PUBLISHED: 11 JANUARY 2016 | ARTICLE NUMBER: 15020 | DOI: 10.1038/NENERGY.2015.20

The frontiers of energy

Great strides have been made over the past century in our ability to harness energy sources, leading to profound transformations — both good and bad — in society. Looking at the energy system of today, it is clear that meeting the energy needs of the world now and in the years to come requires the concerted efforts of many different actors across a range of technologies and approaches. In this Feature, ten leading experts in energy research share their vision of what challenges their respective fields need to address in the coming decades. The issues being faced are diverse and multifaceted, from the search for better materials for fuels, to the design of energy policy and markets for the developing world. However, a common theme emerges: changes to adapt and improve our energy system are greatly needed. By improving our mutual understanding of the issues faced by each area of energy research, these changes can happen more smoothly, efficiently and rapidly.

Renewables are essential

As policymakers grapple with developing global agreements to cut greenhouse gas emissions, science and technology must play a central role in lowering the costs of renewable and low-carbon energy solutions. A few technologies in particular will be vital to meeting the growth in energy demand and achieving the decarbonization transition.

Among those technologies, solar energy has the largest and most homogenously distributed renewable resource. The costs of solar photovoltaics have declined dramatically over the past 8–10 years, due to ever-improving technologies, greater manufacturing scale, strong supporting policies and increasing demand. However, scaling-up current photovoltaic technologies to meet global electricity needs over the longer term remains expensive. Advances in fundamental science, new materials and processes for photovoltaics — such as flexible, thin-film solar cells that can be printed on substrates such as plastic, paper or metal foils — and new system concepts for concentrated solar power, all have the potential to further enhance the relative competitiveness and rapid scale-up of solar power[1].

The lowest cost, non-hydropower renewable energy resource at present is onshore wind. Wind energy sources are globally abundant, with onshore and shallow offshore (depth less than 30 m) wind energy already supplying appreciable amounts of electricity to various countries, including China, Denmark, Germany, India, Ireland, Portugal, Spain, the UK and the US[2]. Mounting turbines on taller towers is enabling access to better wind resources at higher altitudes, making wind a viable source in previously uneconomic regions, such as the Southeastern United States. Nonetheless, wind energy, like solar, suffers from intermittency challenges, but without as good a match between resource and peak demand. Offshore wind offers potential advantages, including higher average wind speeds and a more sustained resource, but its progress will depend on providing low-cost transmission to shore and on leveraging knowledge from the oil and gas industry for mounting turbines. Other ocean energy technologies — wave, tidal, ocean current and ocean thermal — are still relatively nascent, but symbiotic systems of floating offshore wind and/or wave turbines coupled with pumped hydropower energy storage could improve their economic viability[3].

Geothermal energy can also play a much larger role. Particularly where the resource is relatively close to the surface, geothermal systems can provide heating and low-cost, dispatchable electricity — as illustrated by the transformation of Iceland's energy system over the past 50 years. Although not all regions globally have easily accessible geothermal resources, enhanced (or engineered) geothermal reservoirs[4] — in which the permeability of hot, dry rock is artificially increased, so that water can be injected and heated up by the rocks — are ubiquitous and might be made cost effective with innovations in drilling technology and low-temperature power cycles. Access to higher-temperature resources, which will require advances in materials science, could also improve the prospects of geothermal energy.

Technology deployment, policy and cost performance data, along with countries' intended voluntary contributions ahead of the 2015 Paris Climate Change Conference (COP21), have shown that solar and wind energy are poised for major growth if nations can promote a combination of global knowledge sharing, global access to financing and further development of technologies that address renewable intermittency issues, such as energy storage[5]. Political and economic challenges — which have in the past posed major obstacles to globally scaling wind and solar — will need to be overcome for solar and wind to achieve their potential.

Modernizing the electricity grid will also be critical to our energy future. Substantial infrastructure improvements must be made to meet global demand, security, reliability and resiliency needs. Moreover, new power systems, such as microgrids, offer opportunities for deploying renewable technologies in regions with growing demand but little existing infrastructure, including parts of India, Africa and other developing countries. Further deployment of renewables can also be achieved by better understanding energy system issues, including the policy and business models shaping the evolution of the utility industry.

Adopting new policies and strengthening those that favour low-carbon and renewable energy technologies, increasing government financial support for basic energy research, and engaging with industry to help identify, scale up and commercialize the most promising technologies are all important for a successful global transition to a sustainable future. This is a daunting challenge; however, the social and economic imperatives for transforming the global energy system are clear. We have the opportunity to focus our global wealth of problem-solving talent on rapidly, safely and economically deploying new low-carbon energy technologies that will improve people's lives while curbing climate change. ❐

Robert C. Armstrong is the Director at the MIT Energy Initiative and Chevron Professor of Chemical Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139-4307, USA.
e-mail: rca@mit.edu

Quantifying change

In the next decades, policymakers will need to guide evolution in the energy sector to meet aggressive environmental goals, particularly those demanded by climate change mitigation, while still powering economic growth. I see three important questions that economists must help policymakers answer. What technologies will we use to meet environmental goals? What will be the primary business models in the sector? Are different policies appropriate in the developing world?

In general, economists have little direct influence on technological change, especially compared with engineers and physical scientists, and are primarily interested in ensuring that policy decisions are made with both a proper accounting of the likely economic effects they will have, as well as a proper humility about the role of policy in the face of market forces.

At a high level, the energy sector can meet environmental goals either by supplying useful energy with less pollution, for example by deploying more renewables to generate electricity, or by using less energy to produce the same services, for example by increasing energy efficiency by using light-emitting diodes instead of incandescent light bulbs, or some combination of both approaches. Some models have identified numerous cost-effective opportunities to increase energy efficiency[6], which currently seem to lead policymakers to favour demand-side policies[7], such as standards for more efficient appliances. However, recent economic research calls the efficacy of some energy efficiency programmes into question[8–10]. Continued research is needed to identify the most cost-effective ways to mitigate pollution on both the supply and demand sides.

Meanwhile, much of the electricity and natural gas in the world is supplied by vertically integrated state-owned firms or regulated natural monopolies. Similarly, state-owned firms control oil production in many countries. The dominance of these carefully watched monopolies has been justified by both the natural monopoly properties and the national security importance of energy supply — factors that warrant sacrificing the benefits of competition in favour of a single supplier. Restructuring and privatization initiatives, beginning in the 1990s, have increased the opportunities for entry of new, private firms in both the electricity and natural gas industries[11]. In the extreme, policies favouring more distributed (or decentralized) electricity generation have led to concerns in some circles about a 'death spiral' for traditional monopoly electric utilities, although how much of a role distributed solutions will play remains to be seen. Economies of scale seem to continue to favour large, networked monopolies, at least for natural gas and electricity distribution, but governance challenges are more prominent in the developing world, so the arguments for decentralization and more private sector participation may be important there. As technologies evolve, we will continue to benefit from economic analyses of the relative strengths and weaknesses of different market structures.

My own view is that the most important task for economic researchers is to better understand the energy sectors in the developing world. Energy consumption in non-OECD (Organisation for Economic Co-operation and Development) countries surpassed OECD countries in 2008 and is forecast to grow by five times as much over the next 25 years[12]. Given that the infrastructure to meet this demand is not yet in place, the developing world may offer important opportunities to deploy new technologies. The costs of renewable electricity generation and energy efficient technologies have come down over the past decade. On the other hand, fossil fuels, in particular coal, remain abundant and cheap, and the desire to power further economic development with low-cost energy sources is compelling. Minimizing the trade-offs between economic growth and environmental goals will require a much better understanding of the energy sectors and their markets in the developing world than currently exists. ❒

Catherine Wolfram is the Cora Jane Flood Professor of Business Administration and Faculty Director at the Energy Institute at Haas, Haas School of Business, University of California at Berkeley, Berkeley, California 94720-1900, USA.
e-mail: cwolfram@berkeley.edu

Catalysing transport

World transportation fuel consumption currently amounts to 50 million barrels per day (Mbd; 1 barrel = 159 litres), 95% of that being produced from crude oil. The current vehicle fleet is 1.2 billion cars, with a staggering growth to 2.4 billion cars expected by 2035 in line with a doubling of world gross domestic product in that period. CO_2 emissions from the transport sector are forecast to double to 12 gigatonnes per year (Gt yr^{-1}) in this time under a business-as-usual scenario[13]. To limit this unwanted increase, two developments are required: the increased use of alternative fuels (biofuels, liquid petroleum gas, natural gas, electricity) and the production and usage of conventional fuels in a more energy-efficient way. The anticipated reduction of CO_2 emissions from transport fuels is around 4 Gt yr^{-1}, which is unlikely to be met solely by alternative fuels (maximum estimated at 1 Gt yr^{-1}). Thus, enhanced efficiencies of fuel production and consumption will be a key research area in the coming decades.

The strong preference for liquid fuels for transport, rather than solids and gases, is highlighted in Fig. 1, which shows current spot prices in the US of fossil raw materials and products as a function of the atomic ratio of the fuel in question. By the nature of their composition, carbon-rich fuels are solid and hydrogen-rich fuels are gaseous. At a hydrogen-to-carbon atomic ratio (H/C) close to two, we strike a balance and encounter liquids at ambient conditions that are relatively clean, safe and, moreover, have an energy density 50% higher than that of ethanol and almost five times that of compressed natural gas at 20 MPa. The convenience of handling liquids compared with gases cannot be overestimated and is reflected in their much higher market values[14].

For the manufacture of clean and affordable transportation fuels, crude oil is refined. This involves reduction of the molecular weight (cracking) as well as addition of hydrogen, shifting H/C from 1.8 to 2.0 (Fig. 1). The two main cracking processes are fluid catalytic cracking (FCC) and hydrocracking. Catalysis is the key enabling science and technology to allow for progress in these conversion processes. Recent examples involve FCC catalyst structure investigations[15] and exploration of nanoscale effects in hydrocracking catalysts[16]. Both offer considerable potential to increase yields of gasoline and diesel, respectively, increasing the efficiency of the processes.

There are distinct economic incentives for converting natural gas to liquids (GTL) as well as coal to liquids (CTL). However, with the recent large drop in oil prices, capital investment seems to be prohibitive for large-scale GTL, although CTL investments (in particular in China) are ongoing, with a current estimated production of synthetic gasoline and diesel of 0.5–1.0 Mbd. In the near future, small-scale GTL to restrict gas flaring may become attractive, in particular for shale oil and shale gas production. Developments in catalysis and process engineering are required to reduce capital investments for these GTL or CTL processes, with emphasis needed on catalyst selectivity (to suppress methane formation), activity (for process intensification) and stability (to give longer catalyst lifetimes). Direct methane conversion to liquid fuels or chemicals (for example, methanol) will also be pursued in the future in an effort to circumvent the capital intensive manufacture of synthesis gas (a mixture of CO and H_2) in GTL schemes.

Further down the road, solar fuels produced by conversion of CO_2 and H_2O via photocatalysis offer great potential as renewable transportation fuels, although there are a number of scientific and technological challenges and progress must be benchmarked against silicon solar cells in combination with water electrolysis

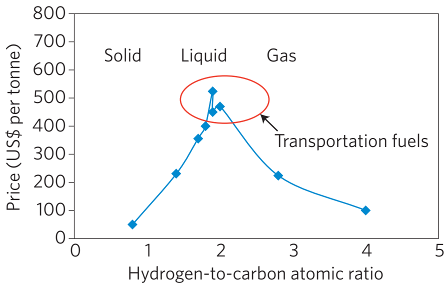

Figure 1 | Spot market prices (excluding taxes, as of 28 October 2015) in US dollars per tonne for fossil fuels ranging from coal to natural gas (data from www.eia.gov and www.bloomberg.com/energy), expressed through their respective hydrogen-to-carbon atomic ratio (H/C)[14]. With increasing H/C, the state of aggregation of the fossil fuels changes from solid (coal) to liquid (gasoline, kerosene and diesel) to gas (liquid petroleum gas and natural gas).

and CO_2 hydrogenation. A recent review indicates that solar water-splitting using Earth-abundant materials with 10% energy conversion efficiency and a ten-year lifetime has not yet been achieved[17].

In summary, it is clear that liquid transportation fuels will be needed for a long time, but through developments in catalysis it should be possible to broaden the resource base, increase process efficiency and reduce the impact on our environment. ❐

Krijn P. de Jong is Professor of Inorganic Chemistry and Catalysis in the Group of Inorganic Chemistry and Catalysis, Debye Institute for Nanomaterials Science, Utrecht University, The Netherlands. e-mail: K.P.deJong@uu.nl

Looking beyond the short term

Large-scale changes to our energy systems are needed if we are to meet our decarbonization targets and transition to a low-carbon world. There is no shortage of scenarios demonstrating what a low-carbon system might look like. Many aspects are common to all scenarios: we must decarbonize power generation; energy efficiency must be improved; we will need a new energy vector for vehicles (probably electricity, possibly hydrogen); and there is a need to decarbonize heating and cooling (which often looks difficult).

These changes require that a new energy infrastructure emerges over decades. Yet short-term political concerns can become disconnected from such long-term changes. And decisions made to serve short-term political pressures can often have long-term and unanticipated consequences. To achieve lasting results and to cut emissions before it is too late, we need urgent — and sustained — policy action. For example, if electricity generation is to be decarbonized during the 2020s — as many scenarios suggest it must — then investment needs to start now, as many projects will take a decade or more to complete. This means developers need to understand policy objectives well into the 2020s, and have confidence that politicians will stick to their plans.

Investor confidence is of profound importance to decarbonization, because the total capital investment required is huge. There is unprecedented interest from international and institutional investors (such as pension funds) in renewable energy. This is because renewable energy projects with a feed-in tariff or similar offer a low-risk and stable revenue stream — provided governments are trusted not to retrospectively meddle with policies.

Institutional investors normally come into schemes that have been in successful operation for a few years. During the development and construction of a power generation scheme, risks are much higher, particularly for relatively new technologies, such as offshore wind, where construction is complex and new techniques are being tested. Utilities, equipment manufacturers and higher-risk investors build and sell successful projects and recycle the revenue to build new schemes. What investors particularly dislike is if the risks associated with finding a good site, getting planning consent and building a complex project are accompanied by political risk that can undermine the project's financial support later on.

The UK makes for an interesting case. The country had built up substantial investor confidence in political commitment to energy system change since 2002. Policies were not perfect, nor were they set in stone. Yet investors were reassured by the political consensus that the UK had achieved in passing the Climate Change Act and in ensuring principles of good governance — notably that any change would be signalled well in advance and that existing investments would be 'grandfathered' (ensuring policies would not be changed retrospectively). Yet since the UK general election in May 2015, there have been at least 15 policy changes, many to cut policies or close them early. In November 2015, the UK energy secretary sought to reassure investors, promising clear policies out to 2025. However political confidence is hard won and easily lost. The UK may have to work hard to rebuild trust.

The lesson is not that policies cannot be changed, but that sudden, unexpected and poorly explained shifts undermine the credibility of political support for decarbonization. The challenge for governments is to balance short-term concerns against long-term goals by explaining clearly in advance what is to be changed and why. Investors may sympathize with a government trying to ensure the low-carbon transition is affordable, but this does not mean principles of good governance can be ignored. ❐

Robert Gross is Policy Director at the Energy Futures Lab and Reader in Energy Policy and Technology, Imperial College London, South Kensington Campus, London SW7 2AZ, UK. e-mail: robert.gross@imperial.ac.uk

The lightest of fuels

Hydrogen is extremely versatile. It can be used to produce energy-rich upgraded biofuels or can be reacted with concentrated CO_2 sources, such as flue gas, to produce methanol or synfuel. Furthermore, hydrogen can be used directly for combustion in a turbine or used in a fuel cell for transportation or grid-scale energy storage. Although many of these conversion and utilization technologies are already being demonstrated or deployed at scale, the cost-effective production of hydrogen from low-carbon sources, including renewable energies, remains challenging.

Low-cost hydrogen is currently produced mainly by steam reforming of natural gas. However, this process also releases CO and CO_2. Two alternative low-carbon approaches are the electrolytic production of hydrogen using sustainable sources of electricity, and direct hydrogen production from water splitting under sunlight by artificial photosynthesis.

Electrolysis is either based on alkaline or polymer-electrolyte-membrane (PEM) technologies. Alkaline electrolysis uses an aqueous solution placed between two electrodes. Water molecules absorb electrons from the cathode to make H_2 molecules and OH^- ions; the ions diffuse across to the anode and give up electrons to make O_2 molecules. Alkaline electrolysers use inexpensive electrocatalysts, such as Ni–Mo at the cathode and Ni–Fe oxide at the anode, but on a large scale require a relatively complex plant to accommodate the caustic solution. Membranes that are highly conductive towards selective transport of OH^- ions and are stable at elevated temperatures would enable more compact, less expensive alkaline electrolysers.

Meanwhile, PEM-based electrolysis employs an all-solid structure based on Nafion polymer as a protonically conductive membrane in conjunction with Pt as the electrocatalyst at the cathode and IrO_2 at the anode. Although the electrocatalysts are made from precious metals, at present they comprise less than 10% of the total PEM-based system cost. Costs could be reduced by replacing the Nafion with cheaper alternatives that still provide the necessary proton conductivity, gas-blocking properties and stability under highly oxidative conditions. At the same time, the availability of Ir, which is among the scarcest elements in the Earth's crust, will be a barrier to the scalability of PEM-based electrolysis to terawatt power levels, and motivates the search for alternative O_2 electrocatalysts that are stable, active and robust under acidic conditions.

To reduce the overall system costs, a disruptive approach to the balance of the electrolyser systems is also required. In that sense, the fact that an electrolyser can operate without consideration of its electricity source makes it well-suited as a flexible, grid-based system for fuel generation. Rather than coupling an electrolyser to a single renewable electricity source, the unit can be connected to many different kinds of low-carbon electricity via the grid, thereby allowing for storage of intermittent electricity in the form of hydrogen fuel during times of low demand but high supply.

Solar-driven water-splitting systems, which employ photons instead of electricity to convert water into hydrogen and oxygen, could provide an even greener fuel source, but must ultimately compete economically with low-carbon grid electrolysis. Such systems must therefore take advantage of very-low-cost materials, synergistic integration of functionality and/or new form factors, such as membrane-bound materials that can work with water vapour or sprinkler systems as the input feed, while exhibiting very high energy-conversion efficiencies. Light absorbers are needed to provide stable photoanodes coupled to suitable photocathodes, in conjunction with morphologies that resemble artificial turf and provide synergistic integration with Earth-abundant electrocatalysts and membranes. A very low system cost for the collection and distribution of hydrogen, comparable to landfill gas collection and piping, is also needed, including drainage systems to collect the reaction products. Although a scalable system has yet to be shown, significant progress has been made on each of the necessary components of a demonstration system. Further advances in materials chemistry, catalyst development, system engineering and nanoscience could enable a commercially viable integrated solar fuels generator that can directly produce hydrogen from sunlight. ❐

Nathan S. Lewis is the George L. Argyros Professor of Chemistry at California Institute of Technology, Division of Chemistry and Chemical Engineering, 210 Noyes Laboratory, 127-72, 1200 East California Boulevard, Pasadena, California 91125, USA.
e-mail: nslewis@caltech.edu

Access to efficiency

Consumers buy energy and use it to achieve a service — transportation, lighting, cooling food and keeping warm. The cost of the service depends on the efficiency of the equipment used by the consumer: energy-inefficient products result in an expensive service. For people on a low income, who are struggling to pay fuel bills, finding the capital for a more energy-efficient piece of equipment is impossible. This money has to come from elsewhere.

Taking the case of fuel poverty in Europe, often the poorest people will be found in the least-energy-efficient homes: the boiler is old, the windows are draughty and heat quickly leaks through the uninsulated walls. The home is cold. The running costs are high because the equipment is old or the insulation is missing. The household gets poor value for their expenditure — especially on warmth. As a result, the occupants often develop cold-related illnesses with the risk of ill health or even death. The children are more likely to have asthma and the elderly have premature heart attacks, strokes or respiratory diseases. In addition, the problem of finding the money to pay the fuel bills results in anxiety, stress and depression. Winter is a miserable period, dreaded by the fuel poor.

This situation incurs costs and consequences to the whole of society. In particular, the bill for healthcare is substantial. In the UK, over 20,000 people die prematurely during the four winter months. And for every death, there are eight to ten people who have had emergency hospital treatment and doctors' visits. The cost of mental ill health is untraceable.

From a climate change perspective, fuel-poor homes are using energy inefficiently and causing unnecessary carbon emissions. If the homes could be made more energy efficient, they would provide affordable warmth and a healthy environment while using less energy and being less polluting.

The debate about whether capital should be spent on providing additional supply or on reducing the demand for energy rarely occurs. Yet, capital spent on improved energy efficiency means reductions in fuel bills for the consumer and in carbon emissions, in new sources of energy supply, as well as lower costs for health services. A greater focus on energy efficiency in buildings and equipment will mean people are warmer and the planet is cooler. But who will divert the money from new supply to reducing demand and how?

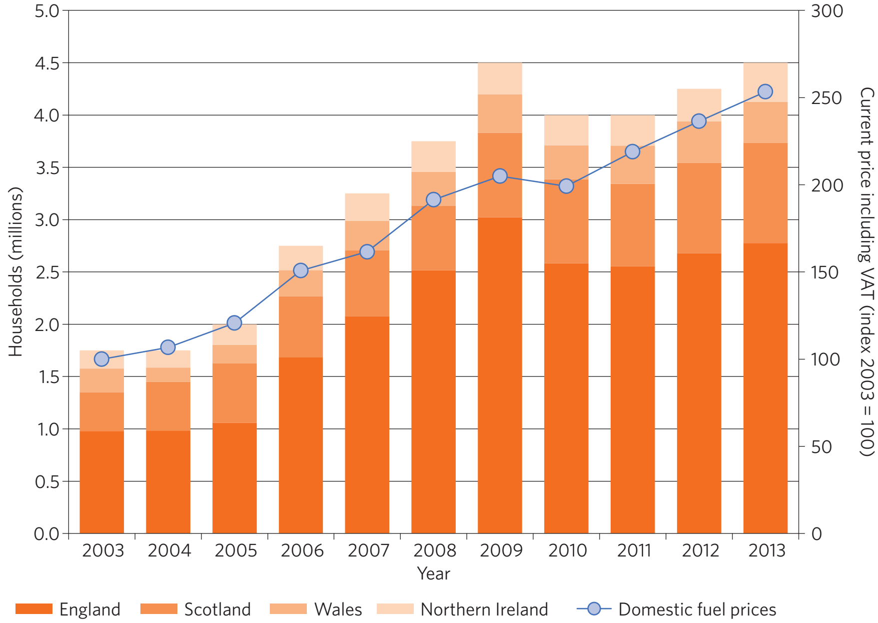

Figure 2 | Fuel poverty figures and energy prices for the UK between 2003 and 2013. Fuel poverty for Wales (2009, 2010, 2011 and 2012) and Northern Ireland (2010, 2012 and 2013) are estimated. Figure adapted from ref. 18, licensed under the Open Government Licence v3.0.

Action from the government in the UK is, at best, inadequate: for the first time since 1976 there are no government-funded programmes of energy-efficiency improvements. The limited investment that exists comes from a levy on everyone's fuel bill to fund utility programmes. These higher fuel bills increase fuel poverty more than is offset by any investments in the energy efficiency of their homes, making it a regressive policy.

Fuel poverty still affects a large number of households in the UK (Fig. 2) — between 10 and 22% depending on which definition is used. What is needed to get these households out of fuel poverty is increased funding and a range of political measures in support of the fuel poor. One important solution is to recognize that buildings are a large proportion of the nation's infrastructure — 80% by value — and should be cherished and improved as an investment. To protect the fuel poor and deliver the UK's legal obligations on climate change, we should be transforming these buildings so that they are truly energy-efficient and consuming very little energy as our legacy for future generations. ❐

Brenda Boardman is Emeritus Fellow at the Environmental Change Institute, Oxford University Centre for the Environment, South Parks Road, Oxford OX1 3QY, UK.
e-mail: brenda.boardman@ouce.ox.ac.uk

Deconstructing biomass

The environmentally sustainable biofuels industry has matured to a critical point where commercial manufacturing facilities have been launched, yet fundamental, multidisciplinary challenges continue to impede widespread, low-cost production of second- and third-generation biofuels that are competitive with petroleum-based fuels. A central focus for the biological conversion of plant polymers, such as lignocellulose, to biofuels is the recalcitrant nature of biomass, which necessitates the use of costly pretreatments and enzyme deconstruction protocols. Likewise, thermal conversion of biomass to bio-oils is challenged by expensive upgrading requirements. Whereas biological conversion technologies are confronted by the chemical structure of biomass and its architecture, thermal conversion technologies are challenged, in part, by the diversity of biomass components.

Advances in elucidating the fundamental genetic factors controlling the resistance of biomass to structural change have grown exponentially over the past decade. By employing forced engineering techniques and screening the natural diversity of biomass, we have come to understand how its components, such as lignin, which is a major part of plant cell walls, can be manipulated to facilitate improved biological deconstruction. Although most current plant genetic engineering methods focus on transformations of single genes — such as at the BioEnergy Science Center (http://bioenergycenter.org/besc/), a research organization funded by the US Department of Energy — future technologies will stack multiple gene changes or genome editing approaches to enhance our ability to convert biomass to fuels by making biomass easier to break down. This control of plant polymer structure will also benefit biomass conversion through thermal routes by reducing the diversity of the structural units, facilitating the upgrading of bio-oils to high-quality fuels.

The development of tailored energy crops requires advances in agronomic science, including enhancing plant productivity, minimizing water demand, increasing resilience to pests and disease and abiotic stresses, and efficient nutrient utilization, while providing favourable life-cycle benefits. In all likelihood, biological biomass deconstruction and conversion platforms will become integrated with specific crops. Although the use of enzymes and fermentative microbes are the mainstay of the present biological platform, developments in consolidated biomass processing have shown that advanced organisms, such as modified *Clostridium thermocellum* or *Caldicellulosiruptor bescii*, can enhance deconstruction of plant carbohydrate polymers while also converting the sugars released to ethanol or other fuels.

Progress will also be required in chemical engineering to design lower-cost catalysts for the upgrading of bio-oils by deoxygenation and hydro-treatment along with the ability to generate and use renewable sources of hydrogen. These advances in biofuels generation will be accompanied by a host of process engineering challenges requiring advances in separation technologies, reactor design, sensors, process control and waste minimization and treatment.

The success of the biological platform has opened the old question of 'what to do with lignin?' Given that it represents ~20–35% of the mass of biomass collected, and less than ~50% of that amount is needed to meet biorefining energy demands, it is clear that value-added applications are needed. Research has highlighted the potential to use lignin for fuels, carbon fibres, 3D printing resins and thermoplastics; but commercialization is often inhibited by complex physical properties and conversion pathways. In the future, lignin will be engineered with specific molecular functionality allowing isolation of lignin with tailored molecular properties to facilitate valorization, simplifying this challenge. Hence, the biological generation of biofuels will move from a single-product production facility to the petroleum production model, in which starting resources are fractionated and all molecular components are used to maximize value generation.

To successfully accomplish this vision, advances in several fronts of plant science, biological conversion, bioinformatics, catalysis, analytical chemistry, and biochemical and chemical engineering are needed. Although these disciplines have a history of addressing grand challenges, the biofuels field needs to deeply integrate and leverage these diverse disciplines while continuously examining their impact on sustainability and the environment. ❐

Arthur J. Ragauskas is a Professor in Biorefining at the BioEnergy Science Center, Joint Institute of Biological Sciences, Biosciences Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA and is at the Department of Chemical and Biomolecular Engineering, Department of Forestry, Wildlife, and Fisheries, Center for Renewable Carbon, University of Tennessee, Knoxville, Tennessee 37996-2200, USA.
e-mail: aragausk@utk.edu

The power of people

Two major forces are revolutionizing modern energy systems: the challenge of addressing global climate change and the recent transformation of information and communications technologies. New technologies and systems will make the electricity grid increasingly decentralized, integrated and automated, while a new mind-set and enhanced level of engagement will enable households and businesses to play a more active role as both producers and consumers. This shift from centralized to distributed, from single-source to multi-source, from unidirectional to multidirectional, highlights the growing network of actors that will be involved in guaranteeing the grid's reliability. Such changes emphasize the need to better understand the human dimensions of energy systems, both social and behavioural.

An important first step towards realizing enhanced levels of engagement by households and businesses lies in quantifying behaviour-based opportunities for energy (and carbon) savings — an approach that moves beyond the traditional and often exclusive focus on energy-efficient technologies. Early studies of behavioural approaches have already identified how policies and programmes focused on behaviours can produce significant savings in household energy consumption[19]. More recent work has expanded on these findings by quantifying achievable savings from behaviours in the commercial sector and by estimating savings opportunities at the city level. Such efforts will undoubtedly continue to gain traction as estimation methods are refined. By implementing them at the subnational level (state or city level), location-specific differences in climate, building stock, technology saturation and energy-related practices could be captured, increasing their effectiveness and deployment.

As a second step, efforts to modernize the electric grid also provide a powerful opportunity to actively engage people in more efficient energy practices both at home and at work[21]. Smart meters are already playing an important role in enabling electric utilities to cut service-related costs and to record minute-by-minute-level information about energy consumption, but this information has yet to be made widely available to households and businesses[20]. Bridging this gap through innovative feedback systems could make it much easier for customers to make better energy choices and to reduce their consumption. In fact, preliminary studies suggest that real-time feedback can reduce household electricity consumption by 9–12% on average[23,23].

On the other hand, unleashing the true potential of real-time feedback initiatives will require a larger and more concerted research effort. Although companies such as OPower have gained widespread attention for their innovative monthly home energy reports and their pioneering use of descriptive and injunctive norms, a wealth of feedback-related opportunities have yet to be tapped. Realizing these opportunities will require a much broader set of studies, using rigorously executed experimental designs, to systematically test the impact of a variety of social science-based programme elements in real-time feedback systems as used by both households and businesses. Such programmes should involve a wide variety of different feedback mechanisms, including the use of mobile technologies, such as smart phones, to share energy-related information. They should also explore the impact of social norms, goal setting, prompts and alarms among a range of possible mechanisms for informing people about their energy consumption and establishing new energy practices. Importantly, these types of approach offer opportunities to limit the amount of attention that is required by end users to make better decisions.

Although researchers still have many questions to address, policymakers, utilities and businesses are beginning to recognize the importance of more people-centric approaches. Understanding the human dimensions of energy offers the promise of generating valuable insights about our energy culture, historical and future shifts in our everyday energy practices, sources of variation in our energy-use patterns, and effective mechanisms for transforming how people, organizations and societies use energy. These insights can empower people and organizations to become the source of innovative, broad-based energy and climate solutions that could dramatically amplify and catalyse our ability to reduce energy consumption and carbon emissions and transform our energy culture. ❒

Karen Ehrhardt-Martinez is Associate Director and Social Science Expert at Navigant Consulting, 1375 Walnut Street, Suite 200, Boulder, Colorado 80302, USA.
e-mail: karen.ehrhardt.martinez@navigant.com

Storage at the threshold

Lithium-ion batteries have enabled the development of personal electronics in the form of cell phones, laptops, tablets and watches that provide instant communication and easy access to information, permanently changing the way society functions. The next storage frontiers are transportation and the electricity grid, requiring storage of much greater power and energy at a lower cost.

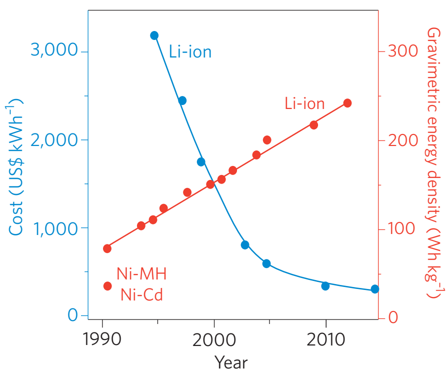

Figure 3 | Performance and cost of lithium-ion batteries since their commercialization in 1991. The energy densities of rechargeable nickel-metal hydride (Ni-MH) and nickel-cadmium (Ni-Cd) batteries, the best available in 1991, are shown in the lower left corner. Figure adapted from ref. 24, Materials Research Society.

To transform transportation, electric vehicles must provide the same set of mobility services as their gasoline counterparts, but at lower economic, environmental and energy costs. Next-generation electric vehicles must be safe, long-range and fast-charging while using less energy, emitting less carbon, and costing less to buy and operate than the incumbent gasoline-powered cars.

Storage for the grid, in contrast, promises an entirely new horizon of electricity services well beyond those provided by existing technologies. For grid operators, these include smoothing the seconds-to-minutes fluctuations of renewable wind and solar generation; time-shifting by several hours the excess night-time wind or daytime solar electricity to meet early evening demand; replacing expensive and inefficient peak-load power plants with cheaper, cleaner and more efficient stored baseload electricity; and regulating frequency and voltage to produce ultra-steady, digital-quality power.

The batteries required for these new services are as diverse as the services themselves, incorporating specific combinations of high or low power, high or low energy, and frequent or infrequent cycling. Distributed storage and generation configured to match local customer needs adds a new dimension of grid architectures that can provide tailored electricity services that are more effective and efficient than those of the traditional centralized grid. Local customer storage needs, spanning residential, commercial, industrial, educational and military sectors, require batteries that are even more diverse and specialized than those for grid operators.

Can lithium-ion batteries provide the necessary platform for all these applications? They do have a remarkable record of continuously increasing performance and decreasing cost (Fig. 3). At their introduction in 1991, the energy density of lithium-ion batteries exceeded that of nickel–metal hydride and nickel–cadmium batteries, the best available at that time, by a factor of approximately two. Subsequent continuous improvements added another factor of three to performance and lowered cost by a factor of ten. The continuing incremental improvement of lithium-ion batteries, however, is constrained by intrinsic limits: the single charge on the lithium ion, the charge storage capacity of intercalation anodes and cathodes, and the operating voltages of liquid electrolytes.

Thus, transformative change in transportation and the grid requires next-generation storage with significantly higher performance and lower cost. Promising routes to next-generation batteries are being pursued: multivalent working ions in place of single-valent lithium; high-energy covalent chemical transformation in place of intercalation; and new combinations of electrodes and organic electrolytes with wider operational voltage windows. Creating these next-generation batteries requires not only new concepts and materials, but also greater understanding of the fundamental science of energy storage phenomena at the atomic and molecular levels. If these beyond-lithium-ion batteries can show a similar discontinuous jump in performance over lithium-ion batteries followed by similar continuous incremental improvements, they will have the potential to transform transportation and the electricity grid. ❐

George Crabtree is Director for the Joint Center for Energy Storage Research (JCESR), a Distinguished Fellow at Argonne National Laboratory, 9700 South Cass Avenue, Argonne, Illinois 60439-4845, USA, and Distinguished Professor of Physics, Electrical and Mechanical Engineering at the University of Illinois at Chicago, 845 West Taylor Street (MC 273), Chicago, Illinois 60607-7059, USA. e-mail: crabtree@anl.gov

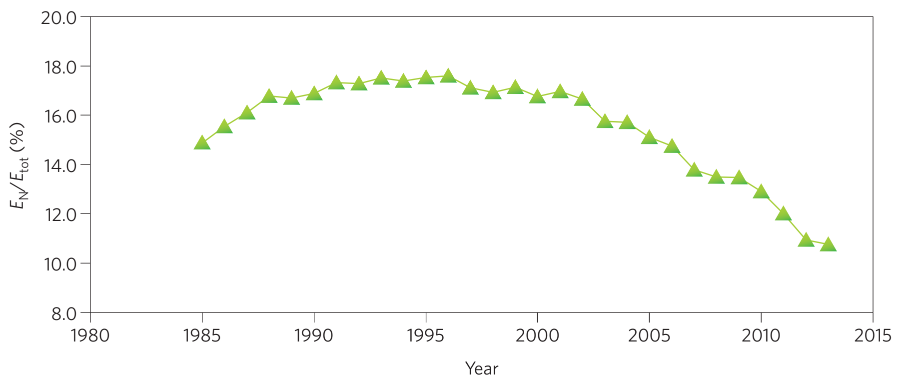

Figure 4 | Nuclear energy (E_N) as a percentage of global electricy generation (E_{tot}). Calculations are based on data from ref. 29.

A gradual decline?

The overwhelming factor shaping the future of nuclear power is its lack of economic competitiveness. Nuclear plants cost a lot to build and operate. This limits the rate of new reactor construction and causes utility companies to shut down old reactors.

A good example of what it takes to build a nuclear power plant in a country with a liberalized electricity market is the recent agreement over the plant at Hinkley Point in the UK. Its construction is currently estimated at £18 billion, which will be covered by cash-rich investors (£6 billion from China General Nuclear Power Corporation), subsidies from taxpayers (£2 billion) and from high electricity tariffs to be charged to the consumer — the government has set a guaranteed price of £92 per megawatt-hour, which is more than twice the average current wholesale cost of electricity. The project also illustrates another characteristic of nuclear plants: rising cost estimates. In 2010, Électricité de France, the main investor, estimated that building two reactors at Hinkley Point would cost £9 billion. The cost has doubled, even before the start of construction.

There is also trouble at the other end: operating aging reactors has become so expensive that the electricity they generate is unable to compete on power markets with natural gas and renewables. As a result, multiple reactors have been closed in the past three years; in October 2015 alone, electric utility companies announced that six nuclear reactors were to be shut down, two in the US and four in Sweden, even though they had paid off their construction costs and been licensed to operate until the 2030s. More nuclear plants are expected to shut down prematurely.

These difficult economic realities explain why nuclear power is in decline in the countries that historically had the most reactors. Although many of these countries continue to promote nuclear power as a low-carbon technology that can mitigate climate change, the argument has weakened significantly as costs of wind and solar energy have declined sharply.

The picture is different in emerging economies: energy demand is growing rapidly, leading to construction of just about every form of electricity generation known. The two most populous of these economies — China and India — have great ambitions for nuclear power, and everything else. During 2014, China brought online 5.3 GW of nuclear power, 20.3 GW of wind turbine power, 21.8 GW of hydropower and 53.3 GW of power from thermal plants (mostly coal). Between September 2014 and September 2015, India commissioned a 1 GW nuclear reactor, coal plants generating 16 GW and wind and solar plants generating nearly 5 GW. In recent years, these two, and several other countries, have generated more energy from non-hydro renewables than nuclear energy[25]. In short, China, India and other developing countries are following an all-of-the-above strategy. As a result, although the overall capacity of nuclear energy might grow, globally the share of nuclear power in electricity generation will continue to drop (Fig. 4). Although costs may currently take a back seat to meeting demand, in the long run the same economic forces shaping the nuclear future in the developed world will limit nuclear growth in the developing world too.

The other factor shaping the future of nuclear energy is the risk of catastrophic accidents. Owing to the nature of the technology, such accidents cannot be ruled out[26]. The Fukushima Daiichi nuclear power plant accident made evident the massive costs of relocating populations and cleaning up contaminated landscapes. Apart from such local and national impacts, nuclear accidents also drive sudden shifts in energy policy around the world[27].

What could change this picture? The nuclear industry and its promoters hope that radically new reactor designs could be developed, commercialized and adopted widely. Classified into assorted and overlapping categories, such as small modular reactors and generation IV reactors, such concepts have been proposed in the past too, but failed to attract buyers. Similarly, for the current crop, few have been willing to invest in or buy these untested designs. Commercialization schedules have been pushed back and many vendors have quit development because of the bleak market outlook. Finally, no reactor design seems capable of simultaneously overcoming all the challenges confronting nuclear power. Besides economics and safety, these also include the generation of radioactive waste, the linkage to nuclear weapons, and, the consequent public opposition[28]. ❐

M. V. Ramana is with the Nuclear Futures Laboratory and the Program on Science and Global Security, Princeton University, 221 Nassau Street, Floor 2, Princeton, New Jersey 08542, USA. e-mail: ramana@princeton.edu

References

1. *The Future of Solar Energy: An Interdisciplinary MIT Study* (MIT, 2015); http://go.nature.com/oGV7Wa
2. Hossain, J. *et al. Wind Energy 2050: On the Shape of Near 100% Renewable Energy — A WWEA Technical Report on Grid Integration* (World Wind Energy Association, 2015); http://go.nature.com/wpORGE
3. Slocum, A. *Sustain. Energ. Technol. Assessments* **11,** 135–141 (2014).
4. *The Future of Geothermal Energy: An Interdisciplinary MIT Study* (MIT, 2006); http://go.nature.com/yFJRUE
5. Trancik, J. *et al. Technology Improvement and Emissions Reductions as Mutually Reinforcing Efforts: Observations from the Global Development of Solar and Wind Energy* (MIT Energy Initiative, 2015); http://go.nature.com/heN2we
6. McKinsey & Company *Unlocking Energy Efficiency in the US Economy* (McKinsey Global Energy and Materials, 2009).
7. Loftus, P. J., Cohen, A. M., Long, J. C. S. & Jenkins, J. D. *WIRES Clim. Change* **6,** 93–112 (2015).
8. Allcott, H. & Greenstone, M. *J. Econ. Perspect.* **6,** 3–28 (2012).
9. Davis, L., Fuchs, A. & Gertler, P. *Am. Econ. J. Econ. Policy* **6,** 207–238 (2014).
10. Fowlie, M., Greenstone, M. & Wolfram, C. *Do Energy Efficiency Investments Deliver? Evidence from the Weatherization Assistance Program* E2e Project Working Paper WP-020 (2015); http://go.nature.com/JANaXp
11. Joskow, P. L. in *Handbook of Law and Economics* Vol. 2 (eds Polinsky, A. M. & Shavell, S.) Ch. 16 (Elsevier, 2007).
12. *International Energy Outlook 2013* (US Energy Information Administration, 2013).
13. *BP Energy Outlook 2035* (BP, 2015); www.bp.com/energyoutlook
14. De Jong, K. P. *Catal. Today* **29,** 171–178 (1996).
15. Meirer, F. *et al. J. Am. Chem. Soc.* **137,** 102–105 (2015).
16. Zečević, J., Vanbutsele, G., de Jong, K. P. & Martens, J. A. *Nature* **528,** 245–248 (2015).
17. Fabian, D. M. *et al. Energ. Environ. Sci.* **8,** 2825–2850 (2015).
18. *Annual Fuel Poverty Statistics Report, 2015* (Department of Energy and Climate Change, 2015).
19. Dietz, T., Gardner, G. T., Gilligan, J., Stern, P. C. & Vandenbergh, M. P. *Proc. Natl Acad. Sci. USA* **106,** 18452–18456 (2009).
20. Michaels, H. & Donnelly, K. in *Proc. ACEEE Summer Study on Energy Efficiency* 11-163–11-173 (ACEEE, 2010); http://go.nature.com/5vUnqg
21. *Assessment of Demand Response and Advanced Metering* (Federal Energy Regulatory Commission, 2011); http://go.nature.com/FQUZxz
22. Ehrhardt-Martinez, K., Donnelly, K. & Laitner, J. A. *Report E105* (American Council for an Energy-Efficient Economy, 2010).
23. Ehrhardt-Martinez, K., Donnelly, K. & Laitner, J. A. in *Energy, Sustainability and the Environment: Technology, Incentives, Behavior* (ed. Sioshansi, F. P.) Ch. 10 (Elsevier, 2011).
24. Crabtree, G., Kocs, E. & Trahey, L. *Mater. Res. Soc. Bull.* **40,** 1067–1076 (2015).
25. Schneider, M. & Froggatt, A. *The World Nuclear Industry Status Report 2015* (Mycle Schneider Consulting, 2015); http://go.nature.com/rrRBwu
26. Perrow, C. *Bull. Atom. Sci.* **67,** 44–52 (November/December 2011).
27. Ramana, M. V. *Bull. Atom. Sci.* **69,** 66–76 (March/April 2013).
28. Ramana, M. V. & Mian, Z. *Energ. Res. Soc. Sci.* **2,** 115–124 (2014).
29. *Statistical Review of World Energy 2015* (BP, 2015); http://go.nature.com/4WH6NZ