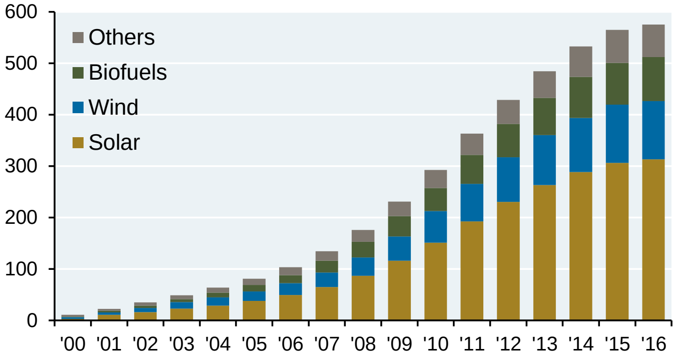
[2] Mountains vs Molehills

The renewable energy revolution has given birth to a lot of great ideas and innovations, with a surge in global renewable energy patents since 2009. But for every idea that transforms the energy landscape, there are more that succeed from a business perspective but do not move the needle on de-carbonization, and others that don't succeed on either front. Wave energy, fuel cells, algae-based fuels, liquid fuels from methane, kite energy, cold fusion, liquid fluoride thorium reactors…these are all topics that clients have asked about, but which are not anywhere near large-scale commercialization. The hype with which these ideas are discussed in the press often obscures how difficult such commercialization would be.

As a result, we've added a "Mountains vs Molehills" section to briefly assess five popular energy topics with respect to their **practical potential for significant de-carbonization over the next 10-15 years**. We graded each topic with a de-carbonization score that ranges from 1 (molehill) to 5 (mountain).

Global cumulative renewable energy patents

Thousands



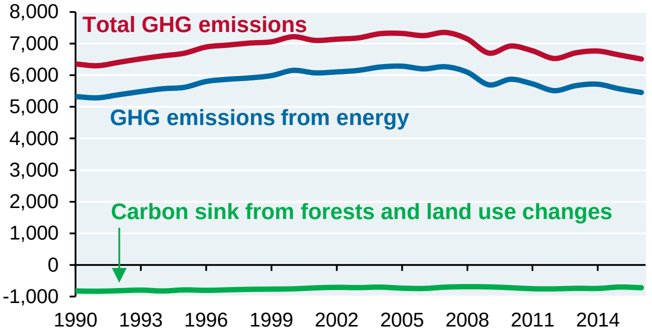
Source: International Renewable Energy Agency. 2016.

Mountains or Molehills?

a) Carbon sequestration via reforestation
b) Carbon capture and storage (underground)
c) Cellulosic ethanol
d) Distributed energy storage via graphene-based supercapacitors
e) Carbon-free smelting of aluminum

a. Forest management as a means of sequestering additional amounts of carbon

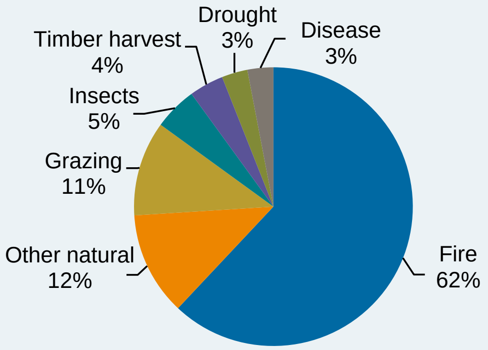
All US forestland encompasses around 750 mm acres and captures 10% of US GHG emissions each year[9]. In 1850, there were 900 mm acres, but returning to this level is unlikely given conversion of forested areas into highways, infrastructure and farmland, and given the 6x growth in US population since then. Ideas for sequestration involve replanting cleared forests, and converting cropland and pastureland.



US forests offset 10% of annual GHG emissions
Million metric tons of CO_2 equivalents per year

Source: US EPA. 2017. Total emissions include agriculture, waste and industrial processes such as chemical, metal and mineral production.

Cleared US forestland by disturbance source, 2014



Source: Al Sample, Journal of Forestry. 2017.

Reforestation refers to replanting of cleared areas which do not require a land use change. A 2017 Journal of Forestry study analyzed 20 million acres of land which has been cleared due to wildfires, insect outbreaks and other disturbances. The study estimated its sequestration potential at 50 million metric tons (MMT) of GHG per year, which could offset almost **1% of annual US GHG emissions.** Reforesting 20 million acres split evenly between private and public land would be a major undertaking; in 2017, the US Forest Service reforested just 122 ***thousand*** acres. Reforestation is needed to offset: (a) aging US forests which absorb less carbon over time; (b) CO_2 released from wildfires, which has averaged 60 - 80 MMT per year since 2013; and (c) the impact of severe hurricanes, one example being Hurricane Michael which destroyed 3 million acres of trees in Florida in 2018.

Afforestation refers to trees planted in previously unforested areas. The concept: carbon payments could incent US farmers to convert cropland and pastures into forests. A 2018 study published in the National Academy of Sciences estimated the potential for 150 MMT of CO_2 sequestered each year, assuming a CO_2 price of $15 per tonne. To be clear, this would be another large undertaking, requiring the conversion of 7-10 million acres of cropland and pastureland. The study's sequestration estimates are lower than prior ones, since they incorporate the need to avoid large adverse social/environmental/economic impacts, the complex reality of farmer decision-making[10], and competing demands for food/biofuels/real estate.

Bottom line: reforestation and afforestation are low-tech solutions that can and do work, but plans to achieve additional sequestration of 3% of annual US GHG emissions would entail substantial costs and private sector participation on an unprecedented scale

Grade: 

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[9] **Greenhouse gas emissions** include carbon dioxide, methane, nitrous oxide and fluorinated gases. In the US, the breakdown of GHG emissions is 82% CO_2, 10% CH_4, 5% NO_x and 3% F-gases.

[10] For example, **converting farmers** lose the optionality of benefitting from higher crop prices; bear the entire risk of wildfire and disease; and often bear the currently high cost of CO_2 sequestration verification (which could decline with the advent of NASA satellite technology monitoring).

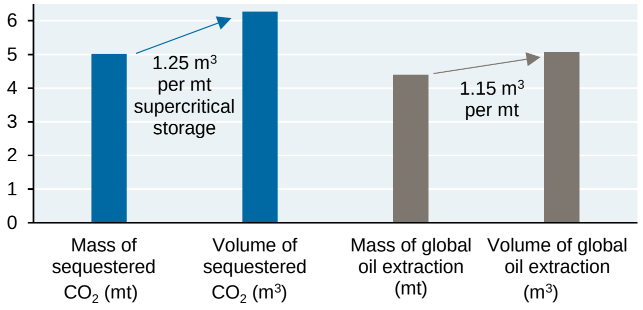
b. Carbon capture and storage (storing CO_2 emissions underground)

Forests are a low-tech approach to sequestration; underground storage through carbon capture (CCS) is a higher-tech one. A 2018 Congressional bill creating tax credits for CO_2 sequestration[11] raised hopes that underground storage will finally become a meaningful part of the de-carbonization solution. Furthermore, recent studies cite little evidence of CO_2 leakage, high confidence in the geological integrity of underground reservoirs[12], and reinforce the importance of CCS to de-carbonization pathways even if leakage occurs.

Even so, history offers reasons for caution. Despite all the hype[13], by the end of 2018, CCS facilities in operation captured and stored **just 0.1% of the world's CO_2 emissions**. Let's put aside issues of large cost overruns and failures of bellwether projects[14], the Department of Energy withdrawing support from large projects (FutureGen), project cancellations in Europe, legal uncertainties about liability associated with CO_2 leaks, and the ~30% energy drag on coal facilities required to perform CCS in the first place. Let's assume these problems are solved via innovation and legislation (aggressive assumption, for sure). The bigger problem with CCS is the scope required to make a difference. To see why, let's assume that the world aims to sequester just 15% of global CO_2 emissions each year, which would be around 5 gigatons.

Compare the volume bars in the chart: to capture 15% of global CO_2 emissions, a CCS compression/transportation/storage industry would have to be able to handle 6 billion cubic meters of CO_2 every year, which is **even greater than the volume of annual global oil transportation and refining**, which has taken 100 years to build; and that's without the benefit that oil provides as an input to transportation and industry. There may be applications where CCS makes sense (enhanced oil recovery, and meeting small amounts of commercial CO_2 demand). But as a big picture solution to CO_2 emissions, CCS scale requirements are very daunting[15]. We'd be very surprised if global CCS exceeded 5% of CO_2 by 2030.

To capture 15% of global CO_2 emissions, CCS would have to be larger than the global oil ecosystem
Billions (metric tons for mass, cubic meters for volume)



Source: BP, JPMAM. 2018. Mt = metric tons, m^3 = cubic meters

Grade: ▲△△△△

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[11] The 2018 bill established **tax credits** of \$35 per tonne of CO_2 sequestered as part of enhanced oil recovery operations, and \$50 per tonne of CO_2 sequestered in geological formations in the absence of oil recovery. To be clear, CCS involves storing *CO_2* underground, while forests store *carbon* and release oxygen back into the atmosphere.

[12] Studies on reservoir reliability include a January 2019 *Scientific Reports* study analyzing 400,000 years of evidence from a naturally-occurring faulted CO_2 reservoir in Arizona, and a 2018 study in *Nature Communications*.

[13] A study from Monash University found substantial evidence of **CCS hype**: a surge in peer-reviewed CCS papers, a much smaller increase in patents, evidence of rising costs and a huge gap between expected and actual project starts.

[14] **Kemper fiasco**. The Kemper Clean Coal plant in Mississippi was supposed to be the world's largest, converting cheap lignite coal into natural gas to generate electricity, and capturing CO_2 for use in enhanced oil recovery at nearby fields. As of July 2016, the plant was more than two years behind schedule, more than \$4 billion over its budget of \$2.4 billion and still not operational. In July 2017, Southern Company and Mississippi Power announced they had **suspended all coal gasification and carbon capture operations** at Kemper and would use natural gas instead. Kemper identified issues with its CCS technology, including design flaws that caused leaks.

[15] The same scale challenges apply to other de-carbonization ideas like "**enhanced weathering**", which would require the mining and distribution of billions of tons of silicate rock each year (even more than the tonnage of annual mining of cement and iron ore) with the goal of having these rocks react with CO_2, extracting it from the atmosphere.

c. Cellulosic ethanol

A good friend is a producer for the news program *60 Minutes*, and she recently produced a segment on a company working on cellulosic ethanol. Its approach: use electron beam accelerators to break down cellulose in plant material, rather than using sulfuric acid or steam explosions. The former head of MIT's chemical engineering department is on the company's board, along with a former Shell Oil executive and a former US Secretary of Energy. Sounds promising, right?

It pays to be skeptical here. The history of cellulosic ethanol is littered with exaggerated hype and failed expectations[16]. While US cellulosic ethanol production rose from 2.2 mm gallons in 2015 to 10 mm gallons in 2017, the capacity of these plants is 88 mm gallons, which in turn is 0.06% of annual US gasoline consumption. A big part of the challenge: corn stover has a volumetric density that is just 6% of gasoline. After accounting for that and ethanol's lower *energy* density vs gasoline, the storage and transportation capacity of a cellulosic ethanol ecosystem would need to be **110x** larger than its gasoline counterpart. That's expensive to build, particularly if you have to also spend money breaking down cellulose.

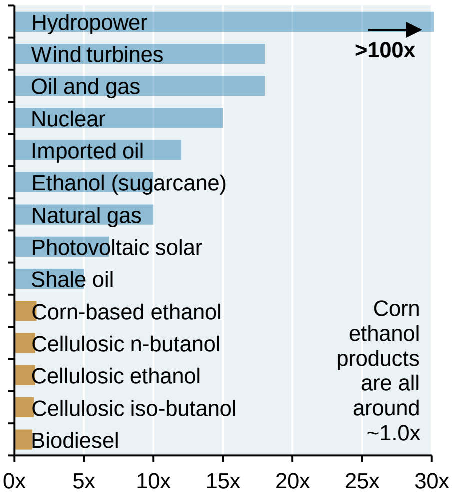
Even so, let's assume the company can lower the cost of cellulosic ethanol production…how much gasoline demand could it displace each year? Let's use an aggressive assumption that all available US corn stover would be used to produce cellulosic ethanol. After accounting for stover that must be plowed back into the soil to maintain its productivity, an assumed haircut for harvesting/evaporation/transportation loss, the conversion ratio of stover into ethanol and energy density differentials, we estimate that cellulosic ethanol could displace just **5%** of US gasoline consumption. Of course, there are other sources of biomass that could be used other than corn stover, but our assumption is optimistic enough regarding available feedstock. *Feasible*, yes. *Likely impact*, very small. One last thing: **energy return on investment** for all forms of corn ethanol are pretty low, as shown on the right.

What % of US gasoline consumption could be displaced by cellulosic ethanol? Around 5%

Description	Value
Stover to grain ratio	1:1
Midpoint stover removal percentage	40%
Metric tons of US corn production	385,000,000
Metric tons of stover available	154,000,000
Kg, annual corn stover	154,000,000,000
Haircut for harvesting, evaporation and transportation loss	15%
Kg, stover left over for conversion to cellulosic ethanol	130,900,000,000
L/kg, conversion ratio of stover to cellulosic ethanol	0.32
Liters of ethanol produced from annual corn stover	41,888,000,000
Energy density of cellulosic ethanol relative to gasoline	66%
Gasoline equivalent liters of cellulosic ethanol	27,771,744,000
Gasoline equivalent gallons of cellulosic ethanol	7,336,541,449
Gallons of US gasoline consumption in 2017	142,980,000,000
% of total gasoline consumption from cellulosic ethanol	**5%**

Sources: Penn State Department of Crop and Soil Sciences; University of Illinois Department of Agricultural and Consumer Economics; Vaclav Smil; David Pimentel (Cornell); Alternative Fuels Data Center, EIA, US Grains Council, JPMAM. 2017.

US Energy Return on Investment



Source: Tao et al, National Renewable Energy Lab; Biofuels, Bioproducts and Biorefining Journal. 2013.

Grade: ▲△△△△

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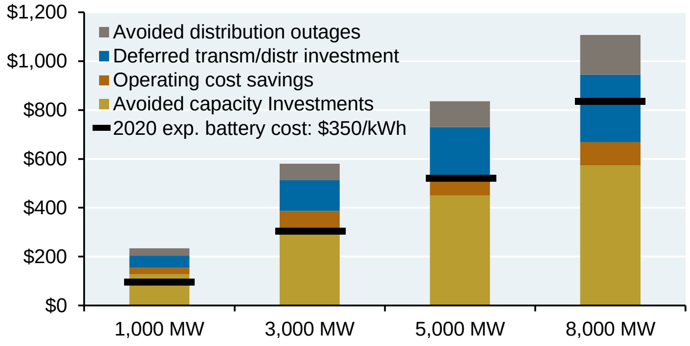
[16] **Cellulosic ethanol hype** includes a 2006 presentation from venture capitalist Vinod Khosla entitled "*Biofuels: Think Outside the Barrel*", that predicted 24.8 **billion** gallons of cellulosic ethanol production by 2017; it was around 10 **million** instead. Companies that built cellulosic ethanol plants include DuPont, Abengoa, INEOS Bio, Range Fuels, Cello Energy, etc. Most of these plants are no longer in operation.

d. Graphene-based supercapacitors for distributed energy storage

Distributed energy storage is critical for achieving greater penetration of renewable energy. The reason: transmission infrastructure is both expensive and politically difficult to build, and in many parts of the world, wind/solar/hydro resources are situated far from urban population centers. This is one of the challenges facing Germany, as we discuss later. As a result, locally distributed energy storage could increase the productivity of renewable energy by reducing the cost of new transmission investment, reducing the need for investment in peaker plant capacity, avoiding distribution outages and reducing peaker plant fuel consumption. The question is whether the economic benefits of energy storage outweigh its costs.

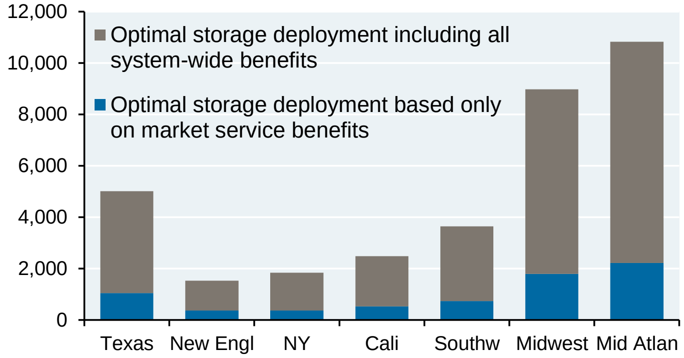
Texas utility Oncor commissioned a study by the Brattle Group to estimate system-wide costs and benefits of distributed storage. As shown in the first chart, the sum of potential benefits are estimated to be greater than costs[17] across different levels of deployment. However, the marginal utility of storage declines as penetration increases since there are typically a limited number of high-cost peaker and transmission projects avoided.

Estimated benefits of storage outweight costs in ERCOT study, US$ millions per year



Source: The Brattle Group. 2018.

Optimal storage levels depend on regulatory changes that allow full benefits to be realized, MW of storage



Source: The Brattle Group. 2018.

An important caveat: the easiest storage benefits to capture are related to market services like energy arbitrage, peaker capacity and frequency regulation. There's a **hornet's nest of issues** that would have to be solved in order to capture the rest, due to restrictions on utility ownership/operation of storage, valuation of customer-level benefits, dispatch priorities, contractual conflicts, etc. The second chart shows lower optimal storage levels by region if the only benefits captured are related to market services.

So, on paper, lithium ion battery storage costs have declined enough to merit inclusion in the grid. As of today, however, utility-scale battery storage is still in its infancy. As of 2017, there was just 1 GW of grid battery storage in the US, compared to 22 GW of pumped hydroelectric storage (most of which was built in the 1970s and 1980s)[18]. Furthermore, both forms of energy storage combined only supplied 0.6% of US electricity in 2017. Currently, 86% of battery capacity is based on lithium ion chemistry, with the remainder split between nickel, sodium and lead acid. If you read green energy blogs, there's a lot of excitement about the potential for graphene-based supercapacitors for energy storage. Let's take a look.

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[17] The cost of individual lithium ion packs is approaching $200 per kWh. However, when using batteries for **utility-scale grid energy storage**, there are additional costs, including DC to AC inverters, power conditioning hardware, software, meters and land/construction costs. We consider $350 per kWh as a reasonable utility-scale estimate.

[18] Similarly, 96% of the global 159 GW in energy storage capacity is based on pumped hydro.

Supercapacitors store energy as a static charge, rather than as an electrochemical reaction as batteries do. They can offer more durability than lithium ion batteries (particularly for remote locations with extreme temperatures[19]), faster charging times (ideal for intraday frequency regulation, generator bridging or short term power reserves) and less lifetime performance degradation[20]. Commercial providers of super-capacitors also claim to have improved their energy density, though they still trail lithium ion batteries substantially in this regard. Costs are higher than lithium ion, but this is before mass production scaling. Tesla's acquisition of Maxwell Technologies could be a sign of greater commercialization potential. To rebalance microgrids, Maxwell claims that a few minutes of supercapacitor storage could replace hours of backup provided by traditional batteries.

Comparison for utility-scale energy storage applications

Feature	Supercapacitors	Lithium ion batteries
Life cycle	1,000,000	2,000 to 10,000
Upfront capital cost	$500 per kWh (w/o production scaling)	$350 per kWh
Round trip DC eff. excluding DC/AC conversion	99% (constant over life)	90% to 99% (degrades over life)
Useable Capacity (% of rated capacity)	100% (constant over life); in practice, 75%-80% (does not degrade)	70% to 90% (degrades over life)
Temperature Range	-30^{0}C to 85^{0}C	0^{0}C to 40^{0}C (higher with climate control)
Max. rate of charge/discharge*	50C	0.25C to 4C
Thermal Runaway	No Risk	Risk greater than zero
Energy Density (Wh/kg, system level)	5 to 30, up to 150 in lab studies	150 to 260 with potential for 400-500
Disposal costs/environmental issues	Given the longer life of supercapacitors, disposal issues are deferred vs lithium ion. As a carbon-based product, graphene appears much less toxic than lithium ion. However, studies do show substantial human and environmental impacts from graphene exposure.	

Source: Electric Power Research Institute, Maxwell Technologies, National Graphene Institute (Manchester, UK), Argonne National Lab. 2018. * C-rates measure speed of charge/discharge. A 1C rating implies charge/discharge in one hour, 2C in 30 minutes, 3C in 20 minutes, 0.50C in 2 hours, etc.

Bottom line: utility-scale battery storage is in its infancy. There are still engineering issues to be solved regarding degradation, maintenance and durability. On paper, declining lithium ion costs may justify battery storage as a replacement for peaker plants in some places. However, substantial changes in rules and incentives are needed to unlock their full economic value. Supercapacitors offer promise in frequency regulation and remote applications, and can serve as complements to a lithium ion storage system for short bursts of high power. But like any unscaled new idea, it's too soon to project their broader impact on energy storage and GHG emissions. I can imagine the scores below improving by 2025 if production scaling drives either cost below $200 per kWh.

Grade: Lithium ion based utility-scale battery storage: △△▲△△

Grade: Supercapacitors: ▲△△△△

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[19] One example: South Dakota based Northwestern Energy has partnered with Kilowatt Labs on supercapacitor storage given the high cost of transmission in a low-density region servicing 1 million people across 300,000 sq miles.

[20] On **lithium ion battery degradation:** According to the Brattle Group, the French utility EDF de-rated its Illinois-based storage project by 30%, and US utility AES announced a "huge de-rate" of its own storage capacity. Such degradation may be real-life confirmation of experiments and simulations by NREL that indicate substantial potential lithium ion capacity loss due to high temperatures, pressure and other mechanical/thermal stress.

e. “Carbon-free” aluminum smelting

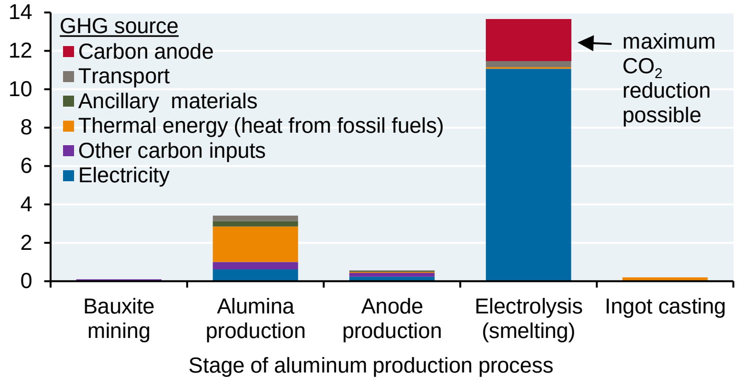
In May 2018, I came across a very exciting headline: “**Apple paves the way for breakthrough carbon-free aluminum smelting method…Apple Played Crucial Role in Development of Joint Venture that Could Change Global Manufacturing**”. That sounds pretty transformational, so I wasted no time in reading it. The idea involved is ingenious, but the scope and impact are less than what I was expecting.

Background: Apple financed a joint venture between Alcoa and Rio Tinto to explore ways of eliminating the need for a carbon-based anode during the process of aluminum electrolysis (the method by which aluminum oxide is converted into aluminum). The venture appears to have succeeded in developing an advanced conductive material that releases oxygen instead of CO_2 as a by-product of aluminum electrolysis. This is great news and a testament to their ingenuity. However, the new approach would only reduce GHG emissions on the margin. The chart below explains why.

Each step in the process used to create aluminum, from bauxite mining to ingot casting, involves GHG emissions with the most energy-intensive step resulting from electrolysis. **Around 84% of GHG emissions from aluminum electrolysis (smelting) are derived from electricity generation; only 16% result from the use of the carbon anode**. When broadening the discussion to the entire aluminum production process, the carbon anode only accounts for ~10% of its GHG emissions.

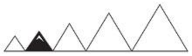
The elimination of the carbon anode in aluminum production could at its upper bound eliminate 138 million tons of CO_2 each year, assuming 63 million tons of annual global production. If so, that upper bound would reduce annual global CO_2 emissions by around 0.4% if adopted universally by producers. The approach might also be adapted for other de-carbonization processes. However, I would not describe the new idea as “carbon-free smelting”, nor would I describe it as “changing global manufacturing”.

Only 16% of electrolysis emissions result from carbon anode, Tonnes of CO_2 equivalent per tonne of aluminum produced



Source: International Aluminum Institute. June 2017.

Grade:



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