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THE ROAD TO ELECTRIC AEROPLANES

GRAVITY ENERGY STORAGE

SOLAR GREENHOUSES
FOR SUSTAINABLE FOOD PRODUCTION

THE ROAD TO ELECTRIC AEROPLANES

INTRODUCTION

As the transportation industry increasingly comes under scrutiny for carbon emissions, more and more aeroplane makers are looking at the possibility of electric aviation for applications that range from air taxis and flying cars to regional aircraft and, most ambitiously, commercial airliners. In this sense, regional aircraft and commercial airliners – as opposed to air taxis and flying cars – do not represent a new urban mobility solution, but rather involve replacing fossil fuel-based engines with electric powertrains. To this end, companies are turning mainly to next-generation batteries and hydrogen systems for a solution. Yet, there are significant hurdles on both the regulatory and technical fronts, with key challenges including safety, development of new infrastructure and having a sufficiently high-energy density to enable travelling meaningful distances.

Figure 1. X57 Maxwell all-electric aircraft under development by NASA.
Source: Allard, 2016

Unique selling proposition

Aeroplane emissions in 2019 accounted for approximately 2.5 per cent of global greenhouse gas emissions, and are forecast to rise by as much as 27 per cent by 2050. With electric aviation, these rising emissions could be significantly reduced. The reliance of the new planes on electricity would result in lower operational costs due to a reduction in electricity costs, and lower maintenance costs than combustion engines. This has the potential to result in cheaper tickets for passengers. Furthermore, the use of electric propulsion systems can result in decreased noise, bringing benefits to communities surrounding airfields. With an electric engine, planes are able to maintain performance at higher altitudes where the air resistance is less, unlike combustion engines that operate less efficiently at these altitudes. The aircraft engine would therefore have to be less powerful to generate equivalent speed.

Technology

An electric aircraft is powered by electric motors. Electricity may be supplied by a variety of methods, including batteries, solar cells and fuel cells, among others. However, the use of electricity for an aircraft's propulsion systems represents a radical change from today's propulsion technologies.

There are generally two different architectures available for electrical propulsion.

- Hybrid-electric architectures augment traditional jet engines with electric motors that a set of batteries feed to drive the fans in the engine. Hybrid configurations use traditional propulsion for large parts of flights due to the current shortcomings of battery capacity. These systems thus draw on electrical power either in high thrust parts of the flight, such as take-off and climb, or switch entirely to battery power during cruise, when thrust requirements are lower.

- Another option is an all-electrical propulsion, in which the sole source is a set of batteries, while the gas turbine and associated fuel system present in hybrid-electric configurations are completely eliminated. Hence, the range of an aircraft with an all-electrical propulsion system will be heavily dependent on battery storage capacity and weight.

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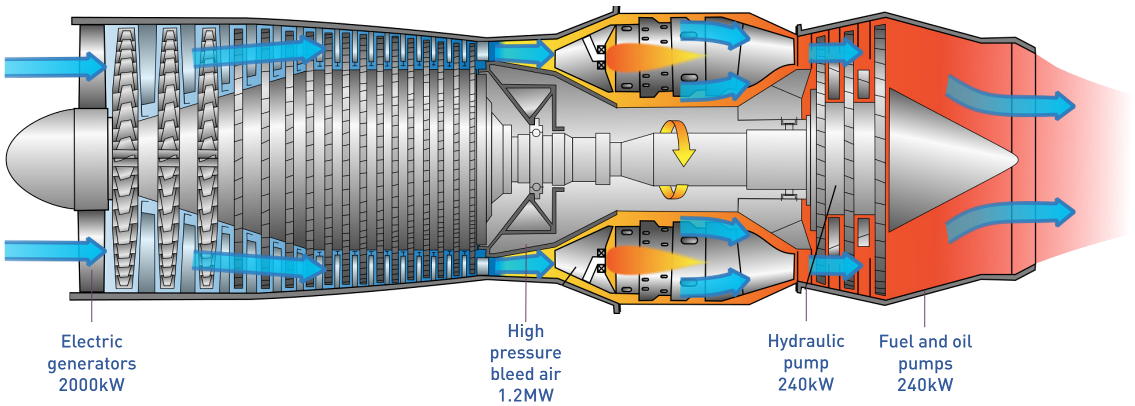

Figure 2. Power consumption of a propulsion system for conventional airplanes.
Source: Jeff Dahl

The use of any of the mentioned architectures will depend on the aircraft application: either small regional aircraft or large commercial airliners. Small regional aircraft encompasses aeroplanes with the capacity to seat between 10 and 20 people, or small cargo planes. These planes target use cases ranging from island hopping to fjord hopping and accessing rural locations. Commercial airliners, on the other hand, can seat more than 100 passengers and travel longer distances.

Small regional aircraft

Today, small aircraft are more numerous than large commercial airliners. According to the General Aviation Manufacturers Association (GAMA), there were about 15,520 turbo-prop planes and 22,270 business jet aircraft (most of which are not commercial airliners) in service globally at the end of 2018. Instead of vertical take-off and landing (VTOL) configurations as in air taxis, small regional aircraft incorporate fixed-wing architectures due to increased efficiencies at cruising altitude and availability of landing strips. Developers of small aircraft are evaluating the use of both hybrid and all-electric power trains. The latter have the potential to enable more aerodynamic aircraft designs due to the lack of a hot exhaust.

Electric aircraft in this category target business cases related not only to the replacement of current non-electric aircraft, but also to competing with road- or rail-based transportation, drawing on the benefits of Electrical Propulsion in terms of reduced noise and zero emissions. Small aircraft are considered as test beds for eventual scale up into larger platforms.

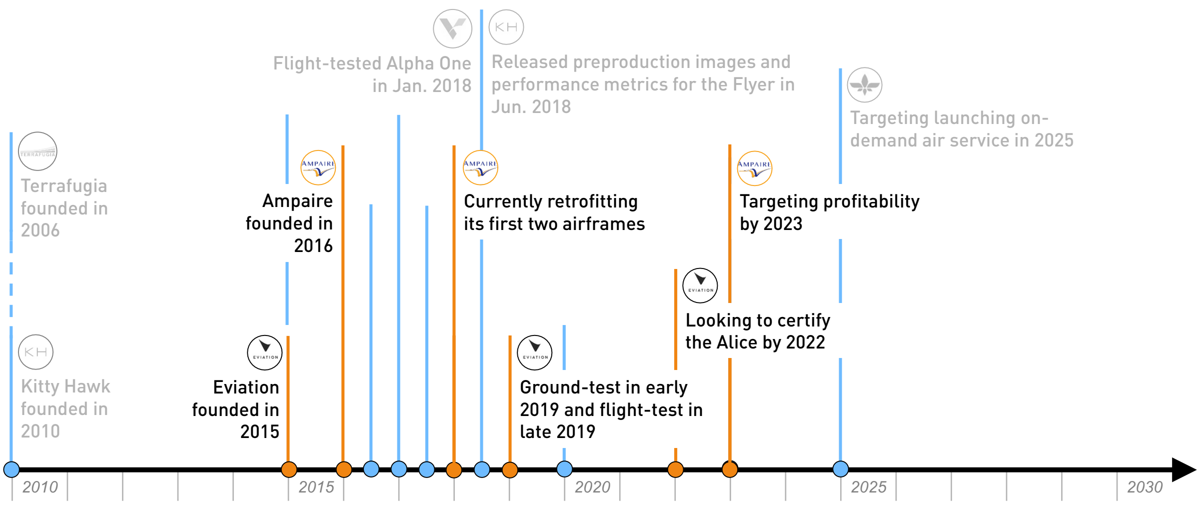

Figure 3. Efforts by start-ups in the small aircraft space.
Source: Lux Research

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Large aircraft manufacturers such as **Airbus** are active in the space, as are component suppliers like **Siemens**. **Boeing**, for example, has recently partnered with **JetBlue** to co-invest in **Zunum Aero**, which plans to eventually scale up its regional development to a 50-seater platform.

There are fewer start-ups targeting this industry rather than the air taxi market. These companies also tend to be younger than the leading start-ups building air taxis and flying cars.

Commercial airliners

Aerospace Original Equipment Manufacturers has been working on electrifying commercial airliners for years, but has not succeeded in overcoming technical and cost hurdles. In 2015, Airbus proposed a pre-competitive consortium to tackle the problem with its competitors, but it had to ratchet down its ambitions from all-electric to hybrid electric. Boeing has pursued electric aircraft without success beyond small-scale experiments. Other engine manufacturers like **Rolls-Royce** have been less active in the space. Start-up activity in the commercial airline market has been minimal due to the long commercialisation timeline and high capital expenditure required to participate.

Challenges and prospects

The electric aircraft industry is still in its early days, and developers face numerous technical and regulatory hurdles that limit their timelines for commercialisation and available geographic markets.

Battery technologies

The most significant limiting factor for the development of electric aircraft lies in the range they can achieve with current energy storage technologies.
Currently, batteries cannot provide the power-to-weight ratio needed for electric aviation to be feasible. For batteries to be at a point where it is economically feasible to work in small-scale aviation, they will need to achieve about four-to-five times their current density. For commercial airliners, a power demand of ~40MW would be required to generate the thrust necessary for airplanes. This represents an increase of ~25 times the current scope of electrical systems in aircraft. Electrification is thus limited by available storage technologies.
Jet fuel yields about 40 times more energy per kilogram (kg) than today's battery technologies. As such, powering a plane the size of a commercial airliner would impact the plane's ability to carry cargo and passengers. In the case of small regional aircraft, **Airbus** estimates that its hybrid electric E-Fan X would require a 2MW electric motor and a 2,000kg battery pack to replace only one of the aircraft's four gas turbine engines.

Meanwhile, electric aircraft developers are building more aerodynamic designs with lighter materials. This will result in a reduced power demand from the aircraft over time.

Battery re-charging
An additional challenge for electric aircraft is the need to enable quick turnaround times from the moment aeroplanes land to then pick up new passengers and take-off. Battery swapping represents a potential solution to this. However, issues around a lack of a charging infrastructure and the degradation of batteries remain. Finally, batteries have higher maintenance costs than gas turbines and require replacement after a limited number of charge cycles (~1,500-2,000).

Power electronics

While the size and weight of energy storage systems are the limiting factors for all-electric commercial airliners, even mild hybridisation is inhibited by the size and weight of the required power electronics systems. Most electricity generation systems of these sizes are currently used for grid applications, where, unlike aircrafts, power electronics are not strictly constrained by available space or weight limits. Power converters are particularly bulky and heavy, and innovations on these systems are needed to enable hybrid propulsion systems.

According to the Advanced Research Projects Agency-Energy (ARPA-E), power converter performance, weight and size could be improved by incorporating innovations in semiconductors, circuit design and system architecture. In August 2018, the United Technologies Research Centre (UTRC) secured two ARPA-E grants through the Creating Innovative and Reliable Circuits Using Inventive Topologies and Semiconductors (CIRCUITS) programme to make more efficient, smaller, lighter power converters for aircraft using silicon carbide (SiC) or gallium nitride (GaN) devices.

Thermal management

A key challenge that exists in the construction of electric aircraft is creating a practical cooling system that can be used. Thermal management for these systems will require a system that can reject anywhere from 50kW to 800kW of heat in flight. Similarly, a cooling system for the integrated power module used for high-power electronics is necessary. Materials will need to be developed for improved thermal performance, and a lightweight system developed for the power electronics cooling. Superconductivity and supercooled electronics will be required to reduce the electrical resistance of the aircraft.

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Generators and motors

Hybrid and all-electric aircraft will all require light, efficient and high-power density motors to fit in with the weight and size constraints of an aircraft, particularly for configurations that employ multiple distributed fans to achieve high propulsive efficiency. Hybrid architectures will also require light, efficient and high-power density generators to convert shaft power to electricity, along with an intermediate, lightweight gearbox to reduce the turbine's high rotational speed to a slower rate suitable for a generator. For generators alone, the power output requirements will be ~40 times higher in an all-electric commercial aircraft than today's aircraft. A **Boeing** 787, which is today the aircraft with the highest electricity demand, only generates 1MW from four 250kW engine-mounted generators.

Common small aircraft flight routes
Country, application

Paris – Geneva *Europe, private flight*	*411 km*
Bergen – Ålesund *Norway, fjord hopping*	*235 km*
Anchorage – Fairbanks *U.S., rural access*	*420 km*
Honolulu – Maui *U.S., island hopping*	*167 km*

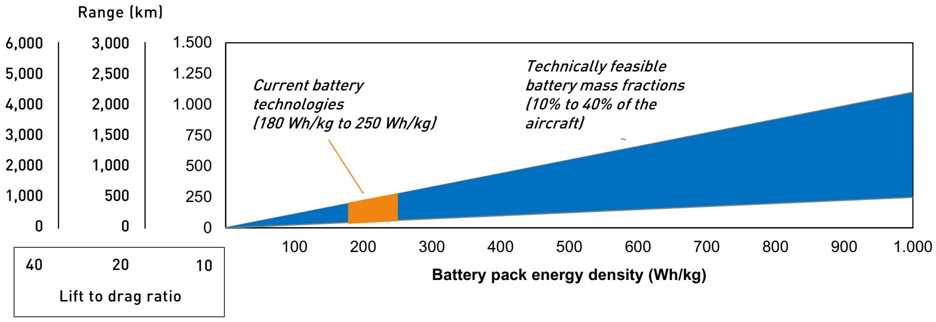

Figure 4. Improvements in battery technologies needed for small aircraft. An electric aircraft's range depends on several factors: available energy, expressed as the battery's energy density (Wh/kg); the masses of the battery system, aircraft, and payload, expressed as the battery's mass fraction of the total mass (%); and the aircraft's aerodynamic properties, expressed as the ratio of lift to drag (L/D). This figure is typically between 10 and 20 for civil aviation aircraft and can reach as high as 40 for gliders. Figure 4 shows how these factors affect the aircraft's range, with possible ranges varying from 40km to 550km for civil applications and up to 1,100km for gliders. These ranges are well within the bounds of flights commonly travelled by small regional aeroplanes.
Source: Lux Research

Innovations to Watch

- **Next-generation batteries:** Next-generation battery technologies such as lithium-sulphur batteries are lighter and cheaper than current Li-ion batteries, but capacity degradation limits the lifespan due to side reactions in the electrodes, and cathode volume expansion is a safety concern. Similarly, solid-state batteries have emerged as a promising candidate to replace conventional liquid electrolytes in today's Li-ion batteries, enabling the use of active materials that can store more energy while also improving safety. However, it will be years until these technologies are ready for commercialisation.

- **Battery packaging:** Novel battery pack designs and innovations will be crucial to improve the safety of batteries powering electric aircrafts. Li-ion batteries have the risk of suffering a "thermal runway", caused by short-circuiting. This could result in a chain reaction that affects all batteries in a pack, causing combustion of the pack. **NASA** has been developing a novel packaging design involving an aluminium block with holes to hold the batteries a millimetre or less apart, isolating them and dissipating heat from any runaway event throughout the block. Similarly, **Rolls-Royce** has been developing liquid cooling techniques where all the cells in a battery directly contact a cooling plate through which a water-and-glycol mixture is piped. The company complements this cooling system with an ultra-strong outside case and continual monitoring of each battery's temperature and voltage to shut off batteries in case issues are detected.

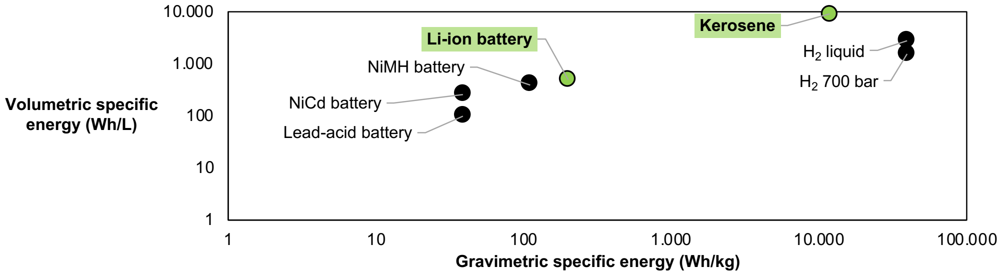

Figure 5. Energy densities of different energy storage systems.
Source: Lux Research

Commercial aspects

Electric aircraft has the potential to create cost savings related to the replacement of fuel-driven engines to all-electric systems. A small turbo-prop aircraft uses ~US$400 on conventional fuel for a 100km to 150km flight. In comparison, all-electric aircraft such as the Pipistrel Alpha Electro have completed flights of similar distances with an electricity cost at US$5.

A commercial consideration for the small regional aircraft market is that recently, airlines have switched to buying larger regional aircraft in the 70 to 90 seat category owing to the high per seat cost of smaller aircraft. As many of the initial set of electrically propelled regional aircraft target the declining smaller end of the regional aircraft market, the manufacturers will have to convince the airlines of the value proposition these new products will offer. Furthermore, regional jets typically fly six to eight sectors per day, so any all-electric regional aircraft will need either very rapid re-charging capability, or the ability to exchange depleted batteries for freshly charged batteries within the time of the aircraft's turnaround at the gate.

Regulatory aspects

To enable the potential of electric aircraft, a regulatory environment enabling new technologies, new platforms and new aviation systems is required.

In 2017, both the European Aviation Safety Agency and the Federal Aviation Administration in the US amended their regulatory frameworks to permit the electrification of small aircraft. The rule changes are very similar and forego technical design specifics in favour of objective-driven requirements. This enables increased design flexibility, allowing developers to more easily incorporate new technologies like battery electric powertrains. Thus, regulatory barriers for small electric aircraft no longer exist in these locations. In the UAE, the Academy of Technical Training has started issuing permits for private individuals to fly electric-powered airplanes after completing training. The training program involves an all-electric plane, dubbed Alpha Electro, which is assembled in the UAE.

In the commercial airliner segment, regulations are largely motivated by international flights' high emissions. According to the European Commission, aeroplane emissions currently account for about 3 per cent of total EU greenhouse gas emissions, and about 4 per cent of world greenhouse gas emissions. The European Commission also estimates that in 2020 the global emissions from civil international flights are 70 per cent higher than 2005 levels, and the United Nations' International Civil Aviation Organisation (ICAO) forecasts that by 2050, they could grow by an additional 300 per cent to 700 per cent.

As such, many of the regulatory efforts affecting electrification of commercial airliners comes from international agencies and organisations looking to curb emissions from international flights. The International Air Transport Association's 2009 goal to reduce aviation emission levels by 50 per cent by 2050 compared with 2005 levels has been a key driver.

But since then, the ICAO's Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) has emerged as the definitive standard for reducing emissions from international fights. The main goal of CORSIA is to keep carbon emissions from international flights at 2020 levels using carbon offsets and other methods such as the use of alternative fuels and the application of energy efficiency measures.

Analogous to automakers designing to meet efficiency standards, airlines will be able to reduce their offset burdens by hybridising propulsion systems, downsizing aircrafts and electrifying some aircraft functions, such as engine start, air conditioning and cabin pressurisation, as well as replacing hydraulic systems with electric actuation. On top of this, the European Aviation Safety Agency aims to categorise aircraft based on their CO_2 emissions.

THE ROAD TO ELECTRIC AEROPLANES

Spotlight on Masdar: Solar Impulse 2

The Solar Impulse 2 electric aeroplane was the first aircraft to fly around the globe powered only by the sun. **Masdar,** Abu Dhabi Future Energy Company, was the official host partner of Solar Impulse 2, and shared the project's long-term vision and desire to explore new horizons. In March 2015, Solar Impulse 2 took off from Abu Dhabi, the capital of the UAE, for its 16-stop journey around the world that included Oman, India, Myanmar, China, Japan, the United States, Spain and Egypt. Over the course of its journey, the aircraft set a number of records, such as the world's longest solar-powered flight in both time (117 hours, 52 minutes) and distance (8,924km). Overall, the aeroplane completed more than 500 flight hours, cruising at altitudes of up to 9,000 metres at average speeds of between 45km/h and 90km/h.

The Solar Impulse 2 has a wingspan of 71.9m, which is more than a Boeing 747 (68.5m) airliner. However, the carbon-fibre body of the Solar Impulse 2 weighs just 2.3 tonnes, about 65 times lighter than a Boeing 747. The wingspan not only improves the aircraft's aerodynamics but provides sufficient area for the integration of solar cells.

Figure 6. The Solar Impulse 2 has a carbon-fibre body covered with 17,248 solar cells.
Source: Masdar

The plane is powered by 17,248 solar cells, which cover the top of the wings, fuselage and tailplane for a total area of 269.5 m2, and rated at 66 kW peak. Similarly, it features four electric motors and 4x21 kWh Li-ion batteries providing 7.5kW each. The batteries are covered by a dense foam for isolation.

While the technologies onboard the Solar Impulse 2 are currently insufficient to enable the transition to electric commercial airliners, they open up prospects for the development of electric aircraft for regional transport in the near-term. The advanced controls manage battery charging and maximise the efficiency of the electric motors and of isolating materials for the batteries and electronics. These controls are also highly applicable to hybrid architectures and small all-electric aircraft. In fact, a spin-off from Solar Impulse, H55, has recently integrated an electric propulsion system in a two-seater aeroplane manufactured by **BRM Aero**. The H55's system is designed to maximise and optimise the use of battery technologies in the electric aircraft – dubbed Bristell Electric – highlighting the value of the technology in the Solar Impulse 2.

Figure 7. Piloted by Bertrand Piccard, Solar Impulse 2 touched down to a rapturous reception at Al Bateen Executive Airport in Abu Dhabi on July 26, 2016, returning to the city where its journey began.
Source: Masdar

Figure 8. Solar Impulse 2 flying over a concentrated solar farm.
Source: Masdar

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KEY DEVELOPERS

Company	Founded (country)	Description	Differentiator
Zunum Aero	2013 (US)	**Zunum Aero** is developing an electric and hybrid regional aircraft, with initial design for a 10-passenger plane with 1,000km range in the "early 2020s".	**Zunum** is developing small passenger aircraft powered by electric motors and ducted fans. It claims that this system will cut travel time by 40 per cent to 80 per cent, and that it will also lower operating costs' time by 40 per cent to 80 per cent.
Airbus	1970 (France)	**Airbus** is developing the E-Fan X aircraft with **Rolls-Royce** and Siemens as a hybrid-electric airline demonstrator.	Development of this aircraft is building on work completed with the **Airbus** E-Fan, a prototype two-seater electric aircraft that was under development by **Airbus**. It uses on-board lithium-ion batteries to power a 2MW electric motor.
Wright Electric	2016 (US)	**Wright Electric** is a start-up aiming to create a 150-seat commercial airliner that runs on batteries and for distances of less than 450km.	It claims its airplanes will be 50 per cent quieter and 10 per cent less expensive to operate than ICE planes. So far, the company has built a two-seat proof of concept, which contains 300kg of batteries. In September 2017, UK budget carrier **EasyJet** announced it was developing with Wright Electric an electric 180-seater aircraft to be developed by 2027.
Ampaire	2016 (US)	**Ampaire** is developing a scalable electric powertrain system with swappable Li-ion batteries for retrofitting small passenger and cargo aircraft with flight paths of less than 150km.	**Ampaire** is also developing its own electric fixed-wing aircraft design, called TailWind, which incorporates a boundary layer ingesting propulsor into the plane's tail fin; the company expects incorporating this propulsor to increase energy efficiency by about 10 per cent.
Joby Aviation	2009 (US)	**Joby Aviation** has spent the past decade developing their own electric motors and their current VTOL design from the ground up.	Key claims of the company include 322km/h cruise speed, 250km flight range, and hundredfold decrease in noise production at take-off and landing compared with conventional aircraft. The new vehicle is being developed to fly as many as five people.

Takeaway and Recommendations

The increasing pressure on the aviation industry to reduce CO_2 emissions has created opportunities for aerospace majors and start-ups to develop novel aircraft with electrical propulsion systems. While the technologies have the potential to significantly reduce carbon emissions, reduce engine noise, improve energy efficiency, and reduce operation and maintenance costs of aircraft, it has a road to commercialisation marred by technical challenges. A key challenge is that today's battery technologies do not have the energy and power densities of jet fuels. The footprint and heat generated by the power electronics driving the motors of electric aircraft represent another roadblock for the adoption of electric aircraft.

The development of next-generation battery technologies will be key to accelerate the deployment of electric aircraft. However, since a four to fivefold increase in energy density is required, commercialisation of all-electric battery-powered aircraft for small regional airplanes will only occur after 10 years. Regardless, the industry is likely to continue its pursuit of batteries as the main energy storage system for electric aeroplanes over other technologies such as hydrogen fuel cells. This is mostly due to the lack of infrastructure for hydrogen supply to airports, the challenges related to bulky storage tanks and the high production costs for green hydrogen.

	Metrics	Comments
	Technology value: High	Electric aircraft have the potential to reduce CO_2 emissions of the aviation industry, which account for ~3 per cent of the world's emissions today. Electric engines can also result in lower operation and maintenance costs for aircrafts.
	Momentum: High	Numerous developers are active in the electric aircraft space, with aerospace majors such as **Airbus** and **Boeing** leading the development of commercial airliners, and multiple start-ups appearing in the past 10 years to develop small regional aircraft.
	Maturity: Low	The development of electric aircraft remains nascent. Developers of small aircraft are planning the first test flights in the next two to three years. No such prospects exist for commercial airliners.
	Risks: High	The space is largely limited by battery technologies, which need to see fivefold improvements in energy density to power small aircraft. Novel materials, thermal management and power electronics systems are also necessary.

GRAVITY ENERGY STORAGE

THE BASICS

As penetration of intermittent renewables increases and changes the energy landscape, long-term storage is required to safeguard power supply and maintain grid stability. Gravity Energy Storage (GES) is a method that uses excess renewable energy to lift resources such as rock, sand, concrete, or water up a gradient for storage as gravitational potential energy. During discharge, energy is released as the weighted masses move to their lowest position and drive a turbine or regenerative braking system for conversion to electricity and transmission to the grid. GES in the form of hydroelectric storage represents more than 95 per cent of global capacity, although drawbacks such as high capital expenditure (CapEx), geographic restrictions and environmental concerns suggest these systems are nearing their maximum implementation and efficiency. Novel GES technologies promise to deliver improved scaling potential and reduced CapEx and operating expenditure (OpEx).

GRAVITY ENERGY STORAGE

GES can be defined as mechanical battery systems that use surplus electricity to increase the height differential between two points of a weighted system, in the form of a piston or moveable resource such as water, rock, sand and concrete. Companies such as **Energy Vault**, **Heindl**, **ARES**, **Gravity Power** and **Gravitricity** are designing and testing a range of novel GES systems, with concepts ranging from a weighted pulley in a mineshaft to electric rail cars travelling up and down hills. Each system offers a unique functionality and set of use cases compared to existing installations.

Pumped Hydro: Benchmarks and Limitations

Pumped hydro currently accounts for more than 95 per cent, or 180 gigawatts (GW), of installed power capacity and 4,300 gigawatt hours (GWh) of energy storage capacity globally. In many scenarios, it represents the only feasible option for storing large amounts of low-cost energy on scales exceeding a few hours – although discharge periods are generally eight to 12 hours. These systems have an operational lifespan of 50 to 100 years and quick load ramping rates. However, some pumped hydro facilities can lack responsivity and are ineffective for power frequency regulation due to a difficulty in varying large water flows.

Pumped hydro exhibits an average CapEx between US$100 and US$350 per kilowatt-hour (kWh) of installed capacity, depending on geographical conditions and local labour costs. Yearly operating expenses (OpEx) are 1% to 4% of CapEx due to costly upkeep of pumping stations and turbines. Although these can be upgraded at most installations, pumped hydro is generally the least scalable of all energy storage methods. The average facility age is 34 years and coming decades will require expensive updates for these to remain operational.
Sites have specific elevation requirements, and thus tend to be in environmentally protected areas. Though pumped hydro exhibits round-trip efficiencies of 70% to 87% with an LCoS averaging between US$90 and US$165 per megawatt-hour (MWh), growth of this GES system will be limited by lack of availability of new sites and low impact of technological advancements.

Emerging GES Technologies

Applications of new GES methods can widen the narrow use cases of pumped hydro and become viable in replacing peaker plants, providing microgrid support, and acting as seasonal energy storage systems. These systems aim at low CapEx, LCoS, physical and environmental footprints, high round-trip efficiency, and the general ability to hold energy in large quantities for long durations with high levels of safety and reliability.

Mountain Gravity Energy Storage

Mountain gravity energy storage (MGES) operates on the same principle as pumped hydro, using modified mining infrastructure to transfer mass up and downhill, but swaps out water for solid, non-essential resources such as sand, gravel, rocks, or concrete. Although the height differential and weight of the system can be scaled to suit the discharge profile of its application, MGES is unable to store and release grid-scale volumes of energy in the eight to 12-hour range. The system could fit in well with micro-grids in the region of 20MW, such as small islands and remote locations, although maintenance requirements may pose a significant obstacle to adoption.

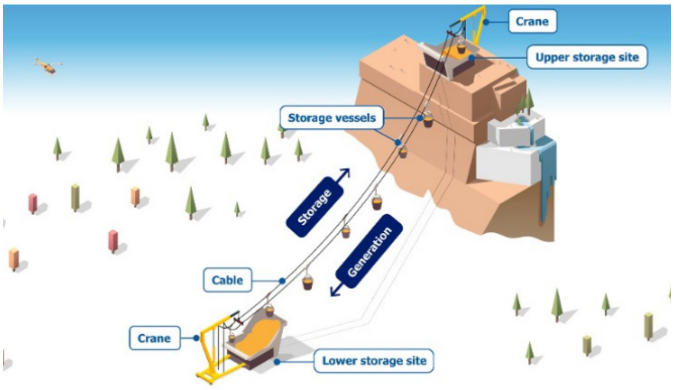

Figure 1. MGES concept rendering.
Source: IIASA

Various statements claim a 40 per cent cost reduction for standard MGES, as in Figure 1, over pumped hydro – with LCoS predicted to range from US$50 to US$100 per MWh. Energy savings are unproven, although the use of well-established and sturdy mining technology for transport of the moving masses is likely to result in low construction costs. **Gravitricity** has designed a straightforward concept in the form of a weighted piston attached to a pulley system that can be raised and lowered down unused mineshafts or an excavated hole, a potentially low-cost method for small-scale applications.

Energy Vault is exploring a similar idea and has been operating a quarter-scale demonstration project in Switzerland since 2018 to test and optimise its system. Their standard 4MW capacity design uses off-the-shelf components for a multi-arm crane sitting atop a 150-metre modular structure, as in Figure 2. The structure is made of 6,000 to 7,000 thirty-five metric tonne composite blocks that are lifted and lowered to meet energy production and demand fluctuations. The blocks are jointly developed with **CEMEX** with the aim to create a composite with a 30-year lifespan that is inexpensive and incorporates local site soil or waste materials that usually end up in landfill, such as debris concrete, coal ash, and industrial slag.

The company claims a linear delivery profile, the ability to regulate frequency with millisecond response times, load ramping up to 4MW in 2.19 seconds, and round-trip efficiencies between 80 per cent and 90 per cent.

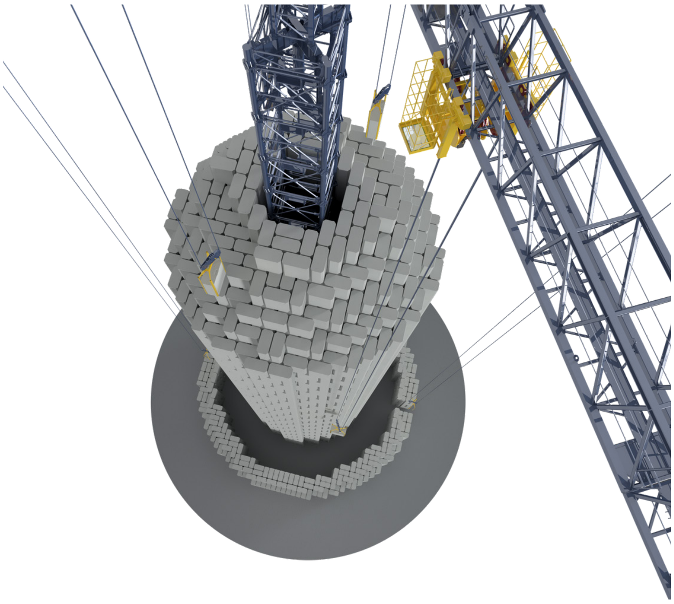

Figure 2. Rendering of Energy Vault's six-arm crane GES system.
Source: Energy Vault

Modularity of the system allows for tailored discharge capacities and profiles that accurately meet grid demand. The system can store energy indefinitely with no dissipation but will likely find use in applications requiring daily discharge for periods less than10 hours. **Energy Vault** predicts an approximate LCoS of US$60 per MWh over a 30-year project lifetime and CapEx of about US$200 per kWh of installed capacity. Although these numbers are credible on paper, the company is likely to face engineering challenges that require significant proof of work and demonstration before seeing widespread adoption.

Subsurface requirements may hinder choice of development sites as foundations must be stable enough to handle the large system weight. Considering the pushback on the aesthetics of wind farms, the structure is likely to meet strong opposition in most locations. Robotic control of 100-metre arms that precisely align interlocking stacked blocks is a significant challenge in any weather and the impact of adverse conditions such as storms or earthquakes are yet to be demonstrated.

A complex system operating in the open will face issues reassembling itself thousands of times and mechanisms to avoid failure must be well-established. If engineering and design issues do not nullify the value proposition of Energy Vault's system, it may present a feasible alternative in certain small- and medium-scale applications, such as deployment alongside solar and wind installations.

Rail Energy Storage (RES)

Rail energy storage (RES) involves moving weighted electric rail cars uphill during periods of excess renewables production. The rail cars apply regenerative braking as they slide downhill to produce electricity. This process is based on well-established technology and likely requires minimal maintenance compared to other GES systems. However, like most GES, drawbacks of the system are primarily geographical, including a large physical footprint and need for specific topography, suggesting implementation will be limited to remote locations. **ARES** has plans under way for a 12.5MWh pilot system in Nevada to test the feasibility of the system.

Hydraulic Hydro Energy Storage (HHES)

An alternative take on pumped hydro is hydraulic hydro energy storage (HHES), explored by companies such as **Heindl** and **Gravity Power**. **Heindl** has designed a concept for freeing large cylindrical masses of rock with minimal excavation and pumping water underneath to raise the block and store energy. During periods of high demand, the rock cylinder begins to settle towards its resting position, forcing water through a turbine at high pressure to produce electricity. This presents an economical alternative to manufacturing a large piston, though demonstration will need to prove engineering concerns, such as friction and rock splitting, are well accounted for.

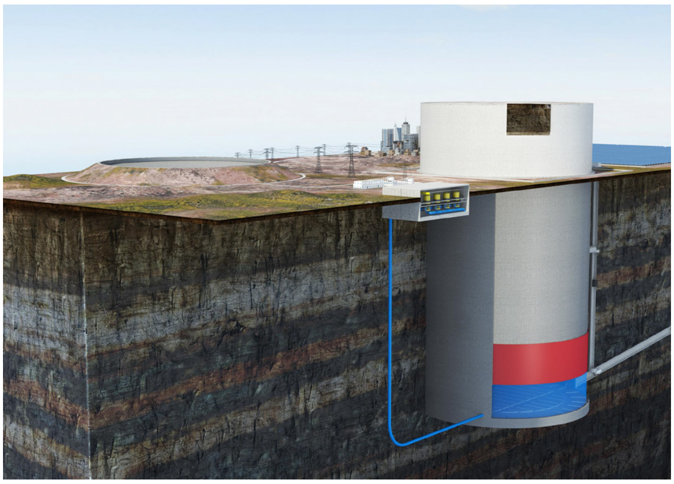

Figure 3. Rendering of Heindl Energy's HHES system.
Source: Heindl Energy

GRAVITY ENERGY STORAGE

A comparative study by Imperial College London Consultants estimates a LCoS of US$94 per MWh for a 10GWh capacity system and US$204 per MWh for a 1GWh system. Over the same range of system capacities, Heindl claims capital expenses of US$160 to US$380 per kWh installed capacity. Round-trip efficiencies of more than 80 per cent, an operational lifetime above 60 years, and yearly OpEx costs under 1% of CapEx are also predicted. HHES requires significantly less water and raw materials to build and operate than pumped hydro, has a smaller footprint relative to storage capacity, and provides dispatching, steep load ramping and black start capabilities.

Key parameters of **Heindl**'s system are height, size and vertical travel distance of the moving mass. Height is the most important factor as it determines operating pressure, where higher pressures require smaller hydroelectric equipment, reservoirs and tunnel diameters. Where pumped hydro is limited to steep terrain, an HHES piston can be raised easily in multiple areas, although it would be easiest to establish on flat surfaces. The company claims that up to 40 per cent of continental land worldwide is suitable for adoption with only minor groundworks.

Gravity Power proposes a similar below-ground design using a concrete piston, an alternative that is likely to be more expensive for large-scale projects than Heindl's concept of minimal excavation. The system may find a use case in microgrid applications or regions without optimal rock composition, rather than grid-scale long-term storage.

Challenges and Prospects

Although the proposed GES methods have various benefits over pumped hydro, they each exhibit significant barriers to entry. MGES and RES maintain similar geographical drawbacks to pumped hydro, whereas HHES encounters a new set of engineering issues to be rectified before development.

MGES offers a reduced environmental and physical footprint over pumped hydro, although still requires large height differentials, and allows for more favourable allocation of water resources. As the energy storage landscape becomes more competitive, MGES is unlikely to offer cost reductions and storage capacities that enable widespread implementation on the grid scale. Energy Vault overcomes some of these issues, however, acceptance of its aesthetics, resistance to adverse weather and reliability of the system are unproven and may prove problematic. The company's planned full-scale project will determine feasibility of an MGES system in practice.

RES offers more than MGES in the way of scalability and lower outlay but is hindered by a large physical footprint and topography constraints that restrict development in most regions. HHES is where the most potential currently exists for a new and improved GES method. Theorised reductions in construction costs, high storage capacity and significantly decreased land requirements in both scale and topography make this an attractive solution on paper. However, developers must submit extensive proof-of-concept work to validate these proposed benefits and provide clearer answers to engineering concerns.

Batteries pose the largest threat to the future of GES, with an average LCoS of about US$250 per MWh and average capital expenses of US$250 to US$350 per kWh of installed capacity for a complete lithium-ion battery system. However, prices vary significantly depending on specification and application, although the battery pack generally accounts for about three quarters of the system cost. This is compounded by limitless scalability, dispatchability and no minimum installed capacity, making batteries highly attractive to energy storage uses of all kinds. If prices continue to decline, and concerns of resource scarcity and environmental damage associated with their manufacturing and recycling are addressed, batteries are likely to hold significant share of the energy storage market.

As in Figure 4, Imperial College London Consultants compared **Gravitricity**'s weighted-pulley system to high-speed flywheels, solid lithium-ion batteries and advanced lead-acid flow batteries in a frequency response application. The findings indicate the potential utility of relatively simple GES technologies in providing ancillary grid services, with a theoretical LCoS of US$141 per kilowatt-year (kWy). **Gravitricity** are currently preparing to build a 250kW demonstration project, followed by a 4MW full-scale prototype that will confirm the feasibility and effectiveness of the system.

Standard high-speed flywheel capacities range from 3kWh to 133kWh and are generally installed in data centres as uninterruptable power supplies. They are difficult to compare to multi-MWh scale GES systems and batteries that are highly variable and scalable in their set-up. Their relatively high capital expense per kWh leads to high costs in this scenario compared to other systems. In flow batteries like advanced lead-acid, energy capacity is a function of electrolyte volume and power is a function of electrode surface area, allowing for high scalability and customisability. They have a relatively short life cycle due to corrosion on the positive electrode, depletion of the active material and expansion of the positive plates. They represent a somewhat underused option in MWh-scale applications, although are likely to acquire significant market share in small- to medium-scale applications as they advance.

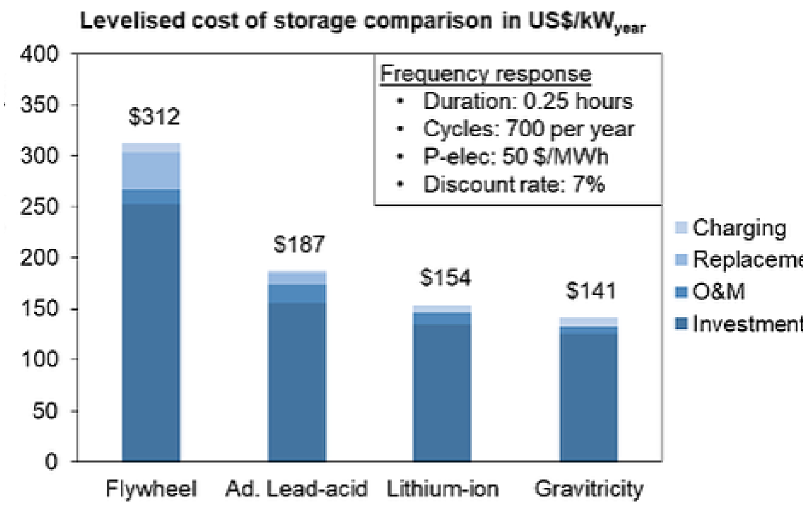

Figure 4. Gravitricity concept and comparison of its LCoS in a frequency response application (US$/kW-year) to other suitable electricity storage technologies.
Source: Imperial College London Consultants

New GES technologies will operate in a very different landscape by the time they are operational, and the market is likely to lose interest in large-scale projects, opting towards smaller-scale distributed assets in both generation and storage. Despite competitiveness and changes in the sector, novel GES can carve out a corner of the energy storage market for specialised use cases.

SOLAR GREENHOUSES FOR SUSTAINABLE FOOD PRODUCTION

INTRODUCTION

Indoor farming, or controlled environment agriculture (CEA), allows control of plant growth conditions such as temperature, humidity, nutrients, air flow, lighting, and air CO_2 concentration. The term describes greenhouse agriculture in general, although chosen technologies, methods and designs will vary depending on local climate. CEA offers large productivity improvements over traditional farming and can enable agriculture in non-arable locations by insulating crops from adverse conditions. Many common crops with CEA use just 10 per cent of the water and nutrients that is used by traditional agriculture. However, greenhouses can consume up to 100 times more energy, mainly as artificial heating and lighting, to maintain conditions. Despite improved yields, this makes conventional greenhouses unfeasible in many poorly electrified parts of the world.

To dampen energy requirements and take greenhouses off-grid, designs are incorporating technologies like transparent solar photovoltaic panels, reflective glazing, passive control systems, and novel thermal storage systems. These developments can bring reliable, high-yield agriculture to impoverished parts of the world that often have arid climates and lack access to a reliable grid – making them ideal candidates to adopt self-sufficient greenhouses incorporating solar power.

SOLAR GREENHOUSES FOR SUSTAINABLE FOOD PRODUCTION

Unique selling proposition

Since 2000, greenhouse food production has increased sixfold to cover more than 9 million acres of land. This trend is driven by increased yields and removal of climate change and seasonal weather fluctuation as factors affecting crop health. Use of resources such water, fertiliser, pesticides, and soil nutrients are also dramatically lower. Minimal pests, and thus pesticides, increases crop survival rates and can enable organic agriculture, adding value in economic and health terms.
Many impoverished parts of the world can be characterised by arid climates and poor or non-existent access to electricity. Agriculture is often small-scale and decentralised in these communities, leading to major economic fallout and food shortages when adverse weather conditions, lack of resources, or unexpected pests and diseases affect crops. Recent locust swarms in Africa and Pakistan that affected the livelihood and food safety of millions attests to the damage that pests can cause to entire regions.

Solar greenhouses incorporate solar photovoltaics (PV), specialised design principles and various other technologies to achieve both the benefits of CEA and minimal reliance on electricity from fossil-fuels to maintain conditions. This overcomes two major issues by offering a self-sufficient system with minimised resource requirements and high insulation against adverse conditions of all kinds. Higher and more consistent yields will provide a stable economic base to farmers, and thus communities, in disadvantaged parts of the world. Arid, and particularly remote, areas of regions in Northern Africa, India, Pakistan, and the Middle East stand to gain significant increases in their agricultural safety and output through the adoption of solar greenhouses. In other parts of the world, solar greenhouses can help commercial farmers more readily meet global demand for out-of-season or resource-intensive crops such as citrus, avocados and tomatoes.

Technology

Components of a solar greenhouse
There are various components and design features to incorporate in a solar greenhouse, as shown in Figure 1. All are optional and can be tailored to meet the specifications of each producer depending on crop varieties and local climate. Other CEA principles may run in tandem with these technologies to further improve efficiency, including vertical farming and soilless farming techniques like hydro, aqua and aeroponics.
Solar greenhouses should be oriented towards the sun and may benefit from insulation on all non-light facing sides if they are net-negative heat suppliers. Artificial lighting is the most common element of greenhouses, and improvements in this domain are predictably in the form of increased efficiency. Heat sinks are the most basic component of greenhouses, though new materials offer large improvements in thermal storage capacity to reduce space requirements. An energy capture system is the central component of solar greenhouses, either in the form of conventional PV or specialised wavelength-selective PV. Capturing solar energy removes reliance on energy from the grid to maintain atmospheric control conditions and systems. A low-cost alternative to PV is specialised glass glazing that reflects specific ultraviolet (UV) and infrared (IR) wavelengths to minimise overheating and plant damage. Autonomous systems and sensors that monitor crop parameters and control resource use are the most advanced technologies and may only see adoption among commercial-scale growers in the near future due to relatively high capital expense.

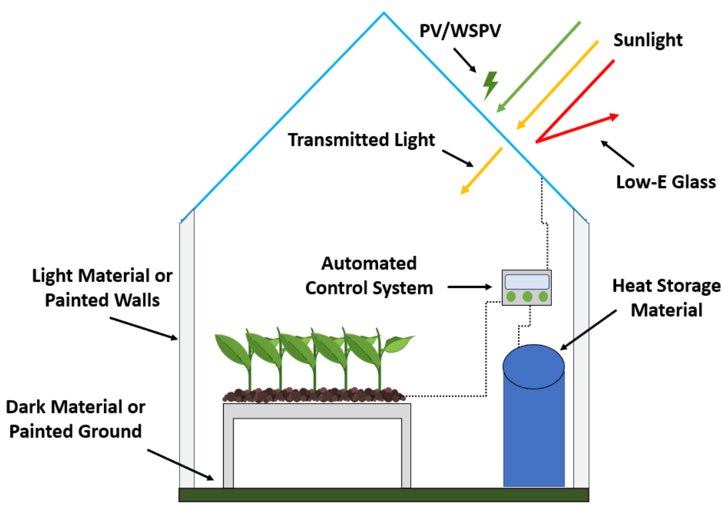

Figure 1. Solar greenhouse schematic and components.
Source: Lux Research

Wavelength-Selective Photovoltaic Systems

Wavelength-Selective Photovoltaic Systems (WSPVs) represent the principal improvement of solar greenhouses over traditional greenhouses that either rely on fossil fuels or conventional PV. WSPVs incorporate strips of PV cells embedded within luminescent solar concentrators (LSC) – a magenta-tinted plastic that transmits a specific spectrum of incidental light laterally to the solar cells. The solar cells in WSPVs are spread far apart to extend the solar collection area, as in Figure 2. This allows for energy capture during the day and discharge at night, enabling plant growth around the clock through systems such as LED lights, irrigation, water desalination, temperature, and humidity controls, without reliance on external electricity.

Figure 2. Close-up of the University of California Santa Cruz's WSPV system.
Source: Nick Gonzalez, UCSC.

Although WSPVs absorb some blue and green wavelengths, they transmit 70 per cent of the photosynthetically active spectrum (400nm to 700nm), allowing plant growth to continue undisturbed. The solar cells themselves cost US$0.65 per watt of installed capacity, 40 per cent less than standard silicon PV, and have efficiencies up to 9.4 per cent, about half of conventional PV. Farmers will need to calculate return on investment based on multiple factors of their greenhouse location in order to verify this value proposition, as conventional PV located near the greenhouse may be beneficial in some applications.

The University of California Santa Cruz (UCSC) housed one of the first research groups to develop and study WSPVs. They studied the growth of dozens of plant varieties in greenhouses equipped with WSPVs, identifying that certain crops exhibited slight water savings and 80 per cent of crops such as tomatoes, cucumber, citrus, and strawberries grew as well as crops in conventional greenhouses, while 20 per cent grew slightly better.

Soliculture was founded in 2012 to produce the WSPVs developed at UCSC and currently offers two variants: a 5 per cent and 7 per cent efficiency model, with different PV densities. The company was recently announced as a top 10 finalist in the FoodTech Challenge, a global competition led by the UAE Food Security Office and Tamkeen that seeks innovative solutions to address food security, of which **Masdar** is a key partner. Developers market redshift light (shifting unused green light into usable red light to feed plants) as a key value proposition, although **Lleaf**'s claims of a 15 per cent to 40 per cent increased output are likely to be seen only in niche applications with specific crop varieties.

Figure 3. UCSC's pilot solar greenhouse with WSPVs.
Source: Nick Gonzalez, UCSC

Energy storage is generally the most expensive component of a solar greenhouse, with various options available. Lithium-ion batteries are most common for small-scale applications due to long service life, minimal maintenance and small storage space. However, commercial-scale developers may look towards higher volume alternatives with a higher outlay and lower levelised cost of storage (LCoS).

Azelio has developed a thermal storage system that uses the principles of molten salt thermal storage with recycled aluminium alloy as the thermal mass. The 100kW to 100MW scalable system channels solar power to heat the alloy until liquified, which then passes through a conventional steam turbine to generate electricity. The company is conducting three tests this year and recently launched alongside **Noor**'s Ouarzazate solar power complex in Morocco, with plans to launch a solar-integration project later this year in Abu Dhabi in collaboration with Khalifa University.

Low-E Glass

Emissivity, the measure of a material's ability to emit thermal radiation and return to the ambient temperature, can be tailored to meet greenhouse heating requirements. Low-emissivity, or low-E glazing, involves a thin, semi-transparent metal coating that minimises the amount of UV and infrared light to pass through a material while leaving all visible light available. Low-E equates to a high absorbance and reflectance for infrared light, trapping most of the incidental heat inside the greenhouse as reflected wavelengths can't escape the coating from inside. This can help keep greenhouses to be cooler in summer and warmer in winter and protects seedlings and fragile plants from sun damage without inhibiting plant growth rates, as most photosynthetically active radiation is preserved.

The glass exhibits a slight haziness due to the presence of a metallic layer, which some non-commercial consumers may find unappealing. **ClearVue** is one developer of a glazing that sits within an activated interlayer sandwiched between two panes of glass. The company claims this interlayer prevents 90 per cent of solar UV and IR radiation from penetrating the glass pane while allowing 70 per cent of visible light to pass through. This glazing can be used alongside WSPVs as the UV and IR radiation are redirected to the edge of the glass and can be harvested through solar cells. Low-E glass is, however, more expensive than regular glass at US$14 compared with US$3 per square foot, although this price difference is unlikely to hinder adoption as energy savings exhibit a payback period of between two and six years. The coating won't scratch off as it's applied to the inside of the glass and will remain effective over 10 to 15 years, depending on climate.

Concentrated Solar

Sundrop Farms operate a commercial-scale hydroponics greenhouse in an arid and region of South Australia that incorporates a concentrated solar tower to supply energy. The 115-metre-high tower has 23,000 mirrors pointed towards it, allowing desalination of seawater and control of all environmental systems. The company sources its carbon dioxide and nutrients sustainably and claims yields of 15 to 30 times higher per hectare than conventional field production. This is a particularly effective method for large-scale operations in regions with high levels of sunlight hours.

Heat Storage Systems

Insulation and thermal storage are key considerations, particularly for greenhouses in highly variable climates, to ensure the even distribution of thermal radiation throughout the night and reduce reliance of fossil fuels to maintain greenhouse conditions. Walls can be coated with light, highly reflective materials to ensure even distribution of light to plants, while floors made of dark materials such as coloured ceramic can act as heat sinks to distribute trapped heat more evenly during the day. Traditionally, black-painted water containers placed under plant beds or masonry in the structure foundations have been able to prevent heat loss to the ground, although a range of new phase-change materials are proving to be more effective heat storage systems. These materials include paraffin, fatty acids and various salts, and offer five to 14 times better heat storage – with large amounts of energy absorbed as latent heat when the materials change from their solid to liquid phase. This represents a cost-effective way to reduce heating demand during no-sunlight hours.

Sensors and Smart Control Systems

As greenhouses incorporate more advanced technologies, integrating sensors and control systems will optimise their use of resources and adapt to meet changes in local climate such as sunlight hours, temperature and fluctuations in the solar spectrum due to ozone damage. Integrated systems using sensors and the Internet of Things can control the deployment of renewable energy generated by WSPVs, for example, at night when heating and UV lights may be required for continuous plant growth of certain crops. Systems that use existing resources to their best use are likely to represent a large portion of future developments within the space of solar greenhouses and will become more intuitive and effective as the technologies they rely on advance.

Innovations to Watch

- **Autonomous systems with adjustable wavelength-selection of WSPVs:** Autonomous systems receiving information from the crop, combined with WSPVs and low-E glazing, can ensure that plants reach optimal sunlight hours per day. Example use cases would be during a period of cold with low sunlight, in which all wavelengths are accepted as priority to maximize photosynthesis and greenhouse heating, or when absorption is increased during periods of excess and potentially damaging sunlight. Future developments will optimise resources to enable off-grid operation.

- **New solar power generation technologies** The Australian Federal Government's Cooperative Research Centre is funding a pilot greenhouse with a new 50 W/m^2 PV glass from Edith Cowan University's Electron Science Research Institute and ClearVue. The Los Alamos National Laboratory is embedding quantum dots in windows for transparent PV. Their research incorporates highly photosensitive nanostructures printed on plastic slabs that absorb and re-emit light at high intensities via internal reflection towards a PV collector located at the edge of the material.

- **Self-contained greenhouse kits:** All-in-one kits, like the Greenery hydroponic farm unit by **Freight Farms**, offer a completely self-contained and insulated greenhouse in a shipping container, offering the potential to use wind or hydro power. These systems may prove especially useful in harsh or arid climates that have limited sunlight or extreme winters that make insulation a priority over solar absorption. **Local Roots** is using this concept to develop and operate a network of small-scale farms serving local communities, resulting in fresh produce year-round with no associated transport emissions.

KEY DEVELOPERS

Company	Founded	Description	Notable Projects / Technologies
Soliculture	2012 (US)	WSPV developer.	Founded by UCSC; numerous installations of their LUMO energy systems across the US and Canada.
Lleaf	2018 (Australia)	WSPV developer.	Founded by UNSW; developer of both a blue and red WSPV for flowering and vegetative stages of crop growth.
ClearVue PV	1995 (Australia)	Low-E glass developer.	Manufacturer of low-E glass; running a joint project with Edith Cowan University to develop a 300m^2 greenhouse with 50W/m^2 PV glass.
Azelio	2008 (Sweden)	Recycled aluminium thermal storage for renewables integration.	Partial energy storage at **Noor**'s 510MW Ouarzazate solar installation in Morocco; planned solar integration project with Khalifa University in 2020.
Local Roots	2013 (US)	Turn-key greenhouse developer.	Offers turn-key shipping container greenhouse kits operated by the company to supply local communities or businesses.
Sahara Forest Project Foundation	2012 (Jordan)	Investigating use of seawater for irrigation and cooling	Wadi Araba project in the Jordanian desert is scaling and uses solar greenhouses to desalinate seawater for irrigation and cooling.

Commercial aspects

A 2015 paper published in the International Journal of Environmental Research and Public Health examined key metrics comparing the growth of lettuce in a greenhouse and using conventional farming methods. The paper noted that conventionally farmed lettuce, over the duration of a year, produced a yield of 3.9 kilograms (kg) per m2, used 250 litres of water per kg of yield, and used 0.3 kWh of energy per kg as artificial lighting and heating.
This compares to greenhouse agriculture with a tenfold yield of 41kg per m2, 92 per cent less water use at 20 litres per kg, although a significantly higher energy requirement of 25kWh per kg. On average across all crops, greenhouse agriculture corresponds to 25 per cent to 50 per cent lower food travel distance compared to conventional farming, a factor that can further reduce costs and greenhouse emissions associated with agriculture. Overall, energy is clearly the deciding factor in assessing the feasibility of greenhouse agriculture and the added value of solar greenhouses becomes clear. This highlights that water-scarce regions with an abundance of renewables generation capacity, particularly solar, are the ideal settings to establish solar greenhouses. The solar greenhouse technologies themselves, such as phase change materials or low-E glazing, are low-cost and present minimal financial risk to commercial greenhouses, which are likely to be early adopters of new technologies to increase their yields. Higher-value systems such as autonomous controls, sensors, energy storage, and photovoltaics are far riskier for community and residential-scale producers and will need to assess the value proposition on a case-by-case basis.

Figure 4. Solar greenhouses in Canada fitted with Soliculture's WSPVs, technology developed by UCSC. Source: Soliculture

Takeaway and Recommendations

Solar greenhouses are a natural progression of traditional greenhouses, incorporating design concepts and technologies that are likely to see significant adoption among producers worldwide. Adoption will be driven primarily by falling PV prices, resource scarcity and the demand for less environmentally impactful agriculture in terms of footprint, yield and pesticide use – especially as weather fluctuations driven by climate change begin to undermine the ability to produce quality crops at large and consistent yields. A range of new technologies are expected to emerge on the market that minimise and optimise resource requirements within greenhouses to ensure their independence from fossil fuels and ability to produce crops regardless of local climate.

	Metrics	Comments
	Technology value: High	Solar greenhouses can have a major impact on global food production if implemented in a cost-effective and entirely off-grid way. They can shift the limiting factor of growth away from electricity access and resistance to environmental factors and towards access to resources such as nutrients, seeds, soil, fertiliser, water.
	Momentum: Medium	Solar greenhouse technologies will see earliest adoption amongst commercial growers, although community and residential-scale producers stand to gain the most from incorporating them and moving towards perennial, off-grid, low-resource, and high-yield agriculture.
	Maturity: Low	Although most producers incorporate at least one technology or element of solar greenhouses in their designs, few have combined all available techniques to their full effect. With few current competitors in each space, cost reductions and increased accessibility will rapidly improve adoption.
	Risks: Low	Capital expenses of some components can be high, and arid regions with access to abundant renewable energy sources are likely to see the strongest financial incentive for adoption. However, maintenance in desert regions could be labour-intensive as PV efficiency declines significantly when soiled.

NEWS UPDATES

COVID-19 crisis can spark developments in multiple fledgling industries

Global crises often trigger drastic changes in innovation velocity. The 1970s oil crisis turned oil into a volatile yet critical resource, catalysing research into alternatives like biofuels and renewable energy. Societal outrage on plastic waste has made recycling a priority even for chemicals and materials companies. Similarly, the COVID-19 crisis is underscoring the importance of digital and automation tools to de-risk the global economy – from physical industry to society to medicine - from humanity's limitations. Technologies to watch include safe telecommunication for working and socialising at a distance, digital twins and mobile robotics to keep factories and product deliveries operating in a "lights-out" scenario, and hydrogen and energy storage infrastructure to create redundancies in differently loaded grids.

Wind farms can provide similar grid services as gas plants

The California Independent System Operator (CAISO), **Avangrid**, **NREL** and **GE** tested, and confirmed, the ability of a 131MW wind farm to provide ancillary grid services like balancing or regulation up and down, frequency response, voltage regulation, and active power control. Existing assets may find new revenue streams with minimal upgrades, although to profit newcomers, renewables incentives and markets must shift to reward ancillary services and not just energy production.

Total and Iberdrola follow earlier move of Shell and Repsol to enter the floating wind market

The Erebus Project is a joint venture between **Total** and **Simply Blue Energy** aiming to install 96MW of floating wind off the coast of Wales and could use Principle Power's semisubmersible foundation. In the same month, **Iberdrola** announced its long-term floating wind strategy, which will start with an EU-backed demonstrator in Norway, to potentially move to large-scale projects in the US and Scotland.

NEWS UPDATES

Partnership to build world's first multi-megawatt scale high temperature electrolyser (HTE)

The Multiphly project, led by French research organisation CEA, with partners **Neste**, **Paul Wurth**, **ENGIE** and **Sunfire**, will install a 2.6MW HTE at **Neste**'s Rotterdam refinery to produce up to 60kg per hour of hydrogen. By using green hydrogen, Neste will significantly lower the carbon intensity of its hydrotreated renewable diesel product and become even more competitive in its target markets.

Consortium evaluates liquid organic hydrogen carriers (LOHC's)

The consortium including **Mitsubishi**, **Chiyoda**, Singapore LNG, and various utilities and port operators, will evaluate the potential of Chiyoda's toluene-based LOHCs to import carbon-free energy into Singapore. The scheme engages downstream customers across a variety of applications and is a big step for the nation's aims to halve emissions from 2030 to 2050 and reach net-zero shortly after.

Mitsubishi Hitachi Power Systems (MHPW) supplies turbines for transition to hydrogen as fuel

MHPW will supply two 420MW combined cycle gas turbines to decarbonise the Intermountain Power Project plant in Utah, in the US. By 2025, the retrofit project will transition the plant from coal to a blend of 30 per cent hydrogen and 70 per cent natural gas. From there, MHPW will develop the challenging combustion chamber upgrades and other modifications to transition the turbines to 100 per cent green hydrogen by 2045. This marks the first industry roadmap for Advanced Class Gas Turbines to fully transition to a zero-carbon fuel.

Volkswagen (VW) announces NMC 811 batteries, a tipping point for Ni-rich Li-ion battery chemistry

Ni-rich cathodes are forecast to comprise half the battery market within a few years. They improve energy density while reducing the need for geopolitically challenging cobalt. First introduced in a few models in China, like the **BMW** X1 and **Nio** vehicles, **VW**'s use of Ni-rich batteries by 2020 is a firm indication that vehicles outside of China will adopt this chemistry, indicating a tipping point for rapid adoption of NMC 811 in the coming years, as well as the coatings and electrolyte additives used to stabilize the chemistry.

TECHNOLOGY BREAKTHROUGHS

Novel electrolysis technique uses cheap nickel-iron oxide catalysts

Most electrolysis uses a proton exchange membrane (PEM) that, despite high production rates, requires acidic conditions and precious metal catalysts like platinum and iridium. A research team from Washington State University and Los Alamos National Laboratory have developed a method under alkaline conditions, abundant catalysts and an ammonium-enriched anion exchange membrane (AEM) to bring performance near state-of-the-art PEM electrolysers. The team now needs to demonstrate on-par durability.

Samsung develops all-solid-state battery prototype

The concept submitted to Nature Energy journal uses a solid electrolyte, high nickel cathode, and 5µm silver nanoparticle-black carbon composite anode – reducing dendrite growth typical of lithium metal anodes and improving battery safety, lifespan and performance. The prototype was 50 per cent smaller by volume than a lithium-ion battery and exhibited a density near 900Wh/L with a 1000-charge lifecycle. The development opens the door for larger capacities and can enable 800km EV travel on a single charge, although incorporating precious metals at commercial scale is likely to be unrealistic.

TOPICS FOR NEXT EDITION

Advanced plastic recycling for circularity

Driven by increasing consumer awareness, governments and corporations are setting aggressive targets to promote plastic recycling. Incumbent mechanical recycling infrastructure is ill-equipped to handle post-consumer waste, leading to low and inconsistent recycling rates, poor-quality recyclates, and, in some cases, incineration of up to 90 per cent of waste to avoid landfilling. Instead, emerging technologies like blockchain-integrated plastics tracking, AI-driven waste sorting and pyrolysis can help convert this mixed waste into oils and polymer precursors, moving industries like textiles and packaging closer to true circularity.

Vehicle-to-grid technologies for grid support

As electric vehicles become pervasive, their batteries hold great potential as grid assets – a concept called vehicle-to-grid (V2G). Since cars are only in use about 5 per cent of the time, grid managers and automotive OEMs see EV batteries as under-utilised assets. While traditional EV charging is binary (either plugged in and charging or unplugged and discharging), V2G involves EVs communicating with the grid to transfer electricity back and forth depending on overall energy demand. In this way, V2G could help with load levelling/load following, frequency regulation, and back-up power applications that are all crucial for managing utility-scale grid systems. Despite the promise, only a few companies have deployed projects to date, and several technological and economical challenges remain before consumers adopt V2G technology.

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