, physical vapor deposition or chemical vapor deposition)	Btu/lb of tool	$EI_{Tool,mnf}$	Estimated on the order of 947 to 1,894 Btu (1 to 2 MJ) per process per cutting insert. We will assume 2 tooling manufacturing steps and 1,894 Btu per step. $EI_{Tool,mnf} = (2*1,894*No_{tool})/(No_{tool} * AM_{tool})$
	Total number of parts produced during tooling lifetime.	No. of parts/lifetime	No_{parts}	Due to their relatively long life, the energy cost of tools and tool maintenance is often amortized over numerous products, thereby making the energy impact relatively insignificant on a per part basis.
	Conventional manufacturing process embodied energy use	Btu/lb	EE_{CM}	Calculated embodied energy for the conventional manufacturing process by taking into consideration Manufacturing Phase Parts A, B, and C.
	Manufacturing energy use per Part	**Btu/part**	**CM_EU**	**The total manufacturing energy use per part – the second bar of the bar chart (Figure 2).**

Equations:

Conventional manufacturing process embodied energy use per lb of part:

$$EE_{CM} = (EI_{CM\_PP} + (M_{CM\_SP,\%} * EI_{CM\_SP}) + (M_{CM\_TP,\%} * EI_{CM\_TP})) + (M_{CM\_PostM,\%} * EI_{CM\_PostM}) + ((EE_{M,tool} * No_{tool} * AM_{tool} + No_{tool} * AM_{tool} * EI_{Tool,mnf}) / (No_{parts} * M_{initial,CM}))$$

Manufacturing energy use per Part:

$$CM\_EU = EE_{CM} * M_{initial,CM}$$

Freight and Distribution Energy Analysis:

This step estimates the energy for freight and distribution of the product from the manufacturing site to point of use or sale. The energy intensities (Btu/lb.miles) of freight and distribution modes are provided in Appendix 5 and 6. Multiplying energy intensities by the final mass of the product and the distance travelled provides the estimate for freight and distribution energy use per part. There are two levels of analysis for this life cycle stage – simple or intermediate.

If significant, there should be a consideration of packaging as it relates to distribution. Parts made at or near the point of use may require little or no packaging whereas items packed for shipment often require materials that cause recycling problems and expenses.

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
Freight and Distribution	Analysis Level	Select	FD_AL	Select analysis level - Simple or Intermediate. Depending upon analysis level, user gets more granularities in terms of freight and distribution modes and associated energy intensities.
	Freight and distribution method (Primary Mode)	Select	$FDmode_{primary}$	Select freight and distribution primary mode.
	Freight and distribution average energy use (Primary Mode)	Btu/lb.mile	$EI_{FD,primary}$	The approximate energy of transportation (primary mode) – pulled from "Freight or Transportation" Tab.
	Average freight and distribution distance travelled by a part by primary mode	miles/mode	$DIST_{FD,primary}$	Provide average distance travelled by the product using the primary mode of transportation from the manufacturing site to point of use or sale. User can use this mode to cover international portion of the freight too.
	Freight and distribution method (Secondary Mode)	Select	$FDmode_{secondary}$	Select freight and distribution secondary mode.
	Freight and distribution average energy use (Secondary Mode)	Btu/lb.mile	$EI_{FD,secondary}$	The approximate energy of transportation (secondary mode) – pulled from "Freight or Transportation" Tab.
	Average freight and distribution distance travelled by a part by secondary mode	Miles/mode	$DIST_{FD,secondary}$	Provide average distance travelled by the product using the secondary mode of transportation from the manufacturing site to point of use or sale. User can use this mode to cover domestic part of the freight too.
	Freight and distribution energy use per part	**Btu/part**	**FD_EU**	**The total freight and distribution energy use per part – the third bar of the bar chart (Figure 2).**

Equations:
Freight and distribution energy use per part:
$FD\_EU = M_{final,CM} *(EI_{FD,primary} * DIST_{FD,primary} + EI_{FD,secondary} * DIST_{FD,secondary})$

Use Phase Energy Analysis:
The use phase energy analysis is important and is explained here. There are two different classes of contributions for use phase analysis: products used in the transportation sector or non-transportation sector use. The user enters the typical life-span of the product in the first row, then selects the sector where the product will be used. Another option within the sector allows for

calculation of use phase energy when a product can be used in the transportation sector as well as another sector (i.e. electric to thermal energy conversion).

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
Use	Typical life-span of the product manufactured using conventional method	Years	P_Life	Product life-span in years. If you know the product life-span in days/months/# cycles, convert it into number of years.
	Sector/application area where this part is being used	Select	APP_Area	Select sector/application area from: Transportation, Commercial Buildings, Residential, Industry, and Space. Transportation sector includes cars, trucks, buses, aircrafts, and even space shuttles. The "transportation + other" scenario takes care of applications where AM product is installed on or carried by a moving vehicle and also improving energy conversion efficiency (electric to thermal, thermal to mechanical, etc.). Under this scenario, the use phase energy consumption per part is the summation of transport and energy conversion related impacts.

In the application area A which includes the transportation sector, products that form part of, or carried by, a transportation system (aerospace, automobiles, etc.) add to the mass of the system during transportation and thereby increase its energy consumption. The transportation table in appendix 5 and 6 lists the energy use per unit weight and distance. Multiplying this by the product weight and the distance over which it is carried gives an estimate of the associated use phase energy.

Use Phase - Step A	**If the use phase is in transportation sector:** Products that form part of, or are carried by, a transportation system add to its mass and thereby augment its energy burden. Strategy is to minimize mass and rolling resistance if the product is part of a system that moves.			
	Is this product part of or carried by a vehicle?	Select	Yes/No	If a product that form part of, or are carried by, a transportation system; select Yes, else select No.
	Select fuel and mobility type	Select	Trans_Type	Select transportation or mobility mode.
	Average energy use	Btu/lb.mile	EI_{Trans}	Average energy use per weight per distance – pulled from "Use Phase" Tab. In principle, average energy use by mobility type in the use phase should be different from the freight and distribution phase. Use phase energy numbers should be just the additional energy use associated with an increase in mass, whereas freight energy use should include not only the energy use

				associated with additional mass, but also a share of the baseline energy use needed to move the vehicle even if it were not carrying any weight.
	Distance travelled per day	miles/day	$DIST_{day}$	Enter usage pattern
	Usage	days/year	$DAYS_{year}$	Enter usage pattern
	Average energy use per lb of payload mass (only if the mobility type in cell D61 is "Spacecraft")	Btu/lb per flight	EI_{space}	NASA's space shuttle consumes around 5 TJ of solid propellant and 15 TJ of hydrogen fuel to lift the 100,000 kg vehicle (including the 25,000 kg payload) to an altitude of 111 km.
	Number of flights per year (only if the mobility type in cell D61 is "Spacecraft")	No. flights per year	$No_{flights}$	Number of shuttle flights per year.
	Use phase life time energy use per unit mass	Btu/lb	UP_EI	Calculated value. $UP\_EI = (EI_{Trans} * DIST_{day} * DAYS_{year} * P\_Life)$, if "Spacecraft", $UP\_EI = (EI_{space} * No_{flights} * P\_Life)$

In the second application area B other non-transportation sectors are considered. Some products are (normally) static but require energy to perform their function (e.g. turbine blades, tooling, molds, etc.). Application area B relates to the power consumed by, or on behalf of the product itself.

Use Phase - Step B	**If the use phase is in other sectors:** Some products are normally static but require energy to perform their function. Strategy is to increase thermal efficiency if the product is a thermal or thermo-mechanical system, or reduce electrical losses if the product is an electromechanical system.			
	Does this product require energy to perform its function?	Select	Yes/No	Select Yes/No
	Please select energy conversion type	Select	E_IO	Select energy in and out
	Average power drawn by the system while in operation	KW	PW_Rate	Enter power in KW. Take into consideration full load, partial load, and standby mode power usage while calculating AVERAGE power drawn by the system. (note: 1 KW = 3412.1 Btu per hour)
	Approximate Usage (days per year)	days/year	$DAYS_{year}$	Enter usage pattern - Consider and adjust for full load, partial load, and standby modes while calculating the usage pattern.
	Approximate Usage (hours per day)	hr/day	$HOURS_{day}$	Enter usage pattern – Consider and adjust for full load, partial load, and standby modes while calculating the usage pattern.
	Use phase energy use per part	**Btu/part**	**UP_EU**	**The total use phase energy use per part – the fourth bar of the bar chart (Figure 2).**

Equations:
Use phase energy use per part:

If the use phase is only in transportation sector:
$UP\_EU = UP\_EI * M_{final,CM}$

If the use phase is only in other sector:
$UP\_EU = (PW\_Rate * DAYS_{year} * HOURS_{day} * P\_Life * 3412.1\ Btu/kWh)$

If the use phase is in both transportation and some other sector:
$UP\_EU = (UP\_EI * M_{final,CM}) + (PW\_Rate * DAYS_{year} * HOURS_{day} * P\_Life * 3412.1\ Btu/kWh)$

Disposal Phase Energy Analysis:
The fifth and final life cycle stage is disposal or end of life. Normally, after a component/part has been used and the part has fulfilled its intended purpose, it goes through one of the following disposal processes:

- Landfill
- Combustion or incineration
- Composting
- Open-loop recycling
- Closed-loop recycling
- Other (Re-engineering/Reuse)

Recycling decreases the amount of solid waste entering landfills and reduces the production requirements of virgin or raw materials. In open-loop recycling, products are recycled into new products that are eventually disposed of. In closed-loop recycling, products are recycled again and again into the same product.

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
Disposal (End of Life)	PRIMARY disposal method for material # 1	Select	$DISP_{M1,Pmode}$	Please select primary disposal method option for material # 1 – Landfill, Combustion or incineration, Composting, Open-loop recycling, Closed-loop recycling, or Other (Re-engineering/Reuse). In open-loop recycling, products are recycled into new products that are eventually disposed of. In closed-loop recycling, products are recycled again and again into the same product.
	Fraction of material # 1 disposed through the selected PRIMARY disposal method	% of final part mass	$DISP_{M1,\%,Pmode}$	A fraction of material # 1 disposed using user selected primary disposal method

	Disposal energy use per unit mass (PRIMARY Disposal Method) - material # 1 (applicable only if open or closed-loop recycling selected - calculated)	Btu/lb	$(EEs_{M,1} - EEp_{M,1})$	This is the difference between secondary (recycled) and primary (virgin) material embodied energies. Negative Btu/lb means that the manufacturing process using the recycled material shows lower burdens. Any additional material recycled is also credited to the product to reflect the good end-of-life performance of product under consideration. For simplicity, the amount of energy needed for deconstruction, sorting, processing, and shipping is not considered.
	Disposal energy use per unit mass (PRIMARY Disposal Method) - material # 1 (applicable for all other disposal methods except open or closed-loop recycling - user input)	Btu/lb	$EE_{M1,other, Pmode}$	This is the amount of energy needed for disposing material 1 using the disposal method other than open or closed-loop recycling. If the disposal method is combustion, energy use per unit mass may be negative.
	SECONDARY disposal method for material # 1	Select	$DISP_{M1,Smode}$	Please select secondary disposal method option for material # 1 – Landfill, Combustion or incineration, Composting, Open-loop recycling, Closed-loop recycling, or Other (Re-engineering/Reuse). In open-loop recycling, products are recycled into new products that are eventually disposed of. In closed-loop recycling, products are recycled again and again into the same product.
	Fraction of material # 1 disposed through the selected SECONDARY disposal method	% of final part mass	$DISP_{M1,\%, Smode}$	A fraction of material # 1 disposed using user selected secondary disposal method
	Disposal energy use per unit mass (SECONDARY Disposal Method) - material # 1 (applicable only if open or closed-loop recycling selected - calculated)	Btu/lb	$(EEs_{M,1} - EEp_{M,1})$	This is the difference between secondary (recycled) and primary (virgin) material embodied energies. Negative Btu/lb means that the manufacturing process using the recycled material shows lower burdens. Any additional material recycled is also credited to the product to reflect the good end-of-life performance of product under consideration. For simplicity, the amount of energy needed for deconstruction, sorting, processing, and shipping is not considered.

	Disposal energy use per unit mass (SECONDARY Disposal Method) - material # 1 (applicable for all other disposal methods except open or closed-loop recycling - user input)	Btu/lb	$EE_{M1,other, Smode}$	This is the amount of energy needed for disposing material 1 using the disposal method other than open or closed-loop recycling. If the disposal method is combustion, energy use per unit mass may be negative.
	Disposal (End of Life) energy use per part	**Btu/part**	**DISP_EU**	**The total disposal energy use per part – the fifth bar of the bar chart (Figure 2).**

Equations:
Disposal energy use per part:

If only one material:
For open or closed-loop Recycling:
$DISP\_EU = M_{final,CM} * M_{1,\%}*(DISP_{M1,\%,Pmode} *(EEs_{M,1} - EEp_{M,1}))+ M_{final,CM} * M_{1,\%}*(DISP_{M1,\%,Smode} *(EEs_{M,1} - EEp_{M,1}))$

For Other Disposal Methods:
$DISP\_EU = M_{final,CM} * M_{1,\%}* DISP_{M1,\%,Pmode} *EE_{M1,other}+ M_{final,CM} * M_{1,\%}* DISP_{M1,\%,Smode} *EE_{M1,other}$

If two raw materials:
For open or closed-loop Recycling:
$DISP\_EU = M_{final,CM} * M_{1,\%}*(DISP_{M1,\%,Pmode} *(EEs_{M,1} - EEp_{M,1}))+ M_{final,CM} * M_{1,\%}*(DISP_{M1,\%,Smode} *(EEs_{M,1} - EEp_{M,1}))+ M_{final,CM} * M_{2,\%}*(DISP_{M2,\%,Pmode} *(EEs_{M,2} - EEp_{M,2}))+ M_{final,CM} * M_{2,\%}*(DISP_{M2,\%,Smode} *(EEs_{M,2} - EEp_{M,2}))$

For Other Disposal Methods:
$DISP\_EU = M_{final,CM} * M_{1,\%}* DISP_{M1,\%,Pmode} *EE_{M1,other}+ M_{final,CM} * M_{1,\%}* DISP_{M1,\%,Smode} *EE_{M1,other} + M_{final,CM} * M_{2,\%}* DISP_{M2,\%,Pmode} *EE_{M2,other}+ M_{final,CM} * M_{2,\%}* DISP_{M2,\%,Smode} *EE_{M2,other}$

AM Calculator

Although the CM and AM Calculators both cover all five phases of life cycle (material, manufacturing, freight & distribution, use, and disposal), questions and steps used in different phases are slightly different. The design of AM Calculator (1) and (2) is similar. As mentioned in the Intro tab section, depending upon the scenario for analysis, the user selects either AM Calculator (1) or both AM Calculators (1) and (2). In this section, the design of the AM Calculator (1) tab is explained. Similar steps are provided in AM Calculator (2).

Part Information:

AM Energy Impacts Assessment Tool - Additive or Advanced Manufacturing Process				
LCA Phase	**Input Parameter**	**Unit**	**Value**	**Tool Guidance**
Part Information	Part name	Name	*Part XYZ*	Enter part/product name manufactured by the additive manufacturing process under consideration.
	Part description	Description	*Brief Description*	Provide brief description of the part and its application, etc.

Raw Material Energy Analysis:

The raw material energy analysis for the AM tab follows the same methodology as the CM tab.

Additive Manufacturing Process				
LCA Phase	**Input Parameter**	**Unit**	**Value** (Note – these terms are used in the formulae below)	**Tool Guidance**
Typical life-span of the product manufactured using the additive manufacturing method		Years	LS_{AM}	Enter product life in terms of # of cycles, years, months, or days.
Material	Additive Manufacturing Process/Technique	Select	AM_{Tech}	Select the type of additive manufacturing process to evaluate
	Material # 1 consumed to produce final part	Select	M_1	Select material # 1 name from the drop-down list. The current version of the tool allows only two raw materials.
	Material # 1 amount - % of total initial mass	%	$M_{1,\%}$	Enter material # 1 amount as a % of total initial mass. If material # 1 amount is < 100%, tool brings up a second material option.
	% Reduction in material - Initial mass	%	$M_{initial,\%Red}$	Calculated. $M_{initial,\%Red} = (M_{initial,CM} - M_{initial,AM})/M_{initial,CM}$
	% Reduction in Final part mass	%	$M_{final,\%Red}$	Calculated. $M_{final,\%Red} = (M_{final,CM} - M_{final,AM})/M_{final,CM}$

Additive Manufacturing Process				
LCA Phase	**Input Parameter**	**Unit**	**Value** (Note – these terms are used in the formulae below)	**Tool Guidance**
	Total input material initial mass	lb/part	$M_{initial,AM}$	Enter input material initial mass - this should include scrap, waste, and material loss during the manufacturing process.
	Final part mass	lb/part	$M_{final,AM}$	Enter final mass of the component/part after going through all the manufacturing and post-manufacturing processes.
	Ratio between initial material used and the weight of the final product - Additive Manufacturing Process	Ratio	$M_{initial,AM}$/ $M_{final,AM}$	The weight ratio between initial input material used for a component and the weight of the final component itself.
	Total engineered scrap or waste generated onsite while producing final part	lb/part	Escrap	This is the difference between total input material initial mass and final part mass.
	Percent of engineered scrap recovered and recycled onsite	%	$Escrap_{\%,recycle}$	User provides a percent of total engineered scrap recovered and recycled on-site. This is different from the recycled material after end of life.
	Material # 1 embodied energy (primary or virgin)	Btu/lb	$EEp_{M,1}$	Embodied Energy for input Material # 1 (primary or virgin) - pulled from the "Embodied Energy - Material" tab.
	Material # 1 embodied energy (recycled engineered scrap)	Btu/lb	$EEs_{M,1}$	Embodied Energy for input Material # 1 (recycled engineered scrap) - pulled from the "Embodied Energy - Material" tab.
	Material Energy Use per Part	**Btu/part**	**M_EU_AM**	**The total material energy per part – the first bar of the bar chart (Figure 2).**

Equations:
If only one raw material:

$$M\_EU\_AM = (M_{1,\%} * M_{initial,AM} - M_{1,\%} *(Escrap_{\%,recycle} * Escrap)) * EEp_{M,1} + (M_{1,\%} *(Escrap_{\%,recycle} * Escrap) * EEs_{M,1})$$

If there are two raw materials:

$$M\_EU\_AM = (M_{1,\%} * M_{initial,AM} - M_{1,\%} *(Escrap_{\%,recycle} * Escrap)) * EEp_{M,1} + (M_{1,\%} *(Escrap_{\%,recycle} * Escrap) * EEs_{M,1}) + (M_{2,\%} * M_{initial,AM} - M_{2,\%} *(Escrap_{\%,recycle} * Escrap)) * EEp_{M,2} + (M_{2,\%} *(Escrap_{\%,recycle} * Escrap) * EEs_{M,2})$$

Manufacturing Energy Analysis:
Manufacturing energy analysis in additive manufacturing tab differs from the CM tab and can be performed using three different analysis levels with increasing levels of complexity:

a. Simple
b. Intermediate, and
c. Advanced

a. Simple analysis:

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
Manufacturing - Simple	Analysis Level	Select	M_AL	Analysis levels - Simple, Intermediate, and Advanced
	Additive manufacturing process embodied energy use	Btu/lb	EI_{AM_PP}	Embodied energy per lb processed for the AM primary process - pulled from the "Embodied Energy - Process" tab. Simple method uses published data based on the type of the AM method (SLM, DMLS, EBM, LS, FDM, and Other)
	Secondary Process (machining/joining/finishing)	Select	AM_SP	Select secondary mode of material processing. Secondary processes take a shaped part and add features, join, and finish it.
	Secondary Process Energy Intensity	Btu/lb	EI_{AM_SP}	Embodied energy per lb processed for the secondary process - pulled from the "Embodied Energy - Process" tab.
	% of material removed by secondary process	%	$M_{AM\_SP,\%}$	Calculated. $M_{AM\_SP,\%} = ((M_{initial,AM} - M_{final,AM}) / M_{initial,AM})$.
	Enter post-machining process or processes (heat treating, stress relieving, brazing, HIP, inspection, etc.)	User defined	AM_PostM	Manually enter post-machining process or processes. Post-machining processes include heat treating, stress relieving, brazing, HIP, inspection, etc.). Care should be taken when the energy content of a secondary process is calculated based on batch processing. When the batch size changes there can be a significant change in the energy intensity per part.
	Enter post-additive manufacturing process or processes energy intensity	Btu/lb	EI_{AM_PostM}	Provide post-machining process energy intensity. If multiple post-machining processes are involved, calculate combined energy intensity.
	% of material going through post-additive manufacturing processes (heat treating, stress relieving, brazing, HIP, inspection, etc.)	%	$M_{AM\_PostM,\%}$	Provide % of material going through the post-machining processes. Typically, this number is going to be 100%.
	Additive Manufacturing process embodied energy use	**Btu/lb**	$\mathbf{EE_{AM,Simple}}$	Embodied energy of additive manufacturing process using the simple method.

Equations:
Additive manufacturing process embodied energy by simple method:
$EE_{AM,Simple} = (EI_{AM\_PP} + (M_{AM\_SP,\%} * EI_{AM\_SP}) + (M_{AM\_PostM,\%} * EI_{AM\_PostM})$

b. **Intermediate analysis:**

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
Manufacturing - Intermediate	Machine Model	Enter	AM_Machine	Intermediate method uses the NAME PLATE data based on the Machine Specs and part material.
	Total Build Time or Production Time	Hr/build	T_build	Total production time includes machine tool cleaning, preheating, exposure, recoating, and cooling down. Include cleaning time only if a machine needs cleaning for each cycle. However, if maintenance, cleaning, etc. takes place during non-production shifts, then do not include it here.
	Number of parts produced per build operation	Number of parts/build	NP	This steps accounts for multiple parts in a single build and its impact on energy.
	Average Power Level in Standby, Preheating, and Cooling Down Modes	kW	$P_{Standby}$	Take an average of energy consumption per hour in Standby, Preheating, and Cooling Down Modes. During preheating there will be a constant energy flow to bring the system to operating temperature, much like preheating an oven. During the build the two large power consumers will be maintaining the environmental temperature and portion of the system depositing raw material (laser, extruder, etc.). Stand-by will involve intermittent power consumption to keep the system at a holding temperature without material deposition.
	% of total build time the machine is in Standby, Preheating, and Cooling Down Modes	%	$Standby_{\%}$	Enter % of total build time the machine is in Standby, Preheating, and Cooling Down Modes.

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
	Average Energy Consumption per hour (kW) when AM machine is in production mode.	kW	P_{Prod}	Average Power Level in Heating, Exposure, and Recoating Mode.
	% of total build time the machine is in production mode and producing parts	%	$Prod_{\%}$	Calculated. % of total build time the machine is in Heating, Exposure, and Recoating Mode.
	AM Process Productivity	lb/hr	$AM_{Productivity}$	Enter machine productivity in lb of mass produced per hour. This depends upon machine type, AM process type, material, the total batch volume (V) and production batch height (h).
	Secondary Process (machining/joining/finishing)	Select	AM_SP	Select secondary mode of material processing. Secondary processes take a shaped part and add features, join, and finish it.
	Secondary Process Energy Intensity	Btu/lb	EI_{AM_SP}	Embodied energy per lb processed for the secondary process - pulled from the "Embodied Energy - Process" tab.
	% of material removed by secondary process	%	$M_{AM\_SP,\%}$	Calculated. $M_{AM\_SP,\%} = ((M_{initial,AM} - M_{final,AM}) / M_{initial,AM})$.
	Enter post-machining process or processes (heat treating, stress relieving, brazing, HIPing, inspection, etc.)	User defined	AM_PostM	Manually enter post-machining process or processes. Post-machining processes include heat treating, stress relieving, brazing, HIPing, inspection, etc.).
	Enter post-additive manufacturing process or processes energy intensity	Btu/lb	EI_{AM_PostM}	Provide post-machining process energy intensity. If multiple post-machining processes are involved, calculate combined energy intensity.
	% of material going through post-additive manufacturing processes (heat treating, stress relieving, brazing, HIPing, inspection, etc.)	%	$M_{AM\_PostM,\%}$	Provide % of material going through the post-machining processes. Typically, this number is going to be 100%.
	Additive Manufacturing process embodied energy use	**Btu/lb**	$\mathbf{EE_{AM,Intermd}}$	Embodied energy of additive manufacturing process using the intermediate method.

Equations:
Additive manufacturing process embodied energy using the intermediate method:
$EE_{AM,Intermd} = (3412.1\ Btu/kWh)*((T\_build * P_{Standby} * Standby_{\%})/(NP * M_{initial,AM})) + (3412.1\ Btu/kWh)*((T\_build * P_{Prod} * Prod_{\%})/(NP * M_{initial,AM})) + (M_{AM\_SP,\%} * EI_{AM\_SP}) + (M_{AM\_PostM,\%} * EI_{AM\_PostM})$

c. Advanced analysis:

Advanced analysis is done in three steps: 1) calculating build time; 2) estimating manufacturing energy consumption; and 3) estimating manufacturing embodied energy. The advanced method is derived based on Martin Baumers's work on estimating process energy flows and costs occurring in the AM technology variant direct metal laser sintering [BAUMERS 2013].

Steps 1 – Calculating Build Time:

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
Manufacturing - Build Time Estimation	Analysis Level	Select	Advanced	Analysis levels - Simple, Intermediate, and Advanced
	Build Time Estimation: The estimate for total build time, T_{Build}, is obtained by combining data from a hierarchy of elements of time consumption.			
	Part name	Name	PN_AM	Use the method of build time estimation and energy consumption estimation based on the part geometry, material, and machine specs. This method is documented in the article "Transparency Built in, Journal of Industrial Ecology, 2012 [BAUMERS 2013]. This is a bottom up approach method.
	Number of parts produced per build operation	Number of parts/build	NP	This step accounts for multiple parts in a single build and its impact on energy.
	Fixed time consumption per build operation	seconds/build	T_{Job}	Provide fixed time consumption per build operation irrespective of number of parts produced. For example, time required for machine atmosphere generation and machine warm-up.
	Fixed time consumption per layer	seconds per layer	T_{per_Layer}	Time required for completing one layer of the material.
	The total number of build layers	layers/build	l	Total number of layers per build operation.
	Total layer dependent time consumption	Seconds/build	T_{Layer}	Obtained by multiplying the fixed time consumption per layer, T_{Layer}, by the total number of build layers l;

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
	The total build time needed for the deposition of part geometry approximated by the voxels	Seconds/build	T_{Voxel}	The summation of the time needed to process each voxel, T_{Voxel} xyz, in a three-dimensional array representing the discretized build configuration
	Build Time per Part	**Seconds/part**	$\mathbf{T_{build}}$	A **voxel** (*volumetric pixel* or *Volumetric Picture Element*) is a volume element, representing a value on a regular grid in three dimensional space.

Equations:
Total build time is calculated using the following equation:

$$T_{build} = (T_{job} + (T_{per\_Layer} * l) + T_{Voxel})/NP$$

Steps 2 – Manufacturing Energy Consumption Estimation:

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
Manufacturing - Energy Consumption Estimation	**Energy Consumption Estimation:**			
	Fixed energy consumption per build operation	Btu	E_{job}	E_{Job} contains all energy consumption attributable to the build job, including energy consumed by the wire erosion process to remove the parts from the build plate.
	Time-dependent energy consumption rate	Btu/second	E_{Time_Rate}	A purely time-dependent element of power consumption must be expected in the continuous operation of the AM machine. This is denoted by the energy consumption rate E_{Time_Rate} (measured in Btu/s), which is multiplied by T_{build} to estimate total time-dependent energy consumption. Modeling E_{Time} as a constant reflects its interpretation as a mean baseline level of energy consumption throughout the build, originating from continuously operating machine components such as cooling fans, pumps, and the control system.
	Time-dependent energy consumption	Btu/build	E_{Time}	Obtained by multiplying the time dependent energy consumption rate, E_{Time_Rate}, by the total build time T_{build}. $E_{Time} = E_{Time\_Rate} * T_{build}$

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
	Fixed energy consumption per layer	Btu/layer	E_{per_Layer}	Provide fixed energy consumption amount per layer.
	Total number of build layers	layers/build	l	Total number of layers per build operation.
	Total layer dependent energy consumption	Btu/build	E_{Layer}	Analogous to build time estimation, E_{Layer} denotes fixed elements of energy consumption per build and layer, for a total number of layers, l.
	The energy needed for the deposition of part geometry approximated by the voxels	Btu/part	E_{Voxel}	E_{Voxel} is the geometry-dependent energy consumption that can be obtained by adding all energy consumption associated with voxel deposition throughout the discretized workplace. Please note that E_{Voxel} does not contain time-dependent power consumption.
	Build Energy Consumption per Part	**Btu/part**	E_{build}	**Total build energy consumption which is the summation of E_{job}, E_{Time}, E_{Layer}, and E_{Voxel}.**

Equations:
Total build energy consumption per part:

$$E_{build} = E_{job}/NP + (E_{Time\_Rate} * T_{buid}) + (E_{per\_layer} * l)/NP + E_{Voxel}$$

Steps 3 – Manufacturing - Manufacturing Embodied Energy Estimation:

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
Manufacturing - Manufacturing Embodied Energy Estimation	**Manufacturing Embodied Energy Estimation:**			
	Build Energy Consumption per Part	Btu/part	E_{build}	As calculated above.
	Total input material initial mass	lb/part	$M_{final,AM}$	As provided above. Total input material initial mass which is going through all the manufacturing and post-manufacturing processes.
	Secondary Process (machining/joining/finishing)	Select	AM_SP	Select secondary mode of material processing. Secondary processes take a shaped part and add features, join, and finish it.

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
	Secondary Process Energy Intensity	Btu/lb	EI_{AM_SP}	Embodied energy per lb processed for the secondary process - pulled from the "Embodied Energy - Process" tab.
	% of material removed by secondary process	%	$M_{AM\_SP,\%}$	Calculated. $M_{AM\_SP,\%} = ((M_{initial,AM} - M_{final,AM})/ M_{initial,AM})$.
	Enter post-machining process or processes (heat treating, stress relieving, brazing, HIPing, inspection, etc.)	User defined	AM_PostM	Manually enter post-machining process or processes. Post-machining processes include heat treating, stress relieving, brazing, HIPing, inspection, etc.).
	Enter post-additive manufacturing process or processes energy intensity	Btu/lb	EI_{AM_PostM}	Provide post-machining process energy intensity. If more than one post-maching processes are involved, calculate combined energy intensity.
	% of material going through post-additive manufacturing processes (heat treating, stress relieving, brazing, HIPing, inspection, etc.)	%	$M_{AM\_PostM,\%}$	Provide % of material going through the post-machining processes. Typically, this number is going to be 100%.
	Additive Manufacturing process embodied energy use	**Btu/lb**	$\mathbf{EE_{AM,Advanced}}$	**This is obtained by adding build energy consumption intensity and post-additive manufacturing processes energy intensities.**
	Manufacturing energy use per Part	**Btu/part**	**AM_EU**	**The total manufacturing energy per part – the first bar of the bar chart (Figure 2).**

Equations:
Additive manufacturing process embodied energy using advanced method of calculations provides the energy on a mass basis:

$$EE_{AM,Advanced} = (E_{build}/ M_{final,AM}) + (M_{AM\_SP,\%} * EI_{AM\_SP}) + (M_{AM\_PostM,\%} * EI_{AM\_PostM})$$

The final calculation in this section is to calculate the additive manufacturing energy use per part based on the mass of the part entered by the user:

Simple method:
$$AM\_EU = EE_{AM,Simple} * M_{initial,AM}$$

Intermediate method:

$AM\_EU = EE_{AM,Intermd} * M_{initial,AM}$

Advanced method:
$AM\_EU = EE_{AM,Advanced} * M_{initial,AM}$

Freight and Distribution Energy Analysis:
This step for the AM tab uses the same methodology as the CM tab.

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
Freight and Distribution	Analysis Level	Select	FD_AL	Select analysis level - Simple or Intermediate. Depending upon analysis level, user gets more granularities in terms of freight and distribution modes and associated energy intensities.
	Freight and distribution method (Primary Mode)	Select	$FDmode_{primary}$	Select freight and distribution primary mode.
	Freight and distribution average energy use (Primary Mode)	Btu/lb.mile	$EI_{FD,primary}$	The approximate energy of transportation (primary mode) – pulled from "Freight or Transportation" Tab.
	Average freight and distribution distance travelled by a part by primary mode	miles/mode	$DIST_{FD,primary}$	Provide average distance travelled by the product using the primary mode of transportation from the manufacturing site to point of use or sale. User can use this mode to cover international portion of the freight too.
	Freight and distribution method (Secondary Mode)	Select	$FDmode_{secondary}$	Select freight and distribution secondary mode.
	Freight and distribution average energy use (Secondary Mode)	Btu/lb.mile	$EI_{FD,secondary}$	The approximate energy of transportation (secondary mode) – pulled from "Freight or Transportation" Tab.
	Average freight and distribution distance travelled by a part by secondary mode	Miles/mode	$DIST_{FD,secondary}$	Provide average distance travelled by the product using the secondary mode of transportation from the manufacturing site to point of use or sale. User can use this mode to cover domestic part of the freight too.
	Freight and distribution energy use per part	**Btu/part**	**FD_EU**	**The total freight and distribution energy use per part – the third bar of the bar chart (Figure 2).**

Equations:
Freight and distribution energy use per part:
$FD\_EU = M_{final,AM} *(EI_{FD,primary} * DIST_{FD,primary} + EI_{FD,secondary} * DIST_{FD,secondary})$

Use Phase Energy Analysis:

The use phase energy analysis for the AM calculations follows the same methodology as the CM tab.

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
Use	Typical life-span of the product manufactured using Additive Manufacturing Process	Years	P_Life	Product life-span in years. If you know the product life-span in days/months/# cycles, convert it into number of years.
	Sector/application area where this part is being used	Select	APP_Area	Select sector/application area from: Transportation, Commercial Buildings, Residential, and Industry. Transportation sector includes cars, trucks, buses, aircrafts, and even space shuttles. The "transportation + other" scenario takes care of applications where AM product is installed on or carried by a moving vehicle and also improving energy conversion efficiency (electric to thermal, thermal to mechanical, etc.). Under this scenario, the use phase energy consumption per part is the summation of transport and energy conversion related impacts.

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
Use Phase - Step A	**If the use phase is in transportation sector:** Products that form part of, or are carried by, a transportation system add to its mass and thereby augment its energy burden. Strategy is to minimize mass and rolling resistance if the product is part of a system that moves.			
	Is this product part of or carried by a vehicle?	Select	Yes/No	If a product that form part of, or are carried by, a transportation system; select Yes, else select No.
	Select fuel and mobility type	Select	Trans_Type	Select transportation or mobility mode.
	Average energy use	Btu/lb.mile	EI_{Trans}	Average energy use per weight per distance – pulled from "Use Phase" Tab. In principle, average energy use by mobility type in the use phase should be different from the freight and distribution phase. Use phase energy numbers should be just the additional energy use associated with an increase in mass, whereas freight energy use should include not only the energy use associated with additional mass, but also a share of the baseline energy use needed to move the vehicle even if it were not carrying any weight.

	Distance travelled per day	miles/day	$DIST_{day}$	Enter usage pattern
	Usage	Days/year	$DAYS_{year}$	Enter usage pattern
	Average energy use per lb of payload mass (only if the mobility type in cell D95 is "Spacecraft")	Btu/lb per flight	EI_{space}	NASA's space shuttle consumes around 5 TJ of solid propellant and 15 TJ of hydrogen fuel to lift the 100,000 kg vehicle (including the 25,000 kg payload) to an altitude of 111 km.
	Number of flights per year (only if the mobility type in cell D95 is "Spacecraft")	No. flights per year	$No_{flights}$	Number of shuttle flights per year.
	Use phase life time energy use per unit mass	Btu/lb	UP_EI	Calculated value. $UP\_EI = (EI_{Trans} * DIST_{day} * DAYS_{year} * P\_Life)$, if "Spacecraft", $UP\_EI = (EI_{space} * No_{flights} * P\_Life)$

Use Phase - Step B	**If the use phase is in other sectors:** Some products are normally static but require energy to perform their function. Strategy is to increase thermal efficiency if the product is a thermal or thermo-mechanical system, or reduce electrical losses if the product is an electromechanical system.			
	Does this product require energy to perform its function?	Select	Yes/No	Select Yes/No. If a product is normally static but requires energy to perform their function, select Yes, else select No.
	Please select energy conversion type	Select	E_IO	Select energy in and out
	Average power drawn by the system while in operation	KW	PW_Rate	Enter power in KW. Take into consideration full load, partial load, and standby mode power usage while calculating AVERAGE power drawn by the system. (note: 1 KW = 3412.1 Btu per hour)
	Improvement in system efficiency from scenario 1 to 2 (only used while comparing CM and AM scenarios)	%	EFF_IMP	Improvement in system efficiency from scenario 1 to 2 scenario due to improved part geometry, reduced weight, improved performance, etc. If there is no improvement then use 0%.
	Approximate Usage (days per year)	Days/year	$DAYS_{year}$	Enter usage pattern - Take into consideration and adjust for full load, partial load, and standby mode power usage while calculating the usage pattern.
	Approximate Usage (hours per day)	hr/day	$HOURS_{day}$	Enter usage pattern - Take into consideration and adjust for full load, partial load, and standby modes while calculating the usage pattern.
	Use phase energy use per part	**Btu/part**	**UP_EU**	**The total use phase energy use/part – the fourth bar of the bar chart (Figure 2).**

Equations:
Use phase energy use per part:

If the use phase is only in transportation sector:
$UP\_EU = UP\_EI * M_{final,AM}$

If the use phase is only in other sector:
$UP\_EU = (PW\_Rate * (1- EFF\_IMP) * DAYS_{year} * HOURS_{day} * P\_Life * 3412.1\ Btu/kWh)$

If the use phase is in both transportation and some other sector:
$UP\_EU = (UP\_EI * M_{final,AM}) + (PW\_Rate * (1- EFF\_IMP) * DAYS_{year} * HOURS_{day} * P\_Life * 3412.1\ Btu/kWh)$

Disposal Phase Energy Analysis:

This step for the AM tab uses the same methodology as the CM tab.

LCA Phase	Input Parameter	Unit	Value	Tool Guidance
Disposal (End of Life)	PRIMARY disposal method for material # 1	Select	$DISP_{M1,Pmode}$	Please select primary disposal method option for material # 1 – Landfill, Combustion or incineration, Composting, Open-loop recycling, Closed-loop recycling, or Other (Re-engineering/Reuse). In open-loop recycling, products are recycled into new products that are eventually disposed of. In closed-loop recycling, products are recycled again and again into the same product.
	Fraction of material # 1 disposed through the selected PRIMARY disposal method	% of final part mass	$DISP_{M1,\%, Pmode}$	A fraction of material # 1 disposed using user selected primary disposal method
	Disposal energy use per unit mass (PRIMARY Disposal Method) - material # 1 (applicable only if open or closed-loop recycling selected - calculated)	Btu/lb	$(EEs_{M,1} - EEp_{M,1})$	This is the difference between secondary (recycled) and primary (virgin) material embodied energies. Negative Btu/lb means that the manufacturing process using the recycled material shows lower burdens. Any additional material recycled is also credited to the product to reflect the good end-of-life performance of product under consideration. For simplicity, the amount of energy needed for deconstruction, sorting, processing, and shipping is not considered.

	Disposal energy use per unit mass (PRIMARY Disposal Method) - material # 1 (applicable for all other disposal methods except open or closed-loop recycling - user input)	Btu/lb	$EE_{M1,other, Pmode}$	This is the amount of energy needed for disposing material 1 using the disposal method other than open or closed-loop recycling. If the disposal method is combustion, energy use per unit mass may be negative.
	SECONDARY disposal method for material # 1	Select	$DISP_{M1,Smode}$	Please select secondary disposal method option for material # 1 – Landfill, Combustion or incineration, Composting, Open-loop recycling, Closed-loop recycling, or Other (Re-engineering/Reuse). In open-loop recycling, products are recycled into new products that are eventually disposed of. In closed-loop recycling, products are recycled again and again into the same product.
	Fraction of material # 1 disposed through the selected SECONDARY disposal method	% of final part mass	$DISP_{M1,\%, Smode}$	A fraction of material # 1 disposed using user selected secondary disposal method
	Disposal energy use per unit mass (SECONDARY Disposal Method) - material # 1 (applicable only if open or closed-loop recycling selected - calculated)	Btu/lb	$(EEs_{M,1} - EEp_{M,1})$	This is the difference between secondary (recycled) and primary (virgin) material embodied energies. Negative Btu/lb means that the manufacturing process using the recycled material shows lower burdens. Any additional material recycled is also credited to the product to reflect the good end-of-life performance of product under consideration. For simplicity, the amount of energy needed for deconstruction, sorting, processing, and shipping is not considered.
	Disposal energy use per unit mass (SECONDARY Disposal Method) - material # 1 (applicable for all other disposal methods except open or closed-loop recycling - user input)	Btu/lb	$EE_{M1,other, Smode}$	This is the amount of energy needed for disposing material 1 using the disposal method other than open or closed-loop recycling. If the disposal method is combustion, energy use per unit mass may be negative.
	Disposal (End of Life) energy use per part	**Btu/part**	**DISP_EU**	**The total disposal energy use per part – the fifth bar of the bar chart (Figure 2).**

Equations:
Disposal energy use per part:

If only one material:
For open or closed-loop Recycling:

$$DISP\_EU = M_{final,AM} * M_{1,\%}*(DISP_{M1,\%,Pmode} *(EEs_{M,1} - EEp_{M,1}))+ M_{final,AM} * M_{1,\%}*(DISP_{M1,\%,Smode} *(EEs_{M,1} - EEp_{M,1}))$$

For Other Disposal Methods:

$$DISP\_EU = M_{final,AM} * M_{1,\%}* DISP_{M1,\%,Pmode} *EE_{M1,other}+ M_{final,AM} * M_{1,\%}* DISP_{M1,\%,Smode} *EE_{M1,other}$$

If two raw materials:
For open or closed-loop Recycling:

$$DISP\_EU = M_{final,AM} * M_{1,\%}*(DISP_{M1,\%,Pmode} *(EEs_{M,1} - EEp_{M,1}))+ M_{final,AM} * M_{1,\%}*(DISP_{M1,\%,Smode} *(EEs_{M,1} - EEp_{M,1}))+ M_{final,AM} * M_{2,\%}*(DISP_{M2,\%,Pmode} *(EEs_{M,2} - EEp_{M,2}))+ M_{final,AM} * M_{2,\%}*(DISP_{M2,\%,Smode} *(EEs_{M,2} - EEp_{M,2}))$$

For Other Disposal Methods:

$$DISP\_EU = M_{final,AM} * M_{1,\%}* DISP_{M1,\%,Pmode} *EE_{M1,other}+ M_{final,AM} * M_{1,\%}* DISP_{M1,\%,Smode} *EE_{M1,other} + M_{final,AM} * M_{2,\%}* DISP_{M2,\%,Pmode} *EE_{M2,other}+ M_{final,AM} * M_{2,\%}* DISP_{M2,\%,Smode} *EE_{M2,other}$$

Results

The design of Results tabs (1) and (2) are similar. As mentioned in the Intro tab section, depending upon the scenario chosen by the user for analysis, the results are shown in either Results tab (1) or Results tab (2). In this section, we are explaining the design for Results tab (1). Similar tables and charts are provided in Results tab (2).

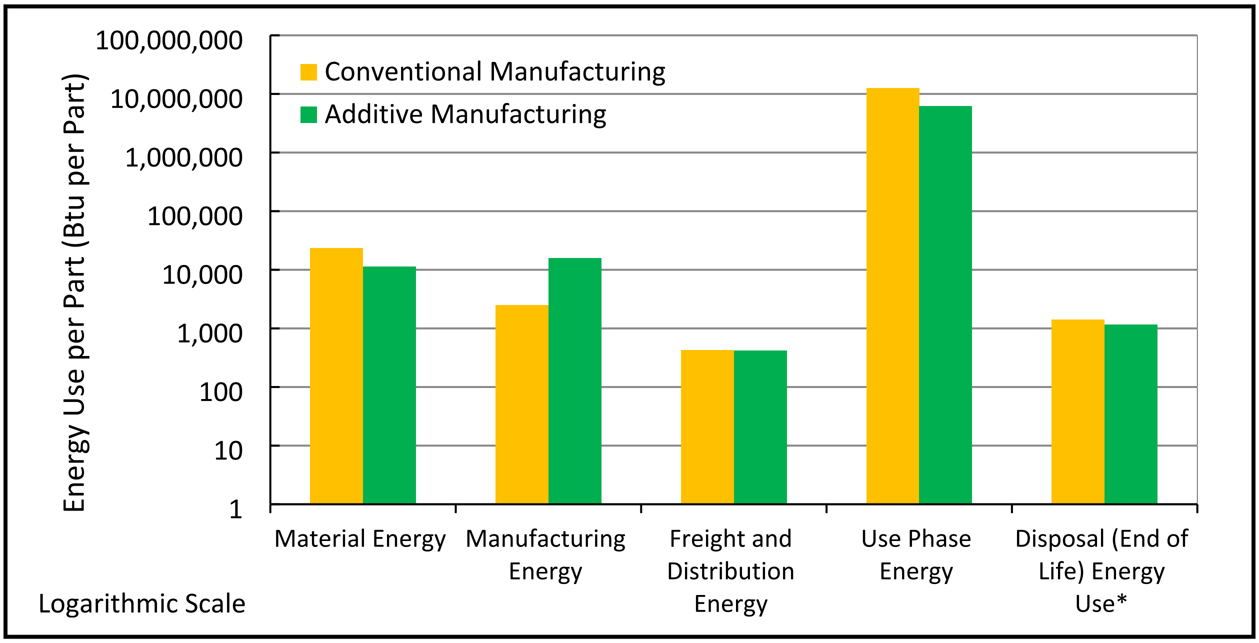
Energy Use per Part:

Table 3 summarizes the energy use at each phase as calculated in the AM and CM tabs and provides the total energy use per part on a life cycle basis.

Table 3: Results Table - Energy Use per Part

Life Cycle Phases	Unit	Conventional Manufacturing	Additive Manufacturing
Material Energy	Btu/part	23,445	11,372
Manufacturing Energy	Btu/part	2,491	15,913
Freight and Distribution Energy	Btu/part	425	416
Use Phase Energy	Btu/part	12,742,943	6,237,335
Disposal (End of Life) Energy Use*	Btu/part	1,408	1,166
Total Energy Use per Part	**Btu/part**	**12,770,713**	**6,266,203**

Figure 8: Results Graph - Energy Use per Part
Figure 8 shows the graphical representation of Table 3 results on a logarithmic scale as presented in the Results tab.



** Negative energy use per part in disposal phase means that the manufacturing process using the recycled material shows lower burdens. Any additional material recycled is also credited to the product to reflect the good end-of-life performance of product under consideration.*

Energy and Energy Cost Savings per Part:

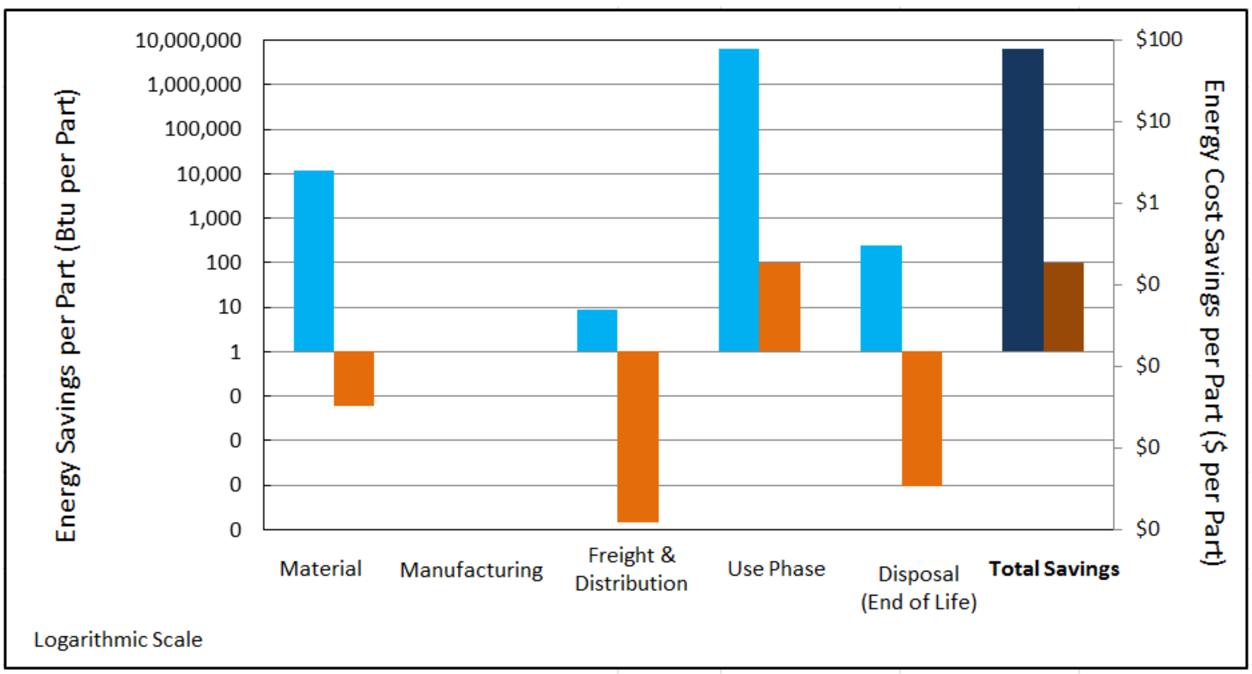
Table 4: Energy Prices by Life Cycle Phase
Table 4 allows the user to enter the cost of energy for each step of the life cycle analysis in order for an estimate of the cost of energy at each stage and in total to be calculated in Table 5. Default values are provided in $/MMBtu but are user entered values for maximum flexibility and to account for variation in energy costs.

	Input Parameter	Unit	Value	Tool Guidance
Provide Unit Energy Prices by each life cycle phase	Raw material related unit energy price	$/MMBtu	$5	Typically, material manufacturing industry uses coal, coke, electricity, natural gas, and fuel oils.
	Manufacturing related unit energy price	$/MMBtu	$5	Typically manufacturing industry uses natural gas, electricity, coal and fuel oils.
	Freight and Distribution related unit energy price	$/MMBtu	$9	Typically transportation industry uses gasoline or diesel as their primary fuels.
	Use phase related unit energy price	$/MMBtu	$15	If the use phase is aerospace industry - jet fuel, passenger vehicle, trucks, trains - gasoline or diesel.
	Disposal (End of Life) related unit energy price	$/MMBtu	$4	It's a combination of gasoline (for transportation), electricity (for sorting and processing), natural gas (for incineration), etc.

Table 5: Results Table - Energy and Energy Cost Savings per Part
This table summarizes the energy savings and cost savings due to energy for each stage. The energy savings is calculated by subtracting the value for each stage of the AM tab calculations from the CM tab calculations (Table 3). The energy cost savings per part is calculated by multiplying the energy savings per part by the energy cost provided in Table 4.

Life Cycle Phases	Energy Savings per Part (Btu/part) (+ve numbers mean savings)	Energy Cost Savings per Part ($/part) (+ve numbers mean savings)
Material	12,074	$0.06
Manufacturing	-13,422	-$0.07
Freight and Distribution	9	$0.00
Use Phase	6,505,608	$98
Disposal (End of Life)	242	$0.00
Total Energy and Energy Cost Savings per Part	**6,504,510**	**$98**

Figure 9: Results Graph - Energy Savings per Part
Figure 9 shows the graphical representation of the energy savings per part as calculated in Table 5 on a logarithmic scale in the Results tab.



Summary of Key Inputs and Assumptions:

The results section also includes a summary table of the key inputs and assumptions (see Figure 10) used in the life-cycle analysis. This table helps users in clearly presenting their inputs/assumptions along with output tables and charts to support the outcomes of their analysis.

Figure 10: A summary of key inputs and assumption

Summary of Key Inputs and Assumptions:

Life Cycle Phase	Parameter	Unit	Conventional Manufacturing	Additive Manufacturing
Manufacturing Process	Process Name		Polymers - Molding	Fused Deposition Modeling (FDM) of Polymers
Material	Material # 1 consumed to produce final part	Material	ULTEM 9085 - Pellets	ULTEM 9085 - Extruded Filament
	Material # 1 amount - % of total initial mass	%	80%	80%
	Material # 1 embodied energy (primary or virgin)	Btu/lb	56,320	58,470
	Material # 1 embodied energy (recycled engineered scrap)	Btu/lb	56,320	58,470
	Material # 2 consumed to produce final part		Polyamide (nylon)	Polyamide (nylon)
	Material # 2 Amount - % of total initial mass	%	20%	20%
	Material # 2 embodied energy (primary or virgin)	Btu/lb	52,666	52,666
	Material # 2 embodied energy (recycled engineered	Btu/lb	18,272	18,272
	Total input material initial mass	lb/part	0.105	0.103
	Final part mass	lb/part	0.095	0.088
	% Reduction in material Initial mass w.r.t. CM Process	%	NA	2%
	% Reduction in Final part mass w.r.t. CM Process	%	NA	7%
Manufacturing	Primary Manufacturing Process	Manufacturing Process	Polymers - Molding	Fused Deposition Modeling (FDM) of Polymers
	Analysis Level		NA	Simple
	Primary Manufacturing Process Energy Intensity	Btu/lb	8,169	76,526
	Secondary Process (machining/joining/finishing)		None	Other Secondary Process
	Secondary Process Energy Intensity	Btu/lb	0	0
	Tertiary Process (machining/joining/finishing)		None	NA
	Tertiary Process Energy Intensity	Btu/lb	0	NA
Freight & Distribution	Analysis Level		Simple	Simple
	Freight and distribution method (Primary Mode)	Primary Mode	Airplane	Ship
	Freight and distribution average energy use (Primary	Btu/lb.mile	24.76	0.84
	Average freight and distribution distance travelled by a	miles/mode	12,000	4,000
	Freight and distribution method (Secondary Mode)	Secondary Mode	Long-Distance Truck	Long-Distance Truck
	Freight and distribution average energy use (Secondary	Btu/lb.mile	3.06	3.06

AM Tool's Capabilities/Constraints:

DOE/ORNL organized a project review meeting to review the Additive Manufacturing life cycle energy impacts analysis work which was held at ORNL on February 5 and 6, 2015. The intent was to bring-in outside and internal researchers including ORNL AM experts, to review the AM LCA tool and essentially have a project review meeting on the needs and utility of such methodology, and examine the current state-of-the-art and the anticipated advancements in AM, data needs and availability, standards, etc. As an outcome of this project review meeting, the following next steps for the AM LCA tool and future improvement opportunities were identified:

- **The current database of AM LCA tool has the limited energy intensity data for additive manufacturing processes**

  The literature review indicates that there are significant inconsistencies in the energy intensity data for additive manufacturing processes. Compared to the traditional manufacturing processes (machining, casting, forging, etc.), process energy intensity data for relatively new additive manufacturing processes is very limited. Detailed data about

MJ/kg (or Btu/lb) for AM processes and for different materials is often lacking. The energy experiments conducted by other researchers so far (see literature summary) were incomplete; the work did not include a full range of power measurements on different additive machines using a range of materials nor have previous studies identify power levels in different operating modes. In general, previous work was focused on specific technologies (e.g. EBM machines) rather than covering all technology platforms (EBM, SLM, FDM, etc.). Within the LCA framework, there are areas where the integration of additional data can improve the energy estimates. There is a need to design and conduct experimental studies on energy, production time, and consumables (compressed air, nitrogen, argon, helium, etc.) and to develop process energy intensity (Btu/lb) and machine productivity (lb/hr) databases for various additive manufacturing platforms and materials. Experimental studies could provide detailed data on energy intensities for the most common AM processes and for different materials. The methodology and the AM tool have been designed to be adaptable to new data and information that can expand the fidelity of the energy estimates. The data from additional experimental studies could be used to validated the AM tool and be directly used in the AM tool to make it more valuable, accurate, and consistent.

- **The materials database of AM LCA tool needs to be updated with AM specific materials**

  The material phase of the AM tool accounts for all the energy required to process a material (or materials) into a form that can be used to fabricate a particular product. The materials used in conventional as well as additive manufacturing processes may come in different forms and shapes. For example: metal ingots vs. metal powders, polymer pellets vs. extruded filaments, etc. The material phase includes all the energy required to process materials from mines to the manufacturing facility gate. This energy consumption is also called the embodied energy of the material. The current database included in the AM tool doesn't cover all the materials used today in various AM processes. Adding AM specific materials in the AM tool database along with their embodied energy data will add significant value and make the tool robust.

- **The LCA tool handles additive-only manufacturing processes.**
  Current version of the AM tool doesn't handle hybrid additive-subtractive manufacturing processes that combine the best features of both AM and CM approaches. A hybrid layered manufacturing process combines the best features of both AM and CM approaches. In this process the near-net shape of the object is first built using AM; the near-net shape is then finish machined subsequently. The AM tool has separate calculators for AM and CM. It would be beneficial to develop a hybrid calculator to do LCA analysis on hybrid additive-subtractive manufacturing processes. For example – Lasertec 65 by DMG Mori Sieki (German company), hybrid system by HMT (UK based company), etc.

- **The tool strictly focuses on assessing the energy required across the entire lifecycle of the part (cradle to grave).**
  The tool is not designed to model various cost components associated with the manufacturing processes. For example: lead-times and associated downtime costs, inventory costs, import/export costs, etc.

- **The tool assesses the energy required to fabricate the end-use part.**
The tool doesn't specifically assess the energy required to build support structures/anchors. Also ignores post-processing of support structures. Parts made with the material extrusion, material jetting, vat photo-polymerization, and metal powder bed fusion processes use supports, which need to be removed after the build. Metal AM parts are often heat treated to remove internal stresses prior to the removal of support structures.
- **The LCA tool focuses and is tested on commonly used AM processes – powder bed fusion, material extrusion, and directed energy deposition.**
The tool is not currently designed for or tested on parts produced by material jetting, binder jetting, sheet lamination, and vat photo-polymerization AM processes.
- **The tool currently contains a limited number of conventional manufacturing processes that may be compared to the additive manufacturing process part.**
The tool can be limited on the number of conventional processes built into the tool input fields without modification. Also, energy intensity data provided in the tool may not cover all post-processing techniques including Heat treating, vibration grinding, micro-machining process, electro-chemical machining, spray coating, metal coating, etc.
- **The tool can be used to compare an additively manufactured and a conventionally manufactured part.** However, the LCA tool may be limited when comparing an additive part that has consolidated hundreds of conventional parts due to part accuracy of energy consumption for consolidation operation or assembly process(es).
- **There are two different classes of contributions for use phase analysis: products used in the transportation sector or non-transportation sector (or stationary) use.**

  The use phase of tool is extensively tested with multiple transport related products (for example - parts used on the aircrafts, components mounted on vehicles, etc.). The use phase needs to be tested for stationary applications too. Some products are normally static or stationary but require energy to perform their function. The parts manufactured by AM processes may help us to increase thermal efficiency if the product is a thermal or thermo-mechanical system, or reduce electrical losses if the product is an electromechanical system. It would be beneficial to test the tool with multiple stationary applications.

CHAPTER 4 – CASE STUDIES

This chapter provides an overview of four specific case studies that demonstrate the application of the AM Energy Impacts Assessment Tool. The first page for each case study provides a process flow diagram and energy savings table. The second page provides a summary of user inputs and assumptions used in the energy use per part analysis.

The four case studies included in this report are:

1. Aerospace Bracket – Electron Beam Machining (EBM) Vs. Conventional Machining
2. Topologically Optimized Aerospace Bracket - EBM vs. Conventional Machining
3. Aircraft Ventilation Assembly – Fused Deposition Modelling (FDM) vs. Injection Molding (IM), and
4. Hat Section Mold/Tool – FDM vs. Conventional Machining

The first two life cycle energy case studies for aircraft brackets compare 1) the same metal part made through additive manufacturing to the part made through the conventional process; and 2) an optimized metal part designed for additive manufacturing to the part designed and produced through the conventional process. The third case study covers the Aircraft Ventilation Nozzle manufactured by the FDM process. It compares the aircraft ventilation nozzle produced by FDM process with the traditional Injection Molding (IM) process. The fourth case study is based on a Hat Section Mold manufactured by the FDM process. This case study compared Hat Section Mold manufactured by the FDM process with the traditional machining process.

Case Study 1: Aerospace Bracket - EBM vs. Conventional Machining

Overview:

The part shown in Figure 11 is a bracket used in aircrafts to affix cabin structures (kitchens, lavatories, galleys, etc.). As previously discussed, some parts have an energy footprint for many years after they leave the factory. This is particularly relevant for the aerospace components which have long service life and where mass reductions can lead to both energy and cost savings. We have therefore selected a recognizable aerospace bracket as the basis of our first case study. The bracket under consideration is manufactured by conventional milling and machining processes with a buy-to-fly ratio of 33:1. The same bracket (same geometry) can be produced by Electron Beam Melting (EBM) process with a significantly lower buy-to-fly ratio (1.5:1). Figure 11 and Table 6 compare the lifecycle energy consumption of a conventional production system with that of an electron beam melting powder bed fusion AM process for a titanium aircraft cabin bracket. The energy savings are primarily the result of significantly reduced buy-to-fly ratio enabled by additive process.

Figure 11: Process Flow Diagram (Case study 1)

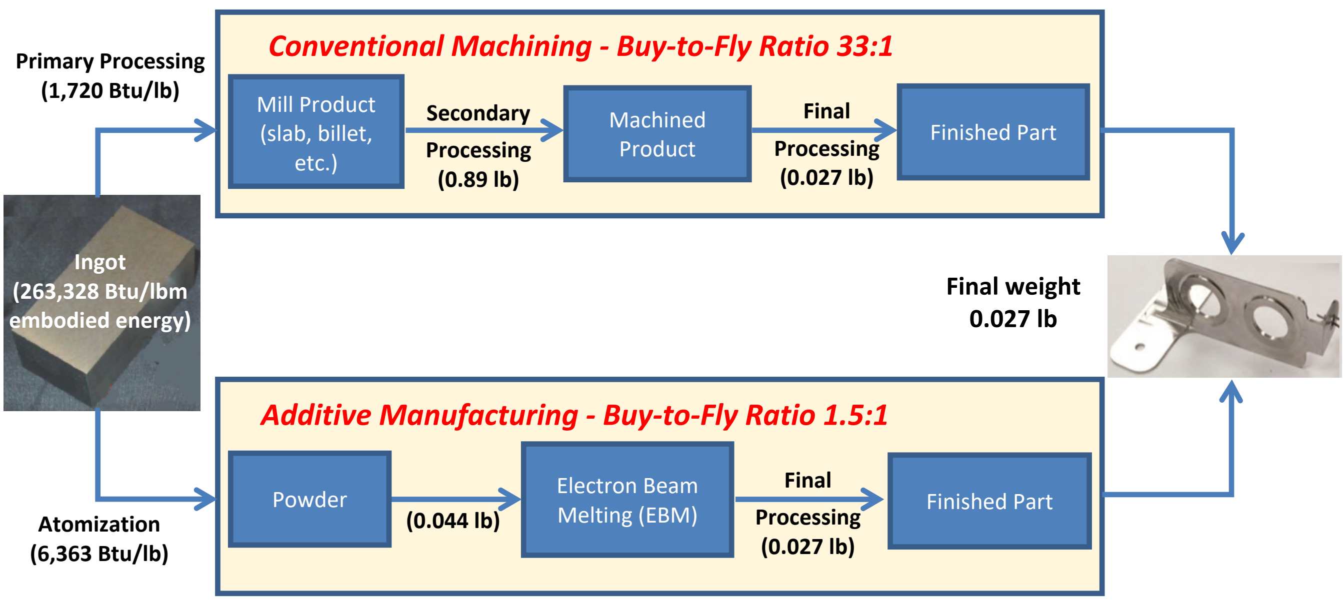


Table 6: Energy Savings Table (Case study 1)

Life Cycle Phases	Unit	Conventional Manufacturing*	Additive Manufacturing	Energy Savings per Part
Material Energy	Btu/part	78,383	8,794	69,590
Manufacturing Energy	Btu/part	3,195	2,308	886
Freight and Distribution Energy**	Btu/part	455	455	0

Use Phase Energy	Btu/part	1,120,311	1,120,311	0
Disposal (End of Life) Energy Use	Btu/part	(4,880)	(4,880)	0
Total Energy Use per Part	**Btu/part**	**1,197,464**	**1,126,988**	**70,476**

*The benchmark energy consumption for conventional manufacturing methods is based on using current best practices and optimal equipment and methodologies for conventional manufacturing. Comparing less than the best for each technology is not really equally comparing the two technologies.
**It is assumed that the parts cannot be manufactured locally and must be shipped, thereby adding shipping charges that could otherwise be avoided. This phase doesn't account for the transport of the commodity product to the AM facility. That part is included in material phase.

Assumptions (Case study # 1):

Life Cycle Phase	Parameter	Conventional Manufacturing	Additive Manufacturing
Manufacturing Process	Process(es) Name:	Forging - Primary Machining - Finishing	Electron Beam Melting (EBM)
Material Phase	Material Name and embodied energy:	Aerospace Bracket – Titanium alloy 263,328 Btu/lb (primary) 37,403 Btu/lb (recycled)	Aerospace Bracket – Titanium alloy powder 269,691 Btu/lb (primary) 43,766 Btu/lb (recycled)
	Amount of material as a % of total initial mass:	100%	100%
	Percent of engineered scrap recovered and recycled onsite.	80%	80%
	Total material initial mass:	0.89 lb	0.044 lb
	Final part mass:	0.027 lb	0.027 lb
Manufacturing Phase	Primary manufacturing or shaping process and embodied energy:	Metals - Rough rolling, forging – 1,720 Btu/lb	Electron Beam Melting (EBM) – 51,133 Btu/lb
Freight and Distribution	Analysis level:	Simple	Simple
	Primary mode for Freight and distribution and embodied energy:	Long-Distance Truck 3.06 Btu/lb/mile	Long-Distance Truck 3.06 Btu/lb/mile
	Average freight and distribution distance travelled by a part by primary mode:	3,107 miles	3,107 miles
	Secondary mode for Freight and distribution and embodied energy:	Local Truck 8.4 Btu/lb/mile	Local Truck 8.4 Btu/lb/mile
	Average freight and distribution distance travelled by a part by secondary mode:	870 miles	870 miles
Use Phase	Typical life-span of the product:	15 Years	15 Years
	Use phase sector:	Transportation	Transportation
	Fuel and mobility type (embodied energy):	Long haul aircraft – Kerosene 2.18 Btu/lb/mile	Long haul aircraft – Kerosene 2.18 Btu/lb/mile
	Distance travelled per day and usage per year	4,971 miles per day and 255 days per year	4,971 miles per day and 255 days per year

	If the use phase is in other sector:	NA	NA
	Energy input and output:	NA	NA
	Power rating:		
	Usage (hours per day and days per year)	NA	NA
Disposal (End of Life)	Disposal method for material (embodied energy):	Closed Loop Recycling	Closed Loop Recycling
	Fraction of material # 1 disposed through the selected disposal method	80%	80%
	Disposal energy use per unit mass - material # 1 (difference between secondary (recycled) and primary material embodied energies.)	-225,925 Btu/lb	-225,925 Btu/lb

Case Study 2: Topologically Optimized Aerospace Bracket - EBM vs. Conventional Machining

Overview:

The part shown in Figure 12 is again an aerospace bracket with a different geometry/design compared to the bracket discussed in case study 1. This bracket is typically produced by conventional milling and machining processes with a very high buy-to-fly ratio (8:1). The same bracket (a bracket with same functionality but with a topologically optimized geometry) can be produced by Electron Beam Melting (EBM) process with a significantly less buy-to-fly ratio (1.5:1). The optimized design results in a bracket that is 65% lighter, saving manufacturing materials and resulting in use phase energy savings. Figure 12 and Table 7 compare the lifecycle energy consumption of a conventional production system with that of an electron beam melting powder bed fusion AM process for a titanium aircraft cabin bracket. The energy savings are primarily due to two reasons: 1) a significantly reduced buy-to-fly ratio, and 2) light-weighing of the final part enabled by additive process.

Figure 12: Process Flow Diagram (Case study 2)

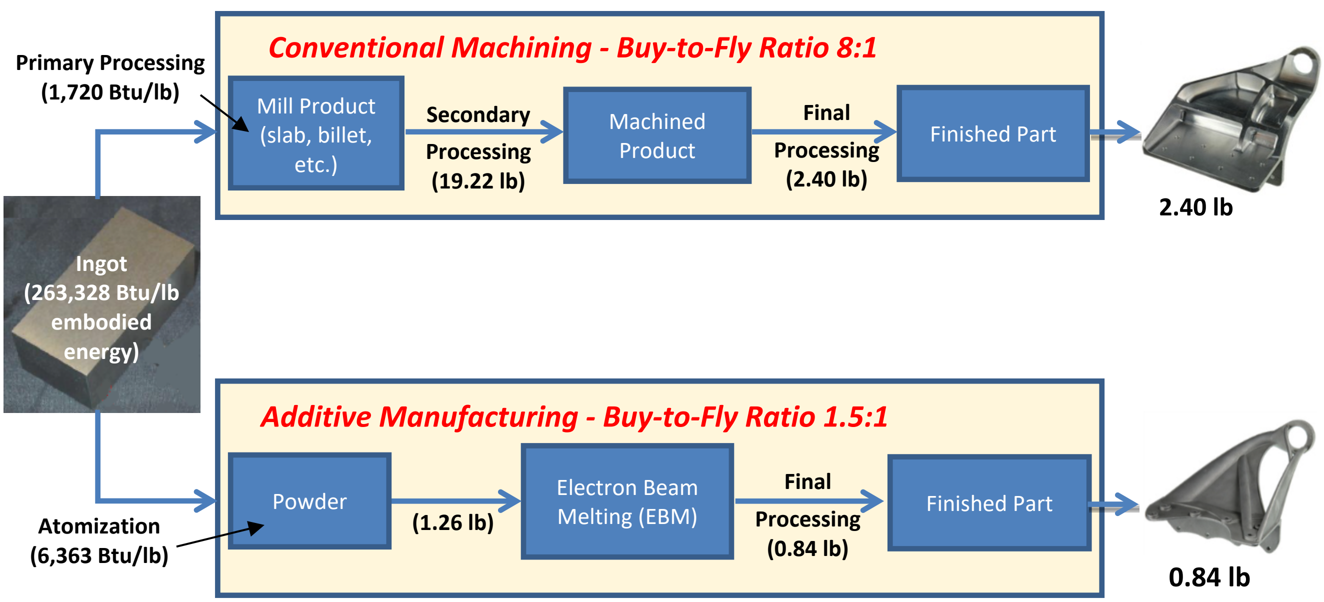


Table 7: Energy Savings Table (Case study 2)

Life Cycle Phases	Unit	Conventional Manufacturing*	Additive Manufacturing	Energy Savings per Part
Material Energy	Btu/part	2,021,120	263,900	1,757,221
Manufacturing Energy	Btu/part	65,485	65,872	(387)

Freight and Distribution Energy**	Btu/part	40,462	14,161	26,301
Use Phase Energy	Btu/part	99,583,158	34,854,105	64,729,052
Disposal (End of Life) Energy Use	Btu/part	(433,775)	(151,821)	(281,954)
Total Energy Use per Part	**Btu/part**	**101,276,449**	**35,046,216**	**66,230,233**

*The benchmark energy consumption for conventional manufacturing methods is based on using current best practices and optimal equipment and methodologies for conventional manufacturing. Comparing less than the best for each technology is not really equally comparing the two technologies.

**It is assumed that the parts cannot be manufactured locally and must be shipped, thereby adding shipping charges that could otherwise be avoided. This phase doesn't account for the transport of the commodity product to the AM facility. That part is included in material phase.

Assumptions (Case study # 2):

Life Cycle Phase	Parameter	Conventional Manufacturing	Additive Manufacturing
Manufacturing Process	Process Name:	Forging - Primary Machining - Finishing	Electron Beam Melting (EBM)
Material Phase	Material Name and embodied energy:	Titanium alloy 263,328 Btu/lb (primary) 37,403 Btu/lb (recycled)	Titanium alloy powder 269,691 Btu/lb (primary) 43,766 Btu/lb (recycled)
	Amount of material as a % of total initial mass:	100%	100%
	Percent of engineered scrap recovered and recycled onsite	80%	80%
	Total material initial mass:	19.22 lb	1.26 lb
	Final part mass:	2.4 lb	0.84 lb
Manufacturing Phase	Primary manufacturing or shaping process and embodied energy:	Metals - Rough rolling, forging – 1,720 Btu/lb	Electron Beam Melting (EBM) – 51,133 Btu/lb
Freight and Distribution	Analysis level:	Simple	Simple
	Primary mode for Freight and distribution and embodied energy:	Long-Distance Truck 3.06 Btu/lb/mile	Long-Distance Truck 3.06 Btu/lb/mile
	Average freight and distribution distance travelled by a part by primary mode:	3,107 miles	3,107 miles
	Secondary mode for Freight and distribution and embodied energy:	Local Truck 8.44 Btu/lb/mile	Local Truck 8.44 Btu/lb/mile
	Average freight and distribution distance travelled by a part by secondary mode:	870 miles	870 miles
Use Phase	Typical life-span of the product:	15 Years	15 Years
	Use phase sector:	Transportation	Transportation
	Fuel and mobility type (embodied energy):	Long haul aircraft – Kerosene 2.18 Btu/lb/mile	Long haul aircraft – Kerosene 2.18 Btu/lb/mile

	Distance travelled per day and usage per year	4,971 miles per day and 255 days per year	4,971 miles per day and 255 days per year
	If the use phase is in other sector:	NA	NA
	Energy input and output:	NA	NA
	Power rating:		
	Usage (hours per day and days per year)	NA	NA
Disposal (End of Life)	Disposal method for material (embodied energy):	Closed Loop Recycling	Closed Loop Recycling
	Fraction of material # 1 disposed through the selected disposal method	80%	80%
	Disposal energy use per unit mass - material # 1 (difference between secondary (recycled) and primary material embodied energies.)	-225,925 Btu/lb	-225,925 Btu/lb

Case Study 3: Aircraft Ventilation Assembly – FDM vs. IM

Overview:

The part shown in Figure 13 is an aircraft cabin air ventilation nozzle, which can be recognized by flyers over the world. The nozzle is in fact an assembly of five individual parts, which are fitted together post manufacture. These five component parts and their relative supply chains are used as the basis for this comparative case study. This case study looks at the product lifecycles of identical assemblies produced by FDM and injection molding. The data for the case study 3 is taken from the Stratasys white paper published in year 2010 [STRATASYS 2010]. Figure 13 and Table 8 compare the lifecycle energy consumption of a conventional production system with that of a Fused Deposition Modeling AM process for an Ultem 9085 aircraft ventilation model. The energy savings are primarily due to the lighter weight of the final part enabled by FDM process.

Figure 13: Process Flow Diagram (Case study 3)

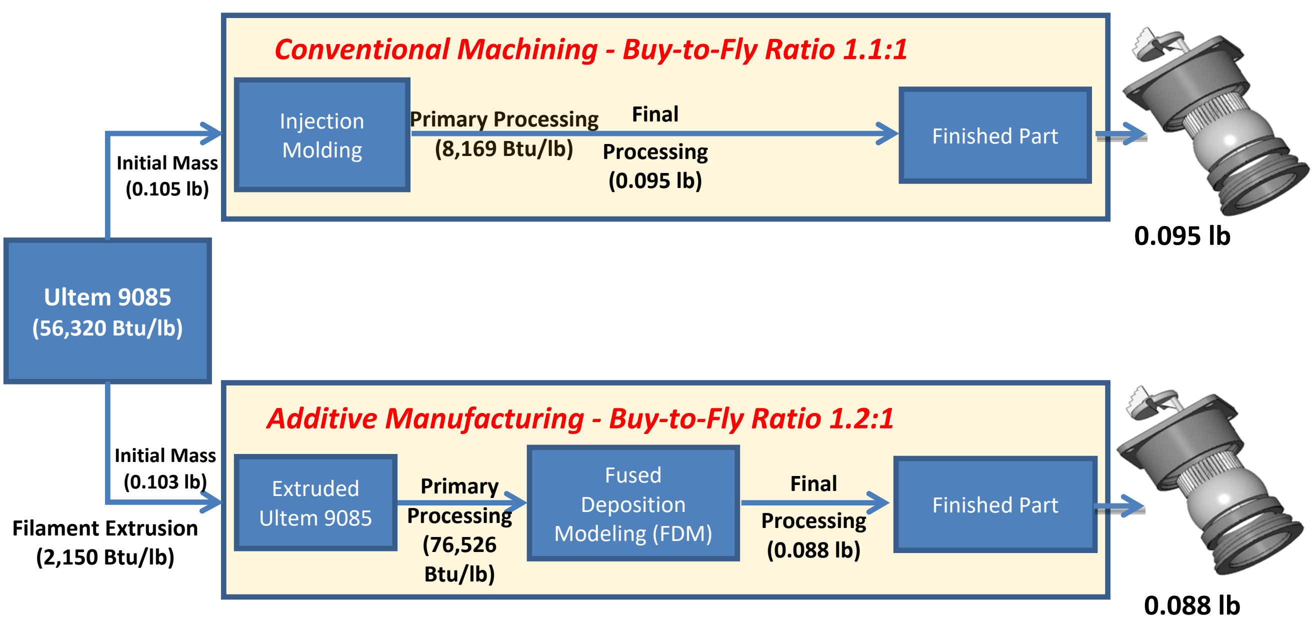


Table 8: Energy Savings Table (Case study 3)

Life Cycle Phases	Unit	Conventional Manufacturing*	Additive Manufacturing	Energy Savings per Part
Material Energy	Btu/part	5,914	6,022	(109)
Manufacturing Energy	Btu/part	858	7,934	(7,076)
Freight and Distribution Energy**	Btu/part	425	394	31
Use Phase Energy	Btu/part	3,091,634	2,863,829	227,805

Disposal (End of Life) Energy Use	Btu/part	1,736	1,608	128
Total Energy Use per Part	**Btu/part**	**3,100,566**	**2,879,787**	**220,779**

*The benchmark energy consumption for conventional manufacturing methods is based on using current best practices and optimal equipment and methodologies for conventional manufacturing. Comparing less than the best for each technology is not really equally comparing the two technologies.
**It is assumed that the parts cannot be manufactured locally and must be shipped, thereby adding shipping charges that could otherwise be avoided. This phase doesn't account for the transport of the commodity product to the AM facility. That part is included in material phase.

Assumptions (Case study # 3) - Reference: [STRATASYS 2010]:

Life Cycle Phase	Parameter	Conventional Manufacturing	Additive Manufacturing
Manufacturing Process	Process Name:	Injection Molding (IM)	Fused Deposition Modeling (FDM)
Material Phase	Material Name and embodied energy:	ULTEM 9085 dried pellets – 56,320 Btu/lb	ULTEM 9085 extruded filaments – 58,470 Btu/lb
	Amount of material as a % of total initial mass:	100%	100%
	Percent of engineered scrap or waste material recovered and recycled onsite	0%	0%
	Total material initial mass:	0.105 lb/part (Part material + 10% spruces.	0.103 lb/part (Part material + 17% support. For calculation, we have assumed that the support material has the same embodied energy as the build material)
	Final part mass:	0.095 lb/part	0.088 lb/part (parts can be produced with variable density, reducing material consumption and part weight)
Manufacturing Phase	Primary manufacturing or shaping process and embodied energy:	Injection Molding (embodied energy 8,169 Btu/lb)	Fused Deposition Modeling (embodied energy 76,526 Btu/lb)
Freight and Distribution	Analysis level:	Intermediate	Intermediate
	Primary mode for Freight and distribution and embodied energy:	32 metric ton truck – Diesel (0.65 Btu/lb/mile)	32 metric ton truck – Diesel (0.65 Btu/lb/mile)
	Average freight and distribution distance travelled by a part by primary mode:	1,189 miles (Raw material source - Delaware, Production location - Eden Prairie)	1,189 miles (Raw material source - Delaware, Production location - Eden Prairie)
	Secondary mode for Freight and distribution and embodied energy:	Light goods vehicle – Diesel (1.73 Btu/lb/mile)	Light goods vehicle – Diesel (1.73 Btu/lb/mile)
	Average freight and distribution distance travelled by a part by secondary mode:	2,141 miles (Assumed that the final customer is located at an aircraft assembly facility in California)	2,141 miles (Assumed that the final customer is located at an aircraft assembly facility in California)

Life Cycle Phase	Parameter	Conventional Manufacturing	Additive Manufacturing
Use Phase*	Typical life-span of the product:	30 years	30 years
	Use phase sector:	Transportation	Transportation
	Fuel and mobility type (embodied energy):	Short haul aircraft – kerosene (2.18 Btu/lb.mile)	Short haul aircraft – kerosene (2.18 Btu/lb.mile)
	Distance travelled per day and usage per year	2,485 miles per day, 200 days per year.	2,485 miles per day, 200 days per year.
	If the use phase is in other sector:	NA	NA
	Energy input and output:	NA	NA
	Power rating:	NA	NA
	Usage (hours per day and days per year)	NA	NA
Disposal (End of Life)	Disposal method for material (embodied energy):	Disposal method – Landfill	Disposal method – Landfill
	Fraction of material # 1 disposed through the selected disposal method:	100% (Ultem 9085 or Polyethermide (PEI) is not a commodity polymer and as such it is highly unlikely that there will be a cost effective recycling route for this material)	100% (Ultem 9085 or Polyethermide (PEI) is not a commodity polymer and as such it is highly unlikely that there will be a cost effective recycling route for this material)
	Disposal energy use per unit mass - material # 1 (applicable for other disposal methods except open or closed-loop recycling - user input)	18,272 Btu/lb	18,272 Btu/lb

*As mentioned before, the data for the case study 3 is taken from the Stratasys white paper published in year 2010 [STRATASYS 2010]. The Stratasys white paper mainly focuses on the CO_2 emissions in material, manufacturing, freight & distribution, and use phases. It doesn't calculate CO_2 emissions per part in the disposal phase. The outcomes from the AM tool closely match with the results provided in the Stratasys white paper except the use phase. The use phase energy use per part (Btu/part) results are significantly different because of the following two reasons:

1. The energy intensity number for the short haul aircrafts in the Stratasys white paper is 14.1 Btu/lb.mile and in the AM Tool 2.18 Btu/lb.mile.
2. The total distance travelled by the short haul aircraft during its lifetime in the Stratasys white paper is 73 million kilometers and 24 million kilometers in the AM tool.

Case Study 4: Hat Section Mold/Tool – FDM vs. Conventional Machining

Overview:

The part shown in Figure 14 is a hat section mold/tool. In last few years, FDM process has demonstrated to provide a variety of pattern, mold, and tooling options that can significantly reduce cycle times and cost. The ability to rapidly process Computer Aided Drafting (CAD) files is an effective means to optimize the mold design, cycle times, and cost of the desired molds/tooling. The case study 4 confirms that FDM tooling is not only functional but also demonstrates a number of programmatic and ergonomic advantages. Because FDM tooling is lighter than traditional tooling methods (forging or casting with heavy machining), the need for fork trucks, hoists, and dollies are reduced. The lightweight molds also reduce energy consumption in the freight and distribution phase. Figure 14 and Table 9 compare the lifecycle energy consumption of a conventional production system for a stainless steel hat section mold with that of a Fused Deposition Modeling AM process for an Ultem 9085 hat section mold. The energy savings are primarily due to the light-weighing of the final part and the reduction in initial raw material needed to produce the hat section mold.

Figure 14: Process Flow Diagram (Case study 4)

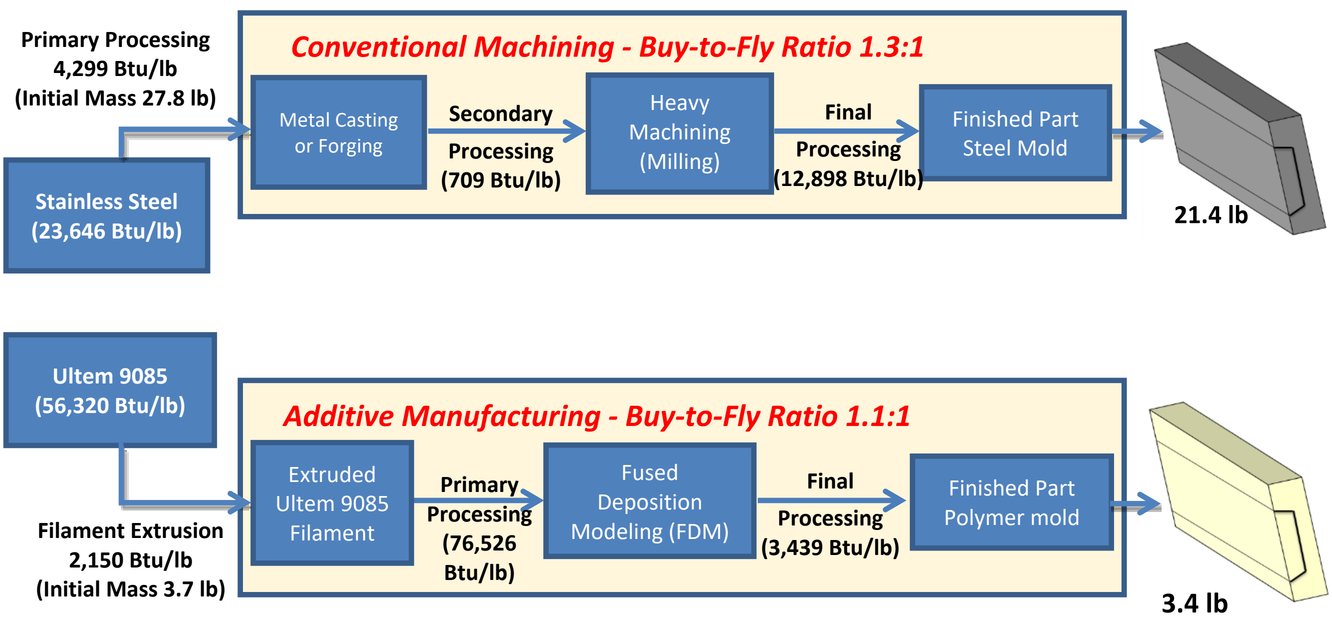


Table 9: Energy Savings Table (Case study 4)

Life Cycle Phases	Unit	Conventional Manufacturing*	Additive Manufacturing	Energy Savings per Part
Material Energy	Btu/part	850,345	288,450	561,895
Manufacturing Energy	Btu/part	137,132	378,905	(241,774)

Freight and Distribution Energy**	Btu/part	296,449	36,666	259,782
Use Phase Energy	Btu/part	0	0	0
Disposal (End of Life) Energy Use	Btu/part	(533,620)	195	(533,815)
Total Energy Use per Part	**Btu/part**	**750,305**	**704,216**	**46,089**

*The benchmark energy consumption for conventional manufacturing methods is based on using current best practices and optimal equipment and methodologies for conventional manufacturing. Comparing less than the best for each technology is not really equally comparing the two technologies.
**It is assumed that the parts cannot be manufactured locally and must be shipped, thereby adding shipping charges that could otherwise be avoided. This phase doesn't account for the transport of the commodity product to the AM facility. That part is included in material phase.

Assumptions (Case study # 4):

Life Cycle Phase	Parameter	Conventional Manufacturing	Additive Manufacturing
Manufacturing Process	Process Name:	Metal casting and heavy machining (milling)	Fused Deposition Modeling (FDM)
Material Phase	Material 1 Name and embodied energy:	Stainless Steel – 36,328 Btu/lb (Primary), 5,159 Btu/lb (Secondary)	ULTEM 9085 extruded filaments – 58,470 Btu/lb (Primary and Secondary)
	Amount of material 1 as a % of total initial mass:	100%	100%
	Percent of engineered scrap recovered and recycled onsite	80%	0%
	Total material initial mass:	27.8 lb	3.7 lb
	Final part mass:	21.4 lb	3.4 lb
Manufacturing Phase	Primary manufacturing or shaping process and embodied energy:	Casting (embodied energy 4,299 Btu/lb), Heavy Machining (709 Btu/lb), Grinding (12,898 Btu/lb).	Fused Deposition Modeling (embodied energy 76,526 Btu/lb), Other finishing processes (3,439 Btu/lb)
	Accounting for Tooling and Machine Tools:	Tungsten Carbide (171,969 Btu/lb) machine tools, Number of tooling 3 and average mass per tooling 1 1 lb/tool. Total number of parts produced during tooling lifetime 100.	NA
Freight and Distribution	Analysis level:	Simple	Simple
	Primary mode for Freight and distribution and embodied energy:	Ship	Long-Distance Truck
	Average freight and distribution distance travelled by a part by primary mode:	7,456 miles (imported from China)	2,485 miles (Domestic travel)

Life Cycle Phase	Parameter	Conventional Manufacturing	Additive Manufacturing
	Secondary mode for Freight and distribution and embodied energy:	Long-Distance Truck	Long-Distance Truck
	Average freight and distribution distance travelled by a part by secondary mode:	2,485 miles (Domestic travel)	155 miles (Domestic travel)
Use Phase	Typical life-span of the product:	1000 Cycles or 1 year	750 Cycles or 0.75 year
	Use phase sector:	Industry	Industry
	Fuel and mobility type (embodied energy):	NA	NA
	Distance travelled per day and usage per year	NA	NA
	If the use phase is in other sector:	NA	NA
	Energy input and output:	NA	NA
	Power rating:	NA	NA
	Usage (hours per day and days per year)	NA	NA
Disposal (End of Life)	Disposal method for material (embodied energy):	Closed-loop Recycling	Landfill
	Fraction of material # 1 disposed through the selected disposal method	80%	100%
	Disposal energy use per unit mass - material # 1 (applicable for other disposal methods except open or closed-loop recycling - user input)	-31,169 Btu/lb	43 Btu/lb (0.1 MJ/kg)

Conclusions:

Over the last few years, there has been an increasing level of interest in the use of AM to increase sustainability and increase energy efficiency. This has led to a number of industrial initiatives and government funded research projects focused on understanding the sustainability of this disruptive manufacturing approach. The case studies discussed in this report have focused on the 'life-cycle' of parts made using AM, and in all cases, have demonstrated that AM could be a more sustainable alternative than conventional manufacturing when used as a production technology for select transport related components. All case studies show that the ability to manufacture lighter weight complex products using less raw material with little (if any) energy penalty in the manufacturing phase. These case studies indicate that AM can be a strong contender as a sustainable production approach.

As we discussed in the report, the life-cycle of a product has five distinct phases. Initially raw materials must be extracted and produced. These materials are then processed using different manufacturing operations; often at different locations necessitating freight and distribution. The part is then put into service and used for its intended purpose. When the product reaches its end-of-life, it can be reused, recycled or disposed of. At each of these stages, energy is consumed, for example - the electrical energy needed to run machine tools, or the energy consumed by vehicles used within the supply chain. For many static products (e.g. parts used in industrial plants, commercial buildings, or residential homes), the vast majority of energy use comes from the production of the raw materials. Hence, using fewer raw materials has a significant benefit. Additional innovations in design enabled by additive manufacturing could also lead to more efficient energy generation (e.g. turbine blades) which could offer additional sustainability benefits. For transport related products, such as aerospace or automotive components, the use phase energy consumption contributes most significantly to the overall life-cycle energy use of the part. Simply speaking, the more a part weighs, the more load it places on the engine of a car, plane or train, and the greater the fuel consumption. Hence, if we can reduce part weight with AM, then we can reduce the overall life-cycle energy use of the part and reduce the resulting greenhouse gas emissions.

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APPENDIX

This appendix contains different values for embodied energies in Life Cycle phases including raw material, process, use, freight and distribution, and recycle. This data represents the most updated values that were obtained from various credible sources. It should be mentioned that this data will be continuously updated as more information becomes available. The data used in this calculator is included in the following six appendices:

Appendix 1: Raw Material Embodied Energy (Btu/lb)
Appendix 2: Cutting Tools Material Embodied Energy (Btu/lb)
Appendix 3a and 3b: Primary Shaping Processes Embodied Energy (Btu/lb)
Appendix 4a and 4b: Additive Manufacturing Processes Embodied Energy (Btu/lb)
Appendix 5: Transportation Mode Embodied Energy (Btu/lb.mile)
Appendix 6: Other Transportation Modes Embodied Energy (Btu/lb.mile)
Appendix 7: Use Phase Energy Consumption (Btu/lb.mile)

Appendix 1: Material Embodied Energy

Material	Material Embodied Energy (Btu/lb) (Primary or Virgin)	Material Embodied Energy (Btu/lb) (Secondary or Recycled)	Data Source
Acrylonitrile Butadiene Styrene (ABS) - Extruded Filament	40,843	20,097	9 & 1
Acrylonitrile Butadiene Styrene (ABS) - Pellets	40,628	19,991	1
Aluminum	90,284	11,178	1
Aluminum alloys	90,284	11,178	1
Blended PC-ABS - Extruded Filament	46,002	46,002	9
Blended PC-ABS - Pellets	44,282	44,282	9
Cast Aluminum (Primary, average)	24,936	9,888	1
Cast iron, ductile	7,739	4,514	1
Carbon fiber (polyolefin-based)	166,810	166,810	1
Carbon fiber reinforced polymer (CFRP)	204,213	204,213	1
Cobalt-chromium alloys	159,072	28,922	1
Copper & Brass	20,421	4,673	9
Copper alloys	25,365	5,804	1
Glass, soda-lime	4,514	3,525	1
Glass, borosilicate (Pyrex)	12,253	9,243	1
Glass fiber	28,160	28,160	1
Glass fiber reinforced polymer (GFRP)	48,366	48,366	1
Gold	108,555,558	294,282	1
Lead alloys	11,608	3,203	1
Magnesium Alloys	135,426	10,533	1
Nickel-chromium alloys	78,031	14,187	1
Nickel-based super alloys	99,957	15,327	1
Phenolics	33,964	33,964	1
Polyamide (nylon)	52,666	18,272	7
Polycarbonate (PC) - Extruded Filament	49,011	19,198	9 & 1
Polycarbonate (PC) - Pellets	46,647	18,272	1
Polyethylene (PE)	34,824	21,496	1
Polyphenylsulfone (PPSU or PPSF) - Extruded Filament	75,237	75,237	9
Polyphenylsulfone (PPSU or PPSF) - Pellets	73,087	73,087	9
Polypropylene	33,964	21,496	1
Polystyrene	41,703	20,421	1
PrimePart FR (PA 2241 FR)	41,488	41,488	7
PrimePart ST (PEBA)	41,488	41,488	7
Rubber, natural	29,020	29,020	1
Silver	634,136	66,638	1
Steel, low carbon	11,393	3,138	1
Steel, low alloy	13,972	3,697	1
Stainless steel	36,328	5,159	1

Titanium alloy (Ti-6Al-4V)	263,328	37,403	1
Titanium alloy powder (Ti-6Al-4V)	269,691	43,766	Ti alloy + atomization (14.8 MJ/kg)
ULTEM 9085 - Extruded Filament	58,470	58,470	9
ULTEM 9085 - Pellets	56,320	56,320	9
Zinc	21,926	4,020	2
Zinc die-casting alloys	25,795	4,729	1

Sources (Appendix 1) - see the reference section for more details.

1. [M. ASHBY]
2. [VICTORIA]
3. [KEOUGH 2011]
4. [ATKINS 2011]
5. [HAMMOND & JONES 2011]
6. [GHENAI 2012]
7. [PENN STATE]
8. [STODOLSKY & VYAS 1995]
9. [STRATASYS 2010]

Appendix 2: Cutting Tool Materials Embodied Energy

Raw Material	**Raw Material Embodied Energy (MJ/kg) (Primary or Virgin)**	**Raw Material Embodied Energy (Btu/lb) (Primary or Virgin)**	**Source**
Carbon tool steels	32.5	13,972	3
High speed steel (HSS)	84.5	36,328	3
Cast cobalt alloys	188	80,611	2
Cemented carbide	1,000	429,923	2
Ceramics (alumina, silicon nitride, silicon carbide)	1,000	429,923	2
Cubic Boron Nitride (CBN)	250	107,481	2
Tungsten Carbide (WC)	400	171,969	1

Sources (Appendix 2) - see the reference section for more details.

1. [DAHMUS 2004]
2. [AZOM]
3. [M. ASHBY]

Appendix 3a: Primary Shaping Processes Energy

Primary shaping processes	**Average Energy Intensity (MJ/kg)**	**Average Energy Intensity (Btu/lb)**	**Data Source**
Metals – Casting	10	4,299	[M. ASHBY]
Metals - Rough rolling, forging	15.9	6,838	
Metals - Extrusion, foil rolling	15	6,449	
Metals - Wire drawing	30	12,898	
Metals - Metal powder forming	25	10,748	
Metals - Vapor phase methods	50	21,496	
Polymers – Extrusion	4.25	1,827	
Polymers – Molding	19	8,169	
Ceramic powder form	25	10,748	
Glass molding	3	1,290	
Hybrids - Compression molding	13.5	5,804	
Hybrids - Spray/Lay up	16	6,879	
Hybrids - Filament winding	3.35	1,440	
Hybrids - Autoclave molding	200	85,985	
Other Primary Process	User Input	User Input	

Appendix 3b: Secondary Shaping Processes Embodied Energy

Secondary Processes	**Average Energy Intensity (MJ/kg)**	**Average Energy Intensity (Btu/lb)**	**Data Source**
Machining – Heavy	108.9	46,819	[M. ASHBY]
Machining - Finishing (light)	8	3,439	
Machining – Grinding	30	12,898	
Machining - Water jet, EDM, Laser	2750	1,182,288	
Joining - Gas welding	1.9	817	
Joining - Electric welding	2.6	1,118	
Joining - Fasteners, small	0.03	13	
Joining - Fasteners, large	0.075	32	
Joining - Adhesives, cold	10.5	4,514	
Joining - Adhesives, heat-curing	29	12,468	
Painting – Painting	55	23,646	
Painting - Baked coatings	65	27,945	
Painting - Powder coating	76.5	32,889	
Electroplating	90	38,693	
Other Secondary Process	8	3,439	

Appendix 4a: Additive Manufacturing Processes Embodied Energy

Additive Manufacturing Processes	Average Energy Intensity (MJ/kg)	Average Energy Intensity (Btu/lb)	Data Source
Powder Bed Fusion Processes (Average):	**131.8**	**56,677**	**Average (Calculated)**
Selective Laser Melting (SLM)	118.2	50,800	1
Direct Metal Laser Sintering (DMLS)	158.4	68,100	1
Electron Beam Melting (EBM)	118.9	51,133	1
Directed Energy Deposition Processes (Average):	**118.2**	**50,815**	**Average (Calculated)**
Laser Engineered Net Shaping (LENS)	NA	NA	Assumed (equal to DMD)
Direct Metal Deposition (DMD)	98.3	42,244	1
Direct Manufacturing (DM)	NA	NA	Assumed (equal to DMD)
Fused Deposition Modeling (FDM) of Polymers	178.0	76,526	2
Other AM Process	User Input	User Input	User input

Appendix 4b: Additive Manufacturing Processes Embodied Energy (*just for reference – not used in the tool*) *[Source 3]*

Technology	Machines	Materials	Average Energy Intensity (MJ/kg)	Average Energy Intensity (MJ/kg)
Stereolithography	SLA-250	Epoxy resin (SLA 5170)	117	50,270
	SLA-3000	Epoxy resin (SLA 5170)	149	64,091
	SLA-5000	Epoxy resin (SLA 5170)	75	32,038
Selective Laser Sintering	Sinterstation DTM 2000	Polyamide	144	61,924
	Sinterstation DTM 2500	Polyamide	107	46,076
	Vanguard HiQ	Polyamide	52	22,504
	EOSINT (M250 Xtended)	Metallic Powder (Bronze + Ni)	19	8,373
	EOSINT (P760)	Polyamide PA2200 Balance 1.0	131	56,492
		Polyamide PA2200 Speed 1.1	143	61,599
		Polyamide PA3200GF	95	40,705
Fused Deposition Modeling	FDM 1650	ABS Plastic	1,247	536,178
	FDM 2000	ABS Plastic	416	178,731
	FDM 8000	ABS Plastic	83	35,752
	FDM Quantum	ABS Plastic	728	312,779
Selective Laser Melting	MTT SLM 250	Metallic Powder SAE 316L	112	47,979
Electron Beam Melting	Arcam A1	Metallic Powder Ti-6Al-4V	61	26,311

Sources (Appendix 4a and 4b) - see the reference section for more details.

1. [BAUMERS 2013]
2. [STRATASYS 2010]
3. [BOURHIS 2013]

Appendix 5: Transportation Mode Embodied Energy

Cargo Emissions WWEST	**Energy Consumption (MJ/kg.km)**	**Fuel Consumption (gal/kg.km)**	**Energy Consumption (Btu/lb.mile)**	**Data Source**
Local Truck	1.22E-02	3.47E-05	8.44E+00	1
Long-Distance Truck	4.43E-03	1.26E-05	3.06E+00	2
Ship	1.21E-03	3.44E-06	8.37E-01	1
Train	9.47E-04	2.70E-06	6.55E-01	2
Airplane	3.58E-02	9.71E-05	2.48E+01	2

Sources (Appendix 5) - see the reference section for more details.

1. [OECD 1997]
2. [FACANHA & HORVATH 2007]

Appendix 6: Other Transportation Modes Embodied Energy

Transportation Type	**Energy (MJ/kg/Km)**	**Energy (Btu/lb/mile)**	**Data Source**
Ocean shipping – Diesel	1.60E-04	1.11E-01	2
Coastal shipping – Diesel	2.70E-04	1.87E-01	2
Barge – Diesel	3.60E-04	2.49E-01	2
Rail – Diesel	2.50E-04	1.73E-01	2
Articulated HGV (up to 55 metric tons) – Diesel	7.10E-04	4.91E-01	2
40 metric ton truck – Diesel	8.20E-04	5.67E-01	2
32 metric ton truck – Diesel	9.40E-04	6.50E-01	2
14 metric ton truck – Diesel	1.50E-03	1.04E+00	2
Light goods vehicle – Diesel	2.50E-03	1.73E+00	2
Family car – Diesel	1.70E-03	1.18E+00	2
Family car – Gasoline	2.60E-03	1.80E+00	2
Family car – LPG	3.90E-03	2.70E+00	2
Family car - Hybrid gasoline-electric	1.55E-03	1.07E+00	2
Super sports car and SUV - Gasoline	4.80E-03	3.32E+00	2
Long haul aircraft - Kerosene	6.50E-03	4.50E+00	2
Short haul aircraft - Kerosene	1.30E-02	8.99E+00	2
Helicopter (Eurocopter AS 350) - Kerosene	5.50E-02	3.81E+01	2

Sources (Appendix 6)- see the reference section for more details.

1. [STROGEN & HORVATH 2013]
2. [M. ASHBY]

Appendix 7: Use Phase Energy Consumption

Mobility Type	Energy (MJ/kg. Km)	Energy (Btu/lb.mile)	Source
Ocean shipping - Diesel	1.60E-04	1.11E-01	2
Coastal shipping - Diesel	2.70E-04	1.87E-01	2
Barge - Diesel	3.60E-04	2.49E-01	2
Rail - Diesel	3.00E-05	2.08E-02	1
Articulated HGV (up to 55 metric tons) - Diesel	7.10E-04	4.91E-01	2
Articulated truck	2.10E-04	1.45E-01	1
40 metric ton truck - Diesel	8.20E-04	5.67E-01	2
32 metric ton truck - Diesel	9.40E-04	6.50E-01	2
14 metric ton truck - Diesel	1.50E-03	1.04E+00	2
Light goods vehicle - Diesel	2.50E-03	1.73E+00	2
Family car - Diesel	1.07E-03	7.40E-01	1
Family car - Gasoline	1.13E-03	7.82E-01	1
Family car - LPG	1.13E-03	7.82E-01	1
Family car - Hybrid gasoline-electric	6.32E-04	4.37E-01	3
Electric vehicles	1.49E-04	1.03E-01	3
Super sports car and SUV - Gasoline	1.04E-03	7.20E-01	2
Airplanes (average)	3.51E-03	2.43E+00	1,4,5
Long haul aircraft - Kerosene	3.51E-03	2.43E+00	3
Short haul aircraft - Kerosene	3.51E-03	2.43E+00	3
Helicopter (Eurocopter AS 350) - Kerosene	5.50E-02	3.81E+01	2
Note: In principle, average energy use by mobility type in the use phase should be different from the freight and distribution phase. Use phase energy numbers should be just the additional energy use associated with an increase in mass, whereas freight energy use should include not only the energy use associated with additional mass, but also a share of the baseline energy use needed to move the vehicle even if it were not carrying any weight.			

Sources (Appendix 7) - see the reference section for more details.

1. [HELMS & LAMBRECHT 2006]
2. [M. ASHBY]
3. [GEYER 2012]
4. [AMERICAN AIRLINES 2007]
5. [LUFTHANSA 2011]