Energy storage becomes even more important for refrigerated lorries or for lorries undertaking extremely long distance journeys in Europe or America. The rules regarding resting time are very strict and so the lorries remain parked in rest areas for substantial durations. Leaving the thermal engine running is not an economically viable solution as the thermal engine efficiency equals only 9% to 11% when stationary.

The use of only electrical energy for transport applications has always been an objective for electricians and that would allow:

– use of clean energy, where there are no waste products and no pollutants;

– a homogeneous system across both power and command areas;

– energy recovery when braking.

*2.3.1.2. Batteries*

Four types of batteries compete for use in electric vehicles[13] [THE 06]

– technology using lead;

– technology using metallic nickel hydride;

– technology based on lithium (lithium ion or lithium polymer);

– technology using sodium-nickel chloride.

There are multiple difficulties associated with batteries:

– Stored energy: lead batteries have a stored energy of 40 Wh/kg whereas new batteries based on lithium or nickel should be able to reach 220 Wh/kg and 100 Wh/kg, respectively.

– Cycling: the number of cycles that a battery can withstand without significant reduction of its capacity. Unlike a battery that is used in a vehicle with an internal combustion engine, batteries in electric vehicles must undergo large discharges, which reduce their lifetime. Lead batteries have a low capacity for cycling (180) and this figure is only slightly better for batteries based on lithium (1,000) or nickel (1,000), where high-energy batteries are being considered. The capacity for cycling is greater for high-power batteries (the data becomes 1,000, 200,000 and 250,000 respectively) but these are not suited to electric vehicles.

– Autodischarge: nickel batteries are penalized after hydrogen diffuses across the electrolyte.

– Prices: lithium batteries are very expensive compared to lead batteries. NiMH batteries are a little less costly.

– Behavior at low temperatures: the performance of lead batteries is reduced at low temperatures; this is the same for other types of battery, especially for lithium-ion technologies. This handicap is important as an electric vehicle should be able to start-up when the temperature is –20°C.

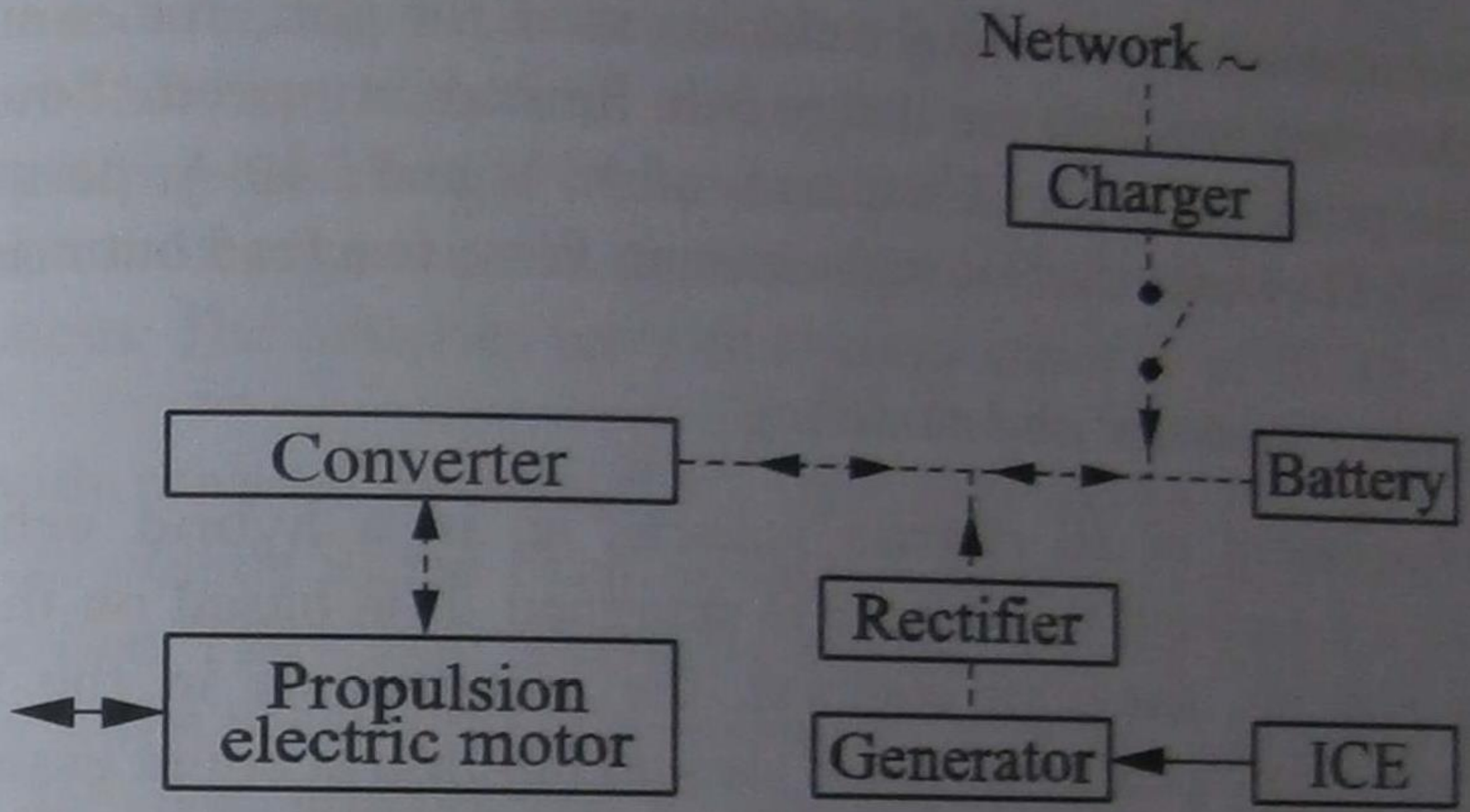



**Figure 2.2.** *Schema of a vehicle with range extender*

### 2.3.1.8. *Range extender*

To compensate for the loss of range in electric vehicles, a small generator is often installed, serving to recharge batteries when the state of charge is too low. The ICE functions at a stabilized speed, corresponding to a very good efficiency. There is no impact on the functioning of an electric vehicle (other than the fact that the voltage of the DC bus is necessarily more elevated because the direction of the current in the battery is reversed). The generator supplies some of the power to the propulsion engine. The schema is very close to that of a series hybrid. Recharging from the network is sometimes known as *plug-in*.

Fuel cells, generally PEFCs[19], can also be used as range extenders. Axane proposes AUXIPAC and Peugeot has presented concept coaches that use that specification ($H_2O$ car).

2.3.1.10. *Energy management and modeling*

Energy management in an electric vehicle, as in a hybrid vehicle, must be considered from the moment the vehicle is designed. It is based on the modeling of the vehicle (mechanics, tire-road contact), the components in the traction chain (motor, power electronics, battery), while also taking into account essential auxiliary functions or functions for comfort. The energy is managed by an onboard computer, which takes into account the SOC and the instructions of the driver. It is even possible to imagine a more intelligent system taking into account the profile of the actual journey (departure-arrival and itinerary defined by means of a GPS system).

## 2.4. Electrical energy complementing another source – hybridization

The narrow range of electric vehicles due to energy storage problems has led to dual-mode vehicles, which generally bring together an ICE with an electric motor, but one can equally bring together two different sources of energy, for example, chemical and electric. Clearly the two modes can be combined in many different ratios, which has led to commercial names that sometimes need deciphering, for example, *stop and go*, *mild hybridization*, *full hybridization*, *boost*, *downsizing*, etc. Different architectures are distinguished according to the coupling between internal combustion and electric motorizations:

– parallel architecture;

– series architecture;

– road coupling.

In all cases, the objective is to limit the consumption of hydrocarbons and, therefore, to limit pollution and the emission of greenhouse gases, indeed to be able to function in urban mode with zero emissions. The range depends on the capacity for storing electrical energy. All architectures do not permit the same energy saving functionalities. Some are more efficient but are restrictive as to the nature of energy sources.

### 2.4.1. *Parallel architecture*

The most basic diagram is given in Figure 2.4, which illustrates what is known as *"stop and go"*.

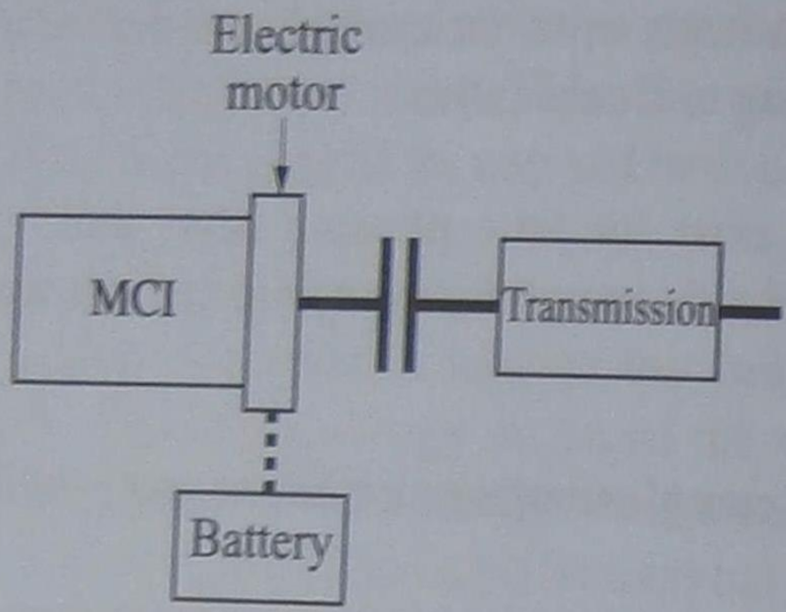



Figure 2.4. *Diagram of start and stop*

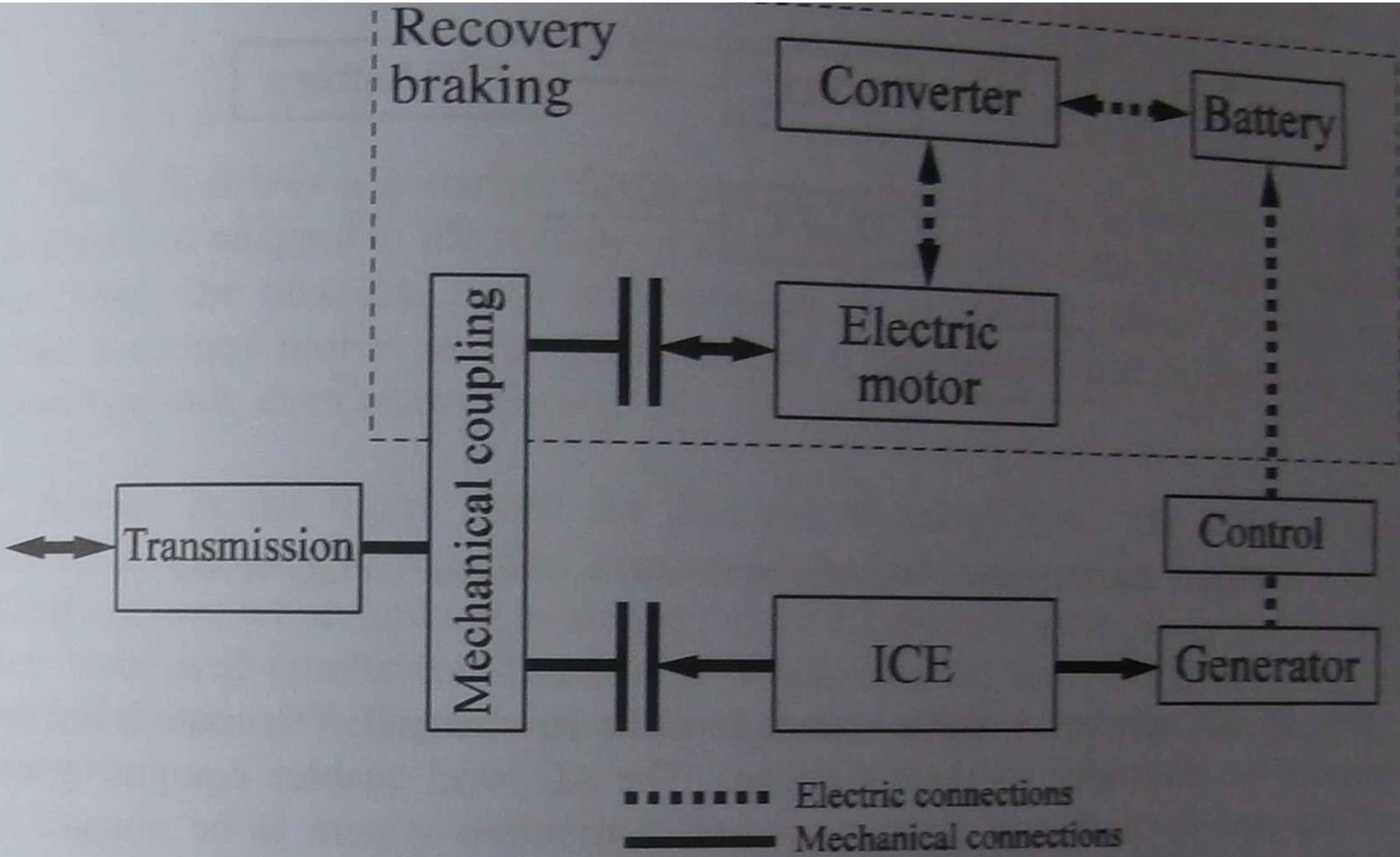



**Figure 2.5.** *Parallel architecture*

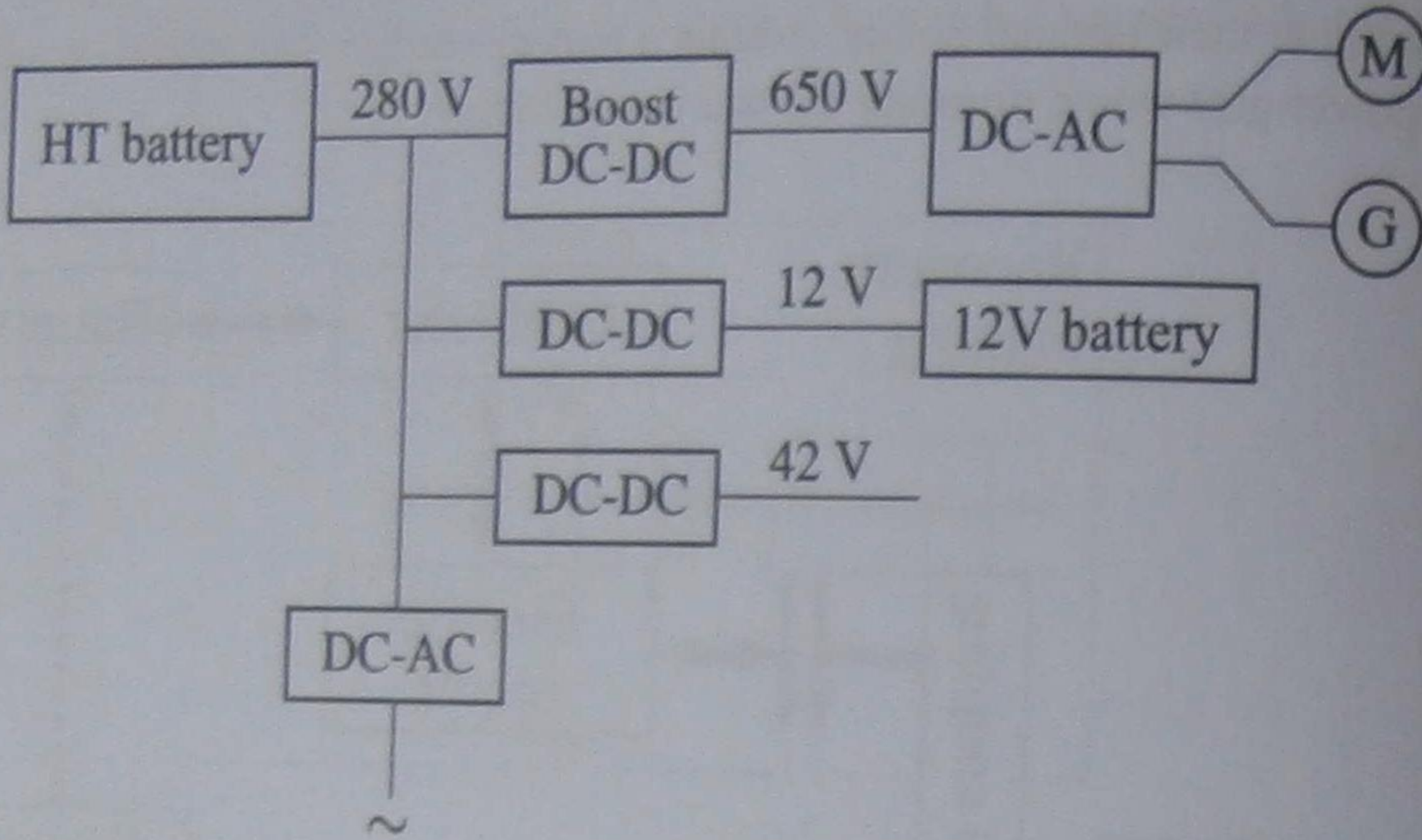



**Figure 2.6.** *Diagram of electrics for a vehicle with four voltage levels*

## 2.4.2. Series architecture

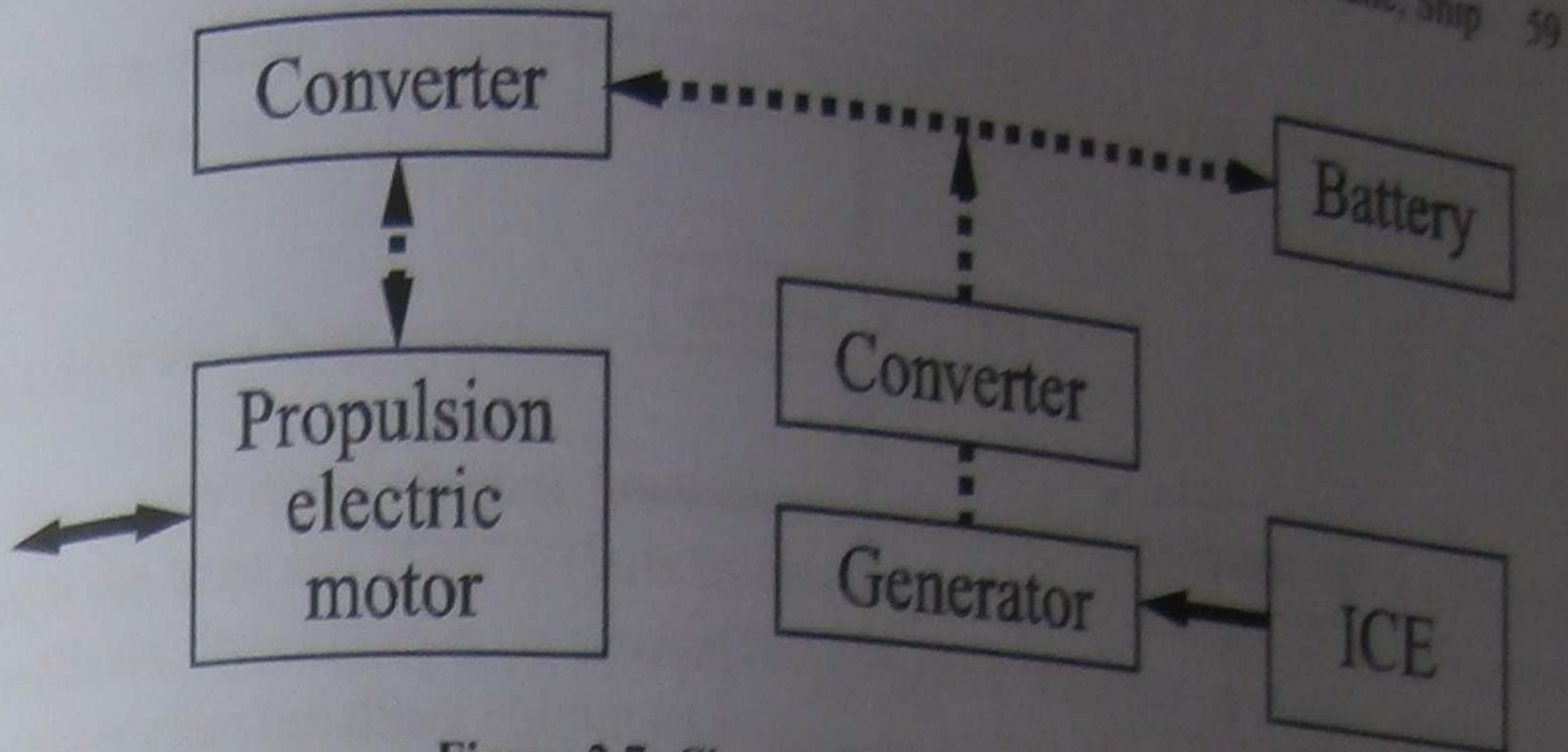



**Figure 2.7.** *Classical series architecture*

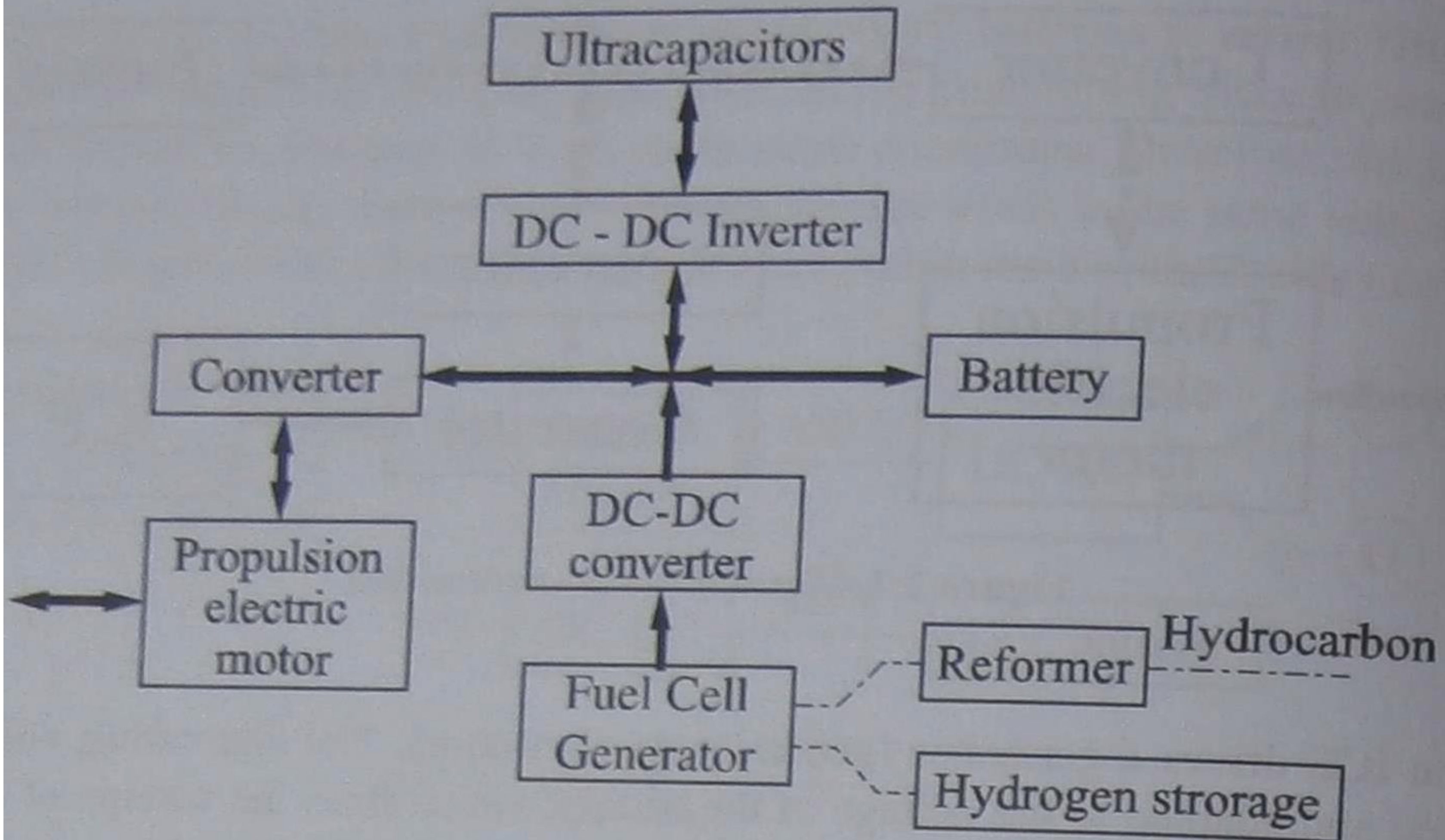



**Figure 2.8.** *Series architecture with fuel cells and ultracapacitors*

Several independent criteria can be used to classify μ-sources:

- level of energy;
- level of power;
- primary source (generation) versus secondary source (conversion);
- storage versus recovery of ambient energy;
- remote supply, etc.

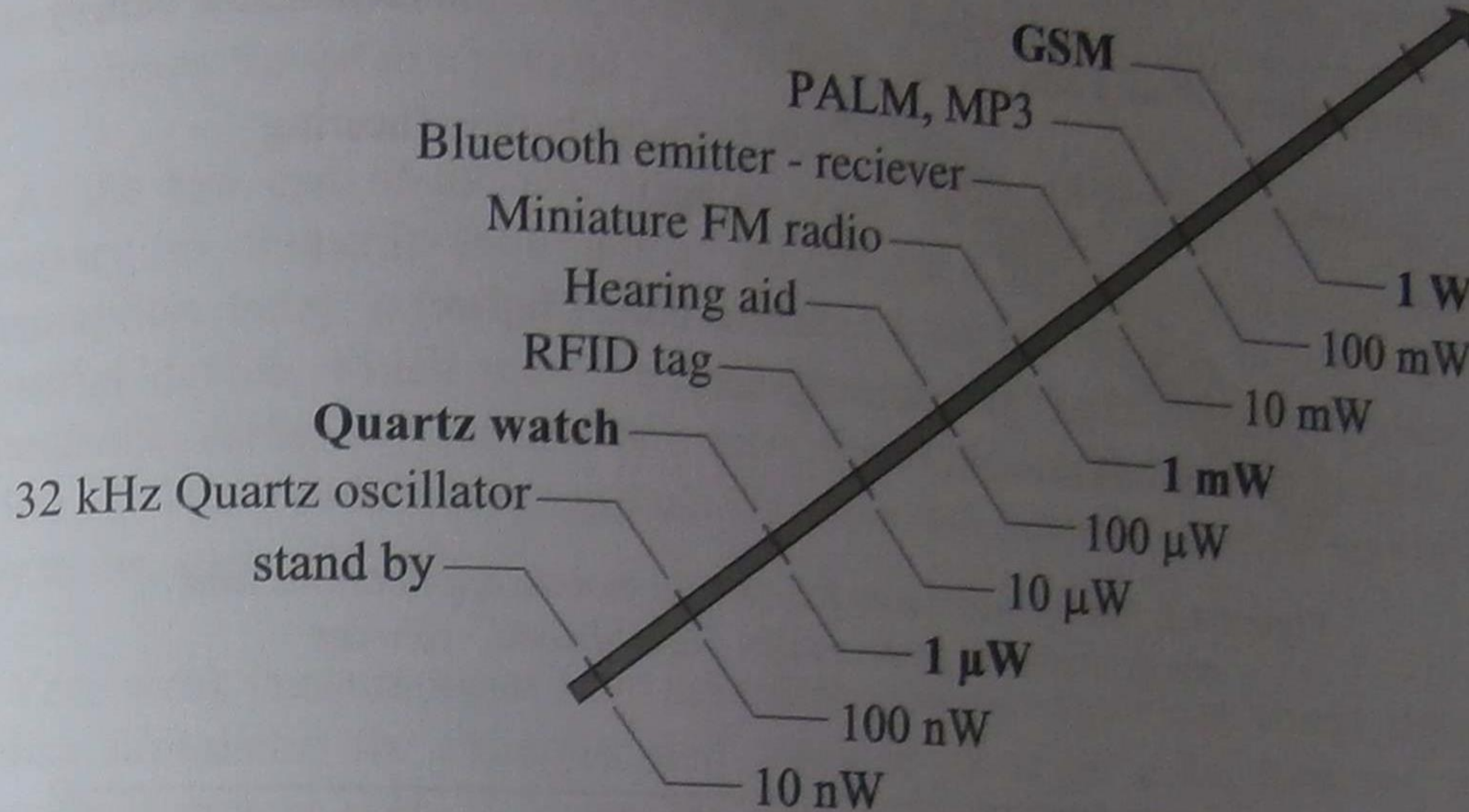



**Figure 4.1.** *Range of powers required by different electronic equipment*

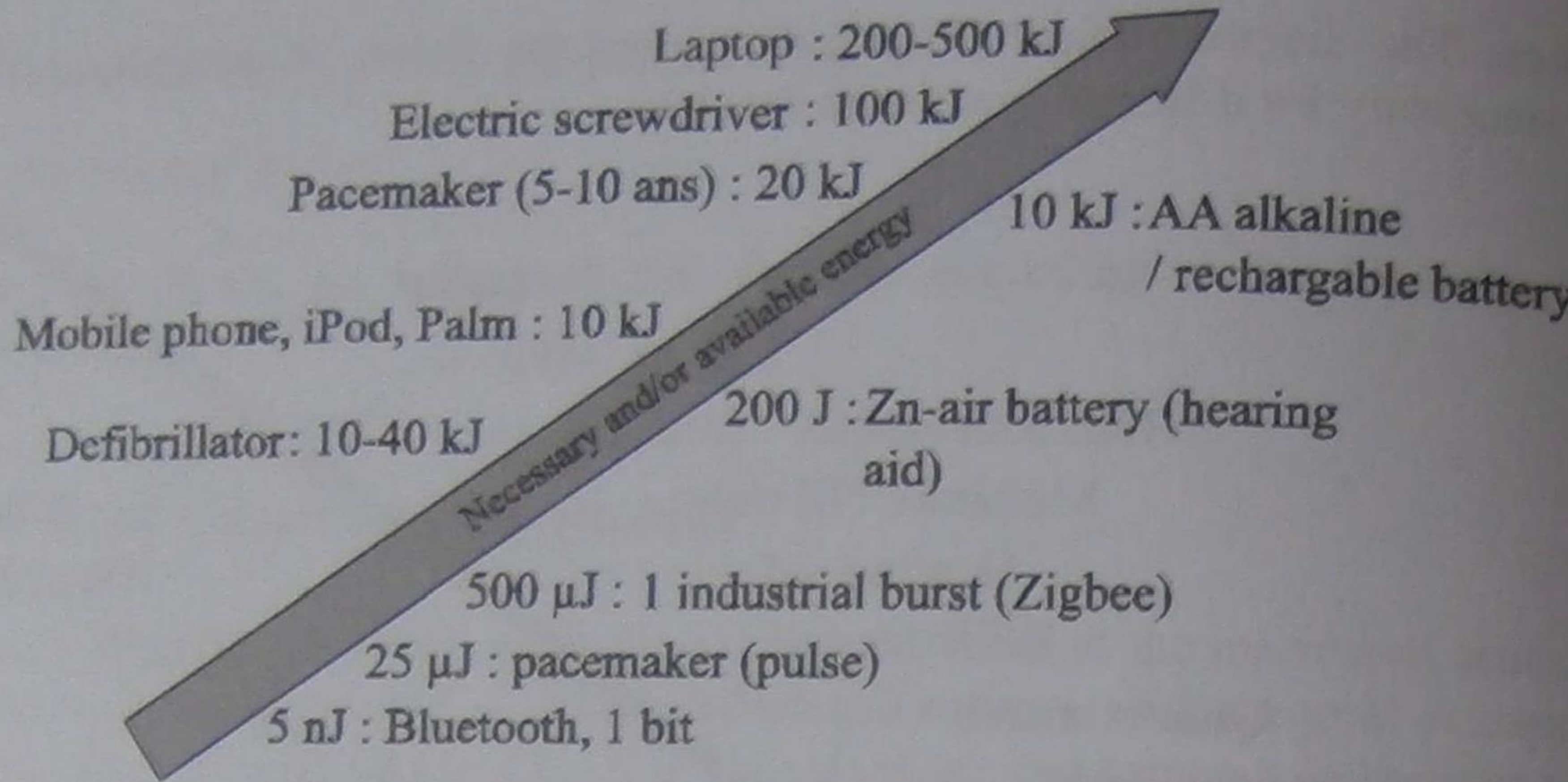



**Figure 4.2.** *Energy necessary for certain mobile applications and energy available from certain "established" sources*

### 4.3. Capacitative storage

Supercapacitors present better performances than batteries in terms of instantaneous power (as much in charging as when discharging), and better performances than capacitors in terms of specific energy. Therefore, they represent a compromise combining promising assets for "mobile" storage.

Numerous works are underway regarding their integration and these principally concern the development of specific materials for electrolytes and electrodes [LIU 08; KIM 02; KAM 07].

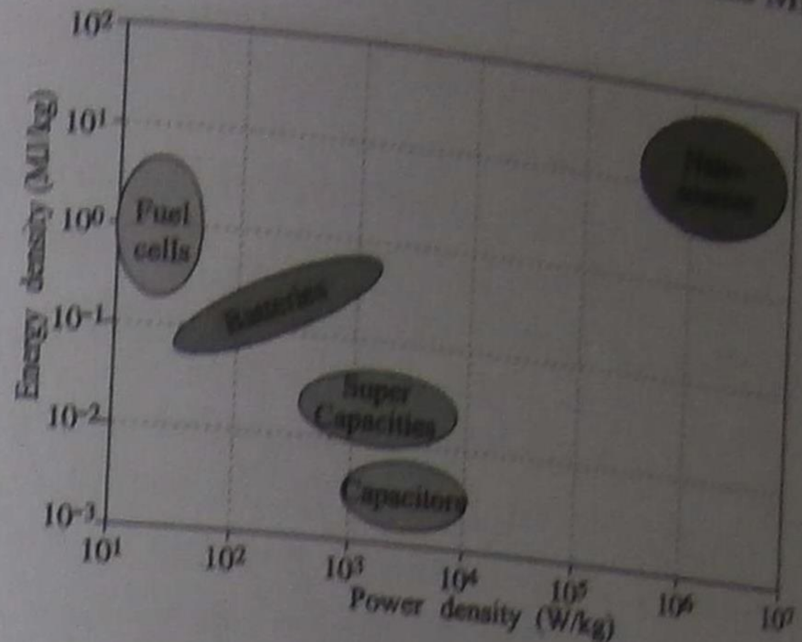



**Figure 4.6.** *Ragone diagram comparing various storage systems (electric) as well as nano-energetic materials (thermal, pyrotechnics)*

## 4.4. Electrochemical storage

We can list three families: cells, batteries (or accumulators), and fuel cells. The literature is full of information on their miniaturization, and we will content ourselves with mentioning their integration on silicon, which is being worked on by numerous laboratories. Figure 4.6 compares various electric storage solutions.

### 4.4.1. *Cells*

When recharging is not required, cells offer a good solution in terms of storage. Alkaline cells, greatly used by the public, offer specific storage performances similar to the best nickel-metal hydride (NiMH) batteries. As for zinc-air batteries, they enable us to obtain specific energy densities which are almost three times more than for lithium-polymer batteries. The table below gives the orders of magnitude of the specific energies that can be obtained using different miniature cell technologies.

### 4.4.3. *Fuel cells*

Fuel cells constitute an attractive solution for certain ranges of onboard energy: the diverse solutions developed are described and compared in recent reviews [KUN 07; MOR 07].

The Fraunhofer Institute for reliability and micro-integration (IZM) and the Technical University of Berlin (TU) have collaborated in developing a fuel cell that provides 12 W and weighs 30 g. Such a power density (400 W/kg) had never been attained by systems that weigh several hundred grams [BUL].

The figure below compares the specific energy available in hydrocarbons (before and after combustion) with that available in electrochemical batteries and with mechanics/fluids. It is clear that the energy available in hydrocarbons and in hydrogen is promising, even if we must take into account the low efficiencies in thermodynamic conversion (5 to 20%).

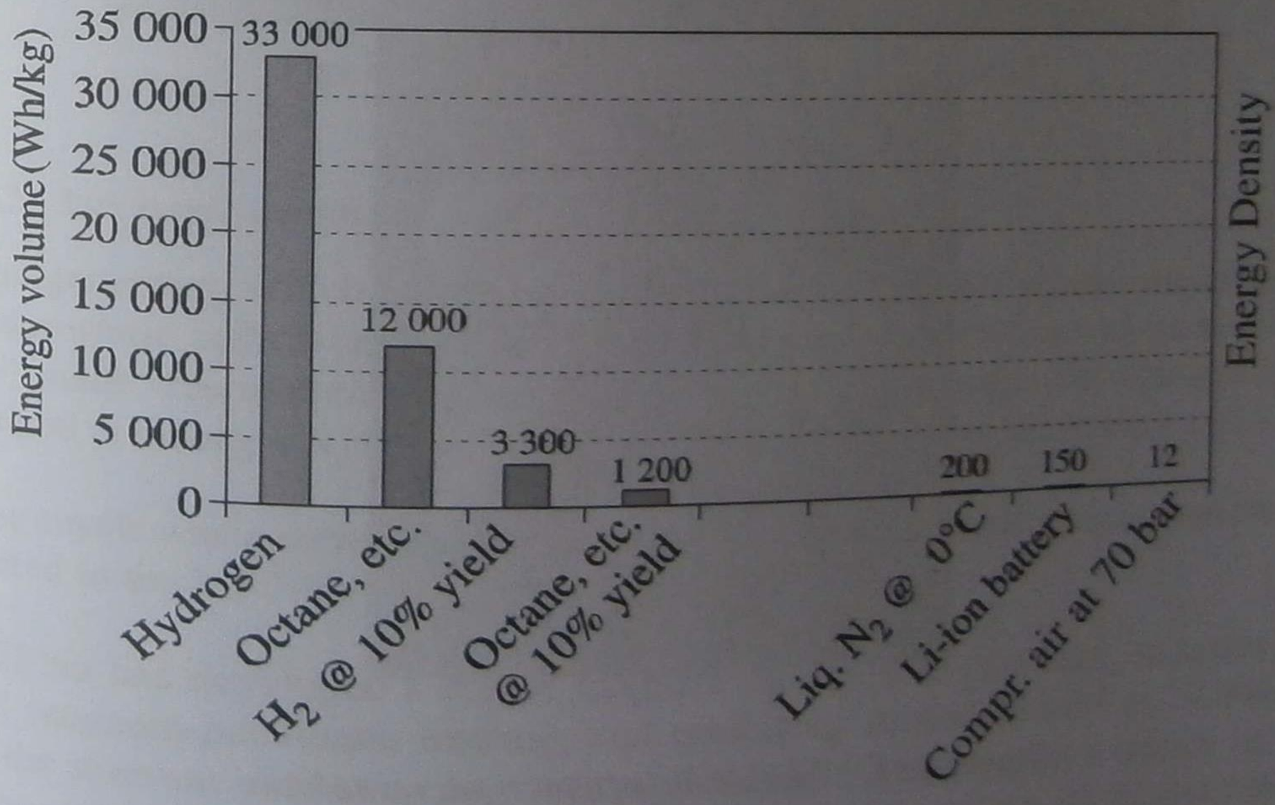



**Figure 4.10.** *Specific energy of hydrocarbons compared to cells and accumulators*

4.5.1. *Power MEMS*

Power MEMS are micro-systems that generate and convert power. They include systems that convert thermal energy into mechanical energy using combustion of a hydrocarbon in a turbine or a piston motor. The principles being used are directly copied from existing macroscopic applications. Examples are turbo-reactors targeting 3 million turns per minute (MIT), rotating Wankel piston motors (Berkeley), linear free pistons (Birmingham, etc.), reaction exhausts and even steam engines (Sandia), coupled with more or less conventional generators.

### 4.5.1.2. *Mechanic-magnetic conversion*

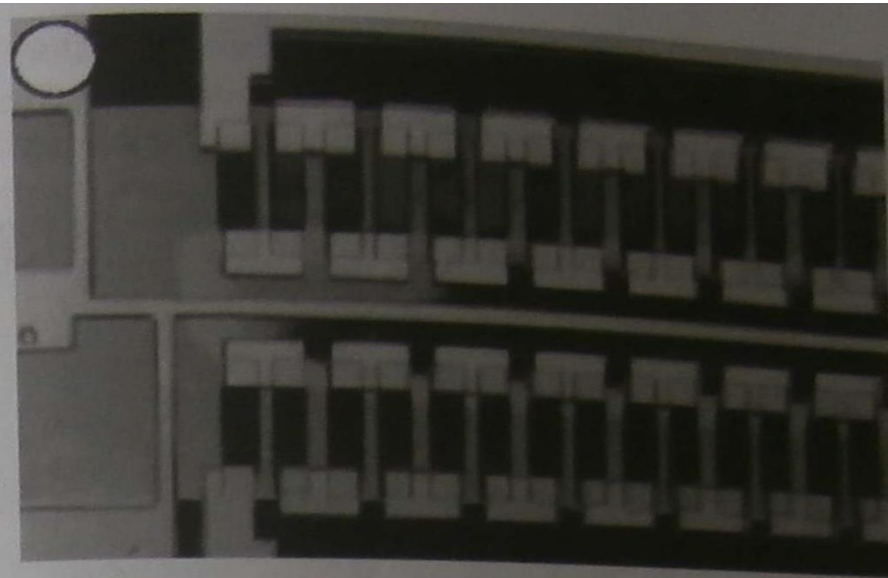
The generator, which had to be linked to the MIT micro-turbine, was originally an electrostatic induction generator; however, recurring problems of breakdown at 100 V made researchers consider "traditional" electromagnetic conversion, as developed at GeorgiaTech [GEO; HER 08a; HER 08b] using induction.

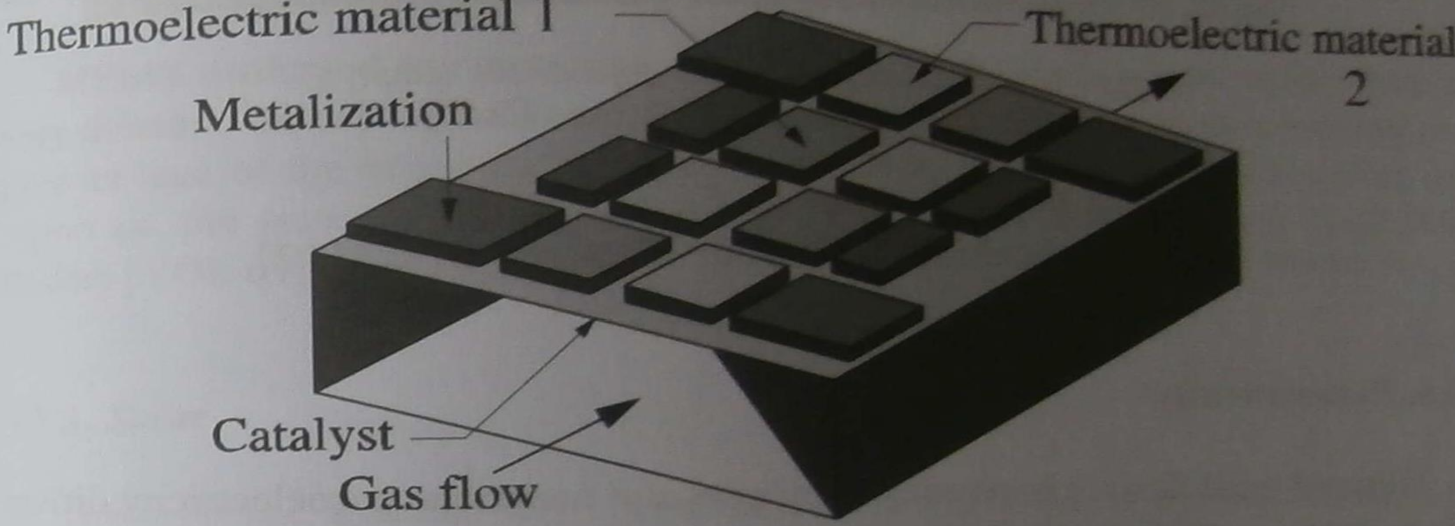
The result was a series of generators using magnets, which were not specifically dedicated to the MIT "hot turbine".

G2Elab has developed a planar magnetic micro-turbo-generator, mounted on a hybrid magneto-pneumatic bearing, and producing around 50 mW at 30,000 rpm (with the relevant electronic conversion) [RAI 06]. Coupled with a dentist turbine, this generator converts 5 W at 400,000 rpm, and could produce 20 W at 1,000,000 rpm.

#### 4.5.1.3. *Thermoelectricity*

Thermo-generators use the Seebeck effect (inverse of the Peltier effect). The Seebeck effect is commonly used to measure temperature using thermocouples. A thermocouple is a junction between two metals that produces a voltage when it is subjected to a difference in temperature. The voltages found are of the order of several tens of microvolts per degree Kelvin (50 µV/°K for a thermocouple of type J). By assembling thousands of thermocouples, it is possible to obtain thermoelectric converters generating voltages of the order of 1 V. Commercial thermoelectric converters can reach efficiencies of 6% provided that they have a temperature difference of several hundreds of degrees Celsius between the hot source and the cold source. Unfortunately, conversion efficiency is directly linked to the thermal gradient, and thus decreases drastically as the temperature difference decreases.






**Figures 4.17.** *Thermo-electric micro-generator with integrated thermocouples*

Electrical energy in watt-sec (or joules)

$$= \text{voltage in volts} \times \text{current in amperes} \times \text{time in seconds}$$

Joule or watt-sec is a very small unit of electrical energy for practical purposes. In practice, for the measurement of electrical energy, bigger units *viz.*, watt-hour and kilowatt hour are used.

$$1 \text{ watt-hour} = 1 \text{ watt} \times 1 \text{ hr}$$

$$= 1 \text{ watt} \times 3600 \text{ sec} = 3600 \text{ watt-sec}$$

$$1 \text{ kilowatt hour (kWh)} = 1 \text{ kW} \times 1 \text{ hr} = 1000 \text{ watt} \times 3600 \text{ sec} = 36 \times 10^5 \text{ watt-sec.}$$

*(iii)* **Heat.** Heat is a form of energy which produces the sensation of warmth. The unit* of heat is calorie, British thermal unit (B.Th.U.) and centigrade heat units (C.H.U.) on the various systems.

*Calorie.* It is the amount of heat required to raise the temperature of 1 gm of water through 1°C *i.e.*,

$$1 \text{ calorie} = 1 \text{ gm of water} \times 1°\text{C}$$

Sometimes a bigger unit namely *kilocalorie* is used. A kilocalorie is the amount of heat required to raise the temperature of 1 kg of water through 1°C *i.e.*,

$$1 \text{ kilocalorie} = 1 \text{ kg} \times 1°\text{C} = 1000 \text{ gm} \times 1°\text{C} = 1000 \text{ calories}$$

*B.Th.U.* It is the amount of heat required to raise the temperature of 1 lb of water through 1°F *i.e.*,

$$1 \text{ B.Th.U.} = 1 \text{ lb} \times 1°\text{F}$$

*C.H.U.* It is the amount of heat required to raise the temperature of 1 lb of water through 1°C *i.e.*,

$$1 \text{ C.H.U.} = 1 \text{ lb} \times 1°\text{C}$$

## 1.6 Relationship Among Energy Units

## 1.6 Relationship Among Energy Units

The energy whether possessed by an electrical system or mechanical system or thermal system has the same thing in common *i.e.*, it can do some work. Therefore, mechanical, electrical and thermal energies must have the same unit. This is amply established by the fact that there exists a definite relationship among the units assigned to these energies. It will be seen that these units are related to each other by some constant.

**(*i*) Electrical and Mechanical**

$$1 \text{ kWh} = 1 \text{ kW} \times 1 \text{ hr}$$

$$= 1000 \text{ watts} \times 3600 \text{ seconds} = 36 \times 10^5 \text{ watt-sec. or Joules}$$

$$\therefore \quad 1 \text{ kWh} = 36 \times 10^5 \text{ Joules}$$

It is clear that electrical energy can be expressed in Joules instead of kWh.

**(*ii*) Heat and Mechanical**

(*a*) $$1 \text{ calorie} = 4{\cdot}18 \text{ Joules} \qquad \text{(By experiment)}$$

(*b*) $$1 \text{ C.H.U.} = 1 \text{ lb} \times 1°\text{C} = 453{\cdot}6 \text{ gm} \times 1°\text{C}$$

$$= 453{\cdot}6 \text{ calories} = 453{\cdot}6 \times 4{\cdot}18 \text{ Joules} = 1896 \text{ Joules}$$

$$\therefore \quad 1 \text{ C.H.U.} = 1896 \text{ Joules}$$

(*c*) $$1 \text{ B.Th.U.} = 1 \text{ lb} \times 1°\text{F} = 453{\cdot}6 \text{ gm} \times 5/9\ °\text{C}$$

$$= 252 \text{ calories} = 252 \times 4{\cdot}18 \text{ Joules} = 1053 \text{ Joules}$$

$$\therefore \quad 1 \text{ B.Th.U.} = 1053 \text{ Joules}$$

It may be seen that heat energy can be expressed in Joules instead of thermal units *viz.* calorie, B.Th.U. and C.H.U.

**(iii) Electrical and Heat**

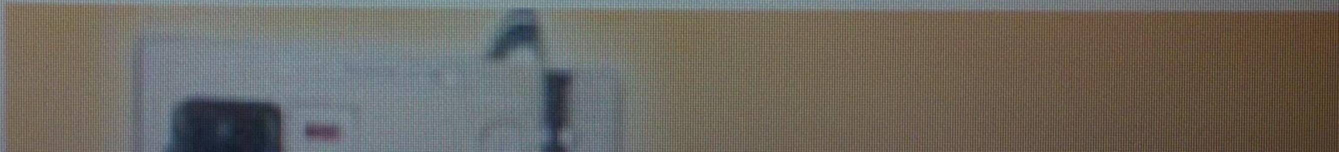
(a)
$$1\text{ kWh} = 1000\text{ watts} \times 3600\text{ seconds} = 36 \times 10^5\text{ Joules}$$
$$= \frac{36 \times 10^5}{4 \cdot 18}\text{ calories} = 860 \times 10^3\text{ calories}$$
$$\therefore \quad 1\text{ kWh} = 860 \times 10^3\text{ calories} \quad \text{or} \quad 860\text{ kcal}$$

(b)
$$1\text{ kWh} = 36 \times 10^5\text{ Joules} = 36 \times 10^5/1896\text{ C.H.U.} = 1898\text{ C.H.U.}$$
$$[\because 1\text{ C.H.U.} = 1896\text{ Joules}]$$
$$\therefore \quad 1\text{ kWh} = 1898\text{ C.H.U.}$$

(c)
$$1\text{ kWh} = 36 \times 10^5\text{ Joules} = \frac{36 \times 10^5}{1053}\text{ B.Th.U.} = 3418\text{ B.Th.U.}$$
$$[\because 1\text{ B.Th.U.} = 1053\text{ Joules}]$$
$$\therefore \quad 1\text{ kWh} = 3418\text{ B.Th.U.}$$

The reader may note that units of electrical energy can be converted into heat and *vice-versa*. This is expected since electrical and thermal energies are interchangeable.

## 1.7 Efficiency



Energy is available in various

## 1.7 Efficiency

Energy is available in various forms from different natural sources such as pressure head of water, chemical energy of fuels, nuclear energy of radioactive substances etc. All these forms of energy can be converted into electrical energy by the use of suitable arrangement. In this process of conversion, some energy is *lost* in the sense that it is converted to a form different from electrical energy. Therefore, the output energy is less than the input energy. *The output energy divided by the input energy is called* **energy efficiency** *or simply* **efficiency** *of the system.*

Measuring efficiency of compressor.

$$\text{Efficiency, } \eta = \frac{\text{Output energy}}{\text{Input energy}}$$

As power is the rate of energy flow, therefore, efficiency may be expressed equally well as output power divided by input power *i.e.*, 100 % efficient.

## 1.8 Calorific Value of Fuels

*The amount of heat produced by the complete combustion of a unit weight of fuel is known as its* **calorific value.**

Calorific value indicates the amount of heat available from a fuel. The greater the calorific value of fuel, the larger is its ability to produce heat. In case of solid and liquid fuels, the calorific value is expressed in *cal/gm* or *kcal/kg*. However, in case of gaseous fuels, it is generally stated in *cal/litre* or *kcal/litre*. Below is given a table of various types of fuels and their calorific values along with composition.

| S.No. | Particular | Calorific value | Composition |
|---|---|---|---|
| 1. | **Solid fuels** | | |
| | (*i*) Lignite | 5,000 kcal/kg | C = 67%, H = 5%, O = 20%, ash = 8% |
| | (*ii*) Bituminous coal | 7,600 kcal/kg | C = 83%, H = 5·5%, O = 5%, ash = 6·5% |
| | (*iii*) Anthracite coal | 8,500 kcal/kg | C = 90%, H = 3%, O = 2%, ash = 5% |
| 2. | **Liquid fuels** | | |
| | (*i*) Heavy oil | 11,000 kcal/kg | C = 86%, H = 12%, S = 2% |
| | (*ii*) Diesel oil | 11,000 kcal/kg | C = 86·3%, H = 12·8%, S = 0·9% |
| | (*iii*) Petrol | 11,110 kcal/kg | C = 86%, H = 14% |
| 3. | **Gaseous fuels** | | |
| | (*i*) Natural gas | 520 kcal/m$^3$ | $CH_4$ = 84%, $C_2H_6$ = 10%<br>Other hydrocarbons = 5% |
| | (*ii*) Coal gas | 7,600 kcal/m$^3$ | $CH_4$ = 35%, H = 45%, CO= 8%, N = 6%<br>$CO_2$ = 2%, Other hydrocarbons = 4% |

## 1.9 Advantages of Liquid Fuels over Solid Fuels

## 2.5 Efficiency of Steam Power Station

The overall efficiency of a steam power station is quite low (about 29%) due mainly to two reasons. Firstly, a huge amount of heat is lost in the condenser and secondly heat losses occur at various stages of the plant. The heat lost in the condenser cannot be avoided. It is because heat energy cannot be converted into mechanical energy without temperature difference. The greater the temperature difference, the greater is the heat energy converted* into mechanical energy. This necessitates to keep the steam in the condenser at the lowest temperature. But we know that greater the temperature difference, greater is the amount of heat lost. This explains for the low efficiency of such plants.

(i) **Thermal efficiency.** *The ratio of heat equivalent of mechanical energy transmitted to the turbine shaft to the heat of combustion of coal is known as* **thermal efficiency** *of steam power station.*

$$\text{Thermal efficiency, } \eta_{thermal} = \frac{\text{Heat equivalent of mech. energy transmitted to turbine shaft}}{\text{Heat of coal combustion}}$$

The thermal efficiency of a modern steam power station is about 30%. It means that if 100 calories of heat is supplied by coal combustion, then mechanical energy equivalent of 30 calories will be available at the turbine shaft and rest is lost. It may be important to note that more than 50% of total heat of combustion is lost in the condenser. The other heat losses occur in flue gases, radiation, ash etc.

(ii) **Overall efficiency.** *The ratio of heat equivalent of electrical output to the heat of combustion of coal is known as* **overall efficiency** *of steam power station i.e.*

* Thermodynamic laws.

**Example 2.1.** *A steam power station has an overall efficiency of 20% and 0·6 kg of coal is burnt per kWh of electrical energy generated. Calculate the calorific value of fuel.*



**Solution.**

Let $x$ kcal/kg be the calorific value of fuel.

Heat produced by 0·6 kg of coal = 0·6 $x$ kcal

Heat equivalent of 1 kWh = 860 kcal

$$\text{Now,} \quad \eta_{overall} = \frac{\text{Electrical output in heat units}}{\text{Heat of combustion}}$$

$$\text{or} \quad 0{\cdot}2 = \frac{860}{0{\cdot}6x}$$

$$\therefore \quad x = \frac{860}{\phantom{0}} = 7166{\cdot}67 \text{ kcal/kg}$$

$0{\cdot}6 \times 0{\cdot}2$

**Example 2.2.** *A thermal station has the following data :*

| | | | | |
|---|---|---|---|---|
| *Max. demand* | = 20,000 kW | ; | *Load factor* | = 40% |
| *Boiler efficiency* | = 85% | ; | *Turbine efficiency* | = 90% |
| *Coal consumption* | = 0·9 kg/kWh | ; | *Cost of 1 ton of coal* | = Rs. 300 |

*Determine (i) thermal efficiency and (ii) coal bill per annum.*

**Solution.**

(*i*) Thermal efficiency $= \eta_{boiler} \times \eta_{turbine} = 0{\cdot}85 \times {\cdot}9 = 0{\cdot}765$ or $76{\cdot}5\ \%$

(*ii*) Units generated/annum = Max. demand × L.F. × Hours in a year

$$= 20{,}000 \times 0{\cdot}4 \times 8760 = 7008 \times 10^4 \text{ kWh}$$

$$\text{Coal consumption/annum} = \frac{(0{\cdot}9)\left(7008 \times 10^4\right)}{1000} = 63{,}072 \text{ tons}$$

∴ Annual coal bill = Rs 300 × 63072 = **Rs 1,89,21,600**

**Example 2.3.** *A steam power station spends Rs. 30 lakhs per annum for coal used in the station. The coal has a calorific value of 5000 kcal/kg and costs Rs. 300 per ton. If the station has thermal efficiency of 33% and electrical efficiency of 90%, find the average load on the station.*

**Solution.**

Overall efficiency, $\eta_{overall} = 0{\cdot}33 \times 0{\cdot}9 = 0{\cdot}297$

Coal used/annum $= 30 \times 10^5/300 = 10^4$ tons $= 10^7$ kg

Heat of combustion = Coal used/annum × Calorific value

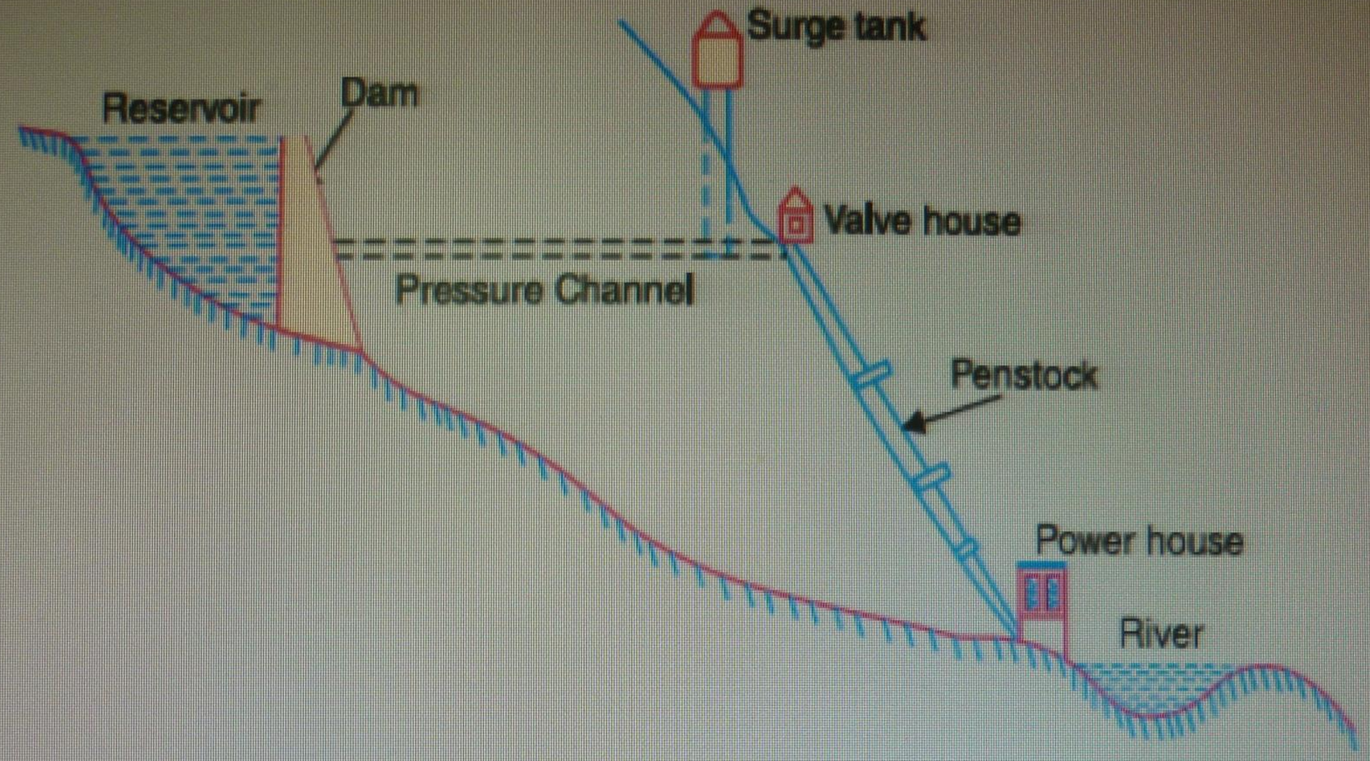
$$= 10^7 \times 5000 = 5 \times 10^{10} \text{ kcal}$$

Heat output $= \eta_{overall} \times$ Heat of combustion

$$= (0{\cdot}297) \times (5 \times 10^{10}) = 1485 \times 10^7 \text{ kcal}$$

Units generated/annum $= 1485 \times 10^7/860$ kWh

$$\therefore \quad \text{Average load on station} = \frac{\text{Units generated / annum}}{\text{Hours in a year}} = \frac{1485 \times 10^7}{860 \times 8760} = \mathbf{1971\ kW}$$




Schematic arrangement of a Hydro-electric plant

**Fig. 2.2**

## 2.9 Choice of Site for Hydro-electric Power Stations

The following points should be taken into account while selecting the site for a hydro-electric power station :

(i) *Availability of water.* Since the primary requirement of a hydro-electric power station is the availability of huge quantity of water, such plants should be built at a place (*e.g.*, river, canal) where adequate water is available at a good head.

(ii) *Storage of water.* There are wide variations in water supply from a river or canal during the alternators, transformers, circuit breakers and other switching and protective devices.

**Example 2.6.** *A hydro-electric generating station is supplied from a reservoir of capacity $5 \times 10^6$ cubic metres at a head of 200 metres. Find the total energy available in kWh if the overall efficiency is 75%.*

**Solution.**

Weight of water available is

$$W = \text{Volume of water} \times \text{density}$$

$$= (5 \times 10^6) \times (1000) \qquad (\because \text{ mass of } 1\text{m}^3 \text{ of water is } 1000 \text{ kg})$$

$$= 5 \times 10^9 \text{ kg} = 5 \times 10^9 \times 9{\cdot}81 \text{ N}$$

$$\text{Electrical energy available} = W \times H \times \eta_{overall} = (5 \times 10^9 \times 9{\cdot}81) \times (200) \times (0{\cdot}75) \text{ watt sec}$$

$$= \frac{(5 \times 10^9 \times 9{\cdot}81) \times (200) \times (0{\cdot}75)}{3600 \times 1000} \text{kWh} = \mathbf{2.044 \times 106 \text{ kWh}}$$

**Example 2.7.** *It has been estimated that a minimum run off of approximately 94 $m^3$/sec will be available at a hydraulic project with a head of 39 m. Determine (i) firm capacity (ii) yearly gross output. Assume the efficiency of the plant to be 80%.*

**Solution.**

Weight of water available, $W = 94 \times 1000 = 94000$ kg/sec

Water head, $H = 39$ m

$$\text{Work done/sec} = W \times H = 94000 \times 9{\cdot}81 \times 39 \text{ watts}$$

$$= 35,963 \times 10^3 \text{ W} = 35,963 \text{ kW}$$

This is gross plant capacity.

(*i*) Firm capacity = Plant efficiency × Gross plant capacity

$$= 0{\cdot}80 \times 35{,}963 = \mathbf{28{,}770 \text{ kW}}$$

(*ii*) Yearly gross output = Firm capacity × Hours in a year

$$= 28{,}770 \times 8760 = \mathbf{252 \times 10^6 \text{ kWh}}$$

(ii) Yearly gross output = Firm capacity × Hours in a year

$= 28{,}770 \times 8760 = \mathbf{252 \times 10^6\ kWh}$

**Example 2.8.** *Water for a hydro-electric station is obtained from a reservoir with a head of 100 metres. Calculate the electrical energy generated per hour per cubic metre of water if the hydraulic efficiency be 0·86 and electrical efficiency 0·92.*

**Solution.**

Water head, $H = 100\,\text{m}$ ; discharge, $Q = 1\,\text{m}^3/\text{sec}$ ; $\eta_{overall} = 0{\cdot}86 \times 0{\cdot}92 = 0{\cdot}79$

Wt. of water available/sec, $W = Q \times 1000 \times 9{\cdot}81 = 9810\,N$

Power produced $= W \times H \times \eta_{overall} = 9810 \times 100 \times 0{\cdot}79$ watts

$= 775 \times 10^3$ watts $= 775$ kW

$\therefore$ Energy generated/hour $= 775 \times 1 = \mathbf{775\ kWh}$

**Example 2.9.** *Calculate the average power in kW that can be generated in a hydro-electric project from the following data*

*Catchment area* $= 5 \times 10^9\ m^2$ ; *Mean head,* $H = 30\ m$

*Annual rainfall,* $F = 1{\cdot}25\ m$ ; *Yield factor,* $K = 80\ \%$

*Overall efficiency,* $\eta_{oveall} = 70\ \%$

*If the load factor is 40%, what is the rating of generators installed ?*

**Solution.**

Volume of water which can be utilised per annum

$$= \text{Catchment area} \times \text{Annual rainfall} \times {}^*\text{yield factor}$$

$$= (5 \times 10^9) \times (1{\cdot}25) \times (0{\cdot}8) = 5 \times 10^9 \text{ m}^3$$

Weight of water available per annum is

$$W = 5 \times 10^9 \times 9{\cdot}81 \times 1000 = 49{\cdot}05 \times 10^{12} \text{ N}$$

Electrical energy available per annum

$$= W \times H \times \eta_{overall} = (49{\cdot}05 \times 10^{12}) \times (30) \times (0{\cdot}7) \text{ watt-sec}$$

$$= \frac{(49{\cdot}05 \times 10^{12}) \times (30) \times (0{\cdot}7)}{1000 \times 3600} \text{kWh} = 2{\cdot}86 \times 10^8 \text{ kWh}$$

$\therefore$ Average power $= 2{\cdot}86 \times 10^8/8760 =$ **32648 kW**

$$\text{Max. demand} = \frac{\text{Average demand}}{\text{Load factor}} = \frac{32648}{0{\cdot}4} = \mathbf{81620\ kW}$$

Therefore, the maximum capacity of the generators should be 81620 kW.

**Example 2.10.** *A hydro-electric power station has a reservoir of area 2·4 square kilometres and capacity $5 \times 10^6$ m$^3$. The effective head of water is 100 metres. The penstock, turbine and generation efficiencies are respectively 95%, 90% and 85%.*

Therefore, the maximum capacity of the generators should be 81020 kW.

**Example 2.10.** *A hydro-electric power station has a reservoir of area 2·4 square kilometres and capacity $5 \times 10^6\ m^3$. The effective head of water is 100 metres. The penstock, turbine and generation efficiencies are respectively 95%, 90% and 85%.*

*(i) Calculate the total electrical energy that can be generated from the power station.*

*(ii) If a load of 15,000 kW has been supplied for 3 hours, find the fall in reservoir level.*

**Solution.**

(*i*) Wt. of water available, $W$ = Volume of reservoir × wt. of $1m^3$ of water

$$= (5 \times 10^6) \times (1000)\text{ kg} = 5 \times 10^9 \times 9{\cdot}81\text{ N}$$

Overall efficiency, $\eta_{overall} = 0{\cdot}95 \times 0{\cdot}9 \times 0{\cdot}85 = 0{\cdot}726$

Electrical energy that can be generated

$$= W \times H \times \eta_{overall} = (5 \times 10^9 \times 9{\cdot}81) \times (100) \times (0{\cdot}726)\text{ watt-sec.}$$

$$= \frac{(5 \times 10^9 \times 9{\cdot}81) \times (100) \times (0{\cdot}726)}{1000 \times 3600}\text{ kWh} = \mathbf{9{,}89{,}175\ kWh}$$

(*ii*) Let $x$ metres be the fall in reservoir level in 3 hours.

$$\text{Average discharge/sec} = \frac{\text{Area of reservoir} \times x}{3 \times 3600} = \frac{2{\cdot}4 \times 10^6 \times x}{3 \times 3600} = 222{\cdot}2x\ \text{m}^3$$

Wt. of water available/sec, $W = 222{\cdot}2x \times 1000 \times 9{\cdot}81 = 21{\cdot}8x \times 10^5$ N

$$\text{Average power produced} = W \times H \times \eta_{overall}$$

$$= (21{\cdot}8x \times 10^5) \times (100) \times (0{\cdot}726)\text{ watts}$$

$$= 15{\cdot}84x \times 10^7\text{ watts} = 15{\cdot}84x \times 10^4\text{ kW}$$

But kW produced = 15,000 (*given*)

$$\therefore \quad 15{\cdot}84x \times 10^4 = 15{,}000$$

$$\text{or} \quad x = \frac{15{,}000}{15{\cdot}84 \times 10^4} = 0{\cdot}0947\text{ m} = \mathbf{9{\cdot}47\ cm}$$

Therefore, the level of reservoir will fall by 9·47 cm.

**Alternative method**

$$\text{Level of reservoir} = \frac{\text{Vol. of reservoir}}{\text{Area of reservoir}} = \frac{5 \times 10^6}{2 \cdot 4 \times 10^6} = 2 \cdot 083 \text{ m}$$

$$\text{kWh generated in 3 hrs} = 15000 \times 3 = 45{,}000 \text{ kWh}$$

If kWh generated are 9,89,175 kWh, fall in reservoir level = 2·083 m

If kWh generated are 45,000 kWh, fall in reservoir level

$$= \frac{2 \cdot 083}{9{,}89{,}175} \times 45{,}000 = 0 \cdot 0947 \text{ m} = \mathbf{9.47 \text{ cm}}$$

**Example 2.11.** *A factory is located near a water fall where the usable head for power generation is 25 m. The factory requires continuous power of 400 kW throughout the year. The river flow in a year is (a) 10 $m^3$/sec for 4 months, (b) 6 $m^3$/sec for 2 months and (c) 1·5 $m^3$/sec for 6 months.*

*(i) If the site is developed as a run-of-river type of plant, without storage, determine the standby capacity to be provided. Assume that overall efficiency of the plant is 80%.*

*(ii) If a reservoir is arranged upstream, will any standby unit be necessary ? What will be the excess power available ?*

**Solution.**

*(i)* **Run of river Plant.** In this type of plant, the whole water of stream is allowed to pass

tion is 25 m. The factory requires continuous power of 400 kW throughout the year. The river flow in a year is (a) 10 $m^3$/sec for 4 months, (b) 6 $m^3$/sec for 2 months and (c) 1·5 $m^3$/sec for 6 months.

(i) If the site is developed as a run-of-river type of plant, without storage, determine the standby capacity to be provided. Assume that overall efficiency of the plant is 80%.

(ii) If a reservoir is arranged upstream, will any standby unit be necessary? What will be the excess power available?

**Solution.**

*(i)* **Run of river Plant.** In this type of plant, the whole water of stream is allowed to pass through the turbine for power generation. The plant utilises the water as and when available. Consequently, more power can be generated in a rainy season than in dry season.

*(a) When discharge* $= 10 \text{ m}^3/\text{sec}$

Wt. of water available/sec, $w = 10 \times 1000 \text{ kg} = 10^4 \times 9{\cdot}81 \text{ N}$

Power developed $= w \times H \times \eta_{overall} = (10^4 \times 9{\cdot}81) \times (25) \times (0{\cdot}8)$ watts

$= 1962 \times 10^3$ watts $= 1962$ kW

*(b) When discharge* $= 6 \text{ m}^3/\text{sec}$

Power developed $= 1962 \times 6^*/10 = 1177{\cdot}2$ kW

*(c) When discharge* $= 1{\cdot}5 \text{ m}^3/\text{sec}$

Power developed $= 1962 \times 1{\cdot}5/10 = 294$ kW

It is clear that when discharge is 10 $m^3$/sec or 6 $m^3$/sec, power developed by the plant is more than 400 kW required by the factory. However, when the discharge is 1·5 $m^3$/sec, power developed falls short and consequently standby unit is required during this period.

$\therefore$ Capacity of standby unit $= 400 - 294 =$ **106 kW**

*(ii)* **With reservoir.** When reservoir is arranged upstream, we can store water. This permits regulated supply of water to the turbine so that power output is constant throughout the year.

$$\text{Average discharge} = \frac{(10 \times 4) + (2 \times 6) + (1{\cdot}5 \times 6)}{12} = 5{\cdot}08 \text{ m}^3/\text{sec.}$$

$\therefore$ Power developed $= 1962 \times 5{\cdot}08/10 = 996{\cdot}7$ kW

Since power developed is more than required by the factory, no standby unit is needed.

$\therefore$ Excess power available $= 996{\cdot}7 - 400 =$ **596·7 kW** regulated supply of water to the turbine so that power output is constant throughout the year.

$$\text{Average discharge} = \frac{(10 \times 4) + (2 \times 6) + (1 \cdot 5 \times 6)}{12} = 5 \cdot 08 \text{ m}^3/\text{sec.}$$

$$\therefore \quad \text{Power developed} = 1962 \times 5{\cdot}08/10 = 996{\cdot}7 \text{ kW}$$

Since power developed is more than required by the factory, no standby unit is needed.

$$\therefore \quad \text{Excess power available} = 996{\cdot}7 - 400 = 596{\cdot}7 \text{ kW}$$

**Example 2.12.** *A run-of-river hydro-electric plant with pondage has the following data :*

*Installed capacity = 10 MW* ; *Water head, H = 20 m*

*Overall efficiency,* $\eta_{overall} = 80\%$ ; *Load factor = 40%*

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* If discharge is 10 m³/sec, power devloped = 1962 kW

If discharge is 1 m³/sec, power devloped = 1962/10

If discharge is 6 m³/sec, power devloped = 1962 × 6/10

(i) *Determine the river discharge in $m^3$/sec required for the plant.*

(ii) *If on a particular day, the river flow is 20 $m^3$/sec, what load factor can the plant supply ?*

**Solution.**

(i) Consider the duration to be of one week.

Units generated/week $= \text{Max. demand} \times \text{L.F.} \times \text{Hours in a week}$

$= (10 \times 10^3) \times (0{\cdot}4) \times (24 \times 7)$ kWh

$= 67{\cdot}2 \times 10^4$ kWh ... (i)

Let Q $m^3$/sec be the river discharge required.

Wt. of water available/sec, $w = Q \times 9{\cdot}81 \times 1000 = 9810\ Q$ newton

Average power produced $= w \times H \times \eta_{overall} = (9810\ Q) \times (20) \times (0{\cdot}8)$ W

$= 156960\ Q$ watt $= 156{\cdot}96\ Q$ kW

Units generated/week $= (156{\cdot}96\ Q) \times 168$ kWh $= 26{,}369$ Q kWh ... (ii)

Equating exps. (i) and (ii), we get,

$$26{,}369\ Q = 67{\cdot}2 \times 10^4$$

$$\therefore \quad Q = \frac{67{\cdot}2 \times 10^4}{26{,}369} = \mathbf{25.48 m^3/sec}$$

(ii) If the river discharge on a certain day is 20 $m^3$/sec, then,

Power developed $= 156{\cdot}96 \times 20 = 3139{\cdot}2$ kW

Units generated on that day $= 3139{\cdot}2 \times 24 = 75{,}341$ kWh

Load factor $= \dfrac{75{,}341}{10^4 \times 24} \times 100 = \mathbf{31.4\%}$

**Example 2.13.** *The weekly discharge of a typical hydroelectric plant is as under :*

| Day | Sun | Mon | Tues | Wed | Thurs | Fri | Sat |
|---|---|---|---|---|---|---|---|

Load factor $= \frac{75{,}341}{10^4 \times 24} \times 100 = 31.4\%$

**Example 2.13.** *The weekly discharge of a typical hydroelectric plant is as under :*

| *Day* | *Sun* | *Mon* | *Tues* | *Wed* | *Thurs* | *Fri* | *Sat* |
|---|---|---|---|---|---|---|---|
| *Discharge($m^3$/sec)* | 500 | 520 | 850 | 800 | 875 | 900 | 546 |

*The plant has an effective head of 15 m and an overall efficiency of 85%. If the plant operates on 40% load factor, estimate (i) the average daily discharge (ii) pondage required and (iii) installed capacity of proposed plant.*

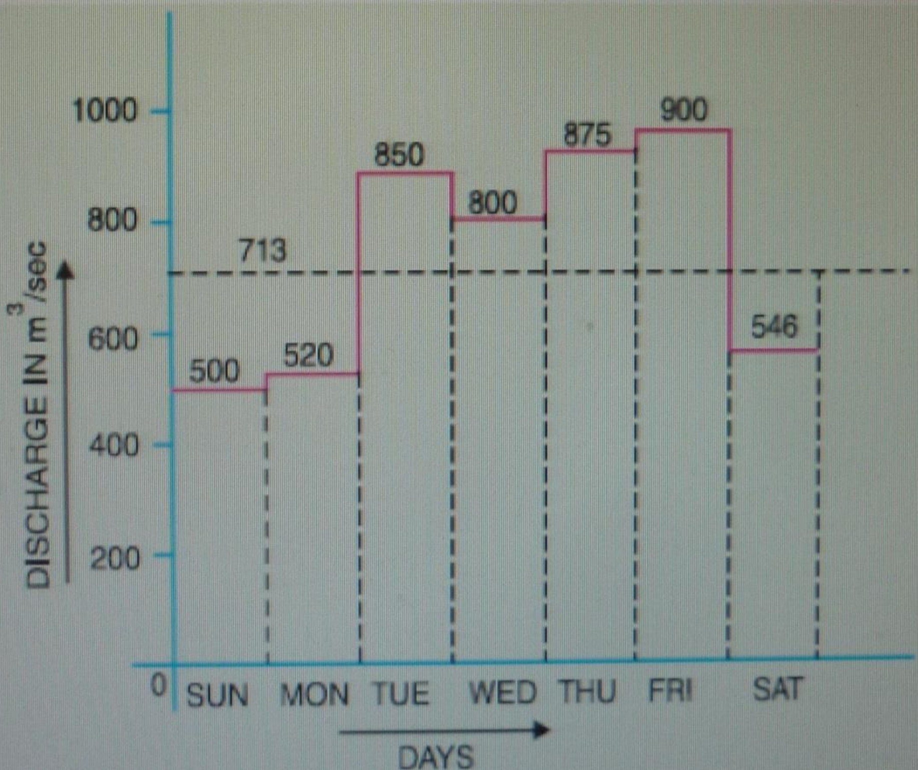



Fig. 2.5

**Solution.**

Fig. 2.5 shows the plot of weekly discharge. In this graph, discharge is taken along *Y*-axis and days along *X*-axis.

(*i*) Average daily discharge $= \dfrac{500 + 520 + 850 + 800 + 875 + 900 + 546}{7}$

$= \dfrac{4991}{7} = \mathbf{713\ m^3/sec}$

(*ii*) It is clear from graph that on three dyas (*viz*., Sun, Mon. and Sat.), the discharge is less than the average discharge.

Volume of water actually available on these three days

$= (500 + 520 + 546) \times 24 \times 3600\ m^3 = 1566 \times 24 \times 3600\ m^3$

Volume of water required on these three days

$= 3 \times 713 \times 24 \times 3600\ m^3 = 2139 \times 24 \times 3600\ m^3$

Pondage required $= (2139 - 1566) \times 24 \times 3600\ m^3 = \mathbf{495 \times 10^5\ m^3}$

(*iii*) Wt. of water available/sec, $w = 713 \times 1000 \times 9{\cdot}81$ N

Average power produced $= w \times H \times \eta_{overall} = (713 \times 1000 \times 9{\cdot}81) \times (15) \times (0{\cdot}85)$ watts

$= 89180 \times 10^3$ watts $= 89180$ kW

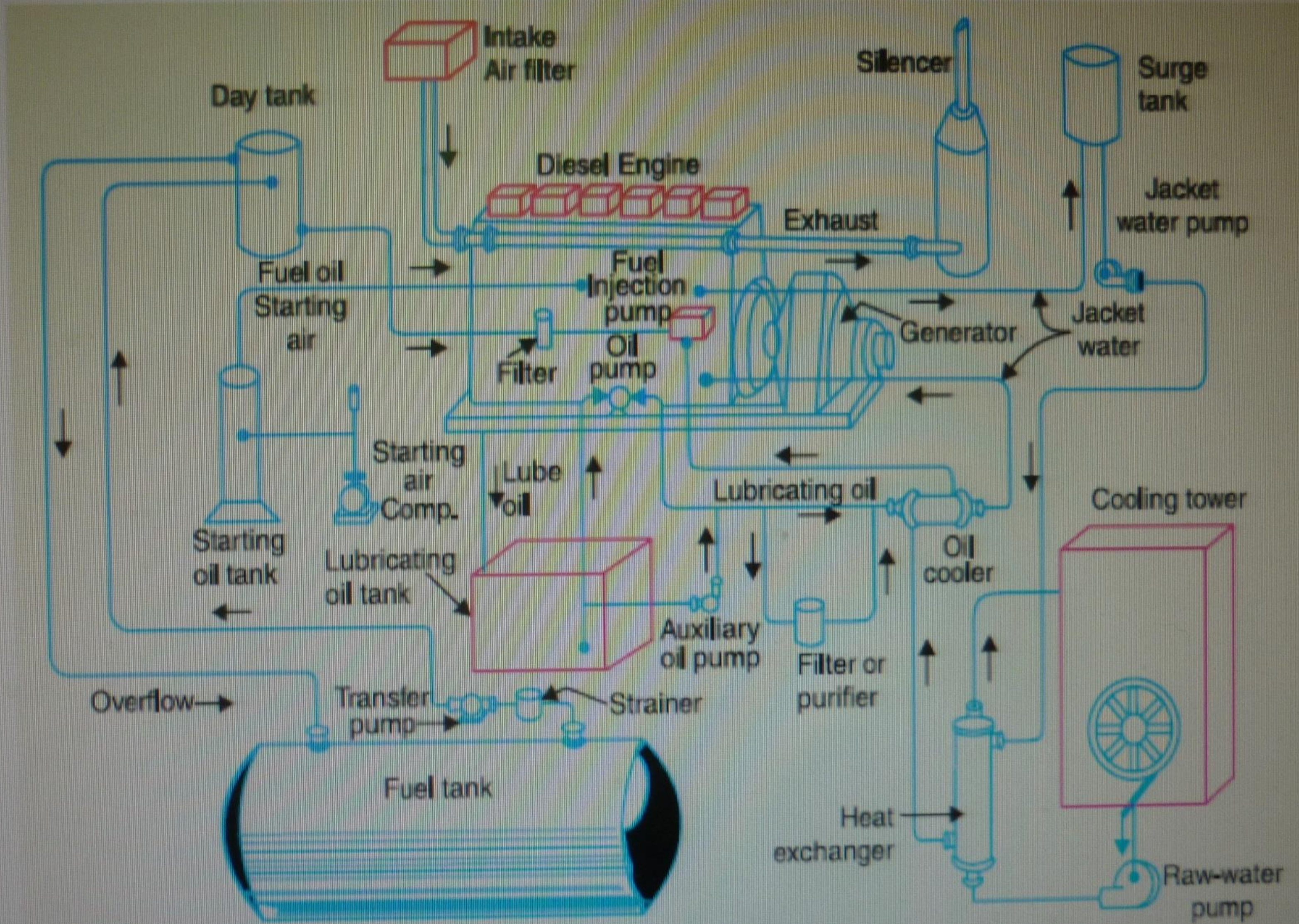
Installed capacity of the plant

$= \dfrac{\text{Output power}}{\text{Load factor}} = \dfrac{89180}{0{\times}4} = 223 \times 10^3\ \text{kW} = \mathbf{223\ MW}$

## TUTORIAL PROBLEMS

1. A hydro-electric station has an average available head of 100 metres and reservoir capacity of 50 million cubic metres. Calculate the total energy in kWh that can be generated, assuming hydraulic efficiency of

The hot water is cooled by cooling towers and is recirculated for cooling.




Schematic arrangement of Diesel Power Plant

**Fig. 2.6**

(v) *Lubricating system.* This system minimises the wear of rubbing surfaces of the engine. It comprises of lubricating oil tank, pump, filter and oil cooler. The lubricating oil is drawn from the lubricating oil tank by the pump and is passed through filters to remove impurities.

handles but for larger units, compressed air is used for starting. In the latter case, air at high pressure is admitted to a few of the cylinders, making them to act as reciprocating air motors to turn over the engine shaft. The fuel is admitted to the remaining cylinders which makes the engine to start under its own power.

**Example 2.14.** *A diesel power station has fuel consumption of 0·28 kg per kWh, the calorific value of fuel being 10,000 kcal/kg. Determine (i) the overall efficiency, and (ii) efficiency of the engine if alternator efficiency is 95%.*

**Solution.**

Heat produced by 0·28 kg of oil $= 10{,}000 \times 0{\cdot}28 = 2800$ kcal

Heat equivalent of 1 kWh $= 860$ kcal

(*i*) $$\text{Overall efficiency} = \frac{\text{Electrical output in heat units}}{\text{Heat of combustion}} = 860/2800 = 0{\cdot}307 = \mathbf{30{\cdot}7\%}$$

(*ii*) $$\text{Engine efficiency} = \frac{\text{Overall efficiency}}{\text{Alternator efficiency}} = \frac{30 \cdot 7}{0 \cdot 95} = \mathbf{32{\cdot}3\%}$$

**Example 2.15.** *A diesel power station has the following data :*

*Fuel consumption/day = 1000 kg*

*Units generated/day = 4000 kWh*

*Calorific value of fuel = 10,000 kcal/kg*

*Alternator efficiency = 96%*

*Engine mech. efficiency = 95%*

*Estimate (i) specific fuel consumption, (ii) overall efficiency, and (iii) thermal efficiency of engine.*

**Solution.**

(*i*) Specific fuel consumption = 1000/4000 = **0·25 kg/kWh**

(*ii*) Heat produced by fuel per day

$$= \text{Coal consumption/day} \times \text{calorific value}$$

$$= 1000 \times 10{,}000 = 10^7 \text{ kcal}$$

Electrical output in heat units per day

$$= 4000 \times 860 = 344 \times 10^4 \text{ kcal}$$

$$\text{Overall efficiency} = \frac{344 \times 10^4}{10^7} \times 100 = \mathbf{34{\cdot}4\%}$$

(*iii*) $$\text{Engine efficiency, } \eta_{engine} = \frac{\eta_{overall}}{\eta_{alt.}} = \frac{34 \cdot 4}{0 \cdot 96} = 35{\cdot}83\%$$

**Example 2.16.** *A diesel engine power plant has one 700 kW and two 500 kW generating units. The fuel consumption is 0·28 kg per kWh and the calorific value of fuel oil is 10200 kcal/kg. Estimate (i) the fuel oil required for a month of 30 days and (ii) overall efficiency. Plant capacity factor = 40%.*

**Solution.**

(*i*) Maximum energy that can be produced in a month

$$= \text{Plant capacity} \times \text{Hours in a month}$$

$$= (700 + 2 \times 500) \times (30 \times 24) = 1700 \times 720 \text{ kWh}$$

$$\text{Plant capacity factor} = \frac{\text{Actual energy produced}}{\text{Max. energy that could have been produced}}$$

*or*

$$0{\cdot}4 = \frac{\text{Actual energy produced}}{1700 \times 720}$$

∴ Actual energy produced in a month

$$= 0{\cdot}4 \times 1700 \times 720 = 489600 \text{ kWh}$$

Fuel oil consumption in a month

$$= 489600 \times 0{\cdot}28 = \mathbf{137088\ kg}$$

(*ii*)

$$\text{Output} = 489600 \text{ kWh} = 489600 \times 860 \text{ kcal}$$

$$\text{Input} = 137088 \times 10200 \text{ kcal}$$