UNIT 4

WORK, ENERGY AND POWER

Unit outcomes: **After completing this unit you should be able to:**

- ✓ **understand concepts related to work, energy and power.**
- ✓ **develop skill of manipulating numerical problems related to work, energy and power.**
- ✓ **appreciate the interrelatedness of all things.**
- ✓ **use a wide range of possibilities for developing knowledge of the major concepts with in physics.**

Introduction

In the last three units you learned some properties of physical quantities, measurements of physical quantities, their SI units, motion of bodies, force, and relationship between force and motion. In this unit you will learn the concepts of work, energy, power and the relationship among them. What is work? How do you define energy? People commonly think of work as being associated with doing something. But now, you will go through the scientific meanings of work, energy, power and their relationships. The term energy has a much wide scope than it will be implied in this unit. Energy in this unit is limited to mechanical energy that is kinetic energy and potential energy.

4.1 Work

Activity 4.1

Discuss the following questions with your friends.

i. What is work in a day to day life and in physics?
ii. When do we say work is done?
iii. Explain the term 'work' especially from the point of view of science/physics.

From the discussion in Activity 4.1 you might have come across different meanings of work.

The usual meaning of work is quite different from the scientific meaning of work. In every day activity, the term work is used equally for mental work and for physical work involving muscular force.

Identify the following activities as: work is done and work is not done.

- You may read a book,
- Engage yourself mentally in thinking about a simple or difficult problem;
- You might be holding a weight with out moving, or carrying a load and moving with uniform horizontal velocity.

In all these activities, according to the scientific definition, you are not doing any work at all.

According to physics, work is said to be done when energy is transformed from one form to others. Work is done, when a force F is applied to a body and the body moves through a distance s on the direction of the force.

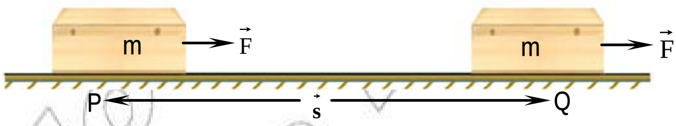

Fig. 4.1 A force $\vec{F}$ does a work

In Fig 4.1 A force (F) moves a block of mass (m) from point ‘P’ to ‘Q’ through a displacement ($\vec{s}$). Hence, work done = applied force × displacement

$$W = \vec{F} \times \vec{s}$$

Where W is work done, $\vec{F}$ is the applied force and $\vec{s}$ is the displacement.

Work is equal to the product of the force and the distance through which it produces. Although both force and displacement are vector quantities, but work is a scalar quantity, having only magnitude.

Lifting a load from the ground and putting it on a shelf is a good example of work. The force is equal to the weight of the load, and the distance is equal to the height of the shelf.

If the force acts in a direction other than that of the motion of the body, then only that component of the force in the direction of the motion produces work. If a force acts on a body constrained to remain stationary, no work is done by the force. Even if the body is in motion, the force must have a component in the direction of motion. The person walking a distance carrying a block of mass is not doing work in carrying the mass (Fig 4.2)

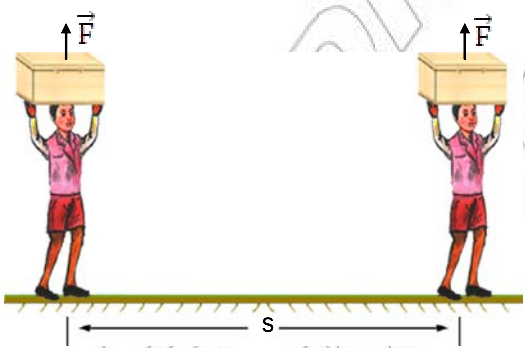

Fig 4.2. A man walking a distance 's', carrying a block of mass "m"

Activity 4.2
Discuss with your friends. The work done by a man carrying a load and walking a distances.

The SI unit of work is **newton meter (Nm)** which is called **Joule (J)**. One **Joule (J)** of work is done when a force of one newton (N) moves an object through a displacement of one meter (m).

1Joule (J) = 1 newton (N) × 1 meter (m).

The unit of work, 'Joule' is named in honor of the famous English physist **James Prescott Joule** (1818-1889), who had contributed a lot on heat energy.

When large or small quantities of work are measured we can use prefixes attached to Joule such as kilojoule (kJ), Megajoule (MJ), millijoule (mJ) and so on. For example 1 kiloJoule (kJ)= 1000 J

1 MegaJoule (MJ)= 1,000,000 J

1 MilliJoule (mJ)= 0.001 J

Worked Examples 4.1

1. A box is pushed by a force of 180N without acceleration 5m along a horizontal floor. How much work is done?

Given	Required	Solution
F = 180N	W = ?	$W = \vec{F} \times \vec{s}$
$\vec{s}$ = 5m		W = 180N × 5m
		= 900N.m
		= **900 J**

2. A mass is displaced from its original position through a distance of 20 m by a force of 100 N.
   a. How much work is done?
   b. What would be the work done, if the force is doubled, having the same displacement.
   c. What would be the work done, if the distance is halved, while the force remains constant?

Given	Required	Solution
$\vec{F} = 100$ N $\vec{s} = 20$ m	W = ?	a) $W = \vec{F} \times \vec{s} = 100$ N×20 m = 2000 Nm = 2000 J = 2 KJ b) when F = 200 N $W = \vec{F} \times \vec{s} = 200$N ×20 m = 4000 Nm = 4000 J = 4 kJ

∴ When the force is doubled, the amount of work done is also doubled.

c) Half of 20 m = 10 m, s = 10 m

$$W = \vec{F} \times \vec{s} = 100 \text{ N} \times 10 \text{ m} = 1000\text{Nm}$$
$$= 1000\text{J} = 1\text{kJ}$$

3. How much force is required to lift a load of 50 kg vertically to a height of 2m, if the work done is 1000 J.

Given	Required	Solution
W = 1000 J $\vec{s} = h = 2$m	F = ?	W = F.S $F = \frac{w}{s} = \frac{1000\text{ J}}{2\text{m}} = 500$ N

Check Points 4.1

1. What are the conditions for doing work?
2. Write the equation used for calculating work in symbols.
3. Calculate the work done by Girma, when he lifts a 20 N load to a height of 1.5m.
4. What happens to the work done when a force is doubled and the distance moved remain the same?

4.2. Energy

Activity 4.3

Discuss with your friends the following points;

i. Lift a heavy stone up in air. Does it have energy?
ii. Now, drop the stone and break another small stone or wood.
iii. What is energy?
iv. Explain the relationship between work and energy.

What does a body that has energy do? How do you measure the energy of a body?

In the previous section you learnt that work is something that is done on objects. In this section you will learn that energy is something that objects possess. A body is said to possess energy when it is capable of doing work. Thus, the energy of a body is measured by the quantity of work that the body does.

Energy is the capacity to do work. Energy is also a scalar quantity as work. The SI unit of energy is the same as the unit of work, Joule (J).

Activity 4.4

Discuss the following questions in a group.

i. Explain the different forms of energy.
ii. Which forms of energy do you think is mostly used in our country?
iii. Discuss the transformation of energy from one form to another.

The world we live in provides us with different forms of energy. Electrical energy, Chemical energy, nuclear energy, solar energy, sound energy, heat energy, mechanical energy, and energies from wind and water are some of the forms of energy.

In this section we focus on mechanical energy. Mechanical energy is the energy possessed by an object due to its motion and position related to the earth's surface.

There are two types of mechanical energy: These are:-

i. Kinetic energy (K.E) and
ii. Potential energy (P.E)

Kinetic Energy (K.E): kinetic energy is the energy of a body due to its motion. For example: running cars, thrown stones, rotating wheels or thrown spears, etc. have kinetic energy due to their motion. The kinetic energy of a body of mass m traveling at speed v is mathematically expressed as:

i.e. $K.E. = \frac{1}{2}\,(\text{mass}) \times (\text{speed})^2$

$K.E = \frac{1}{2} mv^2$

Kinetic energy is a scalar quantity, it has only magnitude

Worked Example 4.2

A bullet of mass 20g is fired at a speed of 250 m/s. What is its kinetic energy?

Given	Required	Solution
m = 20g	K.E = ?	$K.E = \frac{1}{2} mv^2$
= 0.02kg		$= \frac{1}{2} \times 0.02\ kg.\ (250\ m/s)^2$
v = 250m/s		$= \frac{1}{2} \times 0.02 \times 62500\ (kg.\ m^2/s^2)$
		= 625 J

Challenging Question

Discuss with your friend about the kinetic energy of the bullet in the above example; when

a) The velocity is constant, but the mass is doubled,

b) The mass is constant, but the velocity is doubled.

Potential Energy (P.E) is the energy associated with the position of a body relative to the earth's surface. For example, lifted masses above the earth's surface possess potential energy. The term "potential" means “stored”.

The potential energy of a body of mass (m) lifted to a height of 'h' above the ground is mathematically expressed as:

$$P.E = weight \times height \quad (where\ w = mg)$$

$$\Rightarrow P.E = mgh$$

This is an expression for potential energy of a body due to its position. You will learn in higher grades other types of potential energy.

Worked Example 4.3

An 80 kg stone is lifted to the top of a building 30m. How much does the potential energy of the stone increased? (take $g = 10\ m/s^2$)

Given	Required	Solution
m = 80kg	P.E=?	P.E = mgh
h = 30m		$= 80kg \times 10m/s^2 \times 30m$
$g = (10\ m/s^2)$		= 24000J
		= 24 KJ

Worked Examples 4.4

1. How fast must a car of mass 800 kg move in order to have a kinetic energy of 640 kJ?
   If the mass is reduced to 400 kg; for the same kinetic energy, what would be its speed?

Given	Required	Solution
m = 800 kg	v = ?	$K.E. = \frac{1}{2}mv^2$
K.E = 640,000J		$\Rightarrow 640{,}000J = (\frac{1}{2} \times 800\ kg)\ v^2$
= 640 kJ		$\Rightarrow v^2 = \frac{640{,}000J}{400\ kg}$
		$v^2 = 1600\ m^2/s^2$
		$v = \sqrt{1600} = 40m/s$

- If the mass is halved i.e. m =400 kg, then, $K.E = \frac{1}{2}mv^2$

$$640{,}000J = \frac{1}{2} \times 400\ kg \times v^2$$

$$v^2 = \frac{640{,}000J}{200kg} = 3{,}200\ m^2/s^2$$

$$v = \sqrt{3{,}200} \approx 56.57m/s$$

2. A crane is used to lift a concrete in sites where high buildings are being built. How much is the energy expended to lift a concrete of mass 320 kg to the top of a building 40 m high? (Crane is a device used to lift weights.)

Fig 4.3 A crane

Given	Required
m = 320 kg	P.E = ?
h = 40 m	
$g = 10m/s^2$	

Solution

When a body of mass 'm' is lifted up it possesses a potential energy. Thus,

$$P.E = mgh$$
$$= (320\ kg)\ (10m/s^2)\ (40\ m)$$
$$= 128{,}000\ J$$

3. How high should a body of mass 100 kg be lifted in order to have an energy of 1MJ?

Given	Required	Solution
m = 100 kg g = $10 m/s^2$ P.E = 1 MJ = 1,000,000 J	h = ?	From the relation PE = mgh, we get $h = \frac{PE}{mg} = \frac{1,000,000J}{(100kg)(10m/s^2)}$ Thus, h = 1000 m

Check points 4.2

i. What is the relationship between work done and energy?
ii. Name the two types of mechanical energy.
iii. On what quantities does the kinetic energy of a body depends on? Express it in equation (use symbols).
iv. On what quantities does the potential energy of a body depend on? Express it in equation (using symbols).
v. A ball of mass 0.25kg is kicked with a speed of 80m/s. What is its kinetic energy?
vi. a. Write a brief description on the difference between KE and PE.
b. Mention some practical examples for each types of energy.
c. Is there any transformation from KE to PE or vice versa? Explain your answer and give practical examples.

4.3. Transformation and Conservation of Energy

Activity 4.6

Discuss with your friends:

Consider the following different cases:

a. Hydroelectric power stations (Koka Dam, Gilgel Gibe dam etc) supply electric energy to our cities.
b. Using fuel energy in our home to cook some thing.
c. Using dry cells (chemical energy) for lighting a torch, and listening to a radio, etc.

What happens to these different forms of energy? Is energy creatd or destroyed in each case? Explain it.

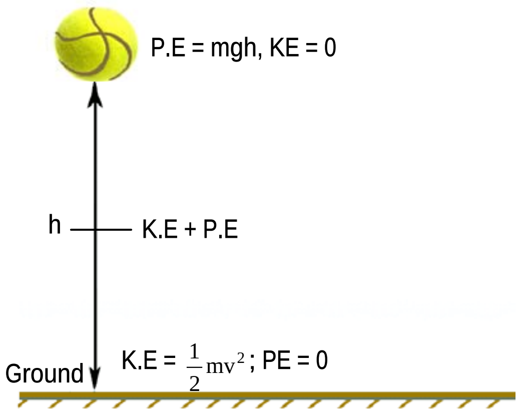

Fig 4.4. Transformation of mechanical energy in falling object

In our daily life, we use different forms of energy. Energy change (transformation) is needed to enable people, machine, computers and other devices to do work. For example, it is our daily experience to see chemical energy of coal, petroleum or gas being changed into heat and light energies in our stoves. But in this topic you shall see only the transformation of potential energy to kinetic energy and viseversa.

For example, consider a ball of mass (m) falls down from the top of a building of height (h) (sec Fig 4.4_). When it is at the top of the building it has only potential energy. That is, P.E. = mgh.

As it starts to fall down, it possesses both potential energy and kinetic energy. The potential energy that it had at the top of the building has now partly changed into kinetic energy. That is, P.E + K.E= mgh +1/2 mv^2.

Finally as the ball strike the ground it possesses only kinetic energy. This means the potential energy of the ball at the top of the building is totally changed into kinetic energy. That is K.E = ½ mv^2.

In this process, the potential energy at the top equals the kinetic energy at the ground level.

$$mgh = \frac{1}{2} mv^2$$

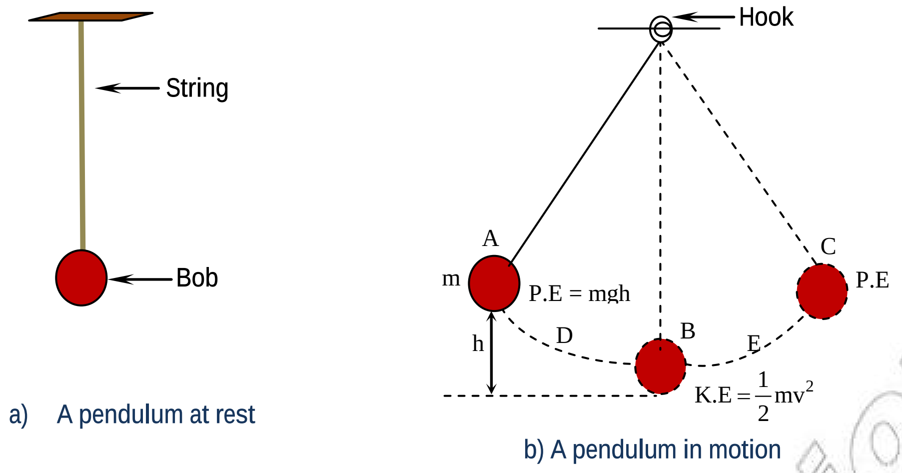

Fig 4.5. Transformation of mechanical energy in a simple pendulum

Activity 4.7

Do the following activities in a group.

Use the following materials: a bob (small mass), a string and a suspended hook from a tall table.

i. Tie the bob to one end of the string and mount it to the hook as shown in the (Fig 4.5a)
ii. Displace the bob of the pendulum to position 'A' as shown in Fig 4.5 (b) and release it.
iii. Explain the law of transformation and conservation of energy

From Activity 4.7 you notice that in a pendulum K.E. and P.E are interchanged continuously. The energy of the bob is all P.E. at position A of the swing and all K.E. as it passes through its equilibrium position (point B)

At other positions such as points D and E it has both P.E and K.E (see fig 4.5 b). Eventually the pendulum stops. At this moment all the energy is changed into heat as a result of overcoming air resistance (air friction).

The law of conservation of Energy is one of the universal laws of nature and it is stated as follows.

“Energy is neither created nor destroyed". It only transforms from one form to other forms.

Energy of falling water

The mechanical energy that a body possesses exists as potential energy or kinetic energy or both. Let us consider the transformation and conservation of mechanical energy of falling water.

Falling water is the main source of hydro-electrical energy in our country, yet we have not used it exhaustively.

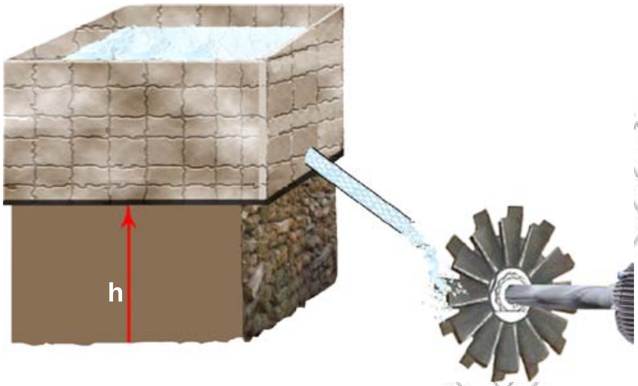

Fig 4.6 A water falling from a tower has potential energy and kinetic energy at the turbine

The diagram in Fig 4.6 shows that the water at the intake tower have only a potential energy due to its position (M.E= P.E). But after it has started to fall through the pipe it acquires a kinetic energy due to its motion. This kinetic energy is used to turn the turbine blades and make the generator to rotate. Finally when the water reaches the turbine blades it has only kinetic energy (M.E= K.E). When the water passes through the pipe its energy is the sum of both kinetic energy and potential energy.

i.e. M.E= P.E. +K.E

Note that the mechanical energy of the water at the dam tower is only potential energy and at the bottom is only kinetic energy. Energy of falling water shows that the total M.E of the system remains constant.

Wind energy

Activity 4.8

Group discussion

i. What is a wind?

ii. What form of energy does it have?

iii. Mention some practical examples where wind is used to do useful work.

A giant wind mill called wind turbine with two or more blades mounted on a tall tower can drive an electrical generator attached to it. This is done when the wind with a kinetic energy rotates the blades. Hence the rotated wind mill causes the generator to rotate and produce electric current. The electric energy produced by a wind mill can be used to lift water from a deep well and to light homes.

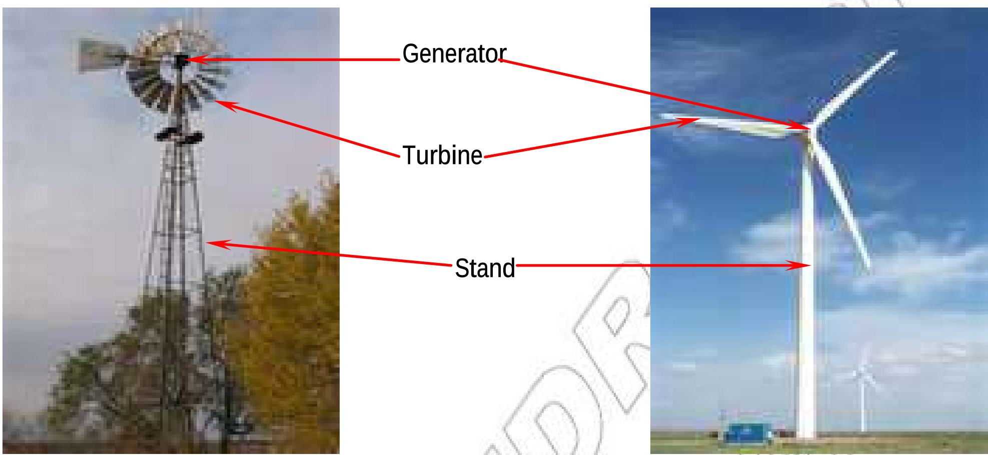

Fig 4.7 Wind mill changes kinetic energy into electrical energy

Check points 4.3

1. What do you understand by the terms:
   a) transformation b) conservation?
2. State the laws of conservation of energy.
3. Explain the different forms of energy possessed by falling water from a high dam to the ground.
4. What form of energy does a wind have? Give examples where wind energy is used by human being.
5. Consider a falling object or an oscillating pendulum. Describe the energy changes in each case.

4.4 Power

Activity 4.9

1. Discuss with your friends and family members what is meant by the term "power" in daily life.
2. Give some examples for:
   - Physical power
   - Political power
   - Personal power
   - Power of persuasion
3. What is the difference between power in daily life and power in scientific usage?
4. Lemlem displaces a block to a 10 m distance in 2 minutes. Tigabu displaces the same block to the same distance in 5 minutes. Who has more power? Lemlem or Tigabu? Explain it.

In most cases we say the same amount of work is done in raising a given weight through a given height, but we never ask in how many seconds or hours the work is done. However, it is necessary to consider the time taken to do the work. Power is a physical quantity that explains the time rate of doing work.

Power is the rate of doing work or rate of energy expenditure

$$\text{power} = \frac{\text{Work done}}{\text{time taken}} = \frac{\text{Energy transfered}}{\text{time taken}}$$

$$p = w/t$$

(where P = power, w= work, and t = time taken)

Like work and energy, power is also a scalar quantity.

The SI unit of power is Joule/second, which is called Watt. A power of 1W is developed when there is a transfer of 1J of energy in one second.

1W = 1 J/s

When larger quantities of power are involved we can use kilowatt (kW) and Megawatt (MW).

Where 1 kW= 1000 W

1 MW= 1,000,000 W

Worked Examples 4.5

1. A machine lifts a 50 kg mass to a height of 60 m in 4s. Calculate the power developed by the machine (take g= 10 m/s^2)

Given	Required	Solution
m= 50 kg	P = ?	power = $\frac{\text{Energy transferred}}{\text{Time taken}}$
h= 60 m		but Energy transferred = PE= mgh
t= 4s		Thus power, P= mgh/t
g= 10 m/s^2		P = $\frac{(50\text{ kg})(60\text{ m})(10\text{ m/sec}^2)}{4\text{s}}$
		Therefore P= 7500 W= 7.5 KW

2. Calculate the power of a pump that can lift 300 liters of water through a vertical height of 12 m in 8 sec
(Note that 1 liter of water= 1 kg of water)

Given	Required
h= 12m	P = ?
t= 8 sec	
m= 300 kg	
g= 10 m/s^2	

Solution

power, P = mgh/t

$\frac{(300\text{ kg})(10\text{ m/s}^2)(12\text{m})}{8\text{ s}}$ = 4500W= 4.5 Kw

Check point 4.4

i. What is the power of an electric “mitad” which transfers 2 kJ of electric energy in one second?

ii. A bucket full of water weighs 3 kg and a water well is 10 m deep. A girl draws water from the well. It takes the girl 2 minutes to draw a bucket full of water from the well.
What is the power of the girl? (take g= 10 m/s^2)

Summary

In this unit you learnt that:

- work is said to be done when energy is transformed. Work is done when a force is applied over a distance in the same direction as the force:- W = F. s
- the SI unit of work and energy is Joule (J).
- Work, Energy and Power are scalar quantities.
- Mechanical Energy is the sum of kinetic energy and potential energy of a body.
- kinetic energy of a body is the energy due to motion and it is expressed as: $KE = \frac{1}{2} mv^2$.
- potential energy of a body is the energy due to its position and is expressed as $PE = mgh$.
- power is defined as the rate of doing work or the rate of transfer of energy and it is expressed as $P = \frac{W}{t}$
- the SI unit of power is Watt (W) which is Joule per second (J/s).

Review Questions and Problems

I. Fill in the blank with the appropriate word or phrase.

1. Work is defined as the product of _________and________.
2. The SI unit of work is ____________.
3. ____________ is the capacity of doing work.
4. The units of Work, Energy and power are________ units.
5. The direction of applied force has to be _______ to the distance in order to say work is done.
6. ____________ tells us that energy is neither created nor destroyed but changes from one form to another.
7. ___________ is the time rate of doing work.
8. The SI unit of power is____________.
9. Mechanical energy is the sum total of_______ and ________.

II. Solve the following problems.

1. A force of 200 N is exerted horizontally on a box of mass 18 kg to displace it through a distance of 6 m. How much work is done?
2. An object of mass 20 kg is lifted to a 25 m building. How much potential energy is stored on the mass? (Take g= 10 m/s^2)
3. A crane lifts a 450 kg concrete to the top of a 50 m building in 5 s. Assuming g= 10 m/s^2, calculate;
   a) The potential energy of the concrete.
   b) The power developed by the crane
4. An artificial satellite of mass 900 kg is launched at a speed of 11,000m/s from its launching station. How much is the kinetic energy imparted to it?
5. How high should a 2 kg mass be lifted from the ground if it is thrown upward at speed of 15 m/s? (Assume g = 10 m/s^2)
6. An electric motor pumps 200 liter of water to a reservoir of height 6m in 2 s. Take g = 10 m/s^2. Calculate the power developed by the motor. Take 1 liter of water = 1kg of water.
7. An electric iron is labeled 1000W. How many Joule of energy is consumed if it is used for one hour?