The path towards sustainable energy

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Civilization continues to be transformed by our ability to harness energy beyond human and animal power. A series of industrial and agricultural revolutions have allowed an increasing fraction of the world population to heat and light their homes, fertilize and irrigate their crops, connect to one another and travel around the world. All of this progress is fuelled by our ability to find, extract and use energy with ever increasing dexterity. Research in materials science is contributing to progress towards a sustainable future based on clean energy generation, transmission and distribution, the storage of electrical and chemical energy, energy efficiency, and better energy management systems.

The world energy consumption in 2012 was 549 quadrillion British thermal units (or quad BTUs, where 1 quad BTU = 293 TWh)[1], the equivalent of continuously having 25 billion horses working for us. The modern-day equivalent of the biological waste of horses is represented by the pollutants created from fossil fuels that currently supply us with 85% of our energy. The CO_2 in the atmosphere has risen from 278 ppm at the beginning of the industrial revolution to >400 ppm today. In addition to CO_2, other significant greenhouse gases (GHGs) are CH_4, N_2O and fluorinated gases, and the total CO_2 equivalent (CO_2e) concentration is >480 ppm. Notably, 75% of this rise has taken place since 1950[2]. Burning fossil fuels also creates other environmental pollutants such as SO_x, NO_x, particulate matters (PM), volatile organic compounds and toxic heavy metals.

As a result of our GHG emissions, our climate is changing. The increasing heat waves and droughts, torrential rainfalls and accompanying floods, and the encroaching seas are all early but ominous warning signs. The Earth's climate system is extremely complex and there are considerable uncertainties in predicting future risks. In addition, due to the huge thermal inertia of deep oceans[3], the warming caused by the heat trapped by GHGs will be slow to reverse. This means that, even if human emissions stop tomorrow, it could take centuries to reach a new equilibrium temperature and appreciate the full extent of the damage created. For these reasons, mitigating the climate risks by dramatically decreasing our GHG emissions is a prudent insurance policy; waiting for additional evidence would be risky business.

"If you don't change direction, you will end up where you are heading," said Lao Tzu, the father of Taoism. Where are we heading? Energy use is projected to climb to 629 quad BTUs by 2020, and 813 quad BTUs by 2040[1]. The global emissions of CO_2 doubled from 1975 to 2015, and are projected to triple by 2040 if we stay on our present course[4].

In 2012, we discussed the opportunities and challenges in the transition to a sustainable future[5], focusing on carbon emissions in the transportation and electricity generating sectors, which account for less than half of GHG emissions. We note that 30% of GHG emissions and most of the CH_4 and N_2O emissions are from agriculture, forestry and land use[4], and the remainder from industrial processes such as chemical, cement and steel production, and heating. Because anthropogenic GHG emissions are coming from virtually every sector of our economy, many solutions are needed to meet this global challenge.

Although fossil fuels will remain a significant source of energy and materials for decades to come, a path to zero emissions is envisioned in Fig. 1. An increasing amount of clean renewable and nuclear energy is being converted into electricity for industrial production and household applications such as lighting and air conditioning, while advances in materials science are lowering the carbon footprint in buildings. Transmission and distribution of electricity is becoming more efficient thanks to breakthroughs in wide bandgap semiconductors and dielectric materials. Electricity stored in batteries is increasingly being used to power electric vehicles and back up intermittent renewables. We will transition from a chemical industry based on oil and gas feedstocks to one that is increasingly based on renewable agricultural residues. As the cost of clean energy continues to plunge, new catalysts will enable us to economically convert CO_2 and H_2O directly into fuels and chemicals. Moreover, metal–organic frameworks (MOFs) and other novel materials are being used to capture carbon from power generation, cement, aluminium, plastic and steel production, and, ultimately, the atmosphere. After recycling as much of the captured carbon as possible, advances in materials science will allow us to permanently sequester the rest of the carbon[6].

Here, we give an overview of the opportunities that recent exciting results in materials science may open in selected areas of energy research. Some of the recent important scientific developments are reviewed in more detail in the accompanying Reviews[7–11].

Photovoltaic devices

The price of solar power modules has plunged from 3 US\$ W^{-1} in 2008 (the price of a module to generate 1 W of power under a defined illumination intensity of 1 sun) to 0.50 US\$ W^{-1} in 2016[12]. In 2011, the US Department of Energy (DOE) SunShot 2020 goals for the full levelized cost of electricity (LCOE, representing the total cost to build and operate an energy producing source over its anticipated lifetime divided by the total amount of electricity produced) were 0.06 US\$ kWh^{-1} and 0.09 US\$ kWh^{-1} for utility and residential solar power, respectively[13]. It appears likely that the SunShot goals will be met. Indeed, the LCOE of solar energy in locations such as Dubai, with excellent solar insolation, is already as low as 0.03–0.04 US\$ kWh^{-1}, according to recent price bids submitted by developers of renewable energy systems in reverse auctions (Fig. 2a)[14]. As a result, the DOE recently announced their 2030 goals of 0.03 US\$ kWh^{-1} and 0.05 US\$ kWh^{-1} LCOE for utility and residential solar power.

Figure 2b shows one pathway of reducing prices from the 2016 benchmark of 0.07 US\$ kWh^{-1} to 0.03 US\$ kWh^{-1}, leveraging on the reductions expected for the fabrication and maintenance costs of solar panels, and on the expected increase in lifetime[15]. In 2015, 69.5% of the production of solar modules was covered by

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polycrystalline silicon technology, 23.9% by single crystalline silicon and 6.6% by CdTe. The power-conversion efficiencies of solar modules are as high as 21% for single crystal silicon, typically 17% for polycrystalline, and 15.6% for CdTe, whereas at the laboratory cell level the highest efficiencies are 25.6%, 21.3% and 21%, respectively[16]. Steady reductions in capital and manufacturing costs, along with financing and policies such as reverse auction bidding are expected to drive the photovoltaic (PV) electricity cost down to 0.03 US$ kWh^{-1}. Future reductions will come from higher module efficiency, longer module and electronics lifetimes (>35 years) and lower efficiency degradation (<0.3% per year).

While conventional Si and CdTe will continue to drive down the cost of PV electricity, to reach values lower than 0.02 US$ kWh^{-1}, new mechanisms to increase the efficiency of solar cells and materials having reduced production and processing costs will be needed. Many of the factors that affect the performance of single and multijunction solar cells are discussed in ref. 8. The limit of single junction cell efficiency, known as the Shockley–Queisser limit, can be overcome by concentrating sunlight with a better management of direct incident and diffuse light — for instance, using nanocone structures to enhance light absorption in solar cells[17] — or by the use of multi-junction cells. Other possible improvements include intermediate bandgap solar cells, photon up- or down-conversion, luminescence concentrators, carrier multiplication, and thermophotovoltaic schemes. Developing methods of coherently transferring energy, as is done in biological photosynthetic systems, is another possibility to improve solar cell efficiency[7]. The use of novel materials may open promising alternative paths to traditional technologies. For instance, perovskite materials[18] such as $CH_3NH_3PbI_3$ have demonstrated their potential within a very short time (less than five years), reaching a power conversion efficiency of 22.1% for small-scale solar cells[19]. In addition to their good performance, perovskites are advantageous for their low-cost processing and for the possibility to tune their absorption spectrum for an optimized integration in multi-junction cells; however, long-term durability remains a major challenge.

Finally, self-cleaning, super hydrophobic surfaces based on nanostructured materials are being investigated to keep the solar module surfaces clear of dirt and sand with minimal water use, as well as to prevent ice formation on airplanes and wind turbine blades, and as antifouling coatings for the hulls of marine vessels. Many of these anti-wetting and anti-icing surfaces mimic the micro- and nanostructures of lotus leaves (Fig. 2c,d) and insect wings[20–22].

Batteries

Robust, rechargeable batteries are essential for electric vehicles (EV) and grid storage. The DOE has set a cost target for EV battery packs of 125 US$ kWh^{-1} to be reached in 2022, which would ensure the wide scale deployment of clean transportation technologies[23]. The current EV battery cells have a specific energy of 200–250 Wh kg^{-1}, but an aggressive goal to reach 500 Wh kg^{-1} with a >10-year life and total mileage of ~150,000 miles has been proposed by the Battery500 Consortium. In grid storage applications, high energy density is less crucial, but requirements on performance stability — more than 6,000 cycles and lifetimes surpassing 20 years — are more stringent.

Lithium-ion batteries (LIBs) have been the dominating technology for applications in transportation and consumer electronics. The current LIB is based on graphite anodes and lithium metal oxide cathodes such as layered $LiNi_xCo_yMn_zO_2$ (NMC), $LiMn_2O_4$ and $LiFePO_4$. $Li_4Ti_5O_{12}$ has also been used as an anode for fast charging in electric buses, but it has lower energy density due to a high anode potential[24]. Further increase in energy and power density calls for new electrode materials.

On the anode side, silicon has ten times higher specific capacity (4,200 mAh g^{-1} for silicon, 2,100 mAh g^{-1} for $Li_{4.4}Si$) than graphite (372 mAh g^{-1}), but it undergoes a four-times volume change between charged and discharged states that may cause mechanical failure. In the past decade, solutions to overcome mechanical fracture and instability of the solid–electrolyte interphase have been proposed based on a variety of nanoscale designs (Fig. 3a)[25]. Lithium metal anodes are another interesting choice due to their high capacity (3,860 mAh g^{-1}). However, dendrite formation, low cycling Coulombic efficiency, short battery life and safety concerns have so far prevented commercialization. Several recent approaches, such as the use of nanoscale design, electrolyte additives, solid-state
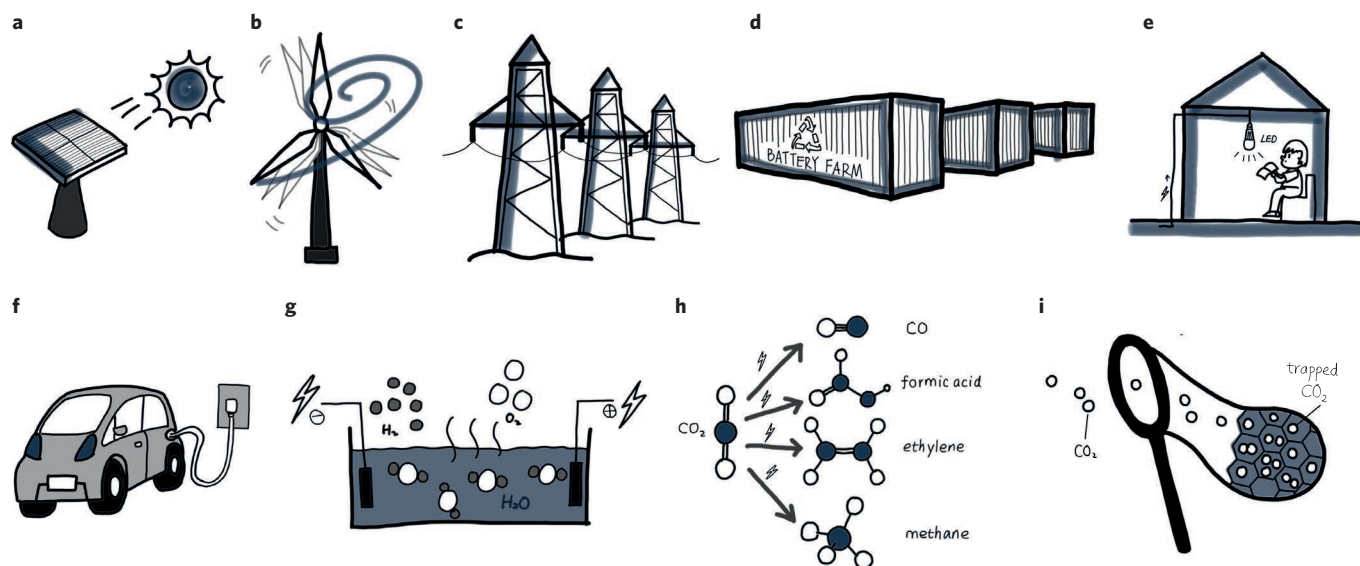
Figure 1 | Renewable energy future. a–i, Advances in materials science and engineering are increasing the efficiency of electricity generation from clean renewable energy sources — solar panels (**a**) and wind turbines (**b**), for instance — as well as electricity distribution (**c**) and storage (**d**). Improved energy management in buildings (**e**) and widespread diffusion of electric vehicles (**f**) are decreasing our carbon footprint. Better catalysts and photoelectrochemical devices allow a more efficient generation of hydrogen and oxygen (**g**), and CO_2 conversion to fuels and chemicals (**h**). Carbon-capture materials (**i**) will decrease the amount of CO_2 released in the atmosphere. Illustration courtesy of Paloma Liu.
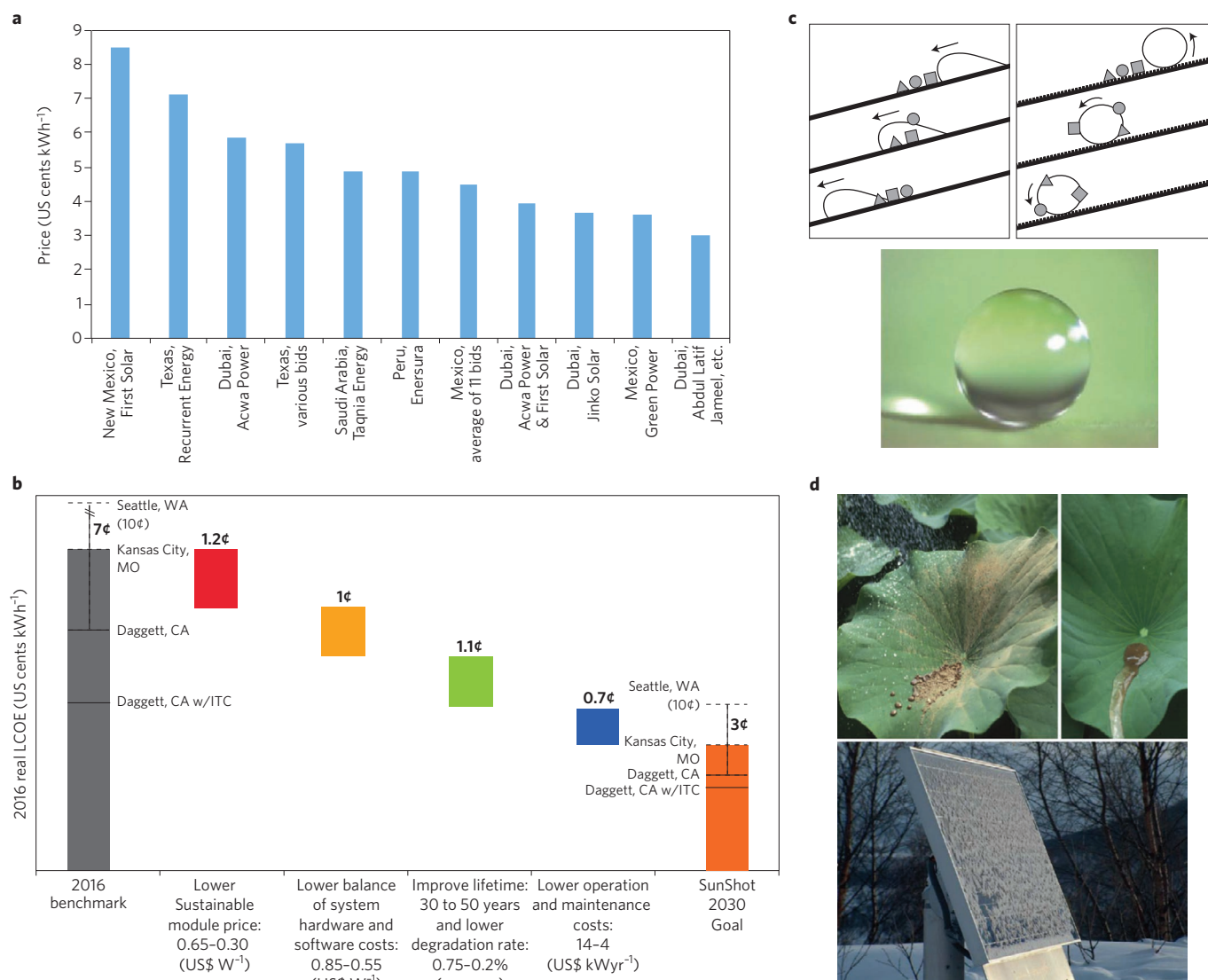
Figure 2 | Photovoltaic technologies. a, Reverse auction prices of unsubsidized solar contracts. The bids in Texas and New Mexico have been multiplied by 1.4 to account for the 30% investment tax credit. **b**, A DOE example of a modelled pathway to reduce LCOE from 0.07 US$ kWh⁻¹ in 2016 to 0.03 US$ kWh⁻¹ by 2030. Each column represents the DOE estimate of the decrease in cost of each major cost to the LCOE of solar energy. **c**, A drop of water on a lotus leaf (bottom) and a cartoon of how a lotus leaf efficiently cleans itself with minimal water use (top), with a non-wetting droplet of water efficiently picking up dirt. **d**, Water helps cleaning dirt from a lotus leaf (top), whereas dirt, snow and ice remain deposited on the surface of untreated solar panels (bottom). Adapted from ref. 14, Important Media Network (**a**); reproduced from ref. 15, DOE (**b**); ref. 20, RSC (**c**); and ref. 21, Elsevier (**d**).

electrolytes, and the combination of lithium metal with graphene oxide hosts[27], show promise to overcome these limitations.

On the cathode side, the continuous improvement of Ni- and Li-rich $LiNi_xCo_yMn_zO_2$ might result in an appreciable improvement of specific capacity (~250 mAh g⁻¹) of batteries, due to the possibility for both transition metal atoms and oxygen to change their oxidation state. However, the chemical and structural stability of these materials needs to be improved[28]. A potentially large capacity improvement could come from sulfur (~1,700 mAh g⁻¹) and O_2 (~1,700 mAh g⁻¹ for Li_2O_2) cathodes, although these technologies are affected by long-term stability issues too. Also in this case, the use of nanostructured architectures[26] (Fig. 3b) may be effective in increasing the cycle life and overall performance of these cathodes. As shown in Fig. 3c, proper combination of some of these anodes and cathodes may allow the realization of lithium-based batteries with practical specific energy ranging from 200 to more than 600 Wh kg⁻¹.

In addition, replacement of Li with more sustainable chemistries based on Na, K, Mg and Al are being investigated, though all the battery components — including anode, cathode, solvent, salt and additives — need to be reconsidered and developed *ad hoc* to make these alternative technologies competitive.

For grid scale applications, the cost, scalability and long cycle/calendar life are more important figures of merit. Redox flow batteries show promise for grid storage, but the cost of the ion-exchange membranes that separate the positive and negative electrolytes used in such devices must be reduced, and the solubility of redox molecules needs to increase[29]. Semi-flow batteries (using one solid and one liquid electrode) such as Zn–halogen[30] and Li–polysulfide[31] systems remove the needs of ion-selective membranes, potentially lowering costs. Aqueous electrolyte-based batteries are attractive due to the low electrolyte cost and excellent safety[32]. A detailed overview of the current status of research on batteries and the development of sustainable materials and architectures for battery applications is reported in ref. 9.

Solar and chemical fuels

The aforementioned progress notwithstanding, it should be considered that the volumetric and gravimetric energy density of current electrochemical batteries is almost 100 times lower than gasoline or diesel fuel. Even a fuel with relatively low energy density such as methanol is likely to contain at least ten times higher chemical energy than any foreseeable sealed battery. The advantages of hydrocarbon fuels that can be stored as liquids near standard temperature and pressure conditions are enormous. The compression and refrigeration costs of liquefying natural gas, plus the need to transport it quickly and store it as a cryogenic liquid are much higher than the associated cost of dealing with liquid fuels. Slow moving oil tankers can be regarded as transcontinental energy transmission conduits, where, remarkably, the cost of moving oil around the world only adds a few pennies to the cost of a gallon of gasoline. As a consequence, when the LCOE of clean electricity will drop to 0.02–0.03 US$ kWh^{-1}, it may be more convenient to store such electricity in the form of chemical fuels and high valuable chemicals through electrocatalytic reactions such as water splitting and CO_2 reduction.

Water splitting, $2H_2O \rightleftharpoons 2H_2 + O_2$, has four related half reactions: hydrogen evolution reaction (HER), oxygen evolution reaction (OER), hydrogen oxidation reaction (HOR) and oxygen reduction reaction (ORR). HER and OER are key for hydrogen fuel production, and HOR and ORR occur in fuel cells. These four reactions traditionally all use precious metal catalysts, yet it may be possible to achieve efficient conversion with earth abundant materials by understanding the catalysis mechanism. For HER, platinum has been the most well-known catalyst, but recent studies show that $3d$ transition metals and their alloys, metal phosphides, sulfides, and hydroxides are also very active[11]. For instance, layered MoS_2 (Fig. 4a)[33] has been shown to present active Mo edge sites[34,35]. For OER, in addition to benchmarked RuO_2 and IrO_2, other transition metal oxides and oxyhydroxides have shown very high activities. Pt and Ir are the most active HOR catalysts, although NiMo is an attractive choice due to its low cost. Pt-based catalysts are the most used in ORR[36] including Pt alloys with transition metals (Fig. 4b). Multimetallic nanostructures offer extremely high surface to volume ratios. In the case of Pt_3Ni nanoframes shown in Fig. 4c, a 36× enhancement in mass activity and 22× enhancement in specific activity for ORR reactions were observed[37]. In addition to exploring different compositions of catalysts, a new approach was recently demonstrated based on electrochemical tuning during lithium insertion and extraction (Fig. 4d) to control the chemical potential, oxidation state and electronic structure, and efficient catalysts have been discovered[38]. The contributions of theoretical simulations and fundamental characterization techniques to the understanding of the catalytic mechanisms and the design of new catalysts are discussed in ref. 10.

The electrochemical reduction of CO_2 to other carbon compounds with higher chemical energy, $CO_2 + H_2O \rightleftharpoons H_xC_yO_z + O_2$, is an attractive method to produce chemical fuels while reducing carbon emissions. The recycling of carbon dioxide into methanol and derived products (such as carbon monoxide[39] and formic acid[40]) in a 'methanol economy' has been proposed as an alternative to the hydrogen economy because of the inherently higher energy density[41–43] of the reaction products. A recent review of catalysts for the electro-reduction of carbon dioxide into fuels is reported in ref. 44.

Alternatives to electrochemical reactions are photoelectrochemical reactions, which utilize sunlight directly to convert water and CO_2 into chemical fuels and feedstocks. As discussed in refs 9,10, the photochemical reactions present numerous material requirements to simultaneously combine photon absorption, charge separation, catalysis and electronic structure alignment with chemical reactions. From an economic perspective, it is important to realize that in all schemes to convert electrical energy or direct solar energy into chemical fuels, the capital expense (and the amortized cost of money) of the commercial plant is a significant fraction of the levelized cost of any chemical plant. An electrochemical facility powered only by local PV will have a seasonal duty cycle of 25% if every day is sunny. To maximize the return on the capital investment, it is desirable to operate the facility as close to full capacity as possible.

Further opportunities

In addition to the research areas discussed here and in the Reviews in this Insight[7–11], other areas of research also deserve attention.

Materials for gas separation and storage. In the petrochemical industry, the initial cracking of long chain hydrocarbons occurs at high temperatures. The further fractionations of light hydrocarbons of similar volatility and molecular sizes such as ethylene/ethane (C_2H_4 and C_2H_6) and propylene/propane (C_3H_6 and C_3H_8) are currently done at low temperatures and high pressures, and their separation is one of the most energy-intensive industrial processes. MOFs have been recently shown to separate small chain hydrocarbons from CH_4 to C_3H_8 with unprecedented selectivity by tuning pore size with nanometer precision and attaching appropriate functional groups[45].

The capture of CO_2 in power generation and in industrial processes is a necessary part of the required transition to deep decarbonization[46]. Carbon capture methods for power plants include post-combustion capture of CO_2 from the flue gas (such as liquid amine), and pre-combustion separation where the fuel is converted
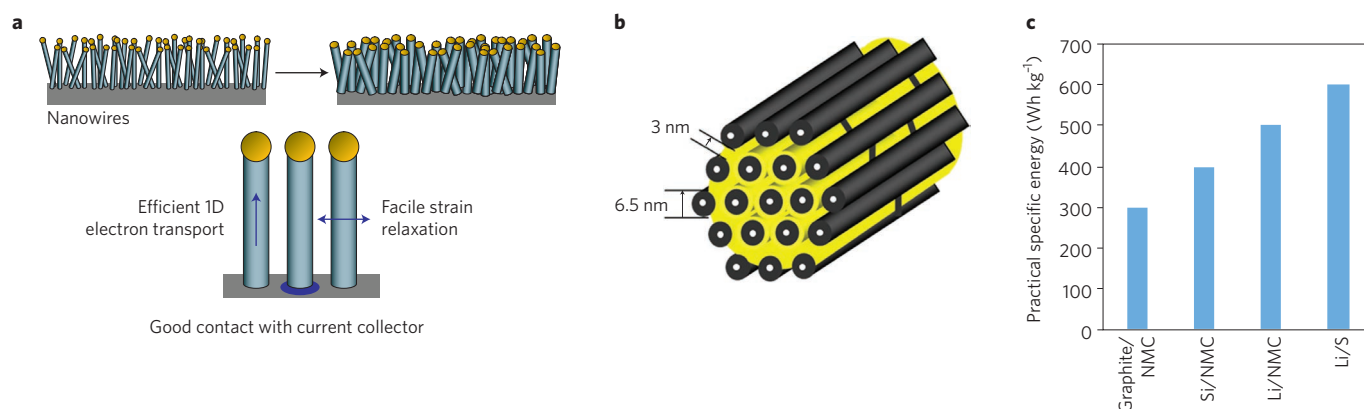
Figure 3 | Materials for batteries. a, Si nanowire electrodes. **b** Sulfur/mesoporous carbon electrode material. **c**, Practical specific energy of cells versus different combinations of electrodes. Reproduced from ref. 25, Nature Publishing Group (**a**); and ref. 26, Nature Publishing Group (**b**).
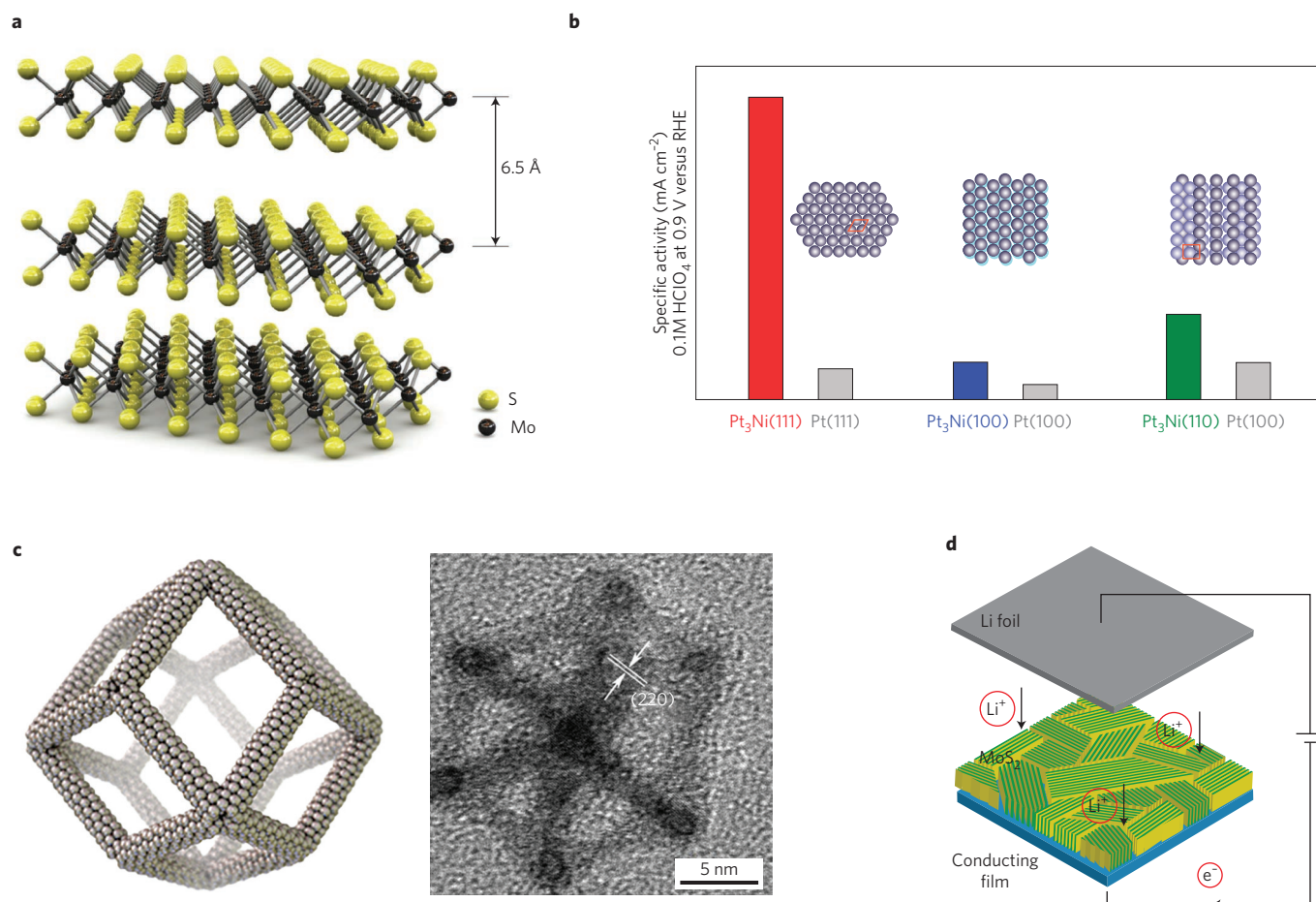
Figure 4 | Materials for catalysis. a, Vertically aligned planes coated with MoS_2 nanofilms. Electrochemically-induced Li intercalation into Li_xMoS_2 varies the HER, and allows the study between electronic structure and catalytic activity. **b**, ORR catalytic activity for different crystal facets of Pt_3Ni alloys and Pt. **c**, Nanoframes with three-dimensional electrocatalytic surfaces. **d**, Electrochemical tuning of electrocatalytic activity. Reproduced from ref. 33, Nature Publishing Group (**a**); ref. 36, AAAS (**b**); ref. 37, AAAS (**c**); and ref. 38, National Academy of Sciences (**d**).

into $CO + H_2$ and then to $CO_2 + H_2$ (such as in integrated gasification combined cycle plants). There is very limited operational experience with carbon capture methods for mid-scale power plants in the range of 300–600 MW. Estimates of the cost of a new carbon capture power plant (based on the operational experience of the first half a dozen commercial-scale plants) vary, but are generally believed to increase the cost of electricity by 30–50%. The cost of retrofitted existing plants will be higher, and in the case of lower thermal efficiency plants the additional parasitic energy load would be prohibitive[47,48]. New materials such as MOFs[49], zeolitic imidazolate frameworks (ZIFs)[50] and other micro- and nanostructured materials offer the possibility of reducing the cost of electricity with CO_2 capture to 15–20% additional cost. Computational methods using genetic algorithms to search for high performing MOFs have been used to identify promising candidate materials[51]. These same classes of materials may also be used in an oxy-combustion configuration, where O_2 is separated from air, and combustion of fuel in a $CO_2 + O_2$ atmosphere yields $CO_2 + H_2O$, which are easily separated. This process may be particularly advantageous in natural gas combustion[52]. Other advanced CO_2 capture approaches include ionic liquids, chemical looping and biofixation[53]. Since the likelihood of going over 550 ppm of CO_2e is reasonably high, we will need direct air capture of CO_2 as well.

Unfortunately, there is no financial incentive beyond enhanced oil recovery to deploy technologies for carbon capture, utilization or sequestration (CCUS). Even with policy incentives, the cost of the first mid-size commercial scale carbon capture power plants — even with new carbon capture materials — will be over US$2 billion. For this reason, international cooperation and information sharing is needed to assist the early testing of CCUS technologies.

Materials for thermal energy conversion and manipulation. Heat management is an important part of energy technology. Direct conversion of waste heat into electricity has been pursued for several decades[54]. A figure of merit for thermoelectric materials is the dimensionless parameter $ZT = (\alpha^2 \sigma / \kappa)T$, where α, the Seebeck coefficient, represents the electric potential generated for a given temperature difference T, σ is the electrical conductivity, and κ is the thermal conductivity. Nanostructuring, heterostructuring and alloying can be used to improve ZT. Recently, thermogalvanic materials have increased the effective ZT to 3.5 and higher[55], since electrochemical reactions often have much larger entropy change and thus a higher temperature coefficient (~ 1 mV K^{-1}) than usual thermoelectric materials.

Effective management of heat through radiation also offers opportunities to decrease the global energy demand. For example, devices and clothes have been engineered to facilitate transmission of 7–14 μm infrared radiation for passive radiative cooling[56,57]. Smart-window systems using electro-, photo- and thermochromic mechanisms to dynamically control infrared transmission through liquid crystals, nanoparticles, such as indium tin oxide, and other materials are used to enhance building energy efficiency[58,59].

Materials for power electronics. Power electronics is essential for the control and conversion of electricity in power systems, motor drives, inverters and converters[60,61]. Silicon has been the predominant semiconductor for these applications, but higher bandgap semiconductors such as SiC and GaN permit more thermally efficient and higher voltage transistors. The major challenge lies in how to grow high quality materials and junctions over a large area. Diamond, with its wider bandgap, high breakdown voltage and extraordinarily high thermal conductivity is ideal for insulated-gate bipolar transistors used in high voltage, high power switching applications; however, doping processes to realize high conductivity in this material are challenging.

Microbial energy conversion. Microbes have been recently explored as biomaterials for energy conversion. In microbial fuel cells, microbial anodes and air cathodes are used to convert organics in solution into electricity[62]. The use of nanotechnologies to increase the surface area and roughness of the anodes can improve the interface with microbes and enhance the electron collection efficiency. Further optimizations are required to decrease voltage and charge losses due to the oxygen gas reduction and diffusion in these cells. Materials science is also being used to increase microbial photosynthesis into chemicals. For example, CdS nanoparticles have been used to increase the photoresponse of microbes and boost their CO_2 reduction efficiency when exposed to solar light[63].

Development and deployment

Materials science is an enabling science and is playing a central role in our transition to sustainable energy. The advances in the past decades have been breath-taking. While accidental discovery remains a major source of new materials, the empirical trial-and-error method of innovation has been profoundly supplemented by a deeper understanding of the basic physics and chemistry of materials and our ability to measure and fabricate materials at the molecular-level and nanoscale.

Such continued scientific advances must be adequately supported by the public sector since much of the materials science research is too long-term to garner private sector investments. Beyond research, there are two 'valleys of death' that have to be crossed in the transition from scientific discovery to innovation and wide scale deployment. The first valley crossing requires patient private sector investors that are found in most venture capital or equity investment firms. The second valley is the scale-up from small pilot projects to commercial-size facilities, where economies of scale can be used to dramatically reduce costs.

For certain technologies, these crossings require government subsidies. As an example, the purchase price of solar PV modules has plunged by 50× since 1980, and by an additional 10× since 2005[64]. The drop since 2005 was largely stimulated by a generous feed-in tariff by the German government that created a large market, which in turn drew huge investments in manufacturing plants.

Wind technology also received substantial government support. Support initially came from the US, but it was the long-term, consistent sustenance from Denmark and Germany that ultimately made wind energy economically competitive. Those subsidies led to improved manufacturing processes of composite materials for wind blades and more robust power electronics. In the future, substitute materials for rare earth magnets and/or more environmentally friendly rare earth refining methods are needed to lower the cost of reliable direct drive turbines.

The development of lithium-ion battery technology followed a different path. The initial market pull was created by laptop computers. The cell phone market has become the major stimulant for high volumetric energy density and fast-charge batteries, while the rapidly emerging drone market seeks the highest gravimetric energy density.

The emerging EV and plug-in hybrid EV markets were aided by purchase rebates, and in some areas of the US, by access to high-occupancy vehicle lanes, regardless of the number of passengers in the vehicle. As a result of these policies, the manufacturing cost of EV batteries decreased three-fold between 2006 and 2015 to ~300 US$ kWh^{-1} for a battery format originally designed for laptop computers. By 2018, the manufacturing cost is expected to drop by another factor of two.

Currently there is neither a market draw nor a regulatory push to dramatically reduce carbon emissions, which is instead essential to avoid human-induced climate change becoming the ultimate 'tragedy of the commons'. The 2015 Paris Agreement was a necessary first step, yet the potentially disastrous long-tail climate risks demand stronger actions.

Most economists agree that the most efficient mechanism to stimulate the shift to a very low carbon economy is a meaningful price on carbon. If the cost of carbon emissions is included in the price of fossils fuels and primary energy intensive industries, they argue that market forces will be more efficient than regulations.

The European Union has put in place a cap-and-trade policy since 2005, where carbon emission is capped but emitters can trade emission allowances. The price of carbon emissions would increase as the cap is progressively lowered in order to provide continuing economic incentive to reduce emissions. Since early 2013, the allowance price has been hovering around €5–6 per tonne of CO_2; however, most experts agree that the price needed to stimulate widespread decarbonization is €70–80 per tonne of CO_2. In hindsight, too many carbon credits were given away in the EU trading scheme. The method of assigning allocation limits for each country is a regulatory headache, open to gamesmanship, and the political will to aggressively lower the cap on carbon remains challenging.

An alternative to a cap-and-trade system is a simple carbon tax. A tax maximizes transparency, minimizes market manipulation and regulatory complexity, and provides investment certainty. However, a carbon tax will raise the cost of energy. A politically more attractive route is a revenue neutral scheme where the money collected with this tax is returned equally to every working adult. The price on carbon can rise gradually to €80 per tonne by 2040 to allow industries and individuals time to adjust. Fossil fuel subsidies should be eliminated as soon as possible and, as the carbon price rises, subsidies for renewable energy can be phased out. Nuclear energy, a carbon-free, energy-on-demand source, can compete with fossil energy with the added costs of carbon capture and utilization or sequestration.

A carbon tax avoids the problem of how to allocate carbon emissions credits between developed and developing countries. It levies the highest taxes on the biggest emitters, and global agreement is not needed. Leaders such as the EU, China and hopefully the US need to lead. The playing field can be levelled with suitable border tariffs supported by the World Trade Organization. This option is especially important to ensure leading countries that their economies will not be handicapped.

The most important aspect of a carbon tax rising inexorably to ~€80 per tonne is that it will rapidly unleash scientific ingenuity, innovation, and market investments that are still needed. In the last six years, the cost of clean energy has plunged and in many areas of the world, the life-cycle cost of wind and solar energy is reaching parity with fossil energy. However, the cost of decarbonizing the first 25% of the world economy is far less than the cost of decarbonizing the last 25%. Achieving affordable and fully clean energy in our electrical and chemical transmission, distribution and storage systems present significant technical and political challenges. We must and shall overcome these challenges: otherwise, to quote Martin Luther King, "There is such a thing as being too late."

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Additional information

Competing financial interests

The authors declare no competing financial interests.