A Novel Method for Grid Energy Storage Using Aluminum Fuel

White paper
Alchemy Research, April 2012

Abstract

Energy storage is a key element in ensuring reliable power supply from renewable energy power stations. Present energy storage technologies leave much to be desired in terms of energy density, cost, efficiency, safety and scalability. The Alydro technology developed by Alchemy Research enables a cost-effective energy storage system with energy capacity in the GWh scale based on aluminum as recyclable and transportable fuel.

Introduction

Electric grid power must be reliable and meet peak consumption, yet the leading renewable energy sources – wind and solar – are intermittent. To balance supply and demand, excess energy needs to be stored during high availability periods, to be used when power consumption exceeds renewable source's supply.

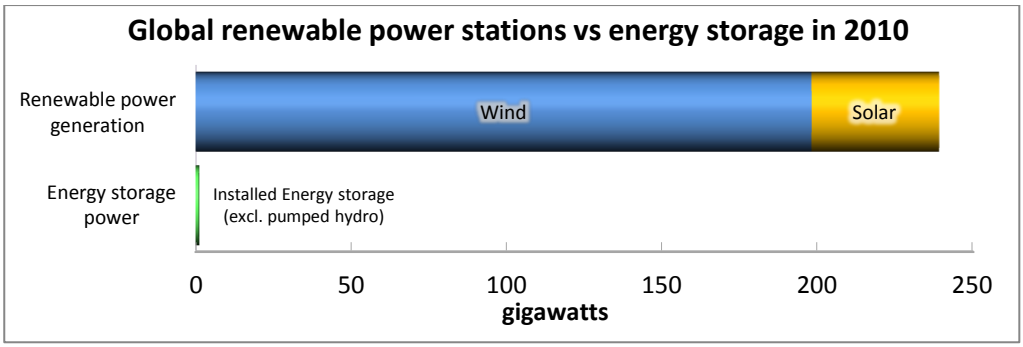
Energy storage system is rated by power and energy capacity.
Power – measured in megawatts – is the rate of energy a storage system can absorb or supply.
Energy capacity – measured in megawatt-hour – is the total energy storage capacity of the system.
The **duration** energy-storage-system can supply power at maximum load is determined by the ratio between energy capacity and power.

According to EPRI[1], renewable power stations require an energy-storage-system having power of up to 400 MW and energy capacity of up to 4 GWh in order to provide utility-scale storage and ancillary services for grid integration.

Global solar power cumulative capacity was 41 GW in 2010[2]. Solar projects under development in the US alone total 28.2 GW[3].

Global wind power cumulative capacity was 198 GW in 2010[2] and is expected to grow to 493 GW by 2016[4].

Yet, excluding pumped hydro – which is not a viable option for the majority of power-stations - the combined power of worldwide installed grid energy storage is under 1 GW[5] and combined energy capacity is just under 6 GWh– a far cry from the requirements of renewable power stations.



This discrepancy is due to prohibitive limitations of present energy storage methods.

[1] **Electric Power Research Institute,** *"Electricity Energy Storage Technology Options"* 1020676, 2010, pp. 53
http://goo.gl/sf9Gp

[2] **REN21,** *"Renewables 2011, Global Status Report"*, 2011
http://goo.gl/I4Es3

[3] **Solar Energy Industries Association,** *"Utility-Scale Solar Projects in the United States"*, 2012
http://goo.gl/M96Ua

[4] **Global Wind Energy Council,** *"Global Wind Report, Annual market update 2011"*, 2012
http://goo.gl/Ul7sv

[5] **International Electrotechnical Commission,** *"Electrical Energy Storage, white paper"*, 2012, pp. 46
http://goo.gl/ZUdlb

Present grid energy storage methods

Pumped-storage hydroelectricity

PSH is the most widely used form of grid energy storage. PSH has energy efficiency of over 70%, but has severe drawbacks where scalability is concerned:

- PSH has very low energy density, and takes up landscape scale area
- PSH requires two nearby reservoirs at considerably different heights
- PSH requires extremely high construction cost

Pumped storage hydroelectricity takes up landscape scale area.

Batteries

Batteries have a very short response time making them suitable for stabilizing power grids. Yet, batteries have several drawbacks as a major form of grid energy storage:

- Relatively low energy density of under **0.5 kWh / liter**
- Limited lifespan of charging / discharging cycles
- High cost per kWh

Flow batteries

Flow batteries are based on reactive chemicals dissolved in electrolyte that can be stored externally before being pumped into an electrochemical cell for generating energy. An advantage of flow batteries over standard batteries is independence of power and energy capacity. The major drawback of flow batteries is energy density much lower even than that of standard batteries.

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Sodium-sulfur batteries

NaS batteries have high efficiency of over 80% and energy density higher than flow batteries. The major drawbacks being:

- Safety – some major fire incidents in NaS batteries sites have been reported
- High cost per kWh

Compressed air

Compressed air energy storage is practical in locations where underground cavern for air-storage is present. Above ground the low energy density of CAES limits its usability for large scale energy storage.

Thermal

Thermal storage using molten salts is a practical solution when the energy source is concentrated heat – as in concentrated solar power. The drawbacks of thermal energy storage are

- Low energy density
- Heat loss making long term energy storage impossible

Other methods

Flywheels and super-capacitors are suitable for stabilizing grid power but their energy density is too low for supplying power for long duration.

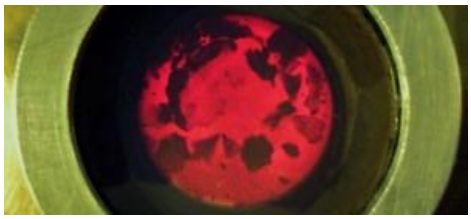
The major challenge with hydrogen energy storage is that high volume hydrogen storage in tanks is expensive and imposes significant safety risks. On-site generation of hydrogen using Alydro is an effective and safe alternative.

Alydro energy storage

About the Alydro technology

Alydro is a new process for producing energy from a reaction of aluminum and water developed by Alchemy Research. Alydro stands for Aluminum-Hydro.

Alydro reaction takes place in a reactor at elevated temperatures of up to 900°C. A stationary Alydro reactor can be built at a large scale to generate megawatts of power in the form of hydrogen and heat.



Prototype Alydro reactor

The only by-product of the Alydro reaction is solid aluminum-oxide which is fully recyclable.

Alydro reactor can generate megawatts of power in the form of hydrogen and heat.

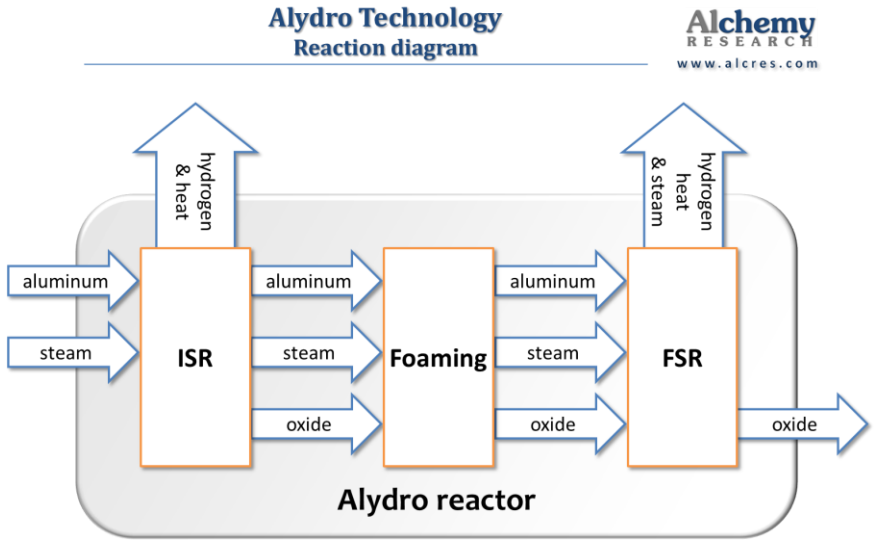
Alydro reaction

The reactants in Alydro are aluminum and water. The reaction products are hydrogen and aluminum-oxide.

$$2\,Al + 3\,H_2O \rightarrow Al_2O_3 + 3\,H_2$$

*2 **Aluminum** atoms and 3 **water** molecules react to form one **aluminum oxide** molecule and 3 **hydrogen** (H_2) molecules*

Aluminum stores 8.6 kWh of energy per kg. The Alydro reaction is highly exothermic - 49.4% of the energy produced by Alydro is released as heat, the other 50.6% are released in the form of hydrogen. The excess heat of the reaction is utilized to sustain the temperature within the reactor required for the reaction to proceed.

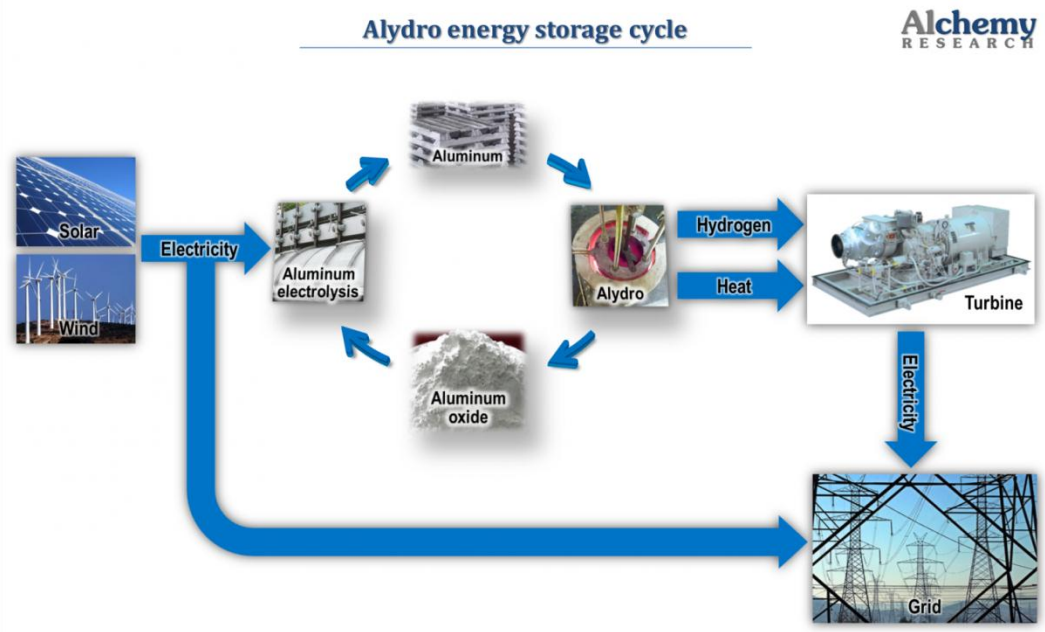


More information about Alydro technology is available under NDA.

How Alydro energy storage works

Alydro enables energy storage by chemical reduction of aluminum-oxide into aluminum and energy generation by aluminum oxidation into aluminum-oxide.

Aluminum used in the process is fully recyclable, resulting in a sustainable energy storage process.



Energy storage using Alydro provides unlimited energy storage for unlimited time with no energy loss.

Energy storage using Alydro energy cycle has some unusual benefits:

- Complete independence of storage power, generation power and energy storage capacity
- Unlimited energy storage for unlimited time with no energy loss
- Possibility to safely transport between sites energy-carrying aluminum and aluminum-oxide for recycling

Process stages

The major stages of the Alydro energy storage cycle are detailed below. It is worth noting how energy absorption power, energy storage capacity and generation power are all independent from each other.

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Storing energy by aluminum electrolysis

Energy from electrical source – e.g. solar panels or wind turbines – powers an aluminum electrolysis smelter to reduce aluminum-oxide into aluminum. The produced aluminum is collected and stored to be used for energy production later.

Aluminum electrolysis by the Hall-Héroult process is a mature industry producing 10s of million tons of aluminum annually.

Emission-free smelters using inert-anodes are expected to become available by 2015. Alydro energy storage systems will utilize inert-anode smelters.

The capacity of electrolysis cells installed should match electrical power available for storage. Storage energy capacity is dependent on the amount of aluminum-oxide that goes through the smelters over time. Power generation capacity depends only on the total power of Alydro reactors installed.

Aluminum fuel

Aluminum in metallic form contains 8.6 kWh of energy per kg. Alydro extracts this energy by oxidizing the aluminum. Therefore, the aluminum used in the Alydro energy-storage-cycle can be considered a fuel. As a fuel, aluminum exhibits some unusual characteristics:

- Aluminum fuel is solid state – enabling low-cost warehousing and transporting
- Aluminum fuel is perfectly safe – it is nonflammable and nontoxic
- Aluminum fuel has an extremely high energy density of 84 MJ/l – 2.5 times that of gasoline, therefore large amounts of energy can be warehoused safely taking up little space
- Aluminum fuel is inert - protected by a thin surface layer of aluminum-oxide that forms on contact with air, aluminum can retain the energy stored in its metallic form for decades with zero loss

Aluminum fuel has an extremely high energy density of 84 MJ/l – 2.5 times that of gasoline.

The ability to store the aluminum fuel safely for very long time, transport the aluminum fuel and recycle it on-site or off-site – enable unprecedented flexibility in the design of energy storage systems.

Generating energy by the Alydro process

The Alydro reactor produces energy by the Alydro process developed by Alchemy Research.

Alydro process brings molten aluminum and steam into reaction at elevated temperatures – generating hydrogen and heat. Water is recycled in the process, so the only by-product is solid aluminum-oxide, which is reserved for recycling into fresh energy carrying aluminum at the on-site electrolysis smelter.

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Power generation capacity depends on the total capacity of Alydro reactors installed. The duration of power generation depends on the amount of aluminum stored.

Energy conversion

The Alydro reactor generates energy in the form of hot hydrogen and high temperature steam. The Alydro energy storage cycle is agnostic on how the generated energy is converted into electricity. Implementation may consist of turbogenerators, fuel-cells and heat engines.

Alydro's extreme temperature gradient and availability of hydrogen as combustion gas as well as a working gas allow for efficient Rankine, Brayton or Stirling cycle implementation.

Benefits of Aldydro energy storage

High energy capacity

Alydro process extracts the energy stored in bulk aluminum. Aluminum has extremely high energy density.

- 1 kg of aluminum stores 8.6 kWh of energy
- Storing 1 MWh of energy requires 116 kg of aluminum taking up space of just 43 liters
- 1 cubic metre of aluminum stores 23 MWh of energy

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The aluminum used as fuel for Alydro does not require special containers – therefore by using Alydro energy storage, extra GWh of energy can be stored at no additional infrastructure cost – just by warehousing more aluminum.

Low cost

Using Alydro, energy is stored by converting aluminum-oxide into aluminum using the industry-standard aluminum electrolysis process. Storing 1 kWh of energy in aluminum costs just $0.22 in the broad market. Furthermore, the major portion of the cost is electricity put into the electrolysis process, and since surplus generated electricity will be used, actual cost will be reduced.

The Alydro reactor generates energy while converting aluminum back into aluminum-oxide.

Efficiency

The efficiency of aluminum electrolysis today is approaching 70% and is improving with each new generation of smelters introduced to the market.

The efficiency of the Alydro process is over 75% where 2.1 kWh of energy are spent to produce 8.6 kWh.

Safety

Both aluminum and aluminum-oxide are nontoxic, nonflammable and nonpolluting. Both are inert solids that can be easily warehoused and transported.

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Long term storage

With Alydro energy storage – energy can be stored for decades with no degradation. The energy is contained in the aluminum itself. Aluminum has excellent corrosion resistance. Tons of aluminum can be warehoused for any period of time while not requiring any special containers.

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Independent scalability of power and energy capacity

Alydro energy storage is unique in its ability to store the energy in a low-cost commodity aluminum – serving as recyclable fuel.
This allows separate scaling of:

- Energy storage rate by installing aluminum-oxide electrolysis smelters to match available energy

- Available Power by installing Alydro reactors with the aggregate power to meet maximum demand
- Energy capacity by warehousing the required amount of aluminum / aluminum-oxide to ensure prolonged power generation

Having energy stored in recyclable solid aluminum has another benefit – aluminum and aluminum-oxide can be efficiently transported between sites to balance supply and demand.

Transportability

Alydro energy storage stores energy in the form of commodity solid aluminum as fuel. This has a significant advantage over other grid energy storage methods in the ability to transport the aluminum fuel between generation sites and likewise transport aluminum-oxide for recycling.

A single trailer loaded with 50 tons of aluminum carries 430 MWh of energy.

- A single trailer loaded with 50 tons of aluminum carries 430 MWh of energy
- Aluminum is nonflammable and nonpolluting solid, making it the safest fuel to transport

That, together with the low-cost of warehousing tons of aluminum enables statewide effective planning of renewable power stations capacity as well as multi-layer failover risk mitigation.

Regional peak in power consumption

When power consumption is expected to peak in a region due to an event or extreme weather conditions - aluminum fuel reserves are transported from remote sites to the affected power stations where the Alydro power generators are deployed to supply extra power.

Seasonal power capacity

Solar power stations capacity is reduced in winter due to shallow sun ray incidence angle and becomes less predictable due to overcast. In Alydro energy storage power stations this leads to higher utilization of Alydro generation, together with lowering on-site aluminum recycling capacity. Larger reserves of aluminum should be brought on-site while aluminum-oxide beyond the site's recycling capacity is transported to other sites for recycling.

Emergency reserves of aluminum fuel

Large amount of aluminum is warehoused centrally and is transported to generation sites in case of an emergency that prevents sustained power supply - either due to a natural disaster or to power station failure.

Load balancing with aluminum fuel

The intermittent nature of renewable energy sources, where Alydro energy cycle mitigates the discrepancy between supply and consumption may lead to a mismatch between amount of recyclable aluminum-oxide accumulated on-site and the level of surplus power for recycling it back into aluminum. To address that, aluminum-oxide is transported from a site having limited surplus power to another site having power glut.

Electrolysis smelters as backup

In case of a broad imbalance between aluminum fuel consumption and on-site aluminum recycling capacity, aluminum-oxide is sold and transported to large-scale industrial aluminum electrolysis smelter where it is reduced into aluminum and in exchange aluminum is bought and transported to the renewable power station. This way the ability to use commodity aluminum for power generation buys the time needed for expanding the renewable power station for increased power capacity without compromising continuous reliability of power supply.

Use of commodity Aluminum for power generation allows expanding the power station without compromising continuous power supply.

Summary

Renewable energy power stations are being planned and constructed worldwide on a larger scale than ever before, but the intermittent nature of renewable energy requires energy storage facility as a key element of any renewable power station integrated into the grid. As shown in this paper - present energy storage technologies cannot scale to meet the required energy capacity.

Alydro is a novel technology using commodity aluminum as a cost-effective recyclable fuel. Alydro can fill the energy storage gap, cost-effectively storing gigawatt-hours of energy, while providing the benefits of safety, no pollution, long term storage with no energy loss, independent scalability of power and energy capacity and transportability of the aluminum fuel.

About Alchemy Research

Alchemy Research was founded in 2012 by the inventor of the Alydro technology, following 3 years of research. Alchemy Research goals are to develop and commercialize the Alydro technology.
The company's headquarters is in Haifa, Israel.

Contact Alchemy Research

To learn more about the Alydro technology or inquire about partnership and investment opportunities with Alchemy Research please visit www.alcres.com or email info@alcres.com