FLEET ARC CENTRE OF EXCELLENCE IN FUTURE LOW-ENERGY ELECTRONICS TECHNOLOGIES

FLEET Schools

Forces and Energy

This unit covers:

- What is energy
- Different forms of energy
- Conservation/transfer of energy
- Generation of electricity
- Critical thinking about the human use of electricity, its implications and the role of the scientists and society

Curriculum links

The resource content and activities are linked to the Australian curriculum. See following curriculum codes:

Yr 5 AC9S5I05
Yr 7 AC9S7U04; AC9S7I06
Yr 8 AC9S8U05; AC9S8I04; AC9S8I06
Yr 9 ACSSU182
Yr 10 ACSSU190; ACSSU229

FLEET researchers employ our understanding of energy to help develop atomically thin materials and electronic circuits for the next generation of energy-efficient electronics. The motivation for FLEET's research, outlined in the next section, is an important discussion for students to consider and it provides context for some of the experiments and critical thinking activities.

Learning outcomes

Students will understand the concept of energy and why it is crucial to our understanding of how everything in the universe works – from sub-atomic particles to the sun, galaxies, your mobile phone and the universe itself. Students will be able to think critically about their own and society's use of energy and about the concept of sustainable energy.

The broad learning components are outlined below

- What is energy and how we measure it
- An understanding of
  - Potential and kinetic energy and their various forms
  - The relationship between energy and work
  - Transfer of energy / conservation of energy and why this is the key to understanding energy
- How to apply a little bit of Newton's 2nd and 3rd laws
- An understanding of electrical energy
- How energy works at the quantum level
- Energy in society

The resource is divided into the following components:

- Energy and work
- Kinetic, potential, conservation and transformation
- Electricity and sustainable energy
- Quantum energy

The Activities are introduced and can be downloaded at the appropriate points in the content of the resource, but we have listed all of them here as well

List of all activities
1. What is energy
2. Energy and work
3. Balloon rockets
4. Potential energy
5. Kinetic energy
6. Double bounce
7. Catapults
8. Energy transfer How far does chocolate get you?
9. Thinking critically about digital technologies
10. Quantum energy: Mass, energy and the oscillating ruler

Energy and work?

What do we mean by energy?

Energy is the capacity of a physical system to do work or cause a change. We will examine what this means in detail below, but to help establish students' baseline understanding of energy get students to do Activity 1.

Get students to do [Activity 1, What is energy]

Why is understanding energy important?

When we design and build stuff important to society such as bridges, cars, electronic technologies, or even developing the optimum diet for humans, we need to understand energy and how it works, otherwise the bridges will collapse, the car's brakes won't stop the car in time and risk human lives, our electronic devices will use too much energy (contributing to larger energy bills and climate change) or keep blowing every fuse in the house, and human health would be compromised. In other words, understanding energy helps us understand how the universe and everything in it works.

What is energy?

There are lots of different forms of energy that we will examine further on, but we first need to understand what energy is. Energy is not something you can see, taste or smell, but we can measure its effect, that is, it is quantifiable. It is essentially a mathematical concept that, most importantly, helps us predict how stuff in the universe will behave, whether we are considering something the size of atoms or as large as the universe itself.
Remember energy is the capacity for something to do work or cause change in a system. A key part of this definition is the concept of work, but work is distinct from energy.

For example, work is apparent when parents tell children to clean up their room and move that box of toys or sport gear from the floor. When they (eventually) push that box across the floor to under the bed, work has been done. Their muscles have done work by exerting a force (pushing) on a box to move it across the floor. The box has done work when it moved across the floor. There is mechanical movement over a distance – muscles moved your arms a distance to push (apply a force to) the box, and the box moved from the floor to under the bed. Energy enabled this movement (work) to happen.

But where does the energy come from? Your muscles get their energy from the food you eat; the box gets its energy from your muscles pushing on it. How much work something can do depends on how much energy it has. But the food itself is not the energy; it is just the source of energy. For the box, its source of energy is the force applied on it by your muscles.

Activity 2 Energy and work. See also Powerpoint presentation

How do we measure energy and work?

The standard unit used to measure energy is the joule. The Calorie is another unit of energy you will come across and you often see on the back of food packets for consumers to use as a guide to the amount of energy available in the food.

How many joules or calories something has, tells us how much energy that something has. The more joules or calories something has, the more work can be done.

[There are a variety of units used to measure energy, for example, as well as the Joule and Calorie there is the British Thermal Unit (BTU) and horsepower.]

And now for some math (years 8-10)

Math can help explain the relationship between energy and work and we can calculate the amount of energy needed or used and how much work is done. We will keep it simple here.

One joule is equal to the work done by a one-newton force acting over a one-metre distance.

A Newton (N) is the force necessary to accelerate a mass of one kilogram at one metre per second per second. Think about the force it took to move that box of toys/sport gear. The heavier the box, the more force would have been required to move it. The further the box was pushed, the more work was done and the more energy was needed to do the work.

While we will stick to Joules here, as a comparison of units, one Calorie (C) is the amount of energy required to raise the temperature of one gram of water by 1˚ Celsius.

References:
https://www.britannica.com/science/energy and
https://www.physics.uci.edu/~silverma/units.html)

Work is done when a force (N) is applied to an object to make it move a certain distance. Thus, work is related to the force applied to something and the distance it moves or is displaced. This relationship can be expressed mathematically as
Work = Force × distance (or displacement)

As noted above, force is measured in Newtons and a force is essentially a push or pull applied to an object such as the box of toys or sport gear to push it under the bed. Distance or displacement is measured in metres. How far did the that box get pushed?

Therefore, work is measured in Newton metres (Nm). And 1 Nm (or one newton of force causing a displacement or movement in one direction of 1 metre) = 1 joule.

Or 1 joule (1 unit of energy) = 1 Newton of force moving an object 1 metre.

For example, let us say your you had to use 50 Newtons of force to push your box 3 metres across the room.
Work (W) = 50 × 3M.
=150Nm

Brain teaser: Does a stationary object – such as your box in the middle of the floor – have any forces acting on it?
Answer: Yes. Gravitational force pulls the box toward the floor and there is an opposite and equal force of the floor pushing back on the box. We know that gravitational force exists because things fall if you drop them from a height. But without the force from the floor opposing the gravitational force, your toy box would keep falling toward the centre of the Earth. In this case, the forces are balanced and the box does not move. When one force (a push or pull) is greater, you will get movement over a certain distance. When something exerts a force (an action) in one direction there will be an equal action in the opposite direction. This is Newton's 3rd law of motion See Activity 3 Balloon Rocket activity and the Home Science version here

Science Asylum video, What the heck in energy

Kinetic, potential, conservation and transformation

Forms of energy

The two broad forms of energy are potential and kinetic and each have different types, which we outline in more det ail below. Others energy forms include sound and thermal energy. We will focus on potential and kinetic here. Light could also be considered a form of energy, but it gets interesting because is has both particle and wave-like properties. In the context of electromagnetic radiation, which ranges from radio to gamma waves, it is all just light with different amounts of energy. For an in-depth look at light, See FLEET Schools teacher resource, Light: reflection, refraction, diffraction.

Potential energy: This is the energy associated with either the position of an object and the forces being exerted on it (e.g., a skateboarder stationary at the top of a ramp), or its structure (e.g., the chemical bonds in different molecules). The many types of potential energy include gravitational, chemical and elastic. Each can be defined in different ways. Collectively, however, potential energy represents the potential that something has to do work.

The skateboarder positioned at the top of the ramp (stationary) has potential gravitational energy. When they lean forward, however, and start hurtling down the ramp, that potential energy is transformed into kinetic energy – movement.

Activity 4 Potential energy. See also Powerpoint presentation

Kinetic energy: Kinetic energy is movement, or the energy of a moving object. To get an object to move we must apply a force. The amount of kinetic energy something has is dependent on its mass and velocity (how fast it is moving). The greater the mass and velocity, the greater the kinetic energy. If something is not moving then it has no kinetic energy.

We can express this relationship between energy, mass and velocity mathematically:
Kinetic energy = $\frac{1}{2}mv^2$
Where m=mass (kilograms) and v=velocity (m/sec).

Students can explore this relationship in more detail in Activity 5 Kinetic energy. See also Powerpoint presentation.

Question: What other famous equation describes a relationship between energy, mass and speed?
[E=mc2]. Way back in 1907, Einstein published his paper that described the now famous equation to describe the relationship between energy, mass and the speed of light (velocity). This equation changed how we think of energy and inertia (matter and movement – or lack of, as the case may be). [We will examine this and another not so famous equation in Quantum energy below]

Transfer of energy and Conservation of energy

There are two really important points to make here: Energy has many forms, but we cannot create or destroy energy – it is conserved. And, for energy to do work it needs to transform from one form to another. These points are probably more important than understanding what energy is because how energy changes allows us to predict how things will behave in the system we are studying, whether that system is at the atomic scale or the universe itself.

Conservation of energy
The conservation of energy is underpinned by the 1st law of thermodynamics, which simply means that the entire energy of the universe is conserved or remains constant. We can only use the energy that already exists. If we use energy to do work such as move a box or skate down a ramp, the energy does not disappear; it is not used up. The energy used to do the work is just transformed into other forms of energy. We will examine how this happens in some of the activities coming up.

A cool thought: From the moment of the Big Bang when our universe was created, all the energy generated at that moment has remained constant since then. No more energy created; none lost.

Transformation of energy

Let us use potential energy as the starting point here, though it could be any form of energy. For example, living things such as humans and plants have potential energy in the chemical bonds in the fats, carbohydrates and sugars stored in the body. Batteries have a different form of potential chemical energy, in the form of their charged particles stored in the two halves of the battery (the positive and negative).

To do work, we need to transform that potential energy into another form. But remember the total amount of energy in the system remains unchanged. It is conserved.

Unfortunately, not all the energy in for example the chemical bonds in fats or carbohydrates, or the battery, is used to do the work we want. There are inefficiencies in the systems. Think about when you use your laptop or mobile phone. They need electrical energy to do work (compute stuff, give off light, sound and heat). You will notice your laptop and phone getting hot if you use it for more than a few minutes. This is caused by electrical resistance, which happens when electrons flowing through a circuit (kinetic energy) interact with the atoms in the circuit. Some of the kinetic energy in electrons transfers to the atoms, which makes them jiggle a lot more and give off heat. This heat energy cannot do useful work for us and it is wasted energy. For an in-depth look at electricity and circuits check the FLEET Schools resource, Electricity, conductors and insulators.

Students can test out the impact of the transfer of energy in the following hands-on activities:

- Activity 6. Double bounce
- Activity 7. Catapults
- Activity 8. Energy transfer. How far does chocolate get you?

See also Powerpoint presentation

Imagine if we could generate electrical energy without losing energy as heat? FLEET is conducting research to achieve just this with the objective of increasing the energy efficiency of digital technologies such as your mobile phones, computers, and more importantly the energy-hungry data centres that process most of the information we create with our devices. Read more detail and discuss this in the next section, Electricity and sustainable energy [link]

Read more about FLEET research here.

Video : Story of FLEET research

Next up. Electricity and sustainable energy. Students get to examine the specific form of energy that is arguably one of the more useful forms for humans, electrical energy. The relevant activity is a critical thinking exercise to get students to consider how we use energy and what are acceptable means to achieve sustainable energy use.

Electricity and sustainable energy

Electrical energy

Electrical energy also has many forms. For example, lightning, is a form of static electricity. You witness static electricity also when you rub a balloon against your hair. One of the most useful forms of electrical energy for humans is when it is generated from a current, which occurs when electrons flow through a circuit. It is the form that we use to power all our devices such as computers, TVs, phones, smoke alarms and electric vehicles. In whatever form electrical energy takes, it involves the movement of electrons in one direction. Learn more about electricity and how it is generated in our unit on conductors, insulators and electricity.

Electrical energy is a form of potential and kinetic energy. A charged particle such as an electron has potential energy when it is stationary within its atom. (Note: an electron is never really stationary. They always jiggle a bit, even when cooled to near absolute zero (Absolute zero = -273˚ Celcius.) If we apply a force, such as the chemical energy from a battery that is connected to a conducting material that is part of a closed circuit, the electrons move in one direction through that conducting material and generate a current (See more on this here). The electrons now have kinetic energy. We measure electrical current in amperes (amps), which is the rate that electrons move through a circuit. The higher the rate of electrons passing through a circuit, the higher the amps and the higher the amount of electrical energy is generated. One ampere of current flowing through a circuit for a second with one volt applied is equivalent to one joule. However, while the moving electrons have kinetic energy, it is not the energy that is powering your electronic devices. The flow of electrons (charged particles) is just what enables the electric energy to flow, which is generated from the electric fields generated by the battery and the surface charges on the circuit once the circuit is closed. What is happening here is quite complex and nuanced as evident in a debate that arose from a thought experiment created by Derek Muller from Veritasium, which sparked a series of follow up videos, many refuting Derek's conclusions. This led to this follow up video from Derek, which explains what is happening in a circuit quite well.*

*The Science Asylum also has a good explanation of where energy comes from in a circuit. *Note these two videos are pitched at approximately year 10 and higher

World, we have a problem

We use electrical energy to power all our electrical equipment that the world now relies on. A lot of that electrical energy is consumed by digital technologies – or computing. That is, anything with a computer chip in it, which today includes cars (about 100 in a modern car), doorbells, cameras, fridges, toasters, coffee makers, watches, phones, oh and computers…..so many things.

The proportion of global energy consumed by digital technologies is continuing to increase rapidly each year and is predicted to soon become unsustainable. That is, the world won't be able to generate enough energy to meet the energy demand from digital devices. This is the motivation for FLEET's research. FLEET is developing novel materials at the atomic scale that will conduct a current without energy loss.

Remember the heat you feel from your laptop or mobile when you use it? That is lost or wasted energy. What would the implications be, if we could conduct electricity without resistance (energy lost as heat)? Essentially, you would require less voltage or initial energy to do the work required. For example, if your device requires X Joules to do the necessary computation, then you need to generate the equivalent of X+1 Joules because the +1 will get lost as heat in the circuits. Or instead of using a 9 volt battery, you only need a 1.5 volt and the battery might last longer before needing to be replaced.

These novel materials will be used to replace silicon in transistors (the brains in your computer chip), circuits and memory storage devices. For more detail about FLEET's research and the research problem we are tackling see here.

To get students to consider how we use energy and what are acceptable means to achieve sustainable energy use, they can do the critical thinking exercises in Activity 9.

Energy and Power

Students will likely associate the concept of energy with power. Power and energy are different concepts. As noted, energy is the ability to do work or cause change. For example, lifting a weight in the gym requires a certain amount of energy to be available; a battery, or an item of food we could eat will hold a certain amount of energy.

Power, on the other hand, is the rate that the energy is used or transformed from one form to another. For example, to lift a weight your body will burn a certain number of calories (energy) per minute or hour (time). A light bulb will use a certain amount of electrical energy per unit of time to provide the necessary light. The heavier the weight or more intense your workout, the more energy per unit of time you will use. The more powerful the light bulb, the more energy (watts) it will consume per unit of time. The power is the amount of energy used per unit of time. Or, it is the rate at which work is done.

While this resource will not cover in any detail the difference in power and energy, it is an important distinction for students to understand.

Ok, now it is time to examine energy from the quantum perspective because it is what underpins so many of the technologies that we interact with on a daily basis – from solar panels to your smart phone.

Quantum energy

Checking out Einstein and going quantum

Quantum and classical physics both have the concept of energy in common. The conservation of energy still applies in quantum physics the same way it does in classical physics. The difference is in the math used to calculate energy and work. In quantum physics it is all about probability – the energy something has is a probability rather than a precise number. It comes down to the concepts of wave functions which is beyond the level of this resource. For advanced students in year 10+ they might be interested in Parth G's examination of quantum energy.

For this resource, wave functions are important, but only in the context that at the quantum level, particles have a wave-like behaviour, which we examine at the level of the electron and what happens to the wave function and mass when we change the energy of electrons. And this is where $E = mc^2$ and the other not-so-famous equation come in.

Light exists as a wave and a particle (or a tiny quantized packet of energy called a photon). Light's energy is described in that not-so-famous equation E=hf that together with the definitely famous $E = mc^2$ underpin our understanding all forms of energy and indeed how the universe works.

For E = hf
E = energy
h is Planck's constant ($= 6.6 \times 10^{-34}$)
f is the frequency of the light.

Similar to a water wave, a light wave has a momentum (movement) in a particular direction, but it is the energy that propagates forwards rather than anything physical. The energy in light can change the properties of materials. Indeed, FLEET exploits this ability to shift materials between a conductive and insulative state, something they hope will be useful to help develop the next generation of low-energy electronics. The energy in photons (ie light behaving as a particle) is also responsible for the production of electrical energy in solar panels.

Find out more about light in our unit, Light, Reflection, Refraction and Diffraction.

In Activity 10, students can do a hands-on activity that demonstrates the results of a recent experiment that showed for the first time, how energy affects the mass of an atom. The experiment has implications for greater precision in how we measure the effects of energy that could help unravel big mysteries of our universe such as dark matter.

The content and support material in Activity 10, Quantum energy: Mass, energy and the oscillating ruler, are adapted from a unit developed by Einstein First and presented in the Shachar Boublil and David Blair (2023) paper.

$E = mc^2$ indicates the proportional relationship between energy and mass. This is evident even at the quantum scale, a phenomenon recently demonstrated by researchers at the Max Planck Institute (Germany) who showed that photons, even though considered massless can, when absorbed by an atom, add mass to that atom. The atom will lose that mass when the photon is later emitted (Schüssler R X et al 2020).

The experiment in Activity 10 is a classroom version of the experiment that the Max Plank researchers conducted to determine this. In the real experiment, the researchers used light (photon) of a specific energy (determined by E = hf) and detected the change in an atom's vibration frequency when it absorbed or emitted the photon. This change in frequency was a demonstration of $E = mc^2$ because it showed that energy (in this instance, the energy of a photon) will affect mass (in this instance, the mass of an atom). This was a multi-million dollar experiment using highly sensitive equipment. We will use plastic rulers and a small weight to demonstrate how energy affects mass.

How did they do it: In short, the researchers had to cool their atoms down to an extremely cold temperature and trap them in a magnetic and electric field to stop them vibrating all over the place and colliding with each other and therefore emitting a whole bunch of different frequencies in the process. Cooled and trapped, the atoms are mostly still emitting a single measurable frequency. The researchers then measure the frequency of the atom after it absorbed a photon then again once that photon was emitted. The atom's frequency is lower when it absorbs the photon and increases when it is emitted. The increased weight of the atom causes its frequency to become lower and this is what the Max Planck researchers measured. Shachar Boublil and David Blair (2023) give a great description of the method the researchers used by the Max Planck researchers to demonstrate this phenomenon.

What does it all mean? Or, so what!

Apart from being the first researchers to successfully measure the miniscule change in the mass of an atom when it absorbs a photon (as predicted by Einstein, but never demonstrated until now), this research has also opened the door to new ways to increase the accuracy of atomic clocks. Why do we need to do this? Because greater accuracies in how we measure time enable us to measure with greater precision what happens when energy effects a change in a system. Building the most precise timekeepers ever imagined can help unravel big mysteries of our universe such as detecting dark matter and to build the next generation of quantum technologies.

Cool fact: the latest atomic clocks are so precise that they are (allegedly) out by just a second every 15 billion years. Read a bit more about NASA's spin-off tech from better atomic clocks.

The Einstein-First Project is a program run by researchers from the University of Western Australia who work with the Gravity Discovery Centre, Ozgrav and the LIGO Scientific Collaboration. This project is a part of the Einsteinian Physics Education Research (EPER) team that involves researchers from Norway, China, South Korea, Italy, Germany, Britain and the United States. The Project teaches the fundamental concepts of modern physics to school students and works to improve STEM involvement in the classroom. They have some really cool resources for teachers and students and I encourage you to check them out.

References

Shachar Boublil and David Blair (2022) Model experiments and analogies for teaching Einsteinian energy, *Physics Education*, **58** (1) **DOI** 10.1088/1361-6552/ac96c0

Schüssler R X et al 2020 Detection of metastable electronic states by Penning trap mass spectrometry *Nature* **581** 42–46