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# Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components

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ABSTRACT

Additive manufacturing (AM) holds great potential for improving materials efficiency, reducing life-cycle impacts, and enabling greater engineering functionality compared to conventional manufacturing (CM), and AM has been increasingly adopted by aircraft component manufacturers for lightweight, cost-effective designs. This study estimates the net changes in life-cycle primary energy and greenhouse gas emissions associated with AM technologies for lightweight metallic aircraft components through the year 2050, to shed light on the environmental benefits of a shift from CM to AM processes in the U.S. aircraft industry. A systems modeling framework is presented, with integrates engineering criteria, life-cycle environmental data, aircraft fleet stock and fuel use models under different AM adoption scenarios. Estimated fleet-wide life-cycle primary energy savings at most reach 70-173 million GJ/year in 2050, with cumulative savings of 1.2–2.8 billion GJ. Associated cumulative GHG emission reductions were estimated at 92.1–215.0 million metric tons. In addition, thousands of tons of aluminum, titanium and nickel alloys could be potentially saved per year in 2050. The results indicate a significant role of AM technologies in helping society meet its long-term energy use and GHG emissions reduction goals, and highlight barriers and opportunities for AM adoption for the aircraft industry.

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## 1. Introduction

Additive manufacturing (AM) has been defined as "the process of joining materials to make objects from three-dimensional model data, usually layer upon layer" (ASTM International, 2012). After many years of development, AM has evolved from applications mostly limited to rapid prototyping of polymeric objects to commercial production of both polymeric and metallic components in a number of different industries (Huang et al., 2013; Wohlers, 2013; Horn and Harrysson, 2012). Early adopters include the aerospace, medical, and automotive industries, which use a variety of different polymers and metals for AM components, the latter of which include steel, aluminum, nickel, and titanium alloys (Frazier, 2014; Melchels et al., 2012).

Compared to conventional manufacturing (CM) processes such as thermoforming, injection molding, and blow molding (for polymeric components) and casting, forging, machining, and finishing (for metallic components), AM holds at least three promising advantages. First, AM enables designs with novel geometries that would be difficult or impossible to achieve using CM processes (Horn and Harrysson, 2012; Tuck et al., 2008), which can improve a component's engineering performance. Second, AM can reduce the "cradle-to-gate" environmental footprints of component manufacturing through avoidance of the tools, dies, and materials scrap associated with CM processes (Morrow et al., 2007; Serres et al., 2011). Third, novel geometries enabled by AM technologies can also lead to performance and environmental benefits in a component's product application (Huang et al., 2013; Horn and Harrysson, 2012). For example, the aircraft industry has adopted a number of different AM components for reducing aircraft mass—including flight deck monitor arms, seat buckles, and various hinges and brackets—which can lead to greater aircraft fuel

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efficiency (Immarigeon et al., 1995; Oak Ridge National Laboratory (ORNL), 2010; Munsch et al., 2012; Carrington, 2013).

This study quantifies the life-cycle energy and greenhouse gas (GHG) emissions savings potential of AM technologies for metallic aircraft components in the United States. As an early adopter of metallic AM components, the aircraft industry provides a compelling case study of the life-cycle environmental savings potential of AM technologies. Firstly, lighter weight aircraft are a critical strategy for reducing societal energy use and GHG emissions (Immarigeon et al., 1995). Aviation is currently the second largest consumer of transport fuels globally (IEA, 2010). In 2009, the world's aircraft consumed 250 million tons of oil equivalents and comprised 12% and 9% of global transport sector energy use and GHG emissions, respectively (IEA, 2010; Schlumberger, 2012). Furthermore, global aircraft fuel use is projected to triple by 2050 due to rapid economic growth and increasing globalization—a growth rate that is faster than any other transportation mode, including automobiles (Faganha et al., 2012; Rodrigue et al., 2009). In the US, air travel's share of transportation sector energy use is 9.4%, though projected growth rates are slower (Energy Information Administration(EIA), 2014).

Secondly, the cradle-to-gate materials mass requirements for metallic AM components promise to be far lower than those for CM processes. Presently, the so-called “buy-to-fly” ratio—the mass of raw material needed per unit mass of finished component—ranges from 12:1 to 25:1 for aircraft components made of aluminum and titanium alloys using CM processes (Oak Ridge National Laboratory (ORNL), 2010; Dornfeld, 2010). These high buy-to-fly ratios result in substantial amounts of materials scrap in the cradle-to-gate manufacturing system (Dornfeld, 2010; Allwood et al., 2011), which leads to high manufacturing costs and large energy and environmental emissions footprints. For these reasons, a growing number of aircraft industry companies such as Airbus, Boeing, and General Electric are beginning to develop, test, and deploy AM components (Immarigeon et al., 1995; Munsch et al., 2012; Carrington, 2013; Kaufmann, 2008; Cole, 2005; GE, 2013).

Despite its growing use, AM has limitations that currently preclude its application to many components and products. The throughput of AM processes is presently low, which makes AM technologies less suitable for high-volume production (Wohlers, 2013). Issues with geometric repeatability, residual stresses, and high surface roughness also present barriers in applications that require high dimensional precision, surface quality, and fatigue resistance (Huang et al., 2013; Horn and Harrysson, 2012; Frazier, 2014). Given the intense focus on improving AM technologies in the industrial and scientific communities, however, it is likely that these obstacles can be overcome in the next 5–20 years (Gausemeier, 2014a, b). Despite these limitations, the aircraft industry has moved forward with AM technologies by strategically focusing on applications to basic interior parts in non-critical applications (Kobryn et al., 2006; GE., 2013a, b).

Studies that quantify the life-cycle energy use and GHG emissions implications of AM components are currently scarce. Table 1 summarizes the existing literature, from which several observations can be made. First, most studies focus only on the direct energy intensity of AM processes without comparisons to the energy and material requirements of the CM processes that are replaced. Second, most studies have considered polymeric AM technologies, due to their maturity, low cost, and widespread availability. Third, energy intensity estimates for AM processes vary widely across studies, primarily due to different material selections, component geometries, and data collection methods, which preclude direct comparisons of study results. Fourth, none of the studies considered application performance improvements due to changes in component geometries or, by extension, the environmental implications of such performance improvements.

This study helps fill this quantitative knowledge gap for the case of selected AM components in the U.S. aircraft fleet. The analysis considers AM technologies for selected steel, aluminum, nickel, and titanium alloy components and compares their cradle-to-gate energy and GHG emission footprints to the case of CM technologies for those same components in an analytically consistent manner. Potential aircraft fuel use reductions due to these lighter weight AM components are estimated over the period 2014–2050 at various rates of market adoption as existing aircraft are upgraded and new aircraft are added to the fleet. As such, the analysis considers the life-cycle energy and GHG emissions implications of AM technologies for a critical global industry over a plausible adoption period. Such analyses are important for assessing the role of AM technologies in helping society meet its long-term energy use and GHG emissions reduction goals, as well as for highlighting opportunities for manufacturing technology adoption that can lead to broader societal benefits.

## 2. Methodology

The analysis framework employed in this study consisted of five major steps. First, several aircraft systems were identified as candidates for near-term adoption of AM components based on a structured selection process that considered geometric, load, and application suitability. Second, the replaceable mass for different metal alloys within each selected component system was estimated using aircraft materials composition data and AM case studies from the industry. Third, a cradle to gate manufacturing life-cycle inventory (LCI) model was developed to estimate energy and GHG emissions reductions associated with replacing existing CM components with lighter weight AM components within the selected systems. Fourth, a temporal adoption model was developed to estimate the penetrations of different AM components as fleet upgrades and additions occur through the year 2050. Fifth, an aircraft fuel use model was applied to estimate the potential energy and GHG emission savings associated with lighter weight aircraft due to AM component adoption. Together, these steps facilitated an integrated analysis of net changes in primary energy use and GHG emissions within the U.S. manufacturing and air transport sectors attributable to the adoption of AM components over the next 36 years. Each step is summarized in the remainder of this section. Further details on the approaches, data sources, and calculations for all steps are provided in the Supplementary Information (SI).

### 2.1. Aircraft component selection

This study adopted major aircraft component system definitions developed by Kroo et al. (Kroo, 2013), which identified 17 major component systems within typical commercial passenger aircraft models and as well as the contributions of each system to total aircraft mass. Given the infeasibility of analyzing the thousands of aircraft components, this study focused on identifying systems that represent the most feasible application opportunities for lightweight AM components in the near term (i.e., within 5–20 years). Feasible applications were defined as those that met specific criteria for load profile, geometric complexity, geometric volume, materials, and other factors as described below.

Feasibility for near-term adoption of lightweight AM components was determined in three steps. First, systems consisting primarily of metallic component assemblies were selected for further analysis based on available aircraft materials data (Kroo, 2013; GE., 1999; Cervenka, 2000). Excluded were component systems such as flight controls, instruments, and electrical systems

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**Table 1**
Quantitative literature on AM processes and applications.

| Study | AM technology | Material(s) | Raw materials energy use | Manufacturing energy use | Comparison to CM processes | Application market implications | Method |
|---|---|---|---|---|---|---|---|
| Luo et al., 1999 (Luo et al., 1999) | SLA | Liquid photopolymer | | 74.52–148.97 MJ/kg | No | No | Data is not empirically measured and eco-indicator is used |
| | SLS | Polymer, Nylon, Polyamide, Polycarbonate | | 107.39–144.32 MJ/kg | No | No | |
| | FDM | ABS | | 83.09–1247.04 MJ/kg | No | No | |
| Morrow et al., 2007 (Morrow et al., 2007) | DMD | H13 tool steel | 35 MJ/part | 3000 MJ/part | Yes | No | Experiment and energy estimation are used. Tooling life cycle case studies of large solid-to-cavity ratio, small solid-to-cavity ratio and remanufacturing are used compared to CNC machining |
| Mognol et al., 2006 (Mognol et al., 2006) | 3DPrinting | / | | 7.56–13.68 MJ/part | No | No | Experiment with part in various orientations |
| | FDM | / | | 1.80–4.50 MJ/part | No | No | |
| | DMLS | / | | 115.20–201.60 MJ/part | No | No | |
| Screenivasan and Bourell 2009 (Sreenivasan and Bourell, 2009) | SLS | Nylon 12 | | 52.20 MJ/kg | No | No | Empirical data is not reported |
| Kellens et al., 2010 (Kellens et al., 2010) | SLS | Polymer | | 36.1 kWh/kg | No | No | Full build experiment and life cycle analysis are conducted |
| | SLM | Stainless steel 316L | | 26.9 kWh/kg | No | No | |
| Baumers et al., 2010 (Baumers et al., 2010) | SLM | Stainless steel 316L | | 111.60–139.50 MJ/kg | No | No | Both single part and full build experiments are conducted |
| | EBM | Ti6Al4V | | 61.20–176.67 MJ/kg | No | No | |
| Baumers et al., 2011a (Baumers et al., 2011a) | SLS | Nylon 12 | | 56.75 kWh/kg | No | No | |
| | SLS | Nylon 12 | | 66.02 kWh/kg | No | No | |
| Baumers et al., 2011b (Baumers et al., 2011b) | SLM | Stainless steel 316L | | 83-106 MJ/kg | No | No | Both single part and full build experiments are conducted |
| | SLM | Stainless steel 316L | | 423-588 MJ/kg | No | No | |
| | DMLS | Stainless steel 17–4 PH | | 241-339 MJ/kg | No | No | |
| | EBM | Ti6Al4V | | 61-177 MJ/kg | No | No | |
| | SLS | PA 12 | | 107-4849 MJ/kg | No | No | |
| | FDM | Polycarbonate | | 519-636 MJ/kg | No | No | |
| Baumers et al., 2013 (Baumers et al., 2013) | DMLS | Used stainless steel 17-4 PH | | 280 MJ/kg | No | No | Experiment is included to test the energy and cost consumption model. |
| Telenko and Seepersad 2012 (Telenko and Carolyn Conner, 2012) | SLS | Nylon | 116 MJ/kg | 130 MJ/kg | Yes | No | Experiment and LCA are included. Case study of paintball gun handle is used to compare to injection molding |
| Kreiger et al., 2012 (Kreiger and Pearce, 2012) | 3D Printing | ABS, PLA | | 0.31, 0.52 kWh/part | Yes. | No | Experiment and LCA are included. Case studies of blocks, spout and juicer are used to compare to injection molding |
| Wilson et al 2014 (Wilson et al., 2014) | LENS | NiCr20Co18Ti I | 335 MJ/kg | 1052 MJ/kg | Yes. | No | Experiment and LCA are included. Remanufacturing of turbine blade is used as a case study compared to 2 arc welding processes (GTAW, PTA) in repairing and casting a new blades |

whose materials complexity precludes near-term AM adoption and component systems that comprise less than 2% of total aircraft mass. Second, the total mass of each selected system was decomposed into three component categories (GE., 1999; Cutler and Jeremy, 2006; Biel, 1993): (1) structural, which refers to components whose primary purpose is to maintain aircraft geometries and bear major system loads (e.g., wing components); (2) functional, which refers to components whose primary purpose is to provide flight functions (e.g., seats); and (3) auxiliary, which refers to all non-structural and non-functional components (as defined above) that are also small geometric volume components (e.g., brackets, hinges, and clips). Third, the load profile, geometric complexity, and geometric volume attributes of each component category were assessed based on available aircraft component data (GE., 1999; Cutler and Jeremy, 2006; MattinglyPratt, 2003; Schaich, 1995). Qualitative ratings of high, medium, and low were assigned

for each attribute to identify component categories with non-critical load profiles, complex geometries, and small to medium geometric volumes as the most likely for near-term AM adoption (Wohlers, 2013; Oak Ridge National Laboratory (ORNL), 2010). Table 2 summarizes the results of the component selection process, in which the component systems and categories for further analysis are indicated in bold typeface based on their final feasibility score. Further details on all data sources and assumptions are provided in Section 2.1 of the SI.

### 2.2. Replaceable mass

For those component systems and categories that were deemed most likely for near-term AM adoption, the next step was to quantify their metal alloy composition and the mass fractions of each metal alloy that might be replaced by AM components. Establishing the materials composition was necessary to estimate the AM replacement potential within each component category and to identify the CM and AM process technologies applicable to manufacturing replaceable components, as discussed further in Section 2.3. Table 3 summarizes this study's estimates of the replaceable mass of aluminum (Al), titanium (Ti), nickel (Ni), and steel alloys within each selected component category. The data in Table 3 were derived by first estimating the total mass of each metal alloy within each component system based on available aircraft materials composition data (GE., 1999; Cervenka, 2000; AeroStrategy, 2009). Next, the mass fractions of each metal alloy that could be replaceable by AM components were estimated based on published AM case studies and industry targets (Carrington, 2013; GE, 2013; Krailling and Novi, 2014), using low and high estimates from the literature to form credible bounds on the mass replacement potentials. Finally, the replaceable mass ranges were calculated by assuming an average aircraft empty operating mass of 40,622 kg for a 142 seat commercial plane, based on empty mass, passenger seats, and passenger miles data for the U.S. aircraft fleet (Airliners.net, 2013; Bureau of Transportation Statistics (BTS), 2013). In total, it was estimated that 9–17% of total typical aircraft mass may be replaceable by AM components in the near term, with 4–5% attributable to a replacement of Al alloy components, 2–5% attributable to replacement of Ni alloy components, 3–6% attributable to replacement of Ti alloy components, and 0.4–1% attributable to steel alloy components. Further details on all data sources and assumptions are provided in Sections 2.2 and 2.3 of the SI.

### 2.3. Component manufacturing energy and emissions analysis

The replaceable mass estimates in Table 3 refer to the total mass of CM components in existing aircraft that might be replaced by AM components in the near term. To estimate net changes in cradle-to-gate manufacturing energy use and GHG emissions associated with a shift from CM to AM processes, this study developed a process-based LCI model of the cradle-to-gate system depicted in Fig. 1. The system boundary includes the following major process steps for both CM and AM pathways: raw materials production, raw materials distribution, component manufacturing, and component distribution to the aircraft assembly plant. Each process step was modeled based on primary energy use and GHG emissions data for the depicted unit processes obtained from the literature. Raw materials production processes included production of ingots, plates, and powders from different primary and secondary metal production routes (Morrow et al., 2007; Allwood et al., 2011; Norgate et al., 2007; Argonne National Laboratory (ANL), 2012; National Renewable Energy Laboratory (NREL), 2012; ecoinvent Centre). Open loop recycling of the materials is also considered (Argonne National Laboratory (ANL), 2012; Sibley, 2011; Ashby, 2012). Distribution processes included shipment by diesel trucks, cargo ships, rail, and aircraft (National Renewable Energy Laboratory (NREL), 2012). Component manufacturing included forging, milling, turning, machining, and casting processes (for CM pathways) and selective laser melting (SLM), direct metal laser sintering (DMLS), and electron beam melting (EBM) processes (for AM pathways)

**Table 2**
Aircraft component systems attribute ratings.

| Component systems | *Component category* | Mass fraction | Load rating | Shape complexity rating | Geometric volume rating | Feasibility evaluation score[a] |
|---|---|---|---|---|---|---|
| Wing systems | | 0.24 | | | | |
| | *Structural* | *0.95* | *High* | *Medium* | *High* | *4* |
| | *Auxiliary* | *0.05* | *High* | *Low* | *Low* | *5* |
| **Body systems** | | **0.19** | | | | |
| | *Structural* | *0.95* | *High* | *Medium* | *High* | *4* |
| | ***Auxiliary*** | ***0.05*** | ***Medium*** | ***Low*** | ***Low*** | ***6*** |
| **Furnish & equip systems** | | **0.13** | | | | |
| | ***Structural*** | ***0.36*** | ***Low-Medium*** | ***Medium*** | ***Low-Medium*** | ***7*** |
| | ***Functional*** | ***0.57*** | ***Low*** | ***Medium*** | ***Medium*** | ***7*** |
| | ***Auxiliary*** | ***0.07*** | ***Low*** | ***Low*** | ***Low*** | ***7*** |
| **Engine** | | **0.12** | | | | |
| | *Structural* | *0.17* | *High* | *Medium* | *High* | *4* |
| | ***Functional*** | ***0.77*** | ***High*** | ***High*** | ***Medium-High*** | ***5.5*** |
| | ***Auxiliary*** | ***0.06*** | ***Medium-High*** | ***Low*** | ***Low*** | ***5.5*** |
| Alighting gear systems | | 0.09 | | | | |
| | *Structural* | *0.95* | *High* | *Medium* | *High* | *4* |
| | *Auxiliary* | *0.05* | *High* | *Low* | *Low* | *5* |
| Tail systems | | 0.04 | | | | |
| | *Structural* | *0.95* | *High* | *Medium* | *High* | *4* |
| | *Auxiliary* | *0.05* | *High* | *Low* | *Low* | *5* |
| **Propulsion systems** | | **0.04** | | | | |
| | ***Functional*** | ***1.00*** | ***High*** | ***High*** | ***Medium*** | ***6*** |
| **Nacelle systems** | | ***0.04*** | | | | |
| | *Structure* | *0.95* | *High* | *Medium* | *High* | *4* |
| | ***Auxiliary*** | ***0.05*** | ***Low-Medium*** | ***Low*** | ***Low*** | ***6.5*** |

[a] To determine feasibility scores, numerical values of 1, 2, and 3 were assigned to ratings of high, medium, and low, respectively, for load and geometric volume. Numerical values of 3, 2, and 1 were assigned to ratings of high, medium, and low, respectively, for shape complexity. Component categories with feasibility scores greater than 5 (bolded in this table) were deemed most likely for near-term adoption of AM components.

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**Table 3**
Replaceable mass by metal alloy, component system, and component category.

| Component system | Category | Replaceable mass in average aircraft (kg)[a] | | | |
|---|---|---|---|---|---|
| | | Al alloy | Ti alloy | Ni alloy | Steel |
| Body systems | Auxiliary | 80–200 | | | |
| Furnishings and equipment | Structural | 70–130 | | | |
| | Functional | 1450–1930 | | | |
| Engine | Functional | | 680–1350 | 940–1880 | 100–190 |
| | Auxiliary | | 50–90 | 50–90 | 50–90 |
| Propulsion systems | Functional | | 330–810 | | |
| Nacelle systems | Auxiliary | | 20–40 | | |
| | **Total** | **1590–2260** | **1070–2290** | **980–1960** | **140–280** |

[a] Based on an average aircraft empty operating mass of 40,622 kg (Airliners.net, 2013; Bureau of Transportation Statistics (BTS), 2013).

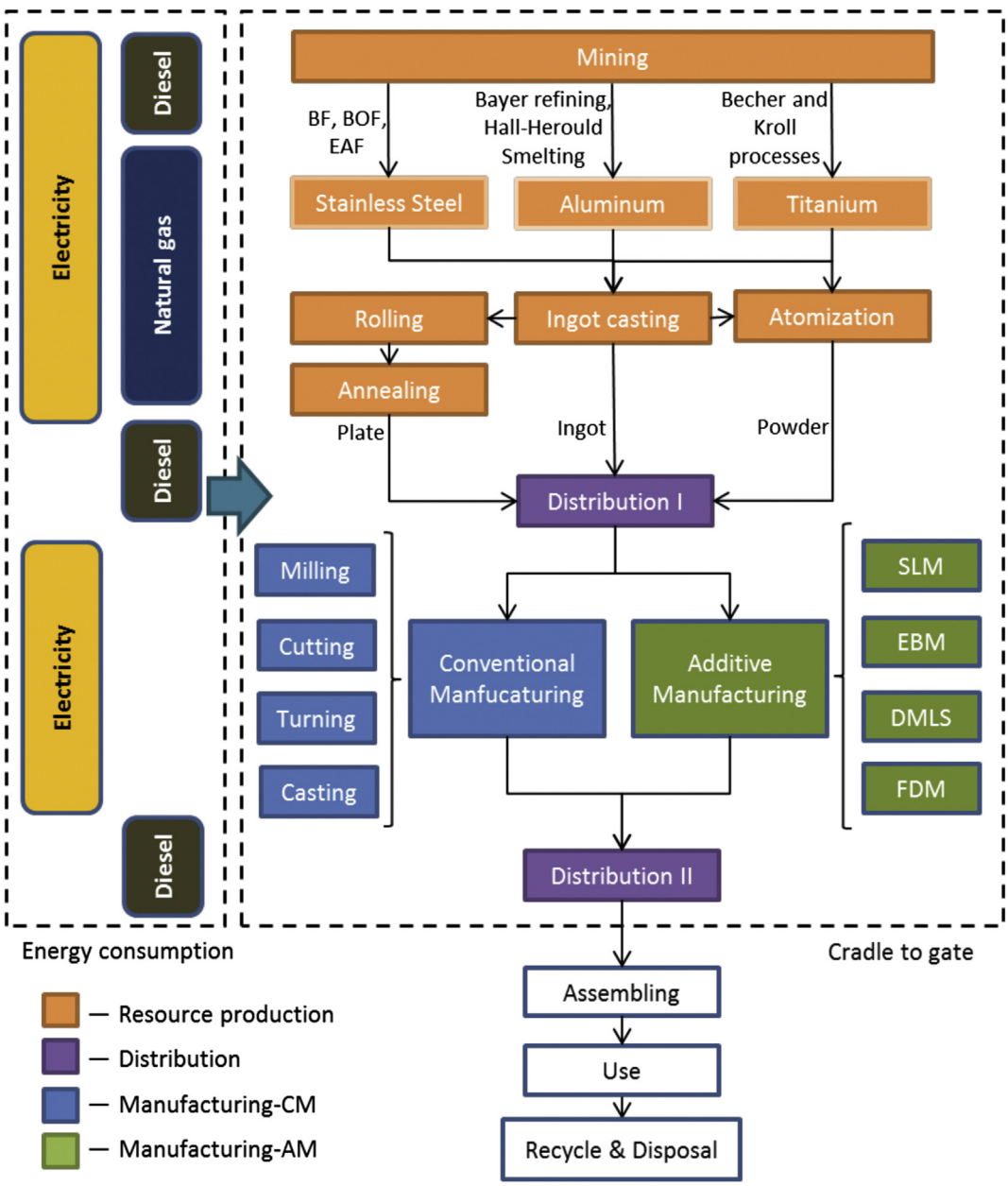


**Fig. 1.** Cradle to gate LCI model system boundary.

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(Baumers et al., 2010; National Renewable Energy Laboratory (NREL), 2012; ecoinvent Centre; Duque Ciceri et al., 2010; Kara and Li, 2011; Dahmus and Gutowski, 2004; Ezugwu and Wang, 1997; Acram, 2013). Primary energy and GHG emissions intensities of all processes are summarized in Sections 3.1–3.1 of the SI, including the corresponding data sources and analysis assumptions. High and low energy and GHG emissions intensity values were established for each process in the model for more robust analysis of the differences between CM and AM pathways.

The model's governing equation for cradle to gate primary energy use for a given component is as follows:

$$\begin{aligned} E_{total} &= E_{materials} + E_{distribution\ I} + E_{manfuacturing} + E_{distribution\ II} \\ &= \varepsilon_{materials} \cdot m_{input} + \varepsilon_{dis\ \ I} \cdot m_{input} + \varepsilon_{mfg} \cdot m_{output} \\ &\quad + \varepsilon_{dis\ \ II} \cdot m_{output} \end{aligned}$$

where $m$ represents mass into or out of a process step (kg), $\varepsilon$ represents the primary energy intensity of a process step (MJ/kg), and $E$ represents the primary energy use of a process step (MJ). The model's governing equation for cradle to gate GHG emissions for a given component is as follows:

$$\begin{aligned} C_{total} &= C_{materials} + C_{distribution\ \ I} + C_{manfuacturing} + C_{distribution\ \ II} \\ &= \gamma_{materials} \cdot m_{input} + \gamma_{dis\ \ I} \cdot m_{input} + \gamma_{mfg} \cdot m_{output} \\ &\quad + \gamma_{dis\ \ II} \cdot m_{output} \end{aligned}$$

where $\gamma$ represents the carbon dioxide equivalent ($CO_2e$) emissions intensity of a process step (kg $CO_2e$/kg), and $C$ represents the $CO_2e$ emissions associated with a process step (kg $CO_2e$). In both equations above, mass inputs and mass outputs are related by the "buy-to-fly" ratio, which is represented by $\alpha$:

$$m_{input} = \alpha \cdot m_{output}$$

The average buy-to-fly ratio of aircraft components using subtractive CM pathways (e.g., milling, cutting, and turning) is 8–12, and can sometimes be as high as 30 (Oak Ridge National Laboratory (ORNL), 2010; Dornfeld, 2010; Acram, 2013). Given the aircraft industry's ongoing efforts to reduce costly materials scrap, this study adopted a conservative average buy-to-fly ratio of 8 for subtractive CM components. For components manufactured primarily through forming CM pathways such as casting or forging, this study assumed a buy-fly ratio of 4.5 for final formed components (Krailling and Novi, 2014), which includes a rough forming process with buy-to-fly ratio of 2 and an additional buy-to-fly ratio of 2.25 for the subtractive finishing operations that follow. In theory AM processes should lead to negligible materials waste (Huang et al., 2013). In current practice, however, AM processes exhibit powder loss and require additional finishing to improve component surface quality, which leads to subtractive materials losses. Based on data in the literature (Shinbara, 2013; Oak Ridge National Laboratory (ORNL), 2013), this study estimated a buy-to-fly ratio of 1.5 for all AM processes.

The cradle-to-gate LCI model was applied to the replaceable mass quantities in Table 3 using the following steps. First, a literature review was conducted to identify credible, quantitative mass analysis case studies of AM replacements within the selected component systems. In particular, case studies describing the geometric design, material use, component mass, AM technologies, and CM processes replaced were identified (Munsch et al., 2012; Krailling and Novi, 2014; The SAVING project, 2009; EOS, 2013; Tomlin and Meyer, 2011). The results of this step are summarized in Table 4, which lists the materials, CM and AM processes, and component mass reductions achieved through AM replacement for each case study component.

Next, for each case study component, transportation distances and modes were estimated for distribution of raw materials and finished components based on representative distances for aircraft component supply chains as identified in the literature (Boeing, 2013). These estimates are summarized in Section 3.4 of the SI. Third, using the LCI model, cradle-to-gate primary energy and emissions analyses were conducted for the AM replacement component and the existing CM component that was replaced in each case study. The results of this analysis are partly summarized in Fig. 2, which displays the differences in average cradle-to-gate primary energy use between the CM and AM pathways for each case study component (left axis), as well the differences in CM and AM process energy intensities (right axis). More detailed analysis results for cradle-to-gate primary energy use and GHG emissions differences for each case study component, including the high and low range estimates for these differences, are summarized in Section 3.4 of the SI.

The results in Fig. 2 highlight the energy saving potential of AM technologies compared to CM technologies. For each case study component, the AM pathway led to significantly lower cradle-to-gate primary energy use compared to the CM pathway, ranging from roughly 2 GJ savings for the bracket to roughly 70 MJ savings for the seat buckle. These energy savings are primarily due to the reductions in resource production energy use attributable to the lower buy-to-fly ratios of AM processes and the reduced mass associated with the AM components' advanced lightweight geometries. Similar reductions were estimated for cradle-to-gate GHG emissions, as summarized in the SI.

Next, the mass reduction data in Table 4 were scaled up to estimate the total mass reduction that would occur within each selected aircraft component system if the full AM replacement potential were realized. Specifically, the results in Table 5 were generated by applying the mass reduction potentials for each case study component (Table 4) to the total replaceable mass ranges for each component system (Table 3) in the following manner. First, a representative case study component was assigned to each component system and component category in Table 3 on the basis of similar function. Second, the mass reduction potential associated with the representative case study component was multiplied by the replaceable mass ranges for all materials within that same component system and component category. Implicit in this approach is that the mass reductions documented in the case study data for each representative component could be replicated across all replaceable mass within the same component system and category. In total, it was estimated that average aircraft empty mass could be reduced by 4–7% through the adoption of AM components in the selected systems, with the greatest potential mass reductions attributable to Al alloys (by metal) and furnishing and equipment and engine system components (by component system).

Finally, the LCI model was used to estimate the total cradle-to-gate reductions in primary energy use and $CO_2e$ emissions associated with the replacement of CM components by AM components when achieving the mass reductions summarized in Table 5. To do so, this study first estimated cradle-to-gate primary energy use of CM components by multiplying the replaceable mass data in Table 3 by the corresponding cradle-to-gate CM primary energy intensities in the LCI model for each component category and material (as described in the SI). Second, the mass of the replacement AM components was calculated by subtracting the mass reductions in Table 5 from the replaceable mass in Table 3 for each component category and material. Third, the cradle-to-gate primary energy use of AM components was estimated by multiplying the estimated mass of AM replacements by the cradle-to-gate AM primary energy intensities in the LCI model (as described in the SI). Finally, this study estimated the total cradle-to-gate reductions in

**Table 4**
Case study component analysis data (Munsch et al., 2012; Krailling and Novi, 2014; The SAVING project, 2009; EOS, 2013; Tomlin and Meyer, 2011).

| Case study component | Material | Original CM pathway | AM technology | Original CM component mass (kg) | Replacement AM component mass (kg) | Mass reduction (CM-AM)/CM |
|---|---|---|---|---|---|---|
| Bracket | Ti alloy | Machining | EBM | 1.09 | 0.38 | 65% |
| Seat buckle | Al alloy | Forging and machining | SLM | 0.16 | 0.07 | 55% |
| Bionic bracket | Ti alloy | Machining | EBM | 0.06 | 0.04 | 35% |
| Engine cover door hinge | Ti alloy | Casting and machining | DMLS | 0.92 | 0.23 | 65% |
| Fork fitting | Al alloy | Casting and machining | SLM | 0.8 | 0.4 | 50% |

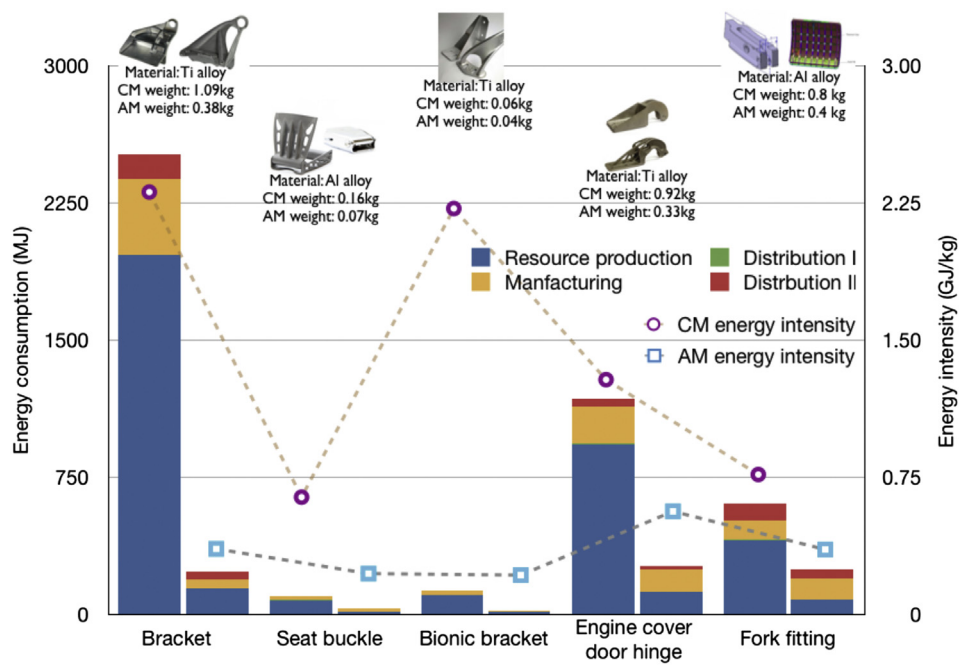


**Fig. 2.** Cradle to gate primary energy results for case study components.

primary energy use per aircraft in Table 6 by subtracting the values obtained in the third step from the values obtained in the first step. An identical approach was taken to generate the estimates in Table 7 for cradle-to-gate $CO_2e$ emissions reductions per aircraft. Further details on the LCI modeling data are provided in Section 3 of the SI.

### 2.4. U.S. aircraft fleet adoption modeling

To model the adoption of AM components within the U.S. aircraft fleet over the period 2014–2050, this study first estimated the temporal availability of AM components within each selected component system and category. Table 8 summarizes the assumed availabilities of AM components based on literature information on the pace of AM technology innovation and the specific attributes of each selected component system and category (Gausemeier, 2014a, b). Further details on temporal feasibility assumptions are provided in Section 2.4 of the SI.

Next, this study developed and employed a temporal model of the U.S. commercial aircraft fleet to estimate the penetration of AM replacements under different adoption scenarios and considering their temporal availability. The component penetration

**Table 5**
Estimated mass reductions by material and component system through AM replacement.

| Component system | Category | Representative component | Mass reduction in average aircraft (kg)[a] | | | | Total |
|---|---|---|---|---|---|---|---|
| | | | Al alloy | Ti alloy | Ni alloy | Steel | |
| Body systems | Auxiliary | Fork fitting | 40–100 | | | | **40–100** |
| Furnishings and equipment | Structural | Bracket | 50–90 | | | | **50–90** |
| | Functional | Seat buckle | 790–1060 | | | | **790–1060** |
| Engine | Functional | Bionic bracket | | 240–470 | 330–660 | 30–70 | **600–1200** |
| | Auxiliary | Bionic bracket | | 20–30 | 20–30 | 20–30 | **50–90** |
| Propulsion systems | Functional | Bionic bracket | | 110–290 | | | **110–290** |
| Nacelle systems | Auxiliary | Engine cover door hinge | | 10–30 | | | **10–30** |
| | **Total** | | **880–1240** | **380–820** | **340–690** | **50–100** | **1650–2840** |

[a] Based on an average aircraft empty operating mass of 40,622 kg (Airliners.net, 2013; Bureau of Transportation Statistics (BTS), 2013).

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**Table 6**
Aircraft level "cradle to gate" primary energy use reductions.

| Component system | Category | Primary energy use reductions (GJ/aircraft)[a] | | | | Total |
|---|---|---|---|---|---|---|
| | | Al alloy | Ti alloy | Ni alloy | Steel | |
| Body systems | Auxiliary | 10–130 | | | | **10–130** |
| Furnishings and equipment | Structural | 20–190 | | | | **20–190** |
| | Functional | 210–1340 | | | | **210–1340** |
| Engine | Functional | | 1020–3050 | 720–4090 | 1–50 | **1740–7180** |
| | Auxiliary | | 70–200 | 40–190 | 0–60 | **110–450** |
| Propulsion systems | Functional | | 490–1830 | | | **490–1830** |
| Nacelle systems | Auxiliary | | 10–50 | | | **10–50** |
| | **Total** | **240–1660** | **1590–5120** | **760–4280** | **2–110** | **2560–11170** |

[a] Based on an average aircraft empty operating mass of 40,622 kg (Airliners.net, 2013; Bureau of Transportation Statistics (BTS), 2013).

**Table 7**
Aircraft level "cradle to gate" reductions in $CO_2$e emissions.

| Component system | Category | $CO_2$e emissions reductions (metric ton/aircraft)[a] | | | | |
|---|---|---|---|---|---|---|
| | | Al alloy | Ti alloy | Ni alloy | Steel | Total |
| Body systems | Auxiliary | 0–12 | | | | **0–12** |
| Furnishings and equipment | Structural | 2–17 | | | | **2–17** |
| | Functional | 12–130 | | | | **12–130** |
| Engine | Functional | | 90–270 | 60–270 | 1–4 | **160–540** |
| | Auxiliary | | 7–17 | 3–13 | 0–5 | **10–35** |
| Propulsion systems | Functional | | 45–160 | | | **45–160** |
| Nacelle systems | Auxiliary | | 2–6 | | | **2–6** |
| | **Total** | **14–160** | **150–450** | **70–290** | **1–10** | **230–900** |

[a] Based on an average aircraft empty operating mass of 40,622 kg (Airliners.net, 2013; Bureau of Transportation Statistics (BTS), 2013).

model considered the adoption rate and market size for new components.

Once AM replacements become available, their adoption in new component production follows a Bass diffusion curve satisfying the equations (Bass, 1969):

$$\frac{f(t)}{1-F(t)} = p + qF(t)$$

$$f(t) = \frac{dF(t)}{dt}$$

where $F(t)$ is the portion of new component production that uses AM, $f(t)$ is the rate of new adoption, $p$ is the coefficient of innovation, $q$ is the coefficient of imitation, and $t$ is the number of years from first adoption.

The estimated market for new components considers the size, age, and turnover in the U.S. fleet of active passenger aircraft. Forecasts for the size of the U.S. fleet are based on the U.S. Department of Energy's Annual Energy Outlook (AEO) 2014 forecasts (Energy Information Administration(EIA), 2014). New components are used in new aircraft, which gradually replace old aircraft as they are retired, and may also replace old components in existing aircraft. Aircraft are retired at rates that depend on the age of the aircraft, based on data from Forsberg (Forsberg, 2012). In addition, we assume that one seventh of all interior parts and one tenth of all engine parts in active aircraft are replaced each year. We also consider the case of accelerated adoption when components are replaced ahead of schedule in order to realize the energy savings benefits of lightweighting. Details on the component penetration model and assumptions are in section 5.1 of the SI.

Three scenarios are considered for the adoption of AM parts in aircraft, which are summarized in Table 9. They differ both in the diffusion parameters that are used, and in the conditions under which retrofits are performed. The values for the technology diffusion parameters in each scenario are based on a range of diffusion rates that have been found in other studies of technologies used in aircraft and related industries (Pae and Lehmann, 2003; Greene, 1992; Das et al., 2013) as described in section 5.1 of the SI. The retrofit assumptions are also different in the three scenarios: in the slow adoption scenario, AM parts are only used in new aircraft. In the mid-range adoption scenario, AM components are also substituted for existing components when they need to be replaced. In the rapid adoption scenario, old components are replaced with AM components ahead of schedule to save fuel.

Fig. 3 shows trajectories for how two representative AM components – one engine component and one furnishing and equipment systems component – are incorporated into the fleet in each

**Table 8**
Temporal availability assumptions.

| Component system | Component category | Availability |
|---|---|---|
| Body systems | Auxiliary | 10 years (2024) |
| Furnishings and equipment systems | Structural | 5-10 years[a] (2019–2024) |
| Furnishings and equipment systems | Functional | 10 years (2024) |
| Engine | Functional | 20 years (2034) |
| Engine | Auxiliary | 10 years (2024) |
| Propulsion systems | Functional | 20 years (2034) |
| Nacelle systems | Auxiliary | 5 years (2019) |

[a] 5 years for galley and lavatory, 10 years for floor panel, fasteners and other.

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**Table 9**
Adoption scenarios.

| Scenario | Years until 80% AM adoption by component producers | Incorporation of AM parts into fleet |
|---|---|---|
| Slow adoption | 28 years (Greene, 1992) | new aircraft only |
| Mid-range adoption | 15 years (Das et al., 2013) | new aircraft and new parts in existing aircraft |
| Rapid adoption | 5 years (Pae and Lehmann, 2003) | new aircraft and new parts in existing aircraft, with accelerated replacement of non-AM parts |

of the three scenarios. Incorporation rates vary greatly between scenarios, with retrofits playing an increasingly important role in the more rapid adoption scenarios.

### 2.5. U.S. aircraft fleet fuel use modeling

The adoption of lighter weight AM components in an aircraft will reduce its weight and therefore the amount of fuel used while operating the aircraft. Each 100 kg reduction in the weight of an aircraft is estimated to save 13.4–20.0 TJ of fuel over the course of a 30 year life of an airplane, or 0.45–0.67 TJ per year, based on the range of estimates in three sources (Lufthansa Group, 2011; Helms and Lambrecht, 2006; American Airlines, 2007). This is equivalent to the fuel savings that would be achieved by 60–90 tons of vehicle lightweighting (Helms and Lambrecht, 2006). The life cycle energy savings and GHG emissions reduction associated with these fuel savings are based on estimates of well-to-wake energy use and carbon-equivalent emissions for jet fuel used in Argonne's GREET model (Argonne National Laboratory (ANL), 2012). These use-phase savings are applied to the active fleet of aircraft that have adopted AM parts.

## 3. Results and discussion

U.S. market-wide primary energy and GHG emissions savings trajectories for the three adoption scenarios are shown in Table 10. In each case, a range of outcomes is given, reflecting the uncertainty in our model assumptions. In the rapid adoption scenario, total primary energy savings potential reaches 70-173 million GJ/year by 2050, with cumulative primary energy savings of 1.2–2.8 billion GJ through 2050. The low and high ends of these ranges represent the combinations of low end and high end values for all model parameters that generate the lowest and highest possible savings. The greatest source of uncertainty is in the portion of each component system that is suitable for replacement with AM parts, followed by uncertainty in the amount of fuel that would be saved from a specified reduction in the mass of an aircraft.

Fig. 4 shows the pattern of primary energy savings over time for the three adoption scenarios. The rapid adoption scenario shows two main waves of adoption, one which begins in 2024 and one which begins in 2034, reflecting our assumptions as to the temporal availability of the different AM components. These waves are not as evident in the slow and mid-range adoption scenarios

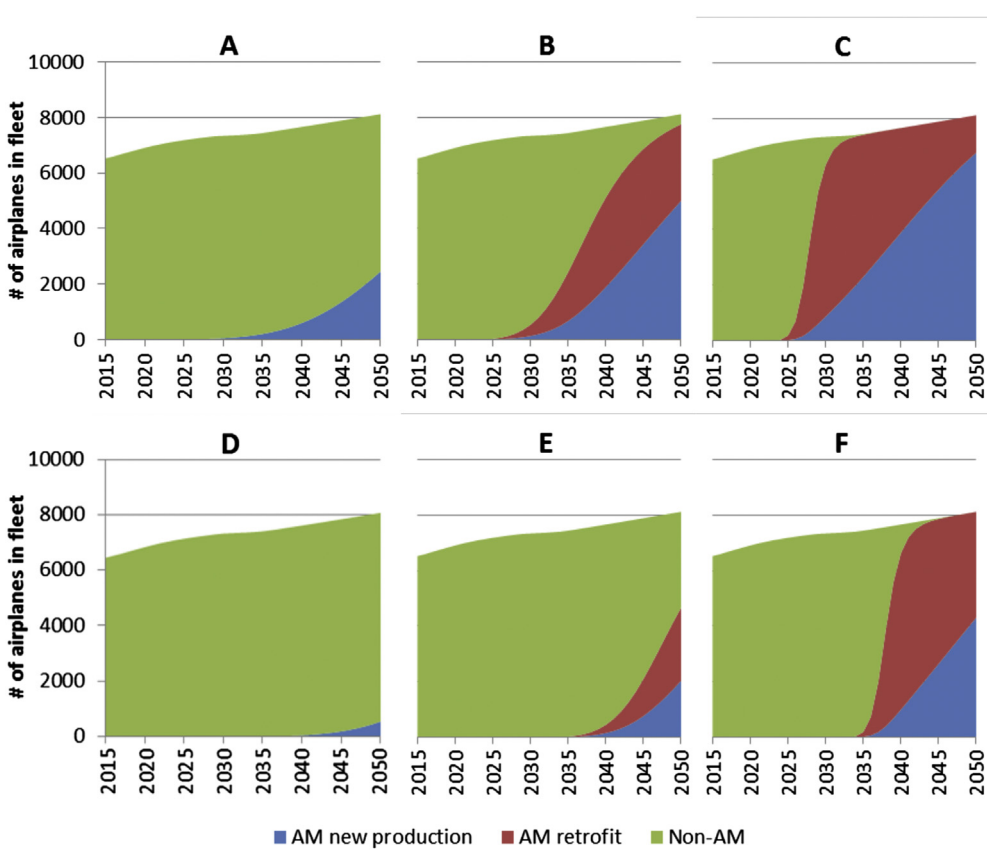


**Fig. 3.** Incorporation of AM components into fleet of aircraft: (A) furnishings and equipment systems, slow adoption; (B) furnishings and equipment systems, mid-range adoption; (C) furnishings and equipment systems, rapid adoption; (D) engine, slow adoption; (E) engine, mid-range adoption; (F) engine, rapid adoption.

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**Table 10**
Energy saving and $CO_2$e reduction ranges, by adoption scenario.

| Year | Projected primary energy savings (million GJ/year) | | | Projected $CO_2$e emissions reduction (million t $CO_2$-equivalent/year) | | |
|---|---|---|---|---|---|---|
| | Slow adoption | Mid-range adoption | Rapid adoption | Slow adoption | Mid-range adoption | Rapid adoption |
| 2020 | 0.001–0.002 | 0.005–0.015 | 0.03–0.09 | 0.0001–0.0002 | 0.0004–0.0012 | 0.002–0.007 |
| 2025 | 0.03–0.07 | 0.2–0.6 | 2–5 | 0.002–0.006 | 0.02–0.04 | 0.15–0.38 |
| 2030 | 0.3–0.7 | 3–7 | 32–65 | 0.02–0.05 | 0.2–0.5 | 2.4–5.0 |
| 2035 | 1–3 | 13–27 | 38–78 | 0.1–0.2 | 1.0–2.1 | 2.9–6.0 |
| 2040 | 4–8 | 28–59 | 60–145 | 0.3–0.6 | 2.1–4.6 | 4.6–11.2 |
| 2045 | 8–19 | 43–97 | 66–163 | 0.6–1.4 | 3.3–7.4 | 5.1–12.6 |
| 2050 | 16–36 | 56–134 | 70–173 | 1.2–2.8 | 4.3–10.3 | 5.4–13.3 |
| Cumulative (2019–2050)[a] | **110–250** | **598–1339** | **1195–2789** | **8.5–19.3** | **46.1–103.4** | **92.1–215.0** |

[a] Units for cumulative savings are million GJ and million t $CO_2$-equivalent.

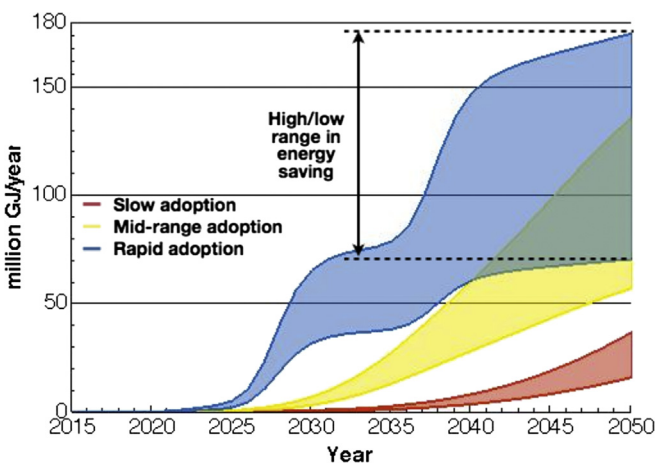


**Fig. 4.** Fleet-wide primary energy use implications of AM Adoption.

because the different waves run together leading to a smoother overall curve.

The majority of the energy savings come from a reduction in airplane fuel consumption due to the lighter weight of the AM parts. In the mid-range adoption scenario, 95–98% of the cumulative energy savings come from this reduction in use-phase fuel consumption, with the other 2–5% coming from cradle-to-gate manufacturing system savings. In the rapid adoption scenario, only 1–2% of the energy savings are in the manufacturing system. Cradle-to-gate savings are lower in the rapid adoption scenario because of the increased production due to the accelerated replacement of parts, but this effect is more than offset by the increase in use-phase savings.

The largest share of use-phase savings come from weight reductions in furnishings and equipment system components. This is followed by engine components, with smaller shares coming from body systems, nacelle systems and propulsion systems. The breakdown for cradle-to-gate savings is different: the largest share of savings comes from engine components, which are made with energy-intensive metals such as titanium. Fig. 5 shows the breakdown of energy savings by component system in the use and production phases for the mid-range adoptions scenario, with high-end savings assumptions. A full breakdown for all scenarios is shown in section 5.2 of the SI.

## 4. Conclusions and future work

The adoption of AM components in aircraft has the potential to provide significant energy savings, due to reduced material requirements needed for production and the fuel economy from lighter weight components. The weight reduction is particularly important for airplanes. If AM components evaluated in this study are used to their full potential, airplane fuel consumption could be reduced by as much as 6.4%.

The LCI analysis of cradle-to-gate energy use also shows that producing AM components may use as little as 1/3 to 1/2 of the energy needed to produce CM components. In our study that evaluated only a few specific AM applications, we identified the potential to save 4050 tons/year Aluminum, 7600 tons/year Titanium and 8110 tons/year Nickel by 2050. Although the metal waste from CM can be recycled, the extra processing adds cost to the life cycle. For some applications, primary metals are required. Considering the potential for achieving significant reductions in metals consumption using AM technologies, useful future research could be directed to evaluating the impact of AM on demand for primary metals, exploring the possibility of using recycled metals for AM, and developing alternative technologies for producing AM metal feeds.

Based on our comprehensive review of the literature, we note a sparseness of LCI data on AM applications, which had the manifest effect of increasing the uncertainty (i.e., range between high and low values) in our energy and carbon savings estimates and forecasts. In our study, the uncertainties were not great enough to negate the estimated savings. However, for other applications where the use-phase benefits are not as significant, the data uncertainties could alter the conclusions. Consequently, we highlight the need for and value of future LCI studies on AM applications.

The scope of this study does not consider all possible energy and carbon savings from AM applications in the aircraft industry. First, it considers only passenger planes. Additional savings could be achieved by using AM parts in the engines of cargo aircraft, which currently make up about 12% of the total commercial airline fleet, and a larger share of fuel use due to the larger average size of cargo planes (Federal Aviation Administration (FAA), 2013). Still more savings could be achieved by using AM parts in military aircraft, which currently use about 19% of all aviation fuel in the USA (Energy Information Administration(EIA), 2014). Second, it is focused only on the U.S. aircraft fleet. Global energy savings potential would be much greater, and this potential would expand rapidly with projected growth in global airline travel.

Our calculations also do not include any secondary weight savings that are made possible in other parts of the aircraft due to the reduced weight of AM parts. Weight reductions in certain parts could generate substantial secondary weight savings – for example, a 1 kg reduction in the weight of fan blades could lead to a 1 kg reduction in the weight of the fan blade containment case, an 0.5 kg reduction in the weight of rotor and engine structures, and a 0.25 kg reduction in the weight of wing and fuselage structures (Red, 2008). However, to achieve these secondary savings would require new airplane designs, and therefore it would likely take longer for these savings to penetrate the fleet.

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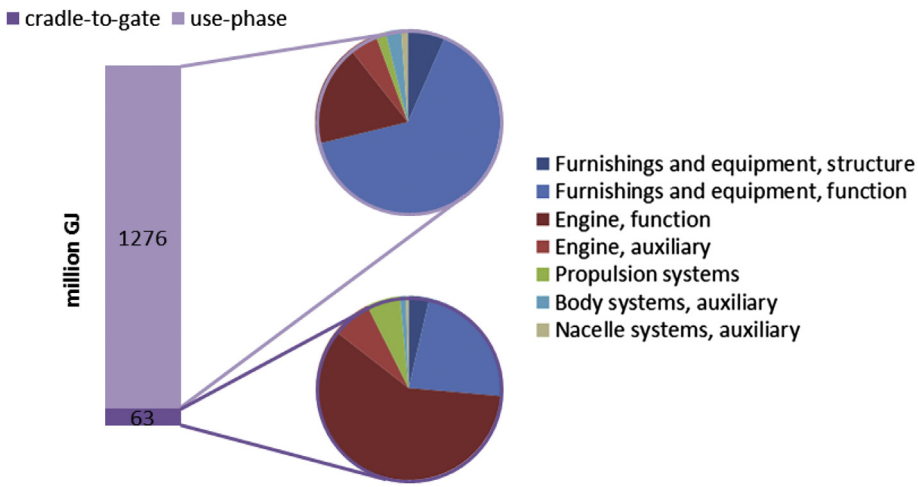


**Fig. 5.** Fleet-wide cumulative primary energy savings through 2050 – breakdowns by life cycle phase and by component for mid-range adoption scenario, high end of range.

We only evaluated direct replacement of aircraft parts. In fact, AM technology offers the transformative potential to replace existing components with redesigned components, which are today impossible to manufacture. These redesigns might allow one component to replace multiple components, reducing the coupling hardware. Or AM could enable fundamentally different designs that perform the desired function with significantly higher energy efficiency, such as more efficient turbine blade and fuel injections.

The cumulative energy and carbon savings that can be achieved by 2050 from using AM parts in airplanes could be significantly greater given earlier adoption. However, technical challenges including machine productivity, geometric repeatability, residual stress, and high surface roughness need to be overcome to achieve earlier adoption. R&D investment focused on developing solutions to these challenges could accelerate the use of AM parts in airplanes.

Beyond airplane components, AM also shows energy saving and economic potential in other areas, such as automotive, industry, tooling, medical and design. This study does not evaluate AM potential in any of these areas, but the results provide some indications as to where AM could lead to significant energy savings. Our results suggest that use-phase savings can be important, so one focus could be on identifying areas with the potential for use-phase savings from lightweight parts or other design improvements enabled by AM. However, even when these use-phase savings do not exist, our LCA results suggest that with wider AM adoption there could be significant material and energy savings in the cradle-to-gate phase – particularly in applications that have high scrap rates and use energy intensive materials such as titanium. In addition, the modular nature of AM could enable cost effective distributed manufacturing, which if adopted on a wide scale could lead to even greater impacts.

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## Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2015.04.109.

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