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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.

Keywords: additive manufacturing, life cycle assessment, lightweight aircraft, energy saving, greenhouse gas emissions

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Highlights

- We estimate the energy and GHG saving potentials of AM lightweight aircraft parts
- Model includes adoption estimation, LCI, fleet stock and scenarios through 2050
- Total fleet-wide life-cycle primary energy savings potentials is 1.2-2.8 billion GJ
- Associated cumulative emission reduction potentials of CO₂e is 93-217 million tons
- Thousands tones of Al, Ti and Ni alloys could be saved per year in 2050

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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”[1]. 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[2-4]. 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[5, 6].

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[4, 7], 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[8, 9]. Third, novel geometries enabled by AM technologies can also lead to performance and environmental benefits in a component’s product application[2, 4]. 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 efficiency [10-13].

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 [10]. Aviation is currently the second largest consumer of transport fuels globally [14]. 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[14, 15]. 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 [16, 17]. In the US, air travel’s share of transportation sector energy use is 9.4%, though projected growth rates are slower [18].

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[11, 19]. These high buy-to-fly ratios result in substantial amounts of materials scrap in the cradle-to-gate manufacturing system[19, 20], 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[10, 12, 13, 21-23].

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 [3]. 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[2, 4, 5]. 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[24]. 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 [25, 26].

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.

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[27]	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 2005[8]	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[28]	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 2010[29]	SLS	Nylon 12		52.20 MJ/kg	No	No	Empirical data is not reported
Kellens et al 2010[30]	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[31]	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	

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 [38], 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 [38-40]. Excluded were component systems such as flight controls, instruments, and electrical systems 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 [39, 41, 42]: (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 [39, 41, 43, 44]. 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 [3, 11]. 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.

Table 2: Aircraft component systems attribute ratings

Component systems	Component category	Mass fraction	Load rating	Shape complexity rating	Geometric volume rating	Feasibility evaluation score*
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
Landing 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

* 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.

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 [39, 40, 45]. 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[13, 23, 46], 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 [47, 48]. 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.

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

Component system	Category	Replaceable mass in average aircraft (kg)*			
		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

* Based on an average aircraft empty operating mass of 40,622 kg [47, 48]

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 Figure 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 [8, 20, 49-52]. Open loop recycling of the materials is also considered [50, 53, 54]. Distribution processes included shipment by diesel trucks, cargo ships, rail, and aircraft [51]. 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) [31, 51, 52, 55-59]. 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.

Figure 1: Cradle to gate LCI model system boundary

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

$$E_{total} = E_{materials} + E_{distribution I} + E_{manufacturing} + E_{distribution II}$$

$$= \epsilon_{materials} \cdot m_{input} + \epsilon_{dis I} \cdot m_{input} + \epsilon_{mfg} \cdot m_{output} + \epsilon_{dis II} \cdot m_{output}$$

where m represents mass into or out of a process step (kg), ϵ 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:

$$C_{total} = C_{materials} + C_{distribution I} + C_{manufacturing} + C_{distribution II}$$

$$= \gamma_{materials} \cdot m_{input} + \gamma_{dis I} \cdot m_{input} + \gamma_{mfg} \cdot m_{output} + \gamma_{dis II} \cdot m_{output}$$

where γ represents the carbon dioxide equivalent (CO₂e) emissions intensity of a process step (kg CO₂e/kg), and C represents the CO₂e emissions associated with a process step (kg CO₂e). In both equations above, mass inputs and mass outputs are related by the "buy-to-fly" ratio, which is represented by α :

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

The average buy-to-fly ratio of aircraft components using subtractive CM pathways (e.g., milling, cutting, and turning) is 8 to 12, and can sometimes be as high as 30 [11, 19, 59]. 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 [46], 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 [2]. 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 [60, 61], 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 [12, 46, 62-64]. 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.

Table 4: Case study component analysis data [12, 46, 62-64]

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%

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 [65]. 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 Figure 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.

Figure 2: Cradle to gate primary energy results for case study components

The results in Figure 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).

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

Component system	Category	Representative component	Mass reduction in average aircraft (kg)*				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

* Based on an average aircraft empty operating mass of 40,622 kg [47, 48]

Finally, the LCI model was used to estimate the total cradle-to-gate reductions in primary energy use and CO₂e 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 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 CO₂e emissions reductions per aircraft. Further details on the LCI modeling data are provided in Section 3 of the SI.

Table 6: Aircraft level “cradle to gate” primary energy use reductions

Component system	Category	Primary energy use reductions (GJ/aircraft)*				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
	Auxiliary		10-50			10-50
Total		240-1660	1590-5120	760-4280	2-110	2560-11170

* Based on an average aircraft empty operating mass of 40,622 kg [47, 48]

Table 7: Aircraft level “cradle to gate” reductions in CO₂e emissions

Component system	Category	CO ₂ e emissions reductions (metric ton/aircraft)*				Total
		Al alloy	Ti alloy	Ni alloy	Steel	
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
	Auxiliary		2-6			2-6
Total		14-160	150-450	70-290	1-10	230-900

* Based on an average aircraft empty operating mass of 40,622 kg [47, 48]

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 [24, 66]. Further details on temporal feasibility assumptions are provided in Section 2.4 of the SI.

Table 8: Temporal availability assumptions

Component system	Component category	Availability
Body systems	Auxiliary	10 years (2024)

Furnishings and equipment systems	Structural	5-10 years* (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)

**5 years for galley and lavatory, 10 years for floor panel, fasteners and other*

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 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[67]:

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

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

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[18]. 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[68]. 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 [69-71] 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.

Table 9: Adoption scenarios

Scenario	Years until 80% AM adoption by component producers	Incorporation of AM parts into fleet
Slow adoption	28 years [70]	new aircraft only
Mid-range adoption	15 years [71]	new aircraft and new parts in existing aircraft
Rapid adoption	5 years [69]	new aircraft and new parts in existing aircraft, with accelerated replacement of non-AM parts

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

Figure 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.

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[72-74]. This is equivalent to the fuel savings that would be achieved by 60-90 tons of vehicle lightweighting [73]. 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 [50]. 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.

Figure 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 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. Figure 5 shows the break-down 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.

Table 10: Energy saving and CO₂e 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 CO₂-equivalent.

Figure 4: Fleet-wide primary energy use implications of AM Adoption

Figure 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

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 [75]. 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[18]. 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[76]. 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.

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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The Energy and Emissions Saving Potential of Additive Manufacturing: The Case of Lightweight Aircraft Components

Supporting Information

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1. Identification of major aircraft component systems

A typical commercial passenger aircraft contains hundreds of thousands of components. It is therefore impractical to assess the potential for lightweight redesigns of each individual component. Rather, this study first identified the major component systems within an aircraft to select those 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 in Section 2.

This study adopted the major aircraft component system definitions and system weights developed by Kroo et al[1], which identified 17 major component systems within typical commercial passenger aircraft models and further provided total weight estimates for each system based on aircraft weight statements. These data are summarized in Table S1. Based on these data, an average mass fraction for each major component system across all aircraft types was calculated by dividing the average component system weight by the average empty aircraft weight. These mass fractions are shown in the last column of Table S1, and were assumed to be representative of the mass composition of the average aircraft in the U.S. commercial passenger aircraft fleet for the purposes of this study.

Several of the systems listed in Table S1 contain a wide variety of components that serve different purposes within their respective systems, not all of which are presently feasible for lightweight redesign using AM technologies. Therefore, these major component systems were further subdivided into three component categories as summarized in Table S2:

- (1) Structural components, which refers to components whose primary purpose is to maintain aircraft geometries and bear major system loads; examples include skin, truss, rib, and stringer in the fuselage, wings and other systems.
- (2) Functional components, which refers to components whose primary purpose is to provide flight functions such as seats, engine turbine, and air-conditioning.
- (3) Auxiliary components, which refers to all non-structural and non-functional components (as defined above) that are also small geometric volume components; examples include small brackets, door hinges, joints and clips in different systems.

Table S1. Aircraft component systems and weight contributions (in kg) [2]

Aircraft component system	727-200	707-320	DC-8-55	DC-8-62	DC-10-10	L-1011	DC-10-40	747	SCAT-15	Avg. mass fraction
Wing system	8,405	12,994	15,835	16,442	22,222	21,501	26,194	40,253	38,075	0.24
Tail system	1,879	2,723	2,246	2,236	6,195	3,887	6,556	5,424	3,896	0.04
Body system	10,167	10,115	10,091	10,752	20,317	22,422	21,102	31,050	24,646	0.19
Alighting gear system	3,605	5,088	5,299	5,193	8,428	9,037	11,379	14,615	13,027	0.09
Nacelle system	1,009	1,441	2,107	3,016	3,852	4,044	4,231	4,912	7,099	0.04
Propulsion system (less dry engine)	1,371	2,406	4,268	3,556	3,480	3,755	6,125	4,357	2,862	0.04
Flight controls system (less auto pilot)	1,354	970	923	952	2,322	2,299	2,353	3,123	4,888	0.02
Auxiliary power plant system	385	-	-	-	721	545	722	815	-	<0.01
Instrument system	375	249	455	415	612	461	746	674	1,542	0.01
Hydraulic and pneumatic group	520	706	1,021	791	1,882	1,996	1,971	2,298	4,840	0.02
Electrical system	1,290	1,789	2,456	1,248	2,434	2,490	2,401	2,406	2,723	0.02
Avionics system (incl. auto pilot)	860	823	848	934	1,282	1,271	1,445	1,875	1,895	0.01
Furnishings and equipment system	6,669	7,655	7,205	6,958	17,269	14,891	15,021	21,776	9,351	0.13
Air conditioning system	817	728	1,083	1,041	1,082	1,517	1,146	1,648	1,279	0.01
Anti-icing system	302	284	360	305	189	134	252	187	95	<0.01
Load and handling system	9	-	25	24	28	-	28	103-406	-	<0.01
Empty weight (less dry engine)	39,017	47,971	52,860	53,865	92,317	90,252	101,674	135,112	116,214	
Dry engine weight	4,390	8,809	7,682	7,855	10,537	13,629	11,606	16,194	20,421	0.12
Empty weight	43,407	56,780	60,542	61,719	102,854	103,881	113,280	151,306	136,635	1
Takeoff gross weight	79,380	141,523	147,420	151,956	195,048	195,048	256,284	351,540	286,217	

Table S2. Mass fractions of categories within major component systems

Component system	Category mass fraction		
	Structural	Functional	Auxiliary
Wing systems	0.95	0	0.05
Body systems	0.95	0	0.05
Furnishings and equipment systems	0.36	0.57	0.07
Engine	0.17	0.77	0.06
Lighting gear systems	0.95	0	0.05
Tail	0.95	0	0.05
Propulsion	0	1	0
Nacelle Systems	0.95	0	0.05

These three component categories were defined to facilitate a more detailed and credible selection process for AM opportunities using the process discussed in Section 2. For each system listed in Table S2, the percent of the system mass that is attributable to each component category was estimated as follows:

- **Furnishing and equipment systems:** All mass fractions are based on an unpublished report from Boeing that contains the weights of furnishing and equipment components. Here, structural components include floor panels and fasteners, cabin panels, ceilings, stowage bins, partitions, air ducts, galley lavatories and windows; functional components include seat assemblies, passenger service units, and evacuation systems; and auxiliary components include the balance of mass from the Boeing data.
- **Engine systems:** All mass fractions are based on engine mass and material composition data from General Electric and Rolls-Royce, which are summarized in Table S3 [3, 4]. Here, structural components are limited to frames; functional components include the turbine, fan assembly, compressor, controls and accessories, and booster and combustor; and auxiliary components include the bearing, seals, and miscellaneous and assembly [3].
- **Nacelle and fuselage systems:** Given that the major purposes of the nacelle and fuselage (i.e., wing, tail, body, and lighting gear) systems are to provide structural support and bear loads, this study estimated that 95% of the mass in these component systems would be comprised of structural components[5]. The remaining 5% of the mass in these component systems was attributed to auxiliary components.

Table S3. Mass fractions and materials within engine systems [3, 4]

Engine system component	Mass fraction	Material (Alloy)
Low pressure turbine	0.204	Nickel, Steel
Frames	0.163	Composites, Steel
Fan assembly	0.156	Titanium
High pressure compressor	0.125	Titanium
Controls and accessories	0.114	Steel and others
High pressure turbine	0.075	Nickel , Steel
Booster	0.061	Nickel, Steel
Combustor	0.039	Nickel
Bearing and seals	0.035	Steel, Titanium, Nickel
Miscellaneous and assembly	0.028	Titanium, Nickel

2. Selection and characterization of component systems for additive manufacturing

The data in Section 1 describe the assumed mass fractions of each major component system within a typical commercial passenger aircraft, as well as the mass fractions attributable to structural, functional, and auxiliary components within each system. The next step in this study was to select and characterize the component systems that represent the most feasible opportunities in the near term for lightweight designs produced using AM technologies. The selection and characterization process was comprised of four key steps, which are described in Sections 2.1-2.4, respectively.

2.1 Component system selection

A recent review of AM technologies suggests that the major factors that influence AM adoption for a given component are its load profile requirements, geometric complexity, geometric volume, and economic value [6]. In general, components with non-critical load profiles, complex geometries, small to medium geometric volumes, and high economic value represents the most attractive applications of current AM technologies [6, 7]. In the aircraft industry, the economic value of components is typically high given their use of advanced materials, engineering performance requirements, and high dimensional precision. Therefore, this study focused on assessing the load profile, geometric complexity, and geometric volume attributes of major aircraft component systems. Table S4 summarizes this study's assessment of these attributes. Each attribute was assigned a qualitative rating of low, medium, or high. Component systems that comprise less than 2% of the mass of the typical aircraft have been neglected for simplicity.

Table S4. Attribute ratings for component system selection

Component systems (<i>component category</i>)	Mass fraction	Load rating	Shape complexity rating	Geometric volume rating	Feasibility Evaluation score
Wing systems	0.24				
<i>Structural</i>	0.95	High	Medium	High	4
<i>Auxiliary</i>	0.05	High	Low	Low	5
Body systems	0.19				
<i>Structural</i>	0.95	High	Medium	High	4
<i>Auxiliary</i>	0.05	Medium	Low	Low	6
Furnishings and equipment systems	0.13				
<i>Structural</i>	0.36	Low-Medium	Medium	Low-Medium	7
<i>Functional</i>	0.57	Low	Medium	Medium	7
<i>Auxiliary</i>	0.07	Low	Low	Low	7
Engine	0.12				
<i>Structural</i>	0.17	High	Medium	High	4
<i>Functional</i>	0.77	High	High	Medium-High	5.5
<i>Auxiliary</i>	0.06	Medium-High	Low	Low	5.5
Lighting gear systems	0.09				
<i>Structural</i>	0.95	High	Medium	High	4
<i>Auxiliary</i>	0.05	High	Low	Low	5
Tail systems	0.04				
<i>Structural</i>	0.95	High	Medium	High	4
<i>Auxiliary</i>	0.05	High	Low	Low	5
Propulsion systems	0.04				
<i>Functional</i>	1.00	High	High	Medium	6
Nacelle systems	0.04				
<i>Structure</i>	0.95	High	Medium	High	4
<i>Auxiliary</i>	0.05	Low-Medium	Low	Low	6.5

2.1.1 Load rating

All structural components were assigned a medium or high load rating depending on the system, given that structural components are inherently load bearing. Structural components in wings, fuselage, tail, alighting gear and engine systems were assigned a high load rating, given the critical load-bearing nature of these systems, such as cyclic loading on wings and tails during flight and impact on the alighting gears during landing[8]. Structural components in furnishing and equipment were assigned low to medium load ratings because the loading caused by human behavior inside of the plane is relatively small compare to loading caused by lifting and landing the aircraft[9].

All functional components in the engine and propulsion systems were assigned a high load rating, since they provide the propulsive forces for the aircraft[10]. The functional components in furnishing systems were given a low load rating since the loading is relatively small compared to other aircraft loads[9]. Auxiliary components in the wings, tails, and alighting gear systems were assigned a high load rating, since they support or connect the structural components, which means they bear nearly the same loads as the structural components. Given the diversity of uses of auxiliary parts in the engine systems, medium to high load ratings were assigned to those components (for example, bearings for the fan assemblies would see high loads, but fasteners used for the electrical wires would be bear much lower loads)[10]. Medium and low to medium load ratings were assigned to auxiliary components within the body and nacelle systems, respectively, given that such components (e.g., auxiliary components for doors) typically bear non-critical loads.

2.1.2 Shape complexity rating

A medium shape complexity rating was assigned to the structural components within all component systems, given that most structural components (e.g., ribs and trusses) use hollowed out designs for weight savings[8]. For furnishing systems, the major functional component is the seat, in which structural components are also hollowed out; therefore, functional components in furnishing systems were assigned a medium rating [11]. Functional components within engine and propulsion systems were all assigned a high shape complexity rating, given that these components are highly engineered for thermodynamic and fatigue performance and typically have complicated and/or precise geometries[10]. Auxiliary parts are all assigned a low shape complexity rating as these parts are typically small and simple parts.

2.1.3 Geometric volume rating

All structural components except those within furnishing systems were assigned a high geometric volume rating due their typically large sizes, especially for flight load-bearing components, which can be several meters in length, width, and/or depth[8]. Structural components in furnishing systems are typically smaller than those in other aircraft systems (e.g., fasteners, partitions and stowage bins) and were accordingly assigned a low to medium geometric volume rating [11]. For consistency with the above ratings, functional components in furnishing systems (majorly seats) were assigned a medium

geometric volume rating and functional components in engine systems (such as the turbine and fan), were assigned medium to high geometric volume ratings. All auxiliary components were assigned a low geometric volume rating based on the logic in Section 2.1.2.

2.1.4 Feasibility scoring

Table S5 summarizes the feasibility scoring scheme used to identify component system categories that are feasible near-term candidates for lightweighting using AM technologies. As described earlier, components with non-critical load profiles (i.e., low load ratings), complex geometries (i.e., high shape complexity ratings), and small to medium geometric volumes (i.e., low to medium geometric volume ratings) represent the most attractive applications of current AM technologies. Based on this fundamental assumption, feasibility scores of 1, 2, and 3 were assigned to each rating in Table S5 to represent low, medium, and high feasibility of AM technology adoption. Feasibility scores were then summed across each component category with each component system to arrive at the final feasibility evaluation scores listed in Table S4. Component systems and categories with feasibility evaluation scores greater than 5 were selected as candidates for near-term lightweighting using AM technologies in this study. The selected component systems and categories are indicated in bold font in Table S4.

Table S5. Feasibility scoring scheme

Rating	Load	Shape Complexity	Volume
High	1	3	1
Medium	2	2	2
Low	3	1	3

2.2 Materials composition

The next step in the selection and characterization process was to estimate the materials composition of each of selected component category within each selected component system. 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 components within component category. Table S6 summarizes this study's assumptions for the average mass composition of each selected component category, expressed as the fraction of total component category mass that is comprised of polymers, aluminum alloys, titanium alloys, nickel alloys, steel alloys, and other materials (materials fractions sum to 1). The data in Table S6 for engine systems were estimated based on engine materials composition data for typical engines from GE (Table S2) and Rolls-Royce [3]. No component-specific materials composition data could be found for body, propulsion, and nacelle systems; therefore, this study estimated that auxiliary components in body systems are made of aluminum alloys and that functional components in propulsion systems and auxiliary components in nacelle systems are made of titanium alloys based on more general system data [8]. The data in Table S6 for the remaining component categories were estimated based on the aforementioned unpublished aircraft materials composition data from Boeing.

Table S6. Material composition assumptions for selected component categories

Component systems (<i>component category</i>)	Mass fraction	Material fraction (sums to 1.00 across materials)						Source(s)
		Polymers	Al alloy	Ti alloy	Ni alloy	Steel	Other	
Body systems	0.19							
<i>Auxiliary</i>	0.05		1.00					Estimated
Furnishings and equipment	0.13							Boeing data
<i>Structural</i>	0.36	0.92	0.07				0.01	
<i>Functional</i>	0.57	0.22	0.64				0.14	
<i>Auxiliary</i>	0.07	0.26					0.74	
Engine	0.12							[3, 4, 10]
<i>Functional</i>	0.77			0.37	0.50	0.05	0.08	
<i>Auxiliary</i>	0.06			0.32	0.32	0.32	0.05	
Propulsion systems	0.04							
<i>Functional</i>	1.00			1.00				Estimated
Nacelle Systems	0.04							
<i>Auxiliary</i>	0.05			1.00				Estimated

2.3 Additive manufacturing applicability

The third step in the selection and characterization process was to estimate the fraction of the materials mass within each selected component category that could realistically be replaced by components manufactured using AM technology (which this study defines as the replaceable fraction). Table S7 summarizes this study's estimates of the replaceable fraction of each material within each component category. This study focused only on opportunities for metal alloys as a matter of scope.

Table S7. Replaceable fraction of materials within selected component systems

Component systems (<i>component category</i>)	Mass fraction	Fraction of material mass replaceable by AM technology						Source(s)
		Polymer	Al alloy	Ti alloy	Ni alloy	Steel	Other	
Body systems	0.19							
<i>Auxiliary</i>	0.05		0.2-0.5					Estimated
Furnishings and equipment systems	0.13							[12-14]and Boeing data
<i>Structural</i>	0.36		0.5-1.0					
<i>Functional</i>	0.57		0.75-1.0					
<i>Auxiliary</i>	0.07							
Engine	0.12							[3, 4, 10, 15]
<i>Functional</i>	0.77			0.5-1.0	0.5-1.0	0.5-1.0		
<i>Auxiliary</i>	0.06			0.5-1.0	0.5-1.0	0.5-1.0		
Propulsion systems	0.04							
<i>Functional</i>	1			0.2-0.5				Estimated
Nacelle systems	0.04							
<i>Auxiliary</i>	0.05			0.2-0.5				Estimated

Replacement fractions were estimated for furnishing systems and engine systems through examination of component information provided in the unpublished Boeing report and the engine component data from GE [3]. In furnishings systems, major metal alloy components were identified as, or within, floor fasteners, stowage bins, partitions, galleys, lavatories, and seats. In engine systems, major metal alloy components were identified as turbines, fans, combustors, boosters, compressors and their auxiliary parts. Potential applications of AM technologies for such components have appeared in the literature to date[12-15]. As such, this study assumed an upper bound on replacement fraction for these metal alloy components of 100%[16]. However, how soon this replacement can occur is governed by this study's analysis of temporal feasibility (see Section 2.4). For functional components within furnishing systems, a lower bound of 75% was selected based on the assumption that only economy class seats would be subject to replacement. For functional titanium and nickel alloy components within engine systems, a lower bound replacement fraction of 50% was adopted based on GE's goal for weight reduction using AM technologies in future aircraft engines [15]. For the remaining metal alloy components in furnishing and engine systems, a lower bound of 50% replacement fraction was chosen as a conservative assumption, and in the absence of literature or empirical data. In the absence of detailed component and materials information for body systems, propulsion systems, and nacelle systems, a conservative replacement fraction range of 20-50% was assumed for components within these systems.

Table S8 summarizes estimates for the total mass of each material that is replaceable by components manufactured using AM technologies in the near term for the typical aircraft in this study. The estimates in Table S8 were calculated by multiplying the mass, materials, and replacement fractions in Tables S1, S6, and S7. These results were scaled to the average mass of an aircraft within the US commercial fleet, which was estimated to be 40,622 kg. This estimate was derived by first constructing a linear relationship between operating empty mass and the number of passenger seats on a plane, and using that relationship to estimate the mass of a plane with an average number of seats. The average number of seats per plane, weighted by miles flown, was estimated to be 142, based on data from the U.S. Bureau of Transportation Statistics on seat miles and aircraft miles flown from June 2012-May 2013[17]. The linear relationship, shown in Figure S1, was estimated by fitting data on operating empty mass and seating capacity for some of the most popular models of aircraft[18].

Figure S1. Relationship between empty mass and seating capacity for U.S. commercial aircraft

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 aluminum alloy components, 2-5% attributable to replacement of nickel alloy components, 3-6% attributable to replacement of titanium alloy components, and 0.4-1% attributable to steel alloy components. The replaceable aluminum alloy mass is associated with the furnishing and equipment component system, while the replace the replaceable nickel, steel, and titanium alloy mass is primarily associated with the engine component system.

Table S8. Replaceable mass by material type and component system

Component system	Category	Replaceable mass in average aircraft (kg)			
		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

2.4 Temporal feasibility

While AM technologies for metal alloys hold great potential, the adoption of metal alloy AM components is currently limited by constraints related to capacity, geometric repeatability, residual stress, and high surface roughness[7]. However it is likely that these obstacles will be overcome in the next 5-20 years. For example, higher capacity AM machines are currently under development [4], alternatives to powder (such as using wire) may increase production rates due to reduced sintering time [6], and mechanics theory and models are being developed to better understand and optimize the materials properties of finished AM parts [4]. Therefore, the final step in the selection and characterization process was to estimate the temporal availability of suitable AM components for each selected component system based on their characteristics.

Several published reports have provided projections on the pace of AM technology development. In particular, the Direct Manufacturing Research Center (a European research agency founded by Boeing, EOS, Evonik industries, SLM Solutions, and University Paderborn) has published a series of technical reports based on consultation with AM professionals, researchers, and engineers[19-23]. The projections in these reports suggest that the capacity and production rate of AM equipment could be highly improved by the early 2020s, and that the surface quality, mechanical properties and other thermal requirements of AM components could be improved by the mid 2020s[23].

This study's estimates for the adoption time period of AM components in each component category and component system are summarized in Table S9. For component categories with low geometric volume and low load requirements, it was conservatively assumed that suitable AM components would be available after five years. This estimate was based on evidence from Airbus, Boeing, Pratt and Whitney, GE, and Rolls-Royce, which are all adopting AM aircraft parts presently or within the next five years for non-critical applications. Examples include titanium brackets used in lavatories and galleys, door hinges, and air ducts[13, 15, 24-26]. Airbus has already replaced 120 different brackets in non-critical applications in the interior of its A350 [13], as well as crew seat panels in its A310 [14]. Other component categories with medium to high geometric volume but with low load requirements were assigned an adoption time of 10 years.

Considering the aircraft industry's strict reliability requirements and its long test cycles[27], the estimated adoption time for large geometric volume components was 10 years, and those with high mechanical strength and performance requirements were assigned an adoption time of 20 years. For engine and propulsion systems with high mechanical and thermal performance requirements, and with medium to high geometric volume, a 20 year adoption time was conservatively assumed.

Table S9. Temporal availability assumptions

Component system	Component category	Availability
Body systems	Auxiliary	10 years (2024)
Furnishings and equipment systems	Structural	5-10 years* (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)

**5 years for galley and lavatory, 10 years for floor panel, fasteners and other*

3. Manufacturing energy and emissions analysis

The data in Section 2 characterized the materials mass within different aircraft component systems that is plausible for replacement by metal alloy AM components over the next 5-20 years. The next step in this study was to construct and apply a "cradle to gate" energy and emissions analysis of manufactured components within the selected component systems to compare the energy and carbon dioxide (CO₂) emissions implications of replacing conventionally-manufactured (CM) components with AM components. The "cradle to gate" system boundary includes the following process steps as depicted in Figure 2 in the main paper: raw materials production, raw materials distribution, component manufacturing, and component distribution to the aircraft assembly plant.

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

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

where m represents mass into or out of a process step (kg), ϵ represents the primary energy intensity of a process step (MJ/kg), and E represents the primary energy use of a process step (MJ).

The governing equation for cradle to gate CO₂ emissions for a given component is as follows:

$$C_{total} = C_{materials} + C_{distribution I} + C_{manufacturing} + C_{distribution II}$$

$$= \gamma_{materials} \cdot m_{input} + \gamma_{dis I} \cdot m_{input} + \gamma_{mfg} \cdot m_{output} + \gamma_{dis II} \cdot m_{output}$$

where γ represents the carbon dioxide equivalent (CO₂e) emissions intensity of a process step (kg CO₂e/kg), and C represents the CO₂e emissions associated with a process step (kg CO₂e).

In both equations above, mass inputs and mass outputs are related by the so-called “buy-to-fly” ratio. The buy-to-fly ratio, which is the mass ratio between the input raw material used make a component and the mass of the finished component itself, is widely used in the aircraft industry to represent the scrape rate or the waste generated during manufacturing, which is represented by α :

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

The analysis assumptions for each process step are presented below.

3.1 Raw materials production

As summarized in Table S8, this study focuses on replacement opportunities for existing components made of alloys of steel, aluminum, nickel, and titanium within selected component systems. Table S10 summarizes this study’s estimates of the primary energy use and CO₂e emissions associated with producing ingots, plates, and powders from each metal alloy, inclusive of ore mining, refining, metal production, and shape forming. For simplicity, and due to lack of data for many different alloy compositions, the estimates in Table S10 are based on ranges of best available literature values for the base material (e.g., titanium) of each alloy as referenced in the table.

Estimates for powder in Table S10 were derived by assuming ingots would be further subjected to powder metallurgy, thereby adding additional primary energy use and CO₂ emissions beyond the values presented for ingots. This study assumed that powder metallurgy would require 2.1 kWh/kg, 1.9 kWh/kg, 2.8 kWh/kg, and 1.9 kWh/kg for steel, aluminum, titanium, and nickel, respectively. The value for steel was based on literature sources [28]. The values for aluminum, titanium, and nickel were based on the following equation, which scales the value for steel to other metal alloys based on their heat capacities and melting points, which are documented in Table S11:

$$\frac{\epsilon_{steel powder}}{T_{steel} \cdot c_{steel}} = \frac{\epsilon_{Al powder}}{T_{Al} \cdot c_{Al}} = \frac{\epsilon_{Ti powder}}{T_{Ti} \cdot c_{Ti}} = \frac{\epsilon_{Ni powder}}{T_{Ni} \cdot c_{Ni}}$$

where ϵ is the powder metallurgy electricity use intensity, T is the melting point and c is the heat capacity for the specific metal alloys. Kilowatt-hours for powder metallurgy were converted to primary energy using a conversion factor of 10.3 MJ/KWh and to CO₂e emissions using a conversion factor of 0.7 kg/KWh based on the average U.S. grid mix[29].

Metal alloy scraps usually have high value in recycling without losing much quality in the final product, and the use of secondary metals can contribute significantly in the metal production supply. Open loop recycling is considered in the calculation of energy and emissions of metals use, which following the equations below:

$$\epsilon_{material} = (1 - \theta) \cdot \epsilon_{material,virgin} + \theta \cdot \epsilon_{material,recycled}$$

where $\epsilon_{material}$ is the primary energy intensity value used for final calculation, the θ is the recycling rate of the metal in the supply, $\epsilon_{material,virgin}$ is the primary energy intensity for the metal, while $\epsilon_{material,recycled}$ is the primary energy intensity for recycling the metal. Similar methods are used for CO₂e emissions. Based on the historical data for metal recycling rates in the United States[30], the value of θ is assumed as 45% for aluminum, titanium and nickel, and 55% for steel. The recycling energy intensity of different metals were collected from literature sources as documented in Table S10.

Table S10. Primary energy and CO₂e intensity of metal production

Material	Type	Primary energy $\epsilon_{material}$ (MJ/kg)	CO ₂ e emissions $\gamma_{material}$ (kg/kg)	Reference
Steel	Ingot	20-41	2.1-4.9	[28, 31-33]
	Plate	26-28	2.6-3.0	[28, 33]
	Powder	18-63	2.2-5.0	[28] + powdering
	Recycled	10-27	0.6-1.9	[34, 35]
Stainless steel	Ingot	56-75	5.0-6.8	[31-33]
	Powder	78-97	5.1-6.9	[31, 32] + powdering
	Recycled	11-13	0.7-0.8	[35]
Aluminum	Ingot	140-230	9.2-22.4	[31, 32, 36]
	Powder	160-230	9.3-22.5	[31, 32] + powdering
	Recycled	22-30	1.9-2.3	[34, 35]
Titanium	Ingot	317-361	31-35.7	[31, 36]
	Powder	346-390	31.2-35.9	[31, 36] + powdering
	Recycled	78-96	4.7-5.7	[35]
Nickel	Ingot	114-239	11.4-16.1	[31, 37-39]
	Powder	134-259	11.5-16.2	[31, 37-39] + powdering
	Recycled	34-38	1.8-2.2	[34, 35]

Table S11. Melting point and heat capacity of metals[40, 41]

Material	Melting point T (K)	Heat capacity c (J/g*K)
Steel	1510	0.45
Aluminum	660	0.91
Titanium	1670	0.54
Nickel	1375	0.45

3.2 Distribution I & II

This study included four different transportation modes associated with distribution of raw materials (distribution stage I) and distribution of finished parts and components for assembly (distribution II): (1) long-haul diesel trucks, (2) diesel engine railway, (3) air freight, and (4) residual fuel engine cargo ships. These four modes represent typical supply chain options for U.S. domestic and international freight. The fuel and emissions intensities of each mode were estimated from literature values on a metric ton (t) per kilometer (km) shipped basis, as summarized in Table S12 [33].

Table S12. Fuel intensity and CO₂e emissions factors for transport modes [33]

Transportation mode	Fuel	Fuel intensity $\epsilon_{i,j}$ (MJ/t-km)	CO ₂ e emissions intensity $\gamma_{i,j}$ (g/t-km)
Cargo ship	Residual fuel	0.19	14.4
Rail	Diesel fuel	0.25	18.9
Road	Diesel fuel	1.34	90
Air	Jet fuel	15.8	1050

The total primary energy and CO₂ emissions intensities of each distribution stage are calculated using the following relations based on distance shipped, values for which are presented in Section 3.4.

$$\epsilon_{dis I} = \sum_i \epsilon_i \cdot d_i, \quad \epsilon_{dis II} = \sum_j \epsilon_j \cdot d_j$$

$$\gamma_{dis I} = \sum_i \gamma_i \cdot d_i, \quad \gamma_{dis II} = \sum_j \gamma_j \cdot d_j$$

where:

d_i = distance of transportation step i of distribution stage I

d_j = distance of transportation step j of distribution stage II

3.3. Component manufacturing

The component manufacturing process step includes all operations necessary for converting raw materials into final components for shipment to the aircraft assembly facility. This study considered both CM and AM processing pathways for producing components within the selected component systems.

Table S13 summarizes this study's estimates for the primary energy and CO₂ emissions intensities of the CM processes that are currently used to produce existing components within the selected component systems. Forming processes include forging and casting; subtractive processes include turning, milling, and machining [40]. For forming processes, the energy intensity is stated in Table S13 based on the mass of the output product (e.g., a near net shape cast part). For subtractive processes, the energy intensity is based on the mass of material removed.

The majority of the estimates in Table S13 were compiled directly from published values in the literature. Those estimates denoted by an asterisk were derived for subtractive processes for which data were only available for steel alloys in the literature. To estimate the CM direct energy use for other alloys, this study used the following relation, which scales the energy requirements for steel alloys to aluminum and titanium alloys based on strain energy required for metals deformation under linear plasticity [42]:

$$\frac{\varepsilon_{steel\ subtractive}}{\rho_{steel}U_{steel}} = \frac{\varepsilon_{Al\ subtractive}}{\rho_{Al}U_{Al}} = \frac{\varepsilon_{Ti\ subtractive}}{\rho_{Ti}U_{Ti}} = \frac{\varepsilon_{Ni\ subtractive}}{\rho_{Ni}U_{Ni}}$$

$$U = \int_0^{\varepsilon_t} \sigma d\varepsilon = \frac{1}{2} \cdot \sigma_y \cdot \varepsilon_y + \frac{1}{2} \cdot (\sigma_y + \sigma_t) \cdot (\varepsilon_t - \varepsilon_y);$$

$$\varepsilon_y = \sigma_y / E$$

where: ε is the manufacturing energy intensity, ρ is the material density, U is the strain energy, σ_y, ε_y are the yield stress and yield strain, σ_t, ε_t are the ultimate stress and ultimate strain, and E is the Young's modulus.

The materials property data used in the above relation for aluminum, titanium, and nickel are summarized in Table S14.

Table S13. Primary energy and CO₂e emissions intensities for CM processes

CM Process	Material	Primary energy intensity (MJ/kg)	CO ₂ e emissions intensity (kg/kg)	Reference(s)
Forging	Steel	13.7-33	1.1-2.2	[43-45]
	Aluminum	16.6	1.1	[46]
	Titanium	48.5-58.7	3.3-4.0	[46]
Turning	Steel	0.88-27	0.1	[45, 47]
Milling	Steel	1.9-8.3	0.1-0.6	[28, 44, 47, 48]
	Aluminum*	2.7-5.6	0.2-0.4	[45, 48]
	Titanium*	4.5-9.5	0.3-0.6	[48]
	Nickel*	8.5-18.3	0.6-1.2	[37, 39, 48]
Machining	Steel	22.2-66	1.5-4.5	[43-45, 48]
	Aluminum*	16.1-47.9	1.1-3.3	[45, 48]
	Titanium*	27.4-81.5	1.9-5.5	[48, 49]
	Nickel*	52.4-155.8	3.6-10.6	[37, 39, 50-52]
Iron casting	Steel	19-29	1.3-2.0	[33, 44]
Die casting	Steel	14.9	1.0	[44]
	Aluminum	33-44	2.2-3.0	[33, 43]
	Titanium	62-72	4.2-4.9	[43, 49]

Table S14. Material properties data [40, 51, 52]

	Density ρ	Young's Modulus E	Yield stress σ_y	Ultimate stress σ_t	Elongation ϵ_t
Material	10^3 kg/m^3	Gpa	Mpa	Mpa	1
Steel	7.8	180	502	860	0.2
Aluminum	2.7	69	95	110	0.3
Titanium	4.5	110	825	895	0.1
Nickel	8.3	218	1062	1420	0.14

The major AM processes currently used for metal alloys are selective laser melting (SLM), direct metal laser sintering (DMLS), and electron beam melting (EBM) [7, 53]. Primary energy intensity estimates for each AM process were derived from published literature values as summarized in Table S15 [54-57], and by converting direct electricity use to primary energy use using a conversion factor of 10.3 MJ/kWh [29]. The CO₂e emissions intensity estimated in Table S14 were derived by converting direct electricity use to CO₂e emissions using a conversion factor of 0.7 kg CO₂e/kWh[29]. The intensity values in Table S15 are based on the output mass of the AM part.

Table S15. Primary energy and CO₂e intensities for AM processes [56]

AM Process	Platform	Material	Primary energy intensity (MJ/kg)	CO ₂ e emissions intensity (kg/kg)
SLM	MTT SLM 250	Stainless steel	83-106	5.6-7.2
	M3 Linear	Stainless steel	423-588	28.8-40.0
DMLS	EOSINT M 270	Stainless steel	241-339	16.4-23.1
EBM	Acram A 1	Ti6Al4V	61-177	4.1-12.0

Available literature data are limited to processing of stainless steel and Grade 5 titanium alloy (Ti6Al4V). Therefore, this study estimated the energy intensities of AM processes for aluminum, nickel, and other titanium alloys based on their heat capacities and melting points using the following relation:

$$\frac{\epsilon_{steel \text{ AM}}}{T_{steel} \cdot c_{steel}} = \frac{\epsilon_{Al \text{ AM}}}{T_{Al} \cdot c_{Al}} = \frac{\epsilon_{Ti \text{ AM}}}{T_{Ti} \cdot c_{Ti}} = \frac{\epsilon_{Ni \text{ AM}}}{T_{Ni} \cdot c_{Ni}}$$

where ϵ is the AM process electricity use intensity, T is the melting point and c is the heat capacity for the specific metal alloys. The above relation is based on the assumption that, since SLM, DMLS and EBM technologies are all powder bed fusion processes that melt power, the electricity consumption of AM processes for other metals could be scaled from that of stainless steel based on the materials' heat capacity and melting point.

Table S16 summarizes the estimated primary energy and CO₂e emissions intensities of other metal alloy AM technologies, based on the aforementioned approach.

Table S16. Primary energy and CO₂e intensity estimates for aluminum, titanium, and nickel alloy AM processes

AM Process	Platform	Material	Primary energy intensity (MJ/kg)	CO ₂ e emissions intensity (kg/kg)
SLM	MTT SLM 250	Al alloy	73-94	5.0-6.4
		Ti Alloy	110-141	7.5-9.6
	M3 Linear	Al alloy	374-520	25.4-35.4
		Ti Alloy	561-780	38.2-53.1
DMLS	EOSINT M 270	Al alloy	213-300	14.5-20.4
		Ti Alloy	320-450	21.8-30.6
EBM	Acram A 1	Nickel alloy	42-122	2.9-8.3

Using the estimates in Tables S13, S15, and S16, the total primary energy and CO₂ emissions intensities of different CM and AM pathways were calculated using the following relations:

$$\begin{aligned}
 \epsilon_{AM} &= \epsilon_{AM}; \\
 \epsilon_{subtractive} &= \epsilon_{machining} * (\alpha - 1); \\
 \epsilon_{casting} &= \epsilon_{casting} * \alpha_{machining} + \epsilon_{machining} * (\alpha_{machining} - 1) \\
 \gamma_{subtractive} &= \gamma_{machining} * (\alpha - 1); \\
 \gamma_{casting} &= \gamma_{casting} * \alpha_{machining} + \gamma_{machining} * (\alpha_{machining} - 1), \text{ in which } \alpha \\
 &= \alpha_{casting} * \alpha_{machining}
 \end{aligned}$$

The buy-to-fly ratios for different manufacturing pathways used in this study were estimated as follows:

- The average buy-to-fly ratio of aircraft components using subtractive CM pathways is 8 to 12, and can sometimes be as high as 30[58-60]. Given the aircraft industry's strong economic incentives for reducing buy-to-fly ration, and that these ratios can vary greatly by component, material, and subtractive CM process pathway, this study adopts a conservative average buy-to-fly ratio of 8 for all subtractive CM components.
- For components manufactured primarily through forming CM pathways such as casting or forging, buy-to-fly ratios are typically lower than for subtractive CM pathways. Based on data in the literature, this study assumed a buy-fly ratio of 4.5 for final formed components[61], which includes a rough forming process with buy-to-fly ratio of 2 and an additional buy-to-fly ration of 2.25 for the subtractive finishing operations that follow.
- Given that AM processes build up components in layer by layer fashion, and internally recycle unused powder at each layer, in theory AM processes should lead to negligible materials waste [7]. In current practice, however, AM processes exhibit powder loss and AM components typically require finishing to improve surface quality, which leads to subtractive

materials loss. Based on data in the literature[62, 63], this study estimates a buy-to-fly ratio of 1.5 for all AM processes.

3.4 Comparisons of CM and AM pathways

The final step in the manufacturing energy and emissions analysis was to estimate the net differences in “cradle to gate” primary energy use and CO₂ emissions associated with replacing CM components with AM components within the selected component systems. Given the wide variety of components within the selected component systems, and the lack of information on engineering specifications for all such components, it was not practical to estimate net differences on a component-by-component basis. Rather, this study took the following estimation approach:

1. A literature review was conducted to identify credible, quantitative energy and 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[12, 26, 61, 64-66].
2. From the available case studies, a representative component was chosen for each component system to serve as a proxy for all replaceable components within that component system.
3. For each representative component, transportation distances and modes were estimated for distribution of raw materials and finished parts based on representative distances for aircraft component supply chains.
4. “Cradle to gate” energy and emissions analyses were conducted for the AM replacement component and the existing CM component that was replaced in each case study, using the framework and data summarized in Sections 3.1-3.3.
5. The net differences between the “cradle to gate” primary energy use and CO₂ emissions of the AM replacement component and existing CM component were calculated and expressed as percent reductions in primary energy use, CO₂ emissions, and final component mass on a per-component basis.
6. The net differences calculated for the representative components were applied to the total mass of replaceable components within each selected component system to estimate the aircraft-level effects of switching from CM pathways to AM pathways.

Table S17 summarizes the representative AM replacement component chosen for each component system, as well as key data obtained from the published case studies on the material, original CM pathway, AM technology, and achieved mass reductions.

Table S17. Representative component analysis data [12, 26, 61, 64-66]

Component system	Component category	Representative component	Material	Original CM pathway	AM technology	Original CM component mass (kg)	Replacement AM component mass (kg)	Mass reduction (CM-AM)/CM
Furnishing &	Structural	Bracket	Ti alloy	Machining	EBM	1.09	0.38	65%

Equipment								
Furnishing & Equipment	Functional	Seat buckle	Al alloy	Forging and machining	SLM	0.16	0.07	55%
	Engine & propulsion	Bionic bracket	Ti alloy	Machining	EBM	0.06	0.04	35%
Nacelle	Auxiliary	Engine cover door hinge	Ti alloy	Casting and machining	DMLS	0.92	0.23	65%
Body systems	Auxiliary	Fork Fitting	Al alloy	Casting and machining	SLM	0.8	0.4	50%

Table S18 summarizes this study's estimates of transportation modes and distances for the distribution of raw materials and finished components associated with the original CM components. This study assumes that CM processes will be replaced by AM processes at the component manufacturing plant; therefore, the transportation distances and modes are identical for the original CM parts and the replacement AM parts in this study. The data in Table S17 are based on Boeing direct supply chain partner data[67], and assume finished component shipment to the U.S. state of Washington for aircraft assembly[68]. Raw material suppliers were assumed to be those companies with the largest raw materials production capacity nearest to the manufacturer[69-74]. The transportation mode for raw materials was assumed to be railway in China and Russia, diesel truck in other countries, and barge if international transportation is involved. For transportation of the final components to assembly, the airplane mode is assumed for large components or if international travel is needed[75]. For inland transportation of small parts, diesel trucking is assumed. All distances were estimated using Google Maps[76]. These data were used to estimate the primary energy use and CO₂ emissions intensities of both distribution steps as discussed in Section 3.2.

Table S18. Distribution system location, mode, and distance estimates [67, 69-74]

Representative component	Fork fitting	Bracket		Engine door cover	Seat buckle	Bionic bracket	
Raw material Supplier	RUSAL	KOBELCO	CHALCO	TIMET	ALCOA	ATI	TIMET
Location	Bogoslovsk, Russia	Moka, Japan	Henan, China	Monroe, NC, US	Wenatchee, WA, US	Pittsburgh, PA, US	Monroe, NC, US
Transport distance d_i	Rail: 2300km; Barge: 824km; Road: 42km	Road: 151km	Rail:700km; Barge: 2090km; Road: 30km	Road: 1907km	Road: 1857km	Road: 451km	Road: 818km
Component manufacturer	Saab Aerostructures	Jamco	Jamco	Spirit AeroSystems Holdings	Ipeco	General Electric	General Electric
Location	Linköping, Sweden	Osawa, Mitaka Tokyo, Japan	Osawa, Mitaka Tokyo, Japan	Wichita, Kansas, US	Torrance, CA, US	Cincinnati, OH, US	Cincinnati, OH, US

Transport distanced_j	Air: 7713km	Road: 30km; Air: 7793km	Road: 30km; Air: 7793km	Road: 2995km	Road: 1893km	Air: 3158km	Air: 3158km
Assembler	Boeing						
Location	Everett, Washington, US						

For each representative component, Tables S19 and S20 summarize this study's estimates for the "cradle to gate" primary energy use and CO₂ emissions associated with the original CM component and the AM replacement component, using the equations and high and low data values summarized in the preceding sections. Importantly, the low difference values are calculated by subtracting the high AM values from the low CM values, and the high difference values are calculated by subtracting the low AM values from the high CM values. The final column in Tables S19 and S20 expresses the "cradle to gate" results per kg of finished component, which allows for scaling results to different production quantities based on the following relations:

$$\frac{E_{c_to_g}}{m_{output}} = \frac{\epsilon_{materials} \cdot m_{input} + \epsilon_{dis I} \cdot m_{input} + \epsilon_{manufacturing} \cdot m_{output} + \epsilon_{dis II} \cdot m_{output}}{m_{output}}$$

$$= \epsilon_{materials} \cdot \alpha + \epsilon_{dis I} \cdot \alpha + \epsilon_{manufacturing} + \epsilon_{dis II}$$

$$\frac{C_{c_to_g}}{m_{output}} = \frac{\gamma_{materials} \cdot m_{input} + \gamma_{dis I} \cdot m_{input} + \gamma_{manufacturing} \cdot m_{output} + \gamma_{dis II} \cdot m_{output}}{m_{output}}$$

$$= \gamma_{materials} \cdot \alpha + \gamma_{dis I} \cdot \alpha + \gamma_{manufacturing} + \gamma_{dis II}$$

Table S19. “Cradle to gate” primary energy intensities of representative components

Representative component	Manufacturing process	Component mass (kg)	Primary energy consumption (MJ)								Cradle to gate primary energy intensity	
			Raw material production		Distribution I	Manufacturing		Distribution II	Total		(GJ/kg)	
			Low	High		Low	High		Low	High	Low	High
Bracket	Machining	1.09	1820	2110	1.8	210	620	134	2170	2870	2.0	2.6
	EBM	0.38	136	154	0.1	23.2	67.3	46.7	206	268	0.5	0.7
	Difference (% change)	0.71 (-65%)	1670 (-92%)	1970 (-94%)	1.7 (-94%)	142 (-68%)	599 (-96%)	87.3 (-65%)	1910 (-88%)	2660 (-93%)	1.3 (-65%)	2.1 (-79%)
Bionic bracket	Machining	0.06	100	116	1.1	11.5	34.2	0.2	113	1534	1.9	2.5
	EBM	0.04	13.9	15.8	0.1	2.4	6.9	0.1	16.6	22.9	0.4	0.6
	Difference (% change)	0.02 (-35%)	85 (-84%)	102 (-88%)	1.0 (-91%)	4.6 (-40%)	31.9 (-93%)	0.1 (-35%)	91 (-80%)	136 (-89%)	1.3 (-70%)	2.1 (-84%)
Engine cover door hinge	Casting	0.92	570	1000	1.9	160	242	45.7	1080	1290	1.2	1.4
	DMLS	0.33	116	132	0.2	104	147	16.2	237	296	0.7	0.9
	Difference (% change)	0.59 (-65%)	730 (-85%)	880 (-88%)	1.7 (-89%)	12.8 (-8%)	138 (-57%)	29.5 (-65%)	780 (-72%)	1050 (-82%)	0.3 (-23%)	0.7 (-49%)
Seat buckle	Forging	0.16	61	97	3.1	14.6	24.6	0.4	79	126	0.5	0.8
	SLM	0.07	11	17	0.1	5.1	36.4	0.2	16.6	53.6	0.2	0.8
	Difference (% change)	0.09 (-55%)	44 (-72%)	86 (-88%)	3.0 (-97%)	-21.8 (149%)	19.5 (-79%)	0.2 (-55%)	25 (-32%)	110 (-87%)	-0.3 (55%)	0.6 (-70%)
Fork fitting	Casting	0.80	313	504	2.8	75.5	127	97.3	490	740	0.6	0.9
	SLM	0.40	64	97	0.5	29.3	208	48.6	142	354	0.4	1.0
	Difference (% change)	0.40 (-50%)	216 (-69%)	440 (-87%)	2.3 (-82%)	-132 (175%)	97.8 (-77%)	48.7 (-50%)	135 (-28%)	594 (-81%)	-0.3 (45%)	0.6 (-61%)

Table S20. “Cradle to gate” CO₂e emissions intensities of representative parts

Representative component	Manufacturing process	Component mass (kg)	CO ₂ e emissions (kg)								Cradle to gate primary CO ₂ e emissions intensity	
			Raw material production		Distribution I	Manufacturing		Distribution II	Total		(kg/kg)	
			Low	High		Low	High		Low	High	Low	High
Bracket	Machining	1.09	167	193	0.1	14.2	42.3	8.9	191	245	175	225
	EBM	0.38	11.0	12.8	0	1.6	4.6	3.1	15.7	20.4	41.4	53.7
	Difference (%) change	0.71 (-65%)	154 (-92%)	182 (-94%)	0.1 (-93%)	9.6 (-68%)	40.7 (-96%)	5.8 (-65%)	170 (-89%)	230 (-94%)	122 (-69%)	184 (-82%)
Bionic bracket	Machining	0.06	9.2	10.6	0.1	0.8	2.3	0	10.1	13.1	169	219
	EBM	0.04	1.1	1.3	0	0.2	0.5	0	1.3	1.8	32.9	45.3
	Difference (%) change	0.02 (-35%)	7.9 (-86%)	9.5 (-89%)	0.1 (-91%)	0.3 (-40%)	2.2 (-93%)	0.0 (-35%)	8.3 (-82%)	11.8 (-90%)	123 (-73%)	186 (-85%)
Engine cover door hinge	Casting	0.92	79	92	0.1	10.9	16.5	3	93	111	101	121
	DMLS	0.33	9.5	11.0	0	7.1	10	1.1	17.7	22.0	53.6	66.6
	Difference (%) change	0.59 (-65%)	68 (-86%)	83 (-90%)	0.1 (-88%)	0.9 (-8%)	9.4 (-57%)	1.9 (-65%)	71 (-76%)	93 (-84%)	34.6 (-34%)	67.1 (-56%)
Seat buckle	Forging	0.16	4.1	9.3	0.2	1	1.7	0	5.3	11.2	33.2	70.0
	SLM	0.07	0.6	1.4	0	0.3	2.5	0	0.9	3.9	13.5	56.2
	Difference (%) change	0.09 (-55%)	2.7 (-65%)	8.7 (-93%)	0.2 (-98%)	-1.5 (149%)	1.3 (-79%)	0.0 (-55%)	1.4 (-26%)	10.3 (-92%)	-23.0 (69%)	56.5 (-81%)
Fork fitting	Casting	0.80	21.3	48.1	0.2	5.1	8.6	6.5	33	64	41.5	79.3
	SLM	0.40	3.6	8.1	0	2	14.1	3.2	8.8	25.5	22.1	63.7
	Difference (%) change	0.40 (-50%)	19.6 (-59%)	75.1 (-93%)	0.2 (-83%)	-9.0 (175%)	6.7 (-77%)	3.3 (-50%)	7.7 (-23%)	54.6 (-86%)	-22.2 (54%)	57.3 (-72%)

4. Aircraft-level estimates

The results in Tables S19 and S20 estimate the mass reduction potential associated with replacing CM pathways with AM pathways for the representative components, as well as corresponding potential reductions in “cradle to gate” primary energy use and CO₂e emissions associated with component manufacturing. In Table S21, mass reduction potentials are scaled up to estimate the total mass reduction for each selected aircraft component system that would occur if the full AM replacement potential were realized (as estimated in Section 2.3 and summarized in Table S8). Specifically, the results in Table S21 were generated by applying the mass reduction potentials for each representative component (Table S17) to the total replaceable mass ranges for each component system (Table S8). First, a representative component was assigned to each component system and component category in Table S8 on the basis of similar function. Second, the mass reduction potential associated with the representative 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. Table S22 expresses the data in Table S21 as percent reductions of total aircraft mass.

Table S21. Estimated mass reductions (in kg) by material and component system through AM replacement

Component system	Category	Representative component	Mass reduction in average aircraft (kg)				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

Table S22. Estimated mass reductions (% of total aircraft mass) by material and component system through AM replacement

Component system	Category	Representative component	Mass reduction in average aircraft (%)				Total
			Al alloy	Ti alloy	Ni alloy	Steel	
Body systems	Auxiliary	Fork fitting	0.10-0.24%				0.1-0.2%
Furnishings and equipment	Structural	Bracket	0.11-0.21%				0.1-0.2%
	Functional	Seat buckle	1.94-2.58%				1.9-2.6%
Engine	Functional	Bionic bracket		0.61-1.21%	0.82-1.64%	0.08-0.16%	1.5-3.0%
	Auxiliary	Bionic bracket		0.06-0.12%	0.06-0.12%	0.06-0.12%	0.2-0.4%
Propulsion systems	Functional	Bionic bracket		0.27-0.68%			0.3-0.7%
Nacelle Systems	Auxiliary	Engine cover door hinge		0.02-0.06%			0.02-0.06%
Total			2.1-3.0%	1.0-2.1%	0.9-1.8%	0.1-0.3%	4.1-7.1%

Tables S23 and S24 summarize the estimated “cradle to gate” reductions in primary energy use and CO₂e emissions, respectively, associated with the replacement of CM components by AM components when achieving the mass reductions summarized in Table S21. To generate the estimates in Table S24, this study first estimated the “cradle to gate” primary energy use of CM components by multiplying the replaceable mass data in Table S8 by the corresponding “cradle to gate” CM primary energy intensities in described in Section 3 for each component category and material. Second, the mass of the replacement AM components was calculated by subtracting the mass reductions in Table S21 from the replaceable mass in Table S8 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 described in Section 3. Finally, this study estimated “cradle to gate” reductions in primary energy use 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 S24 for “cradle to gate” CO₂e emissions reductions. The data in Tables S23 and S24 are expressed as total “cradle to gate” reductions per average aircraft. To obtain estimates of total reductions per kg of empty aircraft, one may divide the values in Tables S23 and S24 by the empty weight of the average aircraft assumed in this study (i.e., 40,622 kg)

Table S23. Aircraft level “cradle to gate” primary energy use reductions

Component system	Category	Primary energy use reductions (GJ/aircraft)				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
	Auxiliary		10-50			10-50
Total		240-1660	1590-5120	760-4280	2-110	2560-11170

Table S24. Aircraft level “cradle to gate” reductions in CO₂e emissions

Component system	Category	CO ₂ e emissions reductions (metric ton/aircraft)				Total
		Al alloy	Ti alloy	Ni alloy	Steel	
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
	Auxiliary		2-6			2-6
Total		14-160	150-450	70-290	1-10	230-900

5. U.S. aircraft fleet adoption and fuel use modeling

5.1 Fleet adoption

To determine the U.S. national primary energy and GHG emissions implications of using lightweight AM parts in passenger aircraft, the use-phase and cradle-to-gate energy and GHG savings found for each aircraft are applied to the US fleet of passenger aircraft. Three possible trajectories for US energy and GHG savings through 2050 are generated based on different assumptions about the rate of new technology adoption and part replacement.

Forecasts for the size of the US fleet are based on the US Department of Energy’s Annual Energy Outlook (AEO) 2014 forecasts for active aircraft fleet in the US [77]. The AEO forecasts, which go through 2040,

are extended to 2050 by assuming the average forecasted growth rate from 2035 to 2040 continues through 2050.

The average size and the number of miles traveled per year by aircraft in the fleet are assumed to be constant over time. This assumption is consistent with AEO forecasts, which predict similar annual growth rates for seat miles demanded (0.9%) as for fleet size (0.8%). An alternative forecast made by the US Federal Aviation Administration (FAA) projects a more rapid increase in seat miles demanded due to an increase in average airplane seating capacity over time[27]. This would increase airplane fuel use relative to the AEO forecasts and also the potential for operational fuel savings from the use of AM parts, as there is greater weight reduction potential in larger aircraft. If actual trends follow the FAA forecasts, energy savings potential from the use of AM parts could be greater than indicated in this paper.

The penetration of AM components into the airplane fleet depends on three factors: the time it takes to work out technological and economic barriers to the use of AM components, the diffusion curve for adoption of new AM technologies by component manufacturers once these barriers are removed, and the turnover rate for conventionally produced parts, either through the retirement of old aircraft or through replacement of parts in existing aircraft. The year in which it becomes technically feasible to substitute AM components for conventional components depends on the type of component. There are three waves of AM component adoption, with adoption beginning either in 2019, 2024 or 2034. These waves correspond to the 5-year, 10-year and 20-year time frames for adoption shown in Table S9. The basis for selecting these adoption time frames is discussed in more detail in the supplemental materials. Once it becomes technically feasible, a Bass diffusion curve determines how fast AM technologies are adopted in new component production[78]. These components are then used in new aircraft, which penetrate the fleet gradually as old aircraft are retired, and may also replace old components in existing aircraft.

Three scenarios are considered for the adoption of AM parts in aircraft, which are summarized in Table S25. They differ both in the diffusion parameters that are used, and in the conditions under which retrofits are performed. A wide range of technology diffusion rates have been observed for different aircraft technologies and time periods. Adoption rates for piston and turbine technologies in the 1940s, 50s and 60s were very slow [79], while successive waves of new generations of aircraft took over rapidly from previous models in the 1960s, 70s and 80s [80]. The average of the diffusion parameters for piston and turbine technologies [79] are used in our slow adoption scenario, and the parameters for our rapid adoption scenario are chosen to reach 80% adoption in 5 years, as was observed for 5th generation aircraft [80]. For the mid-range scenario, intermediate values for the diffusion parameters are used that lead to 80% adoption in 15 years. These values are taken from a study of vehicle adoption of lightweight materials[81].

Three different possibilities for the rate at which AM parts penetrate the fleet of aircraft are also considered. 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.

Table S25. Adoption scenarios

Scenario	Years until 80% AM adoption by component producers	Incorporation of AM parts into fleet
Slow adoption	28 years	new aircraft only
Mid-range adoption	15 years	new aircraft and new parts in existing aircraft
Rapid adoption	5 years	new aircraft and new parts in existing aircraft, with accelerated replacement of non-AM parts

AM components are incorporated into the fleet of aircraft through a combination of new airplane production (P^{AM}), and retrofits, which can be further broken down into baseline retrofits (RB^{AM}) and accelerated retrofits (RA^{AM}). Airplanes in the fleet are also periodically retired at a rate, ρ_a , that depends on the age a of the aircraft. The number of aircraft, F^{AM} , of age a in the fleet in year t , that have adopted AM component c is calculated as follows:

$$F^{AM}_{c,a,2010} = 0$$

$$F^{AM}_{c,0,t} = P^{AM}_{c,t}$$

$$F^{AM}_{c,a,t} = F^{AM}_{c,a-1,t-1} \cdot (1 - \rho_a) + RB^{AM}_{c,a,t} + RA^{AM}_{c,a,t}$$

The retirement rate at each age, ρ_a , is set based on a piece-wise linear approximation (NR_a) of the storage-adjusted retirement age distribution from Forsberg (2012)[82].

$$NR_a = \begin{cases} 5 & \text{if } 1 < a \leq 10 \\ 5 + (450 - 5) \cdot \frac{a - 10}{24 - 10} & \text{if } 10 < a \leq 24 \\ 450 + (5 - 450) \cdot \frac{a - 24}{44 - 24} & \text{if } 24 < a \leq 44 \\ 5 & \text{if } 44 < a \leq 48 \end{cases}$$

$$\rho_a = \frac{NR_a}{\sum_{b \geq a} NR_b}$$

The number of new aircraft produced with AM components, $P^{AM}_{c,t}$, depends on the total production of new aircraft, P_t , and on the adoption level for AM technologies, $a^{AM}_{c,t}$, following:

$$P^{AM}_{c,t} = P_t \cdot a^{AM}_{c,t}$$

$$a^{AM}_{c,t} = F(t - t_c^0)$$

where a^{AM} is set by the Bass curve $F(t)$ defined by $\frac{F'(t)}{1-F(t)} = p + qF(t)$. The innovation and imitation parameters p and q vary by adoption scenario as shown in Table S26. P_t is set to be enough to match

retirements plus the increase in fleet size, which in turn is taken from AEO 2014 b [77]. t_c^0 is the first year that component c becomes available, as specified in Table S9.

The level of adoption of AM components through retrofits depends on the scenario and on the type of component. Engine and interior parts are replaced periodically throughout an airplane's life. Engine parts have limits on the number of cycles (takeoffs and landings) they can go through before they must be replaced. Interiors are refurbished periodically to remove signs of wear and improve passenger experiences. It is assumed that under normal conditions, one tenth of all engine parts and one seventh of all interior parts are replaced each year, based on estimates of the average life of rotating engine parts and on the frequency of interior refurbishment programs [83, 84]. Body, nacelle and propulsion system components are not replaced until the aircraft is retired. In the mid-range adoption scenario, AM components are adopted with the same frequency in retrofits as they are in new production, following the formula:

$$RB_{c,a,t}^{AM} = a_{c,t} \cdot \bar{r}_c \cdot (F_{a-1,t-1} - F_{c,a-1,t-1}^{AM}) \cdot (1 - \rho_a)$$

Where $\bar{r}_c$ is the baseline retrofit rate for component c , and $F_{a-1,t-1}$ is the total fleet size of age $a - 1$ in the previous period. The age distribution of fleet is calculated based on retirement rates and new production, along with an initial age distribution in 2010 shown in Figure S2. This distribution was estimated using a backwards extrapolation of production numbers along with the same retirement rates as used for the forecasts.

Figure S2. Distribution of aircraft ages in 2010

In the rapid adoption scenario, replacement rates for non-AM parts accelerate from the usual rate to 50% per year as the share of new construction that uses AM parts approaches 100%. It is assumed that all accelerated retrofits use AM parts.

$$RA_{c,a,t}^{AM} = a_{c,t} \cdot (r_c^{max} - \bar{r}_c) \cdot (F_{a-1,t-1} - F_{c,a-1,t-1}^{AM}) \cdot (1 - \rho_a)$$

Table S26. Scenario parameters

Scenario	p	q	$\bar{r}_c$ (engine)	$\bar{r}_c$ (furnishings and equipment)	r_c^{max} (engine)	r_c^{max} (furnishings and equipment)
Slow adoption	0.0045	0.18	0	0	0	0
Mid-range adoption	0.0074	0.34	$\frac{1}{10}$	$\frac{1}{7}$	$\frac{1}{10}$	$\frac{1}{7}$
Rapid adoption	0.0074	1.32	$\frac{1}{10}$	$\frac{1}{7}$	$\frac{1}{2}$	$\frac{1}{2}$

The turnover of each airplane component depends on when it becomes available, the adoption scenario, and the retrofit rate. Table S27 shows how two representative AM components are incorporated into the fleet: one engine component that becomes available in 2024, and one furnishings and equipment system component that becomes available in 2034. Incorporation rates vary greatly between scenarios, with retrofits playing an increasingly important role in the more rapid adoption scenarios.

Table S27. Incorporation of AM components into fleet of aircraft

year	Fleet size	furnishings and equip., availability in 2024						engine, availability in 2034					
		slow adoption		mid-range adoption		rapid adoption		slow adoption		mid-range adoption		rapid adoption	
		AM new	AM retro	AM new	AM retro	AM new	AM retro	AM new	AM retro	AM new	AM retro	AM new	AM retro
2014	6445	0	0	0	0	0	0	0	0	0	0	0	0
2015	6520	0	0	0	0	0	0	0	0	0	0	0	0
2016	6588	0	0	0	0	0	0	0	0	0	0	0	0
2017	6672	0	0	0	0	0	0	0	0	0	0	0	0
2018	6750	0	0	0	0	0	0	0	0	0	0	0	0
2019	6827	0	0	0	0	0	0	0	0	0	0	0	0
2020	6903	0	0	0	0	0	0	0	0	0	0	0	0
2021	6972	0	0	0	0	0	0	0	0	0	0	0	0
2022	7029	0	0	0	0	0	0	0	0	0	0	0	0
2023	7088	0	0	0	0	0	0	0	0	0	0	0	0
2024	7134	1	0	1	4	2	25	0	0	0	0	0	0
2025	7179	3	0	6	19	14	164	0	0	0	0	0	0
2026	7219	7	0	14	47	55	638	0	0	0	0	0	0
2027	7256	13	0	28	94	160	1766	0	0	0	0	0	0
2028	7292	22	0	50	165	350	3389	0	0	0	0	0	0
2029	7319	33	0	82	268	596	4750	0	0	0	0	0	0
2030	7334	48	0	125	409	859	5477	0	0	0	0	0	0
2031	7348	66	0	184	594	1131	5729	0	0	0	0	0	0
2032	7361	90	0	263	827	1408	5718	0	0	0	0	0	0
2033	7380	119	0	367	1107	1693	5574	0	0	0	0	0	0

2034	7403	155	0	498	1425	1984	5364	1	0	1	3	2	26
2035	7437	201	0	663	1769	2290	5121	3	0	6	14	15	170
2036	7478	257	0	860	2120	2604	4861	8	0	15	34	59	659
2037	7524	324	0	1087	2457	2925	4593	14	0	31	68	178	1823
2038	7566	402	0	1334	2763	3244	4319	24	0	56	120	389	3496
2039	7612	493	0	1603	3021	3567	4044	37	0	92	194	673	4894
2040	7657	598	0	1888	3226	3888	3769	55	0	144	297	988	5635
2041	7702	718	0	2184	3372	4207	3495	77	0	214	434	1313	5884
2042	7747	852	0	2490	3461	4522	3225	104	0	308	609	1643	5861
2043	7793	1002	0	2801	3497	4833	2959	138	0	429	822	1974	5702
2044	7838	1168	0	3117	3486	5138	2700	180	0	579	1069	2306	5476
2045	7884	1348	0	3434	3433	5435	2449	230	0	759	1343	2639	5219
2046	7930	1544	0	3752	3345	5724	2206	289	0	967	1630	2972	4946
2047	7977	1753	0	4068	3229	6002	1975	359	0	1203	1915	3306	4665
2048	8023	1976	0	4382	3089	6269	1754	440	0	1461	2185	3639	4382
2049	8070	2210	0	4692	2932	6523	1547	535	0	1739	2428	3971	4098
2050	8118	2455	0	4996	2761	6764	1354	643	0	2032	2633	4302	3816

5.2 Fuel use modeling and fleet-wide results

The adoption of lighter weight AM components in an aircraft will reduce its mass and therefore the amount of fuel used while operating the aircraft. Fuel savings, in TJ, from a 100 kg reduction in the mass of an aircraft, $\frac{\Delta F}{\Delta m}$, is estimated to be 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 [85-87]. The primary energy savings ($\epsilon_{jet\ fuel}$) and CO₂e emissions reduction ($\gamma_{jet\ fuel}$) per GJ of jet fuel saved are 1.2 GJ primary energy and 92 kg CO₂e respectively, based on estimates of well-to-wake energy use and carbon-equivalent emissions from jet fuel used in Argonne's GREET model [32].

The primary energy and CO₂ savings trajectories for the US passenger fleet are built from use-phase savings from reduced fuel use and from cradle-to-gate manufacturing system savings from the LCA. Use-phase savings for an average aircraft are applied to the active fleet of aircraft that have adopted AM parts, and manufacturing system savings are applied to all AM parts produced for new aircraft as well as for retrofits of parts that would have been replaced anyway. In the accelerated retrofit scenario, parts that are replaced ahead of schedule incur an energy penalty due the additional part production that is necessary in this scenario.

Cradle-to-gate and use-phase (fuel) energy savings ($\Delta E_{c_to_g,c,t}$ and $\Delta E_{fuel,c,t}$ respectively) and CO₂e savings ($\Delta C_{c_to_g,c,t}$ and $\Delta C_{fuel,c,t}$ respectively) are calculated for each type of component using the following formulas:

$$\Delta E_{fuel,c,t} = \epsilon_{jet\ fuel} \cdot \frac{\Delta F}{\Delta m} \cdot \frac{\Delta m_c}{airplane} \cdot \sum_{a=0}^A F^{AM}_{c,a,t}$$

$$\Delta E_{c_to_g,c,t} = \frac{E_{c_to_g,c}^{CM}}{airplane} \cdot \left(P_{c,t}^{AM} + \sum_{a=1}^A RB_{c,a,t}^{AM} \right) -$$

$$\frac{E_{c_to_g,c}^{AM}}{airplane} \cdot \left(P_{c,t}^{AM} + \sum_{a=1}^A (RB_{c,a,t}^{AM} + RA_{c,a,t}^{AM}) \right)$$

$$\Delta C_{fuel,c,t} = \gamma_{jet\ fuel} \cdot \frac{\Delta F}{\Delta m} \cdot \frac{\Delta m_c}{airplane} \cdot \sum_{a=0}^A F_{c,a,t}^{AM}$$

$$\Delta C_{c_to_g,c,t} = \frac{C_{c_to_g,c}^{CM}}{airplane} \cdot \left(P_{c,t}^{AM} + \sum_{a=1}^A RB_{c,a,t}^{AM} \right) -$$

$$\frac{C_{c_to_g,c}^{AM}}{airplane} \cdot \left(P_{c,t}^{AM} + \sum_{a=1}^A (RB_{c,a,t}^{AM} + RA_{c,a,t}^{AM}) \right)$$

$\frac{E_{c_to_g,c}^{CM}}{airplane}$ and $\frac{E_{c_to_g,c}^{AM}}{airplane}$ give the cradle-to-gate primary energy use per airplane from producing component c with conventional manufacturing and additive manufacturing, respectively, as calculated in section 4. $\frac{C_{c_to_g,c}^{CM}}{airplane}$ and $\frac{C_{c_to_g,c}^{AM}}{airplane}$ give the equivalent numbers for carbon emissions. $\frac{\Delta m_c}{airplane}$ is the mass reductions per airplane associated with each component, shown in Table S21.

The results of these calculations, aggregated across components, are shown in Tables S28-S29. Tables S30-S31 show the share of cumulative use phase and production phase energy and CO₂e savings in each scenario that are attributed to each component system.

Table S28. Energy savings from AM adoption (million GJ/year)

	slow adoption			mid-range adoption			rapid adoption		
year	cradle-to-gate	use-phase	total	cradle-to-gate	use-phase	total	cradle-to-gate	use-phase	total
2014	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0
2015	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0
2016	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0
2017	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0
2018	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0
2019	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0
2020	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.1	0.0-0.1
2021	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.1-0.3	0.1-0.3
2022	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.1	0.0-0.1	0.0-0.1	0.3-0.9	0.3-1.0
2023	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.1	0.0-0.1	0.0-0.1	0.7-1.8	0.7-1.8
2024	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.1-0.2	0.1-0.3	0.0-0.1	1.1-2.8	1.1-2.9
2025	0.0-0.0	0.0-0.1	0.0-0.1	0.0-0.1	0.2-0.5	0.2-0.6	0.0-0.1	2.0-4.7	2.0-4.9
2026	0.0-0.0	0.1-0.1	0.1-0.1	0.0-0.1	0.4-1.0	0.5-1.1	-0.1-0.3	4.6-9.9	4.4-10.2
2027	0.0-0.0	0.1-0.2	0.1-0.2	0.0-0.2	0.8-1.7	0.8-1.9	-0.3-0.6	10.5-21.7	10.2-22.4
2028	0.0-0.0	0.1-0.3	0.1-0.3	0.0-0.2	1.3-2.8	1.3-3.0	-0.5-0.9	19.3-39.0	18.8-40.0
2029	0.0-0.0	0.2-0.4	0.2-0.5	0.1-0.3	2.0-4.3	2.1-4.6	-0.4-1.0	27.0-54.4	26.6-55.4
2030	0.0-0.0	0.3-0.6	0.3-0.7	0.1-0.4	3.0-6.3	3.1-6.7	-0.2-0.8	31.8-64.0	31.6-64.8
2031	0.0-0.0	0.4-0.8	0.4-0.9	0.1-0.6	4.3-8.8	4.4-9.4	-0.1-0.7	34.4-69.2	34.3-69.9
2032	0.0-0.1	0.5-1.1	0.5-1.2	0.1-0.7	5.9-12.1	6.0-12.8	0.0-0.7	35.7-71.9	35.7-72.6
2033	0.0-0.1	0.7-1.5	0.7-1.5	0.1-0.8	7.8-16.0	7.9-16.8	0.1-0.7	36.4-73.5	36.5-74.2
2034	0.0-0.1	0.9-1.9	0.9-2.0	0.2-1.0	10.1-20.6	10.2-21.6	0.1-0.7	37.0-74.9	37.1-75.5
2035	0.0-0.1	1.1-2.4	1.2-2.6	0.2-1.2	12.6-25.8	12.9-27.1	0.1-0.9	37.9-77.2	38.0-78.1
2036	0.0-0.2	1.5-3.1	1.5-3.3	0.3-1.5	15.5-31.6	15.7-33.1	0.2-1.5	39.8-82.9	40.0-84.4
2037	0.0-0.2	1.8-4.0	1.9-4.2	0.3-1.7	18.4-37.7	18.7-39.4	0.3-2.8	44.1-95.5	44.4-98.2
2038	0.1-0.3	2.3-5.0	2.4-5.3	0.4-1.9	21.4-44.0	21.8-45.9	0.4-4.1	50.2-113.6	50.6-117.6
2039	0.1-0.3	2.8-6.2	2.9-6.5	0.4-2.2	24.4-50.4	24.8-52.6	0.6-4.6	55.7-130.0	56.4-134.6
2040	0.1-0.4	3.5-7.6	3.6-7.9	0.5-2.5	27.3-56.9	27.9-59.5	0.7-4.3	59.4-141.0	60.2-145.3
2041	0.1-0.5	4.2-9.1	4.3-9.6	0.6-2.9	30.2-63.5	30.9-66.4	0.8-4.0	61.6-147.6	62.4-151.6
2042	0.1-0.6	5.0-11.0	5.1-11.5	0.7-3.4	33.1-70.2	33.8-73.6	0.8-3.9	63.1-151.8	63.9-155.7
2043	0.1-0.6	5.9-13.0	6.1-13.6	0.9-3.9	35.9-77.1	36.8-81.0	0.9-3.8	64.1-154.8	64.9-158.6
2044	0.2-0.7	7.0-15.3	7.1-16.0	1.0-4.4	38.8-84.3	39.8-88.7	0.9-3.7	64.9-157.3	65.8-161.0
2045	0.2-0.9	8.1-17.9	8.3-18.7	1.1-4.9	41.6-91.6	42.8-96.5	0.9-3.7	65.6-159.4	66.5-163.2
2046	0.2-1.0	9.3-20.7	9.5-21.6	1.2-5.3	44.5-99.1	45.7-104.4	0.9-3.7	66.3-161.5	67.2-165.2
2047	0.2-1.1	10.7-23.8	10.9-24.9	1.3-5.6	47.2-106.6	48.6-112.2	0.9-3.7	67.0-163.4	67.8-167.1
2048	0.3-1.2	12.1-27.1	12.4-28.3	1.4-5.8	49.9-113.9	51.3-119.7	0.9-3.7	67.6-165.3	68.5-169.0
2049	0.3-1.4	13.7-30.7	14.0-32.1	1.4-5.8	52.5-121.0	53.9-126.8	0.9-3.7	68.3-167.2	69.1-170.9
2050	0.3-1.5	15.4-34.6	15.7-36.1	1.4-5.8	54.9-127.7	56.3-133.5	0.9-3.8	68.9-169.0	69.8-172.8
Cumulative	2.4-	107.7-	110.1-	13.9-	584.2-	598.1-	9.4-	1185.4-	1194.8-
2014-2050	11.4	238.5	249.9	63.4	1275.9	1339.3	62.9	2726.5	2789.4

Table S29. CO₂e savings from AM adoption (million tons CO₂e/year)

year	slow adoption			mid-range adoption			rapid adoption		
	cradle-to-gate	use-phase	total	cradle-to-gate	use-phase	total	cradle-to-gate	use-phase	total
2014	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0
2015	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0
2016	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0
2017	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0
2018	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0
2019	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0
2020	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0
2021	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0
2022	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.1	0.0-0.1
2023	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.1-0.1	0.1-0.1
2024	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.1-0.2	0.1-0.2
2025	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.2-0.4	0.2-0.4
2026	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.1	0.0-0.1	0.0-0.0	0.4-0.8	0.3-0.8
2027	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.1-0.1	0.1-0.1	0.0-0.1	0.8-1.7	0.8-1.7
2028	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.1-0.2	0.1-0.2	0.0-0.1	1.5-3.0	1.4-3.1
2029	0.0-0.0	0.0-0.0	0.0-0.0	0.0-0.0	0.2-0.3	0.2-0.4	0.0-0.1	2.1-4.2	2.0-4.3
2030	0.0-0.0	0.0-0.0	0.0-0.1	0.0-0.0	0.2-0.5	0.2-0.5	0.0-0.1	2.4-4.9	2.4-5.0
2031	0.0-0.0	0.0-0.1	0.0-0.1	0.0-0.0	0.3-0.7	0.3-0.7	0.0-0.1	2.6-5.3	2.6-5.4
2032	0.0-0.0	0.0-0.1	0.0-0.1	0.0-0.1	0.5-0.9	0.5-1.0	0.0-0.1	2.7-5.5	2.7-5.6
2033	0.0-0.0	0.1-0.1	0.1-0.1	0.0-0.1	0.6-1.2	0.6-1.3	0.0-0.1	2.8-5.7	2.8-5.7
2034	0.0-0.0	0.1-0.1	0.1-0.2	0.0-0.1	0.8-1.6	0.8-1.7	0.0-0.1	2.8-5.8	2.9-5.8
2035	0.0-0.0	0.1-0.2	0.1-0.2	0.0-0.1	1.0-2.0	1.0-2.1	0.0-0.1	2.9-5.9	2.9-6.0
2036	0.0-0.0	0.1-0.2	0.1-0.3	0.0-0.1	1.2-2.4	1.2-2.6	0.0-0.1	3.1-6.4	3.1-6.5
2037	0.0-0.0	0.1-0.3	0.1-0.3	0.0-0.1	1.4-2.9	1.4-3.1	0.0-0.2	3.4-7.3	3.4-7.6
2038	0.0-0.0	0.2-0.4	0.2-0.4	0.0-0.2	1.6-3.4	1.7-3.6	0.1-0.3	3.9-8.7	3.9-9.1
2039	0.0-0.0	0.2-0.5	0.2-0.5	0.0-0.2	1.9-3.9	1.9-4.1	0.1-0.4	4.3-10.0	4.4-10.4
2040	0.0-0.0	0.3-0.6	0.3-0.6	0.0-0.2	2.1-4.4	2.1-4.6	0.1-0.3	4.6-10.9	4.6-11.2
2041	0.0-0.0	0.3-0.7	0.3-0.7	0.1-0.2	2.3-4.9	2.4-5.1	0.1-0.3	4.7-11.4	4.8-11.7
2042	0.0-0.0	0.4-0.8	0.4-0.9	0.1-0.3	2.5-5.4	2.6-5.7	0.1-0.3	4.9-11.7	4.9-12.0
2043	0.0-0.1	0.5-1.0	0.5-1.1	0.1-0.3	2.8-5.9	2.8-6.3	0.1-0.3	4.9-11.9	5.0-12.2
2044	0.0-0.1	0.5-1.2	0.5-1.2	0.1-0.4	3.0-6.5	3.1-6.8	0.1-0.3	5.0-12.1	5.1-12.4
2045	0.0-0.1	0.6-1.4	0.6-1.4	0.1-0.4	3.2-7.1	3.3-7.4	0.1-0.3	5.1-12.3	5.1-12.6
2046	0.0-0.1	0.7-1.6	0.7-1.7	0.1-0.4	3.4-7.6	3.5-8.0	0.1-0.3	5.1-12.4	5.2-12.7
2047	0.0-0.1	0.8-1.8	0.8-1.9	0.1-0.4	3.6-8.2	3.8-8.6	0.1-0.3	5.2-12.6	5.2-12.9
2048	0.0-0.1	0.9-2.1	1.0-2.2	0.1-0.5	3.8-8.8	4.0-9.2	0.1-0.3	5.2-12.7	5.3-13.0
2049	0.0-0.1	1.1-2.4	1.1-2.5	0.1-0.5	4.0-9.3	4.2-9.8	0.1-0.3	5.3-12.9	5.3-13.2
2050	0.0-0.1	1.2-2.7	1.2-2.8	0.1-0.5	4.2-9.8	4.3-10.3	0.1-0.3	5.3-13.0	5.4-13.3
Cumulative 2014-2050	0.2-1.0	8.3-18.4	8.5-19.3	1.2-5.2	45.0-98.2	46.1-103.4	0.9-5.1	91.2-209.9	92.1-215.0

Table S30. Cumulative primary energy savings from AM adoption, 2014-2050, in million GJ

Component system	Component category	slow adoption			mid-range adoption			rapid adoption		
		cradle-to-gate	use-phase	total	cradle-to-gate	use-phase	total	cradle-to-gate	use-phase	total
Body systems	Auxiliary	0-0	4-14	4-14	0-1	9-34	9-35	0-1	17-63	17-64
Furnishing and equipment systems	Structural	0-1	7-19	7-20	0-2	32-84	33-86	0-2	52-134	52-136
Furnishing and equipment systems	Functional	1-3	79-150	79-154	2-14	432-825	434-839	-1-11	756-1442	755-1453
Engine	Functional	1-5	9-28	11-33	9-38	78-231	87-269	7-37	292-869	299-906
Engine	Auxiliary	0-1	5-13	5-14	1-4	23-64	24-68	1-4	45-125	45-129
Propulsion systems	Functional	0-1	2-7	2-8	1-4	6-23	7-26	2-8	18-69	21-77
Nacelle systems	Auxiliary	0-0	2-7	2-7	0-0	4-15	4-15	0-0	7-24	7-25

Table S31. Cumulative CO₂e savings from AM adoption, 2014-2050, in million tons CO₂e

Component system	Component category	slow adoption			mid-range adoption			rapid adoption		
		cradle-to-gate	use-phase	total	cradle-to-gate	use-phase	total	cradle-to-gate	use-phase	total
Body systems	Auxiliary	0.0-0.0	0.3-1.1	0.3-1.1	0.0-0.1	0.7-2.7	0.7-2.7	0.0-0.1	1.3-4.9	1.3-4.9
Furnishing and equipment systems	Structural	0.0-0.1	0.6-1.5	0.6-1.5	0.0-0.2	2.5-6.5	2.5-6.7	0.0-0.2	4.0-10.3	4.0-10.5
Furnishing and equipment systems	Functional	0.0-0.3	6.1-11.6	6.1-11.9	0.1-1.4	33.3-63.5	33.4-64.8	-0.1-1.1	58.2-111.0	58.1-112.1
Engine	Functional	0.1-0.3	0.7-2.2	0.8-2.5	0.8-2.8	6.0-17.8	6.8-20.6	0.7-2.8	22.4-66.9	23.1-69.7
Engine	Auxiliary	0.0-0.1	0.4-1.0	0.4-1.1	0.1-0.3	1.8-4.9	1.9-5.3	0.1-0.3	3.5-9.6	3.5-9.9
Propulsion systems	Functional	0.0-0.1	0.1-0.5	0.2-0.6	0.1-0.3	0.5-1.7	0.6-2.1	0.2-0.7	1.4-5.3	1.6-6.0
Nacelle systems	Auxiliary	0.0-0.0	0.1-0.5	0.1-0.5	0.0-0.0	0.3-1.1	0.3-1.2	0.0-0.0	0.5-1.9	0.5-1.9

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