

PRACTICE PAPER — NATIONAL CERTIFICATION EXAMINATION FOR ENERGY MANAGERS & ENERGY AUDITORS

PAPER – 4: ENERGY PERFORMANCE ASSESSMENT FOR EQUIPMENT AND UTILITY SYSTEMS

(For Energy Auditors only — Open book: only the official BEE Guidebook Book 4 is permitted)

Question code: 4P4CEA001 – 4P4CEA016 | SOLUTIONS & MODEL ANSWERS

Duration: 2 HRS Max. Marks: 100 Pass: 50% marks in the paper

General instructions:

- Please check that this question paper contains 16 questions
- The question paper is divided into three sections
- All questions in all three sections are compulsory (N-4: answer any ONE alternative)
- All parts of a question should be answered at one place
- Time management guidance: Section - I & II: 10 minutes each, Section - III: 100 minutes
- Use of a non-programmable scientific calculator is permitted; show Given, Formula, Substitution with units and Result for every numerical

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Section - I: BRIEF QUESTIONS

Marks: 10 x 1 = 10

- (i) Answer all Ten questions
- (ii) Each question carries One mark
- (iii) State whether each statement is True or False

1. In a gas-based combined-cycle unit in Andhra Pradesh, the gas turbine converts 34.0 % of the fuel heat into electricity, the HRSG recovers 80 % of the heat in the turbine exhaust as steam, and the steam turbine cycle converts 32.0 % of that steam heat into electricity. Neglecting GT casing losses, the combined-cycle electrical efficiency is about 66 %, i.e. the sum of the gas-turbine and steam-cycle efficiencies.

[4P4CEA001 | Chapter 3: Cogeneration Systems | Combined-cycle efficiency from GT, HRSG and steam-cycle efficiencies]

Answer: FALSE (1 mark)

Given: $\eta_{GT} = 34.0\%$; heat to GT exhaust = $100 - 34.0 = 66.0\%$ of fuel heat; HRSG recovery = 80% ; steam-cycle efficiency $\eta_{ST} = 32.0\%$.

Formula: $\eta_{CC} = \eta_{GT} + (1 - \eta_{GT}) \times \eta_{HRSG} \times \eta_{ST}$.

Substitution: Basis 100 units of fuel heat: GT power = 34.0; exhaust heat = 66.0; steam heat = $66.0 \times 0.80 = 52.8$; ST power = $52.8 \times 0.32 = 16.90$.

Result: $\eta_{CC} = 34.0 + 16.90 = 50.9\%$, not 66 % – false. The steam cycle works only on the part of the fuel heat that the gas turbine rejects and the HRSG recovers, so its efficiency is applied to $(1 - \eta_{GT}) \times \eta_{HRSG}$, never added directly; this is why practical combined cycles reach about 50–55 %, not the sum of the two cycle efficiencies.

Ref: BEE Guidebook Book 4, Ch. 3 (Cogeneration Systems).

2. An oil-fired boiler in a Hosur tyre plant reports an evaporation ratio of 13.2 (fuel GCV 10,250 kcal/kg, feed water 80°C), and its direct efficiency is computed assuming dry saturated steam at $10\text{ kg/cm}^2(\text{g})$ ($h_f = 186\text{ kcal/kg}$, $h_{fg} =$

479 kcal/kg, $h_g = 665$ kcal/kg). A throttling calorimeter shows the steam dryness fraction is only 0.94. The true efficiency is about 3.7 percentage points lower than the reported figure.

[4P4CEA002 | Chapter 1: Boilers | Wet steam – evaporation ratio overstates boiler efficiency]

Answer: TRUE (1 mark)

Given: ER = 13.2 kg steam/kg oil; GCV = 10,250 kcal/kg ($\approx 42,915$ kJ/kg); $h_f(\text{feed}) = 80$ kcal/kg (≈ 335 kJ/kg); $h_f = 186$, $h_{fg} = 479$, $h_g = 665$ kcal/kg ($\approx 2,784$ kJ/kg); dryness $x = 0.94$.

Formula: Wet steam enthalpy $h = h_f + x \times h_{fg}$; $\eta = \text{ER} \times (h - h_{\text{feed}}) / \text{GCV} \times 100$.

Substitution: $h_{\text{wet}} = 186 + 0.94 \times 479 = 636.26$ kcal/kg ($\approx 2,664$ kJ/kg); $\eta_{\text{reported}} = 13.2 \times (665 - 80) / 10,250 \times 100$; $\eta_{\text{true}} = 13.2 \times (636.26 - 80) / 10,250 \times 100$.

Result: $\eta_{\text{reported}} = 75.34\%$; $\eta_{\text{true}} = 71.64\%$; **difference = 3.70 percentage points** – true. Carry-over of water inflates the evaporation ratio without delivering useful heat, so a high ER with wet steam does not mean a high efficiency.

Ref: BEE Guidebook Book 4, Ch. 1 (Boilers).

3. In a Pune pharmaceutical plant, 6,000 kg/h of purified water at 30 °C is heated in a shell-and-tube heater by steam condensing at 120 °C on the shell side. The heater's UA value (overall coefficient $\times$ area) is 9,000 kcal/(h·°C). Because the condensing side stays at constant temperature, the effectiveness follows $\epsilon = 1 - e^{(-NTU)}$, and the water leaves at about 100 °C.

[4P4CEA003 | Chapter 4: Heat Exchangers | Steam-heated water heater – effectiveness from NTU (condensing shell side)]

Answer: TRUE (1 mark)

Given: Water $m = 6,000$ kg/h, $C_p = 1$ kcal/kg °C (≈ 4.19 kJ/kg·K) $\rightarrow C_{\text{min}} = 6,000$ kcal/(h·°C) (≈ 6.98 kW/K); UA = 9,000 kcal/(h·°C) (≈ 10.47 kW/K); $t_{\text{in}} = 30$ °C; steam at 120 °C ($C_{\text{max}} \rightarrow \infty$, $C_r = 0$).

Formula: $NTU = UA / C_{\text{min}}$; $\epsilon = 1 - e^{(-NTU)}$ (one fluid isothermal); $t_{\text{out}} = t_{\text{in}} + \epsilon \times (T_{\text{steam}} - t_{\text{in}})$; $Q = \epsilon \times C_{\text{min}} \times (T_{\text{steam}} - t_{\text{in}})$.

Substitution: $NTU = 9,000 / 6,000 = 1.5$; $\epsilon = 1 - e^{(-1.5)} = 1 - 0.2231 = 0.7769$; $t_{\text{out}} = 30 + 0.7769 \times (120 - 30)$; $Q = 0.7769 \times 6,000 \times 90$.

Result: $\epsilon = 0.777$; **water outlet = 99.9 °C**; **duty Q = 4,19,510 kcal/h (≈ 488 kW)** – true. With one stream condensing, the heat-capacity ratio is zero and the same ϵ -NTU relation holds for any flow arrangement; raising UA by 50 % (NTU 2.25) would lift ϵ only to about 0.89, showing diminishing returns from extra area.

Ref: BEE Guidebook Book 4, Ch. 4 (Heat Exchangers).

4. A closed-circuit cement ball mill in a Satna (MP) plant produces 120 t/h of cement. Samples give a residue on the 45 μm sieve of 32 % in the separator feed, 8 % in the separator fines (product) and 50 % in the separator rejects returned to the mill. The separator therefore handles about 280 t/h, i.e. a circulating load (rejects/product) of about 133 %.

[4P4CEA004 | Chapter 13: Cement Industry | Closed-circuit cement mill – circulating load from separator residues]

Answer: TRUE (1 mark)

Given: Product $P = 120$ t/h; residue on 45 μm : feed $f = 32\%$, fines $p = 8\%$, rejects $r = 50\%$.

Formula: Mass balances: $F = P + R$ and $F \cdot f = P \cdot p + R \cdot r \Rightarrow F/P = (r - p)/(r - f)$; circulating load $R/P = (f - p)/(r - f)$; separator efficiency (fines recovered) = $P(100 - p) / [F(100 - f)]$.

Substitution: $F/P = (50 - 8)/(50 - 32) = 42/18 = 2.333$; $F = 120 \times 2.333 = 280$ t/h; $R = 280 - 120 = 160$ t/h; $R/P = (32 - 8)/(50 - 32) = 24/18$; efficiency = $120 \times 92 / (280 \times 68)$.

Result: Separator feed = 280 t/h; rejects = 160 t/h; circulating load = 133 %; separator efficiency $\approx 58.0\%$ – true. Circulating load is found from the three residues alone, without weighing any stream; a rising circulating load at constant product fineness signals over-grinding or a worn separator, both of which raise mill kWh/t.

Ref: BEE Guidebook Book 4, Ch. 13 (Cement Industry).

5. A 90 kW pump motor in a Nagpur municipal pumping station is fed with line voltages of 418 V, 406 V and 391 V. The resulting voltage unbalance raises the motor's winding temperature rise by only about 7 % (twice the percentage unbalance), so it can be ignored.

[4P4CEA005 | Chapter 5: Electric Motors and Variable Speed Drives | Supply voltage unbalance and motor temperature rise]

Answer: FALSE (1 mark)

Given: Line voltages 418, 406 and 391 V; guidebook/NEMA relation: % increase in temperature rise $\approx 2 \times (\% \text{ voltage unbalance})^2$.

Formula: % voltage unbalance = maximum deviation from the average voltage/average voltage $\times 100$; % increase in temperature rise $\approx 2 \times (\% \text{ unbalance})^2$.

Substitution: Average = $(418 + 406 + 391)/3 = 405.0$ V; deviations = 13, 1 and 14 V $\rightarrow$ maximum 14 V; unbalance = $14/405.0 \times 100 = 3.46 \%$; rise = 2×3.46^2 .

Result: Voltage unbalance = 3.46 %; winding temperature rise increases by about 23.9 %, not 7 % – false. The effect grows with the square of the unbalance, so a 3–4 % unbalance sharply raises losses, shortens insulation life and calls for derating; the guidebook asks for unbalance to be kept within about 1 % by balancing single-phase loads across the phases and checking cables, contactors and capacitor banks.

Ref: BEE Guidebook Book 4, Ch. 5 (Electric Motors and Variable Speed Drives).

6. A 160 kW screw compressor in a Pithampur auto-component plant (FAD 27 m³/min) runs on load–unload control and draws 30 % of its full-load power when unloaded. When the plant demand averages 40 % of the compressor's FAD, the average power drawn is about 64 kW, i.e. proportional to the air delivered.

[4P4CEA006 | Chapter 8: Compressors | Load–unload control at part demand – power and specific power]

Answer: FALSE (1 mark)

Given: Full-load power = 160 kW; unload power = $0.30 \times 160 = 48$ kW; FAD = 27 m³/min; loaded fraction of time = 0.40 (demand = 40 % of FAD).

Formula: Average power = $f_{\text{load}} \times P_{\text{load}} + (1 - f_{\text{load}}) \times P_{\text{unload}}$; specific power = average kW/average air delivered (m³/min).

Substitution: $P_{\text{avg}} = 0.40 \times 160 + 0.60 \times 48 = 64 + 28.8$; $SP_{\text{full}} = 160/27$; $SP_{\text{part}} = 92.8/(0.40 \times 27) = 92.8/10.8$.

Result: Average power = 92.8 kW (58 % of full-load power for 40 % of the air); specific power rises from 5.93 to 8.59 kW/(m³/min), i.e. by 45 % – false. Unloaded running is far from free, which is why the guidebook recommends matching compressor size to demand, a VFD trim machine, or sequencing several units so that only one runs part-loaded.

Ref: BEE Guidebook Book 4, Ch. 8 (Compressors).

7. An IT campus in Bengaluru can install VFDs on its AHU fans for ₹ 30 lakh, saving 1,20,000 kWh a year for 10 years. At a 10 % discount rate the levelised cost of each kWh saved works out higher than the ₹ 7.50 per kWh tariff, so the project is not worth doing.

[4P4CEA007 | Chapter 10: Financial Analysis | Cost of saved energy (levelised) versus tariff]

Answer: FALSE (1 mark)

Given: Investment $P = ₹ 30,00,000$; life $n = 10$ years; $i = 10 \%$; saving = 1,20,000 kWh/year; tariff = ₹ 7.50 per kWh.

Formula: Capital recovery factor $CRF = i(1 + i)^n / [(1 + i)^n - 1]$; annualised cost = $P \times CRF$; cost of saved energy (CSE) = annualised cost/annual kWh saved.

Substitution: $(1.10)^{10} = 2.5937$; $CRF = 0.10 \times 2.5937 / (2.5937 - 1) = 0.1627$; annualised cost = $30,00,000 \times 0.1627 = ₹ 4,88,236$; $CSE = 4,88,236 / 1,20,000$.

Result: $CSE = ₹ 4.07 \text{ per kWh}$, well below the ₹ 7.50 tariff – false. Each kWh saved costs about 54 % of a purchased kWh after allowing for the time value of money (the undiscounted figure would be only ₹ 2.50 per kWh), so the VFDs are clearly worthwhile; CSE lets measures of different life and size be compared on one ₹/kWh scale.

Ref: BEE Guidebook Book 4, Ch. 10 (Financial Analysis).

8. A coke dry quenching (CDQ) unit at an Odisha integrated steel plant cools 100 t/h of red-hot coke from 1,050 °C to 180 °C with circulating inert gas (mean specific heat of coke 0.40 kcal/kg °C). If the CDQ boiler passes 85 % of this sensible heat to steam (steam enthalpy 795 kcal/kg, feed water 105 °C), it generates more than 0.4 t of steam per tonne of coke, heat that wet quenching throws away.

[4P4CEA008 | Chapter 12: Steel Industry | Coke dry quenching – steam recovered per tonne of coke]

Answer: TRUE (1 mark)

Given: Coke = 1,00,000 kg/h; 1,050 → 180 °C; $C_p = 0.40 \text{ kcal/kg °C}$ ($\approx 1.67 \text{ kJ/kg·K}$); recovery = 85 %; $h_{\text{steam}} = 795 \text{ kcal/kg}$ ($\approx 3,329 \text{ kJ/kg}$); $h_{\text{feed}} = 105 \text{ kcal/kg}$ ($\approx 440 \text{ kJ/kg}$).

Formula: Sensible heat $Q = m \times C_p \times \Delta T$; steam = $0.85 \times Q / (h_{\text{steam}} - h_{\text{feed}})$; specific steam = steam/coke.

Substitution: $Q = 1,00,000 \times 0.40 \times (1,050 - 180) = 1,00,000 \times 0.40 \times 870 = 3.48 \times 10^7 \text{ kcal/h}$ ($\approx 40.5 \text{ MW}$); steam = $0.85 \times 3.48 \times 10^7 / (795 - 105) = 2.958 \times 10^7 / 690$.

Result: Steam = 42,870 kg/h = 0.43 t per t coke – true. In wet quenching this heat goes up the quench tower as steam plume; CDQ also gives stronger, drier coke, which lowers the blast furnace coke rate.

Ref: BEE Guidebook Book 4, Ch. 12 (Steel Industry).

9. An oil-fired forging furnace in a Rajkot unit burns oil that needs 3.22 kg of O₂ per kg for complete combustion and is fired with 10 % excess oxygen. Enriching the combustion air from 23.2 % to 27.6 % O₂ by mass (about 21 → 25 % by volume), at the same 10 % excess O₂, reduces the flue gas mass per kg of oil by about 15 %, and with it the flue gas heat loss at the same exit temperature.

[4P4CEA009 | Chapter 2: Furnaces | Oxygen-enriched combustion air – reduction in flue gas mass]

Answer: TRUE (1 mark)

Given: O₂ needed = 3.22 kg/kg oil; excess O₂ = 10 % → O₂ supplied = $3.22 \times 1.10 \text{ kg/kg oil}$; O₂ mass fraction of air 0.232 (normal) and 0.276 (enriched); flue gas = oil + O₂ supplied + inerts (N₂) carried with it.

Formula: Inerts = O₂ supplied $\times (1 - x)/x$; flue gas mass = 1 + O₂ supplied + inerts (kg/kg oil); reduction % = $(1 - \text{enriched/normal}) \times 100$.

Substitution: O₂ supplied = $3.22 \times 1.10 = 3.542 \text{ kg}$; normal: inerts = $3.542 \times 0.768 / 0.232 = 11.73 \text{ kg}$ → flue gas = $1 + 3.542 + 11.73 = 16.27 \text{ kg}$; enriched: inerts = $3.542 \times 0.724 / 0.276 = 9.29 \text{ kg}$ → flue gas = 13.83 kg.

Result: Flue gas falls from 16.27 to 13.83 kg per kg oil, a reduction of 15.0 % – true. Less nitrogen has to be heated to furnace temperature and thrown away up the stack, so enrichment pays most in high-temperature furnaces; the cost of the oxygen and the higher flame temperature (refractory and NO_x) must be weighed against the fuel saved.

Ref: BEE Guidebook Book 4, Ch. 2 (Furnaces).

10. In a 5-stage preheater kiln, the preheater exhaust leaves at 300 °C with 1.48 Nm³ of gas per kg clinker (specific heat 0.35 kcal/(Nm³·°C)), and the clinker leaves the cooler at 120 °C (specific heat 0.19 kcal/kg °C); reference temperature 30 °C. The heat carried away by the clinker leaving the cooler is greater than the preheater exhaust gas loss.

[4P4CEA010 | Chapter 13: Cement Industry | Cement kiln – preheater exhaust versus clinker discharge loss]

Answer: FALSE (1 mark)

Given: PH gas = $1.48 \text{ Nm}^3/\text{kg}$ clinker at 300°C , $C_p = 0.35 \text{ kcal}/(\text{Nm}^3\cdot^\circ\text{C})$; clinker at 120°C , $C_p = 0.19 \text{ kcal}/\text{kg } ^\circ\text{C}$ ($\approx 0.795 \text{ kJ}/\text{kg}\cdot\text{K}$); reference 30°C .

Formula: Loss = quantity $\times C_p \times (t - t_{\text{ref}})$ per kg clinker.

Substitution: PH exhaust = $1.48 \times 0.35 \times (300 - 30)$; clinker = $1 \times 0.19 \times (120 - 30)$.

Result: PH exhaust loss = **139.9 kcal/kg clinker ($\approx 586 \text{ kJ}/\text{kg}$ clinker)**; clinker discharge loss = **17.1 kcal/kg clinker ($\approx 71.6 \text{ kJ}/\text{kg}$ clinker)** (about 8 times smaller) – false. The preheater exhaust (with cooler vent air) is the largest heat loss of a modern kiln, which is why it is the main source for waste heat recovery power.

Ref: BEE Guidebook Book 4, Ch. 13 (Cement Industry).

..... End of Section - I

Section - II: SHORT NUMERICAL QUESTIONS

Marks: 2 x 5 = 10

(i) Answer all the Two questions

(ii) Each question carries Five marks

[4P4CEA011] (5 marks)

Chapter 1: Boilers | Boiler efficiency and steam cost from evaporation ratio – coal versus briquette boiler loading

L-1 A Kolhapur paper mill has two identical 12 TPH boilers that both supply saturated steam at $10.5 \text{ kg}/\text{cm}^2(\text{g})$ (enthalpy $664 \text{ kcal}/\text{kg}$) with feed water at 92°C . Boiler A fires imported coal and Boiler B fires biomass briquettes. A month's log gives:

Parameter	Boiler A (imported coal)	Boiler B (briquettes)
Average evaporation ratio (kg steam/kg fuel)	6.6	4.8
GCV of fuel (as fired)	5,200 kcal/kg	3,750 kcal/kg
Delivered fuel price	₹ 8,400 per t	₹ 5,900 per t

Only one boiler is needed for the swing load of 48,000 t of steam per year. Determine (a) the efficiency of each boiler from the evaporation ratio, (b) the fuel cost per tonne of steam of each boiler and the annual saving from loading the cheaper boiler, and (c) the briquette price at which both boilers give the same steam cost, and the evaporation ratio Boiler A would need to match Boiler B's present steam cost.

MODEL ANSWER

a) Boiler efficiency from evaporation ratio (2 marks)

Given: $h_g = 664 \text{ kcal}/\text{kg}$ ($\approx 2,780 \text{ kJ}/\text{kg}$); $h_f = 92 \text{ kcal}/\text{kg}$ ($\approx 385 \text{ kJ}/\text{kg}$); $ER_A = 6.6$, $GCV_A = 5,200 \text{ kcal}/\text{kg}$ ($\approx 21,771 \text{ kJ}/\text{kg}$); $ER_B = 4.8$, $GCV_B = 3,750 \text{ kcal}/\text{kg}$ ($\approx 15,700 \text{ kJ}/\text{kg}$).

Formula: $\eta = ER \times (h_g - h_f)/GCV \times 100$.

Substitution: $h_g - h_f = 664 - 92 = 572 \text{ kcal}/\text{kg}$ ($\approx 2,395 \text{ kJ}/\text{kg}$)

$\eta_A = 6.6 \times 572/5,200 \times 100$; $\eta_B = 4.8 \times 572/3,750 \times 100$

Result: $\eta_A = 72.60\%$; $\eta_B = 73.22\%$. Boiler B has the lower evaporation ratio but the higher efficiency, because ER depends on the fuel's calorific value – ER alone cannot compare boilers firing different fuels.

b) Fuel cost per tonne of steam and annual saving (2 marks)

Given: Fuel per t steam = $1,000/ER \text{ kg}$; price A = ₹ 8.40/kg, B = ₹ 5.90/kg; swing load = 48,000 t steam/year.

Formula: Steam cost (₹/t) = $(1,000/ER) \times \text{fuel price (₹/kg)}$; annual saving = $(\text{cost}_A - \text{cost}_B) \times \text{annual steam}$.

Substitution: A: $1,000/6.6 = 151.5 \text{ kg coal} \times ₹ 8.40 = ₹ 1,272.73 \text{ per t steam}$

B: $1,000/4.8 = 208.3$ kg briquettes $\times$ ₹ 5.90 = ₹ 1,229.17 per t steam

Saving = $(1,272.73 - 1,229.17) \times 48,000 = 43.56 \times 48,000$

Result: Steam cost: A = ₹ 1,272.73/t, B = ₹ 1,229.17/t; loading Boiler B saves ₹ 20,90,909 (₹ 20.91 lakh) per year.

c) Break-even briquette price and required ER of Boiler A (1 mark)

Given: Steam cost A = ₹ 1,272.73/t; steam cost B = ₹ 1,229.17/t; ER_B = 4.8; coal price ₹ 8,400/t.

Formula: Break-even briquette price = $\text{cost}_A \times \text{ER}_B$ (₹/t fuel); required ER_A = coal price (₹/t)/cost_B.

Substitution: Briquette price = $1,272.73 \times 4.8$

ER_A = $8,400/1,229.17$

Result: Break-even briquette price = ₹ 6,109 per t (only 3.5 % above today's price); Boiler A would need an ER of 6.83, i.e. an efficiency of 75.17 %. The narrow margin means the loading decision must be reviewed whenever fuel prices change.

[4P4CEA012] (5 marks)

Chapter 11: Thermal Power Station | PAT for a thermal power station – gross heat rate from fuel, net heat rate, ESCerts and their value

L-2 A 2 × 250 MW coal-fired station in Odisha is a designated consumer under PAT. Its assessment-year data are:

Parameter	Value
Gross generation	3,720 MU
Auxiliary power consumption	8.6 % of gross generation
Coal consumed / weighted average GCV	25.1 lakh t / 3,480 kcal/kg
Secondary fuel oil (LDO) consumed / GCV	3,100 t / 10,500 kcal/kg
Target net heat rate notified for the cycle	2,596 kcal/kWh
Baseline net generation (for ESCert computation)	3,350 MU
ESCert trading price	₹ 2,150 per ESCert

Take 1 ESCert = 1 toe = 10^7 kcal. Determine (a) the gross heat rate, (b) the net heat rate and whether the target is met, and (c) the ESCerts earned (or to be purchased) and their value.

MODEL ANSWER

a) Gross heat rate (2 marks)

Given: Coal = 25.1 lakh t = 2,51,00,00,000 kg $\times$ 3,480 kcal/kg ($\approx$ 14,570 kJ/kg); LDO = 31,00,000 kg $\times$ 10,500 kcal/kg ($\approx$ 43,961 kJ/kg); gross generation = 3,720 MU = $3,720 \times 10^6$ kWh.

Formula: GHR = total fuel heat/gross generation.

Substitution: Coal heat = 25.1×10^8 kg $\times$ 3,480 = 8.7348×10^{12} kcal ($\approx$ 36.6 PJ); oil heat = $31 \times 10^5 \times 10,500 = 3.255 \times 10^{10}$ kcal ($\approx$ 136 TJ)

Total heat = 8.7674×10^{12} kcal ($\approx$ 36.7 PJ) (oil = 0.37 %); GHR = $8.7674 \times 10^{12}/(3,720 \times 10^6)$

Result: Gross heat rate = 2,356.8 kcal/kWh ($\approx$ 9,867 kJ/kWh).

b) Net heat rate and target check (1 mark)

Given: GHR = 2,356.8 kcal/kWh ($\approx$ 9,867 kJ/kWh); APC = 8.6 %; target NHR = 2,596 kcal/kWh ($\approx$ 10,869 kJ/kWh).

Formula: NHR = $\text{GHR}/(1 - \text{APC}/100)$.

Substitution: NHR = $2,356.8/(1 - 0.086) = 2,356.8/0.914$

Result: Net heat rate = 2,578.6 kcal/kWh ($\approx$ 10,796 kJ/kWh), which is 17.4 kcal/kWh ($\approx$ 72.9 kJ/kWh) better than the 2,596 kcal/kWh ($\approx$ 10,869 kJ/kWh) target – target met. (Net generation = 3,400.1 MU.)

c) ESCerts and their value (2 marks)

Given: NHR reduction beyond target = 17.43 kcal/kWh (≈ 73.0 kJ/kWh); baseline net generation = $3,350 \times 10^6$ kWh; 1 ESCert = 10^7 kcal; ₹ 2,150 per ESCert.

Formula: ESCerts = (target NHR – achieved NHR) $\times$ baseline net generation/ 10^7 ; value = ESCerts $\times$ price.

Substitution: ESCerts = $17.43 \times 3,350 \times 10^6 / 10^7 = 17.43 \times 335$

Value = $5,838 \times ₹ 2,150$

Result: ESCerts earned = 5,838, worth ₹ 1,25,52,747 (₹ 1.26 crore). Each 1 % rise in APC would raise the NHR by about 28.5 kcal/kWh (≈ 119 kJ/kWh) and wipe out most of these certificates, so auxiliary power is as important as boiler and turbine performance under PAT.

..... End of Section - II

Section - III: LONG NUMERICAL QUESTIONS

Marks: 4 x 20 = 80

- (i) Answer all the Four questions
- (ii) Each question carries Twenty marks
- (iii) In N-4, answer any ONE of the four alternatives (a) to (d)

[4P4CEA013] (20 marks)

Chapter 9: HVAC Systems | Air-cooled versus water-cooled chiller plant – cooling load, kW/TR, heat rejection, CW pump and tower fan power, EPI, make-up water and payback

N-1 A convention centre in Hyderabad (built-up area 38,000 m²) is cooled by three air-cooled screw chillers. The energy auditor logged the plant at a steady, typical load and evaluated replacing it with one water-cooled centrifugal chiller, a condenser water (CW) pump and an induced-draft cooling tower. The chilled water pumps and AHUs are common to both options.

Parameter	Value
Chilled water flow / return / supply temperature (existing)	310 m ³ /h / 13.4 °C / 7.8 °C
Total input power of the three air-cooled chillers (incl. condenser fans)	742 kW
Proposed water-cooled chiller: specific power at this load	0.60 kW/TR
CW temperature rise (range) across the condenser	4.8 °C
CW pump: total head / pump efficiency / motor efficiency	24 m / 76 % / 92 %
Cooling tower fans: total air flow / total pressure / fan efficiency / motor efficiency	135 m ³ /s / 16 mmWC / 64 % / 91 %
Equivalent full-load operation	12 h/day $\times$ 300 days = 3,600 h/year
Electricity tariff	₹ 9.20 per kWh
Building annual electricity consumption (existing)	74,20,000 kWh
Cooling tower: cycles of concentration / make-up water cost (tanker)	5 / ₹ 110 per m ³ (drift neglected)
Investment for the water-cooled plant (chiller, tower, pump, piping, civil)	₹ 3.10 crore

Take water density 1,000 kg/m³, Cp 1 kcal/kg °C, 1 TR = 3,024 kcal/h and g = 9.81 m/s².

- a) Estimate the cooling load in kcal/h, TR and kW, and the specific power (kW/TR) and COP of the existing air-cooled plant. **[4 Marks]**
- b) For the water-cooled option, estimate the compressor power, the condenser heat rejection and the CW flow required. **[4 Marks]**
- c) Estimate the electrical input of the CW pump and of the cooling tower fans. **[4 Marks]**
- d) Compare the plant specific power (kW/TR) of the two options; estimate the annual energy and cost saving and the building EPI before and after. **[4 Marks]**

e) Estimate the cooling tower make-up water and its annual cost, the net annual saving and the simple payback.

[4 Marks]

MODEL ANSWER

a) Cooling load and existing plant performance (4 marks)

Given: CHW flow = $310 \text{ m}^3/\text{h} = 3,10,000 \text{ kg/h}$; $\Delta T = 13.4 - 7.8 = 5.6 \text{ }^\circ\text{C}$; air-cooled input = 742 kW.

Formula: $Q = m \times C_p \times \Delta T$; $TR = Q/3,024$; $kW = Q/860$; $kW/TR = \text{input}/TR$; $COP = \text{cooling kW}/\text{input kW}$.

Substitution: $Q = 3,10,000 \times 1 \times 5.6 = 17,36,000 \text{ kcal/h}$ ($\approx 2,019 \text{ kW}$); $TR = 17,36,000/3,024$; $kW = 17,36,000/860$
 $kW/TR = 742/574.1$; $COP = 2,018.6/742$

Result: Cooling load = $17,36,000 \text{ kcal/h} = 574.1 \text{ TR} = 2,018.6 \text{ kW}$; air-cooled plant = 1.293 kW/TR , $COP = 2.72$.

b) Water-cooled chiller – compressor power, heat rejection and CW flow (4 marks)

Given: Load = $574.1 \text{ TR} = 2,018.6 \text{ kW}$; specific power = 0.60 kW/TR ; CW range = $4.8 \text{ }^\circ\text{C}$.

Formula: Compressor kW = $TR \times kW/TR$; heat rejected = cooling kW + compressor kW; CW flow = heat rejected (kcal/h)/($C_p \times \text{range} \times 1,000$) m^3/h .

Substitution: Compressor = $574.07 \times 0.60 = 344.4 \text{ kW}$ ($COP = 2,018.6/344.4 = 5.86$)

Heat rejected = $2,018.6 + 344.4 = 2,363.0 \text{ kW} \times 860 = 20,32,222 \text{ kcal/h}$ ($\approx 2,363 \text{ kW}$)

CW flow = $20,32,222/(1 \times 4.8 \times 1,000)$

Result: Compressor power = 344.4 kW ; condenser heat rejection = $2,363.0 \text{ kW}$ ($= 20,32,222 \text{ kcal/h}$); CW flow = $423.4 \text{ m}^3/\text{h}$.

c) CW pump and cooling tower fan input (4 marks)

Given: CW flow = $423.4 \text{ m}^3/\text{h}$; head = 24 m ; $\eta_{\text{pump}} = 76 \%$; $\eta_{\text{motor}} = 92 \%$. CT air = $135 \text{ m}^3/\text{s}$; $\Delta P = 16 \text{ mmWC}$ ($1 \text{ mmWC} = 9.81 \text{ Pa}$); $\eta_{\text{fan}} = 64 \%$; $\eta_{\text{motor}} = 91 \%$.

Formula: Pump hydraulic kW = $Q (\text{m}^3/\text{s}) \times \rho \times g \times H/1,000$; input = hydraulic/($\eta_{\text{pump}} \times \eta_{\text{motor}}$); fan air kW = $Q \times \Delta P (\text{Pa})/1,000$; input = air kW/($\eta_{\text{fan}} \times \eta_{\text{motor}}$).

Substitution: Pump: $423.4/3,600 \times 1,000 \times 9.81 \times 24/1,000 = 27.69 \text{ kW}$; input = $27.69/(0.76 \times 0.92)$

Fans: $135 \times 16 \times 9.81/1,000 = 21.19 \text{ kW}$; input = $21.19/(0.64 \times 0.91)$

Result: CW pump input = 39.6 kW ; cooling tower fan input = 36.4 kW .

d) Plant specific power, annual saving and EPI (4 marks)

Given: Water-cooled total = $344.4 + 39.6 + 36.4 \text{ kW}$; air-cooled = 742 kW ; $3,600 \text{ h/year}$; ₹ $9.20/\text{kWh}$; building = $74,20,000 \text{ kWh/year}$; area = $38,000 \text{ m}^2$.

Formula: Plant kW/TR = total input/TR; saving = $\Delta \text{kW} \times \text{hours}$; EPI = annual kWh/built-up area.

Substitution: Water-cooled total = $420.4 \text{ kW} \rightarrow 420.4/574.1 = 0.732 \text{ kW/TR}$ (vs 1.293 kW/TR)

Saving = $(742 - 420.4) \times 3,600 = 321.6 \times 3,600 = 11,57,657 \text{ kWh/year}$; $\times ₹ 9.20$

EPI before = $74,20,000/38,000$; EPI after = $(74,20,000 - 11,57,657)/38,000$

Result: Plant specific power falls from 1.293 to 0.732 kW/TR ; saving = $11,57,657 \text{ kWh/year}$ worth ₹ $1,06,50,442$ (₹ 106.50 lakh); EPI falls from 195.3 to $164.8 \text{ kWh/m}^2\text{-year}$. (The air-cooled chillers were 36.0% of the building's consumption.)

e) Make-up water, net saving and payback (4 marks)

Given: CW flow = $423.4 \text{ m}^3/\text{h}$; range = $4.8 \text{ }^\circ\text{C}$; COC = 5 ; $3,600 \text{ h/year}$; ₹ $110/\text{m}^3$; investment = ₹ $3,10,00,000$.

Formula: Evaporation (m^3/h) = $0.00085 \times 1.8 \times \text{circulation rate} \times \text{range}$; blow-down = $E/(\text{COC} - 1)$; make-up = $E + B$; payback = investment/net saving.

Substitution: $E = 0.00085 \times 1.8 \times 423.4 \times 4.8 = 3.109 \text{ m}^3/\text{h}$; $B = 3.109/4 = 0.777 \text{ m}^3/\text{h}$; make-up = $3.887 \text{ m}^3/\text{h}$

Annual make-up = $3.887 \times 3,600 = 13,992 \text{ m}^3 \times ₹ 110 = ₹ 15,39,104$

Net saving = $1,06,50,442 - 15,39,104 = ₹ 91,11,338$; payback = $3,10,00,000/91,11,338$

Result: Make-up = $3.89 \text{ m}^3/\text{h}$ ($13,992 \text{ m}^3/\text{year}$, ₹ 15,39,104); net saving = ₹ 91,11,338 (₹ 91.11 lakh) per year; simple payback = 3.40 years. Water availability and cost must be part of any air-cooled to water-cooled conversion decision.

[4P4CEA014] (20 marks)

Chapter 1: Boilers | LPG-fired boiler – fuel C/H from flue gas analysis, air–fuel ratio, excess air, indirect efficiency and O_2 trim

N-2 A 3 TPH packaged boiler in a Baddi pharmaceutical plant fires LPG supplied by a new vendor whose certificate of analysis was not available. The energy auditor measured the dry flue gas composition by volume with a portable analyser (cross-checked with an Orsat apparatus) and logged the following:

Parameter	Value
Dry flue gas analysis, % by volume	CO_2 11.2, CO 0.3, O_2 3.9, N_2 84.6
Fuel	LPG (hydrocarbon mixture – carbon and hydrogen only)
LPG firing rate / GCV / price	145 kg/h / 11,900 kcal/kg / ₹ 72 per kg
Flue gas temperature / ambient temperature	215 °C / 32 °C
Humidity of ambient air	0.018 kg/kg dry air
Specific heat of dry flue gas / of superheated vapour	0.24 / 0.45 kcal/kg °C
Radiation and unaccounted losses	1.0 %
Steam enthalpy / feed water temperature	663 kcal/kg / 90 °C
Operating hours	6,000 h/year

Air contains 21 % O_2 and 79 % N_2 by volume (molar mass of air 28.84 kg/kmol); atomic masses C = 12, H = 1, O = 16, N = 14. Work on a basis of 100 kmol of dry flue gas.

- Determine the carbon and hydrogen content (% by mass) of the fuel from the flue gas analysis. **[6 Marks]**
- Determine the actual air supplied and the theoretical air per kg of fuel, and the % excess air. **[4 Marks]**
- Determine the mass of dry flue gas per kg of fuel and per hour. **[2 Marks]**
- Estimate the dry flue gas, hydrogen, CO and air-moisture losses, the boiler efficiency by the indirect method, and the steam generation it implies. **[5 Marks]**
- With burner tuning and an O_2 trim system (₹ 9.5 lakh), CO is eliminated and excess air is held at 10 %. Find the new flue gas O_2 , the new efficiency, the LPG saving (kg/h and ₹/year) and the payback. Take the flue gas temperature as unchanged. **[3 Marks]**

MODEL ANSWER

a) Fuel composition from the flue gas analysis (6 marks)

Given: Per 100 kmol dry flue gas: $\text{CO}_2 = 11.2$, $\text{CO} = 0.3$, $\text{O}_2 = 3.9$, $\text{N}_2 = 84.6$ kmol; fuel contains only C and H; air $\text{N}_2/\text{O}_2 = 79/21$.

Formula: Carbon balance: $\text{C} = \text{CO}_2 + \text{CO}$ (kmol); O_2 from air = $\text{N}_2 \times 21/79$; O_2 appearing in dry gas = $\text{CO}_2 + \text{CO}/2 + \text{O}_2$; O_2 used to burn hydrogen = O_2 from air – O_2 in dry gas; H_2O formed = $2 \times$ that O_2 (kmol), $\text{H} = 2$ kg per kmol H_2O .

Substitution: $\text{C} = 11.2 + 0.3 = 11.5 \text{ kmol} = 11.5 \times 12 = 138.0 \text{ kg}$

O_2 from air = $84.6 \times 21/79 = 22.4886 \text{ kmol}$; O_2 in dry gas = $11.2 + 0.15 + 3.9 = 15.25 \text{ kmol}$

O_2 to hydrogen = $22.4886 - 15.25 = 7.2386 \text{ kmol} \rightarrow \text{H}_2\text{O} = 14.4772 \text{ kmol} \rightarrow \text{H} = 14.4772 \times 2 = 28.954 \text{ kg}$

Fuel burnt = $138.0 + 28.954 = 166.954 \text{ kg}$; $\text{C} = 138.0/166.954 \times 100$; $\text{H} = 28.954/166.954 \times 100$

Result: Fuel: C = 82.66 %, H = 17.34 % by mass (C/H = 4.77), consistent with a propane–butane LPG (propane 81.8 % C, butane 82.8 % C).

b) Actual air, theoretical air and excess air (4 marks)

Given: Per 100 kmol dry gas: O₂ from air = 22.4886 kmol; C = 11.5 kmol; O₂ to hydrogen = 7.2386 kmol; fuel = 166.954 kg; M_{air} = 28.84 kg/kmol.

Formula: Actual air = O₂ from air/0.21; theoretical O₂ = C + O₂ for hydrogen (CO burnt completely); theoretical air = theoretical O₂/0.21; EA % = (actual – theoretical)/theoretical × 100.

Substitution: Actual air = 22.4886/0.21 = 107.089 kmol × 28.84 = 3,088.4 kg → 3,088.4/166.954 = 18.499 kg/kg fuel
Theoretical O₂ = 11.5 + 7.2386 = 18.7386 kmol; theoretical air = 18.7386/0.21 = 89.231 kmol → × 28.84/166.954 = 15.414 kg/kg fuel

$$EA = (107.089 - 89.231)/89.231 \times 100$$

Result: Actual air = 18.50 kg/kg fuel; theoretical air = 15.41 kg/kg fuel; excess air = 20.0 %.

c) Dry flue gas (2 marks)

Given: Per 100 kmol: CO₂ 11.2 (M 44), CO 0.3 (M 28), O₂ 3.9 (M 32), N₂ 84.6 (M 28); fuel = 166.954 kg; firing rate = 145 kg/h.

Formula: m_{dfg} = Σ (kmol × molar mass)/fuel mass.

Substitution: Mass = 11.2 × 44 + 0.3 × 28 + 3.9 × 32 + 84.6 × 28 = 492.8 + 8.4 + 124.8 + 2,368.8 = 2,994.8 kg
m_{dfg} = 2,994.8/166.954; × 145 kg/h

Result: Dry flue gas = 17.938 kg/kg fuel = 2,601 kg/h.

d) Losses, efficiency and implied steam generation (5 marks)

Given: ΔT = 215 – 32 = 183 °C; GCV = 11,900 kcal/kg (≈ 49,823 kJ/kg); C = 82.66 %, H = 17.34 %; m_{dfg} = 17.938 kg/kg; AAS = 18.499 kg/kg; 584 + 0.45 × 183 = 666.35 kcal/kg (≈ 2,790 kJ/kg).

Formula: L1 = m_{dfg} × Cp × ΔT/GCV × 100; L2 = 9H × (584 + Cp_v ΔT)/GCV × 100; L3 (CO) = %CO × C/(%CO + %CO₂) × 5,654/GCV × 100; L4 = AAS × humidity × Cp_v × ΔT/GCV × 100; η = 100 – ΣL; steam = fuel × GCV × η/(h_g – h_f).

Substitution: L1 = 17.938 × 0.24 × 183 = 787.8 kcal/kg (≈ 3,298 kJ/kg) → 6.62 %; L2 = 9 × 0.1734 × 666.35 = 1,040.1 kcal/kg (≈ 4,355 kJ/kg) → 8.74 %

L3 = 0.3 × 0.8266/(0.3 + 11.2) × 5,654 = 121.9 kcal/kg (≈ 510 kJ/kg) → 1.02 %; L4 = 18.499 × 0.018 × 0.45 × 183 = 27.42 kcal/kg (≈ 115 kJ/kg) → 0.23 %

$$\Sigma \text{ losses} = 6.62 + 8.74 + 1.02 + 0.23 + 1.0 = 17.61 \% ; \text{ steam} = 145 \times 11,900 \times 0.8239 / (663 - 90)$$

Result: L1 = 6.62 %, L2 = 8.74 %, L3 = 1.02 %, L4 = 0.23 %; efficiency = 82.39 %; implied steam generation = 2,481 kg/h. The hydrogen loss is the largest single loss for LPG and cannot be reduced without condensing heat recovery.

e) Burner tuning with O₂ trim (3 marks)

Given: Theoretical air = 89.231 kmol per 166.954 kg fuel; EA = 10 %; CO = 0; L2 = 8.74 % and radiation 1.0 % unchanged; ₹ 72/kg LPG; 6,000 h; cost ₹ 9,50,000.

Formula: New flue gas per basis: CO₂ = 11.5, O₂ = 0.10 × theoretical O₂, N₂ = 0.79 × 1.10 × theoretical air (kmol); recompute L1, L4; new fuel = old fuel × η_{old}/η_{new}.

Substitution: Air = 1.10 × 89.231 = 98.155 kmol; O₂ = 0.10 × 18.7386 = 1.8739; N₂ = 0.79 × 98.155 = 77.542 kmol; O₂ % = 1.8739/90.916 × 100

m_{dfg} = (11.5 × 44 + 1.8739 × 32 + 77.542 × 28)/166.954 = 16.395 kg/kg → L1 = 6.05 %; L4 = 16.955 × 0.018 × 0.45 × 183/11,900 × 100 = 0.21 %

$$\eta_{\text{new}} = 100 - (6.05 + 8.74 + 0.21 + 1.0); \text{ LPG} = 145 \times 82.39/84.00 = 142.22 \text{ kg/h}$$

Result: Flue gas $\text{O}_2 \approx 2.1\%$; $\eta_{\text{new}} = 84.00\%$; LPG saving = 2.78 kg/h = 16,675 kg/year worth ₹ 12,00,600 (₹ 12.01 lakh); payback = 0.79 years.

[4P4CEA015] (20 marks)

Chapter 3: Cogeneration Systems / Bagasse cogeneration with a double-extraction condensing turbine – bagasse balance, section-wise power, EUF, export and vapour bleeding

N-3 A 6,000 TCD sugar mill in Belagavi (crushing 250 t cane/h) runs a bagasse-fired boiler and a double-extraction-cum-condensing turbo-generator, and exports surplus power to the state utility during the 160-day season (3,840 h). Average season data:

Parameter	Value
Boiler: steam generation / outlet condition / enthalpy	115 t/h / 87 kg/cm ² (g), 515 °C / 820.4 kcal/kg
Feed water temperature (enthalpy)	171 °C (171 kcal/kg)
Boiler efficiency on GCV / bagasse GCV (50 % moisture)	70 % / 2,270 kcal/kg
Bagasse produced	30 % on cane
Extraction-1 to process (8.5 kg/cm ²): flow / enthalpy	12 t/h / 694.5 kcal/kg
Extraction-2 to boiling house (2.5 kg/cm ²): flow / enthalpy	68 t/h / 646.0 kcal/kg
Condensing steam to condenser (0.1 kg/cm ² (a)): flow / enthalpy	35 t/h / 570.0 kcal/kg
Condensate from process returns at / condenser condensate enthalpy	98 °C (98 kcal/kg) / 46 kcal/kg
Gear-box × generator efficiency	95.5 %
Mill and boiling-house load / cogeneration plant auxiliaries	5,800 kW / 2,600 kW
Export tariff	₹ 4.75 per kWh

- Estimate the bagasse burnt per hour and the surplus bagasse available for the off-season (t/h and t per season). **[4 Marks]**
- Taking the steam path through the turbine section by section, estimate the turbine power, the generator output and the overall steam rate. **[6 Marks]**
- Estimate the process heat delivered, the Energy Utilisation Factor (EUF), the heat-to-power ratio and the heat rejected in the condenser as % of fuel input. **[4 Marks]**
- Estimate the exportable power and the season's export revenue. **[2 Marks]**
- Vapour bleeding in the boiling house cuts extraction-2 demand by 8 t/h, and this steam is sent on to the condensing section (boiler steam unchanged). Estimate the extra power, the extra season revenue and the simple payback on ₹ 2.2 crore; comment on the change in EUF. **[4 Marks]**

MODEL ANSWER

a) Bagasse fired and surplus (4 marks)

Given: Steam = 1,15,000 kg/h; $h_s = 820.4 \text{ kcal/kg}$ ($\approx 3,435 \text{ kJ/kg}$); $h_{fw} = 171 \text{ kcal/kg}$ ($\approx 716 \text{ kJ/kg}$); $\eta = 70\%$; GCV = 2,270 kcal/kg ($\approx 9,504 \text{ kJ/kg}$); cane = 2,50,000 kg/h; bagasse 30 % on cane; season 3,840 h.

Formula: Bagasse = steam $\times (h_s - h_{fw}) / (\eta \times \text{GCV})$; surplus = bagasse produced – bagasse fired.

Substitution: Heat to steam = $1,15,000 \times (820.4 - 171) = 1,15,000 \times 649.4 = 7,46,81,000 \text{ kcal/h}$ ($\approx 86.8 \text{ MW}$)

Bagasse = $7,46,81,000 / (0.70 \times 2,270) = 7,46,81,000 / 1,589$; produced = $2,50,000 \times 0.30 = 75,000 \text{ kg/h}$

Result: Bagasse fired = 46,999 kg/h (47.00 t/h); surplus = 28.00 t/h = 1,07,525 t per season for off-season generation.

b) Turbine power, generator output and steam rate (6 marks)

Given: Section 1 (inlet → extraction-1): 115 t/h, 820.4 → 694.5 kcal/kg ($\approx 2,908$ kJ/kg); section 2 (→ extraction-2): 115 – 12 = 103 t/h, 694.5 → 646.0; section 3 (→ condenser): 103 – 68 = 35 t/h, 646.0 → 570.0; $\eta_{\text{gear}} \times \text{gen} = 95.5\%$.

Formula: Turbine power (kW) = $\Sigma [\text{flow through section} \times \text{enthalpy drop}]/860$; generator output = turbine power $\times \eta$; steam rate = inlet steam/generator output.

Substitution: Section 1 = $1,15,000 \times 125.9 = 1,44,78,500$ kcal/h (≈ 16.8 MW); section 2 = $1,03,000 \times 48.5 = 49,95,500$ kcal/h ($\approx 5,809$ kW); section 3 = $35,000 \times 76.0 = 26,60,000$ kcal/h ($\approx 3,093$ kW)

Total = $2,21,34,000$ kcal/h (≈ 25.7 MW) → turbine power = $2,21,34,000/860 = 25,737$ kW

Generator output = $25,737 \times 0.955$; steam rate = $1,15,000/24,579$

Result: Turbine power = 25,737 kW; generator output = 24,579 kW (24.58 MW); overall steam rate = 4.68 kg/kWh.

c) Process heat, EUF, heat-to-power ratio and condenser loss (4 marks)

Given: Extraction-1 = 12,000 kg/h (694.5 kcal/kg ($\approx 2,908$ kJ/kg)), extraction-2 = 68,000 kg/h (646.0 kcal/kg ($\approx 2,705$ kJ/kg)), condensate return 98 kcal/kg (≈ 410 kJ/kg); power = 24,579 kW; fuel heat = 46,999 kg/h $\times 2,270$ kcal/kg ($\approx 9,504$ kJ/kg); condenser: 35,000 kg/h, 570.0 → 46 kcal/kg (≈ 193 kJ/kg).

Formula: Process heat = $\Sigma \text{flow} \times (h_{\text{ext}} - h_{\text{cond}})$; EUF = $(\text{power} \times 860 + \text{process heat})/\text{fuel heat} \times 100$; heat-to-power = process heat (kW)/power (kW); condenser heat = $m \times (h_{\text{exh}} - h_{\text{c}})$.

Substitution: Process heat = $12,000 \times 596.5 + 68,000 \times 548.0 = 71,58,000 + 3,72,64,000 = 4,44,22,000$ kcal/h = 51,653 kW

Fuel heat = $46,998.7 \times 2,270 = 10,66,87,143$ kcal/h (≈ 124 MW); EUF = $(24,579 \times 860 + 4,44,22,000)/10,66,87,143 \times 100$

Heat-to-power = $51,653/24,579$; condenser = $35,000 \times (570.0 - 46) = 1,83,40,000$ kcal/h (≈ 21.3 MW)

Result: Process heat = 4,44,22,000 kcal/h (≈ 51.7 MW); EUF = 61.5 %; heat-to-power ratio = 2.10; condenser rejects 1,83,40,000 kcal/h (≈ 21.3 MW) = 17.2 % of the fuel input.

d) Exportable power and revenue (2 marks)

Given: Generator output = 24,579 kW; mill + boiling house = 5,800 kW; cogen auxiliaries = 2,600 kW; 3,840 h; ₹ 4.75/kWh.

Formula: Export = generation – own consumption; revenue = export $\times$ hours $\times$ tariff.

Substitution: Export = $24,579 - 5,800 - 2,600 = 16,179$ kW; $\times 3,840$ h = 62.13 MU; $\times ₹ 4.75$

Result: Exportable power = 16,179 kW (62.13 MU per season); revenue = ₹ 29,51,05,596 (₹ 29.51 crore).

e) Vapour bleeding – extra power and payback (4 marks)

Given: 8,000 kg/h diverted from extraction-2 (646.0 kcal/kg ($\approx 2,705$ kJ/kg)) through the condensing section to 570.0 kcal/kg ($\approx 2,386$ kJ/kg); $\eta = 95.5\%$; 3,840 h; ₹ 4.75/kWh; cost ₹ 2,20,00,000.

Formula: Extra power = $m \times (h_{\text{ext}2} - h_{\text{exh}})/860 \times \eta$; extra revenue = kW $\times$ h $\times$ tariff; payback = cost/extra revenue.

Substitution: Extra power = $8,000 \times 76.0/860 \times 0.955 = 675.2$ kW; $\times 3,840$ h = 25,92,625 kWh $\times ₹ 4.75 = ₹ 1,23,14,969$

Payback = $2,20,00,000/1,23,14,969$; EUF_{new} = $(24,579 \times 860 + 675.2 \times 860 + 4,44,22,000 - 8,000 \times 548.0)/10,66,87,143 \times 100$

Result: Extra power = 675 kW; extra revenue = ₹ 1,23,14,969 (₹ 1.23 crore) per season; payback = 1.79 years. EUF falls to 57.9 % because 8 t/h of steam now gives up most of its heat in the condenser – a reminder that a lower EUF can still be the better economic choice when exported power is valued above process heat.

[4P4CEA016] (20 marks)

Chapter 11: Thermal Power Station | Answer any ONE: (a) TPS feed pumps and auxiliary power, (b) EAF hot DRI charging, (c) cement clinker cooler, (d) textile dyeing low-liquor machines

N-4 Answer any ONE of the following among the four questions given below (20 marks).

N-4 (a) Thermal power station – boiler feed pumps, CW pumps and auxiliary power consumption

In a 270 MW coal-fired unit in Tamil Nadu (two motor-driven BFPs with hydraulic couplings in service, one standby), the following were measured at an average load of 255 MW:

Parameter	Value
Flow per BFP (measured at pump discharge)	405 t/h
Feed water temperature at BFP suction / density	165 °C / 903 kg/m ³
BFP suction / discharge pressure	8.5 kg/cm ² (g) / 172 kg/cm ² (g)
BFP motor input (each) / motor efficiency / hydraulic coupling efficiency	3,040 kW / 96.0 % / 95.0 %
Feed water flow at economiser inlet (total)	772 t/h
CW pump (one of three running): flow / total head / motor input / motor efficiency	10,800 m ³ /h / 22 m / 860 kW / 94.0 %
Total unit auxiliary power	24.9 MW
Gross unit heat rate	2,395 kcal/kWh
Design BFP efficiency	80 %
Operating hours / value of saved power	7,500 h/year / ₹ 4.10 per kWh

Take $g = 9.81 \text{ m/s}^2$ and neglect the elevation difference between the pressure gauges.

- Determine the BFP total head (m), hydraulic power, shaft power and pump efficiency. **[6 Marks]**
- Determine the recirculation (leak-off) flow returning to the deaerator and the BFP power wasted on it. **[3 Marks]**
- Determine the CW pump efficiency. **[3 Marks]**
- Determine the auxiliary power consumption (%), the BFPs' share of it, and the net heat rate. **[3 Marks]**
- If the passing recirculation valves are attended and the BFPs are overhauled to design efficiency, estimate the new BFP input, the power saved, the new APC and net heat rate, and the annual benefit. **[5 Marks]**

OR

N-4 (b) Steel industry – electric arc furnace energy and hot DRI charging

A mini steel plant in Jalna melts steel in a 60 t AC electric arc furnace (EAF) charged with scrap and cold DRI. The energy auditor compiled the following average data:

Parameter	Value
Tapped liquid steel / charge per heat	60 t / 45 t scrap + 22 t DRI
Heats per day / tap-to-tap time / power-on time	20 / 72 min / 50 min
Electricity per heat (furnace transformer)	27,600 kWh
Oxygen / specific power of oxygen plant	32 Nm ³ per t liquid steel / 0.55 kWh per Nm ³
Injection carbon / GCV	12 kg per t liquid steel / 7,000 kcal/kg
Natural gas in oxy-fuel burners / GCV	6 Sm ³ per t liquid steel / 9,000 kcal/Sm ³
Heat rate for converting electricity to primary energy	2,500 kcal/kWh
Operating days / power tariff	330 days/year / ₹ 7.40 per kWh

A hot DRI transfer system (₹ 28 crore) is proposed so that the 22 t of DRI per heat is charged at 600 °C instead of 30 °C. Take the mean specific heat of DRI as 0.16 kcal/kg °C and the efficiency with which arc energy reaches the bath as 70 %.

- Determine the daily liquid steel output, the metallic yield and the specific electricity consumption including oxygen (kWh/t liquid steel). **[4 Marks]**

- b) Determine the total specific energy consumption in Gcal/t liquid steel on primary-energy basis. **[5 Marks]**
- c) Determine the sensible heat brought in by hot DRI per heat and the electricity saved per heat and per tonne of liquid steel. **[5 Marks]**
- d) Assuming power-on time falls in proportion to electricity per heat, estimate the new tap-to-tap time, heats per day and extra liquid steel per day. **[3 Marks]**
- e) Estimate the annual electricity cost saving at the present production and the simple payback. **[3 Marks]**

OR

N-4 (c) Cement plant – clinker cooler heat balance and cooler upgrade

A 7,500 TPD clinker line in Andhra Pradesh has a grate cooler. A cooler audit (reference temperature 30 °C, per kg clinker) gave:

Stream	Quantity per kg clinker	Temperature	Specific heat
Clinker entering cooler	1 kg	1,400 °C	0.255 kcal/kg °C
Clinker leaving cooler	1 kg	105 °C	0.19 kcal/kg °C
Total cooling air (from fans)	2.05 Nm ³	30 °C	–
Secondary air to kiln	0.60 Nm ³	960 °C	0.335 kcal/(Nm ³ .°C)
Tertiary air to precalciner	0.28 Nm ³	760 °C	0.33 kcal/(Nm ³ .°C)
Cooler vent air (balance of cooling air)	–	230 °C	0.314 kcal/(Nm ³ .°C)

Other data: cooling fans 3,150 kW and vent fan 640 kW (total); kiln specific thermal energy 735 kcal/kg clinker; coal GCV 5,800 kcal/kg at ₹ 9,800 per t; 330 operating days; power ₹ 6.80 per kWh. A new-generation cross-bar cooler upgrade (₹ 22 crore) is expected to raise recuperation efficiency to 76 % and cut cooler specific power to 10.2 kWh/t clinker. Assume every kcal recuperated displaces one kcal of kiln fuel.

- a) Determine the heat brought in by hot clinker. **[2 Marks]**
- b) Determine the heat recovered in secondary and tertiary air and the cooler recuperation efficiency. **[5 Marks]**
- c) Determine the vent air loss, the clinker discharge loss and the radiation loss (by difference), and present the heat balance. **[5 Marks]**
- d) Determine the cooler specific power consumption (kWh/t clinker). **[2 Marks]**
- e) Estimate the fuel and power savings from the upgrade, the new kiln specific thermal energy, the annual rupee saving and the simple payback. **[6 Marks]**

OR

N-4 (d) Textile process house – soft-flow dyeing steam demand and low-liquor-ratio machine replacement

A polyester–viscose process house in Bhilwara (Rajasthan) runs 12 high-temperature soft-flow dyeing machines round the clock, each doing 4 batches per day. Batch data (per machine):

Parameter	Present machine (MLR 1:8)	Proposed low-liquor machine (MLR 1:5)
Fabric per batch / specific heat of fabric	600 kg / 0.4 kcal/kg °C	600 kg / 0.4 kcal/kg °C
Dye bath heated 30 → 130 °C	4,800 litres	3,000 litres
Two hot washes, each heated 30 → 80 °C	2 × 4,800 litres	2 × 3,000 litres
Machine metal mass / specific heat (heated 30 → 130 °C)	2,500 kg / 0.12 kcal/kg °C	2,200 kg / 0.12 kcal/kg °C
Radiation and other machine losses	8 % of useful heat	8 % of useful heat
Extra electrical load (fabric-transport blower)	–	4.0 kW per machine

Steam gives up 494 kcal/kg in the heating coils (condensate not recovered). Boiler: 74 % efficiency, steam enthalpy 660 kcal/kg, feed water 60 °C, coal GCV 4,300 kcal/kg at ₹ 7,200 per t. Fresh water (softened) costs ₹ 40 per m³ and effluent treatment ₹ 60 per m³; every litre of bath and wash liquor ends up as effluent. Power ₹ 8.10 per kWh; 330 days/year (7,920 h). Replacing all 12 machines costs ₹ 55 lakh per machine. Water density 1 kg/litre, Cp 1 kcal/kg °C.

- Determine the heat and steam required per batch, the daily steam demand and the specific steam consumption (kg steam/kg fabric) of the present machines. **[6 Marks]**
- Repeat (a) for the proposed low-liquor machines and find the % reduction in steam per batch. Explain why the saving is smaller than the 37.5 % cut in liquor volume. **[6 Marks]**
- Determine the annual steam and coal saved and the annual fresh water (= effluent) saved. **[4 Marks]**
- Determine the net annual monetary saving after the extra blower power and the simple payback of the replacement. **[4 Marks]**

MODEL ANSWER

N-4 (a) Solution — BFP, CW pumps and auxiliary power

a) BFP head, hydraulic power and efficiency (6 marks)

Given: $\Delta P = 172 - 8.5 = 163.5 \text{ kg/cm}^2 (\approx 160 \text{ bar})$; $\rho = 903 \text{ kg/m}^3 (0.903 \text{ t/m}^3)$; flow = 4,05,000 kg/h = 112.5 kg/s; motor input 3,040 kW; $\eta_{\text{motor}} = 96.0 \%$; $\eta_{\text{coupling}} = 95.0 \%$.

Formula: Head (m) = $\Delta P (\text{kg/cm}^2) \times 10/\rho (\text{t/m}^3)$; hydraulic power (kW) = $m (\text{kg/s}) \times g \times H/1,000$; shaft power = motor input $\times \eta_{\text{motor}} \times \eta_{\text{coupling}}$; $\eta_{\text{pump}} = \text{hydraulic/shaft} \times 100$.

Substitution: $H = 163.5 \times 10/0.903 = 1,810.6 \text{ m}$; hydraulic power = $112.5 \times 9.81 \times 1,810.6/1,000 = 1,998.3 \text{ kW}$

Cross-check: $Q = 4,05,000/903 = 448.5 \text{ m}^3/\text{h}$; $Q \times \Delta P = 448.5/3,600 \times 163.5 \times 98.0665 \text{ kPa} = 1,997.6 \text{ kW}$

Shaft power = $3,040 \times 0.96 \times 0.95 = 2,772.5 \text{ kW}$; $\eta_{\text{pump}} = 1,998.3/2,772.5 \times 100$

Result: Head = 1,810.6 m; hydraulic power = 1,998.3 kW; shaft power = 2,772.5 kW; BFP efficiency = 72.1 % – about 7.9 points below design (worn internals/balancing-drum leak-off).

b) Recirculation flow and wasted power (3 marks)

Given: BFP flow = $2 \times 405 = 810 \text{ t/h}$; economiser inlet flow = 772 t/h; total BFP input = $2 \times 3,040 \text{ kW}$.

Formula: Recirculation = pump flow – boiler feed flow; wasted power = (recirculation/pump flow) $\times$ BFP input.

Substitution: Recirculation = $810 - 772 = 38 \text{ t/h} (4.69 \%)$; wasted = $4.69 \% \times 6,080 \text{ kW}$

Result: Recirculation through passing valves = 38 t/h; BFP power wasted = 285 kW.

c) CW pump efficiency (3 marks)

Given: $Q = 10,800 \text{ m}^3/\text{h} = 3.0 \text{ m}^3/\text{s}$; $H = 22 \text{ m}$; $\rho = 1,000 \text{ kg/m}^3$; motor input = 860 kW; $\eta_{\text{motor}} = 94.0 \%$.

Formula: $\eta_{\text{pump}} = (Q \times \rho \times g \times H/1,000)/(\text{motor input} \times \eta_{\text{motor}}) \times 100$.

Substitution: Hydraulic = $3.0 \times 1,000 \times 9.81 \times 22/1,000 = 647.46 \text{ kW}$; shaft = $860 \times 0.94 = 808.4 \text{ kW}$; $\eta = 647.46/808.4 \times 100$

Result: CW pump efficiency = 80.1 % – healthy; the CW pumps are not a priority.

d) APC, BFP share and net heat rate (3 marks)

Given: Aux = 24.9 MW; gross = 255 MW; BFPs = 6,080 kW; GHR = 2,395 kcal/kWh ($\approx 10,027 \text{ kJ/kWh}$).

Formula: APC % = aux/gross $\times 100$; NHR = $\text{GHR}/(1 - \text{APC}/100)$.

Substitution: APC = $24.9/255 \times 100$; BFP share = $6,080/24,900 \times 100$; NHR = $2,395/(1 - 0.0976)$

Result: APC = 9.76 %; BFPs = 24.4 % of auxiliary power; net heat rate = 2,654.2 kcal/kWh ($\approx 11,113 \text{ kJ/kWh}$).

e) After attending recirculation valves and BFP overhaul (5 marks)

Given: Required flow per BFP = $772/2 = 386$ t/h at the same head; $\eta_{\text{pump}} = 80\%$; $\eta_{\text{motor}} \times \eta_{\text{coupling}} = 0.96 \times 0.95 = 0.912$; 7,500 h; ₹ 4.10/kWh.

Formula: Hydraulic power $\propto$ flow at constant head; new input = hydraulic/($\eta_{\text{pump}} \times 0.912$); saving = old input – new input; new APC and NHR as in (d).

Substitution: Hydraulic per BFP = $1,998.3 \times 386/405 = 1,904.5$ kW; shaft = $1,904.5/0.80 = 2,380.6$ kW; input = $2,380.6/0.912 = 2,610.4$ kW

Saving = $6,080 - 2 \times 2,610.4 = 859$ kW; APC = $(24,900 - 859)/2,55,000 \times 100 = 9.43\%$; NHR = $2,395/(1 - 0.0943)$

Annual benefit = $859 \times 7,500 = 6.44$ MU $\times$ ₹ 4.10

Result: New BFP input = 2,610 kW each; saving = 859 kW; APC falls to 9.43 %; NHR improves by 9.9 kcal/kWh (≈ 41.4 kJ/kWh) to 2,644.3 kcal/kWh ($\approx 11,071$ kJ/kWh); annual benefit = ₹ 2,64,23,382 (₹ 2.64 crore).

N-4 (b) Solution — EAF and hot DRI charging**a) Output, yield and specific electricity (4 marks)**

Given: 60 t/heat $\times$ 20 heats/day; charge = $45 + 22 = 67$ t/heat; 27,600 kWh/heat; oxygen $32 \text{ Nm}^3/\text{t} \times 0.55 \text{ kWh/Nm}^3$.

Formula: Yield = liquid steel/metallic charge $\times 100$; SEC_{el} = kWh per heat/t per heat + oxygen kWh/t.

Substitution: Liquid steel = $60 \times 20 = 1,200$ t/day; yield = $60/67 \times 100$

Furnace = $27,600/60 = 460.0$ kWh/t; oxygen = $32 \times 0.55 = 17.6$ kWh/t

Result: Output = 1,200 t/day; metallic yield = 89.6 %; specific electricity = 477.6 kWh/t liquid steel.

b) Total SEC on primary-energy basis (5 marks)

Given: Electricity = 477.6 kWh/t at 2,500 kcal/kWh ($\approx 10,467$ kJ/kWh); carbon = $12 \text{ kg/t} \times 7,000 \text{ kcal/kg}$ ($\approx 29,308$ kJ/kg); NG = $6 \text{ Sm}^3/\text{t} \times 9,000 \text{ kcal/Sm}^3$ (≈ 37.7 MJ/Sm³).

Formula: SEC = $\Sigma (\text{quantity} \times \text{conversion factor})/10^6$ in Gcal/t.

Substitution: Electricity = $477.6 \times 2,500 = 11,94,000$ kcal/t = 1.194 Gcal/t

Carbon = $12 \times 7,000 = 84,000$ kcal/t = 0.084 Gcal/t; NG = $6 \times 9,000 = 54,000$ kcal/t = 0.054 Gcal/t

Result: Total SEC = 1.332 Gcal/t liquid steel (= 5.58 GJ/t). Electricity is 89.6 % of it; on a direct 860 kcal/kWh ($\approx 3,601$ kJ/kWh) basis the SEC would be only 0.549 Gcal/t, so the conversion basis must always be stated.

c) Heat from hot DRI and electricity saved (5 marks)

Given: DRI = 22,000 kg/heat; $C_p = 0.16 \text{ kcal/kg } ^\circ\text{C}$ ($\approx 0.670 \text{ kJ/kg}\cdot\text{K}$); $30 \rightarrow 600$ $^\circ\text{C}$; arc-to-bath efficiency = 70 %; 60 t/heat.

Formula: Sensible heat = $m \times C_p \times \Delta T$; electricity saved = heat/(860×0.70); per tonne = saving/60.

Substitution: Heat = $22,000 \times 0.16 \times 570 = 20,06,400$ kcal ($\approx 8,400$ MJ) per heat

Electricity saved = $20,06,400/(860 \times 0.70) = 20,06,400/602$; per t = $3,332.9/60$

Result: Hot DRI brings 20,06,400 kcal ($\approx 8,400$ MJ) per heat; electricity saved = 3,333 kWh/heat = 55.5 kWh/t liquid steel (specific electricity falls to 422.1 kWh/t).

d) Productivity gain (3 marks)

Given: Power-on = 50 min for 27,600 kWh; saving = 3,333 kWh/heat; tap-to-tap = 72 min; 1,440 min/day.

Formula: Δ power-on = $50 \times \text{saving}/27,600$; heats/day = $1,440/\text{new tap-to-tap}$; extra steel = $(\text{new heats} - 20) \times 60$.

Substitution: Δ power-on = $50 \times 3,333/27,600 = 6.04$ min; tap-to-tap = $72 - 6.04 = 65.96$ min; heats = $1,440/65.96$

Result: Tap-to-tap ≈ 66.0 min; 21.83 heats/day; extra liquid steel ≈ 110 t/day if the caster and rolling mill can absorb it.

e) Annual saving and payback (3 marks)

Given: Saving = 3,333 kWh/heat; 20 heats/day $\times$ 330 days; ₹ 7.40/kWh; investment ₹ 28,00,00,000.

Formula: Annual saving = kWh/heat $\times$ heats/year $\times$ tariff; payback = investment/annual saving.

Substitution: kWh = 3,332.9 $\times$ 6,600 = 2,19,97,076 kWh; $\times$ ₹ 7.40 = ₹ 16,27,78,365; payback = 28,00,00,000/16,27,78,365

Result: Annual saving = 22.00 MU worth ₹ 16,27,78,365 (₹ 16.28 crore); simple payback = 1.72 years (before counting electrode savings and extra output).

N-4 (c) Solution — Clinker cooler

a) Heat in hot clinker (2 marks)

Given: Clinker 1 kg at 1,400 °C; $C_p = 0.255$ kcal/kg °C (≈ 1.07 kJ/kg·K); reference 30 °C.

Formula: Heat in = $m \times C_p \times (t - t_{ref})$.

Substitution: Heat in = $1 \times 0.255 \times (1,400 - 30) = 0.255 \times 1,370$

Result: Heat in hot clinker = 349.35 kcal/kg clinker ($\approx 1,463$ kJ/kg clinker).

b) Heat recuperated and recuperation efficiency (5 marks)

Given: SA = 0.60 Nm³ at 960 °C, C_p 0.335; TA = 0.28 Nm³ at 760 °C, C_p 0.33 (kcal per Nm³ °C).

Formula: Heat in air = $V \times C_p \times (t - 30)$; recuperation efficiency = (SA + TA heat)/heat in clinker $\times 100$.

Substitution: SA = $0.60 \times 0.335 \times 930 = 186.93$ kcal/kg clinker (≈ 783 kJ/kg clinker); TA = $0.28 \times 0.33 \times 730 = 67.45$ kcal/kg clinker (≈ 282 kJ/kg clinker)

Recovered = 254.38; efficiency = $254.38/349.35 \times 100$

Result: Heat recovered = 254.38 kcal/kg clinker ($\approx 1,065$ kJ/kg clinker); cooler recuperation efficiency = 72.8 %.

c) Vent, clinker and radiation losses – heat balance (5 marks)

Given: Vent air = 2.05 – 0.60 – 0.28 Nm³/kg at 230 °C, C_p 0.314; clinker out 105 °C, C_p 0.19 kcal/kg °C (≈ 0.795 kJ/kg·K).

Formula: Loss = quantity $\times C_p \times (t - 30)$; radiation = heat in – (SA + TA + vent + clinker).

Substitution: Vent air = 1.17 Nm³/kg $\rightarrow 1.17 \times 0.314 \times 200 = 73.48$ kcal/kg clinker (≈ 308 kJ/kg clinker); clinker = $0.19 \times 75 = 14.25$ kcal/kg clinker (≈ 59.7 kJ/kg clinker)

Radiation = $349.35 - (254.38 + 73.48 + 14.25)$

Result: Vent loss = 73.48 kcal/kg (≈ 308 kJ/kg) (21.0 %); clinker discharge = 14.25 kcal/kg (≈ 59.7 kJ/kg) (4.1 %); radiation = 7.24 kcal/kg (≈ 30.3 kJ/kg) (2.1 %).

Heat balance (kcal/kg clinker)	kcal/kg	%
Input: hot clinker	349.35	100.0
Secondary air	186.93	53.5
Tertiary air	67.45	19.3
Vent air	73.48	21.0
Clinker discharge	14.25	4.1
Radiation (by difference)	7.24	2.1

d) Cooler specific power (2 marks)

Given: Fans = 3,150 + 640 = 3,790 kW; clinker = 7,500/24 = 312.5 t/h.

Formula: Specific power = fan kW/clinker t/h.

Substitution: SPC = 3,790/312.5

Result: Cooler specific power = 12.13 kWh/t clinker.

e) Upgrade – savings and payback (6 marks)

Given: Recuperation 72.8 % → 76 %; heat in = 349.35 kcal/kg ($\approx$ 1,463 kJ/kg); coal 5,800 kcal/kg ($\approx$ 24,283 kJ/kg), ₹ 9,800/t; clinker = $7,500 \times 330 = 24,75,000$ t/year; SPC 12.13 → 10.2 kWh/t; ₹ 6.80/kWh; ₹ 22,00,00,000.

Formula: Extra heat = $\Delta\eta \times$ heat in; coal saved = extra heat/GCV; power saved = Δ SPC $\times$ clinker; payback = investment/total saving.

Substitution: Extra heat = $(76 - 72.82)/100 \times 349.35 = 11.12$ kcal/kg clinker ($\approx$ 46.6 kJ/kg clinker) → STEC = 735 – 11.12 = 723.9 kcal/kg clinker ($\approx$ 3,031 kJ/kg clinker)

Coal = $11.12/5,800 \times 1,000 = 1.918$ kg/t clinker $\times 24,75,000$ t = 4,747 t/year $\times$ ₹ 9,800 = ₹ 4,65,19,417

Power = $(12.13 - 10.2) \times 24,75,000 = 47,71,800$ kWh $\times$ ₹ 6.80 = ₹ 3,24,48,240; payback = 22,00,00,000/7,89,67,657

Result: Coal saved = 4,747 t/year (₹ 4,65,19,417); power saved = 47,71,800 kWh/year (₹ 3,24,48,240); total = ₹ 7,89,67,657 (₹ 7.90 crore) per year; new STEC = 723.9 kcal/kg clinker ($\approx$ 3,031 kJ/kg clinker); payback = 2.79 years.

N-4 (d) Solution — Dyeing steam demand and low-liquor-ratio machines

a) Present machines: heat and steam per batch (6 marks)

Given: Dye bath 4,800 kg $\times$ 100 °C; washes 2 $\times$ 4,800 kg $\times$ 50 °C; machine 2,500 kg $\times$ 0.12 $\times$ 100 °C; fabric 600 kg $\times$ 0.4 $\times$ 100 °C; losses 8 %; latent heat 494 kcal/kg ($\approx$ 2,068 kJ/kg); 12 machines $\times$ 4 batches = 48 batches/day.

Formula: Useful heat = $\Sigma m \times C_p \times \Delta T$; heat supplied = useful $\times$ 1.08; steam = heat supplied/494; specific steam = steam/fabric.

Substitution: Dye bath = $4,800 \times 1 \times 100 = 4,80,000$; washes = $2 \times 4,800 \times 50 = 4,80,000$; machine = $2,500 \times 0.12 \times 100 = 30,000$; fabric = $600 \times 0.4 \times 100 = 24,000$ kcal ($\approx$ 100 MJ)

Useful = 10,14,000 kcal ($\approx$ 4,245 MJ); supplied = $10,14,000 \times 1.08 = 10,95,120$ kcal ($\approx$ 4,585 MJ); steam = $10,95,120/494$

Daily steam = $2,216.8 \times 48/1,000$; specific = $2,216.8/600$

Result: Heat per batch = 10,95,120 kcal ($\approx$ 4,585 MJ); steam per batch = 2,217 kg; daily steam = 106.4 t/day; specific steam = 3.69 kg/kg fabric.

b) Low-liquor machines: heat, steam and % reduction (6 marks)

Given: Dye bath 3,000 kg $\times$ 100 °C; washes 2 $\times$ 3,000 kg $\times$ 50 °C; machine 2,200 kg $\times$ 0.12 $\times$ 100 °C; fabric 600 kg $\times$ 0.4 $\times$ 100 °C; losses 8 %; 494 kcal/kg ($\approx$ 2,068 kJ/kg).

Formula: Same as (a); reduction % = $(\text{steam_old} - \text{steam_new})/\text{steam_old} \times 100$.

Substitution: Dye bath = $3,000 \times 100 = 3,00,000$; washes = $2 \times 3,000 \times 50 = 3,00,000$; machine = $2,200 \times 0.12 \times 100 = 26,400$; fabric = 24,000 kcal ($\approx$ 100 MJ)

Useful = 6,50,400 kcal ($\approx$ 2,723 MJ); supplied = $6,50,400 \times 1.08 = 7,02,432$ kcal ($\approx$ 2,941 MJ); steam = $7,02,432/494 = 1,421.9$ kg

Daily = $1,421.9 \times 48/1,000 = 68.25$ t; specific = $1,421.9/600 = 2.37$ kg/kg; reduction = $(2,216.8 - 1,421.9)/2,216.8 \times 100$

Result: Steam per batch falls from 2,217 to 1,422 kg, a reduction of 35.9 % (specific steam 3.69 → 2.37 kg/kg fabric). The liquor volume falls by 37.5 %, but the heat to the fabric and to the machine metal (which change little) does not, so the steam saving is somewhat smaller.

c) Annual steam, coal and water saved (4 marks)

Given: Steam saved = $794.9 \text{ kg/batch} \times 48 \times 330$; coal per kg steam = $(660 - 60)/(0.74 \times \text{GCV})$ with GCV = 4,300 kcal/kg ($\approx 18,003 \text{ kJ/kg}$); liquor saved = $(14,400 - 9,000) \text{ litres/batch}$.

Formula: Annual steam = saving per batch $\times$ batches/year; coal = steam $\times (h_g - h_f)/(\eta \times \text{GCV})$; water = liquor saved $\times$ batches/year.

Substitution: Batches/year = $48 \times 330 = 15,840$; steam saved = $794.9 \times 15,840/1,000 = 12,591 \text{ t/year}$

Coal per kg steam = $600/(0.74 \times 4,300) = 0.1886 \text{ kg}$; coal saved = $12,591 \times 0.1886 = 2,374 \text{ t/year}$

Water saved = $5,400 \times 15,840/1,000 = 85,536 \text{ m}^3/\text{year}$ ($= 259.2 \text{ m}^3/\text{day}$)

Result: Steam saved = 12,591 t/year; coal saved = 2,374 t/year; fresh water and effluent each reduced by 85,536 m³/year.

d) Net saving and payback (4 marks)

Given: Coal 2,374 t at ₹ 7,200; water + effluent 85,536 m³ at ₹ (40 + 60) per m³; blowers $12 \times 4.0 \text{ kW}$ for 7,920 h at ₹ 8.10; investment $12 \times ₹ 55 \text{ lakh}$.

Formula: Net saving = coal ₹ + water/effluent ₹ – extra power ₹; payback = investment/net saving.

Substitution: Coal = $2,374 \times 7,200 = ₹ 1,70,94,619$; water + effluent = $85,536 \times 100 = ₹ 85,53,600$

Blowers = $48 \times 7,920 \times 8.10 = ₹ 30,79,296$; net = ₹ 2,25,68,923

Payback = $6,60,00,000/2,25,68,923$

Result: Net saving = ₹ 2,25,68,923 (₹ 2.26 crore) per year; simple payback = 2.92 years. About 33 % of the benefit comes from water and effluent, which is why low-liquor machines should be appraised on energy, water and effluent together.

..... End of Section - III

ANSWER KEY**Section I – Brief questions (True/False)**

Q	Code	Chapter	Answer
1	4P4CEA001	Chapter 3: Cogeneration Systems	False
2	4P4CEA002	Chapter 1: Boilers	True
3	4P4CEA003	Chapter 4: Heat Exchangers	True
4	4P4CEA004	Chapter 13: Cement Industry	True
5	4P4CEA005	Chapter 5: Electric Motors and Variable Speed Drives	False
6	4P4CEA006	Chapter 8: Compressors	False
7	4P4CEA007	Chapter 10: Financial Analysis	False
8	4P4CEA008	Chapter 12: Steel Industry	True
9	4P4CEA009	Chapter 2: Furnaces	True
10	4P4CEA010	Chapter 13: Cement Industry	False

Sections II and III – headline results (full working in the model answers)

Q	Code	Marks	Headline result
L-1	4P4CEA011	5	Break-even briquette price = ₹ 6,109 per t (only 3.5 % above today's price); Boiler A would need an ER of 6.83, i.e. an efficiency of 75.17 %. The narrow margin means the loading decision must be reviewed whenever fuel prices change.
L-2	4P4CEA012	5	ESCerts earned = 5,838, worth ₹ 1,25,52,747 (₹ 1.26 crore). Each 1 % rise in APC would raise the NHR by about 28.5 kcal/kWh ($\approx$ 119 kJ/kWh) and wipe out most of these certificates, so auxiliary power is as important as boiler and turbine performance under PAT.
N-1	4P4CEA013	20	Make-up = 3.89 m ³ /h (13,992 m ³ /year, ₹ 15,39,104); net saving = ₹ 91,11,338 (₹ 91.11 lakh) per year; simple payback = 3.40 years. Water availability and cost must be part of any air-cooled to water-cooled conversion decision.
N-2	4P4CEA014	20	Flue gas O ₂ $\approx$ 2.1 %; η_{new} = 84.00 %; LPG saving = 2.78 kg/h = 16,675 kg/year worth ₹ 12,00,600 (₹ 12.01 lakh); payback = 0.79 years.
N-3	4P4CEA015	20	Extra power = 675 kW; extra revenue = ₹ 1,23,14,969 (₹ 1.23 crore) per season;

			payback = 1.79 years. EUF falls to 57.9 % because 8 t/h of steam now gives up most of its heat in the condenser – a reminder that a lower EUF can still be the better economic choice when exported power is valued above pro
N-4(a)	4P4CEA016a	20	New BFP input = 2,610 kW each; saving = 859 kW; APC falls to 9.43 %; NHR improves by 9.9 kcal/kWh (≈ 41.4 kJ/kWh) to 2,644.3 kcal/kWh ($\approx 11,071$ kJ/kWh); annual benefit = ₹ 2,64,23,382 (₹ 2.64 crore).
N-4(b)	4P4CEA016b	20	Annual saving = 22.00 MU worth ₹ 16,27,78,365 (₹ 16.28 crore); simple payback = 1.72 years (before counting electrode savings and extra output).
N-4(c)	4P4CEA016c	20	Coal saved = 4,747 t/year (₹ 4,65,19,417); power saved = 47,71,800 kWh/year (₹ 3,24,48,240); total = ₹ 7,89,67,657 (₹ 7.90 crore) per year; new STEC = 723.9 kcal/kg clinker ($\approx 3,031$ kJ/kg clinker); payback = 2.79 years.
N-4(d)	4P4CEA016d	20	Net saving = ₹ 2,25,68,923 (₹ 2.26 crore) per year; simple payback = 2.92 years. About 33 % of the benefit comes from water and effluent, which is why low-liquor machines should be appraised on energy, water and effluent together.