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CHANGING WHAT'S POSSIBLE

METALS Program Overview

B. PROGRAM OVERVIEW

This program seeks to fund transformative new technologies for the primary processing of light metals (Al, Mg, and Ti) and for their cost effective, domestic recycling. These metals are widely viewed as essential to achieving substantial energy savings and reduced carbon emissions through lightweighting in both automotive and aircraft applications; however their widespread adoption will only be realized when they are produced with lower costs, less energy consumption, and reduced carbon emissions so that they are competitive with incumbent structural metals - steel and stainless steel. Of particular interest to primary light metal production are integrated system approaches that allow for one or more of the following operational characteristics: variable energy inputs (including renewable energy), high temperature heat recovery, high temperature thermal storage, and use of domestically abundant ores. Of particular interest to light metal recycling are transformative technologies and processes that enable rapid, high precision, and automated sorting of metals and alloys that are or can be integrated with high efficiency secondary light metal production. Innovative concepts focused on energy intensive and/or high cost stages of both the primary and secondary production processes will also be considered.

The impact of technologies successfully emerging from the program will be to provide substantial benefits germane to the ARPA-E mission, including reduced domestic energy consumption, reduced emissions, and a technological lead in advanced light metal production technologies. These technologies could have both a transformative and disruptive impact on the global structural metals market.

1. BACKGROUND

The light metals Aluminum (Al), Magnesium (Mg), and Titanium (Ti) have the potential to play a significant enabling role in future energy savings across a wide range of applications, including but not limited to: transportation, power production, industrial processing, and structures [1-3]. The high strength-to-weight ratios of these metals means that their use in automotive manufacturing produces more fuel efficient vehicles with no reduction in performance or safety. Titanium has superb native corrosion resistance, while aluminum is typically alloyed with magnesium to give it more ductility, weldability, and corrosion resistance. As shown in Table 1, aluminum and magnesium have strength-to-weight ratios of 130 kNm/kg and 158 kNm/kg, whereas that of steel is 38 kNm/kg. Their respective costs of $2.00/kg and $3.31/kg, as compared to steel at $0.47/kg, indicate that cost is a barrier to adoption in many applications [2,4-7]. Similarly, as shown in Table 2, titanium has the potential to compete with 304 stainless steel in many applications, where the respective strength-to-weight ratios are 120 kNm/kg and 77 kNm/kg. However at comparative costs of $9.00/kg (Ti sponge powder) and $2.40/kg [8-11], cost is also a barrier. In order to achieve the large energy reductions that is possible with greater use of magnesium and aluminum, the primary processing of light metals must reach parity with steel on cost, energy consumption, and CO_2 emissions. Radical new approaches to the processing of light metals are needed to reach parity with steel (Mg and Al) and stainless steel (Ti).

Table 1: Strength, energy, emissions, cost, and density for aluminum, magnesium, and steel [4-7].

	Aluminum	Magnesium	Steel
Strength-to-Weight Ratio (kNm/kg)	130	158	38
Processing Energy* (kWh/kg)	*Hall-Heroult*: 56	*Western Electrolytic:* 43.6 *Pidgeon Process*: 102	6.4
Theoretical Minimum Energy (kWh/kg)	*7.5*	*5.8*	2.4
Emissions ($kgCO_2/kg$)	*Hall-Heroult:* 22	*Western Electrolytic:* 6.9 *Pidgeon Process:* 37	2.3

Domestic Production Cost ($/kg)	2.00	3.31	0.47
Density (kg/m^3)	2700	1800	7870

*Please see Section IX (Glossary) for definition of Processing Energy.

Table 2: Strength, energy, emissions, cost, and density for titanium and stainless steel [8-11].

	Titanium	Stainless Steel (Type 304)
Strength-to-Weight Ratio (kNm/kg)	120	77
Processing Energy (kWh/kg)	*Kroll Process:* 100	21
Theoretical Minimum Energy (kWh/kg)	*4.7*	**Not Available*
Emissions (kgCO_2/kg)	*Kroll Process:* 36	*6.8*
Domestic Production Cost ($/kg)	*Sponge:* 9.00	2.40
Density (kg/m^3)	4500	8030

As shown in Figure 2, the major components contributing to the cost of light metals are raw materials, labor, capital, and energy [7]. Processing of light metals has very poor energy efficiency, as revealed from comparing current processing energies to theoretical minimum processing energies in Tables 1 and 2 [12]. These poor energy efficiencies translate directly into large carbon emissions. A comparison of carbon emissions for producing aluminum and magnesium versus steel is also shown in Table 1, while that for titanium versus stainless steel is shown in Table 2; light metals are also systematically more energy and carbon intense to produce relative to the incumbent structural metals, steel and stainless steel. Thus it is a goal of this program to support the development of transformational new technologies that would enable light metals (aluminum, magnesium and titanium) to be cost competitive with the incumbent structural metals (steel and stainless steel), but also with a concomitant reduction in the energy and carbon intensity associated with their production. This program seeks to provide the technical underpinnings for a disruptive impact in the domestic light metals manufacturing industry and accelerate the adoption of light metals in energy relevant applications. Achieving parity with steel would accelerate the use of lightweight metals in a variety of applications, enabling substantial energy consumption reductions. Other programs, such as the DOE's Vehicle Technology Program, are addressing additional challenges for the use of these light metals in vehicle technologies, notably improved methods for machining and joining to manufacture parts [13].

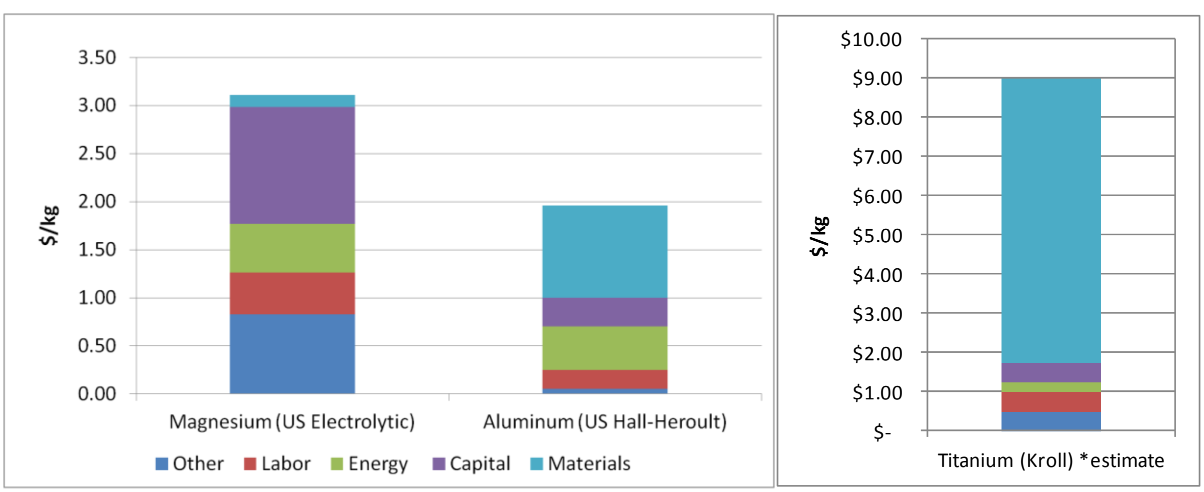

Figure 2: Cost profiles for U.S. magnesium, aluminum, and titanium production based on ARPA-E analysis using data from [4,6-8,10-11].

Light metals are superior to steels in strength-to-weight ratio, and it is therefore instructive to estimate how much light metal is required to replace steel in a structure. Specifically, a material substitution in a fabricated component of given bending strength, should have material thickness ratios (assuming identical cross sectional area) [14],

$$\frac{t_1}{t_2} = \sqrt{\frac{S_2}{S_1}} \tag{1}$$

where t is the part thickness, S is the yield strength of the material, and subscripts 1 and 2 denote materials 1 and 2. In order for the components made from materials 1 and 2 to have the identical cost and same embedded energy and emissions associated with material production, the following scaling relationships apply,

$$\frac{C_2}{C_1} = \frac{E_2}{E_1} = \frac{\chi_2}{\chi_1} = \sqrt{\frac{\rho_1 SR_2}{\rho_2 SR_1}} \tag{2}$$

where C is the cost intensity ($/kg), E is the process energy intensity (kWh/kg), χ is the CO_2 emissions intensity ($kgCO_2/kg$), ρ is the density, and SR is the strength-to-weight ratio. Table 3 summarizes the cost, energy, and emissions intensities for aluminum and magnesium that would give parity to parts made from steel and for those required for titanium to reach parity with stainless steel. **The steel equivalent cost, energy, and emission intensities for the light metals provide benchmark performance targets for light metal production.** These are the basis for the establishment of the cost targets for Al, Mg, and Ti described in Section I.E.

Table 3: Energy, emissions, and cost requirements for parity with steel and stainless steel (current values taken from Tables 1 and 2).

	Aluminum		Magnesium		Titanium	
	Current	Steel Parity	Current	Steel Parity	Current	S.S. Parity
Energy (kWh/kg)	56	20.2	43.6	27.3	100	35
Emissions ($kgCO_2/kg$)	22	7.3	6.9	9.8	36	11.3
Cost ($/kg)	2.00	1.47	3.31	1.98	9.00	4.01

a. Aluminum

Aluminum is found in many commercial structures, consumer products, and parts. The largest markets for aluminum are transportation (34%), packaging (26%), building and construction (12%), electrical (9%), machinery (8%), and consumer durables (7%) [1]. The breadth of applications is due to the low cost of aluminum relative to other light metals and its excellent strength-to-weight ratio, corrosion resistance, thermal and electrical conductivity, and reflectivity. Aluminum demand is still expected to grow significantly due to vehicle lightweighting [15], but without the introduction of disruptive light metal technologies the supply will likely not be domestic. In 2009 shipments of aluminum to the U.S. auto industry totaled 1.9 Mtons and are expected to grow to 2.5 Mtons by 2035 as a result of the need for vehicle lightweighting [16].

The industry-standard for aluminum production is the Bayer process for refining bauxite to alumina followed by the Hall-Heroult process for the smelting of alumina to aluminum. Over 57% of the total energy is consumed by this 100-year-old second step [17]; additionally it is an electrolytic process that consumes carbon anodes and contributes to significant CO_2 emissions. The inefficiencies and environmental impact of the Hall-Heroult process continue to be addressed, but presently only 0.2% per year energy reduction has been realized [18], and occupational hazards for pot room workers persist [19].

The annual world production of aluminum is approximately 45 Mtons, requiring 8.2 quadrillion BTUs (quads) of energy. Comparatively, the U.S. annual production is about 2.0 Mtons, requiring an energy input of 0.4 quads [1,17]. Over the past two decades, the trend of domestic production of primary aluminum has been downward [1]. In 2012, the U.S. market share of world aluminum production was approximately 5% of global demand, down from 11% a decade ago and 20% two decades ago. The U.S. annual demand for aluminum is approximately 4.5 Mtons and this demand is met by both primary and secondary (recycled) production; however, 20% of primary aluminum is imported in order to meet this demand [1].

b. Magnesium

Of the structural metals, magnesium has the highest strength-to-weight ratio. The majority of use, 41%, is for alloying with aluminum to improve its strength, ductility, and corrosion resistance. 32% is for die casting applications, such as automotive components, power tools, cell phone handsets, notebook computers, and others. 13% is for steel desulphurization, and the remaining 14% is for other uses in chemical processing, such as the extraction of titanium from rutile [6]. The U.S. demand in 2011 for magnesium was approximately 0.059 Mtons [1]. Of that total, 0.045 Mtons was produced domestically [20]. U.S. Magnesium LLC is the sole bulk producer of domestic magnesium, with only 1 electrolytic plant remaining (in Utah). China is currently the largest producer of magnesium worldwide with an output of 0.64 Mtons in 2012 [1].

Chinese magnesium is produced in batch using the thermochemical Pidgeon process, which is the reaction of ferrosilicon (FeSi) with dolomite (MgO). The energy requirements and CO_2 emissions of the Pidgeon process for Magnesium are both very high; 102 kWh/kg and 37 kgCO_2/kg, respectively [21]. In comparison, domestic magnesium production is an electrolytic process that requires approximately 43.6 kWh/kg and has emissions of 6.9 kgCO_2/kg [22]. Its total capacity is 0.045 Mtons/yr. The cost of producing Chinese-Pidgeon magnesium is $2.50/kg. The U.S. Magnesium LLC cost, using a more environmentally sound approach, is approximately $3.31/kg [7].

c. Titanium

Titanium is one of only a few metals that have excellent native strength (strength-to-weight ratio), ductility, toughness, and superior corrosion resistance. Similar to magnesium, titanium demand has historically been limited by the high cost associated with the high processing energy. The majority of domestic use, 50%, is for industrial equipment, 35% is for commercial aerospace, 8% is for military aerospace, and the remaining 5% is used in other markets [23]. The worldwide production of titanium is 0.15 Mtons in 2011 with domestic production being 0.018 Mtons [1]. The U.S. annual demand for titanium is approximately 0.05 Mtons, and thus approximately 64% of titanium used for domestic consumption is imported [1]. The demand for titanium in the aerospace sector is expected to grow substantially due to the trend toward aircraft lightweighting [3]. Also, due to its excellent radiation absorption characteristics and corrosion resistance, titanium is extensively used in the nuclear industry [24]. As with the other metals, domestic production of primary titanium is on the decline, and the current domestic annual production is approximately half of what it was during the 1990s.

There are various commercial production processes for titanium. The most widely used are batch processes where titanium dioxide is chlorinated to produce titanium tetrachloride, which is in turn reduced with magnesium (Kroll process) or sodium (Hunter process) to titanium sponge. An energy input of 0.1 quads is required to produce the 0.15 Mtons of global titanium and 0.01 quads for the 0.018 Mtons of domestic production [1,17]. A significant fraction of the materials cost in producing Ti (Figure 2) is associated with the cost of Mg for reduction via the Kroll process.

1. Need for Transformative and Disruptive Technologies in Light Metals Production

Figure 3 shows U.S. and global aluminum production and the percent of primary aluminum imported from the 1970s through 2011. There are two trends that raise concern. The first is that U.S. domestic production of aluminum is steadily on the decline while global production is rapidly rising. The second is that from the early 1990s through 2007 the percent of primary aluminum imported has been steadily on the rise and peaked in 2007 at 40%. Menzie et al. [25] project that by 2025 the global demand for aluminum will more than double, to 120 Mtons/yr, requiring at least an additional 8.7 quads of energy unless disruptive technologies are introduced.

The magnesium and titanium markets are considerably more volatile than that for aluminum but with similar trends. By 2011 64% of titanium was imported to meet domestic demand, and 30% was imported for magnesium.

Due to the energy intensive nature of light metals, importing these metals is equivalent to importing embedded energy, which runs counter to the U.S. goal of reducing energy imports. For example, the embedded energy in imported light metal amounted to 0.2 quads in 2012 and 0.4 quads in 2007. The technologies emerging from this program, which will place light metals on performance/cost parity with steel and stainless steel while significantly decreasing the energy and emissions from their processing, can reduce overall emissions and eliminate the importation of embedded energy. Moreover, these technologies can enable the U.S. to become a significant supplier of light metals to the world markets in order to meet increasing demand.

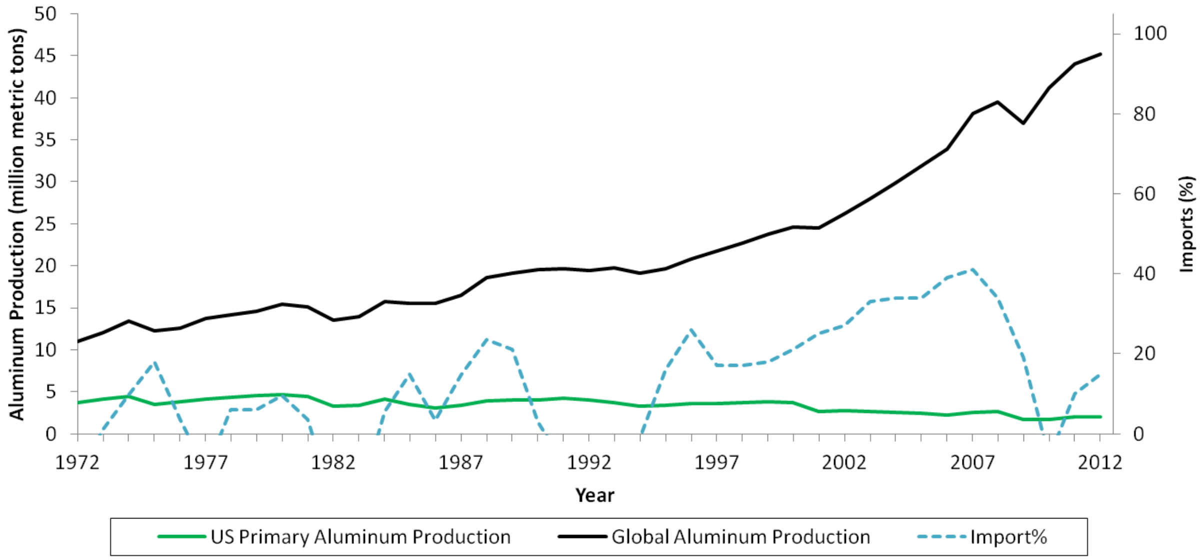

Figure 3: Aluminum production (US and global) and percent of primary aluminum imported from the 1970s through 2012.

2.1 Achieving Intended Energy Savings through Vehicle Lightweighting

The significant trend to manufacture lighter ground and air vehicles is motivated by consuming considerably less energy over the vehicle lifetime. The accelerated focus toward lightweighting ground vehicles is motivated by the aggressive 2025 Corporate Average Fuel Economy (CAFE) standards for cars and light-duty trucks set forth by the U.S. Department of Transportation (DOT) and the U.S. Environmental Protection Agency (EPA) in August 2012. These new standards mandate an increase in fleet fuel economy to 55 mpg by 2025 and build from previous standards requiring fleet fuel economy of 35 mpg by 2016.

The 55 mpg fleet standard cannot be met solely by improvements in the powertrain; radical new strategies and vehicle design will be required. Various groups have assessed the options for meeting these new requirements, but any viable scenario requires a 20-40% reduction in vehicle weight [2]. The DOE Vehicle Technologies Program sets a goal of a 50% weight reduction in passenger-vehicle body and chassis systems [13]. As a result, auto manufacturers are preparing to make use of light metals, especially aluminum/magnesium alloys, given their excellent strength-to-weight ratios. These light metals would replace heavier steel, which has been the metal of choice in automobiles to date.

Similarly, aircraft manufacturers are aggressively moving to deliver lightweight aircraft. For example, the new Boeing 787 aircraft is 20% lighter than the 767 model it is designed to replace [3]. A significant amount of carbon fiber is used to construct the aircraft, but the large galvanic potential between aluminum and carbon fiber can result in aluminum corrosion. Titanium, a high strength alternative structural material with superb ability to resist corrosion is therefore used. The aircraft industry anticipates that future lightweight aircraft will make expanded use of titanium [26] for the aircraft frame; this expansion can clearly be accelerated by reduction of domestic process energy intensity and therefore cost.

Lightweighting of both ground and air vehicles will lead to significant fuel energy savings. An ARPA-E analysis shows that if the entire ground fleet on the road in 2012 had all of its steel replaced with lighter weight aluminum or magnesium, approximately 2.5 or 3.2 quads of fuel energy could be saved per year, respectively. However, offsetting these savings is the enormous amount of energy required to produce aluminum and magnesium compared with steel, which means that approximately 80% of the net energy savings from lightweighting is lost (assumes a ten-year vehicle life). A similar offset exists for the use of titanium in air vehicles; the embedded energy in producing titanium is about 10% of the fuel energy savings over the lifetime of the aircraft (assumes a 20-year life). By meeting the steel equivalent energy intensity benchmarks shown in Table 3, the fleet of lightweight vehicles could realize the 2.5 to 3.2 quads/yr energy savings at the same cost as using steel, and start saving fuel on day 1 of use, rather than needing to make up for an energy debt embedded in the light metal(s). Such a shift toward lightweight vehicle production and usage will enable a transformational shift in fleet fuel economy.

2.2 Scrap Metal Recycling to Enable Energy Savings

Recovery and recycling of light metals has always been a way to make gains in life-cycle production energy savings and to relieve raw ore production stresses. This is increasingly important in light of the expected 2025 global aluminum demand of 120 Mtons/yr and the domestic focus on vehicle lightweighting. After initial production ramp-up to meet new demand followed by the retirement of fleets, recycling will have even greater potential to meet replacement demand and could significantly reduce the required energy and cost to produce the vehicles. This future stands in stark contrast to the status quo in which the U.S. ships most of its metal scrap overseas.

The metal recycling process begins with scrapping automobiles, trailers, white goods (dishwashers, refrigerators, etc.), and metals recovered from municipal waste-to-energy plants. These items are first directed to a large hammermill-type shredder in which they are reduced to fist-size chunks of metal and copious amounts of non-metal (glass, plastic, foam, rubber, paper, etc.). Once shredded, air separation is employed to remove the lightest of the non-metal materials. Large magnets are then used to extract the ferrous-based materials (the majority of the metal fraction), which are then shipped to steel mills. The remaining material is comprised of non-ferrous metals and some non-metals (rock, glass, plastic, and wood) and is referred to as non-ferrous concentrate (NFC); also known as "Zorba". The Zorba fraction can be further “improved” by a combination of sizing, screening, and eddy-current or inductive-coil separators to reject the unwanted non-metals.

Most U.S. Zorba (as much as 50-75% by weight or 0.95-1.4 Mtons/yr) is shipped overseas, typically to China or India. Their low cost labor is very effective at hand sorting the different aluminum grades, along with the other metals [27]; neither the U.S. labor market or existing sorting technologies can match this. After being manually sorted abroad, the scrap metal is manufactured into parts. Only a small fraction of this metal returns to the U.S. as finished products, such as automobile engines; typically domestic manufacturers are forced to use more energy intensive primary light metal. The embedded energy in the scrap metal currently being shipped overseas is approximately 0.3 quads, while the embedded energy in imported metals varies from approximately 0.2-0.4 quads.

However, for cases when the market conditions are favorable in the U.S., the Zorba may undergo further domestic processing by sink-floatation or by X-ray transmission in which it is separated into light and heavy fractions. The light fraction is comprised of aluminum- and magnesium-based alloys called "Twitch". The heavy fraction is comprised of zinc, copper, brass, bronze, or stainless steel, predominantly known as "Zebra". Thus, Zorba equals Twitch plus Zebra. 80-85% of Zorba is the light metal Twitch.

Twitch is comprised of 1) a high-grade aluminum/magnesium alloy which has a low copper and iron content and 2) a low grade aluminum/magnesium alloy that has a higher iron and copper content. The value of Twitch can be significantly upgraded by separating out the high grade aluminum/magnesium alloy. Economical advanced sorting technologies would significantly increase the value of Twitch and enable the domestic recycling of aluminum/magnesium alloy, thus reducing the domestic demand for more energy intensive primary metal.

Light metal demand for vehicle lightweighting will increase, which positively impacts the national goal of energy independence. However, with present U.S. production/importing/exporting patterns and variable energy content for different processes across the globe, the U.S. is effectively importing embedded energy via primary metal (as noted above) and exporting energy in low cost scrap. These outcomes diminish progress towards energy independence. The approach described here to reduce the energy intensity of primary light metal production and to enable high accuracy sorting/recycled light metals production technologies will enable vehicle lightweighting to be a more effective mechanism in moving toward overall energy independence.

A. PROGRAM OBJECTIVES

The previous sections described the impact of new processing and recycling technologies in reducing energy consumption and greenhouse gas emissions while lowering the market cost of domestically produced light metals. The existing bulk production processes for aluminum (Bayer and Hall-Heroult), magnesium (Pidgeon), and titanium (Kroll) have been in industrial practice for many decades. These processes are mature on the learning curve, and their further advancement to provide the cost, energy, and emissions intensity benchmarks, shown in Table 3, do not appear to be on the horizon. Therefore, new pathways for light metal processing and the management of energy throughout them need to be considered. Some alternative approaches that are potentially disruptive to the current practice for light metal processing are now presented as possible avenues for research and development: chemical pathways, energy inputs, heat-recovery/energy-storage/thermal-management, alternative ore feedstocks, and advanced sorting for recycling. These are not meant to be prescriptive, nor should they limit the response to this FOA. (See Section I.D for areas of interest and I.F for areas specifically not of interest).

1. Chemical Pathways

With current technologies, thermochemical reduction of metal oxide to metal typically requires lower capital cost than the comparable electrochemical approach, although the electrochemical approach tends to be more energy efficient. One thermochemical route to light metals production with potentially lower cost, lower energy, and lower emissions is carbothermic reduction. A metal oxide and carbon compound flow through a high temperature thermochemical reactor and reduced metal and carbon monoxide or Syngas exit the reactor under ideal conditions. When methane is used as a feedstock to reduce metal, Syngas is a possible by-product; thus an inherent advantage of carbothermic processing is that the energy used to produce metal also yields another value commodity stream which can help offset the cost of metal production. Carbothermic reforming of metals faces very challenging technical issues, including: thermodynamically unfavorable reactions, reactions that occur only at very high temperature and/or low pressure, oxide back reaction and carbide formation, material compatibility issues at high temperature, separation of the product gases, and high-grade heat capture and utilization. Thoughtful consideration of equilibrium thermodynamics, reaction kinetics, and material compatibility may lead to innovative metal reactor concepts. A very useful tool to understand the thermodynamic constraints on the oxidation and reduction of metals is the Ellingham diagram [28]. Diagnostic tools to further the fundamental understanding of reaction pathways include high temperature XRD, mass spectroscopy, thermogravimetry, scanning tunneling microscopy, Raman spectroscopy, among others.

An interesting electrochemical pathway to light metal production is the use of a conducting solid oxide membrane, such as yttria stabilized zirconia, as an anode. The advantage of this approach is that oxygen passes through the porous zirconia anode and is isolated from the metal; therefore back reactions with oxygen are eliminated. An overview of the method is provided by Pal and Powell [29]. While this method has been successfully implemented for the production of magnesium, challenges remain. These include zirconia anode stability in contact with a high temperature electrolyte, preventing thermal shock and cracking of the anode, obtaining sufficient current density with minimal potential drop across the zirconia anode, and cost effective scale-up to production capacity.

Both the carbothermic thermochemical and zirconia anode electrochemical approaches allow for continuous processing as opposed to batch processing (current practice). The advantages of continuous processing are larger throughput per unit volume and amenability to automation, both of which potentially lead to cost reduction. These are just two of many possible alternative chemical routes to light metals production. More generally, *ARPA-E seeks chemical pathways that allow for continuous processing with a variety of energy input options*.

2. Energy Inputs

While a variety of energy inputs could be used for the reduction of metal oxides, the reaction temperatures are sufficiently high, typically greater than 1400°C, that a significant amount of electrical power or concentrated solar power would be required to reach them. The drawback in using grid power is that during peak hours, the cost is considerably higher than that at off-peak. It would be advantageous to have a flexible production process that can be taken off grid during peak hours, or as needed. This can be accomplished by shutting down the metal production process during peak hours or making use of high temperature thermal energy storage to produce on-site power that can be fed back into the process during peak hours. As more variable renewable energy sources are integrated into the grid, flexible light metal processing with integrated heat storage and recuperation could be used as a load leveling tool.

In addition, flexible processing technologies incorporating heat storage and recovery can also enable renewable energy inputs to be integrated *directly* into the process. For example, light metal production processes designed to operate with the heat from concentrated solar power will need to incorporate variable operation, thermal energy storage, or both. Figure 4 illustrates a conceptual carbothermic metal production process operating with a hybrid solar/grid energy input. Operating under such a scenario requires very complex thermal management, energy storage, and control. It is likely that there is an economic advantage to sustain metal production for as long as possible without shutting down the operation. Grid power and/or high temperature thermal energy storage technologies will enable such operation. As such, *ARPA-E seeks technologies to that are compatible with variable energy sources*.

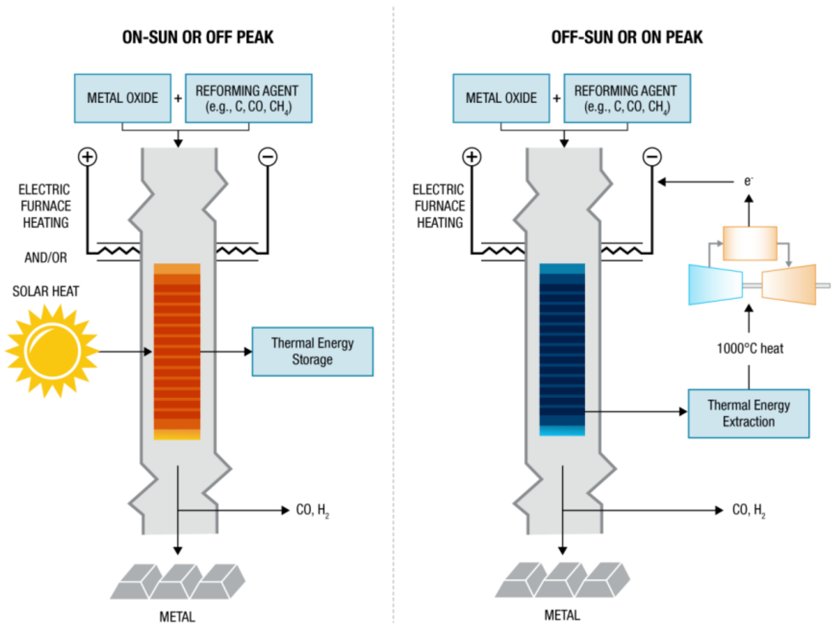

Figure 4: Conceptual carbothermic reactor operating with a hybrid solar/grid energy input.

3. Heat Recovery, Energy Storage, and Thermal Management

The thermal energy losses in conventional light metal processing facilities are substantial and are the origin of the very low energy efficiencies. Processing facilities were not designed with energy efficiency as a goal and are very difficult to retrofit for heat recovery. For example, the Hall-Heroult electrochemical cell has built in heat loss to preserve a thin layer of solid electrolyte that protects the cell from molten cryolyte. The hot off-gas contains particulates and hydrogen fluoride (HF) which are corrosive to typical heat exchangers. The Bayer process also loses substantial thermal energy contained in hot exhaust gases from the calciner. Such losses are on the order of megawatts per facility. In conceiving innovative and transformative light metal production processes, heat recovery and thermal management should be an overarching goal as they will significantly impact the process energy efficiency and therefore cost and emissions.

Thermodynamics dictate that high temperature heat has considerably higher value than that captured at low temperature because it enables more economical electrical power production. Molten metal is an excellent high temperature thermal energy storage medium as it stores both sensible and latent heat; however, a commercial technology to recover it does not currently exist. This is related to the fact that high temperature molten metal is highly reactive. Highly specialized materials and inert gas purge are required for handling, and pumping technologies typically needed for thermal convective transport are not available. The development of a molten metal high temperature thermal storage and heat recovery technology would indeed be transformative for light metal production. *ARPA-E seeks innovative concepts in heat recovery, energy storage, and thermal management to be integrated with light metals processing*.

4. Alternative Ore Feedstocks

Using aluminum as an example, production begins with conversion of Bauxite ore to alumina. The domestic reserves of Bauxite are very low compared with other mineral rich nations, and today the US relies on alumina extracted from Bauxite mined in Jamaica, Guinea, and Brazil. The imported alumina comprises approximately one quarter of the cost to produce aluminum. While the known domestic reserves of Bauxite are very low, there are substantial reserves of an alternative source of alumina, anorthosite, which contains approximately fifty percent silica, thirty percent alumina, and twenty percent calcium oxide [30]. It is estimated that the U.S. has anorthosite reserves on the order of 600 billion tons [31]. A domestic alumina production process from anorthosite at less than $0.50/kg provides a potential path to increased domestic production of aluminum and could be disruptive. *ARPA-E seeks new processes that are able to cost-effectively take advantage of domestically available and abundant ore feedstocks for each of the light metals of interest*.

5. Advanced Sorting Technology for Scrap Metal Recycling

As previously mentioned, the aluminum/magnesium alloy scrap product, Zorba, can be significantly upgraded by separating out the high grade aluminum/magnesium alloy. Economical advanced sorting technologies would significantly increase the value of Zorba and enable the domestic recycling of scrap aluminum/magnesium alloy. The extraction of Twitch from Zorba can be accomplished with inexpensive sink float technology. The selection of high grade aluminum/magnesium alloy from Twitch requires precise and rapid identification of every piece that is transported on the conveyor. The identification of aluminum/magnesium alloys using x-ray transmission (XRT) spectroscopy is a possible solution. However, the intrinsic limitations of an XRT sensor leads to a spectra overlap among similar alloys, which would make alloy separation difficult. A more effective approach could employ x-ray fluorescence (XRF) spectroscopy, although at a higher cost, and economic viability would need to be investigated.

Another possible solution is to tag the alloy with trace amounts of compounds that are easily identifiable, distinguishable, and do not change the properties of the alloy. As an example, doping of building construction materials with barium sulfate, manganese dioxide, or mixtures are used as tags . XRF is used to identify the concentration of the doping material and verify that the construction material is not a lower grade imitation. A less costly solution for metals may be to use infrared fluorescence spectroscopy, with a very small concentration of rare earth complexes to serve as tags. A concern is whether or not the tag concentrations will be diluted and altered during the re-alloying process.

These represent a few alternative technologies to the sorting of the abundant production of domestic scrap light metal. Many others could be imagined and *ARPA-E seeks transformative ideas that will lead to rapid, high precision, and automated sorting technologies for Al, Mg, and Ti alloy scrap*.

B. TECHNICAL CATEGORIES OF INTEREST

The objective of this program is to support the development of transformational new technologies in processing or recycling that enable lightweight metals (aluminum, magnesium and titanium) to be not only cost competitive with the incumbent structural metals (steel and stainless steel), but also with a concomitant reduction in the energy and carbon intensity associated with their production from primary or secondary sources. Accordingly, two categories are of interest:

- **Category 1. Transformative routes to produce primary Al, Mg, and/or Ti (powder, including Titanium Hydride powder), that provide significant reductions to cost, energy, and emissions.**

  Preference will be given to concepts that allow for one or more of the following:
    a. Variable energy inputs
    b. Renewable energy inputs
    c. High temperature heat capture
    d. High temperature thermal storage
    e. Utilization of domestically abundant ores

Integrated system approaches accomplishing one or more of these objectives (a-e) are of interest, but innovative concepts focused on energy intensive and/or high cost stages of the production process will also be considered.

- **Category 2. Transformative technologies that enable rapid, precision, and automated sorting of Al, Mg, and Ti alloy scrap.**
  Integrated sorting technologies and high efficiency secondary light metal production processes that enable finished product from recycled scrap are also of interest.

- **Areas that are discouraged**

Routine or incremental improvements to the Hall-Heroult, Pidgeon, and Kroll processes are discouraged. Transformative improvements in these processes that can be demonstrated to meet the program metrics will be considered on a case-by-case basis.

- **Areas not of interest**
  - Melting technologies
  - Casting technologies
  - Power generation technologies (available technologies for power generation will be assumed, but not funded by ARPA-E through this program)
  - Processes that are not amenable to start-up and shut-down cycles
  - Recycling/secondary production technologies that only offer energy efficiency advantages without also incorporating advanced sorting technologies
  - Solid oxide membrane electrochemical processes for magnesium

C. Technical Performance Targets

ARPA-E sets aggressive technical and economic targets in order to encourage applicants to propose transformative solutions that require creative alternatives, enabled by an expanded science base, to the current state of technology. Only those technologies that have a well-justified potential to approach, meet or exceed the technical and economic performance targets will be considered for funding.

ARPA-E recognizes that laboratory scale prototype technologies may not be able to meet the performance targets without projection to operation at a production scale. In such cases, applicants must submit a rigorous analysis that demonstrates how laboratory prototype performance can be extrapolated to the production scale and meet the performance targets. All proposed technology concepts must demonstrate that they can accommodate sufficient throughput to scale to industrial production.

1. Primary Metal Production

Processing Energy

For the purpose of this funding opportunity, the processing energy intensity is defined as,

$$E = \frac{E_{in} - E_{rec} - E_{ren}}{M_{metal}}$$

where E_{in} is the sum of the energy inputs to the system, E_{rec} is energy recovered and reused in the system, E_{ren} is renewable energy that is directly integrated in and used by the system, and M_{metal} is the mass of metal discharging the system. Renewable energy that is delivered through the grid is not counted.

Note that this definition of energy intensity incentivizes the use of heat recovery and renewable energy within the system – a radical departure from current technology. The process energy efficiency targets for Al, Mg, and Ti are shown in the table below and are equivalent to the benchmarks for parity with steel and stainless steel.

Metal	Al	Mg	Ti
Target E	**≤20 kWh/kg**	**≤27 kWh/kg**	**≤35 kWh/kg**
Industrial Current (Tables 1 and 2)	56 kWh/kg	44 kWh/kg (U.S Mag.) 102 kWh/kg (Pidg.)	100 kWh/kg

CO_2 Emissions

For the purpose of this funding opportunity, the CO_2 emissions are defined as,

$$\chi_{CO2} = \frac{M_{CO2}}{M_{metal}}$$

where M_{CO2} is the mass of CO_2 discharging the system. It is noted that CO discharging the system which is collected and used toward Syngas production or some other end product, is not counted toward emissions. However, should CO be combusted and energy put back into the system, the resulting CO_2 from combustion will be counted toward emissions. The CO_2 emissions targets for Al, Mg, and Ti are shown in the table below.

Metal	Al	Mg	Ti
Target χ_{CO2}	**≤7 kgCO_2/kg**	**≤10 kgCO_2/kg**	**≤11 kgCO_2/kg**
Industrial Current (Tables 1 and 2)	22 kgCO_2/kg	7 kgCO_2/kg (U.S. Mag.) 37 kgCO_2/kg (Pidg.)	36 kgCO_2/kg

Cost

Applicants must provide an estimate of the cost profile for the proposed technology, similar to those shown for aluminum, magnesium, and titanium in Figure 2. This estimate must include an explanation of how the new technology innovation will reduce the current cost profile for the relevant metal(s) such that the projected production costs will meet the end of project target(s). Proposed systems/processes that produce a value stream in addition to the metal (for example Syngas) may compute the value of the additional product and subtract it from the cost. For proposed concepts where cost targets will not be met within the period of performance, applicants must provide a thorough analysis detailing how the target cost will be approached and the timeframe for doing so. The cost targets for Al, Mg, and Ti are shown in the table below.

Metal	Al	Mg	Ti (powder) or Ti-hydride (powder)
Target Cost	**≤$1.50/kg**	**≤$2.00/kg**	**≤$4.00/kg**
Industrial Current (U.S. Tables 1 and 2)	$2.00/kg	$3.31/kg (U.S. Mag.) $2.50/kg (China Pidg.)	$9.00/kg

II. Recycling

Sorting must be done at a rate that can scale to a production rate of at least 4 Tons/hr. The sorting technology should be able to make a decision on the type of alloy for every piece of scrap metal passing through the sorter. The sorting system should achieve a sorting success rate of 99% or greater (the success rate is defined such that for every 100 pieces of scrap that pass through the sorter, on average, the alloy composition of 99 pieces should be correctly identified). Sorting should be done at a total cost of $0.04 per kg of scrap or less.

D. Applications Specifically Not of Interest

The following types of applications will be deemed nonresponsive and will not be reviewed or considered (see Section III.C.2 of the FOA):

- Applications that fall outside the technical parameters specified in the FOA, including but not limited to:
  - Non-enzymatic routes to produce syngas
  - Fuel synthesis pathways that use syngas or CO_2 and H_2 as starting reactants
  - Purely non-biological approaches for methane conversion to liquid fuels
  - Production of hydrocarbon compounds that are neither fuel molecules or fuel molecule precursors, or exist primarily in the gas phase at STP
  - Biological approaches that rely on the accumulation of cell biomass as an intermediate to fuel production.
- Applications that were already submitted to pending ARPA-E FOAs.
- Applications that are not scientifically distinct from applications submitted to pending ARPA-E FOAs.
- Applications for basic research aimed at discovery and fundamental knowledge generation.
- Applications for large-scale demonstration projects of existing technologies.
- Applications for proposed technologies that represent incremental improvements to existing technologies.
- Applications for proposed technologies that are not based on sound scientific principles (e.g., violates a law of thermodynamics).
- Applications that do not address at least one of ARPA-E's Mission Areas (see Section I.A of the FOA).
- Applications for proposed technologies that are not transformational, as described in Section I.A of the FOA. Transformational, as illustrated in Figure 1 in Section I.A of the FOA, is the promise of high payoff in some sector of the energy economy.
- Applications for proposed technologies that do not have the potential to become disruptive in nature, as described in Section I.A of the FOA. Technologies must be scalable such that they could be disruptive with sufficient technical progress (see Figure 1 in Section I.A of the FOA).
- Applications that are not technically distinct from existing funded activities supported elsewhere, including within the Department of Energy (examples include but are not limited to Energy Efficiency and Renewable Energy in both the Vehicle Technologies Program and the Advanced Manufacturing Office) or by other federal agencies (examples include but are not limited to the Department of Defense and the National Science Foundation).

E. References

[1] U.S. Geological Survey, Mineral Commodity Summaries, E. Lee Bray, 2013.

[2] Cheah, L. W., Cars on a diet: the material and energy impacts of passenger vehicle weight reduction in the US. , Ph.D. Thesis, Massachusetts Institute of Technology, 2010.

[3] Boeing 787 from the Ground Up, Aero Magazine, Boeing, 4th quarter, 2006.

[4] Booz Allen Hamilton, Aluminum Cost Profiles. Unpublished Report, March 2013. Analyses are based on costs reported by Hale, W.R., The Global Light Metals Sector Outlook: A Primary Aluminum Perspective, Industrial Insight, pp 26-30, Nov. 2000.

[5] Electric Arc Furnace Steelmaking Costs 2012, Metals Consulting International, 2012.

[6] Wulandari, W, Brooks, G, Rhamdhani, M Monaghan, B, Magnesium: current and alternative production routes, Chemeca: Australasian Conference on Chemical Engineering, 2010.

[7] Das, S., Primary Magnesium Production Costs for Automotive Applications, Journal of Metals, Vol. 60 No . 11, p. 66, 2008.

[8] Choragudi, A., Kuttolamadom, M. A., Jones, J. J., Mears, M. L., & Kurfess, T., Investigation of the Machining of Titanium Components in Lightweight Vehicles, SAE International Congress, 2010.

[9] 304/304L Product Data Sheet, AK Steel, 2007.

[10] Froes, S., Titanium Powder Metallurgy, a review part 1, 2012.

[11] Onillon, J., Aperam, Goldman Sachs Global Metals, Mining & Steel Conference, 2012.

[12] Norgate, T.E., Jahanshahi, S., and Rankin, W.J., Assessing the Environmental Impact of Metal Production Processes, Journal of Cleaner Production, Vol. 15, 8, pp. 838-848, 2007.

[13] Materials Technologies: Goals, Strategies, and Top Accomplishments, US Department of Energy, Energy Efficiency and Renewable Energy - Vehicle Technologies Program, August 2010.

[14] Luo, Alan A, Magnesium: Current and Potential Automotive Applications, JOM Journal of the Minerals, Metals and Materials Society 54,2 pp. 42-48., 2002.

[15] Ducker Worldwide, Aluminum Association Auto and Light Truck Group 2009 Update on Aluminum Content in North American Light Vehicles, Phase I. Troy, Michigan, 2008.

[16] Cheah, L., Heywood, J., Kirchain, R., Aluminum Stock and Flows in US Passenger Vehicles and Implications for Energy Use, Journal of Industrial Ecology, Vol. 13, No. 5, pp. 718-734, 2009.

[17] Norgate, T. E., and Rankin, W.J., Greenhouse Gas Emissions from Aluminum Production–a life cycle approach, Greenhouse gases in the Metallurgical Industries: Policies, Abatement and Treatment, (Met Soc CIM), Toronto 89, 2001.

[18] U.S. Energy Requirements for Aluminum Production: Historical Perspective, Theoretical Limits, and Current Practices, U.S. Department of Energy, EERE Report, February, 2007.

[19] Facts and Voices on the Aluminum Smelting Industry, United Nations brief on aluminum smelters prepared by the Sustainable Development Unit of the ECLAC Subregional Headquarters for the Carribbean, 2007.

[20] Primary Magnesium Production, International Magnesium Association, 2010.

[21] Aghion, E., and Bartos, S., Comparative Review of Primary Magnesium Production Technologies as Related to Global Climate Change, 65th Annual World Magnesium Conference, Warsaw, Poland, May 18-20, 2008.

[22] Das, S., Life cycle Energy and CO_2 Analysis of Solid Oxide Membrane Primary Magnesium Production Technology, U.S. DOE Report No. DE-AC5-00OR22725, 2010.

[23] Titanium Industrial Base, Price Trends, and Technology Initiatives, Rand Corporation, 2009.

[24] Stankovic, S.J., Ilic, R.D., Davidovic, D.M., Petrovic, M., Tadic, S., and Kovacevic, Radiation Absorption Characteristics of Titanium Alloys, Acta Physica Polonica A, Vol. 115, No. 4, pp. 820-822, 2009.

[25] Menzie, W.D., Barry, J.J., Bleiwas, D.I., Bray, E.L., Goonan, T.G., and Matos, G., The Global Flow of Aluminum from 2006 to 2025, USGS Open File Report 2010-1256, 2010.

[26] Bowden, D.M., and Peter, W.H., Near-Net Shape Fabrication Using Low-Cost Titanium Alloy Powders, The Boeing Company, 2012.

[27] Seabrook, J., American Scrap, The New Yorker, January 14, 2008.

[28] Mitchell, B.S., An Introduction to Materials Engineering and Science for Chemical and Materials Engineers, John Wiley and Sons, pp. 180-183, 2004.

[29] Pal, U.B. and Powell, A.C., The Use of solid-Oxide-Membrane Technology for Electrometallurgy, JOM, Vol. 59, No. 5, pp. 44-49, 2007.

[30] Eisele, J.A. and Bauer, D.J., U.S. Bureau of Mines, Recovery of Alumina from Anorthosite by an HCl-F-Gas Sparging Cyrstallization Process, RI 8806, pp. 1-11, 1983.

[31] U.S. Bureau of Mines, Potential Sources of Alumina, IC 8335, pp. 1-148, 1967.