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COMBINED HEAT AND POWER
FOR SUSTAINABILITY

DISTRIBUTED LEDGERS AND BLOCKCHAIN
IN THE POWER INDUSTRY

SUPERCAPACITORS
FOR HIGH POWER APPLICATIONS

COMBINED HEAT AND POWER FOR SUSTAINABILITY

INTRODUCTION

Combined heat and power (CHP) – or cogeneration – systems recover exhaust heat that would normally represent a loss from electricity production. The systems then use this heat in space heating and cooling, or industrial processes. In this way, the overall system efficiency can increase from around 30 per cent in some electricity generation to more than 80 per cent. Cogeneration can also help make better use of renewable energy technologies based on biomass, concentrated solar power and geothermal energy by using them to produce both heat and electricity. As distributed energy resources that couple power and heat production, CHP systems also offer increased grid flexibility and control over fuel choice, while having the potential to provide grid services. However, the integration of CHP systems represents a significant challenge to overcome to realize attractive ROIs that drive adoption.

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Figure 1. CHP unit
Source: TEDOM

Unique selling proposition

CHP finds application mostly in industrial facilities, as well as in commercial and institutional buildings. By coupling electricity and heat generation, CHP systems can reach efficiencies above 80 per cent. This represents a significant improvement over an average of ~50 per cent for electricity and heating services when separately provided in countries such as the US. In industrial applications, the chemical and refining sectors account for nearly 50 per cent share of the CHP capacity in the US. The higher efficiency of a CHP plant compared to an electricity-only plant allows for fuel savings and reductions in greenhouse gas emissions.

Besides providing electricity and thermal energy for plant processes and operations, CHP systems have the ability to provide additional generating capacity when grid demand increases, and renewable sources are not available. In that sense, CHP systems have the potential to help grid operators maintain grid stability by providing services such as frequency regulation.

Technology

In a conventional power plant, thermal energy is first extracted from a fuel, such as natural gas or coal, and used to raise steam, which drives a turbine and, using a generator, converts the turbine's mechanical energy into electrical energy. Large-scale power plants using combined-cycle gas turbines – the most efficient technology for electricity generation – have an electrical efficiency between 50 per cent and 60 per cent. The rest of the energy is lost as heat, typically through cooling towers or exhaust stacks.

In a CHP plant, on the other hand, the rejected heat can be recovered from the exhaust or cooling system via a heat exchanger. This heat can be used to supply heat for buildings, where a heat-only boiler would otherwise be needed, or for industrial processes, such as thermal desalination. Some industrial processes can also exploit CHP technology, for example, where fuel is burned to provide heat for a furnace in the iron and steel industry. In this case, some of this heat is then used to produce electricity. The total efficiency of a CHP plant can thus reach from 70 per cent to nearly 90 per cent depending on the fuel and plant type, as well as on the characteristics of the heat demand.

A CHP design is independent of the type of heat source, so fossil fuels, organic waste and renewable fuels such as hydrogen are all viable options to drive CHP systems.

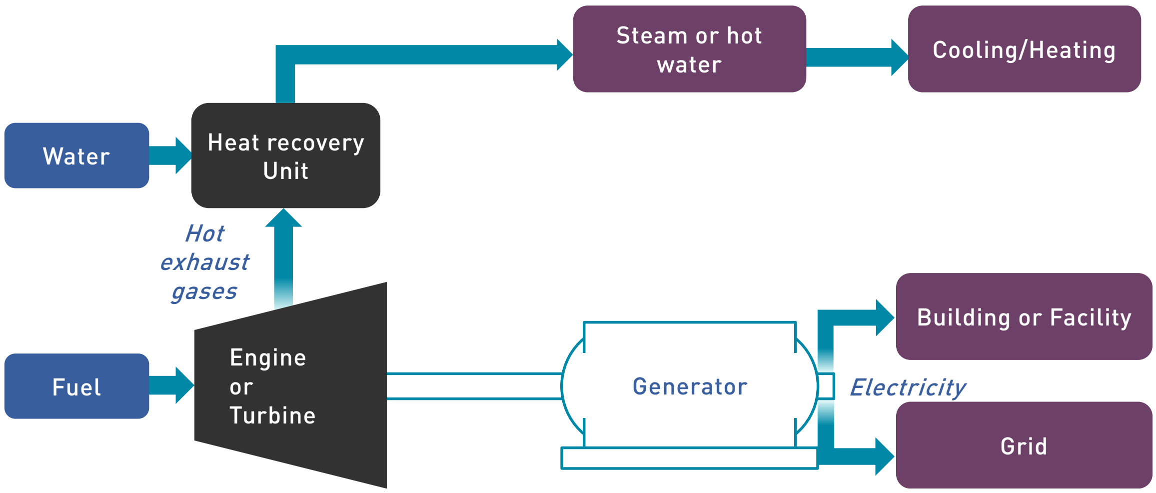

Figure 2. Reciprocating engine or gas turbine with heat recovery.
Source: Lux Research, U.S. DoE

Trigeneration

Trigeneration is a variation of cogeneration. A trigeneration system operates much like a cogeneration plant, but makes use of the waste heat for both heating and cooling purposes. Trigeneration systems thus involve a CHP unit with an absorption chiller that transforms the heat from cogeneration to cold. As trigeneration systems use residual heat from cogeneration, these can reach higher overall efficiencies than CHP plants. Trigeneration plants have the greatest benefit when heat and cooling are continuously needed, such as in data centers and hospitals.

CHP technologies

There are three basic elements to most CHP technologies. The first is the prime mover, which creates mechanical energy. The second is the electrical generator and the third is the heat recovery unit. CHP systems are often categorized based on the type of prime mover that drives the entire system. There are five predominant prime mover technologies used for CHP systems: reciprocating engines, gas turbines, microturbines, fuel cells and boiler/steam turbines.

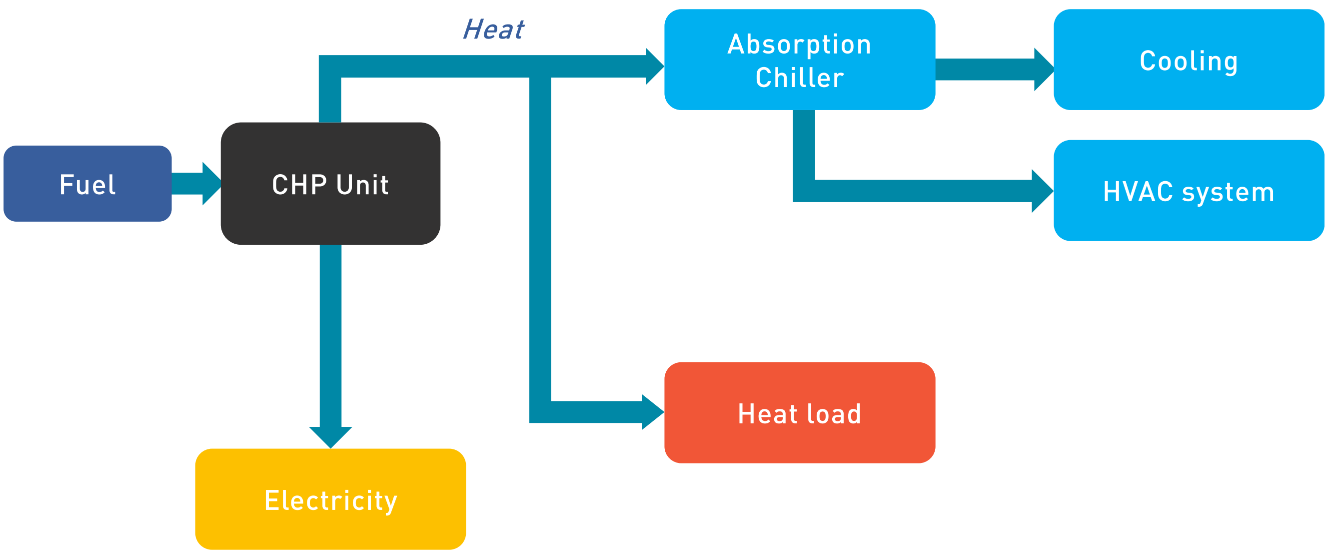

Figure 3. Trigeneration setup.
Source: Lux Research

	Reciprocating engines	Gas turbines	Steam turbines	Microturbines	Fuel cell
Description	Reciprocating engines use a cylindrical combustion chamber in which the linear motion of pistons is transformed into the rotary motion of a crankshaft.	Gas turbines are constant pressure heat engines. Primary gas turbine hardware includes a compressor, a combustion chamber and an expansion turbine.	A steam turbine is driven with high-pressure steam produced by a boiler or heat recovery steam generator.	Microturbines are small combustion turbines that can use gaseous or liquid fuels.	Fuel cells use an electrochemical process to convert the chemical energy in hydrogen.
Size range	10kW to 10MW; most are below 5 MW	30kW up to 300MW	Under 100kW to over 250MW	Available from 30kW to 330kW	5kW to 3,000 kW
Thermal output	Thermal energy can be recovered from the engine exhaust, cooling water and lubricating oil, and then used to produce hot water, low pressure steam, or chilled water (with an absorption chiller).	Gas turbines produce high temperature exhaust and thermal energy can be recovered from this exhaust to produce steam in a heat recovery steam generator. The exhaust can also be used directly for industrial process drying or heating.	CHP configurations use backpressure or extraction steam turbines to generate power and thermal energy. Backpressure steam turbines produce low pressure steam while extraction turbines deliver both low pressure and medium pressure steam.	Microturbines have exhaust temperatures between 250°C and 300°C and this exhaust can be used to produce steam, hot water, or chilled water.	Heat from fuel cells configured for CHP can be recovered to produce hot water, low pressure.
Electrical efficiency	30%-42%	24%-36%	25%-35%	25%-29%	38%-42%
Overall CHP efficiency	75%-85%	65%-81%	80%	65%-75%	60%-75%
Fuel	Reciprocating engines can be operated with a wide range of gas and liquid fuels. For CHP, natural gas is the most common fuel.	Most use natural gas, but can also use light petroleum distillates like gasoline, kerosene, diesel.	Boilers are commonly used to generate steam required for steam turbines, and boilers can utilize a wide range of fuels, including natural gas, oil, coal, and biomass.	Microturbines can be operated with a wide range of gas and liquid fuels. For CHP, natural gas is the most common fuel.	Most fuel cells for CHP applications use natural gas or biogas. The gas is reformed into hydrogen, and the hydrogen is then reacted to generate electricity.
Reliability	Reciprocating engines are a mature technology with high reliability.	Gas turbines are a mature technology with high reliability.	Steam turbines are a mature technology with excellent durability and reliability.	Microturbines are based on the design principles used in larger capacity combustion turbines and, like combustion turbines, microturbines have high reliability.	Fuel cells use an electrochemical process with few moving parts and offer high reliability. While mechanical wear is not an issue, fuel cells do require periodic replacement or refurbishment of catalysts and fuel cell stacks.

* System-level efficiency can be significantly lower with addition of equipment like boilers, and can also depend on unit size

Table 1. CHP technologies
Source: Lux Research

CHP challenges

Not every facility that generates power is suitable for CHP systems. CHP systems are only suitable for sites where there is a need for heating and hot water systems. For larger scale systems, heat and power demand need to remain fairly consistent for maximum efficiency. A key challenge of cogeneration systems is that on-site heat demand is generally lower than on-site electricity needs – although in some cases, heat demand is met and electricity consumption remains lower – meaning that reaching high efficiencies requires undersizing a CHP system for a facility's electricity needs. As a result, a CHP owner must often purchase additional power, weakening a CHP system's value proposition.

Innovations to Watch

- **Integrated CHP with thermal storage:** Thermal energy storage (TES) has emerged as a promising route to further boost system efficiency by capturing more exhaust heat and to better match CHP power production with on-site electricity demand. In March 2019, **Argonne National Laboratory (ANL)** and microturbine developer **Capstone Turbine Corporation** began a joint research project integrating **ANL**'s thermal energy storage system (TESS) with a Capstone microturbine-based CHP unit. During the project, slated to run through 2021 and funded in part by the US Department of Energy Technology Commercialization Fund, **ANL** and **Capstone** will test integrating four hours of thermal energy storage with **Capstone**'s CHP unit. The TES system will integrate into the existing CHP heat exchanger, which utilizes heat at around 300°C in the turbine exhaust gas. **ANL**'s TESS uses a magnesium chloride phase change material (PCM) with a melting point of 150°C integrated into a high-conductivity graphite foam, which helps to overcome the high thermal resistance of the PCM. **ANL** claims that its TESS has a smaller footprint and stores higher-temperature heat than more conventional hot water-based thermal energy storage systems. By incorporating storage, **ANL** and **Capstone** aim to better align turbine operation with a facility's load, as heat and electricity demand often do not perfectly align – thereby improving overall efficiency.
- **Flexible CHP for grid balancing:** Cogeneration can also be used to balance electricity production from variable renewable energy sources. CHP systems installed on the sites of utilities' industrial customers, for instance, can provide many of the benefits that utility-owned peaking plants do. In this regard, small- and medium-sized industrial facilities with high thermal and electric loads are often good candidates for CHP systems. In this case, CHP systems would need to be designed with adequate additional generating capacity to support the electricity grid. Due to their continuous operation in industrial or commercial facilities, CHP units could respond rapidly when grid services are required. The additional revenue from grid services could enhance the benefits of a CHP system while tackling the sizing challenges mentioned previously. Although small-scale flexible CHP systems do not exist today, utility-scale facilities that provide grid services are being planned. In fact, technology developer **Wärtsilä** has recently been awarded two contracts to replace coal-fired power plants with CHP facilities in Dresden and Bremen, Germany. These facilities will become a balancing link between power generation and consumption, improving the resiliency of the grid. To unlock industrial-scale CHP systems providing grid services, technology development is required to enable seamless and automated interaction with the grid and on-site operations where the CHP is installed. With this objective in mind, in 2018, the US Department of Energy allotted US$10 million in funding to seven CHP projects focusing on small-scale CHPs able to provide grid services. Companies such as **Siemens** and **GE** are among the recipients of funding.

Commercial aspects

CHP is a mature technology. There is significant deployment of the technology in large industrial and commercial institutional sectors. In Europe, there was a capacity of 122GWe installed in 2017, equivalent to a share of nearly 12 per cent of total electricity production. In the US, the installed capacity of CHP systems was 81GWe in 2018.

Cost performance of CHP systems varies significantly by the prime mover technology selected. Reciprocating engines, gas turbines and steam turbines are mature technologies having relatively low installed capital costs compared to similar capacity microturbines and fuel cells, which are products that have been more recently commercialized. Gas turbines and microturbines have lower operation and maintenance (O&M) costs compared to reciprocating engines.

Fuel cell O&M costs can be high, depending on the frequency required for replacing the fuel cell stack. The use of CHP systems relying on organic waste or biomass require additional costs associated with the storage and processing of the feedstock. Biomass CHP plants have typical capacities of 1-50 MWe with overall efficiencies of 80 per cent to 90 per cent and investment costs of US$2,200 to US$3,500/kW.

	Reciprocating engines	Gas turbines	Steam turbines	Microturbines	Fuel cell
Total installed cost (US$/kW)	$1,400-$2,900	$1,300-$3,300	$670-$1,100	$2,500-$3,200	$4,600-$10,000
O&M costs (cents/kWh)	0.9-2.4	0.9-1.3	0.6-1.0	0.8-1.6	3.6-4.5

Table 2. Cost comparison of different CHP systems.
Source: U.S. DoE

Economies of scale allow CHP to be cost-effective for high-thermal demand applications in the size range above 5MW. Lower-scale systems are typically cost-effective when sized for thermal demand, but can face significant barriers when interconnecting with their electric utility regarding interconnection standards, utility rates and opportunities to sell electricity back to the grid. These barriers can influence the systems overall cost-effectiveness.

COMBINED HEAT AND POWER FOR SUSTAINABILITY

KEY DEVELOPERS

Company	Founded (country)	Description	Differentiator
Siemens	1847 (Germany)	Provides CHP systems using a variety of configurations and generation units, including gas and steam turbines.	Leading provider of CHP solutions with hundreds of cogeneration plants installed. Installed the Lausward Fortuna plant in Düsseldorf, Germany, which set the record for net efficiency (85%), heating capacity (300MW), and electrical output (603.8MW at 61.5% efficiency).
Wärtsilä	1834 (Finland)	Provider of CHP and trigeneration plants using a hang-on heat recovery system that helps to maintain high electrical efficiency and output regardless of heat production and ambient conditions.	Company focuses on developing systems that can provide flexibility to integrate the growing shares of renewables. As such, its CHP solutions boast fast starting and stopping capabilities.
GE	1892 (US)	Developer of CHP and trigeneration solutions largely based on **GE**'s gas turbine technology.	Besides having an installed capacity of gas turbines, it has been working on the adaptation of gas turbines to run on alternative fuels like hydrogen, further improving the CO_2 footprint of CHP systems.
Capstone	1988 (US)	Developer of microturbine technology for integration in micro CHP systems.	**Capstone** integrates an aero-based turbine engine, a magnetic generator, with patented air bearing technology to develop its microturbines. Currently working with ANL to develop an integrated micro CHP with thermal storage.
Sunfire	2010 (Germany)	Develops high-temperature solid oxide fuel cells (SOFC), which deploys at scale for stationary power applications.	The core technology of the company is a stack of high-temperature solid cells that contain a zirconia electrolyte, nickel anode and lanthanum-based perovskites cathodes. The SOFC operates at a temperature of 860°C and forms part of a combined heat and power (CHP) set-up, having a total system efficiency of 85%.

Takeaway and Recommendations

As resources that couple power and heat production, CHP systems can boost overall system efficiency while meeting the electricity and space heating needs of industrial facilities. Although CHP technologies are not a clean energy generation technology, as a system, they can lower overall CO_2 emissions by reducing fuel utilization. Furthermore, the ability to integrate CHP systems with alternative fuels like biomass, organic waste, or hydrogen, can lead to a significant improvement of the environmental footprint of a facility. While CHP is a mature technology, it is increasingly being regarded as a way to support the grid given the penetration of intermittent renewables. In the UAE, CHPs have the potential to meet the country's cooling needs in a trigeneration configuration. The ability of CHPs to operate in a flexible manner is key to boost adoption of the technology as it provides a way to size systems in a way that both electricity and heating or cooling needs are met.

Metrics	Comments
Technology value: High	The technology has the potential to improve the efficiency of heating, cooling, and power generation to nearly 90 per cent. The system is suitable for sites with high electricity and heating/cooling needs.
Momentum: Medium	Installed capacity of CHP systems has seen a slow growth rate over the past decade. New deployments of CHP systems having the ability to support the grid have been announced in countries like Germany in the past two years.
Maturity: High	CHP systems are a mature technology finding application in industrial facilities, as well as commercial and institutional facilities. Novel systems using microturbines or fuel cells are also emerging.
Risks: Medium	Despite the high system efficiencies CHPs can reach, system integration to meet both heat and electricity demands simultaneously is still a challenge. Currently there are no flexible CHP installations demonstrating the ability to provide grid services.

DISTRIBUTED LEDGERS AND BLOCKCHAIN IN THE POWER INDUSTRY

THE BASICS

The energy grid of the future will comprise of high penetration and decentralization of renewable power generation assets. In this scenario, energy is generated by both large utilities and numerous small-scale "prosumers" that are responsible for significant portions of overall grid supply and demand. Alongside energy storage, new digital platforms are required to facilitate transactions and communication between the network of numerous microgrids as they respond to a variety of ever-changing factors and generate large volumes of data in the process. Distributed ledger and the blockchain can increase efficiency, security and transparency in the power industry by removing intermediaries. This will enable a network of differing assets to effectively respond to grid demand, provide ancillary services, transmit power in its most efficient form and trade renewable energy in small quantities without long-term power purchase agreements.

DISTRIBUTED LEDGERS AND BLOCKCHAIN IN THE POWER INDUSTRY

A distributed ledger involves several unique computer networks that communicate with each other to verify transactions between third parties. This protocol bypasses the need for centralized clearing houses, like banks, as transactions are both verified and processed by peers on the networks. This decreases the possibility of fraudulent charges as the distributed ledger contains more databases (or points of failure) that must be manipulated simultaneously in order to process an illegal or fraudulent charge. As in figure 1, the increased communication with peers leads to superior transparency and safety over the existing processes in transactional systems of many kinds.

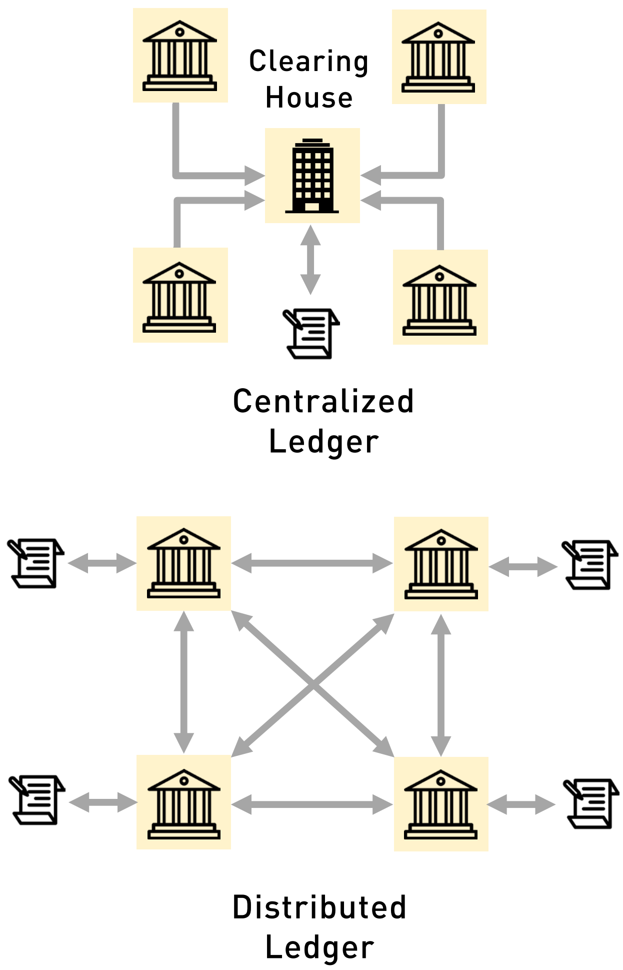

Figure 1. Simplified flow of information structure in a centralized vs. distributed ledger system.
Source: Lux Research

A blockchain is a more complex type of distributed ledger that both validates transactions in a peer-to-peer protocol and maintains a record of prior transactions in a cryptographic and distributed database. While the record of transactions in a standard distributed ledger can be manipulated like any free-standing database, a blockchain requires a proof of work to be conducted by multiple networks on both the transaction in question and the log of prior transactions prior to validation.

Information from multiple transactions is combined into a "block" of transactions, encrypted with a unique identifying "hash" key (a digital serial number), and added to the ongoing "chain". Any party attempting to forge information will be identified by networks validating the transaction claims against multiple points of information, and ultimately denied from entering the chain. A blockchain database exists in several locations at once, is freely accessible to anyone, and is difficult to manipulate compared to centralized exchanges and databases as alteration of all instances of the blockchain are required at the same time to enter fraudulent charges.

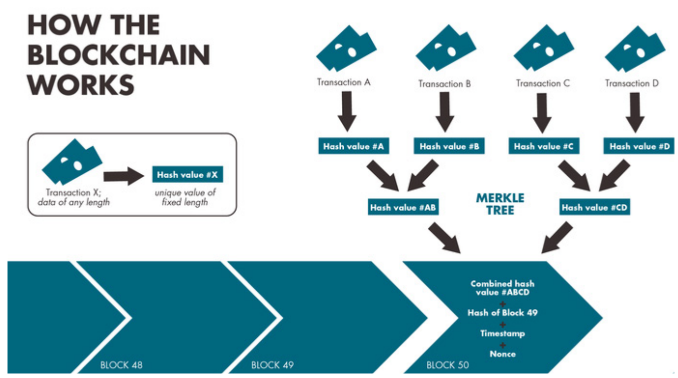

Figure 2. Simplified structure of a blockchain system, showing transactions being formed into encrypted blocks and added to the chain.
Source: Wiki Commons

Blockchain technology is rapidly moving beyond finance and into the power industry to facilitate a variety of functions that enable a decentralized grid to operate at maximum efficiency with respect to energy production, transmission, storage, sale and record-keeping for carbon-offset purposes. Smaller amounts of information are transmitted and received from a larger number of contributors, reducing processing and storage requirements for each stakeholder, while increasing security and efficiency for all parties. By minimizing the role of a large utility distributing energy, the blockchain can bring automation and financial decentralization to a complex grid that is reliant on intermittent and distributed renewable assets.

DISTRIBUTED LEDGERS AND BLOCKCHAIN IN THE POWER INDUSTRY

Future energy outlook

Distributed asset generation and demand fluctuations

As the capital costs of renewable generation assets, such as solar panels, fall and incentives to adopt them increase, the energy ecosystem will undergo dramatic changes. The outlook for this transition is likely to involve several utility-scale renewable energy providers that supply baseloads to the grid (particularly highly urbanized regions) from solar, wind and hydro installations, in addition to numerous kW-scale suppliers operating on a residential or community level.

The tie-in between these small-scale assets and the grid at large represents a significant technological and financial challenge, as the incumbent infrastructure, regulations and trading systems assume centralized generation. Improved management of this system is required to allow small-scale renewable producers to supply on a localized, peer-to-peer level that bypasses bureaucratic inefficiencies and unnecessary energy transmission associated with distribution via the existing centralized pathways.

Grids with high renewables penetration in their current state are also ill-equipped to meet rapid demand spikes as their power is often transmitted to a utility provider, which then distributes accordingly to consumers and supplements the difference with coal or natural gas. Currently, meeting energy demand spikes with non-renewables is a costly process – either directly due to expensive natural gas peaker plants or in the long-term due to CO_2 emission externalities that require decarbonization of legacy assets, R&D for new assets and climate harm reduction in many other areas.

Current workarounds: DERMS & VPPs

Virtual power plants (VPPs) represent the current workaround for small-scale producers facing a lack of supportive infrastructure. They rely on using distributed energy resource management system (DERMS) software to combine production from distributed assets, allowing small-scale producers to aggregate their production to a threshold level for sale to large-scale energy providers.
VPPs essentially create a centralized, albeit far smaller, energy provider from several distributed assets – allowing them to participate within the current infrastructure. This collective bargaining mechanism can enable producers to feed surplus back into the grid, offset their capital costs, and reduce the overall reliance on fossil fuels to meet grid energy demand.

Distributed ledger and blockchain solutions

Peer-to-peer (P2P) transactions

Despite current workarounds, the competitive nature of a peer-to-peer system can return a fairer price for both producers and consumers by minimizing the operating costs associated with including a utility distributor. Robust and flexible digital platforms are required to effectively react to supply and demand fluctuations and connect producers and consumers directly in a competitive marketplace.

Developers such as **Power Ledger, Electron**, and **Drone Energy** have built platforms that incorporate customer matching and automated financial settlements to purchase and sell electricity between consumers, producers, or prosumers in a network. Similar to a stock exchange, although based on current supply and demand and only short-term speculation, these exchanges will transmit power between buyers and sellers. The process can ultimately bring costs to competitive levels, as only grid-maintenance is necessary to transmit energy between stakeholders, and not distribution from a central utility company.

Blockchain platforms currently facilitate more than one million peer-to-peer (P2P) transactions per second. However, developers suggest the technology has a long way to go considering the vast number of small transactions, with scaling linked to the number of participants involved in the platform.

Carbon emissions and offsets tracking

Renewable Energy Certificates (RECs) and other carbon-offset tokens are tradeable credits representing the production of (generally) 1 MWh of renewable energy. As decarbonization efforts ramp up and renewable penetration increases, efficient tracking of these tokens is essential to ensure targets are met by corporations and individuals.

Trading and tracking of RECs is an area in which centralized, and often affiliated with the government, organizations have proven inefficient in dealing with the vast amounts of data. Blockchain platforms are well-suited to tracking generation and consumption of renewable energy and assigning RECs accordingly. The ledger of transactions will always be available to track progress of decarbonization efforts on a governmental and small-scale level and ensure fraudulent tokens or double spending does not affect the marketplace.

DISTRIBUTED LEDGERS AND BLOCKCHAIN IN THE POWER INDUSTRY

Appliance energy optimization

IoT interconnectivity with appliances and the blockchain-operated energy grid can be used to automatically run appliances depending on local power supply and demand. For example, a connected washing machine could turn on just as surplus, or low-cost, levels of production are reached, or go into a hibernation mode if demand spikes unexpectedly. This will ensure that the demand strains of non-essential appliances are shifted to periods when the grid is best able to handle the load – ensuring costs stay consistently low and the need for peaker plants is reduced, or bypassed.

Energy project financing

Distributed ledgers could provide a suitable method for stakeholders to pool investment for large energy projects or innovation. This may be in the form of minor fees charged to all prosumers to maintain the quality of grid supply infrastructure and funnel money into energy R&D in a traceable manner. In an aggressive scenario in which utility providers play a minor role and the responsibility of generation is shifted into private ownership and public organizations for distribution networks, this could be key in maintaining the momentum of innovation in the power industry.

Electric vehicles

Blockchain networks can enable private owners of charging infrastructure to conveniently sell charging services to electric vehicle (EV) owners, leading to improved appeal and adoption of EVs from potential customers turned off by public charging infrastructure scarcity. A blockchain network can facilitate these large numbers of small transactions in a secure, transparent and low-fee manner. As infrastructure is certain to lag behind EV production, optimizing use of existing infrastructure is key to increasing rates of adoption.

More speculative possibilities include inductive chargers that wirelessly charge EVs at stop lights, with smart contracts facilitating very small and rapid transactions.
Additionally, the blockchain is essential to the concept of autonomous EV rideshare fleets. Such fleets would charge, and discharge, based on local renewable production capacity – tapping into the vast battery resources available in EVs to stabilize the grid while generating income for owners.

Challenges and Prospects

There are various challenges associated with the development and adoption of blockchain - based technologies at all levels of the power industry. The most pressing is the fact that blockchain solutions are advancing at a pace where regulatory bodies cannot keep up, leading to outdated and restrictive legislation that interrupts innovation. Key issues hindering clear legal definitions and frameworks include questions of intellectual property, privacy and contract enforceability.

Another often discussed challenge is energy usage. For example, the Bitcoin protocol is estimated to use 22 TWh per year in processing transactions, at a relatively small market cap of about US$180 billion. Detractors of blockchain in general tend to ignore the fact that energy costs, aside from capital costs of computational units required, are one of the few small fees associated with this financial ecosystem. However, the power costs for a renewable asset operating on the blockchain is a fraction of what would be paid to a central utility provider acting as a distributor, clearing house and contract enforcer.

The business case for many start-ups operating these platforms involves their unique coins, generally linked to FIAT currency, and used to exchange power and Renewable Energy Certificates (RECs). Platform-specific tokens can ultimately hinder widespread adoption or cause clashes in regions where two or more blockchain networks are responsible for the VPPs and microgrids supplying and drawing energy from the grid. Interoperability between blockchain platforms is therefore essential.

Linking platforms to public cryptocurrencies such as Bitcoin can largely nullify the challenge of interoperability, although viability for this will become much clearer if Bitcoin becomes more widely adopted and stable. Ultimately, the decentralized power of these energy trading platforms will be nullified unless linked to a public, decentralized cryptocurrency that also benefits from transparency and security.

An interesting prospect is the introduction of smart contracts with performance-based rewards that enable business models that are generally unviable in the existing framework. A recent example in an upstream context is **Aker BP** and **Framo**'s deal in which sensor data from seawater pumps is shared between the companies in a distributed ledger to predict performance and ensure uptime is maximized, with Framo paid based on uptime it delivers. Other major oil companies are investing heavily in the technology in a variety of ways, with **Shell** and **Equinor** recently partnering with the non-profit Rocky Mountain Institute to support the Energy Web Foundation. This non-profit organization aims to develop a standard blockchain platform upon which energy applications can be built.

Distributed ledgers and blockchain platforms are likely to become a key facilitator in the energy transition over the coming decades, enabling consumers and producers of all levels to be involved in the space and have stable access to low-cost, renewable electricity.

SUPERCAPACITORS FOR HIGH POWER APPLICATIONS

INTRODUCTION

Energy storage systems (ESS) play a vital role in the energy, automotive, consumer electronics and medical industries. Performance requirements vary depending on the application and developers often need to prioritise and balance specifications for the best fit ESS. Lithium-ion batteries are popular because of their high energy density and moderate lifetime, two criteria particularly relevant for electric vehicles (EV) and consumer electronics. However, a key challenge of lithium-ion batteries is their limited power density, which limits charge/discharge rates for EV applications and use as an ESS in unstable renewable energy power generation. To bridge this gap, supercapacitors have gained traction as an alternative ESS due to their high specific power and long lifetime, making them potentially suited for fast EV charging applications, as well as renewables power-peaking frequency regulation. For example, as of 2017, Shanghai deployed 200 supercapacitor-powered public electric buses that can fully charge to 100 per cent in 80 seconds.

SUPERCAPACITORS FOR HIGH POWER APPLICATIONS

Unique selling proposition

The advantages of supercapacitors are their high specific power, long lifetime (up to 1 million operating cycles) and robust temperature operating range (typically between -40°C to +70°C). The high specific power allows supercapacitors to provide and receive high bursts of power and to charge quickly. As such, supercapacitors are often used in consumer electronics products for regulating fluctuating loads. Recently, supercapacitors have been used in electric transportation, such as public buses and light rail, as an energy harvester for regenerative braking, as well as for pitch control in wind turbines.

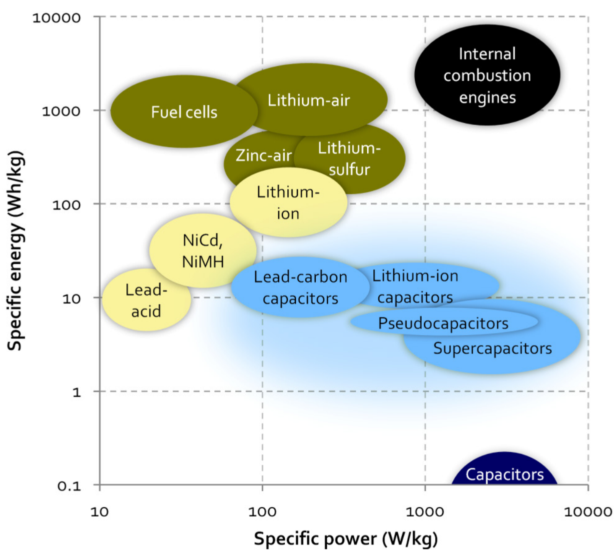

Figure 1. Snapshot comparison of energy storage system's specific energy and specific power in 2013.
Source: Lux Research

Technology

Key terms

- Capacitance refers to a device's ability to store energy in the form of an electric charge, such as static electricity. The higher the capacitance, the more electric charge (and therefore energy) a device can store.
- Energy density refers to the amount of energy a device can store given a unit of weight. EVs prioritize ESSs with high energy density as it reflects how far the vehicle can travel without needing to be recharged.
- Power density refers to the amount of power a device can output given a unit of weight. For an EV, a higher power density is reflected in how fast the vehicle is able to accelerate.
- Voltage refers to the amount of electromotive force a device is able to supply. The higher the voltage, the more force (and therefore power) the device is able to provide.

Supercapacitor basics

Supercapacitors are a type of ESS that store charge in the form of static electricity/capacitance on the surface of an electrode as opposed to the inside of an electrode (as is done for lithium-ion batteries). Surface charges can move quickly by avoiding slow chemical reactions, allowing supercapacitors to provide and absorb high bursts of power. Furthermore, the lack of chemical reactions also means a lack of undesired side-reactions, which limit the lifetime of batteries.

Composition of a supercapacitor

Supercapacitors comprise an electrolyte sandwiched between two identical electrodes and store static electricity in the form of an "electrochemical double layer" (i.e. oppositely charged ions rearrange themselves at the intersection of the electrode/electrolyte surface). As a higher electrode surface area allows a greater amount of charge to be stored, supercapacitors tend to use highly porous materials for their electrodes, such as activated carbon. The device also includes a permeable separator that helps keep the electrodes from touching and short circuiting while allowing the ions in the liquid electrolyte to remain mobile. Most supercapacitors now use lithium-ion salt as part of the electrolyte solution.

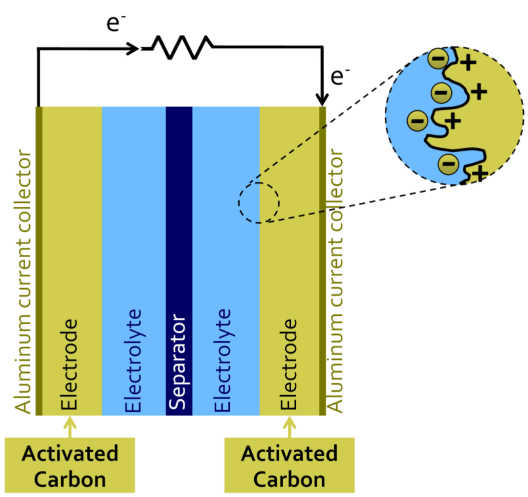

Figure 2. Device architecture of a supercapacitor.
Source: Lux Research

SUPERCAPACITORS FOR HIGH POWER APPLICATIONS

Supercapacitors, capacitors, and batteries

Capacitors are often compared with supercapacitors as both technologies use capacitance as their form of energy storage, although supercapacitors have one to two orders of magnitude greater energy density than capacitors. While conventional capacitors use an insulating dielectric material between two conductive plates, therefore storing charge in the form of electrons and holes, supercapacitors use an electrolyte and electrode configuration, similar to batteries, and store charge in the form of electrons and a charged molecular species, thus resulting in its superior energy density. Nonetheless, as supercapacitors store energy as static electricity as opposed to a chemical reaction, supercapacitors typically contain only 5 per cent of the energy density of a lithium-ion battery. Since supercapacitors are often compared to batteries, this has been a key limiting factor for the adoption of this technology. As the energy density of a supercapacitor is proportional to its capacitance and the square of its working voltage, strategies to improve energy density target one of those two parameters.

Technology	Li-ion battery	Capacitor	Supercapacitor
Mechanism	Chemical	Electrostatic	Electrostatic
Charge time	Long (hours)	Short (seconds)	Short (seconds)
Discharge time	Long (hours)	Very short (seconds)	Short (minutes)
Cycle life	Moderate (~2,000)	Good (>1,000,000)	Good (>1,000,000)
Power density	Moderate (~600 W/kg)	High (ranges from 1,000 to 10,000,000 W/kg)	High (up to 40,000 W/kg)
Energy density	High (~250 Wh/kg)	Very low (<0.1 Wh/kg)	Low (~10 Wh/kg)

Table 1. Comparison of Li-ion battery, capacitor, and supercapacitor performance criteria
Source: Lux Research

Commercial aspects

Over the past few decades, supercapacitors have seen incremental growth by partaking in niche markets ranging from defibrillators to cameras, smoke detectors and as back-up power, among others, totalling a market size of nearly US$900 million. Although this pales in comparison to the lithium-ion battery's market size of US$40 billion (which is attributed to consumers' desire for high energy dense ESS), the supercapacitors' ability to charge quickly and absorb sudden spikes in power are opening applications in a world gradually being electrified.

Significant differences in energy costs also contribute to the disparity in adoption: lithium-ion batteries cost between US$150-$250/kWh, whereas supercapacitor energy costs are closer to US$10,000/kWh.

Developers are also realising that supercapacitors should not be compared to batteries but thought of as complementary to them, leading to systems using one of each.

Key supercapacitor applications:

- **Public buses:** In 2010, **Sunwin**, a joint venture between **Volvo** and **SAIC**, provided 61 supercapacitor powered buses to Shanghai that claimed to be able to charge to 50 per cent within 30 seconds and to 100 per cent within 80 seconds. The buses transported passengers between stops and charged while passengers boarded and disembarked. A key challenge, however, was the supercapacitor's inability to maintain charge throughout a ride during heavy traffic. At the same time, Shanghai's public transportation system was experimenting with a battery + supercapacitor-powered bus system, which was able to capitalise on the battery's high energy density and the supercapacitor's ability to recharge quickly. In 2013, Shanghai requested 200 more of these new hybrid design buses.

- **Regenerative braking:** Spanish rail company **CAF** manufactured a tram, Urbos 3, with its Greentech Freedrive ESS that uses supercapacitors for regenerative braking applications. The trams are able to charge quickly at stops and run between certain stops without needing to connect to an overhead cable.

Figure 3. Spain's supercapacitor-powered Greentech Freedrive, Urbos 3 tram. Source: CAF

These trams have been used in Luxembourg, Granada and the West Midlands, resulting in savings of up to 35 per cent of electricity costs. Companies like **Skeleton Technologies** are thinking of implementing the same technology for automotive applications. The supercapacitors will be used in conjunction with batteries to increase the range and efficiency of the EV.

- **Pitch control for wind turbines:** Wind turbines are prone to failure when the turbine blades exceed their maximum rotational speed, so a pitch control is used to help adjust the angle of the turbine blades to reduce blade speed during times of extreme wind. Wind turbine components need to operate in temperatures that range from −40°C to +55°C, last a long time and, for pitch control, be able to provide short bursts of power during extreme wind conditions.

  Companies such as **Moog** have therefore opted for supercapacitors as the pitch control ESS since they can last up to millions of cycles, operate under a wide temperature range and provide the required power without needing the auxiliary equipment that a battery needs for temperature control.

Innovations to Watch

Supercapacitor research targets improvements in energy density. Approaches taken include tuning electrode morphology to functionalise the electrode and combining a supercapacitor with a battery to form a hybrid supercapacitor battery.

- **Tuning electrode morphology to increase supercapacitor capacitance**
  The capacitance (and therefore energy density) of a supercapacitor is directly affected by the surface area available to ions. Since electrolytic ions are ~0.5 nm in size, they can only adhere to electrode surfaces with porous pathways larger than this. Long and tortuous paths also limit the total surface area to which an ion can adhere. Innovations in electrode processing that control the distribution and size of electrode pores will therefore help increase the energy density of these devices.

- **Functionalizing electrode surface to increase supercapacitor capacitance**
  The ability for a molecule to adhere to a surface is determined by the wettability of a surface. Surfaces with higher wettability easily attract molecules and for supercapacitors, this results in a higher capacitance (and energy density). As functionalizing the surface of an electrode is a method of increasing the wettability of a surface, innovations in this area will help increase the energy density of supercapacitors. For example, in 2015, researchers found that doping the electrodes with nitrogen can increase its energy density by up to four times (from 10 Wh/kg to 40 Wh/kg).

- **Hybrid supercapacitor batteries**
  Hybrid supercapacitor batteries combine the high energy density of batteries and high power density of supercapacitors by combining one capacitor-like electrode with one battery-like electrode. While one electrode stores energy electrostatically, the other stores it chemically. These devices have increased energy density compared to supercapacitors and increased power density compared to batteries, but compared to batteries still have lower energy density, and compared to supercapacitors have lower power density. Nonetheless, these devices make an interesting compromise between two of the desired performance criteria.

SUPERCAPACITORS FOR HIGH POWER APPLICATIONS

KEY DEVELOPERS

Company	Founded (country)	Description	Differentiator
Sunwin (owned by **SAIC Motor**)	2000 (China)	Automotive OEM	In 2010, **Sunwin** developed ultracapacitor powered buses for the Shanghai public transportation group.
CAF	1917 (Spain)	Railway vehicle and equipment manufacturer	**CAF** developed the Greentech Freedrive supercapacitor ESS for tram operation. The trams have been sold since 2011.
Skeleton Technologies	2009 (Estonia)	Supercapacitor manufacturer	**Skeleton Technologies** manufactures and sells supercapacitors to be used for automotive, grid, industrial and transportation applications.
Maxwell Technologies	1965 (US)	Supercapacitor manufacturer	One of the largest manufacturers of supercapacitors. **Maxwell Technologies** was recently acquired by **Tesla** for US$218 million in 2019.
Cap-XX	1997 (Australia)	Supercapacitor manufacturer	**Cap-XX** develops supercapacitors specifically targeting Internet of Things applications. In 2016, they introduced one of the thinnest supercapacitors in the world for these applications.

Takeaway and Recommendations

Commercialised since 1975, supercapacitors have incrementally gained market adoption in a wide variety of applications. And although their adoption has paled in comparison to lithium-ion batteries because of the battery's high energy density, which consumers prioritize, supercapacitors have been increasingly gaining traction for their fast charging and regenerative braking value proposition, which are crucial for an electrified world. As developers are beginning to realize that rather than comparing it as an alternative to lithium-ion batteries, which prioritise energy density, applications like passenger EVs, which prioritise mileage and fast charging, are ideal use cases for a supercapacitor (+ battery) energy storage solution. Going forward, we will likely see an acceleration in adoption of supercapacitors, first beginning with wind pitch control systems, followed by regenerative braking, then EV fast-charging applications .

Metrics	Comments
Technology value: Medium	Supercapacitors have the potential to enable EV fast charging capabilities, especially if used in tandem with lithium-ion batteries. They can also help increase EV range if used for regenerative braking. These two technologies will be key enablers for mass EV adoption.
Momentum: Medium	The supercapacitor market has been historically fragmented with growth being incremental. However, supercapacitor adoption is expected to accelerate alongside the energy transition.
Maturity: Medium	Supercapacitors have been commercialised since 1975 and have many established players, including **Maxwell Technologies**, **Nippon Electric Company** and **Panasonic**. However, there are still a few new players including **Skeleton Technologies**.
Risks: Medium	The business case for supercapacitors is still unclear as there is no clear market that requires these devices. Supercapacitors can help provide additional value to existing markets such as for EVs but are not fundamental for the market to exist.

NEWS UPDATES

TNO develops EMBER, a novel hydrogen production technology

The Netherlands Organization for Applied Scientific Research (TNO) has developed a process based on methane pyrolysis to produce hydrogen from natural gas feedstock with no CO_2 emissions – cracking the gas above 1,000°C in a molten metal reactor and capturing solid-carbon in the metal for later extraction via a molten salt solution. A commercial system is not expected prior to 2035, yet the group estimates a production cost of US$1.3/kg to US$1.5/kg, assuming a solid carbon offtake at approximately US$100/MT. Although water electrolysis leads the space, the unrealistically low electricity prices of US$0.02/kWh needed to compete with steam methane reforming hinder adoption.

Multiple developers are planning e-fuel pilots

As the industry begins to accept that e-fuels will be necessary to decarbonize the marine and aviation sectors, upcoming pilot projects aim to enable large-scale production. A Danish consortium that includes **Maersk** and **Ørsted** is developing a 1.3GW electrolyzer to produce 250,000MT of hydrogen, methanol and various aviation fuels by 2030. Norway's **Norsk e-Fuel** consortium with **Sunfire** and **Climeworks** will produce aviation fuel from CO_2 and green hydrogen, ambitiously targeting 10 million liters in 2023 and a 100-million-liter capacity by 2026. **Repsol**, aiming for carbon neutrality by 2050, invests €60 million in a 50 bbl/d pilot plant, using CO_2 and green hydrogen from a nearby refinery.

NEWS UPDATES

Schmid and Nusaned form joint venture on 3GWh flow battery in Saudi Arabia

The EVERFLOW project is set to begin construction later this year in Dammam 3rd Industrial City. The combined factory and R&D center will produce vanadium redox flow batteries and conduct research on the technology, working towards the nation's aim of installing 57.5GW of renewable energy by 2030. The durability and lifetime of flow batteries are among their key advantages, although the technology has remained uncompetitive with lithium-ion due to far lower scales of production.

Pacific Gas & Energy aims to rebuild a safer, more reliable grid after 2019 wildfires

The Californian utility has announced plans to replace highly flammable mineral oil in 750,000 of its transformers with bio-based esters to avoid propagating wildfires. It is also planning five energy storage projects totaling 423MW to co-locate with legacy geothermal power stations. This will protect producers from negative wholesale prices and may allow additional revenue streams from ancillary grid services.

Germany passes US$10.2 billion national hydrogen strategy and stimulus plan

The strategy will dedicate US$8 billion for new green hydrogen installations (hydrogen produced from renewable-powered electrolysis), aiming to add 5GW capacity. A further US$2 billion will be injected into international collaborative projects to expand Germany's renewable generation capacity. The strategy predicts a yearly 85TWh gap between green hydrogen supply and hydrogen demand in 2030, which will be filled via imports if domestic capacity is not expanded.

Apex Energy launches hydrogen plant with combined heat and power

Building on Germany's national hydrogen strategy, the project will integrate a 2MW electrolyzer, storage tank, stabilizing battery and combined heat and power plant in a refinery in northern Germany. The plant will absorb excess green hydrogen energy and supply power and fuel for transportation to a nearby industrial park. This is expected to be the first of many involving a sector coupling strategy for hydrogen.

TECHNOLOGY BREAKTHROUGHS

Researchers discover compounds to increase ceramic fuel cell performance

Ceramic fuel cells have high efficiency and low emissions if powered by hydrogen, but can also use methane – making it a bridging technology in the transition away from hydrocarbons. However, lowering high operating temperatures (800°C) is key to ensuring longer-term operation, stability, safety and costs. Researchers from the University of Aberdeen in Scotland have discovered "hexagonal perovskites" that can be used in ceramic fuel cells to reduce their operating temperature to 500°C and improve performance. While this temperature still isn't practical in automotive applications, requiring temperatures under 100°C, the development may be valuable for industrial or grid-scale power.

New spraying process promises better perovskite solar cells

Perovskites are synthetic photovoltaic actives that offer improved performance and potentially cheaper manufacturing via spray coating compared to silicon semiconductors used in conventional solar cells. However, freshly sprayed perovskite layers tend to dissolve prior dried layers. Researchers at Thailand's Mahidol University have developed the "sequential spray deposition" process that involves converting the perovskite liquid into very fine droplets heated to around 100°C before application – resulting in solar cells exhibiting clearly-defined multilayers. The development will allow manufacturers to apply different types of perovskites to a material in successive layers to take advantage of multiple sets of properties.

TOPICS FOR NEXT EDITION

Building Energy Management Systems: bridging automation and energy efficiency

Increased urbanisation and larger construction projects are driving the need for effective management of resources in the built world. As more automation and user-comfort oriented technologies enter our home and work environments, so do building's energy requirements, with global building-related energy demand expected to rise by 50 per cent by 2050. Building Energy Management Systems (BEMS) are infrastructures of sensors and computers that gather real-time environmental data and make decisions on how to alter conditions like ventilation, heating, lighting and security based on occupant preferences and energy-efficiency goals. BEMS minimize resource use and emissions while enabling an array of unique services for residents and employees. These systems are quickly becoming a core component of commercial spaces and residential buildings as a means of bridging the gap between increased automation, interoperability of complex systems and decarbonization goals.

Power regulation hardware

The explosive growth of distributed energy resources (DERs) tests the limits of a grid designed for central generation, leading to power and voltage fluctuations that can cause damage to electrical systems both behind and in front of the meter, and increase energy consumption from devices running on overvoltage. As an alternative approach to distributed energy resource management systems software, power regulation hardware is a class of power electronics that measure factors like voltage and power factor and use capacitors and inductors to regulate the AC electricity characteristics. Both large industrials like **ABB** or **Siemens**, and start-ups are developing innovative solutions to improve power quality and save on overall electricity and demand charges. In particular, systems for behind-the-meter applications in, for example, commercial buildings in areas with high renewable integration can offer fast returns on investment.

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