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Energy, Environment and Resource Governance Working Paper

Managing Energy: Rethinking the Fundamentals

Managing Energy Technology

Working Paper Three

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PREAMBLE: MANAGING ENERGY: RETHINKING THE FUNDAMENTALS

In the past half-century a vast array of government and corporate entities has come to manage energy, or some aspect of energy, in one way or another. They have attained high levels of technical achievement and, in some cases at least, economic success. Nevertheless, the results overall have been less than satisfactory. Despite technological and economic advances, some two billion people are still without electric light. Moreover, scientific evidence indicates ever more forcefully that human use of energy is upsetting planetary systems, with consequences that could be catastrophic. The way we manage energy worldwide is creating serious problems for climate and energy security.

We need urgently to reassess the arrangements and processes by which we manage energy, in all its diverse manifestations. We have long known that the technical potential for improvement in many contexts is substantial. But realizing this potential will entail significant changes in institutions, business and finances. Such changes will happen swiftly and effectively enough only if those involved see them as advantageous. We need to understand better how and why people and entities manage energy now. That may enable us to identify ways and incentives to change the arrangements and the processes for the better, with the active participation of the managers.

Working Paper 1, 'Managing Energy Wrong', looks at how we manage energy, who does what and why, and how we might do better. It argues that we focus too much on short-term trade in commodity fuel, and not enough on investment in the user-technology that delivers energy services. For purposes of managing energy we therefore collect the wrong data, and we analyse it wrong. Working Paper 2, on 'Managing Energy Data', explores this issue, challenges the conventional view of energy in society, and offers a more promising vision. The present Working Paper, number 3, on 'Managing Energy Technology', develops the next stage of the analysis, redefining energy technology, examining its interaction with fuel and suggesting how this might evolve.

INTRODUCTION: ENERGY AND TECHNOLOGY

Who manages energy technology? You do. I do. Everyone does. Even the poorest of us humans try to wear some sort of clothing, and seek some sort of shelter. Clothing and shelter are energy technology; indeed they are crucial to our survival, individually and as a species. Your body needs to be at a temperature of about 37 degrees Celsius to function properly, brain and heart and nervous system and all. You digest and process food energy accordingly; even at rest you are giving off perhaps 100 watts of heat. Clothing helps to control the way your body loses or gains heat energy from your surroundings. Shelter makes energy flows to and from your surroundings easier for your clothing to manage. Scientific data on these vital energy processes have given us valuable insights into human biology. But we do not as a rule extend our human energy system boundaries beyond our skin, to include clothing and shelter. Perhaps we should. Donning clothing and seeking shelter are essential stages in managing energy technology.

We have come to construe 'technology' to mean something, perhaps, with a metallic finish, flashing lights, bells and whistles and mysterious functionality. Etymologically, however, technology is 'the practical use of scientific knowledge in industry and everyday life' (*Chambers 21st Century Dictionary*). 'Practical use' includes making and building things. What we make and build are manifestations of our technology – not just the things with metallic finish but every artefact, every physical asset we fabricate using our skills and knowledge. Among the things we make and build is a vast, diverse and continually expanding variety of artefacts that control, manipulate and process energy for us, in one way or another – what we can call energy technology.

What we want energy technology to do for us includes several distinct processes. We want comfort: to maintain a local temperature not too high nor too low, by controlling the flow of heat energy in our vicinity – the key function of buildings, our most important energy technology. We want to cook food: to create and sustain a local temperature at least high enough to boil water, and preferably high enough to make vegetables and meat easily edible and delicious. We want illumination: to create and maintain light, at times and places when and where daylight is too weak or absent. We want to apply and control forces stronger than we can get from muscles, our own or those of working animals. We want refrigeration: to create and maintain a local temperature lower, possibly much lower, than that of our surroundings. We want to work materials: to create and maintain local temperatures high enough to smelt metals from ores, to fire ceramics, to manufacture steel and cement, to fabricate metals, and so on. We want mobility: to move people and goods farther and faster than we can with our own muscles and those of working animals. We want information and communication, for work and leisure, for social interactions that we can now make both local and global.

What is most remarkable about this catalogue of energy processes is that most of us in the fortunate parts of the world take them completely for granted. Far from consciously 'managing' them, or thinking of them as energy processes, we scarcely think of them at all. Nor do we usually recognize buildings, cookers, heaters, lamps, motors, chillers, vehicles and electronics as energy technology. Instead the expression 'energy technology' makes most people think of power stations and power lines, refineries and pipelines and so on, the technology to produce and deliver the fuels and electricity that most people now think of as 'energy'.

As earlier Working Papers in this series have argued, however, scientists and engineers use 'energy' to mean an essential attribute of all physical processes, an attribute they can track and measure. To call fuels and electricity 'energy' is seriously misleading. Bundling oil, coal, natural gas and electricity all together as 'energy' lets politicians and the public think they can substitute one for another. They cannot. Almost any particular modern user-technology – car engine, electric motor, computer, the list is endless – requires a particular fuel or form of electricity meeting tight specifications. Those who produce and sell the fuels and electricity know this very well. Those who make and comment on energy policy, however, often appear not to. They appear to think that energy is energy, in whatever form it comes, especially when it comes as measured quantities of fuel or electricity, sold, bought and paid for. They overlook the fundamental distinctions between the different services we desire, the different energy processes involved and the different user-technologies that deliver the services. Managing energy technology is not one task but many, entailing many different responsibilities and decisions, short-term to long-term, and local to global. Most people most of the time do not even realize they are doing it.

FUEL AND ENERGY

In the dawn of the human species, when we learned how to control fire, we also discovered fuel – material that would burn, to give off useful warmth and light when and where we wanted it. Fuel of one kind or another – firewood, animal dung, whale oil, coal, petrol, heating oil and so on – has been a familiar feature of human society and human experience ever since. By contrast, energy as we now understand it dates back only two centuries. In

1807 the English polymath Thomas Young first used the term in what was to become its modern sense, not just as a metaphor but as a scientific concept, a measurable attribute of physical processes.

Unlike the familiar fuels, energy as a measured quantity has never really been part of everyday life. Even in the twenty-first century no one puts 'energy' on a shopping list. Nevertheless, from the days of caves onwards, humans have been aware of the ambient energy around them. Even though they did not give it a name nor measure it, they intervened in practical ways in ambient energy flows, to improve their circumstances. Clothing and shelter were and are key factors in the remarkable evolution of the human species, its extraordinary adaptability, enabling us to colonize almost every corner of the planet, no matter how hot or cold, how humid or arid. Shelter, from being as basic as a cave, a cage of branches or a tent of animal skin, gradually evolved into what we now know as buildings, including vast structures on an almost geological scale. The primary purpose of buildings, to provide shelter and a comparatively comfortable temperature, has long since been almost forgotten, overtaken by multiple other purposes. Indeed far too many buildings around the world are now seriously inadequate for that original primary purpose; they are uncomfortable if not indeed uninhabitable without extravagant additional fuel and electricity. That is a key issue for the future of managing energy technology.

Our ancestors, aware of the potency – what we now know as the energy – of moving air and moving water, devised windmills, water mills and sails, to help them to grind grain for food and to travel on water. Otherwise, however, human activities requiring force and motion depended on the energy of muscles, human and animal, until almost exactly three centuries ago. Then, in 1712, the English inventor Thomas Newcomen devised what he called an 'atmospheric engine' – what we now know as a steam engine. Newcomen's engine was the first successful practical demonstration of using the stored energy of fuel, in this case coal, to produce force and motion. The main application of the Newcomen engine throughout most of the century was to pump water out of the coal mines that provided the fuel for the engine, an early illustration of a recurring theme: each stage of development of energy technology fostered further development. Until the advent of the steam engine, fuel could be used only to raise temperatures, for comfort, cooking, and processes such as smelting ores, firing ceramics and working metals. Using fuel to provide force and motion was the breakthrough that transformed energy use in society, and transformed society itself in the process.

FUEL AND TECHNOLOGY

At the advent of Newcomen's steam engine, technological artefacts such as tools, engines and other devices were mainly produced individually by artisans and craftspeople, either for their own use or for sale at an agreed price to one other prospective user, effectively on commission. Over the coming two centuries that was to change fundamentally. The steam engine was a major contributor to the change. Starting in 1763 the Scottish inventor and engineer James Watt, working at the University of Glasgow, came up with a crucial modification of Newcomen's design, dramatically reducing the amount of fuel the steam engine needed to operate - what we would now call increasing its fuel efficiency. After struggles with finance, Watt teamed up with another engineer called Matthew Boulton, and found success. When the Newcomen engine started to be used in coal mines, it used the 'small coal' from the same mine, which could not otherwise be sold; its efficiency did not matter much. But Watt’s engine improved fuel efficiency fivefold. Using his engine to pump out the tin mines in Cornwall, where the coal had to come by sea, became economic. Boulton and Watt then leased their engines, charging one-third of the expected saving on coal – a financial innovation looking far into the future. Before 1800 the firm of Boulton&Watt were selling and leasing steam engines in quantity, to the new generation of manufacturing entrepreneurs launching what became known as the industrial revolution. The energy technology business was beginning to emerge.

Newcomen, Watt and Boulton were early examples of engineer-entrepreneurs. Although they did not think of their activities in such terms, they were demonstrating key aspects of managing energy technology. First you had to identify an application – something that energy technology could do, or do better, a service it could render to its human users, such as lifting water out of a flooded mine. Then you had to devise a suitable technology to perform this service, such as a pump operated by a steam engine fired by coal. In order to fabricate this technology according to your design, you had to hire suitably qualified craftspeople, such as those at a foundry, and pay them. Unless you yourself were intending to use the technology, you had to persuade the prospective user of its virtues, so that he would buy it, allowing you to cover your costs and earn an adequate profit for your endeavours. Financing the transaction might also involve middlemen such as bankers or other investors. If your design included original features, you applied for a patent from the government, that would grant you exclusive rights to use them commercially for a set period of time, long enough to earn you a satisfactory return on your original ideas – what came to be called 'intellectual property'. In turn, the purchaser of your technology had to learn how to use it, how to operate and maintain it, to get the service for which the purchaser bought the technology.

For a fuel-using technology such as a steam engine the purchaser also had to locate and buy the fuel, a continuing expense. Fuel merchants had been producing and selling firewood and coal for centuries. Fuel supply technology was saw, pickaxe and shovel. Fuel specifications were basic and undifferentiated. At the beginning of the nineteenth century, the link between fuel and user-technology was similarly basic. Once you moved beyond the bonfire in the open air, you had to be sure you could keep your fire where you wanted it; but the technology went little farther than that. If you were a householder you had, perhaps, a cooker, one or more fireplaces, and holders for candles and oil-lamps. If you were an artisan or craftsman, you might have a boiler, a furnace or a kiln, to dye your textiles, smelt your metals or fire your pottery. As the industrial revolution gathered pace into the nineteenth century, steam engines powered machines in the new factories; but they could burn whatever fuel was available and cheap - usually coal, more or less whatever came out of the mine. Much the same could be said of the innovative applications of steam power for shipping and railroads, in steamships and locomotives, after the ground-breaking examples of Robert Fulton's commercially successful North River Steamboat and the Stephensons' locomotive the Rocket.

Coal merchants of course welcomed the advent of steam engines as an additional market. The combustion technology employed was only one step removed from the open fireplace. The steam engine itself involved much more complex technology, but its firebox was just that, a box to contain the burning fuel. The fuel in turn could be anything combustible. Coal that had long been supplied for household fireplaces and cookers was perfectly adequate for the early steam engines in industry, shipping and railroads.

NETWORK TECHNOLOGY

Working for Boulton&Watt in the 1790s, the engineer William Murdoch made yet another breakthrough with major long-term implications for energy systems. Once again improving on the work of several precursors, Murdoch demonstrated that roasting coal in a closed retort produced a gas that would burn to give illumination, using it to light his house in Cornwall in 1792, and the company's works in Birmingham in 1798. By 1807 Pall Mall in London had become the first public gas-lit street. Within a decade gas-lighting was spreading across Europe and North America, both on private premises and in public spaces.

Gaslighting was a managerial challenge on several levels. A gaslighting entrepreneur had to design or license the technology of retorts, pipes, valves and burners; arrange to fabricate and install them, hiring and paying for the necessary skilled workers; find adequate finance for the investment and operating costs; and persuade prospective customers to sign up for the service. He had to purchase a continuing supply of coal for the retorts, and to dispose of the consequent solid waste. He had to control the production process to ensure a reasonably consistent composition of the fuel gas fed into the pipework, so that it would ignite and burn with a smooth reliable flame at the customers' gaslamps. This was an early manifestation of what was to become of critical importance, the ever more stringent specification for the fuel required by a particular user-technology.

The entrepreneur also had to obtain permission to lay pipes in public spaces such as streets, and maintain and manage the resulting network, a system functioning in real time, over what often soon became a substantial urban area. Gaslighting was the first networked energy technology. Others would follow.

FUEL TO MATCH TECHNOLOGY

Until the mid-nineteenth century the catalogue of fuels in common use for heating, cooking, lighting and motive power included wood, peat, coal, and animal and vegetable fats such as tallow, whale oil and oil from plants. Most user-technology could use any fuel available, and most fuels were not tied closely to any particular user-technology. The link between fuel and user-technology was generally undemanding. Then another fuel emerged, whose impact on human energy systems was to be unprecedented – rock oil or petroleum.

Entrepreneurs were producing petroleum commercially in Poland, Romania, the UK and the US by the late 1850s, initially to distil or 'refine' it to make paraffin or kerosene, a substitute for whale oil for lamplight. Whereas the coal business around the world had existed for centuries, as a stable local business mainly supplying local users, early petroleum exploitation, particularly in the US, was a frantic rush, in which over-supply sometimes made oil cheaper than water. Entrepreneurs made and lost fortunes almost overnight. Local markets for oil were swamped; drillers had to find buyers much farther afield. But transporting oil was more difficult than transporting coal, a major challenge for managing the embryonic oil business. Pipelines and railroads became key factors in the hectically expanding activity. Refining petroleum rapidly became a business in its own right. An entrepreneur called John D Rockefeller combined transport, refining and marketing, including secretive anticompetitive deals and ruthless pricing, to force competitors out of business, making his Standard Oil into a gigantic monolith that dominated the US oil scene until Congress forcibly broke it up in 1911. Elsewhere in the world the oil business was shaped by similarly larger-than-life individuals, buccaneering risk-takers whose activities became the stuff of legend.

But the fuels that made their fortunes needed corresponding technology. Kerosene as a fuel for lighting was already under threat from gaslight and from a more recent innovation, electric light. But refining petroleum also yielded other fractions with different chemical composition and different attributes, including fuel oil for boilers and furnaces, and lubricants for machines, as well as waxes and other saleable commodities. However, one fraction in particular, called petrol or gasoline, was the key to the future of the world oil business. Petrol proved to be a perfect match for a new technology being developed by engineers including Nikolaus Otto, Gottlieb Daimler and Karl Benz, among many others – the internal combustion engine.

At the outset the engineers used fuel gas – lighting gas – for their experimental and early commercial engines, for stationary applications such as motive power in factories, where the engine could be connected to the gas system. But the availability of petrol, a portable liquid fuel that would vaporize inside the engine, ignite and burn like gas, changed the game. No longer needing a fixed connection to a gas supply, engineers were able to mount internal combustion engines on vehicles. Benz's automobile of 1885 was the first in commercial production, but others soon followed. Rudolf Diesel designed and patented an internal combustion engine that used a different fraction of petroleum, one that would ignite spontaneously when compressed.

In the coming decades, the manufacturers of automobiles and the refiners of petrol had to manage their businesses with a close eye on one another. As more people purchased and drove cars, the market for petrol and diesel expanded; as petrol and diesel became more widely available and cheap, more people purchased and drove cars. Not only the petroleum needed to be refined. So did the user-technology. A diesel engine would not run on petrol, nor vice versa. The constraint was going to become increasingly common: a particular user-technology had to have not just any fuel but its particular matching fuel.

ELECTRICITY AND TECHNOLOGY

As the links between technology and petroleum products tightened, another avenue of energy use opened - one with profound implications for links between fuel and technology to deliver services. The phenomenon of electricity had been known since the ancients. In the nineteenth century it at last moved beyond a party trick. Building on the work of Volta, Oersted and others, Michael Faraday demonstrated that moving a wire in a magnetic field made electric current flow in the wire, and conversely that an electric current in a wire produced a magnetic field. Within a few years practical applications of electricity technology began to spread and multiply: the battery, the telegraph, the electricity generator or 'dynamo' turned by steam power or water power, arc-lighting, the electric motor and – at the end of the 1870s – the incandescent lamp.

Invented simultaneously by Thomas Edison in the US and Joseph Swan in the UK, the incandescent lamp, with its high electrical resistance, made possible a system with many lamps in parallel. Any single lamp could be switched on or off with minimal effect on the rest of the system - a desirable feature for central-station generation supplying a number of different customers. Through the 1880s further innovations followed at breathtaking speed, each making the components of the electricity system more technically interdependent.

Edison's systems used so-called 'direct current' or DC, in which the flow of electricity was always in the same direction, like that from an electric battery. But Nicola Tesla and George Westinghouse, among others, promoted a system using so-called alternating current or AC, in which electricity surged back and forth many times a second. Incandescent lamps would work with either DC or AC; but a DC motor would not work with AC. So Tesla designed an elegant AC motor. The invention of the transformer, however, was the major breakthrough for AC. Using a transformer, you could increase the pressure or 'voltage' of electricity while proportionally decreasing the current, or vice versa. Doubling the current quadrupled the energy losses from heating the wires; decreasing the current likewise decreased the losses. Line losses severely limited the distance over which you could send DC electricity economically. With AC and transformers, however, you could minimize losses over longer distances, by sending electricity at high voltage and correspondingly low current, then transforming it back down to the lower voltage required by lamps and motors. In the 1890s, accordingly, AC won the 'battle of the systems'. Edison's own company, General Electric, eased him out the door and began marketing AC systems.

In the early years of arc-lighting on individual premises, some systems used water-power to turn the generator, for instance a converted water-wheel from an on-site mill on the grounds of a stately home. But the distance-limitations for DC operation meant that water-power could be used for so-called hydroelectricity only if it were reasonably close to the location of the lamps and motors. Such opportunities were seriously limited. AC, allowing economic transmission of electricity over much longer distances, dramatically expanded the potential of hydroelectricity. Indeed so dramatic was the potential that one of the first major AC installations, in 1896, was a hydroelectric generating station just above Niagara Falls, supplying electricity to the city of Buffalo some 26 miles away.

The rise of hydroelectricity underlined an attribute of electricity that was to become even more important more than a century later. For some applications, such as the internal combustion engine, the links between fuel and user-technology were growing more stringent. But the link between fuel and electric user-technology was mediated by the electricity system itself. A steam-powered generator could burn a wide range of fuels, any of which could thus, indirectly, power an electric lamp or motor. A hydroelectric generator did not use fuel at all. Instead it used, perhaps, a dam, pipework and a water-wheel – physical assets and infrastructure – to gather and convert a natural flow of ambient energy into electricity that could light lamps, drive motors and deliver other services hitherto usually obtained from fuel.

Hydroelectricity was the first major form of what can be called 'infrastructure electricity', independent of fuel. As the decades passed, hydroelectric generators, installed in ever-larger dams, came to include the largest power stations of all. Meanwhile, just as watermills had been converted to water-powered generators, so suitable windmills were converted to wind-powered DC generators in many remote locations, usually coupled to banks of storage batteries to run lights and motors for isolated farms. Not until much later, however, did wind power begin to scale up in size, generate AC or feed electricity into wide-scale networks.

As electricity systems evolved, they came to accommodate both fuel-based and infrastructure generation on the same system. Over the same period, into and through the twentieth century, electric user-technology multiplied and ramified. Lamps and motors of various kinds were joined in due course by cookers, heaters, refrigerators, toasters, irons, vacuum cleaners, radios and other household goods. Larger-scale electrical technology in industry included not only motors of many kinds and sizes, but also electric furnaces for specialized applications such as smelting alloys, electrochemical smelters for extracting aluminium, electric drying and a rapidly expanding range of electrical relays, sensors and controls for automated processes. Some of this electrical user-technology was to deliver services otherwise provided by fuel-based user-technology, notably cookers, heaters and other applications to raise temperatures. Others, especially applications based on small motors, including household appliances such as vacuum cleaners, delivered services that fuel-based user-technology could not, or not so conveniently. Gas-fired refrigerators were feasible; but gas-fired radios, tried briefly in the 1930s, were not.

FUEL, ELECTRICITY AND TECHNOLOGY

The links between fuel and user-technology developed along distinctly different pathways, depending on whether the user-technology ran on fuel or on electricity. As noted earlier, the mounting enthusiasm for the motorcar spurred the expansion of petrol refining and marketing; conversely, the growing availability and affordability of petrol made the purchase of a motorcar gradually more attractive, although until Henry Ford and mass-production such a purchase was usually a luxurious indulgence of the well-to-do. The designers and manufacturers of cars, however, were not involved in the production or marketing of petrol, and the oil companies selling petrol had no connection with the carmakers. Each relied on the other for business, but they were otherwise unrelated. In any case the oil companies had other customers, for heating oil, lamp oil, lubricants, and other products whose output they could increase or decrease by tuning refineries.

Such was not the case with electricity and electric user-technology. Petrol was a physical commodity. It could be stored until a customer wanted to buy it. Electricity was not a physical commodity; it was a process. Applied electricity started with the battery-operated telegraph. However, for electricity generated mechanically with a dynamo, for arc-lighting, incandescent lamps, DC motors and AC motors, electricity had to be generated more or less instantaneously as it was being used. It could not be stored. Electricity companies therefore wanted to persuade their customers to buy and use a steadily expanding assortment of technology, whose applications would be required at different times of day, to keep the generators and networks, expensive capital investments, busy and bringing in revenue. In the early years of electricity, the same companies that manufactured and operated the generators and cable network also supplied the lamps and motors their customers used. The electricity companies devoted major efforts to what they called 'load-building' – selling user-technology that would be switched on at times when other applications, especially lighting, were not.

In due course, manufacturing and marketing electrical goods became a separate activity. But the technology still had to match the specifications of the system, to be able to use the particular form of electricity it supplied – DC at a particular voltage, or AC at a particular voltage and frequency, at a current that would not overheat. Manufacturers of user-technology had to comply with these technical standards if they wanted their products to be accepted in the marketplace. If you plugged an appliance into the wrong form of electricity supply the result could be spectacular and dangerous. Over time, as more and more manufacturers began to offer electrical appliances and other user-technology, insurance companies and electrical engineering academics gradually established a lengthening list of precise technical specifications for a widening variety of electrical user-technology.

Technical standards such as these, however, said nothing about the actual performance of the product. As applications of user-technology, each with its matching fuel or electricity, rapidly expanded, one attribute received little notice. Whether you were selling fuel or selling electricity, you wanted your customers to buy, pay for and use as much as possible. If your customers used inefficient technology, they had to buy more of your output to get the service they desired. Fuel companies and electricity companies alike had no incentive to offer customers better user-technology. On the contrary, low-performance user-technology boosted sales of fuel and electricity. Many decades later the same perverse incentive still applies. It is taken for granted and goes almost unnoticed.

FUEL AND INFRASTRUCTURE

From the earliest days of petroleum, drillers faced one alarming and potentially dangerous problem. The hydrocarbons did not all emerge from underground in liquid form. A very light fraction vaporized and emerged as a gas, inflammable and explosive. For many decades this natural gas was a nuisance and a hazard. It had to be carefully separated and disposed of, usually by piping it to a tall burner called a flare. By the 1950s, in some places such as Texas, oilfield operators were able to persuade local electricity systems to burn this natural gas as boiler fuel, to generate electricity instead of just flaring it. But operators still regarded natural gas essentially as a problem of hazardous waste disposal. Drillers who found only gas, not oil, considered the well a failure.

Then, in the Netherlands in the late 1950s, drillers discovered a natural gas field so large they could no longer leave it unused. Developing the Groningen gasfield added yet another dimension to energy systems. Using natural gas meant putting in place a network of pipes all the way from the wellhead to the user's gas-burner – akin to the town gas systems still in service in the UK and elsewhere, but capable of carrying much lighter gas at much higher pressure. Establishing a natural gas network was not only a technical challenge and a major investment, but a headache for planning, especially in urban areas, digging up every street and entering every building. Less than a decade later, after the discovery of natural gas under the North Sea in 1967, the UK launched a programme to convert its entire town gas system to natural gas. That entailed not only replacing the entire network of gas-pipes, but also changing every burner in gas-fired user-technology throughout the country. The upgrade programme, a decade long, was intensely controversial. Gas technicians went door-to-door; and users had to permit them to change burners or scrap unchangeable appliances. If you did not, you were disconnected from the system. In retrospect, however, upgrading UK user-technology to run on natural gas was arguably the country's best energy policy decision of the past half-century. Moreover, the decision was not about fuel-supply but rather about improving the technology to use it. It also demonstrated dramatically – and expensively – the stringent requirement to link a particular fuel to its matching user-technology.

In ensuing years the perception of natural gas evolved rapidly, from that of a hazardous waste into that of a highly desirable hydrocarbon fuel over much of the world. It is still flared in vast quantities from oilfields in the Middle East and Africa. Elsewhere, however, transmission pipelines carry natural gas thousands of kilometers, through many countries, from gasfields to users. Liquefaction plants feed liquefied natural gas or LNG into cryogenic tankers to carry it to distribution networks on the other side of the world. Recent discoveries of so-called shale gas, from formations found to be widespread in the US and Europe, have reinforced the role of natural gas as arguably the most important long-term fossil fuel for the twenty-first century. It is versatile and clean-burning, producing no solid waste or sulphur oxides, and its emissions of fossil carbon dioxide are lower than those from coal or oil. It has also established an unexpected symbiosis with electricity, as a fuel for generation over a range of scales and technologies. That also demonstrates a further elaboration of the link between fuel and user-technology. Rather than burning natural gas directly, in user-technology for natural gas, burning it to generate electricity means, indirectly, running electric user-technology on gas. The idea is not new: half a century ago electricity was often referred to as 'coal by wire'. But it reinforces the role of electricity as an intermediary between fuel and user-technology.

When politicians and commentators refer to 'energy infrastructure', they often mean, as examples, the vast physical interconnections of natural gas networks, especially when they are interlinked also with electricity networks. They do not, however, usually mean the user-technology also connected to the system. They should.

FUEL, TECHNOLOGY AND BUSINESS

Those who produce, deliver and sell fuels and electricity include some of the largest and most successful companies in the world. They are successful precisely because they know what they are doing, and where their interests lie. Throughout the history of human energy use, their aim has been and is to sell as much as possible of what they produce. This entirely straightforward and laudable commercial objective brings another in its train. You might buy, say, firewood or fireplace coal to use directly, burning it on an open fire as your ancestors did millennia ago. However, as energy use has evolved, most fuels and all commercial forms of electricity have become much more specialized. You will buy petrol only if you also have a petrol engine that needs that particular class of petrol to run - and so on, through the entire catalogue of specific fuels and forms of electricity the producers provide. You purchase their fuels and electricity in order to run your specific user-technology - the aforementioned cookers, heaters, lamps, motors, chillers, vehicles and electronics. Fuel producers and electricity producers also therefore want you to buy and use this technology, even though they may now have no direct commercial involvement with designing, manufacturing or marketing user-technology.

That was not always the case. Traditional firewood and coal merchants did not care how you burned their fuel, or for what purpose. So long as you bought it and paid for it, the rest was up to you. However, with the advent of town gas, in Britain in the 1790s and then rapidly across Europe, North America and elsewhere, the arrangement changed. If you wanted gaslight, the gaslight company not only produced the combustible gas, by roasting coal in its large retorts; it also laid the pipes to carry the gas to customers, and supplied the burners that gave the smoky, wavering light on customers' premises. The customers paid accordingly. In effect the company was selling, and the customers were buying, a complete service: gaslight.

Almost a century later the same pattern emerged with the new technology of electric light. In its early years, in the 1870s, Thomas Edison and his competitors manufactured and sold complete systems, including generator, cables, switches and arc-lamps, installed on the premises of their necessarily wealthy customers. Then, to bring down the cost, Edison scaled up the generator, to a size too large for the individual premises even of his wealthiest and most extravagant customers. So did his competitors. Following the model of the gaslight system, the electric-light entrepreneurs laid cables through public streets to deliver electricity from a single large generator to light the new incandescent lamps of a number of separate customers on separate premises. In the early years of this central-station arrangement, the company still manufactured and installed the entire system, from generator to lamps. It charged its customers according to how many lamps they had, whether turned on or not. The company was selling, and they were buying, another complete service: the availability of electric light.

Later in the 1880s, however, came a practical electricity meter, a way to measure how much cumulative electricity had flowed through a customer's lamps. From then on the company charged the customer according to the amount of electricity used. This brought about a fundamental change in the financial relationship between the electric-light company and its customers. In the initial arrangement, a customer receiving electric light was effectively repaying to the company, with a profit, the investment the company had made in technology to deliver the light. The customer paid the company an agreed price to have electric light available, to use as and when the customer desired. The cost of the coal for a steam-powered generator was part of the company's internal running cost; individual customers had no direct link with the fuel that produced their light. The advent of the meter, however, meant that the customer was now purchasing a commodity, a measured amount of electricity, whose link to the company's use of fuel was direct and proportional. The customer paid the company for turning on the lamp, not just for having it available.

The meter also brought about a further fundamental change in the nature of the electric-light business. The company charged the customer an agreed price per unit for the number of measured units of electricity used. Using more meant a higher bill. But what the customer wanted was not electricity but light. The essential link between the two was the incandescent lamp, the user-technology that delivered the service. The better the lamp, the less electricity it needed to deliver satisfactory light. For the customer, a better lamp meant a lower bill. It also meant that the customer was, at least implicitly, using less coal to obtain the light. For the company, however, a better lamp on the customer's premises meant a lower revenue stream. The company wanted the customer to use more electricity, not less. The company was happy to use less coal to produce electricity; a better generator on its own premises was obviously desirable. But improving the lamp on the customer's premises went directly contrary to the company's interest. It was an early manifestation of a conflict at the heart of human energy use, a conflict between fuel and user-technology, which remains unresolved more than a century later.

FUEL VERSUS TECHNOLOGY

Until perhaps four decades ago, fuel and user-technology evolved together. Each reinforced the other, in a mutually supportive symbiosis of interests and functions. More and cheaper fuel meant more varied and affordable user-technology; more user-technology meant an expanding market for fuel. By the 1960s, in the rich countries that established the pattern, petrol and heating oil were cheap and abundant. Electricity was ever more widely available and apparently ever cheaper, based on ever cheaper coal, and nuclear power promising to be cheaper still. Natural gas had just arrived, clean and versatile wherever it could be had. User-technology responded accordingly. Prevailing orthodoxy declared that using more fuel and electricity went hand in hand with the economic growth so eagerly pursued. Architects and designers, constructors and manufacturers in many parts of the world created buildings, fittings, appliances, vehicles and other user-technology that could deliver the desired services only by extravagant use of cheap fuel and electricity. Clients and customers bought them. It seemed a good idea at the time.

By the beginning of the 1970s doubts were surfacing. The Torrey Canyon tanker disaster in 1967 and the Santa Barbara offshore oil spill in 1969 exposed the dark side of cheap petroleum. Awakening awareness of a new concept called 'the environment' raised concern about air pollution from coal-fired power stations and radioactive hazards from nuclear plants. Some people began to wonder aloud whether using ever more fuel and electricity was an unalloyed benefit. Then, in October 1973, with war in the Middle East, the Organization of Petroleum Exporting Countries succeeded in quadrupling the world price of oil, and embargoed shipments to the US and the Netherlands because of their support for Israel. The jolt to the global economy reverberated for many months. The 'oil shock' coincided with labour unrest in UK coal mines, shortages of natural gas in the northeastern US and similar disruptions elsewhere; politicians and the media proclaimed an 'energy crisis'.

The initial response to abruptly expensive and unreliable supplies of fuel was a sudden official enthusiasm for 'energy conservation'. The first concerted attempt at managing user-technology as an aspect of energy policy focused mainly on not using it: 'Switch off something NOW', 'turn down the heating and wear an extra sweater', 'turn off the TV and go to bed early' and so on. The general public in many parts of the world soon associated 'energy conservation' cynically with 'freezing in the dark'. The public soon tired of the hairshirt rhetoric. Perhaps recognizing this, the language of official and popular commentary underwent a subtle but significant shift of emphasis. By the late 1970s what had been called 'energy conservation' became 'energy efficiency'. 'Energy efficiency' had a positive, upbeat ring. 'Efficiency', or effectiveness, was clearly desirable in any context. In the context of energy, it meant using fuel or electricity more effectively, not necessarily using less of it. But that also implied an important corollary: the way to use fuel or electricity more effectively was with better, more efficient user-technology. In other words, the key to energy efficiency was managing user-technology.

Many thoughtful commentators pointed to the mediocre energy performance of contemporary buildings and other user-technology, as an opportunity for a more nuanced approach. Managing user-technology as a positive policy measure, not by turning it off but by improving it, began to look both plausible and attractive. It proved, however, to be more complicated and difficult than might have been expected. In rich parts of the world people were used to buying houses, cars, lamps, appliances and other user-technology without thinking at all about the need for or cost of fuel or electricity to run them. They took for granted that someone else would make these requisites available as and when they were needed, at an affordable price. Fuel and electricity suppliers, for their part, were at least ambivalent about the idea of their customers 'saving energy' by buying less of their products.

The hitherto mutually reinforcing roles of fuel and user-technology began to manifest an unfamiliar tension. The tension has intensified ever since. In the twenty-first century we have at last begun to realize that better user-technology competes directly with fuel. The implications for managing energy could be far-reaching.

MANAGING

Responsibility for managing supplies of fuel and electricity is long since well defined. Governments, regulators and companies understand their roles, their motivations and their interactions, although circumstances sometimes thwart their intentions. In centrally-planned economies, governments themselves provide – or try to provide – all the various fuels their citizens desire, often at heavily subsidized prices; they also design, build and operate electricity supply systems, with varying degrees of success. In market economies, governments likewise acknowledge that their citizens expect access to affordable fuels and electricity, as an indirect responsibility of government. Governments accordingly establish company law and appropriate regulation, to enable and persuade private companies and corporations to manage the business of supplying fuels, as profit-making enterprise. Electricity, because of the monopoly attributes of the network, is either government-owned and operated, or comes explicitly under the aegis of a government-mandated regulator, as does natural gas where available. The regulator oversees planning, investment and prices for electricity and gas, to ensure fair and - at least in principle - mutually beneficial transactions between companies and customers. Even after liberalization, where it has occurred, up to perhaps half the cost of a unit of electricity or gas relates to the regulated monopoly network, not to a competitive market. All over the world, managing fuel and electricity supply is, and is expected to be, intended to raise revenue by selling a commodity.

By contrast, until the upheavals of the 1970s, no one had needed to manage user-technology, at least not as an aspect of energy policy. Companies manufactured and marketed houses, appliances, process plant, vehicles and other user-technology according to a wide variety of standards laid down by governments; but energy performance was rarely a consideration. Some countries, notably in Scandinavia, had long imposed and enforced building regulations that stipulated minimum thermal insulation levels for new houses and other buildings. Elsewhere, however, for instance in the UK, such building regulations were specified for reasons of health and safety, not energy. The same was true of standards for technology using fuel such as petrol or natural gas. Electrical standards for lamps, motors, appliances and electronics were specified both for reasons of health and safety and for interoperability. Governments and companies alike found the energy performance of buildings and other user-technology to be a novel and controversial issue. The general public was either indifferent or - more often - confused and annoyed.

Some analysts and commentators nevertheless recognized the topic as an important new dimension for science-based public policy. As the preceding Working Paper in this series described, they began measuring and compiling data on energy performance of buildings and other user-technology, analysing the potential for improvement, and debating policy measures that might help to realize this potential. But putting plausible policy measures into action - managing user-technology, as a practical reality - was quite another matter. It still is.

MANAGING USER-TECHNOLOGY

The first hurdle is the sheer scope of user-technology to be 'managed', whatever that might mean. Buildings alone encompass everything from yurts to skyscrapers, for every imaginable purpose and in every imaginable location. Lamps, motors, heaters, chillers, electronics, vehicles - the range and variety is beyond imagining. So are the circumstances in which we humans use them - urban, rural, residential, commercial, industrial, developed, developing, coastal, inland, summer, winter, temperate, tropical and so on. Who is to manage this cornucopia of technology? Who is responsible for its energy performance, why and on what basis? How might they exercise such responsibility? Who is to manage, and how are they to manage, user-technology already in service, for instance the vast stock of existing buildings, so often inadequate in energy terms?

The shopping list of possible policy measures is extensive; but every measure has its limitations or drawbacks. The first and most obvious measure is simply to provide information about energy performance and its potential for improvement. Even that has proved controversial. Who is to provide the information - and what information? Generalizations about efficient use of energy are just that - generalizations, with limited specific application and even more limited impact. When government departments and agencies try to be more specific about the comparative performance of individual user-technology, manufacturers of household goods, vehicles and other consumer products have objected vociferously. Making any official comparison more quantitative, by actually ranking and labelling goods, has been yet more unwelcome. For the manufacturers concerned, having consumer-research organizations making such comparisons is bad enough; from governments it is even worse.

One major school of thought has long held that a single measure would produce the requisite result right across the board: simply raising the price of fuel and electricity. If a fuel is more expensive, people will use it more carefully - so runs the mantra, endorsed particularly by supporters of free-market precepts. The notion is theoretically sound. In practice, it runs into major obstacles. Who is to raise the price, and on what basis? An individual fuel company might be happy to raise prices, but not if customers then switch to another cheaper supplier. Yet having all suppliers raise prices would be anti-competitive collusion, illegal in market economies. Increasing the tax on fuel such as petrol would raise prices for all suppliers - but fuel users are bitterly opposed to additional taxes, no matter what their purpose.

In any case, as a spur to more efficient use, a higher fuel tax or any other fuel price increase is largely after the fact. People already own significant assortments of user-technology, up to and including houses and other buildings. In theory, a higher fuel price would prompt an owner to upgrade this user-technology, to improve its performance and reduce the amount of more expensive fuel it requires to deliver the desired services. In practice, the requisite capital expense often outweighs the putative savings. Even when savings are effectively guaranteed, such as through improved thermal insulation, owners frequently find the 'hassle' of upgrading more trouble than they think it worth. They grumble about higher fuel bills, but cannot be bothered taking active steps towards managing the technology that incurs them. In many contexts, both individual and corporate, the cost of fuel and electricity is a minor item in the overall budget, compared with other expenditure, and accordingly easy to ignore. Those for whom fuel and electricity costs constitute more than ten per cent of their expenditure are all too often too poor to afford the expense of upgrading their user-technology, such as inadequate housing. Raising the price of fuel simply aggravates their poverty.

A further complication arises when those using a residential or commercial building are tenants, not owners. The terms of a lease usually stipulate that tenants pay the running costs, including bills for fuel and electricity. The absentee owner-landlord therefore has no incentive to invest to upgrade the energy performance of the property. The tenant, in turn will be understandably reluctant to put investment into someone else's property.

Financial incentives to shift the balance between fuel and user-technology can be applied not only by making fuel more expensive but also by making better user-technology cheaper. Governments can offer grants, tax breaks, low-interest loans, rapid depreciation or a combination of such measures. But the onus of actually taking up and employing such offers remains with the user of the technology to be upgraded. Such positive financial incentives often fail to elicit the level of response that straightforward cost-benefit comparisons might suggest.

In principle governments, or governments and companies in concert, can establish minimum performance standards for user-technology, from individual devices and appliances and vehicles up to and including buildings. Once again the vast variety of technology, frequently crossing international borders during design, manufacture, purchase and use, and its often rapid evolution, poses a challenge for those attempting to define such standards. If and when standards have been agreed, enforcing them is a yet greater challenge. An even more controversial corollary is actually to ban the sale of user-technology with inadequate performance. The gradually spreading ban on the egregiously inefficient incandescent lamp has created a bizarre underground trade in illicit light bulbs.

A relatively coherent approach to managing user-technology, called 'demand-side management' or DSM, enjoyed a briefly successful vogue starting in the late 1980s. Its most extensive manifestation, in some US states, was in the form of a mandate from the relevant regulator to local gas and electricity supply companies. Rather than authorizing investment in additional supply, the regulator instructed the supply company to invest in customers' premises to reduce the demand for fuel or electricity. In return, the regulator allowed the company to charge a higher unit price; but the DSM investment meant that customers used less fuel or electricity, making bills not higher but lower. The arrangement worked well while gas and electricity supply remained monopoly systems. But the advent of liberalization at the beginning of the 1990s abolished the monopoly franchise and introduced competition. Regulators could no longer mandate supply companies to invest in customers' premises, when customers were being encouraged to switch suppliers at short notice. Liberalization, wherever it happened, derailed DSM.

Nevertheless the key concept of DSM, of companies earning revenue by investing in customers' facilities, remained – and remains – intriguing. It underlines one essential aspect of managing user-technology. What matters most is not commodity transactions in fuel or electricity, but investment – specifically investment to upgrade or replace the technology itself, to enhance its energy performance. The competition between fuel and user-technology is a competition for attention and for resources – to redirect attention, particularly policy attention, away from fuel towards the technology that delivers the service, and to shift the balance of resources – especially investment – accordingly. Who is to make the investment, with what incentive and on what basis, are the key questions.

GOVERNMENT AND USER-TECHNOLOGY

The obvious starting point is governments. The very idea of energy policy, and indeed of fuel policy even before, originated with governments, as a way to address the expectations of their citizens. Even under the most liberalized arrangements for fuel and electricity supply, if the lights go out citizens blame their governments. Acknowledging this fact of life, governments have long had to accept the ultimate responsibility to ensure supplies of fuel and electricity within their borders, whatever the role of private industry and finance. Nevertheless, in practice, governments have limited powers to guarantee adequate and affordable petroleum products or natural gas. Many countries now import most if not all of the hydrocarbon fuels they use. Their governments are at the mercy of the markets and, sometimes, the international politics that can disrupt international traffic in hydrocarbons.

Governments can do little to manage disruptions of imported supplies. What they can do, and have tried to do since the upheavals of the 1970s, is to reduce a country's vulnerability, by reducing its dependence on imported fuels. Countries such as the UK and the US, with their own hydrocarbon resources, have tended to emphasize increasing indigenous production, despite the obvious limitations of this approach. But an alternative approach, available to any government, not only those with their own hydrocarbons, is to take active measures to reduce the amount of fuel the country requires to run its stock of user-technology. As indicated earlier, the catalogue of potential measures is extensive, although each has its drawbacks. But one measure above all could tip the competitive balance between fuel and user-technology, in favour of the latter.

Governments tend to think of energy policy as something that governments do to affect the actions of others, perhaps companies or private individuals. But the most potent energy policy leverage available to governments arises because governments themselves are major users of fuel and electricity, in their own extensive arrays of user-technology, including the buildings they own or lease. They can take the practical initiative, redirecting their energy attention away from the fuel they buy and refocusing it on how they use the fuel, demonstrating how to use it better by upgrading their own user-technology. Instead of telling the rest of us what to do, governments can show us. Managing Energy Wrong, the first Working Paper in this series, exhorted governments to

'... launch programmes to upgrade their own facilities, their own energy service infrastructure, to much higher standards – better insulation, doors and windows, better lighting, better controls, better appliances and electronics, probably even complete local systems using on-site generation of electricity, heat and cooling.

'Such government programmes could create the conditions for the new form of energy business we need. They would make managing energy explicitly a matter of investment in infrastructure, especially energy service infrastructure, as it must be. Government upgrade programmes, with their scale, variety and continuity, would be a launching pad, to persuade major energy players to create effective and profitable energy service companies to bid for and carry out the work. They would create skilled jobs everywhere. They would also offer the private sector a vivid example of the benefits of such investment. Bulk orders for upgrades would bring down the unit cost of innovative materials and technologies. And of course, properly managed, government upgrade programmes would save all us taxpayers money. Imagine what such an approach could accomplish all over the world, enhancing climate and energy security while bringing economic advantages to countries, companies and citizens alike.'

Most important of all, such government programmes would launch a new approach to managing energy technology, concentrating first, explicitly and not merely as an afterthought, on the energy technology that matters most – user-technology.

That is the crucial aspect of such programmes – not just the jobs, nor the financial, economic and environmental benefits that accrue. That is why they must be not merely ad hoc and piecemeal, as has been usual hitherto, but coherent and long-term, monitored and publicized continuously – real energy policy in action. Such government programmes can change the way we think about energy in our global society. They can underline the essential realization that human use of energy is not really about short-term transactions in commodity fuels – it is about long-term investment in technology and infrastructure, especially user-technology and user-infrastructure. That understanding ought to underpin energy policy, energy regulation, energy business, energy institutions, energy journalism and energy education.

Major upgrade programmes of the kind suggested need not be limited to governments. Some enlightened companies have already undertaken similar programmes on their own facilities, and indeed continue them. Indeed some of the most extensive upgrades have been and are being carried out by fuel companies themselves. But company programmes, valuable though they undoubtedly are, lack the crucial dimension of public education, to change fundamentally the way we think about energy in society, to manage and use the technology to best effect.

In the context of their current business model, fuel companies are unlikely to stress unduly the advantage of using less fuel. That, of course, raises a further question. Should that traditional business model change, and if so how? The next Working Paper in this series will discuss 'Managing Energy Business', and how it might evolve.

TECHNOLOGY, ELECTRICITY AND INFRASTRUCTURE

Shifting the focus of energy policy from fuel to technology may have another crucial corollary, affecting not use but supply. Human society uses two kinds of electricity. One we generate using the stored energy in fuel, such as coal, natural gas or uranium. The other we generate using technology to convert natural ambient energy into electricity, including hydro, wind, photovoltaic, solar thermal, wave, tidal and geothermal. This electricity does not use fuel. Most people call it 'renewable'. A more accurate term, as noted earlier, is 'infrastructure electricity'. It is created and delivered not by combustion or any other reaction but rather by the function of technology in the form of physical assets. The technology, the physical assets involved, can be of widely differing kinds and sizes, from the largest generators in the world to the smallest - from the Three Gorges dam to your photovoltaic calculator. Once the assets are in place and functioning, whenever the natural ambient energy is available the infrastructure converts it into electricity, for us to use however we wish.

Like user-technology, infrastructure generating technology competes directly with fuel – the more infrastructure generation on an electricity system the less fuel it needs. That raises an intriguing possibility. Two of the most urgent issues now facing policy-makers around the world, energy security and climate change, both arise primarily because of society's dependence on fuel. This Working Paper argues that we should shift the balance of energy policy attention and resources away from fuel towards user-technology. It could also offer a further, similar argument, for a shift away from fuel-based electricity to infrastructure electricity – another manifestation of the competition between fuel and technology. But one major difference must be acknowledged. Upgrading user-technology is already in many instances clearly a favourable financial and economic option. The investment entailed will produce an early return in the form of savings on fuel no longer needed. The economic and competitive status of most infrastructure electricity technology is less clear-cut.

It is site-specific, depending on the nature and scale of the natural ambient energy resource at any given location and time. It varies widely from one technology to another, even for closely related options such as onshore and offshore wind. The material requirements may be substantial, including basics such as steel and concrete and exotics such as lithium and cadmium, whose costs may be rising rapidly. The financial outlay is front-loaded, investment rather than running cost; almost all the expenditure must take place before an installation generates a single unit of electricity or revenue. The return on this investment may depend on the future price of a unit of electricity a decade or two hence, now seriously uncertain in most contexts, as indeed is the discount rate and the cost of servicing the capital investment. Many examples of proposed infrastructure generation also face difficulties with planning and permitting.

That said, however, as infrastructure generation matures and fuel problems mount, the case for a gradual and continuing shift away from fuel-based to infrastructure electricity grows steadily stronger, parallelling the shift away from fuel towards user-technology. As the transformation evolves, the impact on energy business and governance and indeed on human behaviour will be profound and far-reaching. As the competition between fuel and technology intensifies, the role and nature of energy in human society are going to change, and so is society.

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