Techno-Economic Analysis for Shear Assisted Processing and Extrusion (ShAPE) of High-Strength Aluminum Alloys

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National Renewable Energy Laboratory

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List of Acronyms

AA7075	aluminum alloy 7075
CapEx	capital expenditure
DCF	discounted cash flow
DOE	U.S. Department of Energy
DFMA	Design for Manufacture and Assembly
ft	foot
h	hour
in.	inch
J	joule
kg	kilogram
kW	kilowatt
kWh	kilowatt-hour
lb(s)	pound(s)
m	meter
mm	millimeter
MN	meganewton
MWh	megawatt-hour
MSP	minimum sustainable price
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
R&D	research and development
s	second
SG&A	sales, general, and administrative [expenses]
ShAPE	Shear Assisted Processing and Extrusion
TEA	techno-economic analysis
USGS	United States Geological Survey
yr	year

Executive Summary

Aluminum alloy 7075 (AA7075) is a high-strength aluminum alloy, attractive for uses in automotive, aviation, aerospace, defense, and marine applications. However, AA7075 has not yet been widely adopted because of high cost, slow extrusion speed, high energy use, a narrow process window, and sensitivity to incipient melting common in conventional extrusion methods. Alternative extrusion methods may overcome these limitations.

One alternative extrusion method that shows promise is solid-phase processing, a family of emerging techniques that process bulk metals under severe plastic deformation without melting. Solid-phase processing methods are notable because they offer a way to manufacture metals and alloys with the potential for enhanced performance at lower cost. Research funded by the U.S. Department of Energy Advanced Manufacturing Office is exploring the use of a new solid-phase processing approach called Shear Assisted Processing and Extrusion (ShAPE) for the manufacture of AA7075 extrusions. The Pacific Northwest National Laboratory is leading the development, testing, and characterization of ShAPE. This is showing that high-speed ShAPE extrusions (e.g., above 12 meters per minute [m/min]) are significantly faster than the 1–2 m/min possible with conventional AA7075 extrusions.

In ShAPE, a rotating die is rammed against a metal feedstock, which results in heating from deformation and friction. The metal softens because of this heat while spiral scroll features on the face of the rotating die force material between the mandrel and the die to form hollow-profile extrusions. This combination of linear and rotational shear, unique to ShAPE, enables extensive grain refinement and uniform dispersion of secondary phases. In addition to extrusion over the mandrel, ShAPE is also capable of porthole and port bridge die techniques. Preheating the tooling and billet is not required with ShAPE because all the necessary heat is generated by the process.

As part of this Advanced Manufacturing Office project, the National Renewable Energy Laboratory collaborated with Pacific Northwest National Laboratory to perform a techno-economic analysis and manufacturing analysis on ShAPE. These analyses quantify the potential cost and energy reductions of the ShAPE process compared to today's conventional extrusion methods. The process steps incorporated into the models include preheating, extrusion, quenching, stretching, cutting, and artificial aging. Based on the part size, the models include estimates for processing speed, energy and material use, and labor requirements. Capital expenditures and operating costs for each step have also been estimated.

Initial findings from the techno-economic and energy analyses indicate that AA7075 hollow tubes created with ShAPE at 20 millimeters per second (mm/s) could use ~70% less energy than hollow tubes that are conventionally heated and extruded at a low extrusion speed (20 mm/s). The energy savings can be higher (~76%) for a higher extrusion speed (117 mm/s). The reduction in energy use is primarily a result of using faster extrusion speeds and direct-chill-cast (unhomogenized) billets, which eliminates the preheating step of the conventional process. The techno-economic model translates capital expenditures and operation and maintenance costs to a manufacturing cost and then to a minimum sustainable price per ton of extruded product for multiple facility capacities.

The results of test scenarios show that ShAPE can be 55% cheaper than conventional extrusion. Using unhomogenized billets and high-speed extrusion (195 mm/s) and removing the solution heat treatment stage increase savings for the ShAPE model 60% by cost and 85% by energy with respect to conventional extrusion.

Removing the preheat step for ShAPE production leads to a large energy savings—approximately 282 megawatt-hours for a production volume of 50 tons/year at an extrusion speed of 20 mm/s—when compared to conventional extrusion at the same extrusion speed. Although this does not lead to a significant cost impact because of the cost of electricity in the product, the energy savings do convert to emissions savings. The removal of the preheat step alone, using an average emissions factor for the United States, leads to a potential CO_2 savings of approximately 118 metric tons per year. When the 70% total energy savings for ShAPE with an extrusion speed of 20 mm/s is considered, the relative CO_2 savings could be approximately 269 metric tons per year.

Future improvements in the techno-economic modeling could account for a powder model, various aluminum alloys, different sizes of machines, and the next generation of the ShAPE machine. It is vital for future validation efforts to work with industry partners to determine and validate key conventional extrusion parameters. The focus has been on creating an extrusion model that could provide insight for the ShAPE system, which has been successfully achieved. Future efforts will need to validate the ShAPE model with a manufacturing facility utilizing the ShAPE machine in real production runs.

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1 Introduction

The aluminum industry can be divided into metal- and product-producing sectors. Based on the United States Geological Survey (USGS) data, the worldwide metal-producing sector manufactured approximately 65,200,000 metric tons (t) of primary aluminum metal, of which 37,080,000 t originated from China in 2020 (USGS 2021). In 2020, domestic primary aluminum production in the United States was 1,012,000 t and secondary aluminum production was 3,050,000 t (USGS 2021). Domestic production data were based on information compiled from the USGS monthly surveys, which were sent to seven primary aluminum smelters owned by three companies (Alcoa Corporation, Century Aluminum Company, and Magnitude 7 Metals, LLC).

The use of aluminum extrusion in product design and manufacturing has increased significantly in recent decades, reaching a global market size of 28.08 million t in 2020 (IMARC n.d.). The growth of the global aluminum extrusion market is expected to accelerate with a compound annual growth rate of almost 3.97% to reach a volume of 35.47 million t between 2021 and 2026 (IMARC n.d.). The increase in the construction of environmentally friendly, energy-efficient, green buildings and the growing automotive sector, especially electric vehicles, are the key factors driving market growth.

Aluminum is used in many diverse applications that differ substantially in product use, performance requirements, and relevance to energy use. Aluminum is used in transportation applications (automotive and aerospace), which constitutes approximately 28% of overall aluminum production (U.S. Department of Energy [DOE] 2017). Other applications include medical devices and equipment, electronics and communications, computers and electrical equipment, construction and infrastructure, consumer goods and packaging, compressed gas storage for hydrogen fuel tanks, and wind turbine blades (DOE 2017).

Primary aluminum production involves refining raw material (bauxite) to prepare alumina and converting it into aluminum by smelting. Secondary production involves the production of aluminum ingot from a combination of mostly recycled and processed aluminum scrap as well as some primary aluminum (DOE 2017). Both primary and secondary cast aluminum ingots are then further processed or used to produce rolled, casted, or extruded aluminum products in semifinished shape production (Figure 1).

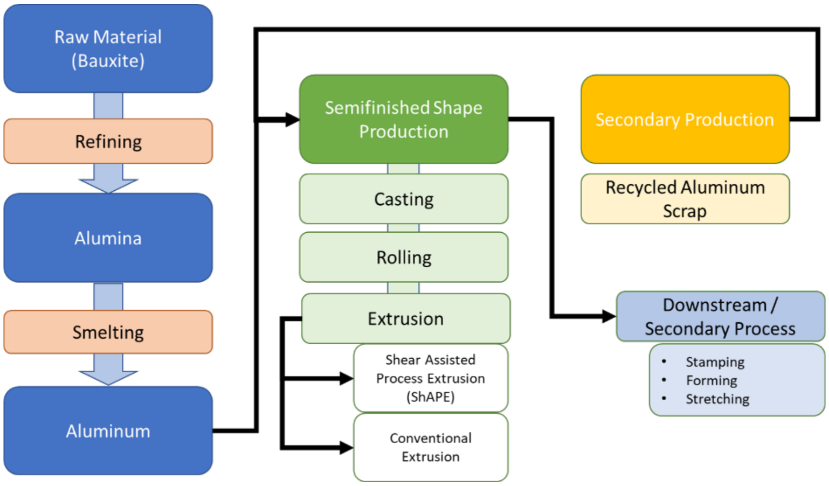


Figure 1. Aluminum manufacturing supply chain and process flow diagram

1.1 Conventional Aluminum Extrusion Model

Extrusion is the process of forcing an aluminum ingot or billet through a hardened steel die to form an elongated shape of a consistent cross section. Prior to extrusion, the billet is heated. Extruded products include rods, bars, tubes, and specialized products interchangeably called shapes, sections, or profiles. A powerful ram pushes the aluminum through the die; when it emerges from the die opening, it is in the same shape as the die and is pulled out along a runout table (DOE 2007).

Rolling and extrusion are one of the most common processing techniques for aluminum. Aluminum extrusion is remarkable because the process combines high productivity with an essentially infinite variety of extremely complex shapes, cross sections, or profiles that cannot be economically duplicated in any other process. Furthermore, aluminum can be readily extruded; this process is either extremely difficult or impractical for many other metals (DOE 2007).

In 2010, the United States produced approximately 3.197 billion pounds of extruded aluminum products or ~1,450,000 t (DOE 2017). It is possible to produce almost any cross-sectional shape, including hollow shapes or cross sections with complex enclosed configurations (DOE 2007). Theoretically, it is possible to extrude products without the need of additional heat treatments and without loss of material. In such a case, the minimum theoretical energy to extrude a product comprises only two components: the energy required to preheat the billet to extrusion temperature, and the energy required to deform the material through a die.

The energy required to deform the material through the die is highly dependent on the size and shape of the product and the die design. The hotter the material is, the lower the deformation energy required. The simpler the die, the lower the extrusion energy requirement. Calculation of the minimum extrusion force is complex and can only be estimated with theoretical and empirical models. Typical force and stress-strain formulas have the simplified forms shown in Eqs. (1) and (2):

$$F = A_o \left(\frac{\sigma_m}{\eta}\right) \varepsilon \tag{1}$$

where

σ_m is the mean stress for the strain

A_o is the original cross-sectional area

η is an efficiency factor

ε is the strain and corresponds to the reduction area:

$$\varepsilon = ln\left(\frac{A_o}{A_f}\right) \tag{2}$$

A_f is the final cross-sectional area.

The very large variations in alloy properties, particularly the infinite numbers of possible shapes, make it impossible to calculate a theoretical minimum energy requirement. This value can only be determined by analyzing a specific process, extruded profile, and alloy. The perimeter of the profile and the radius of intersecting edges have a large influence on the force required for extrusion. A rough approximation of a minimum energy value can be made by examining the entire aluminum extrusion industry yield and energy values, and assuming an overall process heating efficiency and electric/hydraulic system efficiency. This approach provides an estimate of the minimum energy, 0.44 kilowatt-hours per kilogram (kWh/kg) of aluminum, when efficiencies are assumed to be 50% for heating and 75% for the electric/hydraulic system. These assumptions imply that overall, extrusion facilities operate at about 34% energy efficiency (DOE 2007).

Aluminum alloys are very suitable for extrusion; many types of profiles can be produced from easily extrudable alloys, including the 1000 series (99.00% minimum aluminum), 2000 series (with copper), 3000 series (with manganese), 5000 series (with magnesium), 6000 series (with magnesium and silicon), and 7000 series (with zinc). The alloy series (Misiolek and Kelly 2005) are listed in Table 1.

Table 1. Aluminum Extrusion Alloys by Series

Series	Alloys
1000 Series	1060, 1100, 1350
2000 Series	2011, 2014, 2024, 2219
3000 Series	3003, 3004
5000 Series	5066, 5083, 5086, 5154, 5454, 5456
6000 Series	6005, 6005A, 6020, 6040, 6060, 6061, 6063, 6066, 6070, 6082, 6101, 6105, 6162,6262, 6351, 6463
7000 Series	7001, 7003, 7004, 7005, 7029, 7046, 7050, 7075, 7079, 7116, 7129, 7146, 7178

Aluminum alloy 7075 (AA7075) is a high-strength, low-weight metal alloy that can handle high mechanical stresses. These properties make AA7075 attractive for high-stress parts in automotive, aviation, aerospace, and defense applications (Alcoa Global Cold Finished Products n.d.). AA7075 has not been adopted more broadly because it is expensive to manufacture and difficult to extrude. Relevant challenges include a high cost with conventional extrusions, inherently slow extrusion speed, high energy use, high ram pressure, a narrow process window, high flow stress, and sensitivity to incipient melting. Alternatives or improvements to conventional extrusion methods can address those challenges. One viable alternative extrusion method for AA7075 is solid-phase processing—a family of emerging techniques that process bulk metals under severe plastic deformation without melting. Solid-phase processing methods are notable because they offer a way to manufacture metals and alloys with potential for enhanced performance at a lower cost.

1.2 Shear Assisted Processing and Extrusion

Shear Assisted Processing and Extrusion (ShAPE), pioneered at the Pacific Northwest National Laboratory (PNNL), is a new extrusion technology (Whalen et al. 2019). The ShAPE process has been patented with U.S. Patents 10,189,06 and 11,045,851 (Joshi et al. 2021; Lavender et al. 2019); four other patents are pending (Whalen et al. 2019). Maturation of the ShAPE process would create a new cross-cutting U.S. manufacturing technology that advances key objectives within the DOE Advanced Manufacturing Office, namely, process intensification, reduced energy consumption, lower cost, and materials for extreme and harsh environments (DOE 2017). High-strength aluminum alloys are the subject of this research because of their long-term, reliable operation in a range of harsh service environments. For example, innovative uses include vehicle lightweighting, aerospace structures, and ultra-deep-water oil and gas drilling (Gelfgat et al. 2004).

In ShAPE, a rotating die is rammed against a metal feedstock, which results in heating from deformation and friction (Sikirica et al. 2021). The metal softens because of this heat while spiral scroll features on the face of the rotating die force material between the mandrel and the die to form hollow-profile extrusions (Figure 2). This combination of linear and rotational shear, which is unique to ShAPE, enables extensive grain refinement, uniform dispersion of secondary phases, and alignment of crystalline structures (Sikirica et al. 2021).

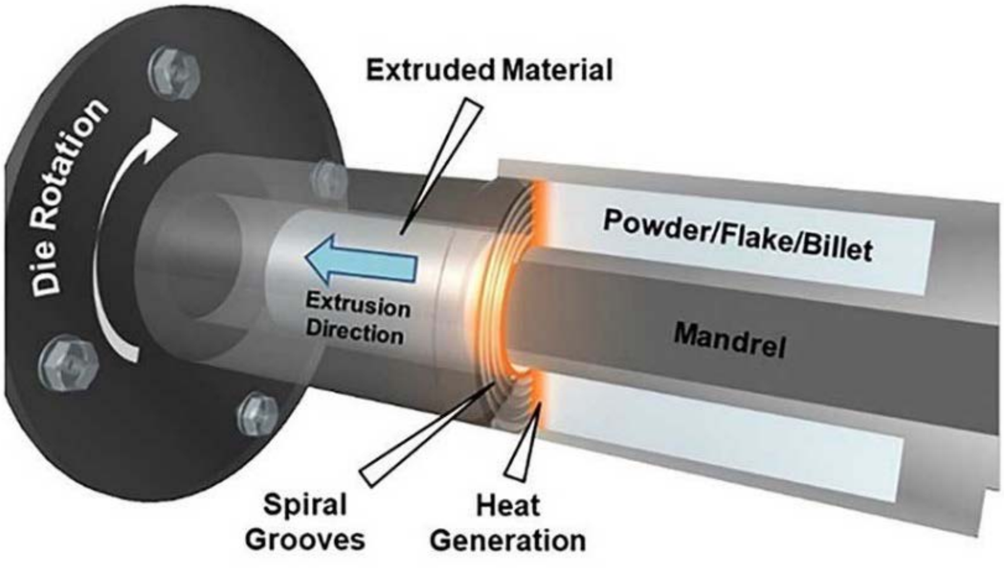


Figure 2. Schematic of the ShAPE extrusion process. *Illustration from Pacific Northwest National Laboratory (PNNL)*

Presently, the main barrier to widespread use of high-performance aluminum alloy extrusions is cost (Sikirica et al. 2021). For example, the cost of AA7075 extrusion is, in general, approximately 25%–75% more expensive than the more commonly used AA6061 (Online Metals n.d.; Online Metals 2019; Parts Badger n.d.). The higher cost of AA7075 (and 7000 series aluminum alloys in general) is primarily driven by the low extrusion speed that is necessary to avoid the melting of strengthening precipitates. Another factor contributing to high cost is the energy-intensive thermal processing steps needed to homogenize castings, preheat billets prior to extrusion, and solution heat treat after extrusion. Exotic aluminum alloy extrusions made by powder metallurgy are even more expensive and would realize higher use in industry if cost could be significantly reduced. The high cost of powder metallurgy aluminum alloys is due, in part, to the numerous thermomechanical processing steps and atomization required to consolidate and create the powder with the desired properties.

2 Manufacturing Cost Model

The National Renewable Energy Laboratory (NREL) manufacturing cost model includes a complete analysis using raw material specifications, machining processes, and final product. In this specific example the final product is the extruded aluminum part.

2.1 Material and Part Specifications

Tooling and die sets were fabricated and installed on the PNNL ShAPE machine, as shown in Figure 3. Experiments at PNNL have allowed standard homogenized and as-cast billets to be used for extruding parts. The tooling was used to fabricate extrusions from AA7075 as-cast billets with an outer diameter of 12 millimeters (mm) and a wall thickness of 1.0 mm. The extrusion ratio (area of billet / area of shape) is 20:1 and yields extrusions 2 meters (m) long and 31.75 mm (1.25 inches [in]) in diameter from 100 mm long billets. (Whalen, Olszta, et al. 2021). The extrusion of as-cast billets was performed using the process parameters in Table 1 and then heat treated to the T6 condition prior to mechanical testing. The T6 condition includes a heat treat at 480 degrees Celsius (°C) for 1 hour (h), immediate water quenching, and then a heat treat at 120°C for 48 h (Whalen, Reza-E-Rabby, Wang, et al. 2021).

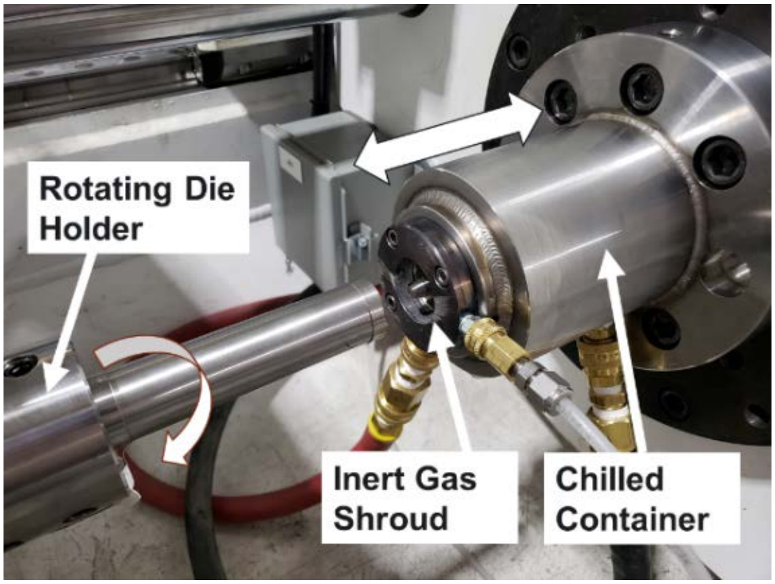


Figure 3. Tooling for extrusions with an outer diameter of 12 millimeters (mm) and wall thickness of 1 mm (in the direction shown by white two-sided arrow). *Photo from PNNL*

The manufacturing cost model is designed based on a model for extruding a 30,480 mm long (100 foot [ft]) hollow tube with an outer diameter of 12 mm (0.472 in.) and an inner diameter of 10 mm (0.394 in.) from a single AA7075 hollow billet that is 1,560 mm (61.42 in.) long with an outer diameter of 31.7 mm (1.248 in.) and an inner diameter of 10 mm (0.394 in.) (Figure 4). Figure 4 is modified from the Design for Manufacture and Assembly (DFMA) software (Boothroyd Dewhurst Inc. n.d.).

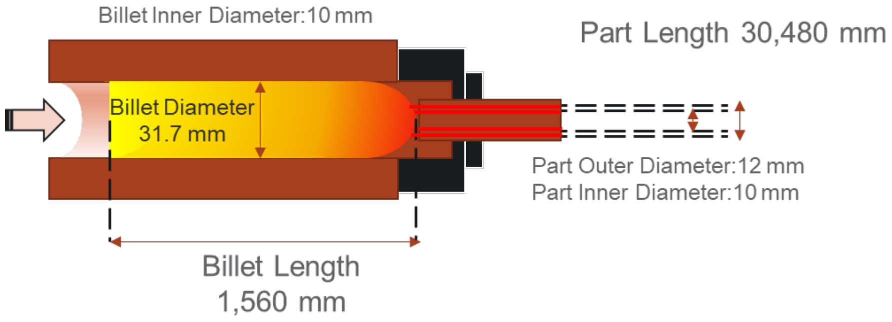


Figure 4. Diagram of the billet and part specifications (not to scale)

Table 2 shows the key parameters and dimensions for the billet and extruded parts for conventional and ShAPE models. The AA7075 billet price of $5.46/kg is from DFMA (Boothroyd Dewhurst Inc. n.d.).

Table 2. Billet and Extruded Part Specifications for Conventional and ShAPE Models

Unit	Specification	Conventional and ShAPE
n/a	Part material type	AA7075
$/kg	Aluminum billet price[a]	$5.46
g/cm$^{3(b)}$	Aluminum density	2.81
mm	Part external perimeter	314
mm	Part internal perimeter	282
mm	Part length	30,480
n/a	Number of cuts	5
mm	Part outer diameter	12
mm	Part inner diameter	10
mm^2	Part cross-section area	35
mm^3	Part volume	1,052,779
mm^3	Cut-through volume	48
kg	Part weight	0.59
mm	Billet outer diameter	31.7
mm	Billet inner diameter	10.0
mm	Billet length	1,560
mm^2	Billet cross-section area	710
mm^3	Billet volume	1,108,128
mm^3	Net billet volume	1,052,722
kg	Billet weight	3.46
n/a	Parts/billet	1.00
mm	Total extruded length/billet	30,478
m	Total extruded length/billet	30.48
n/a	Extrusion ratio	19.54
g/mm	Extrusion unit mass	97.06

[a] AA7075 Aluminum billet price from design for manufacturing and Assembly (DFMA) library

[b] g/cm^3 = grams per cubic centimeter

2.2 Energy Intensity of Extruded Parts

Homogenizing is the first heat treatment process of the as-cast billets; it produces a uniform distribution of the alloying elements and dissolves the brittle grain boundary precipitates (Sheppard 1999). The homogenization can be done through either direct-fuel-fired or electric-resistance heating. The homogenization process may follow different stages at various temperatures based on the characteristics of the aluminum alloy. The first stage (Stage 1) heats the billet from room temperature (20°C) to 200°C and holds at 200°C for 2 h and is followed by a homogenizing annealing treatment (Stage 2) at 470°C for 24 h (Figure 5). It is possible to have homogenization furnaces with a 55-t capacity (Sagermann

2017); therefore, a single batch would be enough to hold 15,637 billets that are needed for a dedicated AA7075 manufacturer to achieve an annual manufacturing volume of 50 t per year (t/yr). The furnace power capacity is estimated at 350 kilowatts (kW) for a 55-t-capacity furnace (JR Furnace n.d.). The energy requirement for homogenizing billets can be calculated using Eq. (3).

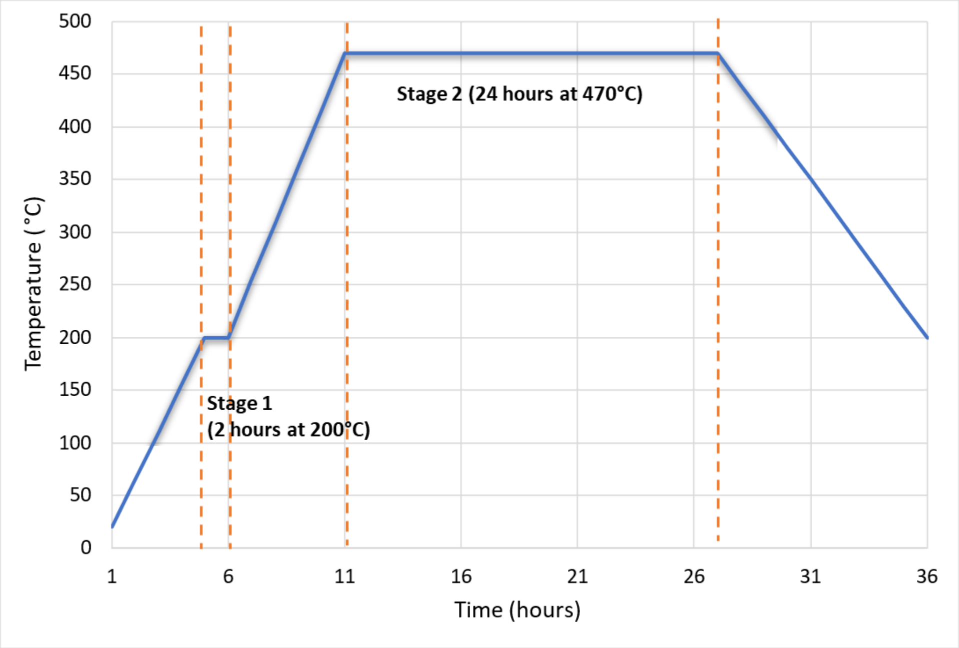


Figure 5. Diagram showing the homogenization stage of AA7075. *Data from PNNL*

$$Q\ (kWh) = 2.77e^{-7} \times \sum_{n=1}^{n} (\mathrm{m} \cdot \mathrm{c} \cdot \Delta\mathrm{T})_n + \sum_{n=1}^{n} \frac{(P \cdot t_n)}{b} \qquad (3)$$

where
m = total mass (in kilograms [kg])
c = specific heat (in joules per kilogram degree-Celsius [J/kg·°C])
T = temperature (in °C)
t = time (in h)
P = furnace power (in kW)
n = stage number
b = batch size (number of billets).

AA7075 with zinc as the primary alloying element has a specific heat of 960 J/kg·°C (MatWeb 2021). The total weight of one billet is 3.46 kg. Thus, the thermal power required to homogenize one billet is calculated as 0.91 kWh per billet (0.26 kWh/kg). The total energy requirement per extrusion (which includes five parts, each 20-ft long) is 7.24 kWh/kg for the ShAPE model base-case scenario. This is equivalent to ~4% of the total energy requirement of the processes for the ShAPE model base-case scenario.

2.3 Manufacturing Process Flow

Extrusion of high-strength aluminum alloys includes six main process steps (Figure 6). These are: (1) preheating, (2) extrusion, (3) quenching, (4) stretching, (5) cutting, and (6) artificial aging (Stars Aluminum Extrusion n.d.). The NREL model boundary excludes the extrusion logs, cutting into billets, homogenizing billets, if needed, and packing/delivering the final extruded parts. Figure 7 shows the process steps that are included in the NREL model.

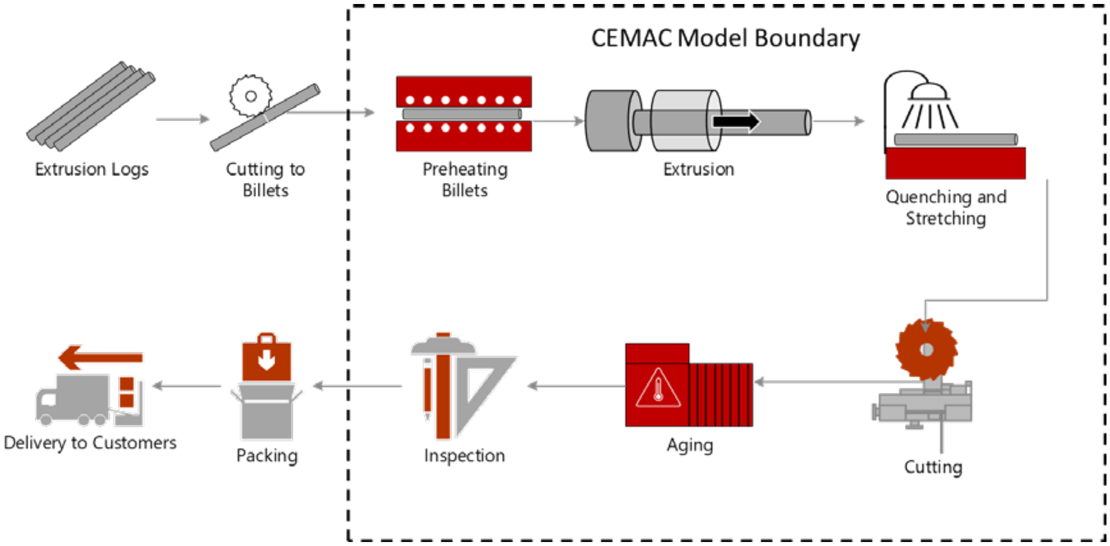
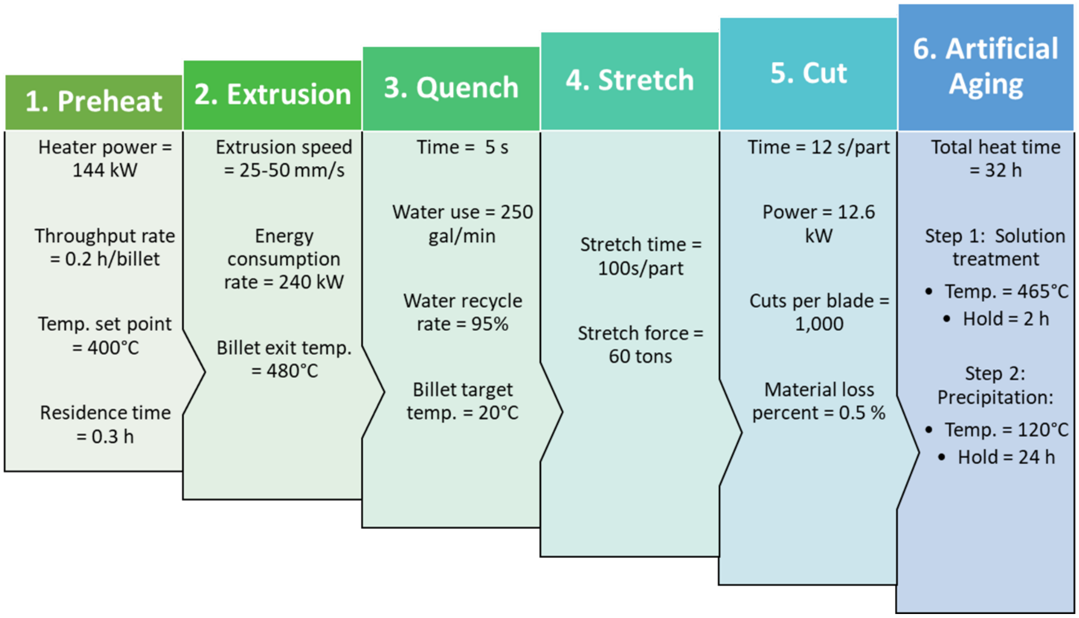


Figure 6. Manufacturing process flow diagram for conventional extrusion and ShAPE of high-strength aluminum alloys.

CEMAC = Clean Energy Manufacturing Analysis Center



1. Preheat	2. Extrusion	3. Quench	4. Stretch	5. Cut	6. Artificial Aging
Heater power = 144 kW Throughput rate = 0.2 h/billet Temp. set point = 400°C Residence time = 0.3 h	Extrusion speed = 25-50 mm/s Energy consumption rate = 240 kW Billet exit temp. = 480°C	Time = 5 s Water use = 250 gal/min Water recycle rate = 95% Billet target temp. = 20°C	Stretch time = 100s/part Stretch force = 60 tons	Time = 12 s/part Power = 12.6 kW Cuts per blade = 1,000 Material loss percent = 0.5 %	Total heat time = 32 h Step 1: Solution treatment • Temp. = 465°C • Hold = 2 h Step 2: Precipitation: • Temp. = 120°C • Hold = 24 h

Figure 7. Specifications of six process steps for the conventional extrusion model

2.4 Machine Inventory and Factory Model

A minimum machining rate for each machine based on annual maximum allowable working hours and operation hours was estimated with and without setup time for the factory model. The value for maximum allowable working hours is set to 4,964 h based on 365 labor days, 8 labor hours with 2 shifts per day, and 85% production up-time (Akar et al. 2018). Table 3 shows the factory model specifications used in the analysis (Akar et al. 2018).

Based on industry-standard practices, these machines are as fully utilized as possible across several different projects. For this cost analysis, the capital cost share associated with facilities, space, and machine depreciation for the time when the machine is used on manufacturing the extruded parts is proportional to the use time. This splits the capital expenditures (CapEx) for the equipment between the extrusion of a specific part and other parts that the manufacturer is involved in. In other words, the analysis only takes the CapEx share associated with facilities, space, and machine depreciation for the time when the machine is used on manufacturing the specified extruded part, not for the full 4,964 hours per year.

Table 3. Factory Model Specifications and Unit Cost Inputs for Manufacturing Cost Model

Units	Parameter	Assumption
n/a	Number of shifts	2
h	Hours per shift	8
d	Operating days per year	365
%	Production up-time	85
h	Operating hours per year	4,964
\$/kWh	Energy cost[a]	0.05
\$/L	Water cost[a]	0.0038
$\$/m^2/yr$	Floorspace cost	113.67
\$/h	Labor rate for manufacturing	25
\$/h	Labor rate for research and development (R&D)	54

[a] Values are for the state of Texas and the electricity price is from the U.S. Energy Information Administration (U.S. Energy Information Administration [EIA] 2020a)

The amount of required machinery was selected based on the total operational hours for different volumes of manufacturing and on maximum allowable working hours. If one of each machine type (one preheater, one extruder, one quencher, one stretcher, one cutter, one artificial ager) were chosen for all types, there would be enough manufacturing capacity to produce up to a volume of 50 t/yr. For greater than 50 t/yr, additional machines would be required (Table 4).

The annual volume of manufacturing was limited to 400 t as a maximum threshold for the analysis, based on annual manufacturing capacities and project portfolio per facility. Annual straight-line depreciation was selected for capital costs associated with machinery, as handled in accounting procedures. Facility cost is defined based on the minimum required working area for each machine. Energy cost is calculated based on the average power consumption of each machine operating for a given number of hours. Storage and shipping costs of the extruded parts are not included in the factory model. Increasing annual volume of manufacturing raises the number of machines needed for the process steps. However, this increase is not linear because of the total operating hours of the machine per process and the maximum allowable working hours. As an example, from Table 4, two extruder machines are needed for a manufacturing volume of 50 t/yr. If the annual manufacturing volume is doubled, only one more extruder machine is needed to be able to extrude the desired number of parts.

Table 4. Number of Required Machines for ShAPE in Different Volumes of Manufacturing at Maximum Allowable Working Hours

Volume (tons/yr)	Extruder	Quencher	Stretcher	Cutter	Ager
10	1	1	1	1	1
25	1	1	1	1	1
50	2	1	1	1	1
100	3	1	1	1	1
200	5	1	2	1	2
300	8	1	3	1	3
400	10	1	4	1	4

The investment cost and power requirements for machinery, including additional tooling costs, are summarized in Table 5. Power requirements for the ShAPE machine is presented in parentheses. Equipment and tool lifetime is also important for calculating the depreciation of the equipment and the frequency of tool replacement.

Table 5. Main Investment Cost and Power Requirements for the Equipment

Parameters	Conventional - (ShAPE)	Units
Preheating		
Generator power	143.3	kW
Preheat equip. investment	$300,000	$
Equipment lifetime	20	yr
Extrusion		
Extrusion power requirements	11 - (47)	kW
Line investment	$1,000,000 - ($2,000,000)	$
Tool lifetime	1,524	m of parts
Tool investment	$10,000	$
Quenching		
Quenching motor	55.9	kW
Number of quenching motors	4.0	n/a
Total quenching motor power	223.7	kW
Quench investment	$200,000	$
Stretching		
Stretching power requirement	95.6	kW
Stretcher investment	$50,000	$
Cutting		
Saw investment	$106,503	$
Saw blade cost	$500	$
Saw replacement rate	10,000	kg of Al
Artificial Aging		
Heating power requirement	12.6	kW
Aging investment	$1,000,000	$

2.5 Parameters for Process Steps

2.5.1 Preheating of Billets

After the billet is cut to the desired length, it moves to a tunnel heater that heats the aluminum to around 470°C, although the exact temperature depends on the characteristics of the aluminum. The billet preheating process step is only applied to the conventional extrusion model. This process step is not needed in the ShAPE model and has been repeatedly shown as not needed by PNNL's process and material tests (Whalen et al. 2021). Billet preheating parameters for conventional extrusion are shown in Table 6.

Table 6. Billet Preheating Parameters

Parameters	Conventional	Units
Generator power	143.3	kW
Footprint for preheating	50.0	m^2/line
Workers/preheater	0.5	#/line
Preheating unplanned downtime	2.0	hour/day (h/d)
Throughput rate	0.2	h/billet
Set point temperature	400	°C
Ambient temperature	20.0	°C
Residence time of billet in heater	0.3	h
Reject rate	0.0%	%
Time at set point	0.04	h
Setup time	1.0	h
Billet transfer time	1.0	h
Number of billets heated at same time	1	n/a
Parts per "batch"	10,000	n/a

2.5.2 Extrusion

Once the billet heats up, it gets coated with a lubricant so that it will not stick to anything as it goes through the process. The heated material goes into a cradle with dies that match what is needed in the final product. A ram then forces the billet through the dies, when required. One of the most critical aspects of this step is maintaining a consistent temperature. Ram speed is defined as 1 mm/s for conventional extrusion. The optimum ram speed for ShAPE is 6 mm/s, but it can vary between 1 and 10 mm/s. Extrusion step parameters for both conventional extrusion and ShAPE are shown in Table 7. Changing the ram speed changes the extrusion speed based on the extrusion ratio.

Table 7. Input Parameters for the Extrusion Process Step for the Conventional Extrusion and ShAPE Models

Parameters	Conventional	ShAPE	Units
Extrusion energy consumption rate	47	11	kW
Extrusion station space requirement	100	100	mm^2
Extrusion line unplanned downtime	3	3	h/d
Extrusion line average die change time	30	30	min
Press line installation percent	25%	25%	%
Press line aux. equipment percent	25%	25%	%
Press line maintenance percent	10%	10%	%
Tool lifetime	1,524	1,524	m of parts
Equipment life	20	20	yr
Ram speed	1	6	mm/s
Extrusion exit speed	20	117	mm/s
Workers per line	1	1	n/a
Reject rate	1.0%	1.0%	%
Hydraulic oil volume	4,500	4,500	liter (L)
Dead cycle time (including upset and burp cycle)	12	12	s
Material loss percent (butt size)	10%	10%	%
Billet exit temperature	480	480	°C
Setup time	0.5	0.5	h
Tooling change time	2.0	2.0	h/change

2.5.3 Quenching

Once the material goes through the dies during extrusion, it gets hot and needs to be cooled using air or water. This step is called quenching. In our model, water is used as a cooling agent in the quenching step. Quenching parameters for both conventional extrusion and ShAPE are shown in Table 8.

Table 8. Input Parameters for the Quenching Process Step for the Conventional Extrusion and ShAPE Models

Parameters	Conventional	ShAPE	Units
Quenching motor	55.9	55.9	kW
Number of quenching	4.0	4.0	n/a
Total quenching motor	223.7	223.7	kW
Quenching footprint	10.0	10.0	m^2
Water usage	946.35	946.35	L/min
Pump pressure	1.724	1.724	megapascal (MPa)
Quench line installation	25%	25%	%
Quench line aux.	25%	25%	%
Quench line	10%	10%	%
Equipment life	20	20	yr
Workers per line	0	0	%
Reject rate	0.0%	0.0%	%
Material loss percent	0.0%	0.0%	%
Cooling rate	93.0	93.0	°C/s
Water recycling rate	95.0%	95.0%	%
Time of quenching	0.00143	0.00143	h/part
Target temperature	20.0	20.0	°C

2.5.4 Stretching

By placing a gripper on both ends of the material, the extrusion machine then stretches the material. By doing so, the piece is pulled straight by applying 1.6 t of force, which stretches the extruded part by 2%. Stretching parameters for both conventional extrusion and ShAPE are shown in Table 9.

Table 9. Input Parameters for the Stretching Process Step for the Conventional Extrusion and ShAPE Models

Parameters	Conventional	ShAPE	Units
Stretch force	1.6	1.6	t
Stretching footprint	15.0	15.0	m^2
Stretching power requirement	95.6	95.6	kW
Time to stretch per piece	100	100	s
Stretch installation percent	25%	25%	%
Stretch line aux. equipment percent	25%	25%	%
Stretch line maintenance percent	10%	10%	%
Equipment life	20	20	yr
Stretcher investment	$50,000	$50,000	$
Workers per line	0	0	n/a
Material loss	2.0	2.0	m

2.5.5 Cutting

After being stretched to 30,480 mm (100 ft), pieces get cut to the length that is needed for the final part 6.096 mm (20 ft). Cutting stage parameters for both conventional extrusion and ShAPE are shown in Table 10.

Table 10. Input Parameters for the Cutting Process Step for the Conventional Extrusion and ShAPE Models

Parameters	Conventional	ShAPE	Units
Sawing footprint	19.0	19.0	m^2
Cut time	0.2	0.2	min
Saw motor and hydraulic motor combined power	12.6	12.6	kW
Equipment life	20	20	yr
Workers per line	0	0	n/a
Material loss percent	0.50%	0.50%	%
Cuts per billet	0.9	0.9	n/a
Billets per year	56	56	n/a
Cuts per year	49	49	n/a
Saw blade replacement time	0.5	0.5	h
Operation air pressure	0.6	0.6	MPa
Oil consumption	0.1	0.1	L/min
Oil cost	2.0	2.0	$/L

2.5.6 Artificial Aging and Solution Treatment

Finally, the extruded aluminum is artificially aged. For this, the part or component gets heated to roughly 175°C for at least 4 h. During that time, the aluminum hardens. Artificial aging and solution treatment stage parameters for both conventional extrusion and ShAPE are shown in Table 11.

Table 11. Input Parameters for the Artificial Aging Process Step for the Conventional Extrusion and ShAPE Models

Parameters	Conventional	ShAPE	Units
Solution treatment temperature	465	465	°C
Solution treatment hold time	1.0	1.0	h
Precipitation treatment temperature	120	120	°C
Precipitation treatment hold time	24	24	h
Heating power requirement	65	65	kW
Hold temperature power requirement	0.0	0.0	kW
Heat time	6.0	6.0	h
Setup time	0.5	0.5	h
Aging installation percent	25%	25%	%
Aging line aux. equipment percent	25%	25%	%
Aging line maintenance percent	10%	10%	%
Workers per line	0	0	n/a
Material loss percent	0%	0%	%
Parts to age at one time	1,000	1,000	n/a
Equipment life	20	20	yr
Machine footprint	100	100	m^2
Parts per batch	1,000	1,000	n/a
Mass per batch	3,019	3,019	kg
Specific heat of aluminum	1,044	1,044	J/kg·°C

3 Economic Model

3.1 Minimum Sustainable Price

The minimum sustainable price (MSP) is the minimum price that a company would have to charge for a good or service to cover all variable and fixed costs and make sufficient profit to pay back investors at their minimum required rates of return (Goodrich et al. 2013). The MSP is computed by setting the net present value of an investment equal to zero with the internal rate of return equal to the weighted average cost of capital. The U.S. capital assets pricing model is used to derive these debt and equity ratios and weight them by their relative contribution to the overall capital structure of the firm to estimate weighted average cost of capital values (Ross, Westerfield, and Jordan 2009). The detailed NREL/Joint Institute for Strategic Energy Analysis methodology can be found in (Kurup et. al 2021).

The initial equipment and facilities expenditures are calculated over straight-line depreciation. The length of the calculation is set by the analysis period, and the discount rate is calculated from the required rates of return; the MSP is then derived by an iterative algorithm that runs until the net present value of the cash flows equals the total initial capital expenditure for the ShAPE model.

3.2 Discounted Cash Flow Analysis

Within the discounted cash flow (DCF), the analysis accounts for several considerations for manufacturing, such as capital cost; fixed operating costs (labor, depreciation, inflation and taxes, insurance, and rent); typical sales, general, and administrative (SG&A) expenses; typical design and engineering cost; inflation on cost of goods sold; and warranty coverage. Table 12 summarizes the input parameters for the DCF analysis. Three financial scenarios were used while calculating MSP. The low scenario estimates conservative research and development (R&D) expenses and SG&A expenses, which leads to a lower weighted average cost of capital. The mid scenario estimates business-as-usual, and the high scenario estimates aggressive R&D expense and SG&A expense.

Table 12. Financial Parameters and Inputs for Discounted Cash Flow (DCF) Analysis

Inputs for DCF Calculations	Low Values	Mid Values	High Values	Units
Inflation on cost of goods sold	3.0	3.0	3.0	%
SG&A expenses	5.0	10.0	15.0	%
R&D expenses	2.0	3.0	4.0	%
Corporate interest rate	3.3	3.3	3.3	%
Initial loan (or bond) maturity	10	10	10	yr
Corporate tax rate	30	30	30	%
Cost of equity	10.6	10.6	10.6	%
Cash flow analysis period	20	20	20	yr
Working capital collection period	10	10	10	yr
Calculated weighted average cost of capital	6.2	5.3	4.1	%
Working capital inventory turnover	4	4	4	yr
Working capital payable period	10	10	10	yr
CapEx initial target capital structure	50.0	64.0	75.0	%
Replacement equipment target capital structure	50.0	50.0	50.0	%
Depreciable life for plant	25	25	25	yr
Capital replacement loan maturity	10	10	10	yr
Equipment depreciation type	7-yr straight-line	7-yr straight-line	7-yr straight-line	n/a
Tooling depreciation type	7-yr straight-line	7-yr straight-line	7-yr straight-line	n/a
Building depreciation type	7-yr straight-line	7-yr straight-line	7-yr straight-line	n/a

4 Techno-Economic Analysis

Manufacturing techno-economic analysis (TEA) is applied for both conventional and ShAPE models, but MSP is calculated only in the ShAPE model by applying DCF. The reason for this is that the MSP assumptions and calculations apply to a single manufacturing facility producing one type of product using AA7075. In large commercial conventional extrusion facilities, many different products are manufactured using different aluminum alloys.

4.1 Conventional Extrusion and ShAPE Model Results

In the context of TEA, the conventional extrusion case has been analyzed at manufacturing volumes ranging between 10 t/yr and 400 t/yr. The base-case scenario for conventional extrusion with an extrusion speed of 20 mm/s and annual manufacturing volume of 50 t (which is equivalent to 78,189 extruded and cut parts, each 6.1 m [20 ft] long) has a manufacturing cost of $45/lb of product (Figure 8) and $57/part (Figure 9). The unit cost of manufacturing stabilizes at ~$41/lb of product and ~$52/part for an annual volume of manufacturing higher than 100 t. It is also important to highlight that these unit costs are based on a factory model with two shifts (8 hours each) and a production up-time of 85%.

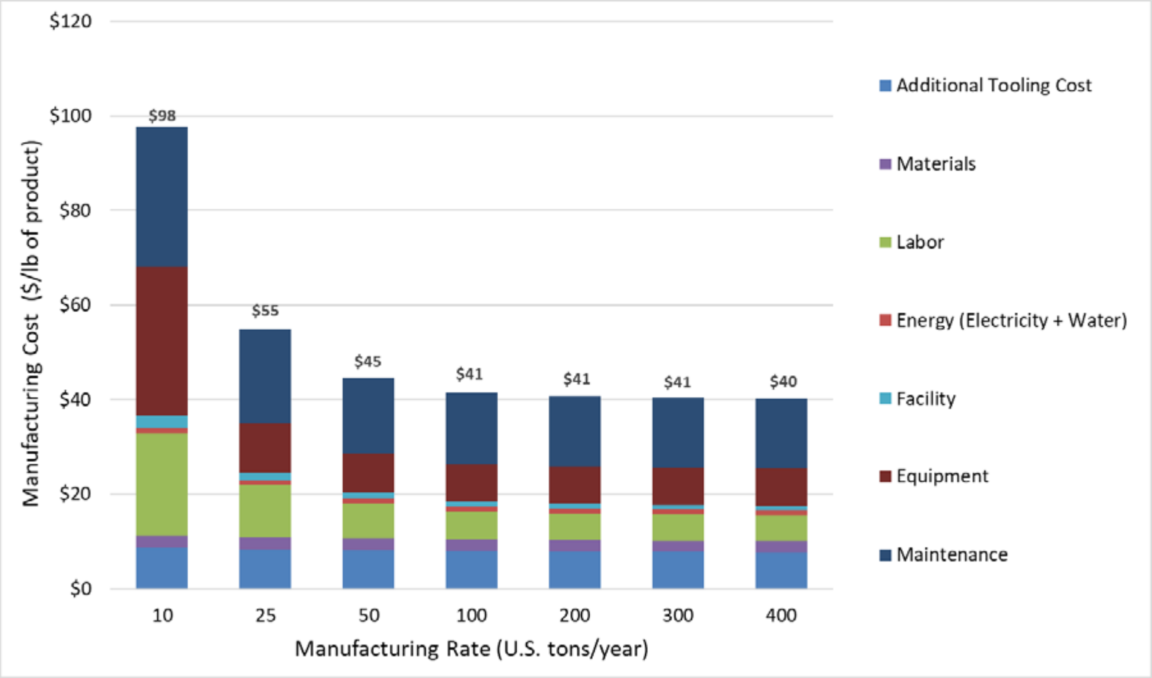


Figure 8. Manufacturing cost per pound of product for AA7075 for the conventional extrusion model with respect to different manufacturing volumes.

Factory model is set as two 8-h shifts with 85% production up-time.

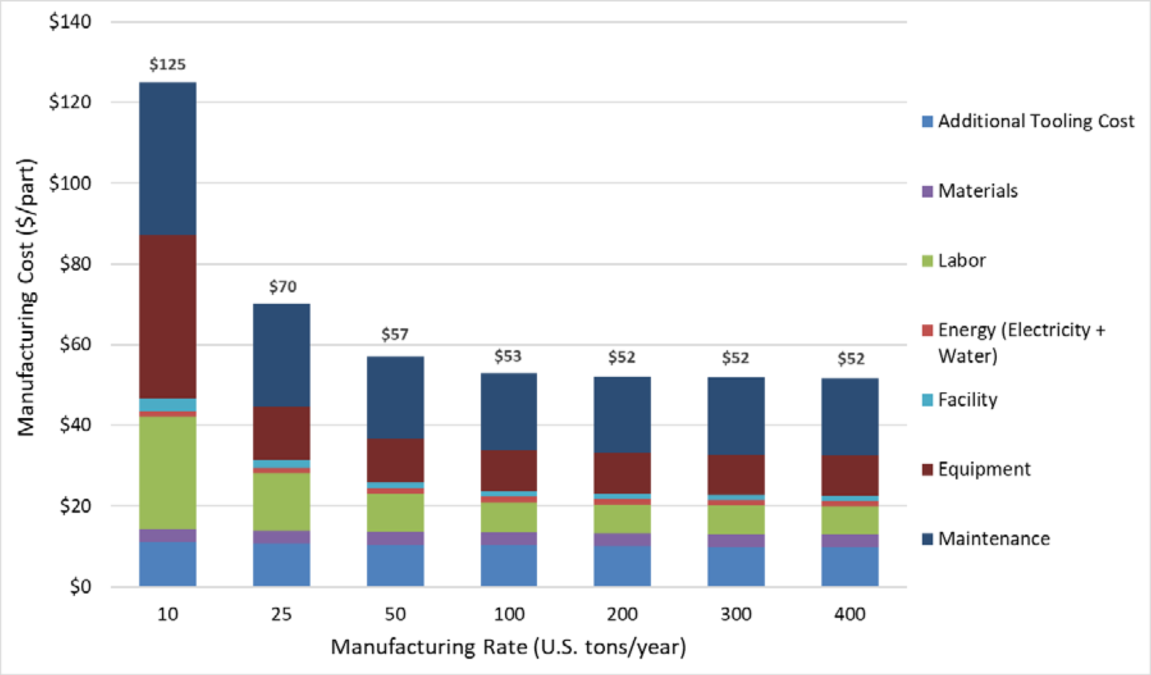


Figure 9. Results of manufacturing cost breakdown for AA7075 for the conventional extrusion model with respect to different manufacturing volumes.

Factory model is set as two 8-h shifts with 85% production up-time.

The base-case scenario for the ShAPE model with an extrusion speed of 117 mm/s and annual manufacturing volume of 50 t (which is equivalent to 78,189 extruded and cut parts, each 6.1 m [20 ft] long) has a manufacturing cost of $20/lb of product (Figure 10) and $26/part (Figure 11). The calculated MSP for the ShAPE base case ranges between $44/part and $50/part for the low, mid, and high financial scenarios. The unit cost of manufacturing stabilizes at ~$15/lb of product and ~$20/part for an annual manufacturing volume higher than 100 t. It is also important to highlight that the unit costs are based on a factory model with 2 shifts (8 hours each) and a production up-time of 85%.

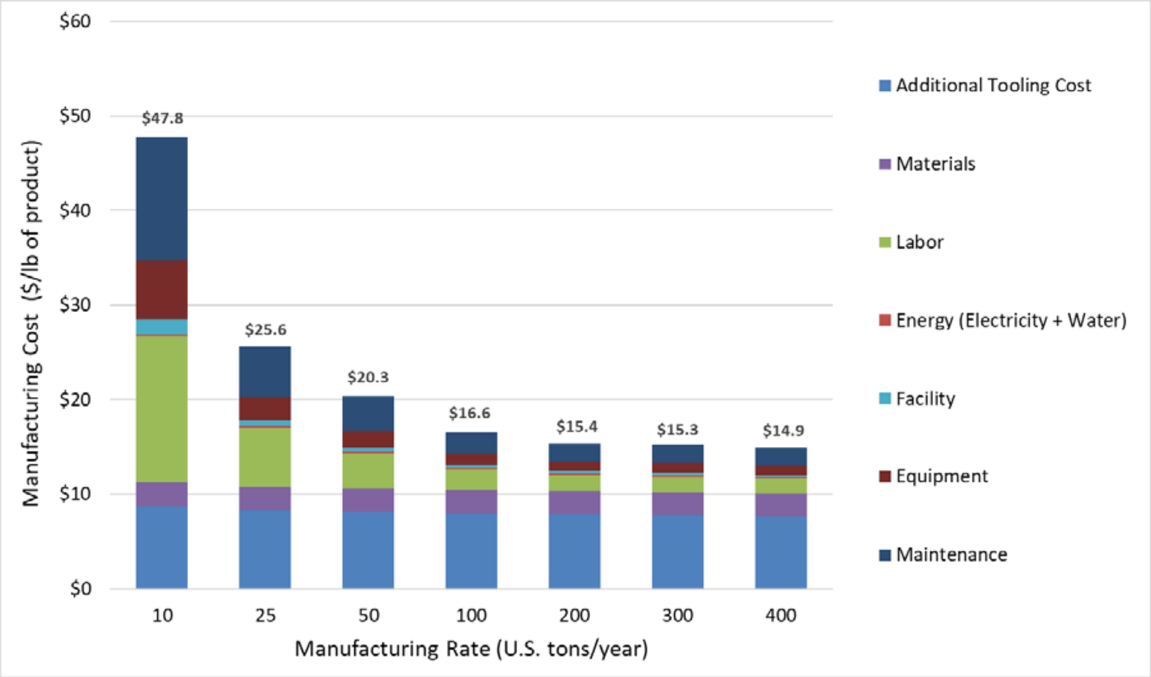


Figure 10. Manufacturing cost per pound of product for the ShAPE base-case model for AA7075 with respect to different manufacturing volumes.

Factory model is set as two 8-h shifts with 85% production up-time.

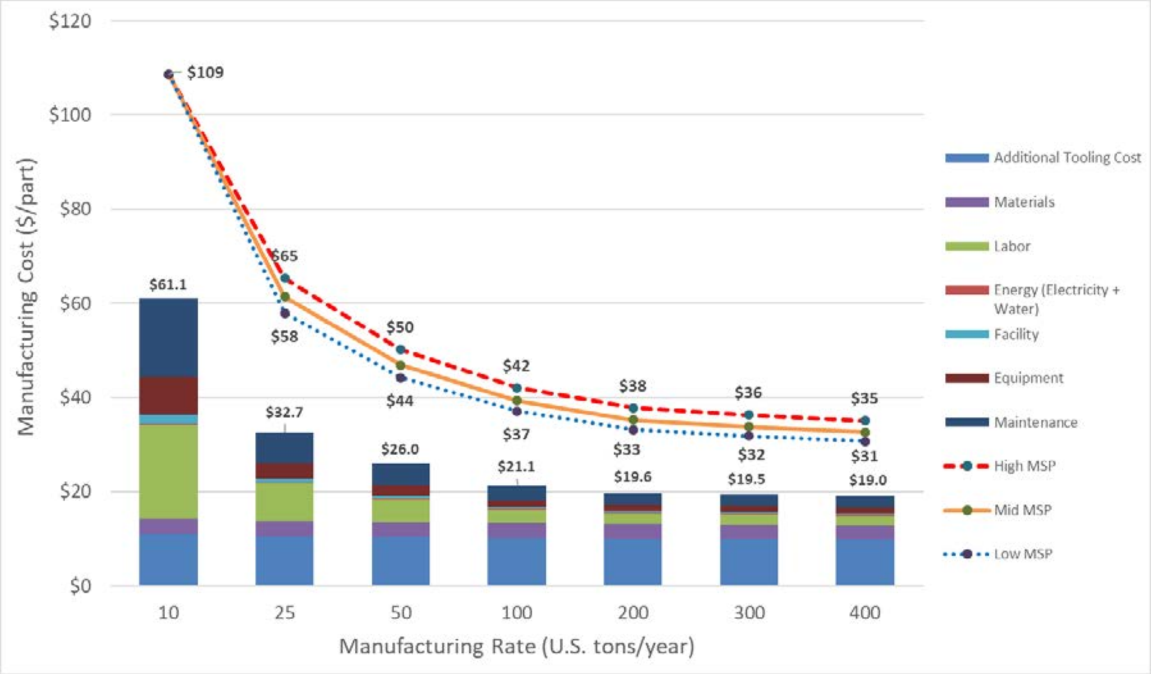


Figure 11. Results of manufacturing cost and minimum sustainable price (MSP) for the ShAPE base-case model for AA7075 with respect to different manufacturing volumes.

Factory model is set as two 8-h shifts with 85% production up-time.

The energy consumption breakdown per process step for the conventional model (Figure 12) shows that the most energy-consuming process is the extrusion itself, followed by preheating and stretching. On the contrary, the energy consumption breakdown per process steps of the ShAPE base-case model (Figure 13) shows that stretching is the most energy-consuming process, followed by extruding, because there is significant energy savings from the ShAPE machine. The third most energy-consuming step is the artificial aging and solution treatment.

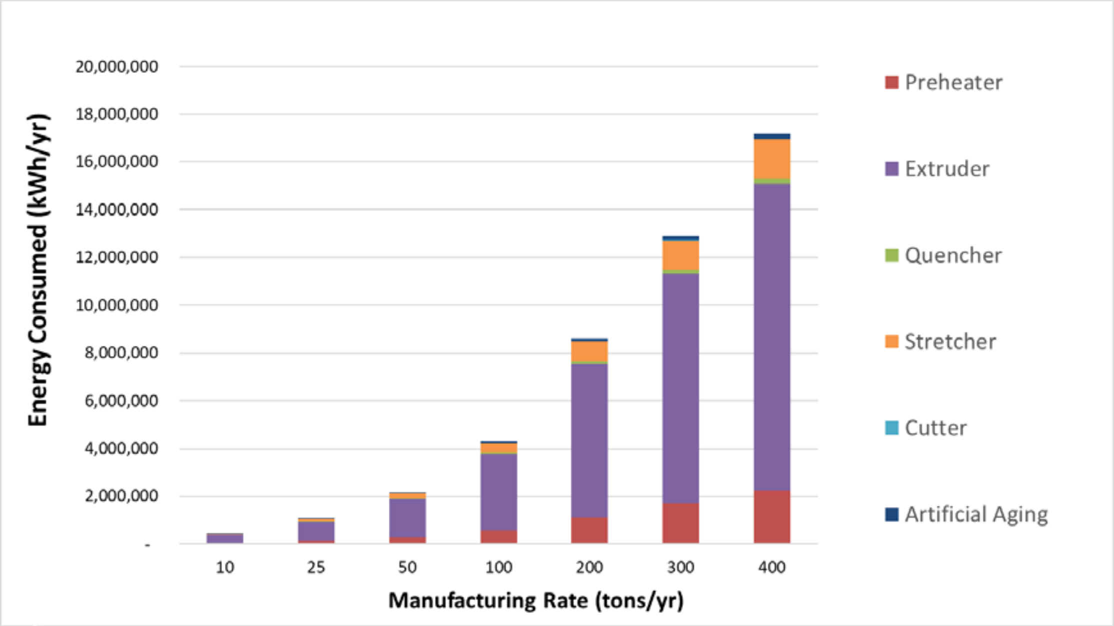


Figure 12. Energy consumption per process step for the conventional model with respect to different manufacturing volumes.

Extrusion speed is set to 20 mm/s.

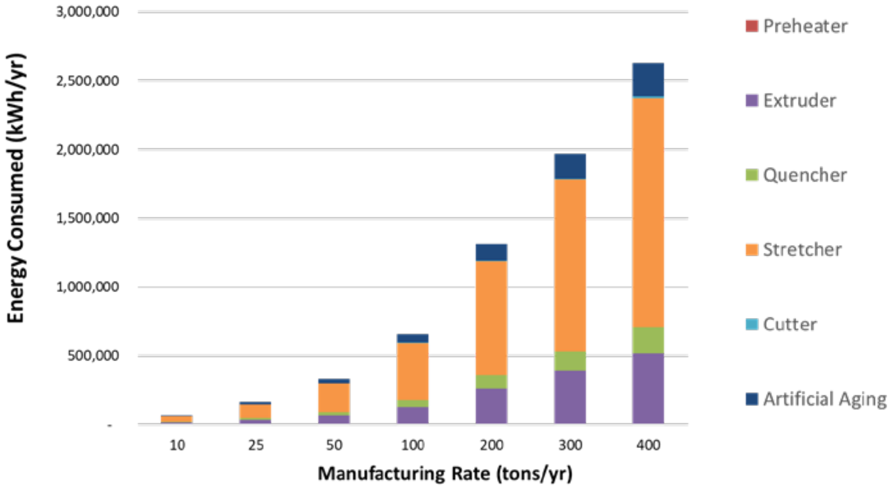


Figure 13. Energy consumption per process step for the ShAPE base-case model with respect to different manufacturing volumes.

Extrusion speed is set to 117 mm/s.

4.2 ShAPE Energy Savings Comparison

The total energy consumption of the conventional extrusion model with an extrusion speed of 20 mm/s and an annual manufacturing volume of 50 t is ~2,150,000 kWh/yr, in which the extruder constitutes ~75% of the total energy consumption (Figure 14). The total energy consumption of the ShAPE model at the same extrusion speed and manufacturing volume as the conventional model is only ~376 MWh/yr, in which the extruder constitutes ~58% of the total energy consumption (Figure 14). Compared to conventional extrusion for an extrusion speed of 20 mm/s, the ShAPE production of 50 t potentially uses 70% less total energy.

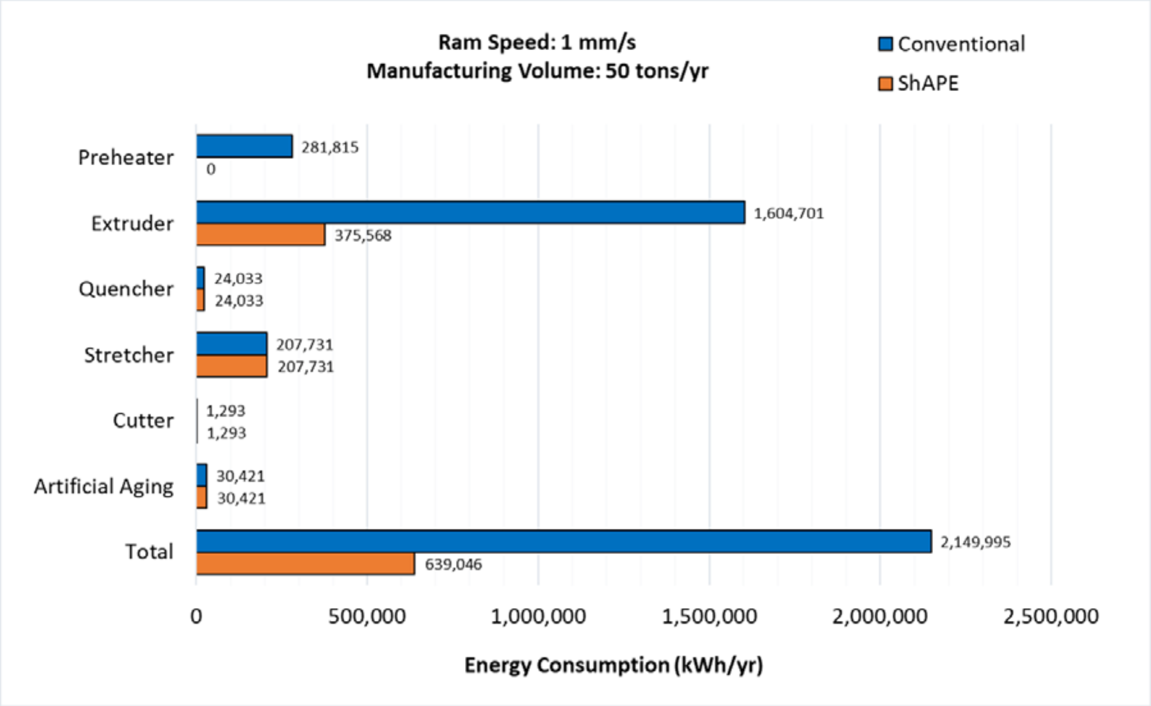


Figure 14. Comparison of energy consumption or process steps in conventional extrusion and ShAPE at a manufacturing volume of 50 t/yr

Extrusion speed is set to 20 mm/s for both cases.

The ShAPE model with an extrusion speed of 20 mm/s provides ~70% savings in energy consumption in overall processes, with an energy intensity of 12,800 kWh/yr/t. Conventional extrusion has an energy intensity of 43,000 kWh/yr/t when the extrusion speed is set to 20 mm/s. This is mostly from significant energy savings in the extrusion step and elimination of the preheating step. The energy savings is even higher in the extrusion process. The ShAPE base-case model provides ~76% energy savings when the extrusion speed is increased to 117 mm/s. Figure 15 shows the comparison of total energy consumption between the conventional extrusion and ShAPE models at different manufacturing volumes, and Figure 16 shows energy consumption for only the extrusion step at different manufacturing volumes.

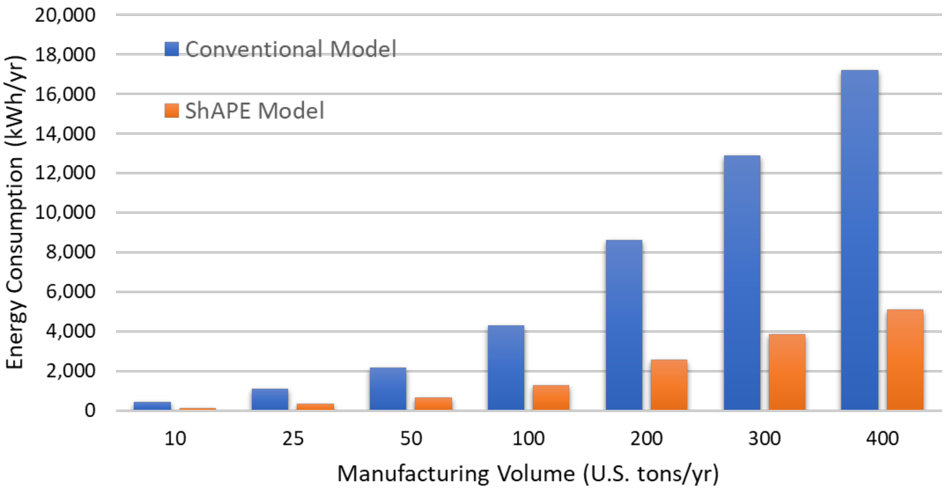


Figure 15. Comparison of total energy consumption between the conventional extrusion and ShAPE models.

Extrusion speed is set to 20 mm/s for both cases.

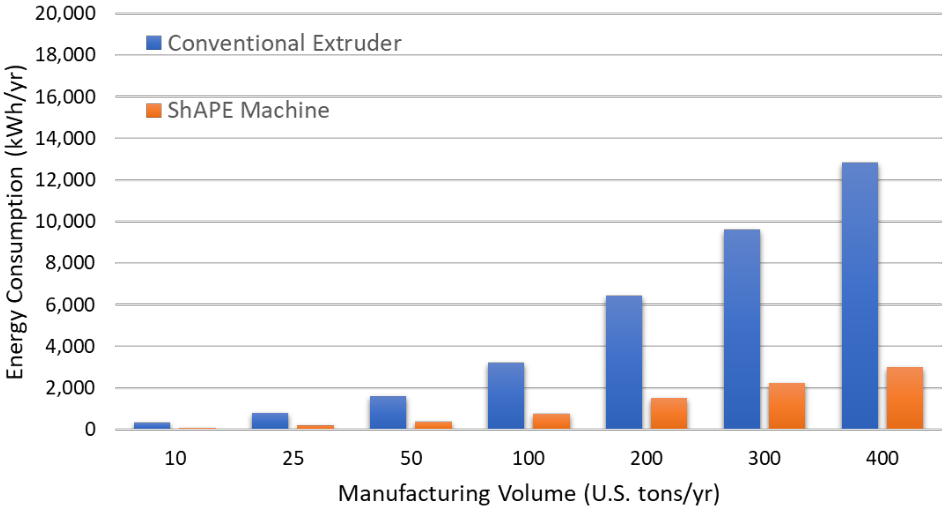


Figure 16. Comparison of energy consumption between the conventional extruder and ShAPE machine.

Extrusion speed is set to 20 mm/s for both cases.

The thermal power required to homogenize one billet is calculated as 0.91 kWh (0.26 kWh/kg) which is equivalent to ~4% of the total energy requirement per extrusion with the ShAPE model base-case scenario.

4.3 Additional TEA Scenarios

Four additional manufacturing scenarios have been defined in addition to conventional extrusion and the ShAPE base case by making slight variations in the raw material cost, billet homogenization stage, extrusion speed, ram speed, billet preheating, artificial aging step, and solution heat treatment stage (Table 13). The billet inner and outer diameters, final product length, and annual volume of manufacturing (50 t/year) have been kept constant for all scenarios to compare results on the same scale.

Billet preheating is only required in the conventional model. In other ShAPE scenarios, the preheating step is excluded. The impact of unhomogenized billets is reflected in a 10% price discount for raw material in the cost model. This discount has been received through communications with Kaiser. The thermal energy needed to homogenize the billet can be calculated as described in Section 2.3.1.

Table 13. Model Specifications for Scenarios To Test the Manufacturing Cost Model

	Conventional	ShAPE Base Case	ShAPE Scenario 1	ShAPE Scenario 2	ShAPE Scenario 3	ShAPE Scenario 4
Manufacturing volume	50 t/yr	50 t/yr	50 t/yr	50 t/yr	50 t/yr	50 t/yr
Homogenized billets	Yes	Yes	Yes	No	No	No
Billet cost	$5.46/kg	$5.46/kg	$5.46/kg	$4.91/kg	$4.91/kg	$4.91/kg
Part diameter inner/outer	10/12 mm	10/12 mm	10/12 mm	10/12 mm	10/12 mm	10/12 mm
Final product length	6.01 m	6.01 m	6.01 m	6.01 m	6.01 m	6.01 m
Ram speed	1 mm/s	6 mm/s	1 mm/s	6 mm/s	6 mm/s	10 mm/s
Extrusion speed	20 mm/s	117 mm/s	20 mm/s	117 mm/s	117 mm/s	195 mm/s
Billet preheating	On	Off	Off	Off	Off	Off
Artificial aging time	24 h	24 h	24 h	24 h	10 h	24 h
Solution heat treatment	On (2 h)	On (1 h)	On (1 h)	On (1 h)	On (0.75 h)	Off

The test scenario results show that ShAPE can be 55% cheaper and 85% more energy-efficient than conventional extrusion because of high extrusion speed (117 mm/s), elimination of the preheating stage for billets, low investment cost, and higher energy efficiency. Even if the ShAPE model had a lower extrusion speed (20 mm/s) like that in Scenario 1, the manufacturing cost is 55% lower and 70% more energy-efficient than the conventional extrusion (Figure 17). Using unhomogenized billets and high-speed extrusion (10 mm/s) and removing the solution heat treatment stage in Scenario 4 increases savings for the ShAPE model—60% by cost and 85% by energy—with respect to conventional extrusion.

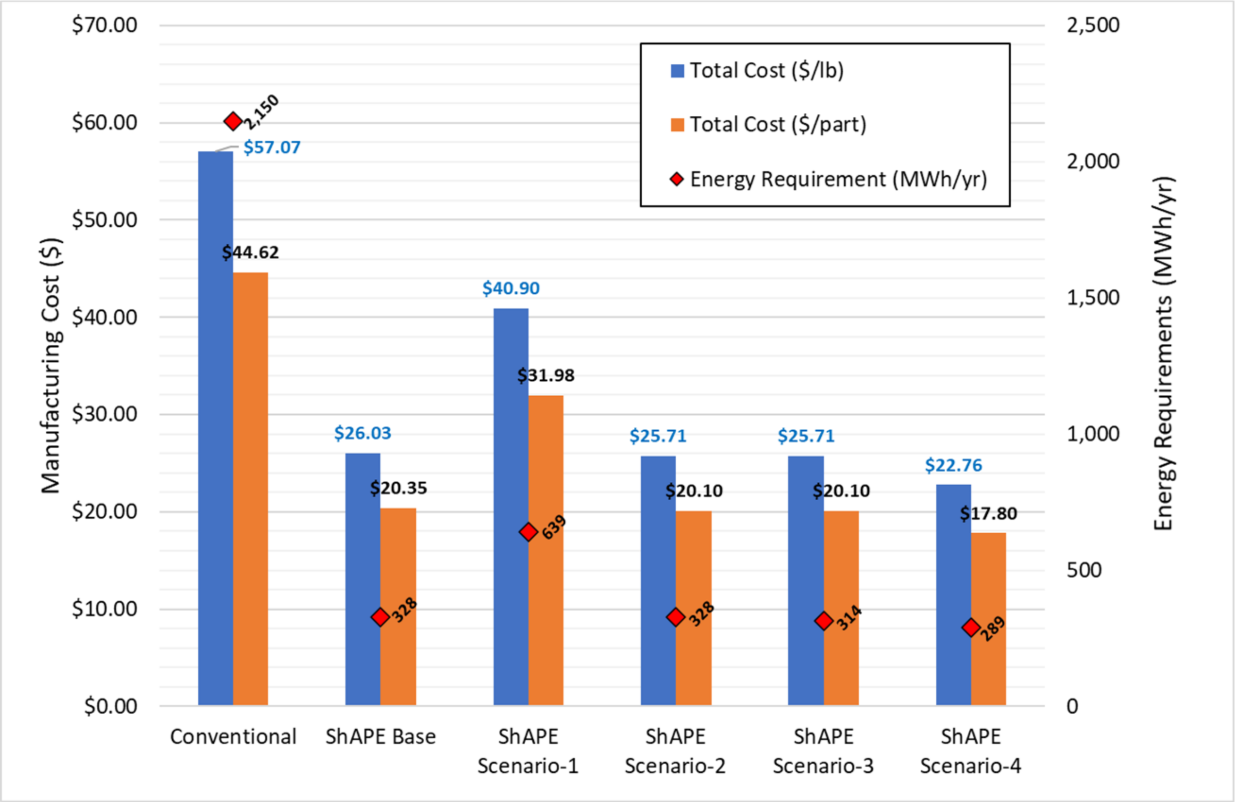
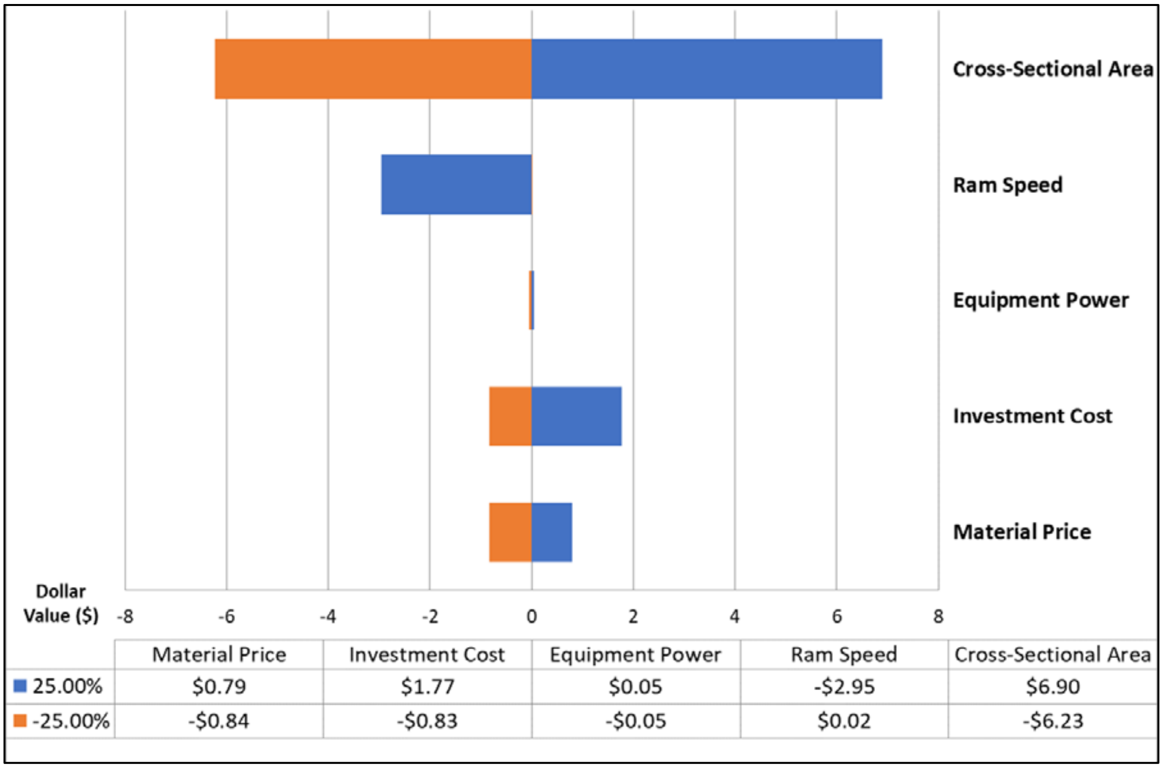


Figure 17. Comparison of total manufacturing cost and energy requirements for the conventional extrusion and ShAPE scenarios

4.4 Sensitivity Analysis for Base-Case Scenario (50 U.S. tons/yr)

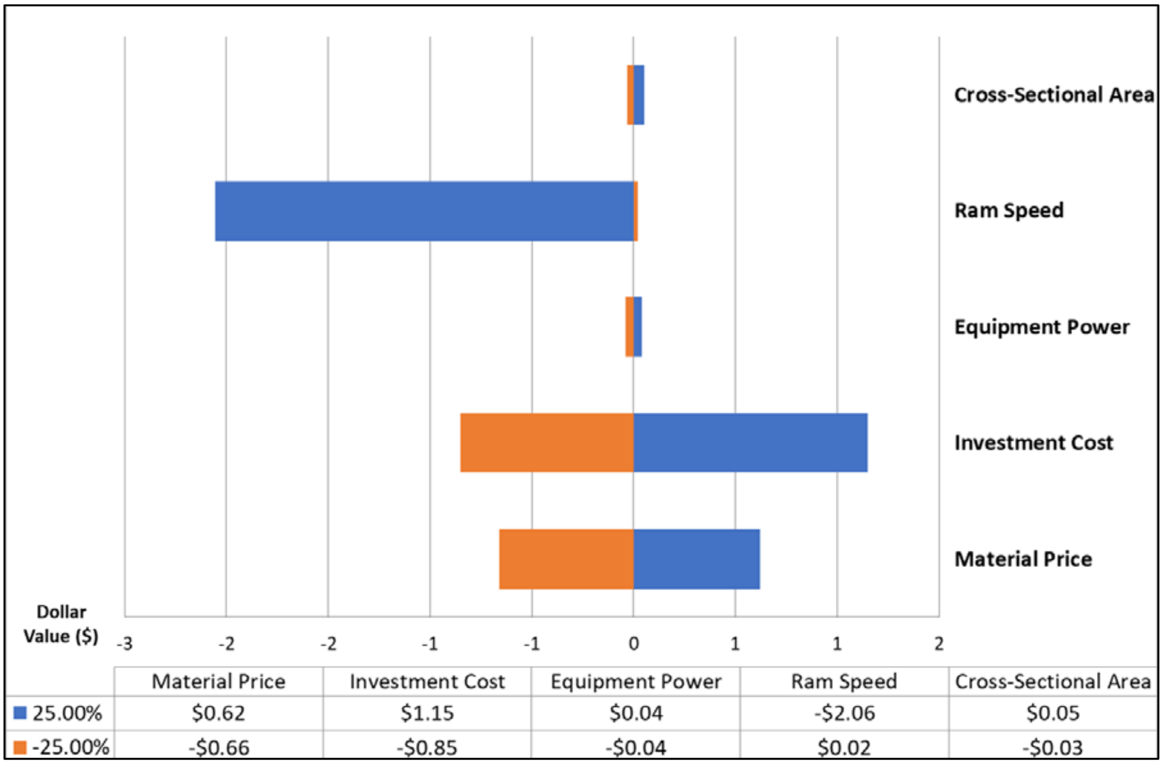
A sensitivity analysis is done by varying the material cost, investment cost, equipment power, extrusion speed, ram speed, extruded part length, and billet length by 25% and showing the impact on manufacturing cost per extruded part (Figure 18) and manufacturing cost per pound of extruded product (Figure 19). The total manufacturing cost for the ShAPE base-case model at a manufacturing volume of 50 t/yr is $26 per extruded part and $20/lb of product. The sensitivity results show the deviation from this baseline cost.

The results of the sensitivity analysis showed that the billet length and extruded part length are the most sensitive parameters, as shown in Figure 18. Also, the part length has the opposite effect on cost per extruded part versus cost per pound of extruded product. Another important parameter is the extrusion speed, which is dependent on the ram speed. Whereas the effect of a 25% increase in extrusion speed is significant in cost per part, a 25% decrease does not have the same magnitude of impact. Extrusion speed in the ShAPE model can range between 20 and 195 mm/s. A 25% increase in investment cost and equipment power are showing up to 3% change on the unit cost per part for 50 t/yr manufacturing volume. Based on the sensitivity analysis results, the material price is found to be the least sensitive parameter within a range of ±25%. A significant manufacturing cost drop could be expected if the billet price could drop by 80% by using secondary scrap material.



	Material Price	Investment Cost	Equipment Power	Ram Speed	Cross-Sectional Area
🟦 25.00%	$0.79	$1.77	$0.05	-$2.95	$6.90
🟧 -25.00%	-$0.84	-$0.83	-$0.05	$0.02	-$6.23

Figure 18. Sensitivity analysis for ShAPE manufacturing cost per extruded part at a manufacturing volume of 50 t/yr



	Material Price	Investment Cost	Equipment Power	Ram Speed	Cross-Sectional Area
🟦 25.00%	$0.62	$1.15	$0.04	-$2.06	$0.05
🟧 -25.00%	-$0.66	-$0.85	-$0.04	$0.02	-$0.03

Figure 19. Sensitivity analysis for ShAPE manufacturing cost per pound of extruded product at a manufacturing volume of 50 t/yr

4.5 Environmental and Subsidiary Impacts of ShAPE

The TEA and detailed manufacturing analysis focused on the speed, cost, and energy benefits of the ShAPE process and PNNL's current system. There are several environmental benefits and impacts that are worth highlighting as well.

At present, conventional extrusion machines require a preheat step prior to extrusion (Table 13). Based on the research conducted at PNNL, all the modeled scenarios for ShAPE exclude the preheat step. The first minor impact of removing the preheat step leads to a floorspace savings of ~50 m^2 for new manufacturers that could omit the preheating station. Much more significant impact of removing the preheat step for ShAPE production leads to a large energy savings (e.g., 281.8 MWh for 50 t/year of production at an extrusion speed of 20 mm/s, as shown in Figure 14). Whereas this does not lead to a significant cost impact because of the cost of electricity in the product, the energy savings do convert to emissions savings. The U.S. average carbon dioxide (CO_2) emissions of electricity consumed is 0.92 lb/kWh (EIA 2020b). Removing the preheat step alone, using the U.S. average emissions factor, leads to a potential CO_2 savings of approximately 259,270 lbs, which is equivalent to nearly 118 t of CO_2. When the 70% total energy savings of the conventional base case and Scenario 1 for ShAPE (1 mm/s) is considered (i.e., 2,150 MWh/yr compared to 639 MWh/yr as in Figure 14), the relative CO_2 savings could be approximately 593,400 lbs, or 269 t.

The net-generation of electricity in Texas was approximately 483,201,031 MWh in 2019 (EIA 2020a), and the CO_2 emissions in 2019 from the electricity generation sector were approximately 202.3 million metric tons (EIA 2021), leading to an emissions factor of approximately 1.083 CO_2 lbs/kWh. This is similar to the U.S. Southwest for 2019, which had an emissions factor or 1.093 lbs/kWh (Xcel Energy 2019). Therefore, in Texas, a ShAPE manufacturing plant producing 50 tons of AA7075 per year at an extrusion speed of 1 mm/s, could produce an estimated 692,086 lbs (314 t) of CO_2. This would be considerably less than the estimated 2.3 million lbs (1,056 t) of CO_2 emissions if the conventional extrusion case is used.

As highlighted, unhomogenized or as-cast billets can be used in ShAPE, therefore leading to further energy and emissions savings, because the furnace emissions would also be negated prior to the billet extrusion steps. Typically, large homogenization furnaces use natural gas (Otto Junker n.d.), which would have much greater emissions than an electrical resistance furnace as described in Section 2.2.1.

Another key change in the extrusion process is the potential use of waste or recycled material as feedstock for the billets. ShAPE tests at PNNL have used waste scraps of AA7075 and then extruded with similar material characteristics as virgin extruded material (Whalen, Reza-E-Rabby, Taysom, et al. 2021). For many aluminum extruders, the waste or scrap metal is an added cost (e.g., having to transport the scrap off-site). If, for example, scrap AA7075 can be used, the billet or feedstock cost can be reduced significantly, potentially by 50%. In the ShAPE base case, reducing the cost from \$5.46/kg to \$2.73/kg for 50 tons of extruded parts per year would change the cost of the manufactured product. The \$26.03/lb of manufactured cost for the ShAPE base case (as in Figure 17) could then become \$23.30/lb (~10% reduction). The reduction from using the waste material would also lead to a reduction in the initial production of the virgin material.

5 Model Validation

Efforts have been made to validate as much of the TEA as possible. Power requirements for machines and processes have been validated with PNNL. Costs for certain items (e.g., the cost of the as-cast billets) were obtained through communications with Kaiser.

The DFMA model has mostly similar input values when compared to the conventional model (Table 14). DFMA uses homogenized billets as material. One of the key parameters that needs to be validated is the homogenous billet price. DFMA can model up to 1-m-long extruded parts using specific extrusion machines in its machine library. In DFMA, the optimal billet preheat temperature is 381°C, the maximum surface exit temperature is 465°C, the required press force for conventional extrusion is 52.96 meganewtons (MN), the optimal exit speed is 0.019 m/s, and the optimal extrusion speed is 19 mm/s.

Table 14. Summary of Process Validation via Design for Manufacture and Assembly (DFMA)

Parameter	Conventional – ShAPE	DFMA	Units
Material type	Aluminum 7075	Aluminum 7075	n/a
Aluminum billet price	5.46	5.46	$/kg
Final part length[a]	5,974	1,000	mm
Part outer diameter	12	12	mm
Part inner diameter	10	10	mm
Part cross-section area	35	35	mm^2
Billet length	1,480–1,560	1,300–1,600	mm
Ram speed	1–10	1.52	mm/s
Extrusion exit speed	20–126	19	mm/s
Billet exit temperature	480	465	°C
Billet scrap percent	10	10	%
Dead cycle time	21	12	s
Solution soak temperature	465	477	°C
Solution soak time	1.0–2.0	1.5	h
Aging temperature	120	120	°C
Aging time	24	24	h

[a] Final part length is after the cutting step

6 Discussions

The NREL model and analysis undertaken for conventional and ShAPE extrusion scenarios assumes electric heating rather than natural gas for areas like the homogenization furnace and the preheater. It is important to note that natural gas or electricity can be used for heating the aluminum billets (e.g., for homogenization and the preheater) (Otto Junker 2021). The focus for the report is electricity, primarily because a new conventional or ShAPE manufacturing facility is likely to be electrically driven. Electric batch-homogenization furnaces, for example, are approximately 83% efficient, compared to direct fuel-fired furnaces, which have an efficiency of 61%–72% (Valder 2010). There was high industrial natural gas price volatility in 2020 and 2021 (EIA 2019), compared to electricity rates paid by industry and manufacturers (EIA 2020a). As such, for the analysis, we avoided the significant price volatility of natural gas by modeling electricity prices.

The manufacturing model for billets can model conventional and ShAPE AA7075 scenarios and at present uses a default and constant electricity price of \$0.05/kWh. This is representative of the manufacturing facility based in Texas (EIA 2020a). Partly as a result of the availability of abundant energy, Texas has significant aluminum processing and production. For example, in 2017 the Hydro Aluminum group built a 55-t homogenization furnace, and the Commerce Texas site processes ~100,000 t of scrap aluminum into extrusion billets (Sagermann 2017). As such, Texas is a suitable location choice for the model. While Texas is known as a significant natural gas user, it has also shown nearly a 200% increase in wind generation in the last decade (Marshall and Thompson 2019). Therefore, Texas represents a state where the renewable energy portion in the grid is reducing the carbon emissions. The varying energy price for industrial end users will affect the cost per part or cost per pound, though as shown in the sensitivity analysis, electricity prices are not the biggest cost driver for conventional or ShAPE extrusions. As such, the use of a constant electricity price is suited for providing a temporary snapshot of a product's manufactured cost.

The outlined analysis did not consider carbon prices, social impact, and the negative externalities associated with production. The current price of carbon emissions is \$17.41/t for California (International Carbon Action Partnership 2021). With the likelihood of future carbon emissions penalties or costs, the cost of conventional or ShAPE extruded products could increase. This requires further investigation to gauge the specific impact of a carbon tax based on the state in question. As highlighted, conventional and ShAPE extrusion of 50 t/yr of AA7075 at 1 mm/s could lead to 1,056 and 314 t of CO_2 emitted, respectively. This could then lead to an additional CO_2 cost of approximately \$18,400 per year for conventional and \$5,500 per year for ShAPE, or approximately \$370/t or \$109/t, respectively, of extruded product. This is a significant potential impact on manufacturing in the future, though it will be state-dependent, and at present Texas would not be affected. If aluminum extruders faced penalties in the future for carbon emissions, the potential to use ShAPE may also improve from both energy and emissions perspectives.

The environmental impacts and carbon intensity for the electricity consumed by a manufacturing facility will be dependent on the state and local grid-generation profiles. For example, in 2019 Austin had a carbon intensity of 0.739 lbs/kWh (City of Austin n.d.), approximately 32% less than the Texas average of 1.083 lbs/kWh. Thus, the selection of Austin could lead to reductions in the CO_2 emitted in the manufacturing process. At present, we have assumed the electricity for a manufacturing facility will come from the grid, but it is possible that a site could generate significant amounts of its electricity needs via combined heat and power. The CO_2 emissions would be impacted by the combined heat and power fuel.

With rapid future decarbonization of the power sector, the state and local grids will change over time, particularly with increased renewable penetration. It is likely the United States and state-level carbon intensity factors will improve. The 2020 NREL Standard Scenarios developed by Cole et al. (2020) highlights analysis of hundreds of potential United States grid simulations and capacity additions, which could lead to variable renewable energy sources like wind and solar photovoltaics generating 32% of U.S. needs by 2030, and 55% of U.S. needs by 2050 (Cole et al. 2020). Texas follows a similar grid change with increasing renewables and reductions in CO_2 emissions. For example, in the NREL Standard Scenarios, it is estimated that by 2050, 75% of Texas' electricity could be generated by variable renewable energy sources compared to 28% today (NREL 2021). Reducing the carbon intensity over time will lead to improved carbon intensity factors; therefore, electrically driven manufacturing processes like ShAPE are likely to benefit and see increased adoption.

The ShAPE model built and analyzed for this report is based on PNNL's current extrusion machine, and future improvements and research directions have not been captured. The NREL team have worked closely with PNNL to apply the current parameters. There are future improvements being worked on at PNNL that include direct quenching of the extruded parts as the material exits the ShAPE machine. The next version of the ShAPE machine is also likely to increase in size to allow for larger-diameter tubes to be extruded (Sikirica et al. 2021). The next generation of the ShAPE machine will be important to model.

At present, the ShAPE model assumes that the straightness of the extruded 100-ft parts is the same as conventional extrusions. There is no evidence to substantiate whether the extrusions are straighter, and so the same straightening process and energy are used after the extrusion step for ShAPE. It is known that ShAPE test samples have produced mechanical properties of extruded AA7075 that are comparable, and in many cases better than, conventional extrusions. For example, tests on as-cast billets have shown a 5% improvement in the ultimate tensile strength and a 50% increase in elongation than conventional AA7075 using homogenized billets (Sikirica et al. 2021). Current testing at PNNL has focused on the extrusion properties rather than the whole modeled process. If the ShAPE process improved the mechanical properties and needed less straightening, there could be further energy reduction in the produced products. This needs further investigation.

The analysis highlighted a rough estimation of the energy for homogenizing the billets used 50 t/yr of manufacturing. The estimated value of 0.91 kWh per billet (0.26 kWh/kg), assumed a single 55-t-batch furnace, and that all 15,637 billets could be homogenized simultaneously. This is for a very large facility, and it is likely that a dedicated AA7075 producer (either conventional or, if needed, ShAPE) may not have access to such a large furnace. It is likely that smaller batches would be homogenized, such as a 3-t homogenization furnace (Valder 2010), and so 20 batches would be needed. This would considerably increase the homogenization energy needed for conventional extrusions. The current ShAPE scenarios account for the as-cast billet and the removal of the homogenization with a 10% cost-per-kilogram savings per billet. The current manufacturing and cost model for conventional and ShAPE processes does not consider the homogenization step, and as such can be added to in the future.

Although work was undertaken on developing a ShAPE model that could use powder or scrap, this report has reported the billet extrusion results. The use of scrap (if, for example, it could reduce the billet cost by 50%) could lead to a 10% reduction in overall cost per pound of product. Investigation with PNNL will be needed on the quantity of scrap AA7075 that can be used as part of the feedstock used to produce extruded ShAPE components, though the increase in scrap is likely to further reduce the cost per part.

7 Conclusions

NREL worked with PNNL to undertake the TEA and manufacturing cost analysis of the innovative ShAPE process and extrusion machine. Here, we include some key conclusions.

ShAPE has the potential to be significantly less energy-intensive and less costly for small and large volumes of AA7075 manufacturing than conventional extrusions. The analysis revealed that the base case for ShAPE could use ~76% less energy than conventional AA7075 extrusions at 1 mm/s. With a 50 t/yr production capacity for both the conventional and ShAPE base case, the ShAPE product could potentially be ~54% cheaper ($26.03/lb compared to $57.07/lb). But this cost differential assumes that ShAPE production systems could meet the modeled costs. Large conventional manufacturers will vary the product cost based on the demands in the markets and orders received. ShAPE will need to prove the potential energy, cost, and speed savings in commercial settings.

With the growing prominence of lightweighting for the automotive industry (DOE 2017) and the need to address climate concerns, aluminum manufacturing and extrusion is likely to see continued growth in the future. The use of 7000 series aluminum extruded parts for the automotive industry is estimated to grow with a compound annual growth rate of 5.8% from 2021 to 2031 (Persistence Market Research 2021), reaching an estimated global market value of $93 billion by 2031. AA7075 will likely be important not only for the automotive industry but for other sectors like aviation. With a developed ShAPE process, commercially available machines that prove that low cost, low energy, and very fast extrusions meet and exceed current standards could help open the 7000 series alloys to other applications typically where 6xxx series alloys are used today. ShAPE can also extrude much simpler 6xxx series aluminum as well. Future analysis can consider 6000 series and new markets that could open with a reduced cost of 7xxx series extrusions.

Today’s ShAPE machine is available from Bond Technologies. This machine can extrude materials with very fine grain structures and low energy input, and it can use scrap or low-grade material like chips and swarf (Bond Technologies n.d.). The next generation of the ShAPE machine (i.e., ShAPE 2.0) will have increased torque and force capacity that will enable larger-diameter extrusions at a more industry-relevant scale. In 2019, PNNL, as part of a competitive process, was awarded a Clean Energy Grant to develop ShAPE 2.0 for processing magnesium and other lightweight alloys (Washington State Department of Commerce 2019).

Future improvements in TEA modeling could account for a powder model, different aluminum alloys, various sizes of machines, and the next generation of the ShAPE machine. It is vital for future validation efforts to work with industry partners to determine and validate key conventional extrusion parameters. For example, by working with large and midsized aluminum extruders, improved machine characteristics could be modeled. The focus has been on creating an extrusion model that could provide insight for the ShAPE system. Future efforts will be needed to validate the ShAPE model with a manufacturing facility utilizing the ShAPE machine in real production runs.

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