

The Renaissance of Renewable Energy

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Everything in the universe may be described in terms of energy. Galaxies, stars, molecules, and atoms may be regarded as organizations of energy. Living organisms may be looked upon as engines which operate by means of energy derived directly or indirectly from the sun. The civilizations, or cultures of mankind, also, may be regarded as a form or organization of energy.

Leslie White, 1943

What Is Energy?

1.1 Aristotle in Times Square

The term ‘energy’ has become ubiquitous, as likely to be heard in a yoga class as at a physics lecture. In its everyday use, it has become synonymous with force, vigour, well-being and a certain kind of atmosphere. We talk about people or places having energy, a certain kind of energy, or lacking it altogether. We’ve become so used to using the words ‘energy’ and ‘energetic’ as pliant descriptors that we’re liable to overlook their scientific significance.

A first-time visitor to Times Square, the heart of one of the world’s busiest cities, is likely to first comment on the ‘energy’ of the place. But does this use of the term bear any relation to its scientific meaning? The Greek term *ἐνέργεια* (*energeia*), the origin of the English word, was probably coined by Aristotle. It combines the prefix *en*, meaning ‘in’ or ‘at’, with *ergon*, meaning ‘action’ or ‘work’. According to Aristotle, all living beings are defined by this attribute; they are ‘at work’, in contrast to inactive, inanimate objects. So *energeia*, for Aristotle, was intimately connected to movement. This philosophical concept of energy remained for more than 2,000 years the main usage of the term. As late as 1737, the philosopher David Hume wrote that there were “no ideas, which occur in metaphysics, more obscure and uncertain, than those of power, force, energy or necessary connexion”.

The first attempts to define energy in scientific terms date back to the seventeenth century. Isaac Newton established that the same force (gravity) which causes an apple to fall from a tree also determines the movement of the planets around the sun. Newton’s contemporary Gottfried Leibniz identified something he called *vis viva* (literally ‘living force’), the force of any moving thing. Leibniz began the process of

quantifying energy when he concluded that while the force of a moving object depends both on its mass (weight) and its velocity (speed), velocity was far more important than mass. In other words, a light but fast-moving object has far more force than a heavy but slow-moving one. Just imagine catching a basketball, which weighs about 600 grams, thrown by a teammate. Now compare this with the impact of a 10-gram bullet fired from a gun.

The human understanding of energy took a huge leap forward during the Industrial Revolution, pioneered by industrialists who were motivated as much by commercial ambition as by scientific enquiry. For them, energy was not an abstract idea; it was the force needed to drive the machines that were rapidly replacing human and animal labour. They therefore redefined energy as the ability to perform work. This remains the most common definition to this day. But what exactly do we mean by work? An ox pulling a plough is clearly at work. The animal's 'biological' energy is converted into furrows. In scientific terms, the ox exerts a force over a distance. Since prehistoric times, humankind's work, like that of the ox, has mainly involved moving objects, whether spears, arrows, goods or the plough. By the mid-eighteenth century, it was the turn of machines, and in order to build and use those machines, people needed to understand and quantify energy.

Most work requires more than the mere application of energy. To be effective, that energy must be concentrated. We see this when we open a bottle of beer or a soft drink. It would take a very strong (and thick-skinned) person to tear the cap from the bottle without using a tool. However, even a young child can perform the same task with a bottle opener. This is because the opener works as a lever, concentrating the energy at the point where it is needed to remove the cap. When energy is concentrated not in terms of space (such as at the rim of a bottle) but in terms of time, the concept of power comes into play. Most people have gone through the ordeal of moving house at least once. If we do the move ourselves, the time required will depend largely on the muscle power we can muster from obliging friends and family members. If you have a few bodybuilders in the family, the move will be quick. If you are relying mainly on your kids, you should hire the van for the entire week. This, essentially, is the difference between energy and power: power is the *rate* at which energy is generated and consumed to perform work.

James Watt (1736–1819) was particularly interested in power. He spent most of his life improving the steam engine, which works by heating water to form steam. The vapour occupies a greater volume

than liquid water does and so pushes upwards, raising a piston, just as water boiling in a pot raises the lid. Thus, Watt (and others before him) succeeded in converting the energy of heat into the energy of movement, which can be harnessed to perform a wide variety of tasks, from pumping water to turning a wheel. To convince his customers of his machine's efficacy, Watt came up with the term 'horsepower', which explains its power output relative to the main energy source of his day, the draft horse. This term, which is still used to rate certain types of engines, was later, fittingly, replaced by the *watt* as the international unit of power.

Converting Energy

Watt's horsepower measured the output of his machines, but it fell to another entrepreneur-engineer to measure the transformation of one form of energy to another. While exploring ways to improve his brewery, James Joule (1818–1889) made a breakthrough. He had been thinking of changing over from the steam engine to the newly developed electric motor. Before doing so, he wanted to compare the amount of work that could be performed by each machine. Joule constructed a device resembling an egg beater immersed in a jar of water, and he used a weight and pulley to turn the blades of the 'beater' (see Figure 1.1). The movement of the water molecules created heat, which Joule was able to measure using a thermometer. The greater the weight (force) he used, the faster the beater turned, and the greater the rise in temperature. In this way, he discovered a simple yet remarkably accurate way of measuring the relationship between work and heat.

Joule's experiment led to the formulation of one of the most important principles of physics: the first law of thermodynamics. This states that energy can be neither created nor destroyed, but merely changed from one form to another. Think of what happens when a car brakes: the energy of its movement is not lost, just converted into another form of energy. The brake pads, discs and surrounding air are warmer than they were before the driver braked. This principle is crucial to understanding how energy can be generated and used.

The Enigma of Energy

By the twentieth century, scientists had learned to quantify and measure energy, yet there remained something inherently mysterious

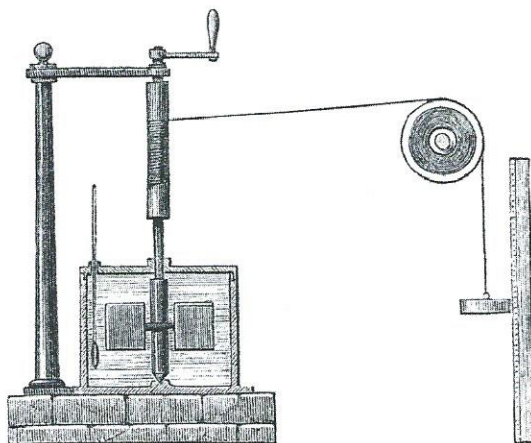


Figure 1.1. Joule's apparatus for measuring the relationship between work and heat. The fall of the weight causes the blades to turn, stirring – and thus heating – the water inside the container (calorimeter). A thermometer measures the rising temperature.

about the concept. Richard Feynman, one of the towering figures of modern physics, went as far as to admit that “in physics today, we have no knowledge of what energy is” (1970).

Energy, as we currently understand it, is force, work and power. It is at the heart of what it means to be alive: the ability to manipulate our environment to meet our needs. Thus, Aristotle's definition of energy remains essentially valid today. If the father of Western philosophy were to have stepped into a time machine that touched down on Times Square, he would recognise around him the principle of energy in action, through two factors: motion and work.

1.2 Energy: What Gets Lost in ‘Translation’

Robert Frost memorably defined poetry as “what gets lost in translation.” Just as meaning is inevitably lost as ideas are converted from one language to another, there is no way to convert energy without loss. Energy efficiency, like translation, is merely about minimizing that loss.

As a teacher, I always require that my students work in groups, where each person's grade is influenced by that of the whole group. It often happens that a student complains about a group-mate, typically that he or she is not pulling their weight and therefore jeopardising

the performance of the group. This reflects the second principle of thermodynamics. The second principle states that an enclosed system naturally tends towards maximum disorder, or entropy. Mountains are gradually worn down by wind and water, houses need to be regularly repaired and maintained, and teenage students have a gift for creating mayhem. Being a good student means applying a great deal of order to one's behaviour. Yet this is an energy-consuming process. Sometimes my students opt for a strategy that involves a much lower energy investment; instead of studying and supporting each other, they try to sow doubt in my mind and blame each other, thus creating disorder in the classroom.

Students are not the only ones affected by entropy. All living beings expend an enormous amount of energy every day of their lives just maintaining the status quo. Order is needed to survive and triumph, at least for a while, over the many external forces that are out to get us. To live we must actively counteract the second principle, and this requires that we expend energy. The second principle implies not only that it is far easier to destroy (creating disorder) than to build (creating order) but also that any conversion will inevitably entail some dissipation of energy, usually in the form of heat. Strictly speaking, the energy converted into heat has not been lost. However, it is not easily recovered. Staring into an open wood fire on a cold winter's evening, it is easy to become mesmerised by the sparks rising with the smoke. What we are witnessing is the chemical energy stored in the wood being converted into heat and light. However, the second principle prevents the opposite occurring: heat and smoke cannot be converted back into a woodpile. Part of the energy has been so widely dispersed that it cannot be retrieved.

The Low Efficiency of Energetic Conversions

Strictly speaking, the terms 'energy production' and 'energy loss' are incorrect, as – according to the first law of thermodynamics – energy can be neither created nor destroyed. What we observe in physics or chemistry is merely a conversion from one form of energy into another. Fully efficient energy conversion is possible only in theory, and indeed most conversions are highly inefficient. The engine of a car provides a good example of how energy gets 'lost' in conversion. Cars run thanks to a controlled explosion in the combustion chamber. Thus, chemical energy (fuel) is first converted into thermal energy (heat), and then into kinetic energy (motion). However, within

Table 1.1. *Comparison of different forms of energy conversion and their efficiencies*

Process/technology	Conversion	Efficiency	Energy loss
Photosynthesis (wild plants)	light → chemical bonds	0.2–0.3%	heat
Photosynthesis (crops)	light → chemical bonds	2–5%	heat
Muscles	chemical → movement	30%	heat
Candle	chemical → light	0.01%	heat
Candle	chemical → heat	99.99%	light
Incandescent light bulb	electric → light	10%	heat
LED lamp	electric → light	50%	heat
Steam engine	chemical → heat → movement	5%	heat, noise
Electric engine	electric → movement	80%	heat, noise
Car (internal combustion engine)	chemical → heat → movement	10%	heat, noise
Gas turbine	chemical → heat	> 95%	noise
Gas turbine	chemical → heat → mechanical	60%	heat, noise

this threefold conversion process only 10 per cent of the chemical energy contained in the petrol or diesel is converted into motion. So, what happens to the other 90 per cent? About three-quarters of it is lost either as heat or consumed by the car's cooling system, while the remainder is lost as a result of friction (of tyres gears and air drag), idling, and auxiliary functions such as air-conditioning and power steering. Some conversions are even more inefficient (for example, a candle transforms no more than 0.01 per cent of the chemical energy in the wax into light), while others are considerably more efficient: an electric motor transforms about 80 per cent of the electricity consumed into mechanical energy.

1.3 The Various Forms of Energy

Consider for a moment what it takes to read these lines. First, there is the energy required to maintain a constant body temperature, then that used by the movement of the eye, and finally the energy required by the brain to process the message. At no moment in our

lives do we cease to expend energy. Even during sleep the human body performs a variety of tasks: the heart beats; blood circulates; enzymes and hormones digest, protect, repair, and maintain temperature; and the brain, our most energy-intensive organ, works to maintain control of the body. Like the human body, the world partakes in a constant exchange of energy. It is, in the words of energy expert Vaclav Smil, "the only universal currency. One of its many forms must be transformed into another in order for stars to shine, planets to rotate, living things to grow, and civilizations to evolve" (Smil 2000).

Gravity is perhaps the first type of energy we experience in life. As a baby emerges from her mother's womb, she experiences for the first time a sense of weightedness. This force - no doubt disconcerting to a newborn - is truly universal. All bodies in the universe, from atoms to stars, exert a gravitational attraction on one another. This force is directly proportional to the mass of the attracting body and indirectly proportional to the distance from it. That is why astronauts can bounce around on the moon like slow-motion trampolinists (our satellite has one-fourth the mass of our planet) and why we are drawn to the Earth rather than the sun (the sun's mass is more than 300,000 times that of the Earth, but it is 150 million kilometres away).

A falling object, attracted by gravity, exerts another form of energy: kinetic energy. This can be transferred from one moving object to another, as when a tennis racket strikes a ball. However, not all the energy is converted in this way. Because the atoms within the tennis ball are excited and vibrate, they generate heat, or thermal energy. Heat is therefore a form of kinetic energy, generated at the atomic level.

Heat can be transferred either by the physical impact of particles or in the form of electromagnetic waves. We are familiar with mechanical waves; by their nature they are tangible - whether as sound travelling through air, waves in the ocean or ripples in a pond. Yet electromagnetic waves are an equally constant and natural feature of our world, in the form of radio waves, microwaves, X-rays, and gamma rays. Light is one such electromagnetic wave. Heat also radiates, in the form of infrared rays that can be "seen" by some species of snake through special thermal receptors.

The ancient Greeks found that amber, when rubbed against animal fur, exerted an attraction on small objects. As a result of this discovery, the Greek term for amber (*elektron*) forms the root of the

English word 'electricity.' Electricity describes the presence and flow of electrons, tiny negatively charged particles that orbit the nucleus of every atom. Manifestations of electricity include lightning, static electricity and the flow of electrical current in a copper wire. Certain elements, particularly metals, easily release and receive electrons. When we flick a light switch or turn on an appliance, we take advantage of a flow of electrons jumping from atom to atom along a copper wire, a flow that began, in most cases, at the nearest power plant.

A chemical reaction occurs when one chemical element 'donates' electrons to another. The fascination and comfort many of us feel while staring into a campfire may be attributable to the fact that combustion is humankind's oldest source of external energy. A typical combustion reaction sees carbon react with oxygen, releasing carbon dioxide (CO_2), water (H_2O), and energy in the form of heat and light.

Every chemical transformation is accompanied by an increase or decrease in energy. In order to lift a book from the floor onto a table, we need to expend energy; the muscles of our arms convert some of the chemical energy we consumed as food into mechanical energy. To *raise the book even higher onto a bookshelf, we must expend even more energy.* The floor, the table and the bookshelf represent three energetic levels. If the book falls from the shelf, the energy we invested in it will be released in kinetic and thermal energy, as the molecules in the air and the floor are excited. Because of this, we say that the book on the bookshelf has potential energy.

There are numerous ways to store energy. For example, electric energy may be stored in a battery and kinetic energy behind a dam. The electrons in the battery and the water molecules behind the dam are 'poised' to release energy. The sum of potential and kinetic energy is known as mechanical energy. This is the energy associated with the motion or position of an object. The classic example is a swinging pendulum. The pendulum passes back and forth between kinetic and potential energy. It attains its maximum kinetic energy and zero potential energy in the vertical position, because it reaches its greatest speed and is nearest the Earth at this point. At the extreme positions of its swing, on the other hand, it will have its least kinetic and greatest potential energy. The energy never leaves the system but is constantly converted between kinetic and potential. The pendulum slows down and eventually stops only because a part of the energy is converted into heat through air drag and friction at the pivot.

1.4 Qualities of Energy

Earthquakes and lightning are among nature's most dramatic shows of force. Little wonder that so many cultures have constructed myths and legends around these phenomena, imagining wrathful gods venting displeasure and exacting vengeance. Even without a divine interpretation, these are awe-inspiring events. The 2011 earthquake that in few minutes triggered floods and nuclear meltdown in Japan released enough surface energy to power the city of Los Angeles for a year. A typical lightning bolt releases about one million megawatts, enough to meet the electricity needs of Germany and France, though only for a fraction of a second! Yet we are unlikely to tap these immense sources of natural energy anytime soon. The energy of a lightning bolt is far too concentrated (any conductor or battery we can currently envisage would be fried to a crisp), and that of an earthquake far too dispersed to harness. Solar radiation, by stark contrast, strikes the Earth's surface with only 13 watts of power per square meter, yet is far more useful, as we can convert it relatively easily into electricity.

For energy to be useful, it must have at least one of three basic characteristics: it must be sufficiently but not excessively concentrated; it must be storable; and it must be transportable. Not all forms of energy (thermal, chemical, electrical, etc.) have the same level of usability, and only chemical fuels meet all three requirements. Electricity meets the first and the third conditions. Although it may be stored in sufficient quantity to power small appliances, such as phones, laptops and flashlights, electricity storage at an industrial scale is still a long way off. That is why hospitals rely on diesel generators rather than batteries in case of blackouts. Thermal energy may satisfy the first condition but can be stored and transported only at low intensity (e.g., in a thermos flask).

The Three Characteristics of Useful Energy

Concentrated: The tide is able to raise and lower every vessel in a port, but is of little help in raising even a small boat within a few minutes or maintaining that position for days. It is often possible to alter the concentration of an energy supply, but it is far more difficult to concentrate dispersed energy than to disperse concentrated energy.

(continued)

Storable: A conventional diesel-engine car can run for about 700 kilometres on a single tank of fuel. This is the great advantage of fuel-based energy sources. Even the most efficient electric cars can only manage about a third of that distance on a single charge, and they require several hours to recharge.

Transportable: Natural gas or electricity can be channelled through pipes and cables for thousands of kilometres, while losing very little of their energy. Heat, by contrast, is rapidly dispersed and requires thick insulation for transport even over short distances.

1.5 The Biology of Energy

When we humans compare ourselves to other species, it is usually to emphasise our more attractive qualities. Thus, a burly man may be compared to a lion or an oak, a beautiful woman to a swan or a rose. Few humans would feel flattered at being compared to a mushroom. Yet, in one very crucial respect, we have more in common with fungi than with an oak or a rose. We humans – like all other animals, all forms of fungi, and some types of bacteria – are heterotrophs. This means that we need to consume other organisms to survive. The oak and the rose, however – like all plants, all algae and some bacteria – are autotrophs. This means they are able to synthesize their own food (from the Greek *autós*, meaning self, and *trophē*, meaning nourishment). They use solar energy to power a reaction that converts water and carbon dioxide into organic biomass (sugar). We call this chemical process photosynthesis (from the Greek *photos*, meaning light).

The synthesis of highly ordered sugar molecules from unordered and scattered molecules of carbon dioxide and water could not happen spontaneously. That would contravene the second principle of thermodynamics, according to which all things tend towards decay and disorder. It is the input of solar energy that makes the transformation possible.

Once an organism has obtained its food, whether through photosynthesis or by consuming other organisms, it converts that fuel into energy. This process – essentially a kind of cellular combustion – is known as respiration. Oxygen absorbed by the lungs is distributed through red blood cells to every cell in the human body. In the cells, the oxygen reacts with the organic fuel to produce energy. The by-products of this reaction – water and carbon dioxide – are exhaled through the lungs and excreted through the kidneys. Plants respire

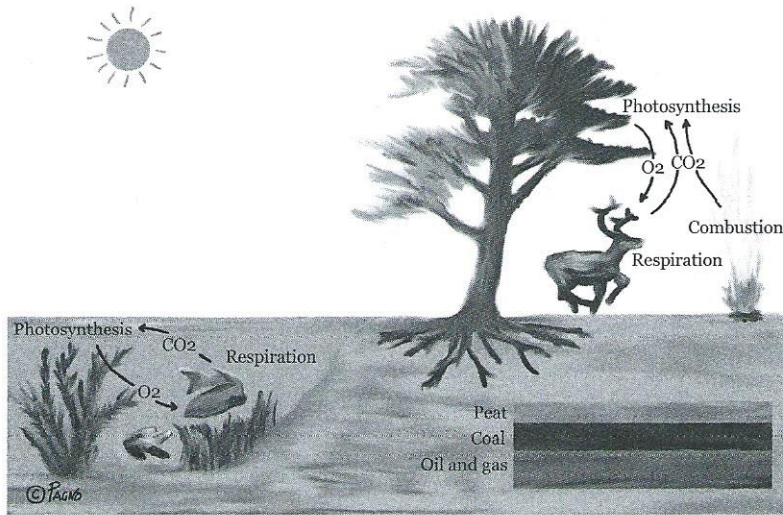


Figure 1.2. All life depends on the ability of some organisms to transform inorganic matter into organic matter using solar energy. The sun, therefore, is the first link in the chain of life.

in a similar way, releasing carbon dioxide and water through their leaves.

Many living organisms, including most animals, have a second way of converting food to energy: fermentation. Unlike respiration, fermentation does not require oxygen. In evolutionary terms, it is also far older than respiration, but around eighteen times less efficient. Not surprisingly, then, all multicellular organisms, from plants to fungi and animals, rely mainly on respiration. Organisms that depend entirely on fermentation include yeasts and some bacteria. The pungent odours that emanate from rotting food are caused by the by-products of fermentation (carbon dioxide, alcohol, lactic acid and acetic acid). All methods of food storage and conservation, from smokehouses to fridges, aim to prevent or slow down fermentation. Animals use fermentation as a kind of backup, when more energy is needed than can be supplied using respiration, usually because of an inability to breathe quickly enough. Humans also take advantage of fermentation to make numerous food products – including alcoholic drinks, yogurt, bread and vinegar.

Ultimately, all life on Earth is supported by the relationship between the sun and autotrophic organisms, as the energy stored in their cells is transferred to other organisms in the food chain. At

the end of its life, every organism enters what is called the detritus chain: its biomass is decomposed by insects and bacteria. As a result, the complex organic molecules, full of chemical energy, that make up the organism return to the soil as simple inorganic molecules that can be recycled into biomass by autotrophs. In this way, all life is part of an energetic flux. The irony of our recent 'discovery' of recycling as an approach to waste management is that all the processes on which our lives depend involve the principle of recycling. When herbivores eat grass or carnivores eat herbivores, they consume part of the solar energy stored in biomass via photosynthesis. The atoms that comprise our body belonged just a few days ago to another living organism, and perhaps a few years ago to another human being.

1.6 From Rubbing Sticks to Splitting Atoms: The History of Human Energy Use

According to the American biophysicist Alfred Lotka, any organism or organic system will tend to increase in size and complexity as long as there is enough available energy. Mould, for example, will spread over a piece of moist bread as long as there is space available and organic material from which to recover energy. Once this energy source is exhausted, the mould dies and is itself consumed by bacteria. Humans, like all animals, are heterotrophs, obtaining our energy by ingesting organic compounds. The astonishing reproductive success of our species is largely attributable to our consistent ability to discover new sources of energy and to optimise their use.

Between seven and six million years ago the dominant vegetation in East Africa changed from woody forest to savannah. Formerly tree-dwelling primates were forced to adapt to life on open grasslands. Evolutionary scientists have identified this as the moment when the earliest stage of the human line (known as hominids) diverged from the evolutionary line of apes (Pollard 2009). The change in environment forced the first major evolutionary change in the history of humankind: the development of upright gait (Lovejoy 1988; McHenry 2009; Wong 2006). The major advantage of walking upright was that it freed up the front limbs for other uses. The evolution of the human hand with its opposable thumbs allowed us to grasp and hold objects, leading to another great evolutionary achievement: the manufacture and use of tools.

Scientists have interpreted the use of tools as a key indicator of intelligence, yet tool usage was probably as much a cause as an effect of greater brain power. As early humans experimented with more complex and intricate tools, they came to rely more on cognitive faculties and less on instinct and emotion. Over millennia, this resulted in evolutionary growth in the corresponding parts of the brain. However, a larger brain also entails a greater energetic cost. The human brain consumes about 400 kilocalories per day, three times that of a chimpanzee. The larger, more energy-intensive brain paid its way by allowing us to increase our energy budget, first and foremost through the ability to develop and use tools, which in turn helped us to obtain more food, build shelter and make clothing. Our more complex brains were therefore a success in evolutionary terms because they contributed to a net energy gain (Isler and van Schaik 2009).

While early humans displayed major differences of psychology and social organisation, from a purely energetic point of view they lived much like other mammals: to obtain food they relied exclusively on muscle strength and the elementary stratagems of hunting and gathering. The energy requirements of the hunt provided a powerful incentive to socialize. Since a lone hunter's chances of killing large animals were low, groups of hunters cooperated to pursue, trap, kill and slaughter an animal, and to transport the meat back to the settlement. As this was generally beyond the ability of a single family, hunter-gatherers formed larger social groups and shared the fruits of collective effort.

Those prehistoric societies that evolved amidst a plentiful food supply naturally saw a gradual increase in social complexity, up to the levels associated with the most advanced agrarian societies: permanent settlements, high population density, large-scale food storage, social stratification, elaborate rituals and early forms of cultivation.

Fire: The First External Energy Source

Tools allowed hominids to make the most of their muscle power by concentrating energy, but it was only when they learned to use and control fire that they were able to harness and manipulate an external source of energy. No other animal has done this. In this sense, the discovery of fire was a watershed in the evolution of humanity, marking the birth of what we might call *Homo energeticus* (Niele 2005). With fire, humans were able to cook food, warm

their surroundings and keep dangerous predators and insects at bay. Firelight also extended the productive day in winter. It is likely that hominids discovered fire by accident, as a result of lightning or wild-fires, and for several hundred millennia were able to use but unable to start it. This meant that fires had to be tended and maintained over generations.



From fire control to fire making.

The fossil record suggests that food may have been cooked as early as 1.9 million years ago, while the earliest reliable evidence for controlled use of fire dates to about 400,000 years ago. Roughly 100,000 years ago (David et al. 2009) humans learned to start fire at will, using either stones such as flint to create sparks or the friction of dry wood to create embers. By the start of the late Stone Age (about 40,000 years ago), human mastery of fire had advanced to the point of using lamps that burned animal fats (Smil 2006), and just a few millennia later humans were firing clay into pottery figures.

$$E + T = C$$

Twenty thousand years ago, the Earth was still in the grip of its most recent ice age. The polar ice caps extended southward to the latitudes of modern-day London and New York, and mammoth roamed the subarctic tundra of central Europe and Asia. Crouching in the sparse, wind-gnarled bushes, two groups of hunters, very different in gait and appearance, stared out into the open plains.

Humans and wolves competed for the same prey and both had social systems that enabled them to hunt in packs. They learned to fear and eventually respect each other, and they finally discovered the advantages of teaming up. Initially, this partnership was probably based purely on mutual advantage. For the wolf, the human use of weapons meant a share in a greater number of kills, and perhaps even an occasional taste of larger prey, such as mammoth. For humans, the wolf's speed and ferocity was the equivalent of a new weapon.

Not long after we began to keep and breed dogs as hunting partners, humans domesticated sheep and goats (ca. 9000 BCE), giving us a reliable source of energy in the form of meat and milk, and facilitating the move away from hunting and gathering to agriculture. Agriculture emerged independently in the Fertile Crescent, South Asia, Oceania, Africa's Sahel and several parts of the Americas, starting with the eight so-called Neolithic founder crops: emmer wheat, einkorn wheat, barley, peas, lentils, bitter vetch, chickpeas and flax (Brown et al. 2008). By 4000 BCE, agriculture was widely practised in many of the fertile regions of the world, and cattle, pigs, horse and dromedary camels had also been domesticated. Highly organised net fishing of rivers, lakes and ocean shores also brought in great volumes of food. So profound were the changes to human lifestyles brought by this new relationship to food energy, that anthropologists refer to this as 'The Neolithic Revolution'. Agriculture and the domestication of animals changed humans' energetic pathways and our cultural evolution. Not only did agriculture give us a stable and predictable food supply but, thanks to selective cultivation, it gave us varieties of plants with far higher energy yields than are found in the wild. A wild grain such as einkorn wheat converts only 0.3 per cent of the sunlight energy that strikes its leaves into biomass, while modern strains have conversion rates ten times higher.

Agriculture allowed humans to maintain a relatively stable environment, thus ensuring a more predictable future. It was this predictability that allowed us to develop complex social structures and

culture. The reduced daily pressure to secure food allowed humans to devote time to other pursuits: the refinement of tools and language, the construction of more permanent settlements, and the development of complex social relationships. In this way, agriculture is the most essential of all cultural achievements. Were we to try and express this in an equation to rival Einstein's, we might say that $E + T = C$, or energy (through an abundant food source) plus time (through the predictability of that energy source) begets culture.

Playing with Fire

For millennia, wood, dung and crop residues were the main fuel sources for heating and cooking. Indeed, these are still important domestic fuels in many countries. Fire was, of course, used not only for cooking and heating but also as a source of light. Oil lamps (burning animal and vegetable fats) have been used since the Paleolithic age (up to 40,000 years ago), while the more practical and versatile candle, using plant and animal waxes, was developed about 2,000 years ago. These remained the principal method of lighting right until the early nineteenth century (Smil 2006).

One of the main reasons wood was eventually replaced as a major fuel was its value for other applications, particularly as a building material and as the raw material for charcoal. Wood is made of lignin, which consists of carbon, hydrogen and oxygen. By superheating the wood, we can remove the hydrogen and oxygen atoms in the form of water (H_2O), leaving pure carbon. This is a vastly accelerated replication of what happens in the earth when coal is formed, hence the name of this by-product: charcoal. The ability to make charcoal was developed about 5,000 years ago. The importance of this discovery is that it provided a fuel with a greater energy density than wood. Charcoal also produces far less smoke, so it is well suited for indoor cooking. But by far its most significant application was in the smelting of metals, which opened the way for vastly more effective tools and weapons.

From Human Power to Horsepower

The desire for a more stable source of food led humans to domesticate wild animals; sheep and goats initially, followed by pigs, oxen and chickens. Humankind also realised that it could take advantage of certain animals' superior strength to pull sledges, ploughs and wheeled

wagons. Thus, about 6,000 years ago, the ox became our first beast of burden. A millennium later, the first wild horses were captured from the steppes of Central Asia and bred for food. Again, it wasn't long before this animal's potential as a source of labour was discovered and (literally) harnessed. By the middle of the second millennium BCE, horses were central to almost every human activity, from agriculture to industry and from trade to war. The horse accompanied us well into the industrial era, and as late as the 1930s, horse-drawn carts were a common sight in industrialised cities (Kavar and Dovč 2008).

Prime Movers

Humankind's quest for energy began with tools that concentrated our own muscle power; continued with the use of fire for heat, light and cooking; later involved the cultivation of secure, high-energy foods; and eventually led us to harness the muscle power of larger animals. The most recent leap forward has been the invention of machines that can run without the involvement of human or animal muscles. Scientists refer to such machines, which convert a naturally occurring source of energy into mechanical power, as 'prime movers'.

Around the third century BCE, the power of running water was first harnessed by the ancient Greeks. Over the next millennium, waterwheel technology spread throughout the Mediterranean and to most of Asia and northern Europe. While the design and efficiency of these machines improved steadily over time, medieval watermills had a power output of only a few kilowatts, roughly equivalent to a modern hair dryer. Nevertheless, the waterwheel remained the most efficient pre-industrial prime mover and was a key factor in Europe's technical supremacy during the early stages of industrialization.

The second most important pre-industrial prime mover was the windmill. Windmills were first used in Persia around the tenth century. As the name suggests, these were used to mill grain, and later to pump water for irrigation (Smil 2008). Despite these and numerous other innovations, the way energy was used did not substantially change from prehistoric times to the eighteenth century. By 1800, people were still using animal muscle for work and transport, animal and vegetable fats for lighting, biomass for heating and methods of agriculture that had not greatly changed for millennia.

This all changed with the Industrial Revolution. What began in England, thanks to plentiful and easily accessible coal reserves, spread to France, Germany, Italy and the United States, and eventually reached

Table 1.2. *The power of different prime movers*

	Early use	1800s	1900s	2000s
Waterwheel	< 1 kW	200 kW	400 kW	
Windmill	< 1 kW	100 kW	400 kW	
Water turbine		5 kW	10,000 kW	1,000,000 kW
Steam engine	4 kW	100 kW	5,000 kW	
Steam turbine		10 kW	1,000 kW	2,000,000 kW
Gas turbine			100 kW	200,000 kW

Source: Smil (2008).

most of the world. New machines and tools allowed, for the first time, thermal energy to be converted into kinetic energy, driving a wide variety of machines. While many of the applications, such as mining and weaving, had been practiced for centuries or even millennia, the new machines allowed for great advances in scale, speed and efficiency. Just as horsepower improved early farmers' ability to work the land, the harnessing of thermal energy through the steam engine, and later the steam turbine, allowed a leap forward in manufacturing.

The invention of the steam engine set in motion a chain reaction of innovation and consumption that continues to this day. As people moved from villages to cities to work in factories, their habits of energy consumption changed. European and American populations exploded in the nineteenth centuries, and so too did the pressure on existing energy resources. Just as we face the challenge of diminishing fossil fuel resources today, societies of the nineteenth century had to find ways to replace wood and organic oils, up to then the principal fuels for heating, cooking and light.

The first country in the world to break its reliance on biomass fuel was England. Because of the twin demands of building (ships and houses) and fuel (for industry and domestic needs), most of the great English forests had already been cut down by the mid-1500s. The only way to avoid economic collapse was to find an alternative fuel. That alternative was coal. Coal was not exactly a new discovery; it had been used as early as 200 BCE by the Chinese and in Europe since Roman times (Smil 2008, Smith 1997). However, until the emergence of the British coal-mining industry, coal was extracted only from outcrops or shallow seams. New inventions such as steam-driven pumps allowed for larger and deeper mines. From the second half of the sixteenth

century onwards, coal was mined extensively in England and Scotland, and by 1700 it had replaced wood as the main heating fuel. This early adoption of coal, and the resulting head start in terms of extraction methods and technologies, made Britain the cradle of the Industrial Revolution.

The development of railways allowed coal to be transported cheaply over long distances. Railways are an excellent example of how technical innovation exercised both a pull and a push effect on energy consumption: large amounts of coal were needed to produce steel for the railways, and the railways in turn allowed coal to be transported in bulk to the steelworks.

The Industrial Revolution changed not only the amount of energy consumed but also the way it was used. While coal sufficed initially as a fuel for locomotives, the internal combustion engine required high-energy liquid fuels. This led to the discovery of our most versatile fuel source to date: mineral oil. The ancient Chinese, Babylonians, Persians, Greeks and Romans had known about and used petroleum as a fuel for lighting and heating. However, it was not until the nineteenth century that mineral oil was used on an industrial scale. This was partly because it was difficult to extract, but also because it is dirty and inefficient in its raw state.

In preindustrial societies, most people were much less active at night. Candles and lamp oil were expensive and therefore used sparingly by all but the wealthy. Instead, people sat around fires at night, exchanging stories or performing stationary work such as mending clothes or tools. With the Industrial Revolution came a great migration into cities, rapid population growth, and the availability of much cheaper, factory-made goods. In cities, people were less inclined – and usually couldn't afford – to limit their daily work to the hours of natural light. The explosion in demand for lighting oil begat the whaling industry. Sperm whales yielded oils that burned far more cleanly and brightly than other animal fats did. By the time Herman Melville published *Moby-Dick* in 1851, the U.S. whaling fleet alone numbered 700 ships and was unloading 160,000 barrels of whale oil each year in the ports of New England (Smil 2008). As whale populations rapidly declined, coal gas and kerosene came to the rescue – of both the whales and the human consumers.

The world's first oil tycoon was neither a Texan cowboy nor an Arab sheik. Ignacy Łukasiewicz, a Polish pharmacist from the town of Gorlice on the fringes of the Austrian Empire, had experimented for several years with ways of distilling mineral oil. His breakthrough

came in 1853 when the local hospital borrowed one of his kerosene lamps to conduct an emergency operation at night. Impressed by how brightly and cleanly the lamp burned, the hospital placed an order for further lamps and fuel. Łukasiewicz soon abandoned his pharmacy business to concentrate on the commercial application of his discovery. Within ten years he was not only mass-producing kerosene and lamps but was also the owner of several oil wells.

The first large commercial oil fields were tapped in the Caucasus region in the late nineteenth century. By the 1930s all of the world's leading economies were heavily dependent on oil, and by the middle of the century many of the world's biggest oil fields had been discovered. Primary among these were the immense fields of the Persian Gulf region, which hold, by present estimates, two-thirds of the world's reserves. The discovery of major oil fields was accompanied by the invention of new transportation technology, in much the same way as electricity generation and supply later spawned the development of myriad new electrical devices. The age of mass mobility had begun.

Demand for Liquid Fuels

The development of fossil-fuelled transportation removed one of the greatest limitations on land transport. Until the nineteenth century, raw materials, goods and people could only be transported over land using the muscle power of horses, oxen or camels. This made land transport costly and slow, and as a result only high-value goods, such as silk, precious stones and spices, were transported this way. The reliance on animal power for land transport extended well into the twentieth century. Railways initially took over the function of long-distance transport over land, but the horse was still needed to transport goods and people within the rapidly growing cities of Europe and North America. By the end of the nineteenth century, there were 300,000 working horses in London, one for every twenty people (Smil 2008). However, once the internal combustion engine reached mass production (by the 1920s in Europe and North America), horses quickly disappeared from the streets of Western cities.

We tend to think of our modern dependence on oil largely in terms of gasoline, yet the role of oil in modern industrial economies goes far deeper. As well as providing the basis of most transport fuels, oil is also the raw material for most fertilisers and pesticides, various chemicals, plastics, artificial fibres, lubricants, tar and asphalt. A trip

to the supermarket by car relies on oil in many more ways than just the transportation fuel. First, there is the car itself, which, except for the chassis, engine and wheels, is largely made from oil-derived polymers. Second, the road on which we drive was probably constructed using asphalt. Finally, many of the clothing items, most of the packaging and much of the food we may buy at the store were produced with the direct or indirect involvement of mineral oil.

Most of us are aware of the importance of petroleum oil in satisfying the energy needs of modern civilisation, so it has become axiomatic to refer to our modern age as the age of oil. Yet it would be more correct to call it the fossil fuel age, since coal remains a much-utilised (and indeed growing) fuel for electricity production, and natural gas, the most recently harnessed of the fossil fuels, could soon rival oil in importance. A mixture of methane, butane, propane and other hydrocarbons, natural gas occurs either alongside mineral oil or dissolved within it. Like oil, natural gas has been known to humans for millennia, but it was even harder to utilise because of its form and volatility. The earliest known use of natural gas was in China during the Han dynasty (200 BCE), when it was siphoned from shallow underground pockets using bamboo tubing and used to boil seawater for salt production.

The first industrial-scale gaseous fuel was not natural gas, but town gas, a synthetic derivative of coal. Much of the street and domestic lighting in European and North American cities of the late nineteenth and early twentieth centuries was provided by town gas. Gasworks were an iconic feature of many industrialised towns and cities until the 1960s, by which time town gas had been largely replaced by electricity and natural gas. Three innovations were needed before natural gas could become a major household and industrial fuel: development of safe burners for mixing gas and air, wider high-pressure pipelines, and gas compression. Though a relative latecomer to the energy mix, natural gas has become the preferred fuel of the modern age for heating, cooking and electricity generation.

Energy at the Flick of a Switch

One could argue that we are still living through the Industrial Revolution, as most of our energy is still generated by burning fossil fuels. The main difference today is that we have added a new link to the energy conversion chain: electricity. The industrial generation of electricity represents an energy revolution in its own right. While the

ancient Greeks had some understanding of electricity, as reflected in the origin of the term, it remained a scientific curiosity until the early nineteenth century. Thanks to the work of scientists such as Michael Faraday and Thomas Edison, electrical power was generated and harnessed for a variety of purposes.

Faraday led the way by discovering electrical induction; that a magnet moving within a copper coil will generate electrical current. This paved the way for the first electrical turbines, capable of converting mechanical to electrical energy. Edison's contribution to the development of electricity was even more profound. Like James Watt, Edison was both a scientist and a businessman. This gave him a strong incentive to develop machines for generating electricity and to provide a commercial system to transmit and distribute it. Edison built and operated the first power station in the United States, and he invented numerous devices capable of using electrical current, most famously the incandescent lightbulb.

The great advantage of electricity over combustion fuels is that it is rapidly and efficiently transportable and can be converted to other forms of energy (mechanical, thermal, light, etc.) at relatively high rates of efficiency. Moreover, it is clean, and can be made available instantaneously – literally 'at the flick of a switch'.

Energy at War

The Battle of Mons was one of the first engagements of the First World War. It began in late August 1914 when British cavalry happened upon their German counterparts on the French-Belgian border. The British riders chased the Germans for several kilometres before dismounting and engaging them in a gun battle.

Imagine muskets or swords in place of rifles, and a very similar battle could have taken place several centuries, even millennia, before. Yet just thirty years later the technology of warfare had been transformed, driven by enormous investment in military research through two world wars, the second of which ended with the discovery and use of a vastly more destructive weapon than any hitherto known. J. Robert Oppenheimer, one of the scientists who led the Manhattan Project, said of this new technology: "It has led us up those last few steps to the mountain pass; and beyond, there is a different country" (Rhodes 2010, p 3).

Solar radiation is the result of the fusion of hydrogen atoms in the sun's core, producing helium. However, the helium released has a

slightly smaller mass than the sum of the hydrogen atoms. The 'missing' mass has been released as energy. This reaction was described in Einstein's famous formula $E = mc^2$. What this means is that the energy (E , expressed in joules) of any matter is equal to its mass (m , expressed in kilograms) multiplied by the speed of light (c) squared. Since the speed of light is immense (300,000 kilometres per second), the amount of energy theoretically contained in any kilogram of matter is similarly vast.

The discovery of nuclear energy opened up, as Oppenheimer foresaw, new horizons. Up to that time, most energy conversion involved combustion – first of biomass, then of fossil fuels. Nuclear energy represented a huge technological breakthrough: the ability to harness the most primal energy source of all – that of atoms and stars. Initially, many believed that this heralded an age of limitless energy. Lewis Strauss, chairman of the United States Atomic Energy Commission, claimed in a 1954 speech, "Our children will enjoy in their homes electrical energy too cheap to meter" (Smil 2010, p. 31). Strauss's claim was not as illusory as it may now appear. It was based not on the promise of nuclear fission, which relies on the relatively rare metal uranium, but on the belief that humans would one day harness the power of nuclear fusion, using the most abundant element on Earth, hydrogen.

The last great energy transformation of the twentieth century was the discovery, or rather rediscovery, of renewable energy. Until the Industrial Revolution, all the external energy sources used by humans – animal power, biomass, wind and water – were renewable. The rediscovery began with waterpower and the construction of large dams with turbines to produce electricity. In many countries hydropower played a major role in industrial development and urbanisation. Following the oil crises of the 1970s, there was also concern about energy independence and the future viability of fossil fuels. This greatly boosted research into energy alternatives. As a result, technologies such as wind turbines and photovoltaic (PV) solar panels, which had until then only been used for very specific and limited purposes (such as satellites), were developed for commercial use. By the late twentieth century, an additional impetus for renewable energy had emerged: concern about global warming and climate change.

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Praise for this book:

'... a beautifully written and illustrated, even-handed overview of renewable energy, looking at the problems as well as the potential, in a very accessible way ... an excellent guide to the choices ahead.'

David Elliot, The Open University, UK

'... clearly illustrates the opportunities and challenges inherent in replacing fossil fuels with renewable energy sources ... should appeal to a wide range of readers who want to know more about how they may be able to influence the difficult transition to a low-carbon energy future.'

Robert L. Evans, The University of British Columbia

'This sober and thorough introduction to energy use and sustainable options should be accessible to a wide selection of readers from high-school kids and non-science college students to political decision makers.'

Bent Sørensen, Roskilde University, Denmark

One of the most important issues facing humanity today is the prospect of global climate change, brought about primarily by our heavy dependence on fossil fuels. If we continue to use the present mix of fuels even as the world's economy and population grow we will invite very serious consequences. Common sense dictates that we switch to more renewable and sustainable sources of energy.

This book provides detailed yet easily understandable information about sustainable energy alternatives in the context of growing public concern about climate change, the impending fuel crisis and environmental degradation. It details the history of energy use and the factors that have led to the current interest in energy alternatives, and assesses the chances of renewable energy replacing fossil fuels.

The authors manage to make a highly complex and often intimidating subject not only accessible but also engaging and entertaining. This book unpacks but never simplifies the science of energy, leavening the more technical passages with anecdotes, metaphors, examples and imagery. By also dealing with the history, politics and economics of energy use, it offers both scientific and non-scientific readers a deeper understanding of one of the most important issues of our age.

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