

As renewable energy grows and **fossil fuels** decline there will be increasing need to store **renewable energy** so that peak demands can be met.

## Background

Between 1990 and 2017 the world population increased from 5.3 billion to 7.6 billion, i.e. a 43% increase. During that same period demand for electricity more than doubled worldwide while in the EU it grew by 26%.

Until 2005 over 99% of global electricity was generated from fossil fuels (burning coal, peat, oil or gas), **hydro** and **nuclear energy**. Since then the contribution to electricity generation from other energy sources has increased from about 1% to 6.7% globally and from 2.6% to 15% in the EU. These contributions are expected to increase significantly.

## Meeting demand

On a large scale the demand for electricity varies during the course of the day and from season to season in fairly predictable ways. When demand is low some power stations might be taken off the **national grid** to be brought on stream again when higher demand is expected. Hydro power is particularly useful for meeting short term peaks in demand.

Like hydro power, wind and solar power are renewable forms of energy. However, unlike hydro power, wind and solar power cannot be turned on just when required. They vary with the weather and time of day in sometimes unpredictable ways. **Wind turbines** typically require a minimum wind speed of around 10 km/h (3–4 m/s) and **solar power** cannot operate at night.

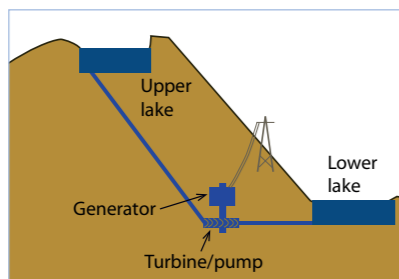


15 MW Solar power facility in Nevada, USA

## Is it possible to store energy?

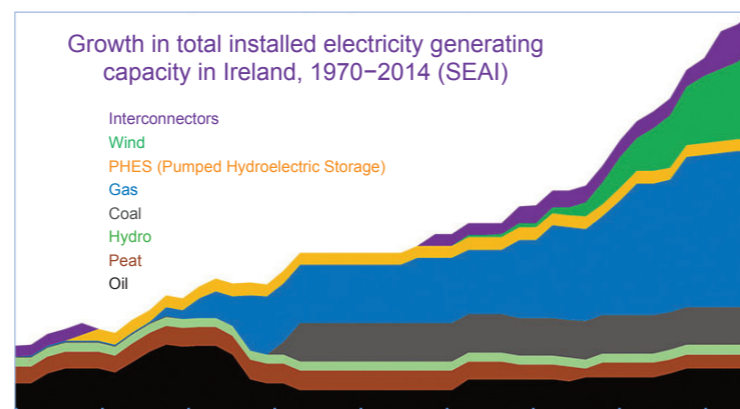
Energy can be stored in many ways. For small scale requirements such as a mobile phone, energy can be stored in a rechargeable battery (as chemical energy).

For large scale energy storage the **gravitational potential energy** of water is widely used. At night when electricity demand is low the electricity output of a power station can be used to pump water from a low level to a storage facility at a higher level. For example, at Turlough Hill (1974) in Co Wicklow water is pumped to a hilltop lake when demand is low; then when there is a peak in demand the water is allowed to return to the lower lake, generating almost 300 **MW**. The power station can go from standstill to full power in 13 seconds, in contrast to fossil fuel plants which can take several hours to achieve full power because they have to boil water to produce steam to drive the generators.



## Changes in electricity generation

In 1929 the newly commissioned 85 MW hydroelectric power station, at Ardnacrusha on the Shannon, met almost 100% of the electricity needs of the country. Today it can supply less than 2% of the peak demand (> 4500 MW). In the past 90 years our electricity generating capacity has grown dramatically (see graphic).



Over the rest of this century it is expected that the use of fossil fuels for electricity generation will decline and that the contribution from solar and wind will increase. However, the unpredictable nature of these **renewables** will make energy storage all the more important.

## Pumped hydroelectric energy storage (PHEs)

This is a proven technology, as outlined above, which today accounts for about 99% of global energy storage. PHEs combines high **power** with large **capacity**. At present there is only one PHEs facility in Ireland (Turlough Hill). The overall **efficiency** of PHEs is around 75%.

Although most PHEs plants use freshwater, some using seawater have been evaluated and others are planned (e.g. Okinawa, Hawaii, Chile, Australia).

## Compressed air energy storage (CAES)

In compressed air energy storage (CAES) air is pumped in a large sealed space (e.g. a disused mine) where it is stored at high pressure (e.g. 70 atmospheres). As it is released it drives a **turbine** generator.

CAES can be comparable to PHEs – in terms of energy storage – and is generally much less conspicuous. However, it is not as efficient.

When air is compressed it becomes hot; this effect is very obvious to anyone who has pumped a football or a bicycle wheel. While the compressed air is stored it gradually cools to the **ambient temperature**. When it is released it cools below the ambient temperature and does not expand to the volume it originally had. So overall efficiency is generally less than 50%.

A 290 MW CAES plant has been in operation in Huntorf, Germany, since 1978 with an overall efficiency of about 41%. A 110 MW plant in McIntosh, USA, has been operating since 1991 with an overall efficiency of about 54%. Various methods have been devised to boost the efficiency of CAES by storing the heat produced during compression in order to return it to the air during decompression.

## Thermal energy storage (TES)

There are many ways of storing heat (thermal energy) for use at some later time ranging from hours to days or even months. Installed TES systems use a wide variety of storage materials including:

- molten salt, e.g. Delingha (China); 135 MW; (2016). Also Crescent Dunes Solar Energy Project (California); 110 MW (2015)
- thermal oil, e.g. Solaben 1, 2 & 3 (in Spain); 50 MW each; (2012)

The stored heat can be used for district heating systems or may be used to generate steam to drive electricity generators.

Many other heat storage technologies are currently being investigated.

## Batteries

In the past, batteries were only suitable for storing small amounts of electricity, such as in mobile phones. Improvements in technology in recent years have now resulted in the development of large, grid scale batteries. Batteries provide a direct storage and retrieval system for electricity and are ideal for matching supply to fluctuating demand, particularly in more isolated areas such as island communities. A good example is Kodiak Energy Association (KEA) in Alaska, which installed a 3 MW system in 2012 using **lead-acid batteries** but upgraded it to **lithium-ion batteries** in 2017. Globally, lithium-ion batteries are increasingly being used in preference to lead-acid batteries. However, with decreasing costs for the technology, larger batteries on bigger systems are now being manufactured. This includes multiple grid-scale batteries being installed in Europe, Asia and America, with a 100 MW unit recently installed in South Australia.

## Flywheel Energy Storage (FES)

A flywheel is typically a heavy well balanced wheel. Once it is spinning it has rotational kinetic energy. The faster it spins the more energy it has.

In a flywheel energy storage system an electric motor sets a cylindrical mass spinning. When energy is required the spinning mass turns the motor which then acts as a generator.

Europe's first FES is in Rhode, Co Offaly. It is a hybrid system (flywheel + batteries) with a power of 240 kW.

## Load balancing and frequency matching

It is often not feasible to completely switch off generators that are driven by steam turbines and so it is important to store as much of the energy as possible. For the national grid the most important role of energy storage is **load balancing**, that is, topping up the supply when the demand is high, particularly when there are short-term 'spikes' in demand.

In Ireland (and in Europe generally) the electricity supply uses **alternating current** (AC) which has a frequency of 50 **hertz**. All power stations on the national grid must match that frequency to ensure that the system remains stable, and the frequency of the system remains as close to 50Hz as possible.

Wind turbines do not all spin at the same speed and in order to integrate them into the system their output is first converted to **direct current** (DC). This is then converted electronically to alternating current at the correct frequency (50 Hz) and the correct **phase**, i.e. the output is exactly in step with the mains voltage.

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## Syllabus References

The main syllabus references for the lesson are:

### Leaving Certificate Physics

- Different forms of energy.
- Conversions from one form of energy to another.
- Principle of conservation of energy. (p. 9)
- Energy stored in a capacitor (p. 17)
- Structure and principle of operation of a simple a.c. generator.
- Conversion of a.c. to d.c. Practical applications. (p. 44)
- Heat capacity, specific heat capacity. E.g. Storage heaters (pp. 11, 29)

*Science and Technology in Action* is also widely used by Transition Year classes.

## Learning Outcomes

On completion of this lesson, students should be able to:

- Explain why there is a growing need to use renewable energy sources instead of fossil fuels
- Explain how energy storage can be used to make the best use of wind and solar energy
- Outline how the major energy storage systems operate
- Outline how renewable energy sources can be integrated into the national grid
- Explain why energy storage systems are not 100% efficient
- Explain what is meant by 'load balancing'.

## General Learning Points

These are additional relevant points which are used to extend knowledge and facilitate discussion.

- The global demand for electricity is increasing at a faster rate than the population increase.
- As fossil fuels are depleted more renewable sources will be needed.
- Electricity cannot always be generated when required using wind and solar energy. Storage of energy can help when there is not enough, even if it is not 100% efficient.
- There are many ways of storing energy. Pumped hydroelectric energy storage (PHES) is the most widely used method.
- Many newer energy storage systems are being developed. Some are best for meeting short-term spikes in demand while others can be online for several hours or even days.
- The national grid uses alternating current. To integrate any electricity generator into the grid its output must have the correct voltage, frequency and phase.

## Student Activities

1. If one kilogram drops a distance of one metre its potential energy is reduced by 9.8 N m (i.e. 9.8 J). How much energy is stored in 2,000,000 cubic metres of water that is pumped to a storage lake 500 metres higher up? (Note: The density of water is 1000 kg m<sup>-3</sup>.)
2. Show that an angular velocity of 1000 rpm (revolutions per minute) is equal to about 105 radians per second (rad s<sup>-1</sup>). (Note: A full circle is 2π radians)
3. Flywheel energy: The rotational kinetic energy ( $E$ ) of a uniform solid cylinder is given by:  $E = \frac{1}{2} m r^2 \omega^2$ , where  $m$  is its mass (kg),  $r$  is its radius (m) and  $\omega$  is its angular velocity (rad s<sup>-1</sup>). If a cylinder of diameter 1 m and mass 5500 kg spins at 15,000 rpm, what is its rotational kinetic energy?
4. A flywheel is used to drive a 250 kW generator. If the total energy of the flywheel is 3 GJ how many minutes will it take to reduce its energy by 10%.
5. Make a poster or computer presentation to summarise the main methods used to store energy for electricity generation.
6. Coal-fired and oil-fired power stations generally operate at full capacity and are shut down only for maintenance. Find out how electricity demand varies during the course of the day (in summer or in winter). How is the supply adjusted to meet the varying demand?



## True/False Questions

- a) Since 1990 the population has increased by 43% but the electricity demand has increased by more than 100%. T F
- b) Hydro, wind and solar power are renewable energy sources that can supply all the energy needs of the country. T F
- c) Because wind and solar power are not available all the time the energy must be stored in some way until required. T F
- d) The national grid uses alternating current. T F
- e) The output from wind and solar generators can be linked directly to the national grid. T F
- f) Pumped hydroelectric energy storage (PHES) is the most widely used large scale energy storage method. T F
- g) Batteries store chemical energy. T F
- h) Flywheels store electrical energy. T F
- i) CAES is more efficient than PHES. T F
- j) Energy storage systems are widely used to supply electricity when the demand fluctuates rapidly. T F

Check your answers to these questions on [www.sta.ie](http://www.sta.ie).

## Examination Questions

### Leaving Certificate Physics (OL) 2013, Q. 11

- (a) What are the key components of the national grid?
- (b) Why are high voltages used to transmit power over the national grid?
- (c) Why is the power supplied to domestic customers at lower voltages?
- (d) Name two renewable and two non-renewable energy sources used to generate electricity.
- (e) The national grid uses alternating current (a.c.) rather than direct current (d.c.). What is the difference between them?
- (f) Name the device used to convert high voltages to lower voltages.
- (g) Give the principle of operation of the device named in part (f).
- (h) Name the unit of electrical energy that is used in the delivery of electricity to homes and businesses.

### Leaving Certificate Physics (OL) 2005, Q. 11

- (a) Define energy.
- (b) What energy conversion takes place when a fuel is burnt?
- (c) Name one method of producing electricity.
- (d) Give one factor on which the potential energy of a body depends.
- (e) What type of energy is associated with wind, waves and moving water?
- (f) Give one disadvantage of non-renewable energy sources.
- (g) How does the sun produce heat and light?
- (h) In Einstein's equation  $E = mc^2$ , what does  $c$  represent?

### Leaving Certificate Physics (HL) 2012, Q. 11

... The power  $P$  of the wind can be calculated from  $P = \rho Av^3$  where  $\rho$  is the density of the air,  $A$  is the area the wind acts on and  $v$  is the speed of the wind. In theory it is possible to extract 58% of this energy in a wind turbine. ...

- (a) What is the effect on the power of the wind if the wind speed is doubled?
- (b) Why is it not possible to extract all of the energy in the wind striking a wind turbine blade?
- (c) What is electromagnetic induction?
- (d) How is the output voltage of a wind turbine changed to 230 V a.c.?
- (f) What is the tip speed (the linear velocity of the outer end) of a blade of radius 30 m when it completes a revolution every 3 seconds?
- (g) Small scale wind turbines are sometimes used to charge batteries. The a.c. output voltage has to be converted to a d.c. voltage. How is this achieved?
- (h) Name one other renewable source of energy.

## Did You Know?

### Cost of renewables versus fossil fuels

- To meet the growing global demand for electricity new generation facilities are built every year. Since around 2016 the capacity of new renewables exceeds that of new fossil fuel capacity.
- Many forms of renewable energy are already more economic than fossil fuels: biomass, geothermal, hydro and onshore wind. In the next two years or so it is estimated that photovoltaic and offshore wind will also be more economic. (International Renewable Energy Agency [report](#): *Renewable Power: Sharply Falling Generation Costs.*)
- The EU as a whole is well on track to produce 20% of its total energy from renewables by 2020. Although Ireland has a lower target (16%) it seems that it will be challenging for us to meet it. This could cost the country €75m per annum in penalties.

## Biographical Note

### Rechargeable batteries

The **lead–acid** battery, invented in 1859 by French physicist Gaston Planté, is the oldest type of rechargeable battery. It is still widely used in petrol and diesel motor cars. Lead–acid batteries are very heavy but they can supply the large currents necessary to start a car (e.g. 40 A). They hold their charge quite well and are relatively inexpensive.

The **nickel–cadmium** battery (**NiCd**) was invented by Waldemar Jungner of Sweden in 1899. It uses nickel oxide hydroxide and metallic cadmium as electrodes. Because cadmium is toxic, NiCd batteries have been almost completely replaced by nickel–metal hydride (**NiMH**) batteries (beginning about 1989).

The **lithium-ion** battery was introduced in the market in 1991, is the choice in most consumer electronics, such as laptops, tablets and mobile phones. They have excellent energy density and hold their charge quite well when not in use. Improved types continue to be produced. (See Wikipedia for further information.)

## Revise The Terms

Can you recall the meaning of the following terms? Revising terminology is a powerful aid to recall and retention.

alternating current, ambient temperature, capacity, direct current, efficiency, fossil fuels, gravitational potential energy, hertz, hydro, lead-acid battery, lithium-ion battery, load balancing, MW, national grid, nuclear energy, phase, power, renewable energy, renewables, solar power, turbine, wind turbine.

Check the Glossary of terms for this lesson on [www.sta.ie](http://www.sta.ie)