A Global Transition to Clean Energy: Challenges and Opportunities

An ACS-e! Discovery Report that examines the science behind the movement to advance and adopt clean energy technologies around the world

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About This Report

About The Author

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I. EXECUTIVE SUMMARY

Renewable energy captures headlines with stories about splashy start-up companies and reports of new technologies with improved efficiencies or manufacturing processes. Other stories dissect policy debates about infrastructure, subsidies, and installation costs. Following the area story by story, it can seem like changing the world's energy system away from fossil fuels is an intractable problem.

But there are signs that renewable energy is starting to have an impact. Denmark, Portugal, and Germany have run for several days using all renewable energy.[1] The International Energy Agency predicts that, by the early 2030s, more electricity will be produced by renewables than by coal.[2] Electricity production using energy from the sun, wind, or water is a key component of many clean-energy plans. But other technologies are needed as well: fuel derived from plants to replace gasoline and diesel, renewable sources of methane to replace natural gas, and large-scale storage to ensure renewable energy is available even when the sun is not shining or the wind is not blowing. Energy efficiency reduces the amount of energy we consume as a society. One aspect of energy efficiency is recycling everyday items like paper, metal cans, and plastic bottles; converting trash to usable products; recycling tires to make fuel; and recycling electronic waste to recover metals and plastic.

For any clean energy technology, from electricity production to new fuels for transportation, it's important to consider carbon emissions from the production and processing of the technology, to see if it really does reduce greenhouse gas emissions. In the case of electricity, at least, it looks like renewable energy is making a difference. Preliminary data from the International Energy Agency show that global energy-related carbon dioxide emissions in 2015 were the same as the year before, possibly due to 90% of the new electricity generation in 2015 coming from renewable sources.[3]

II. FOSSIL FUELS

Of all the sources of climate-warming greenhouse gases, burning fossil fuels for energy releases the most emissions, the majority of which is carbon dioxide. Transitioning to renewable energy from natural sources like wind, sun, water, or heat from within the planet are all considered ways to reduce energy-related emissions, though renewable energy currently only represents slightly more than a quarter of the world's total energy capacity.[4]

As countries incorporate renewable energy into their systems, they continue to burn coal and natural gas for energy, as well as oil for transportation fuel. New supplies of each of these fuels change how much each contributes to carbon emissions, though not always for the better. An increased supply of natural gas in the U.S. has spurred the construction of more natural gas-fired power plants, which release less carbon than their coal cousins. On the other hand, crude oil is becoming increasingly difficult to extract or refine, thus potentially increasing carbon emissions for gasoline and diesel production. Tracking the relationship between energy production and carbon emissions starts first with examining how we use fossil fuels now and in the future. Following is an overview of the major countries involved in the production and combustion of coal, natural gas, and oil around the world.

Coal

In 2014, about 40% of the world's electricity came from burning coal and other hydrocarbon-containing solids. Coal combustion generates almost half of the carbon dioxide emissions from burning fossil fuels, which is the largest greenhouse gas contributor to global warming.[2]

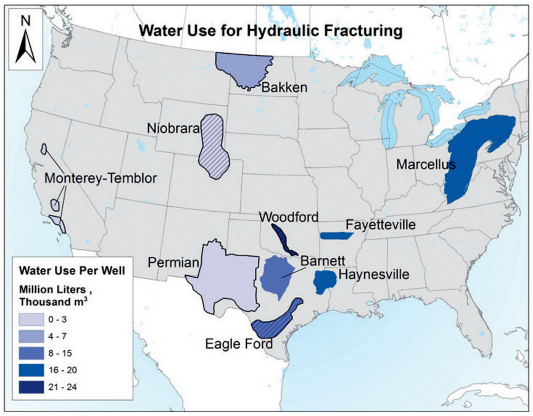
China leads the world in coal production and consumption.[2] Although the country is building coal-fired power plants at a high rate, there is little demand for the additional capacity they would produce, as the country already has more than enough power. However, there are signs that coal consumption is falling in China, which recently abandoned plans to build 200 more coal-fired power plants.[5] In the U.S., the world's second largest emitter of carbon dioxide,[2] coal is no longer king. More than 80% of power plants retired in 2015 were coal powered, a move spurred by low natural gas prices and environmental regulations.[6] In April 2016, the largest coal company in the U.S. filed for bankruptcy. And by the end of this year, the U.S. Energy Information Administration (EIA) expects natural gas to surpass coal as the major fuel for electricity generation.

By 2040, the International Energy Agency predicts that demand for coal will plateau in China. A recently discovered reservoir of natural gas trapped in deep shale in China—the largest such reservoir in the world—could provide an alternative to coal, as it has in the U.S.[7] But the EIA report predicts coal use will grow in India, as population, incomes, and manufacturing increase in the country over the next few decades.

Natural gas

Natural gas is an attractive fuel for energy because its' combustion produces less carbon dioxide than coal, gasoline, or oil. Natural gas is also experiencing a boom in production and consumption in the U.S., resulting from advances in horizontal drilling and hydraulic fracturing over the past decade. The process, commonly known as fracking, has enabled energy companies to extract natural gas trapped in shale in Texas, North Dakota, Pennsylvania, New York, and other states. The increased supply of natural gas has subsequently lowered the price of the fuel, which has in turn spurred the construction of power plants that burn natural gas. So great has the growth been that the EIA predicts natural gas will surpass coal as the main source of energy for electricity in the U.S. during 2016. Although shale gas reserves can be found worldwide, only three countries — the U.S., Canada, and China — produce shale gas commercially.[8]

Shale gas is trapped in the pores of rock with low permeability to the gas. To remove the gas, operators open the rock, expose the pores, and remove the gas (and possibly oil) from the pores. Fracturing the rock deep underground involves two steps: Well operators first drill a vertical well, turning the drill and boring horizontally through rock when they reach the level of the gas. Next, the entire well is layered with steel pipes and cement. In the horizontal portion of the well, operators puncture the cement and steel liners, and pump pressurized fluid into the well. The fluid pushes into the rock, fracturing the shale. Some injected water returns to the top of the well, where it is collected. Then natural gas flows through the fractures and into the well. A similar process is used to extract oil from shale formations. The injected fluid is mostly water and sand, which is used to hold the fractures open. The median amount of water needed for each well can range from 1.5 to 20 million liters, depending on the area being drilled.[9]



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Fluid that returns to the surface following fracturing is stored, reused, or injected into the ground. In case of accidental spills or leaks, there is increasing pressure being placed on drilling companies to disclose more about the composition of the fracking fluid. Less than 1% of the fracking fluid is chemicals that influence the viscosity of fluid and help deliver proppants into the fracture. Other ingredients are biocides to kill microbes that produce corrosive gases.[10] However, it’s hard to know exactly which additives are in the fracking fluid at a particular well. Some U.S. states are beginning to require additive disclosure, but many allow exemptions for ingredients claimed to be trade secrets.[11]

In a recent analysis linking the structure of disclosed additives to their toxicology, researchers from the Helmholtz Zentrum München found that many of the additives were non-toxic, but some were known to be harmful to humans or the environment. Also, some additives, like biocides or polymerizable ingredients that alter the viscosity of the fluid on demand, are designed to react underground.

The researchers argue that, because subsurface temperature and pressure could alter the structure of these molecules, it is difficult to understand their potential health and environmental impacts without knowing their original structure.[12]

Well operators include biocides in their fracking fluids because some underground microbes produce hydrogen sulfide gas that corrodes equipment. But some underground hydrogen sulfide may occur naturally. In these wells, biocides may not be needed in the fracking fluid. Water injected into multiple wells in the Bakken formation in North Dakota reaches temperatures where microbes could not survive, and elemental analysis of the hydrogen sulfide from samples of fracking fluid at the sites indicate that it was produced abiotically.[13]

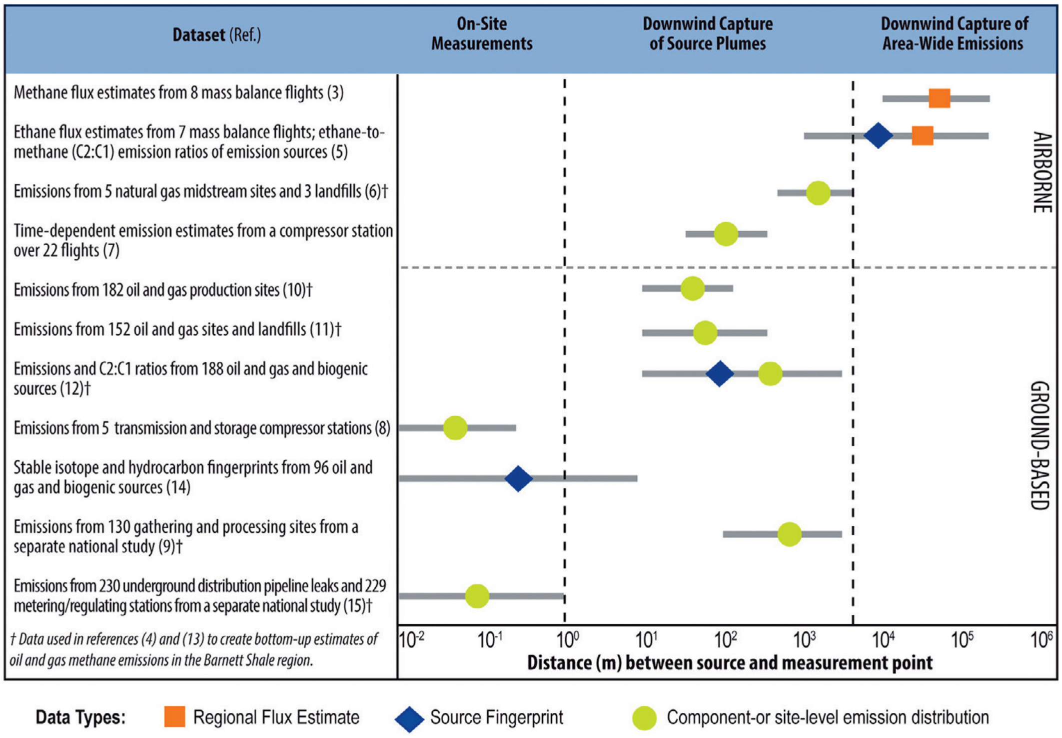
Energy companies are increasingly hiring chemists to identify and find more environmentally friendly chemicals for use in fracking fluid.[14] The ACS Green Chemistry Institute recently established the Hydraulic Fracturing Roundtable to share knowledge among member companies involved with the oil and gas industry. In 2015, researchers at Pacific Northwest National Laboratory reported a polymeric additive that reacts with carbon dioxide to form a hydrogel. The polymer expands when it becomes a gel, generating pressure that fractured rock in the lab. The researchers say that the polymer has low toxicity and contains chemical functionalities that act as natural biocides and corrosion inhibitors, characteristics that could mean fewer other additives might be needed in fracking fluid.[15]

The water that returns to the top of a well after fracturing contains salt and radioactive elements found in the geology of the shale formation. Halides such as bromide, iodide, and ammonium, dissolved in the fracking fluid while underground, could generate carcinogenic disinfection by-products during chlorination, if the fluid ends up at a drinking water treatment plant after spilling into a river.[16]

In early January 2015, almost 3 million gallons of fracking fluid leaked into two North Dakota creeks that ran into the Missouri River.

Another concern about natural gas production is methane leaking from wells or processing facilities. Methane accounts for 11% of U.S. greenhouse gas emissions, but it has about 25 times more global warming potential (a measure of the amount of energy absorbed by the gas over its lifetime) than carbon dioxide does.[17] In mid-May 2016, the U.S. EPA issued rules to cut methane emissions from new oil and gas wells, as well as requiring well operators to provide emissions information from existing wells to inform regulation of existing operations. The new rules follow an update of the agency's greenhouse gas inventory with new data and better calculations, which found that the oil and gas sector produced about 30% of the country's methane emissions, representing a greater proportion than livestock and landfills.[17]

But the amount of methane emitted from oil and gas operations — and its potential impact — is contentious.[18] One reason is that gathering estimates of methane emissions is challenging. A series of 10 papers reported data from a two week coordinated methane measurement campaign at Barnett Shale in North Texas. The papers showed how emissions measured directly at natural gas processing plants complemented those captured downwind of stationary sources like landfills, as well as measurements gathered by planes flying over production and processing sites.[19]



Multiscale measurements used to characterize methane emissions from oil and gas sources in the Barnett Shale.

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Another challenge in mitigating methane emissions is identifying the leakiest wells so they can be fixed; a small percentage of oil and gas wells account for the largest emissions.[20]

However, reducing methane emissions may not slow the temperature rise associated with global warming unless carbon dioxide emissions peak by 2050, as suggested by a study from researchers at the University of Oxford.[21] Methane, and other pollutants with a short lifetime in the atmosphere, only impact temperature rise for about 20 to 40 years. If the temperature rise associated with carbon dioxide emissions does not stabilize by 2050, the researchers argue, then today's methane emissions will be irrelevant, as their atmospheric lifetime will have expired and they will no longer be a cause of warming.[18]

Oil

After refining, a barrel of crude oil yields mainly gasoline, diesel, and jet fuel, as well as smaller amounts of chemical feedstock, liquified petroleum gas, and residual fuel oil.[22] The proportions of the end refined products vary by the composition of the raw crude.

Saudi Arabia leads the world in crude exports, while the U.S. leads for crude imports and refinery capacity.[2] The U.S. is also the fastest-growing producer of crude oil, supplied by tight oil recovered from impermeable shale deposits in Texas and North Dakota using horizontal drilling and hydraulic fracturing techniques. The remaining reserves of crude oil are increasingly producing heavy oil, which has a higher density and sulfur content than the light, sweet crude from the Middle East. Heavy oil is more difficult to refine than sweet crude, so processing these new supplies of crude could increase carbon dioxide emissions. In contrast, tight oil from the U.S. is similar in density and sulfur content to current oil from the Middle East, so refining this new source of U.S. crude would not be expected to show a decrease in refinery emissions or less energy being used during refining.[23]

There are large heavy oil reserves in the Gulf of Mexico, Venezuela, and Eastern Europe. In Canada, a version of heavy oil is found in the Alberta tar sands, which contains a viscous substance called bitumen that is found mixed in with sand. Tar sands can be directly dug out of the ground, or well operators can pump steam into the ground to melt the bitumen so that the oily substance can be pumped out. Canada exports much of its oil to the U.S., and this supply accounted for about half of U.S. crude imports as of August 2015.[24] However, bitumen contains more carbon than traditional crude oil, so it has the potential to release more carbon dioxide when burned.[22] Tar sands also require energy-intensive processes for extraction and refining, which could also increase emissions from this fuel. One model predicts that greenhouse gases produced from Canadian oil sands during extraction through combustion are 20% greater than that from crude oil.[25]

III. BIOFUELS

Biofuels derived from plants have been touted as carbon-neutral transportation fuels, with the explanation that the amount of carbon dioxide released when burning the biofuel would approximate the amount the plants absorbed while growing. Ethanol produced from corn or sugarcane is the most common biofuel, and soy, rapeseed, and sunflower oil are sources of biodiesel, the most commonly used biofuel in Europe. About 70% of the world's biofuel supplies in 2012 were produced and consumed in the U.S. and Brazil.

Policies to reduce fuel carbon emissions or increase biofuel consumption have driven the adoption of corn-based ethanol and vegetable oil-based diesel. But now it appears these food-based biofuels could create more carbon emissions than fossil fuels. Converting long-standing grassland to fields of corn or soybeans releases carbon stored in the soil. This land conversion also changes global agriculture and economics in ways that increase carbon emissions.

Second-generation biofuels, derived from cellulose in wood chips, dried corn stalks, or plants like switchgrass, may be able to deliver reduced carbon emissions. But these cellulosic biofuels have yet to reach mainstream markets, in part because they are more difficult to produce than corn-based fuels.

Bioethanol and biodiesel

In the U.S., most bioethanol is produced by breaking cornstarch down into sugars, and then converting those sugars into ethanol using microbial fermentation. Growth in corn ethanol production has been supported by the Renewable Fuels Standard, first established by the U.S. EPA in 2007, which regulated the amount of biofuels that fuel blenders add to gasoline and diesel through 2022. Today, almost 95% of the gasoline in the U.S. contains ethanol.

Corn ethanol has the highest greenhouse gas emissions among biofuels. The Environmental Working Group (EWG), an advocacy group, argues that corn ethanol contributes more climate-warming emissions than gasoline.[26] One factor for the increased emissions involves releasing carbon from soil when converting long-standing grassland to cropland for corn. Although the Renewable Fuel Standard mandates that ethanol cannot be produced from cropland established after 2007, the official method of cropland accounting tracks aggregated, net changes in cropland area, which can hide localized areas of cropland expansion and abandonment. A recent study of cropland expansion indicated that 22% of land converted to agricultural production from 2008 to 2012 was long-standing grasslands that hold the most carbon in the soil.[27]

However, switching the feedstock to dried corn leaves, husks, and cobs, the EWG says, can reduce the carbon intensity of ethanol production by 96% compared to gasoline. Corn stover, woody plants, and perennial grasses such as switchgrass and miscanthus, contain large amounts of the sugar polymer cellulose in their cell walls. Once extracted, the cellulose can be fermented into ethanol and other fuels. These cellulosic crops and wastes are useful feedstocks for biofuel because they can be grown on land unsuitable for agriculture, or in the case of corn stover, on land already used for crops. However, cellulosic ethanol is more difficult to produce than corn ethanol because the cellulose has to be separated from lignin before processing.

In 2015, two cellulosic ethanol plants opened in Iowa, processing and fermenting corn stalks, leaves, and cobs.[28] But plans to build other plants have stalled, in part due to changing U.S. renewable fuel regulations. In late 2015, the U.S. EPA reduced the renewable fuel requirements for 2016 to below the levels set for that year in 2007, essentially limiting the already-saturated ethanol market. Increasing the required amount of ethanol blended with gasoline would increase demand for the biofuel, but the oil and automotive industries say that most engines cannot run with gasoline containing more than 10% ethanol, as is currently available. While some flex-fuel cars can run on E85 (51–83% ethanol blended with gasoline), few of these cars are on the road today. Biofuel producers are worried that the reduced limits for the Renewable Fuel Standard will slow the development of cellulosic ethanol production.[29]

Another common biofuel is biodiesel produced from palm, soy, rapeseed, and sunflower oil, as well as refined animal fats. In Europe, biodiesel derived from vegetable oil is 70% of the biofuel market in the region, as most passenger cars there are diesel powered.[30] But like bioethanol, biodiesel could also be increasing carbon emissions relative to diesel fuel. A recent report from the European Commission indicates that only carbon emissions from changes to land use as a result of palm, soy, and rapeseed production for biodiesel are higher than the lifecycle emissions from diesel fuel.[31]

The European Union’s Renewable Energy Directive has been modified to cap the required amount of food-based biofuels at 7% of the at least 10% renewable transport fuel by 2020. As in the U.S., environmental advocacy groups in the region, like Transport & Environment, are calling to end biofuel production from food-based crops, switching to advanced biofuels from perennial grasses and wood waste instead.

Land use and crop choice

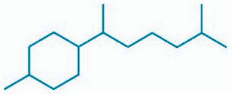
Why is there concern now that first-generation biofuels, like corn-based ethanol and soy-based biodiesel, produce more emissions than their corresponding fossil fuels? The answer comes from improved estimates of indirect land use changes as a result of biofuel production. Indirect land use changes account for six factors that affect the relationship between global agriculture and economics in response to growing crops for fuel rather than food.[32] For example, biofuel crops grown on agricultural land prevent that land from being used for food production. Less food production in one country changes food prices and patterns of consumption around the world. If forests or grasslands are also cleared to grow biofuel crops, then carbon released from the soil during clearing should also be considered as part of the overall carbon emissions generated from that biofuel.

Indirect land use changes are inherently uncertain, as they depend on the crop grown, the fuel produced, and the model used to estimate emissions changes. The models work with two imagined scenarios: land use changes between a world with more biofuel demand and one with less. Despite the uncertainties, such models are based in agricultural economics, and similar models are commonly used for other agricultural and energy policies.[33] As recent studies show, accounting for indirect land use changes could make the carbon emissions from first-generation biofuels, like corn ethanol or some food-based biodiesel, greater than those from fossil fuels.[31, 32]

However, the same studies suggest that cellulosic biofuels can be produced in ways that may reduce carbon emissions. Woody crops growing on underutilized land that has low carbon stocks could benefit the local environment. A pilot project in Sardinia growing giant reed, already invasive in the country, as well as a project in Macedonia growing switchgrass and sorghum on fields that would otherwise be fallow in winter, indicate the potential for soil improvement and better use of available land.[34]

Biofuels beyond corn

At the Joint BioEnergy Institute at Lawrence Berkeley National Laboratory in California, researchers are looking for the next generation of cellulosic biofuels, starting by understanding more about the fundamental plant biology involving cellulose and lignin. Jennifer Mortimer, director of plant systems biology at the Institute, uses solid-state nuclear magnetic resonance spectroscopy to image the structure of the sugar polymers cellulose, hemicellulose, and lignin in plant cell walls. The structure of these polymers is responsible for the mechanical properties of the cell wall and could provide atomic clues to aid the breakdown and separation of the polymers. Her group has also engineered a plant to produce 30% less lignin and that yields more sugar after processing.[35] Harry Beller, biofuels pathway director at the Institute, engineers microbes to produce new fuel molecules, like aliphatic methyl ketones that could be blended with diesel fuel, isoamyl alcohol, and carbon ring-containing molecules such as pinene and bisabolane, to make jet fuel.[35]



Bisabolane

(+)-α-Pinene

Isoamyl alcohol

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Wolfgang Marquardt, at RWTH Aachen University, also envisions biofuels made from molecules other than ethanol. He and a colleague outline a model to identify promising molecules created from a variety of plant-derived intermediates and tailored to maximize efficiency and reduce emissions from a particular engine.[36] The model first identifies a type of engine, either spark ignition as in a typical gasoline car, or compression ignition, as in a diesel engine. The operating conditions of each engine differ in how fuel enters the engine, the temperature at which the air-fuel mixture burns, and how the flame travels through the cylinder. These differences in combustion properties directly affect efficiency and emissions. Next, the model screens fuel candidates based on their physical properties. Although the relationship between molecular physical properties and combustion conditions is complicated and not well understood, general trends can be identified based on experience with fossil fuels and some renewable fuels. For example, density, viscosity, and surface tension could impact the mixing of fuel and air, which influences emissions. The melting point determines whether or not the fuel will be liquid. And the derived cetane number ranks a molecule's ignition under compression relative to cetane, which relates to the combustion parameters or operating conditions of an engine. Finally, fuel candidates are screened by structure to identify the ones easily synthesized from intermediates made by chemical or biological disassembly of plant sugars. Structures that contain peroxides, for example, are removed from consideration due to their instability.

The researchers tested a few of the fuel candidates identified by this model in engines.[37] In a compression ignition engine, 1-octanol produced less soot coming from the engine, compared to regular diesel fuel. The higher oxygen content of 1-octanol may result in less unburnt fuel that forms particles after combustion. In a spark ignition engine, 2-butanone enabled a 20% efficiency gain during normal operation compared to gasoline, because the fuel-air mixture could be compressed more before combustion. Greater compression enables combustion to generate more mechanical energy that powers the engine.

IV. RENEWABLE METHANE

Natural gas is used as a clean-burning fuel to produce electricity, generate heat for homes and businesses, and power cars and buses. Because natural gas is at least 85% methane, renewable sources of methane can replace it in existing applications and infrastructure. Methods for obtaining “renewable methane” include capturing it from landfills, as well as gathering it from biogas plants that process food waste, animal manure, or solid waste from wastewater treatment plants.

The feedstock for biogas production varies by country. Germany contains the most biogas plants in Europe, using mostly agricultural waste as feedstock.[38] Denmark produces biogas from manure, which is in excess in the country. The United Kingdom and South Korea gather biogas from landfills. In Sweden, biogas comes from sewage and food waste, and the country leads the world in using it for transportation.[39] In the U.S., the majority of biogas comes from wastewater. In developing countries, digesters built on a household scale treat waste while generating energy for cooking and heating.[40]

Power-to-gas plants represent another option for producing methane that could also help ease the transition to renewable energy by storing the energy as chemical fuel. These plants, which are growing popular in Germany, use excess renewable energy to produce hydrogen and chemically reduce carbon dioxide to methane; the methane can then be fed into the existing natural gas infrastructure.

Biogas

At biogas plants, food waste, plant waste, manure, or municipal solid waste enters a digester containing various microbes. The microbes break down fats, sugars, and proteins in these wastes in four steps: hydrolysis into amino acids, sugars, and fatty acids; acidogenesis of those products to generate compounds like propionate, butyrate, ethanol, and lactate; acetogenesis of those compounds to produce acetate, hydrogen, and carbon dioxide; and methanogenensis to produce methane and carbon dioxide.

The conversion efficiency of biogas production depends on the starting material, digester design, and conditions inside the digester such as pH and temperature. It is common to separate the first two steps of the process, hydrolysis and acidogenesis, from the last two steps because the methane-generating microbes function best at a pH higher than the optimal pH for acidogenesis.[41]

The ratio of carbon to nitrogen in the feedstock reflects the amount of nutrients in the digested waste, and it must be optimized to produce the most methane. An excessively low C/N ratio can result in ammonia production that inhibits microbial growth, and a high C/N ratio can also inhibit microbial growth by limiting the amount of available nitrogen for metabolism.[41] One common way to tailor the C/N ratio is to co-digest wastes, mixing animal manure with food waste.[42]

Additives such as acid, base, and inorganic metal can improve digestion efficiency, and thus enhance methane production.[41] These additives can also consume unwanted byproducts. For example, iron reacts with hydrogen sulfide to form iron sulfide. However, some additives can be expensive, and they may pose problems for disposing the solids remaining after digestion.

Raw biogas contains carbon dioxide, methane, and other impurities such as hydrogen sulfide, nitrogen, and oxygen. The methane concentration of raw biogas is lower than that of natural gas, so the biogas needs to be purified, or upgraded, for the methane to be used in existing applications. There are many different ways to upgrade biogas, from passing the gas through water, which absorbs the carbon dioxide and hydrogen sulfide, to using membranes that physically separate components of the raw gas.[43] The separated carbon dioxide can be fed into a power-to-gas plant and converted to more renewable methane.

Power-to-gas

At a power-to-gas plant, unused energy from wind, solar, or hydropower drives the electrolysis of water to produce hydrogen gas. In some of these plants, the hydrogen gas enters a second reactor, containing a nickel catalyst that combines the hydrogen with carbon dioxide captured from a biogas plant, for example, to produce methane.[44] The methane can then be directly injected into the natural gas infrastructure. It also provides a way to store renewable energy as a gaseous fuel.

Power-to-gas plants are being built around Germany, including the largest industrial scale plant, as well as 14 pilot and demonstration projects, and 17 more under construction.[45] This growth dovetails with the country's biogas and renewable energy growth, both

Biomass to Syngas

Gasification of biomass produces syngas, a mixture of carbon monoxide and hydrogen, with some carbon dioxide and water. Bio-derived syngas could replace syngas currently made from coal or petroleum, which is used to make methanol, hydrocarbons, ammonia, and other chemicals.[46] Once cleaned, bio-derived syngas could also be used as fuel for boilers, electrical turbines, or eventually fuel cells.[47] Power plants that currently use syngas produced from coal gasification are more efficient than those that burn coal for energy.

During gasification, biomass is heated to 500-1400°C in the presence of air, oxygen, steam, or carbon dioxide. Although gasification involves heat, it is not a combustion process. Gasification can be thought of as a combination process, where carbonized char combines with heated, pressurized carbon dioxide or steam to produce syngas. Alternatively, combustion is a separation process: volatile compounds react with oxygen, breaking down to produce carbon dioxide and carbon monoxide and releasing heat.

encouraged by the government's ambitious initiative to have 80% of the country's electricity produced with renewable energy by 2050.

The two steps in a power-to-gas plant, the electrolysis of water and the catalytic conversion of carbon dioxide to methane, are well known. However, the challenge comes from finding an electrolysis method that can respond to the intermittent power from the renewable energy sources. Alkaline electrolyzers have been commercially available for decades, although the corrosive fluids in these reactors increase maintenance costs. Electrolyzers with a polymer membrane can respond to power surges within minutes, but these systems currently cost more than alkaline electrolyzers. In the future, electrolyzers containing a solid oxide ceramic electrolyte could provide the highest efficiency — but they are still too expensive to use on a large scale at this time.

V. CARBON CAPTURE

Carbon capture technologies aim to remove carbon dioxide from the exhaust gases of power plants, cement plants, and factories. It's typically envisioned for coal-fired power plants, as they are the largest single source of carbon emissions. But few carbon capture systems have been deployed at coal-fired power plants, because the systems are expensive and require extra energy to operate. More than half of the 15 industrial-sized carbon capture projects retrieve carbon from natural gas processing facilities. Other capture projects under construction include installations at steel mills, fertilizer factories, and chemical plants. Future applications of carbon capture are envisioned for cement plants[48] and natural gas power plants.[49]

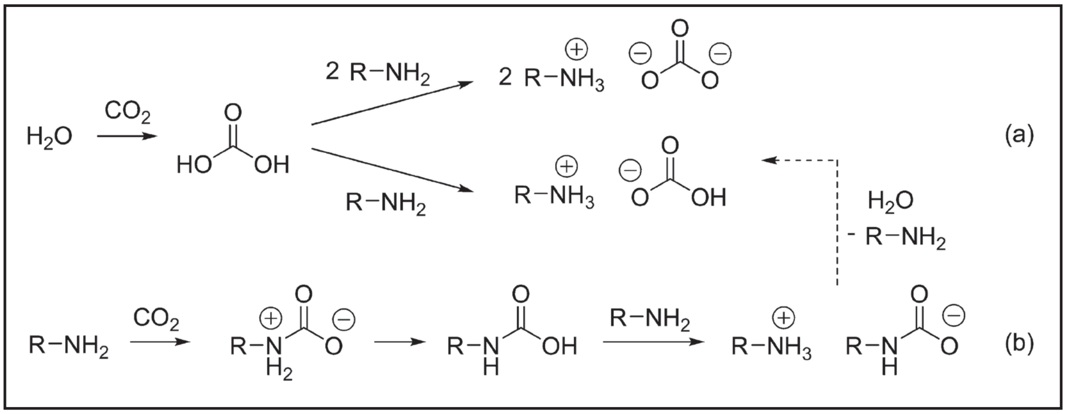
Captured carbon dioxide could be pumped underground for long-term storage, or it could be used to make useful products like foam, cement, and plastic. However, carbon capture is a controversial technology. Some researchers, environmental groups, and energy agencies argue the technology will not be developed in time to have a meaningful impact on climate change.[50] Others argue that it allows society to keep burning fossil fuels, rather than switching to cleaner sources of energy. But that same position can also support carbon capture: a recent analysis says that capture extends the amount of fossil fuels we could burn through 2100 without exceeding temperature targets.[51]

The capture process

The most promising process for capturing carbon dioxide on an industrial scale is amine scrubbing. In this process, flue gas passes through an aqueous solution of an amine, such as monoethanolamine.[52] This primary amine reacts with carbon dioxide in the exhaust gas to form a carbamate. Passing hot steam though the amine solution releases the carbon dioxide, regenerating the solution for another round of capture. Condensing the water vapor leaves pure carbon dioxide.

One challenge for carbon capture technology is reducing the energy needed to regenerate the amine solution. Some look to improve the engineering of the system. Other researchers are examining the process on a molecular scale, studying the mechanism and energetics of the amine-carbon dioxide reaction. They hope to identify intermediates and products that could be separated using less energy.[53]

Researchers at ExxonMobil used *in situ* nuclear magnetic resonance spectroscopy to follow the reaction between carbon dioxide and various amines in aqueous and non-aqueous solution. They wanted to identify amines that led to intermediates that could maximize carbon capture efficiency — that is, one mole of carbon dioxide combined with one mole of amine. Typically, two moles of amine are needed to capture one mole of carbon dioxide. It's important to note that the first product of the reaction between an amine and carbon dioxide in carbon capture is a carbamate. To maximize the amount of carbon dioxide captured per amine molecule, it is advantageous to hydrolyze the carbamate to a bicarbonate that contains one part amine and one part carbon dioxide (a). Otherwise, the carbamate forms an ammonium salt, which contains two moles of amine per mole of carbon dioxide (b).



Pathways for CO2 reactions with amines in aqueous solution: (a) Direct formation of the ammonium bicarbonate/carbonate and (b) Formation of a carbamate via zwitterion/carbamic acid

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In the nuclear magnetic resonance studies, the researchers found that tertiary amines, such as dimethylaminoethanol, in aqueous solution tend to form carbonate and bicarbonate products that are less thermally stable than corresponding products from the reaction of primary and secondary amines.[54] This means that tertiary amines would decompose more easily, and thus require less heat for regeneration.

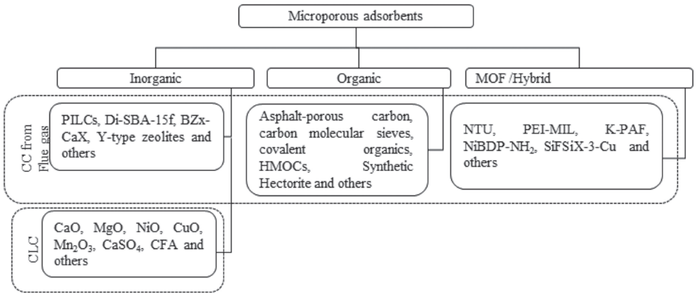
Primary and secondary amines have different advantages: a faster reaction rate and better capture under low carbon dioxide partial pressure.

The ExxonMobil researchers then studied the mechanism of carbon capture in non-aqueous solutions.[55] Dissolving an amine in an organic solvent like dimethyl sulfoxide or toluene, or in an ionic liquid, stabilizes an intermediate carbamic acid that has the desired 1:1 amine-to-carbon dioxide ratio. The researchers found that weakly basic amines in non-aqueous solution formed carbamic acids with reduced thermal stability, indicating that they could be routes to low-temperature carbon capture.

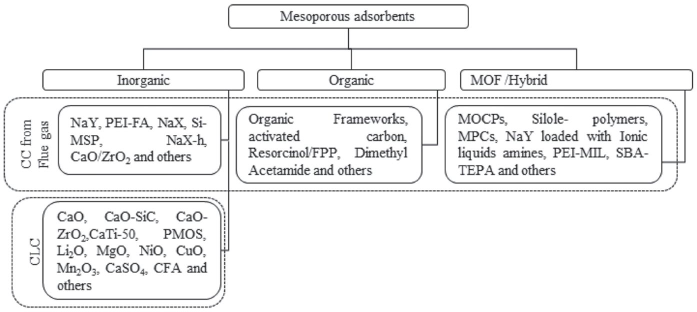
Last, the researchers studied systems containing a mixture of amines.[56] An amine mixture can be chosen to capture carbon dioxide most effectively at a given temperature and pressure, depending on the intermediates that carbon dioxide forms with each base and how the other base stabilizes those intermediates.
In non-aqueous solutions, some amine mixtures can hold multiple moles of carbon dioxide per mole of capturing amine. For example, ethanolamines in a solution of dimethylsulfoxide and tetramethylguanidine can react with up to three moles of carbon dioxide at the alcohol and amine ends of the molecule.

A strategy for capturing carbon that is still in the research phases involves trapping it in membranes or adsorbent materials, such as porous zeolites, metal-organic frameworks, or activated carbon.[57]

As an added environmental benefit, some researchers are attempting to build carbon dioxide-adsorbent materials from waste materials like steel slag[58] or coal ash.



Microporous adsorbents used for carbon capture (CC) from flue gas and in situ CC from chemical looping combustion (CLC).



Mesoporous adsorbents for CC and CLC.

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Storage

Once carbon dioxide is captured from exhaust gas, it can be compressed and transported to empty oil reservoirs for storage. Carbon storage is already being tested on industrial and pilot scales in North America, Europe, Asia, and Australia.[59] But the long-term success of this strategy depends on the carbon dioxide staying underground and not escaping to the atmosphere. Models to predict the carbon dioxide-trapping potential of various rocks need data on how carbon dioxide travels through the pores in the rocks, how it interacts with the brine trapped inside the pores,[60] and how reactive sites in the rock could catalyze the mineralization of carbon dioxide into solid carbonates.[59]

Even if the natural properties of the rock enable carbon dioxide to stay underground, it could still leak out through infrastructure remaining from drilling. Young-Shin Jun at Washington University in St. Louis studied how carbon dioxide reacts with the cement that lines a wellbore, and how those reactions impacted the mechanical properties of the cement. Microscopy images revealed that carbon dioxide dissolved particular regions of the cement, causing both the strength and the elastic modulus of the bulk cement to decrease by more than 80%.[61]

The most permanent way to store captured carbon dioxide is to convert it to solid carbonate minerals, catalyzed either by rocks inside an underground reservoir or triggered by chemical reactions above ground.[62] However, slow reaction rates for both processes contribute to increased costs compared to injecting the gas underground. So researchers are experimenting with accelerating mineralization with ash from coal or municipal waste combustion, underground microbes and mine tailings,[63] and slag from steel making.

Utilization

Another way to permanently store captured carbon dioxide is to convert it to useful materials, such as foam, cement,[64] and plastic.[65] These materials can then be sold, offsetting the capture costs. But utilizing waste carbon dioxide can be energy intensive and too expensive to make economic sense, particularly if hydrogen is needed for a process.[66]

Nevertheless, more than 250 carbon capture and utilization projects are in development worldwide. Covestro plans to open a plant in Germany to make a polyurethane intermediate using 20% waste carbon dioxide later this year. Within the next five years, Ford plans to outfit its vehicles with foams and hard plastics made from carbon dioxide captured from power plants.[67] Several European companies are building plants to produce urea and methanol from waste carbon dioxide.[66]

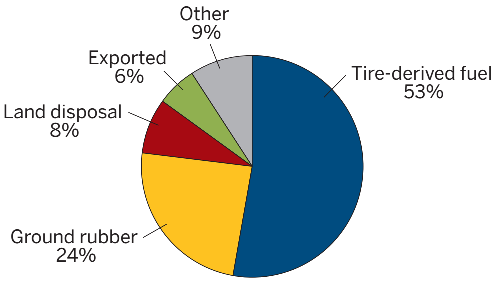
Trash decomposing in U.S. landfills is the third largest source of methane, a more potent greenhouse gas than carbon dioxide. Methane emissions are directly linked to the amount of trash produced and the amount recycled. Methane being emitted from U.S. landfills declined between 1990 and 2001 as a result of increased recycling efforts, but grew between 2001 and 2009 as the amount of trash in landfills increased.[68] More countries are recycling their municipal waste, diverting it away from landfills. Recycling common products like aluminum and steel cans, and plastic bottles uses less energy than it does to make a brand new product.

Specific types of waste can be recycled or reused to generate energy or useful products. About half the ash produced at coal-fired power plants is added to building materials, instead of being disposed of in landfills or storage ponds. Used tires can be thermally converted to energy or fuel. And recycling electronic waste provides a way to recover rare earth elements that are in short supply.

Coal ash to building materials

Coal ash, the powder remaining after burning coal, is the second largest source of waste in the U.S., after household trash. About half of the coal ash produced is reused in applications like drywall manufacturing and as cement in concrete.[69] The remaining ash is disposed in landfills or storage ponds. The American Coal Ash Association says regulatory uncertainty about the classification and disposal of coal ash has prevented more of it from being reused. To that point, the U.S. EPA released updated rules about coal ash disposal in 2015.[69] The agency continues to regulate it as nonhazardous solid waste, though the new regulations are stricter about disposal and enforcement. But because coal ash contains toxic compounds like dioxins, polyaromatic hydrocarbons, and heavy metals like chromium, cadmium, and arsenic, environmental advocacy groups want coal ash to be classified as hazardous waste.

Where Old Tires Go



Scrap tires generated in 2013 = 233 million

SOURCE: Rubber Manufacturers Association

Reprinted in part from: *Chem. Eng. News,* 2015, *93*(16): 16–18.

Tires to oil

About 230 million tires are thrown away every year in the U.S., according to the Rubber Manufacturers Association.[70] Tire recycling is difficult because it’s hard to reverse the vulcanization process used to create rubber with the desired properties. More than half of the waste tires are burned for energy. Others are shredded and added to asphalt or ground cover at playgrounds.

Burning tires without oxygen creates oil that could be refined into diesel fuel. However, sulfur and aromatic compounds in the scrap tire pyrolysis oil have to be removed before the oil could be sent to a refinery. Researchers in Spain used a supported platinum and palladium catalyst to remove the heavy aromatics and sulfur in the scrap tire pyrolysis oil, generating crude that could be sent to a refinery and converted to diesel fuel.[71] Heating a mixture of shredded used tires and used motor oil also creates crude oil that could be refined into diesel fuel.[72]

Metal recovery and recycling electronic waste

Extracting metallic elements from ore is energy intensive, so recycling metals can save some of the energy used to produce new products. For rare earth elements used in electronics and platinum group metals used in catalysts in vehicle emissions control systems, recycling could further maintain the already limited supply of these elements.

To recover metals, researchers are looking to retrieve elements dissolved in seawater.[73] Metals in household goods and personal care products also end up at wastewater treatment plants, either washed down the drain or scattered into soil and carried by runoff.[74] Researchers are using scanning electron microscopy, along with other methods, to identify the metals in sewage sludge, searching for solids that might be the most economically lucrative and resource-wise for element recovery.[75]

Recycling from electronic waste, or “e-waste,” currently recovers aluminum, copper, iron, steel, and precious metals like gold, silver, and platinum. The recycling processes are not optimized to recover rare earth elements such as neodymium, dysprosium, and praseodymium in hard disk drives, cell phones, and other devices. Less than 1% of rare earth elements are extracted from e-waste.[76]

At many electronic waste processing plants, the first step of recycling hard disk drives involves shredding the drives. At a recycling plant in Denmark, this process starts with pulverizing the magnets inside the drives, and the magnetic powder, containing rare earth elements, sticks to the surfaces of the shredding equipment, and the elements are lost.[77] However, if the magnets are removed from computers and other electronics first, then the rare earth elements inside the magnets can be removed with membrane extraction.[76]

About a third of the weight of electronic waste, including electrical equipment like refrigerators, is plastic. A two-step extraction process can recover polycarbonates from this type of waste, generating a product with similar purity and molecular weight distribution to newly synthesized polycarbonates. The process costs about 70% less than synthesizing the plastics from petroleum-based feedstock.[78]

VII. RENEWABLE AND SUSTAINABLE ELECTRICITY

Electricity production is the single largest source of the world's greenhouse gas emissions. But the industry is experiencing a revolution: In 2014, the majority of new power plants built around the world consumed renewable energy.[4] Portugal, Denmark, and Germany have run successful trials in which they used renewable energy exclusively for several days,[1] and they have maintained reliable electric grids while incorporating intermittent sources of energy, like wind and solar power.[79] In developing countries, mini-grids powered by renewable energy could help get electricity to people who don't have it.[80]

Despite being phased out in a few countries, nuclear energy is still part of some clean energy plans, although building new plants is a lengthy and controversial process. However, nuclear power is not considered to be renewable energy because it consumes uranium, a non-renewable fuel. But it is thought to be in a sustainable energy category because enough fuel is available to generate 100 years of electricity.

Solar

Solar panels, or photovoltaics, convert sunlight into electricity for households, businesses, and communities. As the cost of solar panels decreases, the number of installations increases, with panels attached to rooftops, placed in fields, and floating on lakes. About 44% of the world's solar panels are installed in Europe,[81] and the U.S. just passed the milestone of one million installations. Solar energy is a key component of many renewable energy plans, but it currently provides only about 1% of the world's electricity.[82]

Most solar panels are made from silicon semiconductors. However, alternative designs and materials, like dye-sensitized solar cells, organic photovoltaics, perovskite photovoltaics, and inorganic quantum dot solar cells, tend to capture headlines with promises of being cheaper, thinner, more efficient, more flexible, or more easily produced than current solar panels. While these materials are still in the research phases, some companies are starting to release products using some of these technologies.[83] Thin, transparent, dye-sensitized solar cells or organic photovoltaics could be used to build solar capacity into buildings, rather than on top of them. These materials could be integrated into exterior structures or sandwiched between glass in windows.

Meanwhile, the search continues for new photovoltaic materials with increased efficiency for converting light absorption into electricity. Some new materials are variations of existing structures, although computer models help researchers identify materials with previously unknown structures.[84] One model that related a molecule's structure to its electronic properties identified metal-free dyes for dye-sensitized solar cells, which typically contain a ruthenium dye.

Concentrating solar thermal plants produce solar power on a larger scale than solar panels can. At some of these plants, concentric rings of mirrors focus sunlight onto a central tower. At the world's largest solar plant, Ivenpah, in California's Mojave Desert, concentrated sunlight converts water in the central tower to steam, which is used to drive electrical turbines. Changing the material in a solar plant's central tower could provide a way to store solar energy. At the Crescent Dunes plant in Nevada, sunlight heats molten salt in the central tower. The heat in the salt can be used directly to generate steam to run turbines, or the hot salt can be stored in an insulated tank and recovered to generate 10 hours of electricity during periods of cloud cover. Another class of materials, metal hydrides, could also be used for energy storage instead of molten salt at concentrating solar thermal plants.[85] Made from inexpensive, readily-available materials such as magnesium, calcium, and titanium, metal hydrides are 10 to 30 times more energy dense than molten salt, so less salt could be used to store the same amount of energy, thus reducing storage costs.

Wind

Most wind power comes from onshore wind farms where towers with turbines line ridge tops and valleys in open areas. Fiber-reinforced blades attached to each turbine catch the wind and turn a rotor, attached by a shaft to an electrical generator. In the U.S., wind energy first started to be deployed in the 1980s, and renewable energy tax credits have spurred industry growth over the past decade. In 2015, wind capacity increased 66 GW worldwide, to a total capacity of 416 GW.[81] One-third of that capacity is installed in China, although Europe and the U.S. lead the world in actually generating wind energy.

Generally speaking, winds over the ocean are stronger than those over land, so offshore wind farms can potentially generate more energy than those onshore. But offshore farms are generally more expensive to build and maintain than those onshore, so fewer have been constructed. In 2015, global offshore wind capacity was 11.7 GW and growing.[81] Offshore wind farms are currently being constructed off the coast of Scotland and the northeastern U.S.

Hydropower

Hydropower, where rushing water turns an electricity-generating turbine, provides more than half of the world's renewable energy.[81] Large hydropower projects collect water behind a dam and direct the water through turbines at the dam's base. Smaller projects can provide isolated rural areas with access to electricity.[86]

There's potential for growth in hydropower, at least in the U.S., but uncertain subsidies, regulations, and environmental concerns may hinder that growth.[87] Like many energy technologies, hydropower also presents an environmental dilemma: Does the renewable energy produced from large hydropower plants offset the ecological consequences to rivers and streams choked by dams? Comparing a modern large hydropower project in Costa Rica with taking down an aging one in the U.S., shows that it's not clear if the environmental consequences are worth the greenhouse gas savings from not burning fossil fuels for electricity. The new Costa Rican dam practically guarantees the country can run completely off renewable energy when it goes online, while in the U.S., destroying aging dams removes sources of renewable hydropower but restores river ecosystems.[88]

Hydropower projects off the coast of Australia and Scotland generate energy from turbines turned by ocean tides, waves, or currents. While few offshore hydropower projects are operational, this type of energy generation has large potential. In the U.S., about one-third of the country's electricity could come from offshore hydropower, but these turbines are challenging to industrialize because working in the ocean is more difficult than working on land.[89] Still, the U.S. Department of Energy is encouraging research and development: nine finalists are competing to win part of a $2.25 million prize for new wave energy converter designs. The environmental impacts of offshore hydropower are less known than those of dams for conventional hydropower because few projects are operational, but initial studies suggest impacts could be minimal as devices only have to be moored to the ocean bottom.

Geothermal

Geothermal energy is one of the oldest forms of renewable energy, with documents recording its use in naturally occurring hot springs in ancient times. Ancient predecessors aside, the first power plant in the modern age to convert geothermal energy to electricity was built in Italy in the early 1900s. At geothermal electric plants, boreholes access water warmed to 100–300°C by the heat inside the planet.[90] Pumps in the plants bring the heated water to the surface, where it is converted to steam that drives electrical turbines. Condensed steam is then re-injected underground.

In 2015, there were 12.8 GW of geothermal energy installed worldwide, about 6.5% of the estimated available resource.[91] In some countries, geothermal energy provides up to 25% of the country's electricity. Future growth in geothermal energy is predicted in Latin America, East Africa, and the Philippines. Geothermal energy is considered to be a renewable resource because the sun constantly brings heat to the terrestrial surface, while the surface constantly transfers the planet's internal heat to the atmosphere. For geothermal energy to be sustainable, that heat needs to be extracted at the same rate it's replenished.

Most geothermal electric plants take advantage of naturally occurring reservoirs of hot water and steam, often located near fault lines in the planet's crust. Another source of geothermal energy is deep aquifers, where water temperatures can reach more than 60°C. The majority of geothermal energy growth is predicted to come from areas where there is little steam, and heat from the earth is extracted from hot rocks. Enhanced geothermal systems use existing or manmade fractures in rock as underground heat exchangers. Fluid, usually water, pumped into the rock gets heated as it travels through the fractures. Then the warmed fluid is pumped to the surface from a different borehole, and its heat is used to generate electricity.

Nuclear

Nuclear power is the world's second largest source of low-carbon energy. It provides continuous energy using less land than wind and solar power. Inside a nuclear reactor, decomposition of radioactive uranium atoms releases neutrons that rocket into other uranium atoms, splitting them, releasing more neutrons, and starting a self-sustaining chain reaction of nuclear fission. The nuclear decomposition releases heat used to convert water to steam. The steam is then used to power electricity-generating turbines, similar to coal or natural gas power plants.

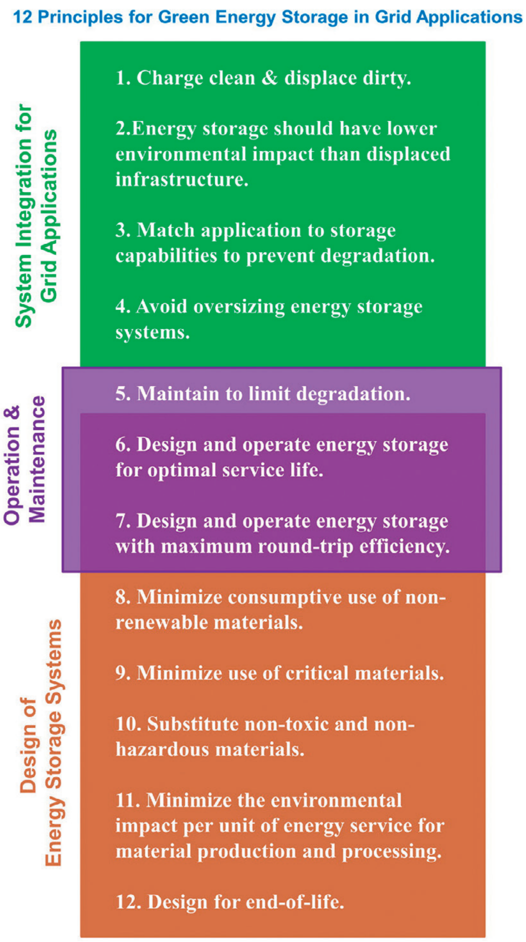
Although nuclear plants produce electricity without carbon emissions, they are often a controversial part of clean energy plans because of safety concerns. Accidents at nuclear plants in the U.S., Russia, and Japan released potentially cancer-causing radiation into the air and soil, which will impact people living near the plants for decades as the radiation levels slowly decrease over time.

Russia, China, and the U.S. are building new nuclear plants, which can take up to a decade to construct. But the changing economics of the energy industry may discourage nuclear plants as part of some countries' clean energy future. In the U.S., falling natural gas prices encourage replacement of coal-fired power plants with ones that run on natural gas. Subsidies for wind and solar energy encourage construction of those farms, rather than more nuclear plants.[92] And increased renewable energy drives energy prices so low that nuclear power can't compete.[93]

Nuclear power also lost favor in 2011 when a tsnuami damaged the Fukushima Daiichi nuclear plant in Japan, releasing radiation into the air and ocean. After that accident, many countries started looking at closing their nuclear plants. Between 2022 and 2035, Belgium, Germany, and Switzerland will phase out their nuclear plants.[94] Japan closed its nuclear plants following the Fukushima accident, restarting the first plant in August 2015 and building coal-fired power plants to generate more electricity in the country.

VIII. ENERGY STORAGE

Energy storage is seen as contributing to the growth of renewable energy because it can help modulate the surges and dips in electricity production inherent with solar and wind power. Storage mandates are one way that regions have started to develop large-scale storage technologies. For example, California has mandated 1.3 GW of energy storage by 2020. However, if stored energy comes from fossil fuel combustion, carbon emissions from the electricity sector could increase.[95] One reason for this is that the storage station would charge at night, when the off-peak power comes from coal-fired power plants.



12 Principles for Green Energy Storage in Grid Applications

1. Charge clean & displace dirty.
2.Energy storage should have lower environmental impact than displaced infrastructure.
3. Match application to storage capabilities to prevent degradation.
4. Avoid oversizing energy storage systems.
5. Maintain to limit degradation.
6. Design and operate energy storage for optimal service life.
7. Design and operate energy storage with maximum round-trip efficiency.
8. Minimize consumptive use of non-renewable materials.
9. Minimize use of critical materials.
10. Substitute non-toxic and non-hazardous materials.
11. Minimize the environmental impact per unit of energy service for material production and processing.
12. Design for end-of-life.

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To sort out the various environmental impacts that energy storage can have, researchers at the University of Michigan laid out 12 principles for green energy storage, inspired by the 12 principles for green chemistry.[96] These principles account for system integration for grid applications, the maintenance and operation of energy storage, and the design of energy storage systems including materials and production. They can also be applied to any energy storage technology.

The lead-acid car battery is a cheap (although low-capacity) way to store energy. Larger versions of lithium-ion batteries commonly used in electronic devices are starting to enter the mainstream, envisioned to be installed along with solar panels. Batteries with alternate designs or chemistries aim to reduce the costs of current technologies. Another energy storage device, a supercapacitor, delivers bursts of electricity on demand, compared to the slow release of power from a battery. Finally, pumped hydropower storage, once paired with nuclear power plants, could be applied to renewable energy.

Large-scale storage with batteries

Batteries are beginning to be installed with solar panels in homes and businesses, to store unused power that would otherwise be sold back to electric companies. The electric car company Tesla is planning to open a large lithium ion battery factory in Nevada at the end of July 2016. The factory will double the world's capacity of lithium batteries, and will drive down their cost by 30%, the company's chief technical officer told National Public Radio.[97] Tesla's chief executive officer also chairs Solar City, a solar panel installation company that controls 39% of installation leases in the U.S. Solar City will install batteries with all of its solar panels starting in 2018, therefore creating demand for Tesla's batteries.[98]

Redox flow batteries are attractive for large-scale storage, because the capacity of these batteries can easily be increased.[99] Redox flow batteries store charge in electrolyte solutions that each contain an electrode and are separated by an ion-permeable membrane. Larger tanks of electrolyte, commonly metal ions in water, increase the storage capacity. Redox flow batteries offer increased safety because their aqueous electrolyte is less flammable than the organic electrolyte used in lithium-ion batteries. But the large tanks of liquid make these batteries heavy and bulky.

Funding from the U.S. Department of Energy's Advanced Research Projects Agency-Energy (ARPA-E) supports the development of alternative battery technologies for large-scale storage, like liquid metal batteries or iron flow batteries that are cheaper and last longer than current vanadium-based technology.[100] These projects are currently scaling up their technologies or attracting venture capital.

Although energy storage is typically talked about with optimism, it could also have a negative aspect. A current debate involves excess solar power typically sold back to the electric grid. Some states are considering legislation to limit the rate that electrical companies pay for this extra solar power. Homeowners making less money from their solar panels may opt to save the energy by installing batteries. Enough customers switching to storage could change the way the electrical distribution system operates. Currently, power lines carry energy from a centralized generation plant to areas that need it. More solar installations paired with batteries, however, means more power is generated where it's used. Power industry experts say energy storage may not drive all consumers off the grid, and it could help to establish a system with more resilience and backup reliability.[98]

Supercapacitors

Supercapacitors were first developed in the 1960s. Like batteries, they contain two electrodes submerged in liquid electrolyte. But capacitors store charge electrostatically, instead of electrochemically. This means they can deliver energy instantly, but they cannot store as much energy as batteries can.

Because of their different charge storage and delivery properties, supercapacitors are seen as complements to batteries in various applications. For example, in an electric car, a supercapacitor could deliver a burst of power to start the car, while batteries trickle out energy to the lights and other accessories. However, supercapacitors are more expensive than batteries, so their practical applications are currently limited. Researchers are working to decrease this cost by improving the capacitor design and electrode materials, lately focusing on activated carbon.[101] One promising material is called MXene.[102] Atomic layers of a metal atom alternate with carbide or carbonitride layers. MXenes store charge electrostatically, like a supercapacitor, and the material also transfers electrons from molecules in the electrolyte, like a battery. It could be useful for energy storage applications that need storage and delivery capabilities between that of a battery and a capacitor. More than 70 MXenes have been created since the materials were first synthesized in 2011. Researchers are still learning about the material's fundamental properties, such as how its structure influences charge transport.[103]

Pumped hydropower

Despite the focus on batteries for energy storage, the most common energy storage method today is pumped hydropower. These storage stations are being built in California, Spain, and China, and stations once used to store nuclear power in Japan could be revived[104] as facilities to store renewable energy.

At a pumped hydropower plant, excess energy is used to pump water from one reservoir to another at a higher elevation. Releasing the water from the higher reservoir drives hydroelectric turbines located downhill. Pumped hydropower plants can provide 10 to 100 times more power than a battery. But they consume more energy than they produce, and the rapid fluctuations in water levels can have ecological consequences.[105]

Batteries for electric cars

Hybrid cars contain both an electric engine and a gasoline (or diesel) engine. In a full hybrid, like the Toyota Prius, the car can run off the gasoline and battery motors simultaneously, it can use the battery-powered electric motor for city driving, or it can activate the gasoline motor for heavy loads like driving uphill. Energy captured during braking recharges the batteries. Mild hybrids, like those made by Honda, depend on the gasoline motor for power, and use the electric motor for starting and idling. Again, energy captured during braking recharges the car's batteries. Instead of lithium-ion batteries, lead-carbon batteries could become common in these cars.[108] They are cheaper than their lithium-ion counterparts and charge faster than all-lead batteries in conventional vehicles.

Electric and hybrid cars are driving the market for lithium-ion batteries, and chemical companies are beginning to invest in materials for these batteries.[106] Two companies in the United Kingdom are working toward making cheaper batteries for electric cars.[107] Faradion makes sodium batteries and contends that the cost savings come from cheaper materials used to make the battery cathode. Unlike lithium-ion batteries, sodium batteries can be completely drained of charge, so there is less risk of fire during storage and transport. However, sodium batteries have lower cell voltage than lithium-ion batteries, so some analysts think these batteries will only be useful in niche markets.[107] The second company, Oxis Energy, makes lithium-sulfur batteries, which are also cheaper than lithium-ion batteries. But the capacity of these batteries decreases shortly after the number of charging cycles deemed as an acceptable battery lifetime, so cycle life has to be improved for these batteries to be used in cars.

IX. CONCLUSION

Looking at individual pieces of the world's energy puzzle, including fossil fuel extraction, renewable energy technology development, and government policies, can make the whole subject seem intractable and overwhelming, and frustratingly slow to progress despite the urgency to act to reduce the impact of global warming. But taking a step back and seeing how far the energy landscape has changed over the past decade, there's reason to hope. Some types of renewable energy are starting to take a foothold, even outpacing some fossil fuels. Pilot projects and some industrial-scale projects are demonstrating how to scale up renewable energy technologies developed in research labs. Individual countries are developing clean energy policies, and more than half the world's countries signed a United Nations treaty called the Paris Agreement in April 2016, agreeing to take action to limit global temperature rise. While it's hard to know exactly what the world's low-carbon energy future will look like, it's reasonable to expect that a blend of approaches will be required: switching power plants to run on natural gas instead of coal, developing solar and wind power, using biofuels for transportation, and reducing waste.

X. REFERENCES

1. Nunez, C. "Portugal Ditched Fossil Fuel Power for 4 Days. Can We Go Longer?" *National Geographic* (web date May 27, 2016); available online at http://news.nationalgeographic.com/energy/2016/05/portugal-100-percent-renewable-energy-wind-solar-hydroelectric/.
2. International Energy Agency. "World Energy Outlook 2015" (report), 2015; available online at http://www.worldenergyoutlook.org/weo2015/.
3. International Energy Agency. "Decoupling of global emissions and economic growth confirmed" (press release), March 16, 2016; available online at http://www.iea.org/newsroomandevents/pressreleases/2016/march/decoupling-of-global-emissions-and-economic-growth-confirmed.html.
4. Renewable Energy Policy Network for the 21st Century. "Renewables 2016: Global Status Report" (report), 2016; available online at http://www.ren21.net/status-of-renewables/global-status-report/.
5. Forsythe, M. "China Curbs Plans for More Coal-Fired Power Plants." *The New York Times* (web date April 25, 2016); available online at http://www.nytimes.com/2016/04/26/business/energy-environment/china-coal.html.
6. U.S. Energy Information Agency. "Coal made up more than 80% of retired electricity generating capacity in 2015" (press release), March 8, 2016; available online at http://www.eia.gov/todayinenergy/detail.cfm?id=25272.
7. Feng, B. "China Backpedals On Shale Gas." *Chem. Eng. News,* 2015, *93*(3): 22–23.
8. U.S. Energy Information Administration. "Shale gas and tight oil are commercially produced in just four countries" (press release), February 13, 2015; available online at http://www.eia.gov/todayinenergy/detail.cfm?id=19991.
9. Kondash, A., and Vengosh, A. "Water Footprint of Hydraulic Fracturing." *Environ. Sci. Technol. Lett.* 2015, *2*(10): 276–280.
10. Arnaud, C. H. "Figuring Out Fracking Wastewater." *Chem. Eng. News,* 2015, *93*(11): 8–12.

11. Morrison, J. "Uneven State Rules And Trade Secrets Rule Fracking Debate." *Chem. Eng. News,* 2015, *93*(11): 13–14.

12. Elsner, M., and Hoelzer, K. "Quantitative Survey and Structural Classification of Hydraulic Fracturing Chemicals Reported in Unconventional Gas Production." *Environ. Sci. Technol.* 2016, *50*(7): 3290–3314.

13. Wilson, E. K. "Toxic Biocides May Not Be Needed Routinely at Fracking Sites, Study Shows." *Chem. Eng. News,* 2016, *94*(15): 6.

14. Bomgardner, M. M. "Better Chemistry Flows to the Oil and Gas Industry." *Chem. Eng. News,* 2015, *93*(15): 13–17.

15. Ritter, S. K. "Hydrogel Could Green Up Fracking." *Chem. Eng. News,* 2015, *93*(17): 7.

16. Harkness, J. S., Dwyer, G. S., Warner, N. R., Parker, K. M., Mitch, W. A., and Vengosh, A. "Iodide, Bromide, and Ammonium in Hydraulic Fracturing and Oil and Gas Wastewaters: Environmental Implications." *Environ. Sci. Technol.* 2015, *49*(3): 1955–1963.

17. U.S. Environmental Protection Agency. "U.S. Greenhouse Gas Inventory: 1990-2014" (report), April 15, 2016; available online at https://www3.epa.gov/climatechange/ghgemissions/usinventoryreport.html.

18. Mooney, C. "Why We're Still so Incredibly Confused about Methane's Role in Global Warming." *The Washington Post* (web date May 2, 2016); available online at https://www.washingtonpost.com/news/energy-environment/wp/2016/05/02/why-were-still-so-incredibly-confused-about-methanes-role-in-global-warming/.

19. Harriss, R., Alvarez, R. A., Lyon, D., Zavala-Araiza, D., Nelson, D., and Hamburg, S. P. "Using Multi-Scale Measurements to Improve Methane Emission Estimates from Oil and Gas Operations in the Barnett Shale Region, Texas." *Environ. Sci. Technol.* 2015, *49*(13): 7524–7526.

20. Davenport, M. "Accounting For Methane Emissions From Oil And Gas Wells." *Chem. Eng. News,* 2015, *93*(1): 18.

21. Allen, M. R., Fuglestvedt, J. S., Shine, K. P., Reisinger, A., Pierrehumbert, R. T., Forster, P. M. "New Use of Global Warming Potentials to Compare Cumulative and Short-Lived Climate Pollutants." *Nat. Clim. Change* (published online May 2, 2016); available online at http://dx.doi.org/10.1038/nclimate2998.

22. Gordon, D. "Understanding Unconventional Oil" (report), May 2012; available online at http://carnegieendowment.org/files/unconventional_oil.pdf.

23. Hirshfeld, D. and Kolb, J. A. "Analysis of Energy Use and CO2 Emissions in the U.S. Refining Sector, With Projections for 2025." *Environ. Sci. Technol.* 2012, *46*(7): 3697–3704.

24. U.S. Energy Information Administration. "As total U.S. crude imports fall, Canada's import supply share rises" (press release), November 12, 2015; available online at http://www.eia.gov/todayinenergy/detail.cfm?id=23732.

25. Lockwood, D. "Gauging The Carbon Cost Of Fuel From Canadian Oil Sands." *Chem. Eng. News* (web date June 22, 2015); available online at http://cen.acs.org/articles/93/web/2015/06/Gauging-Carbon-Cost-Fuel-Canadian.html.

26. Cassidy, E. "Better Biofuels Ahead: The Road to Low-Carbon Fuels" (report), November 3, 2015; available online at http://www.ewg.org/research/better-biofuels-ahead.

27. Lark, T. J., Meghan Salmon, J., and Gibbs, H. K. "Cropland Expansion Outpaces Agricultural and Biofuel Policies in the United States." *Environ. Res. Lett.* 2015 *10*(4); available online at http://iopscience.iop.org/article/10.1088/1748-9326/10/4/044003/meta.

28. Bomgardner, M. M. "Cellulosic Ethanol Comes into View." *Chem. Eng. News,* 2016, *94*(15): 26.

29. Bomgardner, M. M. "Groups Pressure EPA on Biofuels Mandate." *Chem. Eng. News,* 2015, *93*(44): 6.

30. Transport & Environment. "Globiom: the basis for biofuel policy post-2020" (report), April 2016; available online at https://www.transportenvironment.org/sites/te/files/publications/2016_04_TE_Globiom_paper_FINAL_0.pdf.

31. Valin, H., Peters, D., van den Berg, M., Frank, S., Havlik, P., Forsell, N., and Hamelinck, C. "The Land Use Change Impact of Biofuels Consumed in the EU: Quantification of Area and Greenhouse Gas Impacts" (report), August 27, 2015; available online at https://ec.europa.eu/energy/sites/ener/files/documents/Final%20Report_GLOBIOM_publication.pdf.

32. Malins, C., Searle, S., and Baral, A. "A Guide for the Perplexed to the Indirect Effects of Biofuels Production" (report), September 4, 2014; available online at http://www.theicct.org/guide-perplexed-indirect-effects-biofuels-production.

33. Plevin, R. J., Beckman, J., Golub, A. A., Witcover, J., and O'Hare, M. "Carbon Accounting and Economic Model Uncertainty of Emissions from Biofuels-Induced Land Use Change." *Environ. Sci. Technol.* 2015, *49*(5): 2656–2664.

34. Searle, S., Petrenko, C., Baz, E., and Malins, C. "Crops of the Biofrontier: In Search of Opportunities for Sustainable Energy Cropping" (report), April 13, 2016; available online at http://www.theicct.org/crops-of-the-biofrontier-opportunities-for-sustainable-energy-cropping.

35. Bomgardner, M. M. "Seeking Better Biofuels." *Chem. Eng. News,* 2015, *93*(42): 8-13.

36. Dahmen, M., and Marquardt, W. "Model-Based Design of Tailor-Made Biofuels." *Energy Fuels,* 2016, *30*(2): 1109–1134.

37. Hoppe, F., Heuser, B., Thewes, M., Kremer, F., Pischinger, S., Dahmen, M., Hechinger, M., and Marquardt, W. "Tailor-Made Fuels for Future Engine Concepts." *Intl. J. Engine Res.* 2016, *17*(1): 16–27.

38. International Gas Union. "Biogas – from refuse to energy" (report), 2015; available online at http://www.igu.org/sites/default/files/node-page-field_file/IGU%20Biogas%20Report%202015.pdf.

39. European Biogas Association. "EBA Biomethane & Biogas Report 2015 Published!" (summary), 2015; available online at http://european-biogas.eu/2015/12/16/biogasreport2015/.

40. Surendra, K. C., Takara, D., Hashimoto, A. G., and Khanal, S. K. "Biogas as a Sustainable Energy Source for Developing Countries: Opportunities and Challenges." *Renewable Sustainable Energy Rev.* 2014, *31:* 846–859.

41. Mao, C., Feng, Y., Wang, X., and Ren, G. “Review on Research Achievements of Biogas from Anaerobic Digestion.” *Renewable Sustainable Energy Rev.* 2015, *45*: 540–555.

42. Divya, D., Gopinath, L. R., and Merlin Christy, P. “A Review on Current Aspects and Diverse Prospects for Enhancing Biogas Production in Sustainable Means.” *Renewable Sustainable Energy Rev.* 2015, *42*: 690–699.

43. Sun, Q., Li, H., Yan, J., Liu, L., Yu, Z., and Yu, X. “Selection of Appropriate Biogas Upgrading Technology-a Review of Biogas Cleaning, Upgrading and Utilisation.” *Renewable Sustainable Energy Rev.* 2015, *51*: 521–532.

44. Götz, M., Lefebvre, J., Mörs, F., McDaniel Koch, A., Graf, F., Bajohr, S., Reimert, R., and Kolb, T. “Renewable Power-to-Gas: A Technological and Economic Review.” *Renewable Energy*, 2016, *85*: 1371–1390.

45. Fellet, M. “Power-to-Gas Plants Use Renewable Energy to Make Sustainable Fuel.” *MRS Bulletin: Energy Quarterly*, 2016, *41*(3): 190-191.

46. Ahmad, A. A., Zawawi, N. A., Kasim, F. H., Inayat, A., and Khasri, A. “Assessing the Gasification Performance of Biomass: A Review on Biomass Gasification Process Conditions, Optimization and Economic Evaluation.” *Renewable Sustainable Energy Rev.* 2016, *53*: 1333–1347.

47. Yung, M. M., Jablonski, W. S., and Magrini-Bair, K. A. “Review of Catalytic Conditioning of Biomass-Derived Syngas.” *Energy Fuels*, 2009, *23*(4): 1874–1887.

48. Hills, T., Leeson, D., Florin, N., and Fennell, P. “Carbon Capture in the Cement Industry: Technologies, Progress, and Retrofitting.” *Environ. Sci. Technol.* 2016, *50*(1): 368–377.

49. Biliyok, C., Canepa, R., and Hanak, D. P. “Investigation of Alternative Strategies for Integrating Post-Combustion CO2 Capture to a Natural Gas Combined Cycle Power Plant.” *Energy Fuels*, 2015, *29*(7): 4624–4633.

50. Maddali, V., Tularam, G. A., and Glynn, P. “Economic and Time-Sensitive Issues Surrounding CCS: A Policy Analysis.” *Environ. Sci. Technol.* 2015, *49*(15): 8959–8968.

51. Evans, S. “Study: Most Fossil Fuels Unburnable without Carbon Capture.” *CarbonBrief* (web date May 19, 2016); available online at http://www.carbonbrief.org/study-most-fossil-fuels-unburnable-without-ccs.

52. Rochelle, G. T. “Amine Scrubbing for CO2 Capture.” *Science*, 2009, *325*(5948): 1652–1654.

53. Boot-Handford, M. E., Abanades, J. C., Anthony, E. J., Blunt, M. J., Brandani, S., Mac Dowell, N., Fernández, J. R., Ferrari, M.-C., Gross, R., Hallett, J. P., Haszeldine, R. S., Heptonstall, P., Lyngfelt, A., Makuch, Z., Mangano, E., Porter, R. T. J., Pourkashanian, M., Rochelle, G. T., Shah, N., Yao, J. G., and Fennell, P. S. “Carbon Capture and Storage Update.” *Energy Environ. Sci.* 2014, *7*(1): 130–189.

54. Kortunov, P. V., Siskin, M., Baugh, L. S., and Calabro, D. C. “*In Situ* Nuclear Magnetic Resonance Mechanistic Studies of Carbon Dioxide Reactions with Liquid Amines in Aqueous Systems: New Insights on Carbon Capture Reaction Pathways.” *Energy Fuels*, 2015, *29*(9): 5919–5939.

55. Kortunov, P. V., Siskin, M., Baugh, L. S., and Calabro, D. C. "*In Situ* Nuclear Magnetic Resonance Mechanistic Studies of Carbon Dioxide Reactions with Liquid Amines in Non-Aqueous Systems: Evidence for the Formation of Carbamic Acids and Zwitterionic Species." *Energy Fuels*, 2015, *29*(9): 5940–5966.

56. Kortunov, P. V., Baugh, L. S., Siskin, M., and Calabro, D. C. "*In Situ* Nuclear Magnetic Resonance Mechanistic Studies of Carbon Dioxide Reactions with Liquid Amines in Mixed Base Systems: The Interplay of Lewis and Brønsted Basicities." *Energy Fuels*, 2015, *29*(9): 5967–5989.

57. Sreenivasulu, B., Sreedhar, I., Suresh, P., and Raghavan, K. V. "Development Trends in Porous Adsorbents for Carbon Capture." *Environ. Sci. Technol.* 2015, *49*(21): 12641–12661.

58. Tian, S., Jiang, J., Yan, F., Li, K., and Chen, X. "Synthesis of Highly Efficient CaO-Based, Self-Stabilizing CO2 Sorbents via Structure-Reforming of Steel Slag." *Environ. Sci. Technol.* 2015, *49*(12): 7464–7472.

59. Bourg, I. C., Beckingham, L. E., and DePaolo, D. J. "The Nanoscale Basis of CO2 Trapping for Geologic Storage." *Environ. Sci. Technol.* 2015, *49*(17): 10265–10284.

60. Zhao, H., Dilmore, R., Allen, D. E., Hedges, S. W., Soong, Y., and Lvov, S. N. "Measurement and Modeling of CO2 Solubility in Natural and Synthetic Formation Brines for CO2 Sequestration." *Environ. Sci. Technol.* 2015, *49*(3): 1972–1980.

61. Li, Q., Lim, Y. M., Flores, K. M., Kranjc, K., and Jun, Y.-S. "Chemical Reactions of Portland Cement with Aqueous CO2 and Their Impacts on Cement's Mechanical Properties under Geologic CO2 Sequestration Conditions." *Environ. Sci. Technol.* 2015, *49*(10): 6335–6343.

62. Romanov, V., Soong, Y., Carney, C., Rush, G. E., Nielsen, B., and O'Connor, W. "Mineralization of Carbon Dioxide: A Literature Review." *ChemBioEng Rev.* 2015, *2*(4): 231–256.

63. McCutcheon, J., Wilson, S. A., and Southam, G. "Microbially Accelerated Carbonate Mineral Precipitation as a Strategy for *in Situ* Carbon Sequestration and Rehabilitation of Asbestos Mine Sites." *Environ. Sci. Technol.* 2016, *50*(3): 1419–1427.

64. Berg, N. "How Can We Reduce Concrete's Hefty Carbon Footprint?" *Ensia* (web date April 13, 2016); available online at http://ensia.com/articles/how-can-we-reduce-concretes-hefty-carbon-footprint/.

65. Borman, S. "Green Carboxylation Could Convert Biomass to Plastic." *Chem. Eng. News* (ACS San Diego 2016 Meeting Coverage) [web date March 16, 2016]; available online at http://acssandiego2016.cenmag.org/green-carboxylation-could-convert-biomass-to-plastic/.

66. Scott, A. "Learning to Love CO2." *Chem. Eng. News,* 2015, *93*(45): 10–16.

67. Peters, A. "Ford Will Soon Be Making Car Parts Out Of CO2 Pollution." *Co.Exist* (web date May 16, 2016); available online at http://www.fastcoexist.com/3059905/ford-will-soon-be-making-car-parts-out-of-co2-pollution.

68. U.S. Energy Information Administration. "Emissions of Greenhouse Gases in the U.S." (report), March 31, 2011; available online at http://www.eia.gov/environment/emissions/ghg_report/ghg_methane.cfm.

69. Ritter, S. K. "A New Life For Coal Ash." *Chem. Eng. News,* 2016, *94*(7): 10–14.

70. McCoy, M. “The Elusive Dream Of Tire Recycling.” *Chem. Eng. News,* 2015, *93*(16): 16–18.

71. Hita, I., Rodríguez, E., Olazar, M., Bilbao, J., Arandes, J. M., and Castaño, P. “Prospects for Obtaining High Quality Fuels from the Hydrocracking of a Hydrotreated Scrap Tires Pyrolysis Oil.” *Energy Fuels*, 2015, *29*(8): 5458–5466.

72. Jonusas, A. and Miknius, L. “Influence of the Process Conditions on Yield, Composition, and Properties of the Products Derived from the Thermolysis of Scrap Tire and Used Engine Oil Blends.” *Energy Fuels*, 2015, *29*(11): 6978–6987.

73. Diallo, M. S., Kotte, M. R., and Cho, M. “Mining Critical Metals and Elements from Seawater: Opportunities and Challenges.” *Environ. Sci. Technol.* 2015, *49*(16): 9390–9399.

74. Westerhoff, P., Lee, S., Yang, Y., Gordon, G. W., Hristovski, K., Halden, R. U., and Herckes, P. “Characterization, Recovery Opportunities, and Valuation of Metals in Municipal Sludges from U.S. Wastewater Treatment Plants Nationwide.” *Environ. Sci. Technol.* 2015, *49*(16): 9479–9488.

75. Ritter, S. K. “Digging Through New Types Of Waste To Recycle Metals.” *Chem. Eng. News,* 2015, *93*(14): 25–27.

76. Kim, D., Powell, L. E., Delmau, L. H., Peterson, E. S., Herchenroeder, J., and Bhave, R. R. “Selective Extraction of Rare Earth Elements from Permanent Magnet Scraps with Membrane Solvent Extraction.” *Environ. Sci. Technol.* 2015, *49*(16): 9452–9459.

77. Habib, K., Parajuly, K., and Wenzel, H. “Tracking the Flow of Resources in Electronic Waste–The Case of End-of-Life Computer Hard Disk Drives.” *Environ. Sci. Technol.* 2015, *49*(20): 12441–12449.

78. Weeden, Jr., G. S., Soepriatna, N. H., and Wang, N.-H. L. “Method for Efficient Recovery of High-Purity Polycarbonates from Electronic Waste.” *Environ. Sci. Technol.* 2015, *49*(4): 2425–2433.

79. Roselund, C. and Bernhardt, J. “Lessons Learned Along Europe’s Road to Renewables.” *IEEE Spectrum* (web date May 4, 2015); available online at http://spectrum.ieee.org/energy/renewables/lessons-learned-along-europes-road-to-renewables.

80. Fairley, P. “Renewable Minigrids Should Be the End Goal for Rural Poor.” *IEEE Spectrum* (web date May 22, 2015); available online at http://spectrum.ieee.org/energywise/energy/renewables/electrification-rumble-renewable-minigrids-challenge-the-big-grids-primacy.

81. International Renewable Energy Agency. “Renewable Energy Statistics 2016” (report), 2016; available online at http://www.irena.org/menu/index.aspx?mnu=Subcat&PriMenuID=36&CatID=141&SubcatID=2738.

82. Unger, D. “America Now Has 27.2 Gigawatts of Solar Energy: What Does That Mean?” *InsideClimate News* (web date May 25, 2016); available online at http://insideclimatenews.org/news/24052016/solar-energy-27-gigawatts-united-states-one-million-rooftop-panels-climate-change-china-germany.

83. Jacoby, M. “The Future of Low-Cost Solar Cells.” *Chem. Eng. News,* 2016, *94*(18): 30–35.

84. Jacoby, M. “How Computers Are Helping Chemists Discover Materials That Don’t Yet Exist.” *Chem. Eng. News,* 2015, *93*(47): 8–11.

85. Fellet, M. "Research on Metal Hydrides Revived for Next-Generation Solutions to Renewable Energy Storage." *MRS Bulletin: Energy Quarterly*, 2013, *38*(12): 1012-1013.

86. Levitan, D. "As Small Hydropower Expands So Does Caution on Its Impacts." *Yale environment360* (web date August 4, 2014); available online at http://e360.yale.edu/feature/as_small_hydropower_expands_so_does_caution_on_its_impacts/2790/.

87. Cushman, Jr., J. H. "Hydropower, the Unloved Renewable, Shows Potential for Growth." *InsideClimate News* (web date April 28, 2015); available online at http://insideclimatenews.org/carbon-copy/28042015/hydropower-renewable-shows-potential-growth-energy-department-report.

88. Wade, L. "The Death and Birth of the American Dam." *Wired* (web date May 19, 2016), available online at http://www.wired.com/2016/05/death-birth-american-dam/.

89. Levitan, D. "Why Wave Power Has Lagged Far Behind as Energy Source." *Yale environment360* (web date April 28, 2014); available online at http://e360.yale.edu/feature/why_wave_power_has_lagged_far_behind_as_energy_source/2760/.

90. International Energy Agency. "Technology Roadmap: Geothermal Heat and Power" (report), 2011; available online at https://www.iea.org/publications/freepublications/publication/technology-roadmap-geothermal-heat-and-power.html.

91. Matek, B. "2015 Annual U.S. & Global Geothermal Power Production Report" (report), 2015; available online at http://geo-energy.org/reports/2015/2015%20Annual%20US%20%20Global%20Geothermal%20Power%20Production%20Report%20Draft%20final.pdf.

92. Gross, D. "The Half-Life of America's Nuclear Plants." *Slate* (web date May 16, 2016); available online at http://www.slate.com/articles/business/the_juice/2016/05/america_is_getting_new_nuclear_plants_in_tennessee_and_georgia_we_need_more.html.

93. Fairley, P. "Has U.S. Nuclear Power's Death Spiral Begun?" *IEEE Spectrum* (web date March 25, 2016); available online at http://spectrum.ieee.org/energy/nuclear/has-us-nuclear-powers-death-spiral-begun.

94. Nuclear Energy Agency and International Energy Agency. "Technology Roadmap: Nuclear Energy, 2015 Edition" (report), 2015; available online at http://www.iea.org/publications/freepublications/publication/Nuclear_RM_2015_FINAL_WEB_Sept_2015_V3.pdf.

95. Hittinger, E. S. and Azevedo, I. M. L. "Bulk Energy Storage Increases United States Electricity System Emissions." *Environ. Sci. Technol.* 2015, *49*(5): 3203–3210.

96. Arbabzadeh, M., Johnson, J. X., Keoleian, G. A., Rasmussen, P. G., and Thompson, L. T. "Twelve Principles for Green Energy Storage in Grid Applications." *Environ. Sci. Technol.* 2016, *50*(2): 1046–1055.

97. Sommer, L. "A Rare Look Inside The 'Gigafactory' Tesla Hopes Will Revolutionize Energy Use." *National Public Radio* (web date April 18, 2016); available online at http://www.npr.org/sections/alltechconsidered/2016/04/18/474346868/a-rare-look-inside-the-gigafactory-tesla-hopes-will-revolutionize-energy-use.

98. Gibb, S. K. "Batteries Paired With Solar Panels Could Shake Up Electric Utility Sector." *Chem. Eng. News,* 2015, *93*(11): 24–25.

99. Jacoby, M. "How Redox Flow Batteries Could Stabilize Our Electric Grids." *Chem. Eng. News,* 2016, *94*(6): 26–28.

100. Bomgardner, M. M. "ARPA-E Shows Off Its Big Batteries." *Chem. Eng. News,* 2015, *93*(11): 21–22.

101. Reisch, M. S. "Supercapacitor Makers Charge Ahead." *Chem. Eng. News,* 2015, *93*(5): 20–21.

102. Jacoby, M. "For Energy Storage, MXene Materials Show Increasing Promise." *Chem. Eng. News,* 2015, *93*(1): 23–24.

103. Fellet, M. "Scanning Probe Microscopy Reveals Nanoscale Pathways for Ion Transport in a Future Energy Storage Material." *Materials360 Online* (web date April 15, 2016); available online at http://www.materials360online.com/newsDetails/61498.

104. Fairley, P. "A Pumped Hydro Energy-Storage Renaissance." *IEEE Spectrum* (web date March 18, 2015); available online at http://spectrum.ieee.org/energy/policy/a-pumped-hydro-energystorage-renaissance.

105. Roach, J. "For Storing Electricity, Utilities Are Turning to Pumped Hydro." *Yale environment360* (web date November 24, 2015); available online at http://e360.yale.edu/feature/for_storing_electricity_utilities_are_turning_to_pumped_hydro/2934/.

106. McCoy, M. "Chemical Firms Target Batteries." *Chem. Eng. News,* 2015, *93*(37): 8.

107. Scott, A. "Challenging Lithium-Ion Batteries With New Chemistry." *Chem. Eng. News,* 2015, *93*(29): 18–19.

108. Scott, A. "Lead Makers Fight to Stay in Batteries." *Chem. Eng. News,* 2016, *94*(10): 30.

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