Now for the Third Energy Revolution – it's Nuclear

Wade Allison, University of Oxford, UK wade.allison@physics.ox.ac.uk

The civilised world needs energy on a massive scale to support its population and standard of living. The laws of physical science show where that can come from. Any natural source needs to be primed by some agent and be stable enough to provide energy under control, whenever and wherever required. The science of energy is well established and offers solutions in just three groups widely separated in power: pre-industrial, chemical, and nuclear. At critical turning points in the human story a new group has been adopted and society has been completely transformed. Now is such a point with the decision to go carbon-free.

Turning back to a pre-industrial regime could not provide today's needs – "renewables" are not a viable principal source. The only option is nuclear with its million-fold superiority in energy density, its inherent physical control and natural biological safety. However the public are simply unaware of these exceptional benefits. In the past they have not been told the truth, sometimes for political reasons and at other times to promote exciting fiction. To establish the dominant use of nuclear energy the greatest challenge is educational, to provide a fully informed image of nuclear science in schools and the media and to overturn much of the precautionary culture of the past 70 years. Global climate change is a far greater threat than nuclear ever was.

The anxiety expressed by young people today about Climate Change is reasonable, but they offer no thought-out solution. We should examine the available scientific options in a form accessible to those without specialised knowledge and starting from what natural science has to say about energy and where to find it? (In the following precision is set aside to allow the science underlying the orders of magnitude to be clear and simple.)

Little has changed in our understanding of energy since the earliest years of the 20^{th} century. Even the extraordinary discovery of gravitational waves in 2015 slotted into Einstein's 1915 predictions without modification. Physicists are always hoping for the excitement of the unexpected, but that is rare. So what physics has to say about energy is not likely to change. Furthermore, it can be understood in simple terms.

Energy is conserved which means it cannot be created or destroyed, only moved around, changed from one form to another, concentrated or dispersed. So, the search for energy is about finding where it is concentrated, and any concentration of available energy we can call *fuel*.

Left to itself a boulder will roll downhill – dispersing its energy in motion, noise and destruction, for instance. There are two questions about a boulder on a hillside – as about available energy concentrations generally. Firstly, how did it get there? It must have been put there by a more powerful agent. Secondly what stops it rolling down out of control? Fuel needs to be stable and under sufficient control to deliver energy only when needed.

The concentration of energy in different fuels covers a truly vast range and we need to be quantitative, although roughly will do. Energy density can be measured in kilowatt-hours per kilogramme (kWh per kg), where kWh is the unit used on every electricity bill. How many kWh per kg are stored in a boulder at the top of a 100m high hill? Or equivalently in water retained behind a 100m high dam, which is more easily controlled? The answer is 100m×9.81=981 joules per kg, that is 1/3600 kWh per kg. The other familiar form of energy is rapid motion. For speed V metres per second the energy density is $\frac{1}{2}V^2$. At 30 mph this is 1/4000 kWh per kg, similar to hydro power. However much higher dams and very high speeds are not readily available and would be dangerous if they were. So these values of energy density are typical for the sources we see around us.

Life is in the business of managing change, and creatures get the energy to do what they want from their food. Today the energy density is often printed on the outside of the packet! For example, "381 kJ per 100 g serving" which is almost exactly 1 kWh per kg. Interestingly, this is over a thousand times greater than the values for the primitive hydro and kinetic energy described above. Where is this extra energy hidden? The true explanation was not apparent until the atomic structure of matter was revealed in the early years of the 20th century.

Meanwhile early in prehistory mankind used his unique intelligence to make use of fuel *external* to his own body. First, he used other creatures – oxen, horses, dogs – to provide added strength, speed and protection. Then he felled trees, made boats and used the power of the wind to travel the seas. Using wood and leaves as fuel he learnt to control fire, cook food, work with metals and survive better than other creatures unable to make this transition, his first Energy Revolution.

Although he gained supremacy over all other creatures his standard of living was appalling, life was short and the population remained small. Not only were the prehistoric “renewables” weak but they were unreliable. On top of seasonal, daily and geographic patterns of deprivation there were severe fluctuations for weeks and months at a time, that caused famine and destruction.

But then 200 years ago mankind used his intelligence to his second Energy Revolution. During the Industrial Revolution he learnt how to exploit fossil fuels, first by burning coal to make steam, and later by burning oil and gas directly. Their energy density is about 7 kWh per kg, a thousand times higher than for "renewables". But more important was their reliability, 24/7 “come rain or shine”. At least that was true for those with access to the fuel. A century and more of war and economic rivalry marked the struggle to secure this access. Nevertheless, the world population increased eight-fold, life expectancy doubled, and the standard of living improved beyond measure.

The energy of fossil fuels – and food – resides in the atomic structure of matter. All materials are made of atoms, all of similar size, $L = 10^{-10}$ metres across, that is one over ten thousand million. Each atom holds a number of electrons (mass m). It is the social changes of these electrons that hold or release the energy concerned. How large are these energies?

	Pre-industrial era (“renewables”)	**Industrial Revolution (chemical/carbon)**	**The future (fission and fusion)**
Fuel	water, wind, solar, vegetation	Coal, oil, gas and food	Uranium and thorium (and hydrogen)
Typical energy density (kWh per kg)	0.0003	1 to 7	20 million
Lifetime energy for one person (tonnes)	e.g. 10 million tonnes over 100 m dam	500 tonnes coal,1800 tonnes CO2 emitted	1 kg = 1/1000 tonne
Points in favour	Familiar, accepted	24/7 availability, standard of living	24/7 availability, compact, resilient, no harm to life or nature
Points against	Intermittent, damage to nature	CO2 emissions, poor safety	Popularly feared, unfamiliar, education lacking
Energy primed by	Daily sunshine	ancient sunshine	ancient gravitational collapse

To answer that question we should refer to Quantum Mechanics, a fundamental feature of science. It describes the behaviour of all matter in terms of waves, although only on the smallest scales does this make a noticeable difference. The electron waves have to fit in their atoms and, as shown by de Broglie in 1923, their wavelength is Planck's Constant (h) divided by the momentum of the electron. This means that these electrons have energies on the scale of $h^2/(8mL^2)$, which equals 4 volts. For a carbon atom that is an energy density 9 kWh per kg. All electronics, all batteries, all chemistry and all interactions with light – these all work with the behaviour of electrons in atoms on this energy and voltage scale. In fact there is little scope for variation by factors more than four or five.

Technologies that build on this story are highly developed and are fundamental to our modern world. The salient points are summarised in the column of the Table labelled Industrial Revolution. The problem with carbon and chemistry as a source of energy is the carbon dioxide waste that affects both atmosphere and oceans – an inevitable consequences of burning carbon fuels of any kind in air. The full extent of the damage this causes is not yet clear, although the world seems minded already to discontinue the use of carbon fuels as soon as possible.

The popular reaction has been to revert to the pre-industrial solution. But this was quite inadequate in pre-industrial times and remains just as weak and intermittent today. Attempts have been made in Germany and elsewhere to compensate for its weakness by harvesting its energy on a vast scale. Huge tracts of land are denied to nature by flooding, square miles of panels and enormous turbines. However, this cannot compensate for its intermittency and German carbon emissions have not fallen while its electricity prices have increased significantly. The effect on the environment is damaging in every way and the experiment is seen to be a failure. https://www.ft.com/myft/following/8fb0ab05-0e38-4bce-9e33-199b9b087c44

The human race used its intelligence to find a new answer twice before, once in prehistory when it learnt to harness external energy for the first time, and then again at the start of the Industrial Revolution. Now it must do so again.

Natural science has just one answer, and its extraordinary suitability is summarised briefly in the final column of the Table. But where does this solution come from? If chemical energy resides with the electronic atom where does this nuclear energy reside and why is it *ten million* times more concentrated than chemical energy? Strangely the same wave behaviour that successfully describes the energies of electronic technology also describes the nuclear scale.

At the centre of each atom there is a positively charged nucleus with a size L that is 100,000 times smaller than the atom, that is $L = 10^{-15}$ metres across. It is made of protons and neutrons, each with a mass 2000 times greater than an electron. The same argument giving an energy scale, $h^2/(8mL^2)$, for chemistry is applied to the waves of protons and neutrons in a nucleus but now with the appropriate values of m and L. The answer is 5 million times greater than for the electrons. That factor is the nuclear story! It means that 1 kg of fuel would suffice for all the energy needs of one person for a life time, instead of emitting 1800 tons of CO_2 by burning coal or releasing 10 million tonnes of water from behind a dam. Not only is the quantity of fuel needed minute, but so is the corresponding nuclear waste. This is a point that the media and other commentators seem unable to take on board.

But this raises a very challenging question. What agent in the Universe had an *even greater* energy sufficient to prime the nuclear fuel that is available today? In terms of the picture we had earlier: who rolled the nuclei up the hill? The answer is that the nuclei of uranium and thorium were created in events of gravitational collapse, such as supernovae, black holes and neutron star activity that occurred long before the Earth was formed. We know much about these today and see them happening elsewhere in the Universe although the basic ideas were understood already in the 1930s by Sir Arthur Eddington and others.

A last question that is no less important: what stabilises these nuclei and prevents them releasing their energy prematurely? Fire releases its chemical energy prematurely when it "catches alight", a seriously dangerous occurrence as seen recently at Grenfell Tower, Notre Dame and the fires in California and elsewhere. With an energy a million times greater the possibility of a nuclear catching incident seems prohibitively alarming. However complete reassurance is at hand, and not from some manmade regulation but from watertight physical principles that work like this. The huge electric field surrounding each nucleus with its positive charge and tiny size, means that nuclei can *never* meet one another – except once in a billion years at the centre of the Sun where they provide its energy. These celibate nuclei can do absolutely nothing – except rotate which is the motion detected in an MRI scan, curiously. However, a very few varieties are "up the slope" and can decay emitting radiation. Some are in our own bodies, others in rocks and soil. This is the natural radioactivity in which life has been immersed for billions of years.

Other than by radioactive decay or at the centre of a star the only way that nuclear energy can be released is with a neutron. Since this is not electrically charged it does not see the electric field defending each nucleus and may react with it to release energy. However, neutrons are unstable and decay with a half-life of ten minutes. So the key that can override nuclear safety gets thrown away! Free neutrons cannot last unless they are locked in a nucleus, so there are none. Such is the thoroughness of the physical safety of nuclear energy.

For life to survive in this natural radiation environment it had to evolve overlapping fool-proof ways to recover from the damage inflicted by low and moderate radiation exposures. Indeed, the whole design of cellular biology is based on the need to overcome the twin threats of oxygen and radiation, but that is a longer story. The point is that it is a happy one.

The public should realise that nuclear energy is more than a match to replace carbon with a plentiful energy supply, available at all times and all places. Fear of nuclear and its radiation is often used to provide entertainment and excitement, but that lacks a scientific basis. Nuclear energy is far safer than any other energy source as the record shows. Much precautionary bureaucracy needs to be swept aside and bonds of trust established through a new education, both for the public and for those young people needed to build and run enough new nuclear power stations throughout the world, both of present designs and those in development.

Worldwide scientific education and the replacement of fossil fuel plants by nuclear are the only realistic responses to Climate Change and evidently it is about to happen on a grand scale https://twitter.com/Atomicrod/status/1121002960106983424

Some accessible books for further reading

Sustainable Energy – Without the Hot Air Sir David MacKay, UIT Cambridge Ltd 2009
http://www.inference.eng.cam.ac.uk/sustainable/book/tex/cft.pdf

Radiation and Reason Wade Allison (2009) ISBN 978-0-9562756-1-5
http://www.ypdbooks.com/science-and-technology/1690-wade-allison-special-book-pack-YPD01882.html

Radiation and Health Thermod Henriksen (2015)
http://www.mn.uio.no/fysikk/tjenester/kunnskap/straling/radiation-and-health-2015.pdf

Nuclear is for Life, Wade Allison (2015) ISBN 978-0-9562756-4-6
http://www.ypdbooks.com/science-and-technology/1690-wade-allison-special-book-pack-YPD01882.html

30 April 2019