

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: 3P4CEA001 – 3P4CEA016 | 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. A smoke-tube boiler in a Rajkot pharmaceutical unit generates 15,000 kg/h of dry saturated steam of enthalpy 668 kcal/kg from feed water at 95 °C. Its equivalent evaporation "from and at 100 °C" is about 15,900 kg/h, i.e. higher than the actual evaporation.

[3P4CEA001 | Chapter 1: Boilers | Equivalent evaporation "from and at 100 °C"]

Answer: TRUE (1 mark)

Given: Actual evaporation $Q = 15,000 \text{ kg/h}$; $h_g = 668 \text{ kcal/kg}$ ($\approx 2,797 \text{ kJ/kg}$); $h_f = 95 \text{ kcal/kg}$ ($\approx 398 \text{ kJ/kg}$) (feed water at 95 °C); latent heat at 100 °C = 540 kcal/kg ($\approx 2,261 \text{ kJ/kg}$).

Formula: Equivalent evaporation (from and at 100 °C) = $Q \times (h_g - h_f) / 540$.

Substitution: Equivalent evaporation = $15,000 \times (668 - 95) / 540 = 15,000 \times 573 / 540$.

Result: Equivalent evaporation = 15,917 kg/h – true. Because each kg of actual steam needs 573 kcal/kg ($\approx 2,399 \text{ kJ/kg}$), more than the 540 kcal/kg ($\approx 2,261 \text{ kJ/kg}$) latent heat at 100 °C, the "from and at" figure exceeds the actual 15,000 kg/h; it lets boilers with different feed temperatures and pressures be rated on one basis.

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

2. A furnace-oil-fired crucible furnace in a Chennai die-casting unit melts a 3,000 kg batch of aluminium from 30 °C and superheats it to 720 °C using 210 kg of oil (GCV 10,200 kcal/kg). Take specific heat of solid and liquid aluminium as 0.23 and 0.26 kcal/kg °C, melting point 660 °C and latent heat of fusion 94 kcal/kg. The furnace efficiency is about 22 %.

[3P4CEA002 | Chapter 2: Furnaces | Aluminium melting furnace – efficiency including latent heat of fusion]

Answer: FALSE (1 mark)

Given: $m = 3,000 \text{ kg}$; solid $30 \rightarrow 660 \text{ }^\circ\text{C}$ ($C_p 0.23 \text{ kcal/kg }^\circ\text{C}$ ($\approx 0.963 \text{ kJ/kg}\cdot\text{K}$)); fusion 94 kcal/kg ($\approx 394 \text{ kJ/kg}$); liquid $660 \rightarrow 720 \text{ }^\circ\text{C}$ ($C_p 0.26 \text{ kcal/kg }^\circ\text{C}$ ($\approx 1.09 \text{ kJ/kg}\cdot\text{K}$)); oil $= 210 \text{ kg} \times 10,200 \text{ kcal/kg}$ ($\approx 42,705 \text{ kJ/kg}$).

Formula: Useful heat per kg $= C_{p,s}(t_m - t_1) + L_f + C_{p,l}(t_2 - t_m)$; $\eta = m \times \text{useful heat per kg} / (\text{fuel} \times \text{GCV}) \times 100$.

Substitution: Useful heat per kg $= 0.23 \times 630 + 94 + 0.26 \times 60 = 144.9 + 94 + 15.6 = 254.5 \text{ kcal/kg}$ ($\approx 1,066 \text{ kJ/kg}$); $\eta = 3,000 \times 254.5 / (210 \times 10,200) \times 100 = 7,63,500 / 21,42,000 \times 100$.

Result: $\eta = 35.6 \%$, not 22% , so the statement is false. The 22% figure (22.5%) results if the latent heat of fusion is wrongly left out of the useful heat (only 160.5 kcal/kg ($\approx 672 \text{ kJ/kg}$) of sensible heat).

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

3. A back-pressure turbine in a sugar-mill cogeneration plant receives steam at an enthalpy of 790 kcal/kg and exhausts at an actual enthalpy of 622 kcal/kg ; the combined gear-box, mechanical and generator efficiency is 94% . Its steam rate is about 5.4 kg/kWh .

[3P4CEA003 | Chapter 3: Cogeneration Systems | Steam rate of a back-pressure turbine]

Answer: TRUE (1 mark)

Given: $h_1 = 790 \text{ kcal/kg}$ ($\approx 3,308 \text{ kJ/kg}$); h_2 (actual) $= 622 \text{ kcal/kg}$ ($\approx 2,604 \text{ kJ/kg}$); η (gear $\times$ mechanical $\times$ generator) $= 0.94$; $1 \text{ kWh} = 860 \text{ kcal}$ ($\approx 3,601 \text{ kJ}$).

Formula: Steam rate (kg/kWh) $= 860 / [(h_1 - h_2) \times \eta_{\text{gear-mech-gen}}]$.

Substitution: Steam rate $= 860 / (168 \times 0.94) = 860 / 157.92$.

Result: Steam rate $= 5.45 \text{ kg/kWh}$ – true. A higher actual enthalpy drop (better stage efficiency) lowers the steam rate for the same process steam demand.

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

4. In a shell-and-tube lube-oil cooler, $9,000 \text{ kg/h}$ of oil ($C_p 0.52 \text{ kcal/kg }^\circ\text{C}$) is cooled from $128 \text{ }^\circ\text{C}$ to $84 \text{ }^\circ\text{C}$ by $11,500 \text{ kg/h}$ of cooling water heated from $31 \text{ }^\circ\text{C}$ to $48.2 \text{ }^\circ\text{C}$. The heat duties of the two streams agree within 2% , so the test data can be accepted.

[3P4CEA004 | Chapter 4: Heat Exchangers | Heat balance closure across a lube-oil cooler]

Answer: FALSE (1 mark)

Given: Oil: $9,000 \text{ kg/h}$, $C_p 0.52 \text{ kcal/kg }^\circ\text{C}$ ($\approx 2.18 \text{ kJ/kg}\cdot\text{K}$), $128 \rightarrow 84 \text{ }^\circ\text{C}$; water: $11,500 \text{ kg/h}$, $C_p 1.0 \text{ kcal/kg }^\circ\text{C}$ ($\approx 4.19 \text{ kJ/kg}\cdot\text{K}$), $31 \rightarrow 48.2 \text{ }^\circ\text{C}$.

Formula: $Q = m \times C_p \times \Delta T$ for each stream; imbalance % $= (Q_{\text{hot}} - Q_{\text{cold}}) / Q_{\text{hot}} \times 100$.

Substitution: $Q_{\text{oil}} = 9,000 \times 0.52 \times 44$; $Q_{\text{water}} = 11,500 \times 1.0 \times 17.2$.

Result: $Q_{\text{oil}} = 2,05,920 \text{ kcal/h}$ ($\approx 239 \text{ kW}$); $Q_{\text{water}} = 1,97,800 \text{ kcal/h}$ ($\approx 230 \text{ kW}$); imbalance $= 3.94 \%$ – more than 2% , so the statement is false. Before using such data for U-value or fouling analysis the flow or temperature instruments (or shell heat loss) must be checked.

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

5. A 55 kW motor with a full-load efficiency of 93.0% had a full-load stator copper loss of 1.40 kW . After rewinding, its stator resistance per phase is 10% higher (all other losses unchanged). Its full-load efficiency falls by more than one percentage point.

[3P4CEA005 | Chapter 5: Electric Motors and Variable Speed Drives | Effect of rewinding on motor efficiency]

Answer: FALSE (1 mark)

Given: Output $= 55 \text{ kW}$; $\eta_{\text{old}} = 93.0 \%$; stator Cu loss $= 1.40 \text{ kW}$; resistance $+10 \%$ $\rightarrow$ extra loss $= 0.14 \text{ kW}$ at the same current.

Formula: Input_{old} $= \text{output} / \eta$; input_{new} $= \text{input}_{\text{old}} + \text{extra stator Cu loss}$; $\eta_{\text{new}} = \text{output} / \text{input}_{\text{new}} \times 100$.

Substitution: $\text{Input}_{\text{old}} = 55/0.93 = 59.14 \text{ kW}$; $\text{input}_{\text{new}} = 59.14 + 0.14 = 59.28 \text{ kW}$; $\eta_{\text{new}} = 55/59.28 \times 100$.

Result: $\eta_{\text{new}} = 92.78 \%$, a fall of only **0.22 percentage point** – false. A nominal 10 % rise in stator resistance raises only the stator I^2R component; a large drop after rewinding points to core damage (overheated stripping) or wrong turns.

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

6. An ID fan handles flue gas at 165 °C. Taking the gas as air with a density of 1.293 kg/m³ at 0 °C and neglecting the static pressure correction, the gas density at the fan inlet is about 1.06 kg/m³.

[3P4CEA006 | Chapter 6: Fans and Blowers | Flue gas density at fan inlet temperature]

Answer: FALSE (1 mark)

Given: $\gamma_0 = 1.293 \text{ kg/m}^3$ at 0 °C (273 K); gas temperature $t = 165 \text{ °C}$.

Formula: Corrected gas density $\gamma = 273 \times 1.293 / (273 + t)$.

Substitution: $\gamma = 273 \times 1.293 / (273 + 165) = 352.99 / 438$.

Result: $\gamma = 0.806 \text{ kg/m}^3$, not 1.06 kg/m³, so the statement is false. Using a wrong (higher) density understates the velocity calculated from the pitot reading ($v = C_p \sqrt{2 g \Delta p / \gamma}$) and therefore the flow and efficiency.

Ref: BEE Guidebook Book 4, Ch. 6 (Fans and Blowers).

7. Trimming the impeller of an over-sized centrifugal pump from 315 mm to 290 mm (same speed) reduces its flow by about 8 %, its head by about 15 % and its power by about 22 %.

[3P4CEA007 | Chapter 7: Pumps | Impeller trimming – flow, head and power reduction]

Answer: TRUE (1 mark)

Given: $D_1 = 315 \text{ mm}$; $D_2 = 290 \text{ mm}$; speed unchanged.

Formula: Affinity laws for impeller diameter: $Q_2/Q_1 = D_2/D_1$; $H_2/H_1 = (D_2/D_1)^2$; $P_2/P_1 = (D_2/D_1)^3$.

Substitution: $D_2/D_1 = 290/315 = 0.9206$; $(D_2/D_1)^2 = 0.8476$; $(D_2/D_1)^3 = 0.7803$.

Result: Flow **–7.9 %**, head **–15.2 %**, power **–22.0 %** – true. Trimming is a permanent, low-cost correction when the pump is throttled to meet a lower system requirement.

Ref: BEE Guidebook Book 4, Ch. 7 (Pumps).

8. A spinning mill runs 24 ring frames of 1,008 spindles each in three shifts. In one day the ring frames consumed 10,450 kWh and produced 3,800 kg of 40s yarn. Its ring frame specific energy is 2.75 kWh/kg (UKG) and about 0.144 kWh per spindle shift.

[3P4CEA008 | Chapter 15: Textile Industry | Ring frame specific energy – UKG and kWh per spindle shift]

Answer: TRUE (1 mark)

Given: Energy = 10,450 kWh/day; yarn = 3,800 kg/day; spindles = $24 \times 1,008 = 24,192$; shifts = 3 per day.

Formula: UKG = kWh / kg yarn; kWh per spindle shift = kWh / (number of spindles × shifts).

Substitution: UKG = $10,450 / 3,800$; kWh/spindle shift = $10,450 / (24,192 \times 3) = 10,450 / 72,576$.

Result: UKG = **2.75 kWh/kg**; **0.144 kWh per spindle shift** – true. Both indicators must be compared at the same (reference) count, since finer counts need more energy per kg.

Ref: BEE Guidebook Book 4, Ch. 15 (Textile Industry).

9. An AHU in a Kolkata shopping mall handles 30,000 m³/h of air (density 1.2 kg/m³). Air enthalpy is 58.6 kJ/kg at the coil inlet and 39.4 kJ/kg at the coil outlet. The cooling load delivered by the AHU is about 55 TR.

[3P4CEA009 | Chapter 9: HVAC Systems | AHU cooling load from air-side enthalpy difference]

Answer: TRUE (1 mark)

Given: Air flow = 30,000 m³/h; $\rho = 1.2 \text{ kg/m}^3$; $h_{\text{in}} = 58.6 \text{ kJ/kg}$; $h_{\text{out}} = 39.4 \text{ kJ/kg}$; 1 TR = 3,024 kcal/h ($\approx 3.52 \text{ kW}$); 1 kcal = 4.18 kJ.

Formula: Heat load (TR) = $m \times (h_{in} - h_{out}) / (4.18 \times 3,024)$, with m in kg/h.

Substitution: $m = 30,000 \times 1.2 = 36,000 \text{ kg/h}$; $TR = 36,000 \times (58.6 - 39.4) / (4.18 \times 3,024) = 36,000 \times 19.2 / 12,640.32$.

Result: Cooling load = 54.7 TR (= 192 kW) – true. Comparing this air-side load with the chilled-water-side load reveals duct leakage and unwanted heat ingress.

Ref: BEE Guidebook Book 4, Ch. 9 (HVAC Systems).

10. A 500 MW unit has a turbine cycle heat rate of 1,985 kcal/kWh and a boiler efficiency of 87.5 %. Its gross unit heat rate is about 1,737 kcal/kWh.

[3P4CEA010 | Chapter 11: Thermal Power Station | Unit heat rate from turbine heat rate and boiler efficiency]

Answer: FALSE (1 mark)

Given: Turbine heat rate = 1,985 kcal/kWh ($\approx 8,311 \text{ kJ/kWh}$); boiler efficiency = 87.5 %.

Formula: Gross unit heat rate = turbine heat rate / boiler efficiency.

Substitution: Unit heat rate = $1,985 / 0.875$.

Result: Unit heat rate = 2,268.6 kcal/kWh ($\approx 9,498 \text{ kJ/kWh}$) (gross unit efficiency = $860/2,268.6 = 37.9\%$) – false. The figure of 1,737 kcal/kWh ($\approx 7,272 \text{ kJ/kWh}$) comes from wrongly multiplying by the boiler efficiency; boiler losses always raise the unit heat rate above the turbine heat rate.

Ref: BEE Guidebook Book 4, Ch. 11 (Thermal Power Station).

..... 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

[3P4CEA011] (5 marks)

Chapter 5: Electric Motors and Variable Speed Drives | Field determination of motor efficiency – no-load test, hot stator resistance, slip and stray loss

L-1 A 90 kW, 415 V, 152 A, 4-pole, 50 Hz, delta-connected, class F induction motor drives a process water pump in a Vapi chemical plant. Its name-plate full-load speed is 1,484 rpm. The energy auditor carried out the field tests below:

Test / parameter	Value
No-load test at rated voltage and frequency: line current / input power	41.0 A / 2,780 W
Stator resistance per phase measured at ambient 30 °C	0.082 Ω
Assumed winding operating temperature (class F)	120 °C
Stray load loss (IEEE 112 value for 1–125 HP motors)	1.8 % of rated output

Following the guidebook field method, determine (a) the iron plus friction and windage losses, (b) the stator copper loss at full load at operating temperature, (c) the full-load slip and rotor input, (d) the full-load input, efficiency and power factor, and (e) the full-load efficiency if the stray loss is taken as 0.5 % of rated output (IS/IEC convention). Comment.

MODEL ANSWER

a) Iron + friction and windage losses (1 mark)

Given: No-load input $P_{nl} = 2,780 \text{ W}$; no-load line current = 41.0 A; $R (30^\circ \text{C}) = 0.082 \Omega$ per phase; delta connection $\rightarrow$ phase current = $I/\sqrt{3}$.

Formula: Stator Cu loss at no load = $3 \times (I_{nl}/\sqrt{3})^2 \times R = I_{nl}^2 \times R$; $P_{i+fw} = P_{nl} - \text{stator Cu loss}$.

Substitution: Stator Cu loss (no load) = $41.0^2 \times 0.082 = 137.84 \text{ W}$

$$P_{i+fw} = 2,780 - 137.84$$

Result: Iron + friction and windage losses = 2,642.2 W.

b) Stator copper loss at full load (120 °C) (1 mark)

Given: $R_1 = 0.082 \Omega$ at $t_1 = 30^\circ\text{C}$; $t_2 = 120^\circ\text{C}$; full-load current = 152 A.

Formula: $R_2 = R_1 \times (235 + t_2)/(235 + t_1)$; full-load stator Cu loss = $3 \times (I/\sqrt{3})^2 \times R_2 = I^2 \times R_2$.

Substitution: $R_{120} = 0.082 \times (235 + 120)/(235 + 30) = 0.082 \times 355/265 = 0.1098 \Omega$

$$\text{Stator Cu loss} = 152^2 \times 0.1098 = 23,104 \times 0.1098$$

Result: $R_{120} = 0.1098 \Omega$ per phase; full-load stator copper loss = 2,538.0 W.

c) Full-load slip and rotor input (1 mark)

Given: $N_s = 120 \times 50/4 = 1,500 \text{ rpm}$; $N_{FL} = 1,484 \text{ rpm}$; rated output = 90,000 W.

Formula: Slip $S = (N_s - N)/N_s$; rotor input $P_r = \text{output}/(1 - S)$ (rotor Cu loss = $S \times \text{rotor input}$).

Substitution: $S = (1,500 - 1,484)/1,500 = 16/1,500 = 0.01067$

$$P_r = 90,000/(1 - 0.01067)$$

Result: Slip = 0.01067 (1.07 %); rotor input = 90,970.4 W (rotor copper loss = 970.4 W).

d) Full-load input, efficiency and power factor (stray 1.8 %) (1 mark)

Given: $P_r = 90,970.4 \text{ W}$; stator Cu = 2,538.0 W; $P_{i+fw} = 2,642.2 \text{ W}$; stray = $0.018 \times 90,000 = 1,620 \text{ W}$.

Formula: $P_{\text{input}} = P_r + \text{stator Cu loss} + P_{i+fw} + \text{stray loss}$; $\eta = \text{output}/P_{\text{input}} \times 100$; $\text{PF} = P_{\text{input}}/(\sqrt{3} \times V \times I)$.

Substitution: $P_{\text{input}} = 90,970.4 + 2,538.0 + 2,642.2 + 1,620 = 97,770.5 \text{ W}$

$$\eta = 90,000/97,770.5 \times 100; \text{PF} = 97,770.5/(\sqrt{3} \times 415 \times 152) = 97,770.5/1,09,257.8$$

Result: Full-load input = 97,770.5 W; efficiency = 92.05 %; power factor = 0.895 (total losses 7,770 W).

e) Efficiency with stray loss at 0.5 % of output (1 mark)

Given: Stray = $0.005 \times 90,000 = 450 \text{ W}$; other components as in (d).

Formula: $P_{\text{input}} = P_r + \text{stator Cu loss} + P_{i+fw} + \text{stray loss}$; $\eta = \text{output}/P_{\text{input}} \times 100$.

Substitution: $P_{\text{input}} = 90,970.4 + 2,538.0 + 2,642.2 + 450 = 96,600.5 \text{ W}$; $\eta = 90,000/96,600.5 \times 100$

Result: $\eta = 93.17 \%$, i.e. 1.11 percentage point higher than with the IEEE stray value. Comment: the stray-loss assumption alone shifts the answer by more than 1 point, which is why field-test efficiencies (and name-plate slip) must be used with caution; the guidebook notes actual stray losses of motors up to 200 HP are 1–3 %.

[3P4CEA012] (5 marks)

Chapter 9: HVAC Systems | Cooling tower test – range, approach, effectiveness, evaporation, COC and make-up water economics

L-2 An induced-draft counter-flow cooling tower serves the water-cooled chillers of an IT park in Chennai. Readings taken during a performance test:

Parameter	Value
Circulating cooling water flow (ultrasonic meter)	820 m ³ /h
Hot water (inlet) / cold water (outlet) temperature	36.4 °C / 31.2 °C
Ambient wet bulb temperature	27.9 °C
Chlorides in circulating water / in make-up water	360 ppm / 90 ppm
Operating hours / cost of tanker make-up water	6,000 h/year / ₹ 85 per m ³

Take density 1,000 kg/m³, C_p 1 kcal/kg °C and neglect drift loss. Determine (a) the range, approach and effectiveness, (b) the heat rejected (kcal/h, kW and TR), (c) the evaporation loss, (d) the cycles of concentration

(COC), blow-down and make-up water requirement and its annual cost, and (e) the annual water and cost savings if COC is raised to 6 by better water treatment.

MODEL ANSWER

a) Range, approach and effectiveness (1 mark)

Given: Hot water = 36.4 °C; cold water = 31.2 °C; WBT = 27.9 °C.

Formula: Range = $T_{\text{hot}} - T_{\text{cold}}$; approach = $T_{\text{cold}} - \text{WBT}$; effectiveness = $\text{range} / (\text{range} + \text{approach}) \times 100$.

Substitution: Range = 36.4 – 31.2; approach = 31.2 – 27.9; effectiveness = $5.2 / (5.2 + 3.3) \times 100$

Result: Range = 5.2 °C; approach = 3.3 °C; effectiveness = 61.2 %.

b) Heat rejected (1 mark)

Given: Flow = 820 m³/h = 8,20,000 kg/h; range = 5.2 °C.

Formula: $Q = m \times C_p \times \text{range}$; kW = kcal/h ÷ 860; TR = kcal/h ÷ 3,024.

Substitution: $Q = 8,20,000 \times 1 \times 5.2 = 42,64,000 \text{ kcal/h}$ ($\approx 4,958 \text{ kW}$); $42,64,000 / 860$; $42,64,000 / 3,024$

Result: Heat rejected = 42,64,000 kcal/h = 4,958 kW = 1,410 TR.

c) Evaporation loss (1 mark)

Given: Circulating flow = 820 m³/h; range = 5.2 °C.

Formula: Evaporation loss (m³/h) = $0.00085 \times 1.8 \times \text{circulation rate (m}^3/\text{h)} \times \text{range (}^\circ\text{C)}$.

Substitution: $E = 0.00085 \times 1.8 \times 820 \times 5.2$

Result: Evaporation loss = 6.52 m³/h (0.80 % of circulation).

d) COC, blow-down, make-up and cost (1 mark)

Given: Chlorides: circulating 360 ppm, make-up 90 ppm; E = 6.52 m³/h; 6,000 h/year; ₹ 85 per m³.

Formula: COC = chlorides in circulating water / chlorides in make-up; blow-down B = $E / (\text{COC} - 1)$; make-up = E + B (drift neglected).

Substitution: $\text{COC} = 360 / 90 = 4.0$; $B = 6.52 / (4 - 1) = 2.17 \text{ m}^3/\text{h}$; make-up = 6.52 + 2.17 = 8.70 m³/h

Annual make-up = $8.6986 \times 6,000 = 52,191 \text{ m}^3$; cost = $52,191 \times 85$

Result: COC = 4.0; blow-down = 2.17 m³/h; make-up = 8.70 m³/h (52,191 m³/year) costing ₹ 44,36,266 (₹ 44.36 lakh) per year.

e) Savings at COC = 6 (1 mark)

Given: COC = 6; E unchanged = 6.52 m³/h.

Formula: $B = E / (\text{COC} - 1)$; make-up = E + B; saving = (old make-up – new make-up) × hours × water cost.

Substitution: $B = 6.52 / 5 = 1.30 \text{ m}^3/\text{h}$; make-up = 7.83 m³/h

Saving = $(8.6986 - 7.8287) \times 6,000 = 5,219 \text{ m}^3/\text{year}$; × ₹ 85

Result: Water saved = 0.87 m³/h = 5,219 m³/year, worth ₹ 4,43,627 (₹ 4.44 lakh) per year; only blow-down falls – evaporation is fixed by the heat load.

..... 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)

[3P4CEA013] (20 marks)

Chapter 1: Boilers | Rice-husk-fired boiler – indirect method with CO, surface (wind) and unburnt losses, direct-method cross-check and economiser retrofit

N-1 Parboiling and paddy drying in a rice mill near Karnal draw saturated steam from a 14 TPH water-tube boiler burning rice husk. A 6-hour trial was run with the husk weighed on a platform scale. Readings:

Measured item	Reading
Husk composition as fired, % by mass	C 37.6, H 4.8, N 0.4, O 31.5, S 0.05, moisture 9.8, ash 15.85
Husk GCV (as fired) / delivered price	3,320 kcal/kg / ₹ 3,800 per t
Husk firing rate	3,050 kg/h
Stack gas analyser (dry): O ₂ / CO ₂ / CO	6.8 % / 13.1 % / 0.18 % (1,800 ppm)
Stack gas / surrounding air temperature	192 °C / 31 °C
Water vapour content of surrounding air	0.0205 kg/kg dry air
Cp of dry stack gas / of water vapour	0.23 / 0.45 kcal/kg °C
Bed (bottom) ash : fly ash split	30 : 70
Calorific value of bed ash / fly ash residue	1,050 / 720 kcal/kg
Casing: exposed area / mean skin temperature / wind speed	160 m ² / 68 °C / 1.2 m/s
Steam output and its enthalpy	12,600 kg/h; 664 kcal/kg
Feed water inlet / yearly running	62 °C / 7,200 h

- Work out the stoichiometric air, the % excess air and the air actually supplied per kg of husk. **[3 Marks]**
- Work out the dry stack gas produced per kg of husk, constituent by constituent. **[2 Marks]**
- Using the BEE guidebook procedure, quantify: stack (dry gas) loss; hydrogen loss; fuel-moisture loss; air-moisture loss; CO (incomplete combustion) loss; casing loss using the wind-velocity formula; fly ash and bed ash unburnt losses. **[9 Marks]**
- Arrive at the indirect efficiency, compare it with the input–output (direct) figure and give the steam-to-husk evaporation ratio. **[3 Marks]**
- A feed-water economiser (installed cost ₹ 22 lakh) is proposed to cool the stack gas from 192 °C to 152 °C, all other readings unchanged (take the casing, CO and ash losses as unchanged in %). Work out the new efficiency, the yearly husk and rupee saving for unchanged steam output, the heat picked up by the feed water and its outlet temperature, and the simple payback. **[3 Marks]**

MODEL ANSWER**a) Combustion air (3 marks)**

Given: C = 37.6 %, H = 4.8 %, O = 31.5 %, S = 0.05 %; O₂ in flue gas = 6.8 %.

Formula: Theoretical air (kg/kg fuel) = $[11.6 C + 34.8 (H - O/8) + 4.35 S]/100$; EA % = $O_2/(21 - O_2) \times 100$; AAS = $(1 + EA/100) \times \text{theoretical air}$.

Substitution: $H - O/8 = 4.8 - 31.5/8 = 0.8625$; theoretical air = $[11.6 \times 37.6 + 34.8 \times 0.8625 + 4.35 \times 0.05]/100 = (436.16 + 30.015 + 0.2175)/100$

EA = $6.8/(21 - 6.8) \times 100 = 6.8/14.2 \times 100$; AAS = 1.4789×4.6639

Result: Theoretical air = 4.664 kg/kg; excess air = 47.89 %; actual air supplied = 6.897 kg/kg husk. (The high oxygen content of husk sharply reduces its air requirement.)

b) Mass of dry flue gas (2 marks)

Given: C = 0.376, S = 0.0005, N = 0.004 kg/kg; AAS = 6.897 kg/kg; excess air = 2.233 kg/kg.

Formula: $m_{\text{dfg}} = C \times 44/12 + S \times 64/32 + N + AAS \times 0.77 + (AAS - \text{theoretical air}) \times 0.23$ (mass of CO₂ + SO₂ + fuel N₂ + air N₂ + excess O₂).

Substitution: CO₂ = $0.376 \times 44/12 = 1.3787$; SO₂ = $0.0005 \times 2 = 0.0010$; N₂ (fuel) = 0.0040

$$N_2 \text{ (air)} = 6.897 \times 0.77 = 5.3110; \quad O_2 \text{ (excess)} = 2.233 \times 0.23 = 0.5137$$

Result: Mass of dry flue gas = 7.208 kg/kg husk.

c) Losses (indirect method) (9 marks)

Given: $\Delta T = 192 - 31 = 161 \text{ }^\circ\text{C}$; GCV = 3,320 kcal/kg ($\approx 13,900 \text{ kJ/kg}$); $584 + 0.45 \times 161 = 656.45 \text{ kcal/kg}$ ($\approx 2,748 \text{ kJ/kg}$); ash = 0.1585 kg/kg; husk = 3,050 kg/h.

Formula: $L1 = m_{\text{dfg}} \times C_p \times \Delta T / \text{GCV} \times 100$; $L2 = 9H \times (584 + C_{p_v} \Delta T) / \text{GCV} \times 100$; $L3 = M \times (584 + C_{p_v} \Delta T) / \text{GCV} \times 100$; $L4 = \text{AAS} \times \text{humidity} \times C_{p_v} \times \Delta T / \text{GCV} \times 100$; $L5 = \%CO \times C / (\%CO + \%CO_2) \times 5,654 / \text{GCV} \times 100$; $L6 \text{ surface loss (W/m}^2\text{)} = 0.548 [(T_s/55.55)^4 - (T_a/55.55)^4] + 1.957 (T_s - T_a)^{1.25} \sqrt{[(196.85 V_m + 68.9)/68.9]}$; $L7/L8 = \text{ash per kg fuel} \times \text{fraction} \times \text{GCV of ash} / \text{GCV} \times 100$.

Substitution: $L1 = 7.208 \times 0.23 \times 161 = 266.9 \text{ kcal/kg}$ ($\approx 1,117 \text{ kJ/kg}$) $\rightarrow 266.9 / 3,320 \times 100 = 8.04 \%$

$L2 = 9 \times 0.048 \times 656.45 = 283.6 \text{ kcal/kg}$ ($\approx 1,187 \text{ kJ/kg}$) $\rightarrow 8.54 \%$; $L3 = 0.098 \times 656.45 = 64.3 \text{ kcal/kg}$ ($\approx 269 \text{ kJ/kg}$) $\rightarrow 1.94 \%$

$L4 = 6.897 \times 0.0205 \times 0.45 \times 161 = 10.24 \text{ kcal/kg}$ ($\approx 42.9 \text{ kJ/kg}$) $\rightarrow 0.31 \%$

$L5 = 0.18 \times 0.376 / (0.18 + 13.1) \times 5,654 = 28.81 \text{ kcal/kg}$ ($\approx 121 \text{ kJ/kg}$) $\rightarrow 0.87 \%$

$L6: T_s = 341 \text{ K}, T_a = 304 \text{ K}$: radiation = $0.548 \times [(341/55.55)^4 - (304/55.55)^4] = 286.6 \text{ W/m}^2$; convection = $1.957 \times 37^{1.25} \times \sqrt{[(196.85 \times 1.2 + 68.9)/68.9]} = 375.8 \text{ W/m}^2$

Total = $662.4 \text{ W/m}^2 \times 0.86 = 569.7 \text{ kcal/h} \cdot \text{m}^2$ ($\approx 663 \text{ W/m}^2$); $\times 160 \text{ m}^2 = 91,152 \text{ kcal/h}$ ($\approx 106 \text{ kW}$); $L6 = 91,152 / (3,050 \times 3,320) \times 100 = 91,152 / 1,01,26,000 \times 100 = 0.90 \%$

$L7 \text{ (fly ash)} = 0.1585 \times 0.70 \times 720 = 79.88 \text{ kcal/kg}$ ($\approx 334 \text{ kJ/kg}$) $\rightarrow 2.41 \%$; $L8 \text{ (bottom ash)} = 0.1585 \times 0.30 \times 1,050 = 49.93 \text{ kcal/kg}$ ($\approx 209 \text{ kJ/kg}$) $\rightarrow 1.50 \%$

Result: $L1 = 8.04 \%$, $L2 = 8.54 \%$, $L3 = 1.94 \%$, $L4 = 0.31 \%$, $L5 = 0.87 \%$, $L6 = 0.90 \%$, $L7 = 2.41 \%$, $L8 = 1.50 \%$; total losses = 24.51 %.

Loss	kcal/kg husk	%
L1 Dry flue gas	266.9	8.04
L2 Hydrogen in fuel	283.6	8.54
L3 Moisture in fuel	64.3	1.94
L4 Moisture in air	10.24	0.31
L5 Partial combustion (CO)	28.81	0.87
L6 Surface radiation & convection	29.89	0.90
L7 Unburnt in fly ash	79.88	2.41
L8 Unburnt in bottom ash	49.93	1.50
Total	813.6	24.51

d) Efficiency, direct-method cross-check and evaporation ratio (3 marks)

Given: Total losses = 24.51 %; steam 12,600 kg/h; $h_g = 664$, $h_f = 62 \text{ kcal/kg}$ ($\approx 260 \text{ kJ/kg}$); husk 3,050 kg/h $\times 3,320 \text{ kcal/kg}$ ($\approx 13,900 \text{ kJ/kg}$).

Formula: $\eta \text{ (indirect)} = 100 - \Sigma \text{ losses}$; $\eta \text{ (direct)} = Q \times (h_g - h_f) / (q \times \text{GCV}) \times 100$; evaporation ratio = Q/q .

Substitution: $\eta \text{ (indirect)} = 100 - 24.51$

$\eta \text{ (direct)} = 12,600 \times (664 - 62) / (3,050 \times 3,320) \times 100 = 75,85,200 / 1,01,26,000 \times 100$; ER = $12,600 / 3,050$

Result: $\eta \text{ (indirect)} = 75.49 \%$; $\eta \text{ (direct)} = 74.91 \%$; evaporation ratio = 4.13 kg steam/kg husk. The two methods agree within 0.59 percentage point, which validates the test data (the small gap reflects blow-down, which the indirect method does not count, and measurement uncertainty).

e) Feed-water economiser (3 marks)

Given: Stack gas $192 \rightarrow 152^\circ\text{C}$; $\Delta T = 152 - 31 = 121^\circ\text{C}$; $584 + 0.45 \times 121 = 638.45 \text{ kcal/kg}$ ($\approx 2,673 \text{ kJ/kg}$); $m_{\text{dfg}} = 7.208 \text{ kg/kg}$; AAS = 6.897 kg/kg ; L5–L8 unchanged = 5.68% ; steam $12,600 \text{ kg/h}$; economiser ₹ $22,00,000$.

Formula: Recompute L1–L4 with the new ΔT ; new husk rate = old rate $\times \eta_{\text{old}}/\eta_{\text{new}}$; heat picked up = new husk rate $\times$ (fall in stack losses $\times$ GCV); feed water rise = heat/(steam flow $\times C_p$); payback = cost/annual saving.

Substitution: $L1 = 7.208 \times 0.23 \times 121/3,320 \times 100 = 6.04\%$; $L2 = 0.432 \times 638.45/3,320 \times 100 = 8.31\%$; $L3 = 0.098 \times 638.45/3,320 \times 100 = 1.88\%$; $L4 = 6.897 \times 0.0205 \times 0.45 \times 121/3,320 \times 100 = 0.23\%$

Total losses = 22.14% ; $\eta_{\text{new}} = 77.86\%$; husk = $3,050 \times 75.49/77.86 = 2,957.5 \text{ kg/h}$

Saving = $92.5 \text{ kg/h} \times 7,200 \text{ h} = 666.1 \text{ t/year}$; $\times ₹ 3,800 \text{ per t}$

Heat picked up = $2,957.5 \times 2.3615/100 \times 3,320 = 2,957.5 \times 78.40 = 2,31,872 \text{ kcal/h}$ ($\approx 270 \text{ kW}$); feed water rise = $2,31,872/12,600$

Result: $\eta_{\text{new}} = 77.86\%$ (+2.36 points); husk saving = $92.5 \text{ kg/h} = 666.1 \text{ t/year}$, worth ₹ $25,31,126$ (₹ 25.31 lakh) per year; heat recovered = $2,31,872 \text{ kcal/h}$ ($\approx 270 \text{ kW}$); feed water leaves the economiser at about 80.4°C (rise 18.4°C); simple payback = 0.87 years . (Keep the stack above the acid dew point – low for husk, which has almost no sulphur.)

[3P4CEA014] (20 marks)

Chapter 8: Compressors | Reciprocating compressor capacity by the nozzle method – isothermal and volumetric efficiency, pressure reset and heat recovery

N-2 A two-stage, water-cooled, double-acting reciprocating air compressor (rated free air delivery $22 \text{ m}^3/\text{min}$ at $7.0 \text{ kg/cm}^2(\text{g})$) supplies a glass-container plant in Firozabad. Its capacity was tested by the nozzle method as per IS 10431, with the receiver held at $7.0 \text{ kg/cm}^2(\text{g})$ by a throttle valve upstream of the flow nozzle. Test data:

Parameter	Value
Flow coefficient k / nozzle throat diameter	$0.98 / 68 \text{ mm}$
Compressor inlet: absolute pressure / temperature	$1.02 \text{ kg/cm}^2(\text{a}) / 34^\circ\text{C}$
Before the nozzle: absolute pressure / temperature	$1.09 \text{ kg/cm}^2(\text{a}) / 43^\circ\text{C}$
Differential pressure across the nozzle	0.048 kg/cm^2
Gas constant of air	287.1 J/kg K
Motor input power during the test (at $7.0 \text{ kg/cm}^2(\text{g})$ delivery)	138 kW
LP cylinder: bore / stroke / number of cylinders; speed	$360 \text{ mm} / 170 \text{ mm} / 1 \text{ (double acting)}; 740 \text{ rpm}$
Operating hours / electricity tariff	$8,000 \text{ h/year} / ₹ 8.20 \text{ per kWh}$

Use $1 \text{ kg/cm}^2 = 98,066.5 \text{ N/m}^2$ and $\text{FAD } Q_1 (\text{m}^3/\text{s}) = k \times (\pi/4) d^2 \times (T_1/P_1) \times \sqrt{2 \Delta P P_3 R/T_3}$, where suffix 1 = compressor inlet and suffix 3 = before the nozzle (pressures in N/m^2 , absolute).

a) Determine the free air delivery (m^3/s , m^3/h and m^3/min) and the capacity shortfall against the rating. [5 Marks]

b) Determine the isothermal power, the isothermal efficiency (on input power, as in the guidebook) and the specific power consumption in kW per m^3/min . [4 Marks]

c) Determine the compressor displacement and the volumetric efficiency. [3 Marks]

d) The farthest user needs $6.0 \text{ kg/cm}^2(\text{g})$ and the line loss is 0.3 kg/cm^2 . If the delivery pressure is reset to $6.3 \text{ kg/cm}^2(\text{g})$, estimate the new power, assuming power varies with $\log_e$ of the pressure ratio at constant isothermal efficiency, and the annual energy and cost savings. [4 Marks]

e) 75% of the input power is rejected to the jacket, inter-cooler and after-cooler water. If 60% of this heat is recovered to preheat boiler make-up water (oil-fired boiler: efficiency 84% , GCV $10,200 \text{ kcal/kg}$, oil at ₹ 52 per kg), estimate the annual oil and cost savings and the hot water flow available if the water is heated from 32°C to 68°C . [4 Marks]

MODEL ANSWER

a) Free air delivery by nozzle method (5 marks)

Given: $k = 0.98$; $d = 0.068 \text{ m}$; $P_1 = 1.02 \text{ kg/cm}^2(\text{a})$ ($\approx 1.00 \text{ bar(a)}$), $T_1 = 307 \text{ K}$; $P_3 = 1.09 \text{ kg/cm}^2(\text{a})$ ($\approx 1.07 \text{ bar(a)}$), $T_3 = 316 \text{ K}$; $\Delta P = 0.048 \text{ kg/cm}^2$ ($\approx 0.047 \text{ bar} = 4.71 \text{ kPa}$); $R = 287.1 \text{ J/kg K}$; rated FAD = $22 \text{ m}^3/\text{min}$.

Formula: $Q_1 = k \times (\pi/4) d^2 \times (T_1/P_1) \times \sqrt{2 \Delta P P_3 R/T_3}$ (SI units); shortfall % = $(\text{rated} - \text{actual})/\text{rated} \times 100$.

Substitution: $P_1 = 1.02 \times 98,066.5 = 1,00,027.8 \text{ N/m}^2$; $P_3 = 1.09 \times 98,066.5 = 1,06,892.5 \text{ N/m}^2$; $\Delta P = 0.048 \times 98,066.5 = 4,707.2 \text{ N/m}^2$

$(\pi/4) d^2 = 0.7854 \times 0.068^2 = 0.003632 \text{ m}^2$; $T_1/P_1 = 307/1,00,027.8 = 3.06915 \times 10^{-3}$

$\sqrt{2 \times 4,707.2 \times 1,06,892.5 \times 287.1/316} = 30,237.3$

$Q_1 = 0.98 \times 0.003632 \times 3.06915 \times 10^{-3} \times 30,237.3$

Result: FAD = $0.3303 \text{ m}^3/\text{s} = 1,189.0 \text{ m}^3/\text{h} = 19.82 \text{ m}^3/\text{min}$; shortfall = $(22 - 19.82)/22 \times 100 = 9.9 \%$ – indicates worn valves/rings or a choked suction filter.

b) Isothermal power, isothermal efficiency and specific power (4 marks)

Given: $P_1 = 1.02 \text{ kg/cm}^2(\text{a})$ ($\approx 1.00 \text{ bar(a)}$); $P_2 = 7.0 + 1.02 = 8.02 \text{ kg/cm}^2(\text{a})$ ($\approx 7.86 \text{ bar(a)}$); $Q_1 = 1,189.0 \text{ m}^3/\text{h}$; input = 138 kW .

Formula: Isothermal power (kW) = $P_1 \times Q_1 \times \log_e r / 36.7$ (P_1 in $\text{kg/cm}^2(\text{a})$, Q_1 in m^3/h , $r = P_2/P_1$); isothermal efficiency = isothermal power / input power; specific power = kW / FAD (m^3/min).

Substitution: $r = 8.02/1.02 = 7.8627$; $\log_e r = 2.0621$

Isothermal power = $1.02 \times 1,189.0 \times 2.0621/36.7 = 68.15 \text{ kW}$; $\eta_{\text{iso}} = 68.15/138 \times 100$; SPC = $138/19.82$

Result: Isothermal power = 68.15 kW ; isothermal efficiency = 49.4% ; specific power = $6.96 \text{ kW per m}^3/\text{min}$ (0.1161 kWh/m^3) – high for a two-stage reciprocating machine at $7 \text{ kg/cm}^2(\text{g})$ ($\approx 6.86 \text{ bar(g)}$), consistent with the capacity shortfall.

c) Displacement and volumetric efficiency (3 marks)

Given: LP cylinder $D = 0.36 \text{ m}$; $L = 0.17 \text{ m}$; $S = 740 \text{ rpm}$; $\chi = 2$ (double acting); $n = 1$.

Formula: Displacement (m^3/min) = $(\pi/4) \times D^2 \times L \times S \times \chi \times n$; volumetric efficiency = FAD / displacement $\times 100$.

Substitution: Displacement = $0.7854 \times 0.36^2 \times 0.17 \times 740 \times 2 \times 1$; $\eta_{\text{vol}} = 19.82/25.61 \times 100$

Result: Displacement = $25.61 \text{ m}^3/\text{min}$; volumetric efficiency = 77.4% .

d) Lower delivery pressure (4 marks)

Given: New delivery = $6.3 \text{ kg/cm}^2(\text{g})$ ($\approx 6.18 \text{ bar(g)}$) $\rightarrow P_2 = 7.32 \text{ kg/cm}^2(\text{a})$ ($\approx 7.18 \text{ bar(a)}$); present power 138 kW at $r = 7.8627$; $8,000 \text{ h}$; ₹ 8.20 per kWh.

Formula: $P_{\text{new}} = P_{\text{old}} \times \log_e(r_{\text{new}})/\log_e(r_{\text{old}})$; saving = $(P_{\text{old}} - P_{\text{new}}) \times \text{hours} \times \text{tariff}$.

Substitution: $r_{\text{new}} = 7.32/1.02 = 7.1765$; $\log_e r_{\text{new}} = 1.9708$

$P_{\text{new}} = 138 \times 1.9708/2.0621 = 131.89 \text{ kW}$; saving = $6.11 \text{ kW} \times 8,000 \text{ h}$

Result: New power = 131.89 kW (4.4% lower); saving = $48,894 \text{ kWh/year} = ₹ 4,00,931$ (₹ 4.01 lakh) per year.

e) Heat recovery for boiler make-up water (4 marks)

Given: Input = 138 kW ; 75% to cooling water; 60% recovered; boiler $\eta = 84 \%$; GCV = $10,200 \text{ kcal/kg}$ ($\approx 42,705 \text{ kJ/kg}$); ₹ $52/\text{kg}$; $8,000 \text{ h}$; water $32 \rightarrow 68 \text{ }^\circ\text{C}$.

Formula: Heat recovered = input $\times 0.75 \times 0.60$; oil saved = heat (kcal/h)/($\eta_{\text{boiler}} \times \text{GCV}$); water flow = heat/($C_p \times \Delta T$).

Substitution: Heat = $138 \times 0.75 \times 0.60 = 62.1 \text{ kW} = 53,406 \text{ kcal/h}$

Oil = $53,406/(0.84 \times 10,200) = 6.233 \text{ kg/h}$; $\times 8,000 \text{ h} = 49,866 \text{ kg/year}$; water = $53,406/(1,000 \times 36)$

Result: Oil saved = 6.23 kg/h = 49,866 kg/year, worth ₹ 25,93,008 (₹ 25.93 lakh) per year; hot water available ≈ 1.48 m³/h at 68 °C.

[3P4CEA015] (20 marks)

Chapter 3: Cogeneration Systems / Gas-engine trigeneration with exhaust-fired VAM in a hospital – heat rate, VAM COP, EUF, economics and gas-price sensitivity

N-3 A 600-bed hospital in Hyderabad runs a natural-gas engine trigeneration plant. Engine exhaust drives a double-effect exhaust-fired vapour absorption machine (VAM) for air conditioning, and jacket-water heat is used for laundry, kitchen and CSSD hot water. Average data during a 4-hour performance test:

Parameter	Value
Engine generator output (gross) / engine auxiliary consumption	1,200 kW / 3.5 % of gross
Natural gas consumption / GCV	300 Sm ³ /h / 9,500 kcal/Sm ³
Exhaust gas flow / specific heat	1.85 kg/s / 0.27 kcal/kg °C
Exhaust temperature at VAM inlet / outlet	470 °C / 180 °C
VAM: chilled water flow / return / supply temperature	130 m ³ /h / 12.5 °C / 7.5 °C
VAM additional auxiliaries (pumps, cooling tower fan)	18 kW
Jacket water heat available / fraction usefully used	410 kW / 75 %
Grid tariff / NG price (GCV basis)	₹ 11.50 per kWh / ₹ 40 per Sm ³
Alternative: electric chiller plant SEC / PNG hot-water boiler efficiency	0.70 kW/TR / 88 %
Engine O&M cost / operating hours / project cost	₹ 0.85 per kWh gross / 6,000 h/year / ₹ 9.5 crore

Take 1 TR = 3,024 kcal/h, 1 kW = 860 kcal/h, water density 1,000 kg/m³ and Cp 1 kcal/kg °C.

- Calculate the fuel rate, heat rate, gross and net electrical efficiency of the engine generator. **[4 Marks]**
- Calculate the exhaust heat supplied to the VAM, the refrigeration produced (TR) from the chilled water measurements, and the actual COP of the VAM. **[5 Marks]**
- Determine the energy utilisation factor (EUF) of the trigeneration system and its heat-to-power ratio. **[3 Marks]**
- Compare the hourly cost of trigeneration (gas + O&M) with the cost avoided (grid power for the net export to the hospital bus, electric chiller power for the same TR, and PNG for the same hot water). Find the annual net benefit and the simple payback. **[5 Marks]**
- Find the simple payback if the NG price rises to ₹ 46 per Sm³, and the break-even NG price at which the net benefit becomes zero. **[3 Marks]**

MODEL ANSWER

a) Engine generator performance (4 marks)

Given: P_{gross} = 1,200 kW; aux = 3.5 %; NG = 300 Sm³/h × 9,500 kcal/Sm³ (≈ 39.8 MJ/Sm³).

Formula: Fuel rate = NG/P; heat rate = NG × GCV/P; $\eta_e = P \times 860 / (NG \times GCV) \times 100$; P_{net} = P_{gross} × (1 – aux).

Substitution: Heat input = 300 × 9,500 = 28,50,000 kcal/h (≈ 3,314 kW); fuel rate = 300/1,200; heat rate = 28,50,000/1,200

$\eta_{gross} = 1,200 \times 860 / 28,50,000 \times 100$; P_{net} = 1,200 × 0.965 = 1,158 kW; $\eta_{net} = 1,158 \times 860 / 28,50,000 \times 100$

Result: Fuel rate = 0.25 Sm³/kWh; heat rate = 2,375 kcal/kWh (≈ 9,944 kJ/kWh); $\eta_{gross} = 36.21\%$; $\eta_{net} = 34.94\%$ (heat input = 28,50,000 kcal/h (≈ 3,314 kW)).

b) VAM heat input, refrigeration and COP (5 marks)

Given: Exhaust 1.85 kg/s, Cp 0.27 kcal/kg °C (≈ 1.13 kJ/kg·K), 470 → 180 °C; chilled water 130 m³/h, 12.5 → 7.5 °C.

Formula: Q_{exh} = m × Cp × ΔT; Q_{evap} = m_{chw} × Cp × ΔT; TR = Q_{evap}/3,024; COP = Q_{evap}/Q_{exh}.

Substitution: $Q_{\text{exh}} = 1.85 \times 3,600 \times 0.27 \times (470 - 180) = 6,660 \times 0.27 \times 290 = 5,21,478 \text{ kcal/h} (\approx 606 \text{ kW})$

$Q_{\text{evap}} = 1,30,000 \times 1 \times (12.5 - 7.5) = 6,50,000 \text{ kcal/h} (\approx 756 \text{ kW}); \text{TR} = 6,50,000/3,024; \text{COP} = 6,50,000/5,21,478$

Result: Exhaust heat to VAM = 5,21,478 kcal/h ($\approx 606 \text{ kW}$); refrigeration = 214.9 TR ($\approx 756 \text{ kW}$); actual COP = 1.246 (close to the rated 1.25 for a double-effect exhaust-fired machine, so the VAM is healthy).

c) EUF and heat-to-power ratio (3 marks)

Given: $P = 1,200 \text{ kW}$; exhaust heat used = 606.4 kW; jacket heat used = $410 \times 0.75 = 307.5 \text{ kW}$; fuel input = 3,314.0 kW.

Formula: $\text{EUF} = (\text{electrical output} + \text{useful thermal output})/\text{fuel input} \times 100$; heat-to-power ratio = useful heat/electrical output.

Substitution: $\text{EUF} = (1,200 + 606.4 + 307.5)/3,314.0 \times 100$

Heat-to-power = $(606.4 + 307.5)/1,200$

Result: EUF = 63.8 %; heat-to-power ratio = 0.76 (versus about 36 % for power-only generation).

d) Hourly economics and payback (NG ₹ 40 per Sm^3) (5 marks)

Given: Net power to hospital = $1,158 - 18 = 1,140 \text{ kW}$; cooling = 214.9 TR ($\approx 756 \text{ kW}$); hot water = 2,64,450 kcal/h ($\approx 308 \text{ kW}$); tariff ₹ 11.50/kWh.

Formula: Avoided cost = grid power + electric chiller power ($\text{TR} \times 0.70 \text{ kW/TR}$) $\times$ tariff + PNG for hot water [$\text{heat}/(0.88 \times \text{GCV}) \times \text{price}$]; trigeneration cost = $\text{NG} \times \text{price} + \text{O\&M}$; payback = project cost/annual net benefit.

Substitution: Grid power avoided = $1,140 \times 11.50 = ₹ 13,110/\text{h}$; chiller = $214.9 \times 0.70 = 150.5 \text{ kW} \times 11.50 = ₹ 1,730/\text{h}$

PNG avoided = $2,64,450/(0.88 \times 9,500) = 31.63 \text{ Sm}^3/\text{h} \times 40 = ₹ 1,265/\text{h}$; total avoided = ₹ 16,106/h

Trigeneration cost = $300 \times 40 + 1,200 \times 0.85 = ₹ 12,000 + ₹ 1,020 = ₹ 13,020/\text{h}$

Net benefit = ₹ 3,086/h $\times 6,000 \text{ h} = ₹ 1,85,13,810$; payback = $9,50,00,000/1,85,13,810$

Result: Net benefit = ₹ 3,086 per hour = ₹ 1,85,13,810 (₹ 1.85 crore) per year; simple payback = 5.13 years.

e) Sensitivity to the gas price (3 marks)

Given: $\text{NG} = ₹ 46 \text{ per Sm}^3$; electricity-related avoided cost = ₹ 13,110 + ₹ 1,730 per hour (unchanged).

Formula: Net benefit(p) = [grid + chiller avoided] + PNG avoided(p) – [$\text{NG} \times p + \text{O\&M}$]; break-even when net benefit = 0: $p = (\text{grid} + \text{chiller avoided} - \text{O\&M})/(300 - \text{PNG Sm}^3/\text{h avoided})$.

Substitution: At ₹ 46: avoided = ₹ 16,295/h; cost = $300 \times 46 + 1,020 = ₹ 14,820/\text{h}$; net = ₹ 1,475/h $\times 6,000 = ₹ 88,52,590$

Payback = $9,50,00,000/88,52,590$; break-even $p = (13,110 + 1,730 - 1,020)/(300 - 31.63)$

Result: At ₹ 46 per Sm^3 the payback stretches to 10.73 years; the break-even NG price is ₹ 51.50 per Sm^3 . Gas-engine trigeneration is viable only with full use of exhaust and jacket heat and a firm gas-price contract.

[3P4CEA016] (20 marks)

Chapter 12: Steel Industry | Answer any ONE: (a) HP heater and HP cylinder, (b) secondary steel PAT SEC, (c) cement WHR power, (d) hotel DG, lighting and heat pump

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

N-4 (a) Thermal power station – top HP heater and HP turbine cylinder performance

A 210 MW reheat unit in Maharashtra was tested at full load. Design and test data are given below:

Parameter	Test value	Design value
Feed water flow through HP heater-6	640 t/h	–
Saturation temperature at heater-6	248.6 °C	–

shell pressure		
Feed water inlet / outlet temperature	205.8 °C / 244.2 °C	– / 247.0 °C
Drain (condensate) outlet temperature	213.5 °C	–
TTD / DCA of heater-6	–	1.6 °C / 5.6 °C
Feed water enthalpy at inlet / outlet	211.0 / 252.4 kcal/kg	–
Extraction steam enthalpy / drain enthalpy	742.0 / 219.0 kcal/kg	–
HP turbine: inlet enthalpy / actual exhaust enthalpy / isentropic exhaust enthalpy	806.6 / 732.5 / 717.9 kcal/kg	HP cylinder efficiency 86.0 %
Turbine heat rate (design) / boiler efficiency	2,010 kcal/kWh / 86.5 %	–

Heat-rate sensitivities (OEM curves): 1.1 kcal/kWh per °C shortfall in final feed water temperature; 2.6 kcal/kWh per percentage point drop in HP cylinder efficiency. Coal: GCV 3,600 kcal/kg, ₹ 4,200 per tonne. Annual PLF 80 % (8,760 h).

- Determine the temperature rise, TTD and DCA of heater-6 and their deviations from design. **[4 Marks]**
- Determine the extraction steam flow to heater-6 by heat balance and express it as % of feed water flow. **[4 Marks]**
- Determine the HP cylinder efficiency and its deviation from design. **[4 Marks]**
- Estimate the combined turbine heat-rate deviation, the unit heat-rate deviation, and the annual extra coal and its cost. **[6 Marks]**
- State two likely causes of the high TTD and DCA. **[2 Marks]**

OR

N-4 (b) Secondary steel plant – gate-to-gate SEC and PAT ESCerts

A designated consumer in Raipur makes TMT bars through the coal-based DRI kiln → induction furnace → continuous casting → rolling mill route. A waste-heat-recovery (WHR) boiler on the DRI kiln exhaust drives a captive turbo-generator. Assessment-year data:

Item	Quantity	Calorific value / note
Non-coking coal to DRI kilns	2,10,000 t	4,800 kcal/kg
Grid electricity purchased	2,450 lakh kWh	convert at 860 kcal/kWh (as given)
Furnace oil to billet reheating furnace	9,200 t	10,050 kcal/kg
WHR power generated and consumed internally	1,150 lakh kWh	from DRI kiln waste gas
Liquid steel from induction furnaces / its electricity use	2,28,000 t / 1,450 lakh kWh	–
TMT bars (equivalent product)	2,10,000 t	–

Baseline SEC = 0.665 toe/t TMT; PAT target = 4.0 % reduction. 1 toe = 10^7 kcal; 1 ESCert = 1 toe. ESCert price ₹ 1,500; furnace oil ₹ 48,000 per tonne; grid power ₹ 7.60 per kWh.

- Calculate the total energy input (kcal, Gcal and toe) and the gate-to-gate SEC (toe/t and Gcal/t). Explain why WHR power is not added. **[6 Marks]**
- Calculate the target SEC and the ESCerts earned (or to be purchased). **[4 Marks]**
- Calculate the induction furnace SEC (kWh/t liquid steel) and the energy saving (kWh and toe) if it is brought down to 620 kWh/t. **[4 Marks]**
- Hot charging of billets cuts furnace oil by 30 %. With this and the induction furnace improvement of (c), find the new SEC, the additional ESCerts, and the total annual benefit (energy cost saving + value of all ESCerts). **[6 Marks]**

OR

N-4 (c) Cement plant – waste heat recovery power potential and project appraisal

A 6,000 TPD clinker plant in Karnataka (cement output 26 lakh t/year) plans a steam-Rankine WHR power plant with a preheater (PH) boiler and an air-quenching-cooler (AQC) boiler. Data:

Parameter	PH exit gas	Cooler vent / mid-tap air
Flow	3,90,000 Nm ³ /h	2,60,000 Nm ³ /h
Specific heat	0.345 kcal/Nm ³ °C	0.315 kcal/Nm ³ °C
Temperature at WHR boiler inlet / outlet	320 °C / 200 °C (raw mill drying needs 200 °C)	340 °C / 110 °C
Overall conversion efficiency (heat to gross power)	19.5 %	21.5 %

WHR auxiliary consumption 8 % of gross; operation 7,600 h/year; avoided grid tariff ₹ 7.40 per kWh; O&M ₹ 4.2 crore/year; project cost ₹ 115 crore; life 10 years; discount rate 10 %.

- Calculate the heat recoverable from the PH gas and from the cooler air (kcal/h). **[5 Marks]**
- Calculate the gross and net power output (MW) and the overall heat-to-power efficiency. **[5 Marks]**
- Calculate the annual net generation, its contribution in kWh/t cement and the annual net saving. **[4 Marks]**
- Calculate the simple payback, the NPV at 10 % over 10 years and the discounted payback period. **[6 Marks]**

OR

N-4 (d) Hotel – DG set performance, lighting power density and heat-pump water heating

A 180-room beach resort in Goa was audited. Data:

Parameter	Value
500 kVA DG set: average load / HSD consumption (measured)	280 kW / 82 litres per hour
HSD density / GCV / price	0.83 kg/litre / 10,700 kcal/kg / ₹ 92 per litre
DG lubricating oil + maintenance cost	₹ 1.50 per kWh
DG running hours / of which peak-logging while grid is available	1,800 h/year / 600 h/year
Grid tariff (all inclusive)	₹ 9.40 per kWh
Lobby, banquet and corridors: area / installed lighting load	4,200 m ² / 52.5 kW
Proposed LED retrofit: lighting power density / cost	8.2 W/m ² / ₹ 18.5 lakh; 14 h/day, 365 days
Hot water: 28,000 litres/day from 28 °C to 60 °C, now by LPG boiler	efficiency 82 %; LPG GCV 11,900 kcal/kg; ₹ 100 per kg
Proposed heat pump: COP / cost	3.8 / ₹ 24 lakh

- Calculate the specific energy generation ratio (kWh/litre), heat rate, thermal efficiency and cost of generation of the DG set, and the annual saving if peak logging is stopped. **[7 Marks]**
- Calculate the present lighting power density and the annual energy and cost savings from the LED retrofit. **[5 Marks]**
- Calculate the daily hot water heat demand, the present LPG cost, the heat pump energy and cost, and the annual saving. **[5 Marks]**
- Find the combined simple payback of the LED and heat-pump measures. **[3 Marks]**

MODEL ANSWER**N-4 (a) Solution — HP heater and HP cylinder****a) Temperature rise, TTD and DCA (4 marks)**

Given: $T_{sat} = 248.6\text{ °C}$; FW in = 205.8 °C ; FW out = 244.2 °C ; drain out = 213.5 °C ; design TTD 1.6 °C , DCA 5.6 °C .

Formula: Temperature rise = FW out – FW in; TTD = T_{sat} – FW out; DCA = drain out – FW in.

Substitution: Rise = 244.2 – 205.8; TTD = 248.6 – 244.2; DCA = 213.5 – 205.8

Result: Temperature rise = 38.4 °C; TTD = 4.4 °C (+2.8 °C over design); DCA = 7.7 °C (+2.1 °C over design).

b) Extraction steam flow (4 marks)

Given: FW = 6,40,000 kg/h; h_{fw}: 211.0 → 252.4 kcal/kg (≈ 1,057 kJ/kg); h_{ext} = 742.0 kcal/kg (≈ 3,107 kJ/kg); h_{drain} = 219.0 kcal/kg (≈ 917 kJ/kg).

Formula: m_s × (h_{ext} – h_{drain}) = m_{fw} × (h_{fw,out} – h_{fw,in}).

Substitution: Heat to feed water = 6,40,000 × 41.4 = 2,64,96,000 kcal/h (≈ 30.8 MW)

m_s = 2,64,96,000 / (742.0 – 219.0) = 2,64,96,000 / 523

Result: Extraction steam = 50,662 kg/h (7.92 % of feed water flow).

c) HP cylinder efficiency (4 marks)

Given: h₁ = 806.6 kcal/kg (≈ 3,377 kJ/kg); h₂ (actual) = 732.5 kcal/kg (≈ 3,067 kJ/kg); h_{2s} (isentropic) = 717.9 kcal/kg (≈ 3,006 kJ/kg); design 86.0 %.

Formula: η_{HP} = (h₁ – h₂) / (h₁ – h_{2s}) × 100.

Substitution: η_{HP} = (806.6 – 732.5) / (806.6 – 717.9) × 100 = 74.1 / 88.7 × 100

Result: HP cylinder efficiency = 83.54 %, i.e. 2.46 percentage points below design.

d) Heat-rate deviation and coal impact (6 marks)

Given: FW shortfall = 247.0 – 244.2 = 2.8 °C; HP efficiency deficit = 2.46 points; boiler η = 86.5 %; generation = 210 × 0.80 × 8,760 = 1,47,16,80,000 kWh/year.

Formula: ΔTHR = Σ (deviation × sensitivity); ΔUHR = ΔTHR / η_{boiler}; extra coal = ΔUHR × generation / GCV.

Substitution: ΔTHR = 2.8 × 1.1 + 2.46 × 2.6 = 3.08 + 6.40 = 9.48 kcal/kWh (≈ 39.7 kJ/kWh) (0.47 % of design THR)

ΔUHR = 9.48 / 0.865 = 10.95 kcal/kWh (≈ 45.8 kJ/kWh); extra heat = 10.95 × 1,47,16,80,000 = 1.6122 × 10¹⁰ kcal/year (≈ 67.5 TJ/year)

Extra coal = 1.6122 × 10¹⁰ / 3,600 = 44,78,341 kg = 4,478.3 t/year; cost = 4,478.3 × ₹ 4,200

Result: ΔTHR = 9.48 kcal/kWh (≈ 39.7 kJ/kWh); ΔUHR = 10.95 kcal/kWh (≈ 45.8 kJ/kWh); extra coal = 4,478 t/year costing ₹ 1,88,09,032 (₹ 1.88 crore) per year.

e) Likely causes (2 marks)

Result: (i) High TTD – tube fouling/scaling or plugged tubes reducing surface, or non-condensable gases (air) blanketing the shell because of poor venting; (ii) high DCA – low shell water level letting steam enter the drain-cooling zone, or a damaged drain-cooler zone/partition plate (bypassing). One mark each for any two valid causes.

N-4 (b) Solution — Secondary steel PAT assessment

a) Total energy and SEC (6 marks)

Given: Coal 2,10,000 t × 4,800 kcal/kg (≈ 20,097 kJ/kg); grid 2,450 lakh kWh × 860 kcal/kWh (≈ 3,601 kJ/kWh); FO 9,200 t × 10,050 kcal/kg (≈ 42,077 kJ/kg); TMT 2,10,000 t.

Formula: Energy (kcal) = quantity × CV; Gcal = kcal ÷ 10⁶; toe = kcal ÷ 10⁷; SEC = total toe / TMT production.

Substitution: Coal = 2,10,000 × 1,000 × 4,800 = 1.0080 × 10¹² kcal = 1,00,800 toe (≈ 4,220 TJ)

Grid = 2,450 × 10⁵ × 860 = 2.1070 × 10¹¹ kcal = 21,070 toe (≈ 882 TJ); FO = 9,200 × 1,000 × 10,050 = 9.2460 × 10¹⁰ kcal = 9,246 toe (≈ 387 TJ)

Total = 1.31116 × 10¹² kcal (≈ 5,490 TJ) = 1.31116 × 10¹² / 10⁶ = 13,11,160 Gcal = 1,31,116 toe (≈ 5,490 TJ)

SEC = $1,31,116/2,10,000 = 0.6244 \text{ toe/t}$ ($\approx 26.1 \text{ GJ/t}$); in Gcal/t = $13,11,160/2,10,000$

Result: Total energy = 13,11,160 Gcal = 1,31,116 toe ($\approx 5,490 \text{ TJ}$); SEC = 0.6244 toe/t ($\approx 26.1 \text{ GJ/t}$) TMT = 6.244 Gcal/t. WHR power (31.9 % of the plant's electricity) is generated from heat already counted in the DRI coal, so adding it would count the same energy twice; only energy crossing the plant boundary is counted.

b) Target and ESCerts (4 marks)

Given: Baseline 0.665 toe/t ($\approx 27.8 \text{ GJ/t}$); reduction 4.0 %; actual SEC = 0.6244 toe/t ($\approx 26.1 \text{ GJ/t}$); production 2,10,000 t.

Formula: Target SEC = baseline $\times (1 - 0.04)$; ESCerts = (target SEC – actual SEC) $\times$ production (positive = earned).

Substitution: Target = $0.665 \times 0.96 = 0.6384 \text{ toe/t}$ ($\approx 26.7 \text{ GJ/t}$); ESCerts = $(0.6384 - 0.62436) \times 2,10,000 = 0.01404 \times 2,10,000$

Result: Target SEC = 0.6384 toe/t ($\approx 26.7 \text{ GJ/t}$); the plant over-achieves and earns 2,948 ESCerts.

c) Induction furnace SEC (4 marks)

Given: IF electricity = 1,450 lakh kWh; liquid steel = 2,28,000 t; target 620 kWh/t.

Formula: IF SEC = kWh / t liquid steel; saving = (SEC – 620) $\times$ t; toe = kWh $\times 860/10^7$.

Substitution: SEC = $1,450 \times 10^5/2,28,000 = 636.0 \text{ kWh/t}$

Saving = $(635.96 - 620) \times 2,28,000 = 36,40,000 \text{ kWh}$; $\times 860/10^7$

Result: IF SEC = 636.0 kWh/t; saving = 36,40,000 kWh/year = 313.04 toe ($\approx 13.1 \text{ TJ}$).

d) New SEC, additional ESCerts and benefit (6 marks)

Given: FO cut = $0.30 \times 9,200 = 2,760 \text{ t} = 2,773.8 \text{ toe}$ ($\approx 116 \text{ TJ}$); IF saving = 313.04 toe ($\approx 13.1 \text{ TJ}$) (all from grid power).

Formula: New SEC = (total toe – savings)/production; ESCerts = (target – new SEC) $\times$ production; benefit = FO saved $\times$ price + kWh saved $\times$ tariff + ESCerts $\times$ price.

Substitution: New SEC = $(1,31,116 - 2,773.8 - 313.04)/2,10,000 = 0.6097 \text{ toe/t}$ ($\approx 25.5 \text{ GJ/t}$)

ESCert = $(0.6384 - 0.60966) \times 2,10,000 = 0.02874 \times 2,10,000 = 6,035$ (additional 3,087)

FO saving = $2,760 \times ₹ 48,000 = ₹ 13,24,80,000$; power saving = $36,40,000 \times ₹ 7.60 = ₹ 2,76,64,000$; ESCerts = $6,035 \times ₹ 1,500 = ₹ 90,52,500$

Result: New SEC = 0.6097 toe/t ($\approx 25.5 \text{ GJ/t}$); ESCerts = 6,035 (3,087 more); total annual benefit = ₹ 16,91,96,500 (₹ 16.92 crore). The energy-cost saving dwarfs the ESCert value – PAT is a nudge, the real gain is the fuel and power bill.

N-4 (c) Solution — Cement WHR power

a) Heat recoverable (5 marks)

Given: PH: 3,90,000 Nm³/h, Cp 0.345 kcal ($\approx 1.44 \text{ kJ}$) per Nm³ °C, 320 $\rightarrow$ 200 °C; cooler: 2,60,000 Nm³/h, Cp 0.315 kcal ($\approx 1.32 \text{ kJ}$) per Nm³ °C, 340 $\rightarrow$ 110 °C.

Formula: Heat recoverable = V $\times$ Cp $\times$ (T_{in} – T_{out}).

Substitution: Q_{PH} = $3,90,000 \times 0.345 \times 120 = 1,61,46,000 \text{ kcal/h}$ ($\approx 18.8 \text{ MW}$)

Q_{cooler} = $2,60,000 \times 0.315 \times 230 = 1,88,37,000 \text{ kcal/h}$ ($\approx 21.9 \text{ MW}$)

Result: Q_{PH} = 1,61,46,000 kcal/h ($\approx 18.8 \text{ MW}$); Q_{cooler} = 1,88,37,000 kcal/h ($\approx 21.9 \text{ MW}$); total = 3,49,83,000 kcal/h ($\approx 40.7 \text{ MW}$).

b) Gross and net power (5 marks)

Given: Conversion efficiency 19.5 % (PH), 21.5 % (cooler); 860 kcal = 1 kWh; auxiliary 8 %.

Formula: Gross power (MW) = $Q \times \eta_{\text{conv}}/860/1,000$; net = gross $\times (1 - 0.08)$; overall efficiency = gross $\times 860$ /total heat.

Substitution: $P_{\text{PH}} = 1,61,46,000 \times 0.195/860/1,000 = 3.661 \text{ MW}$; $P_{\text{cooler}} = 1,88,37,000 \times 0.215/860/1,000 = 4.709 \text{ MW}$

Gross = 8.370 MW; net = 8.370×0.92 ; overall $\eta = 8.370 \times 1,000 \text{ kW} \times 860/3,49,83,000 \times 100$

Result: Gross = 8.37 MW; net = 7.70 MW (auxiliary 0.670 MW); overall heat-to-power efficiency = 20.6 %.

c) Annual generation and saving (4 marks)

Given: Net = 7.701 MW; 7,600 h; cement = 26,00,000 t; ₹ 7.40/kWh; O&M ₹ 4,20,00,000.

Formula: Net kWh = net MW $\times 1,000 \times h$; kWh/t = kWh/cement; net saving = kWh $\times$ tariff – O&M.

Substitution: $E = 7.7006 \times 1,000 \times 7,600 = 5,85,24,869 \text{ kWh}$; per t = $5,85,24,869/26,00,000$

Gross saving = $5,85,24,869 \times 7.40 = ₹ 43,30,84,033$; net = ₹ 43,30,84,033 – ₹ 4,20,00,000

Result: Net generation = 5,85,24,869 kWh/year (22.51 kWh/t cement); net annual saving = ₹ 39,10,84,033 (₹ 39.11 crore).

d) Payback, NPV and discounted payback (6 marks)

Given: Investment = ₹ 1,15,00,00,000; annual net saving = ₹ 39,10,84,033; $i = 10 \%$; $n = 10$ years.

Formula: Simple payback = investment/annual saving; NPV = saving $\times [1 - (1 + i)^{-n}]/i$ – investment; discounted payback when cumulative PV = investment.

Substitution: SPB = $1,15,00,00,000/39,10,84,033 = 2.94$ years; annuity factor = $[1 - 1.10^{-10}]/0.10 = 6.1446$

PV = $39,10,84,033 \times 6.1446 = ₹ 2,40,30,42,084$; NPV = $2,40,30,42,084 - 1,15,00,00,000$

Cumulative PV: yr 1 = ₹ 35,55,30,939; yr 2 = ₹ 67,87,40,883; yr 3 = ₹ 97,25,68,106; yr 4 = ₹ 1,23,96,83,762

DPB = $3 + (1,15,00,00,000 - 97,25,68,106)/26,71,15,657$

Result: Simple payback = 2.94 years; NPV = ₹ 1,25,30,42,084 (₹ 125.30 crore); discounted payback = 3.66 years – an attractive project.

N-4 (d) Solution — Hotel

a) DG set performance and peak lopping (7 marks)

Given: Load = 280 kW; HSD = 82 L/h $\times 0.83 \text{ kg/L}$; GCV = 10,700 kcal/kg ($\approx 44,799 \text{ kJ/kg}$); ₹ 92/L; O&M ₹ 1.50/kWh; 600 h peak lopping; grid ₹ 9.40/kWh.

Formula: SEGR = kWh/litre; heat rate = fuel kg/h $\times$ GCV/kW; $\eta = 860/\text{heat rate} \times 100$; cost/kWh = price per litre/SEGR + O&M; saving = (DG cost – grid tariff) $\times$ kW $\times$ hours.

Substitution: SEGR = $280/82 = 3.415 \text{ kWh/L}$; fuel = $82 \times 0.83 = 68.06 \text{ kg/h}$; heat input = $68.06 \times 10,700 = 7,28,242 \text{ kcal/h}$ ($\approx 847 \text{ kW}$)

Heat rate = $7,28,242/280 = 2,600.9 \text{ kcal/kWh}$ ($\approx 10,889 \text{ kJ/kWh}$); $\eta = 860/2,600.9 \times 100$

Cost = $92/3.415 + 1.50 = 26.94 + 1.50$; saving = $(28.44 - 9.40) \times 280 \times 600$

Result: SEGR = 3.41 kWh/litre; heat rate = 2,601 kcal/kWh ($\approx 10,890 \text{ kJ/kWh}$); $\eta = 33.1 \%$; generation cost = ₹ 28.44 per kWh; stopping peak lopping saves ₹ 31,99,200 (₹ 31.99 lakh) per year.

b) Lighting power density and LED retrofit (5 marks)

Given: Installed load = 52.5 kW over 4,200 m²; proposed LPD = 8.2 W/m²; 14 h $\times$ 365 days; ₹ 9.40/kWh.

Formula: LPD = installed lighting load (W)/area (m²); saving = (old kW – new kW) $\times$ hours $\times$ tariff.

Substitution: LPD = $52,500/4,200 = 12.5 \text{ W/m}^2$; new load = $8.2 \times 4,200/1,000 = 34.44 \text{ kW}$

Saving = $(52.50 - 34.44) \times 14 \times 365 = 18.06 \times 5,110 = 92,287 \text{ kWh}$; $\times ₹ 9.40$

Result: Present LPD = 12.5 W/m^2 ; saving = $92,287 \text{ kWh/year} = ₹ 8,67,494$ (₹ 8.67 lakh) per year.

c) Heat pump versus LPG boiler (5 marks)

Given: Hot water = $28,000 \text{ kg/day}$, $28 \rightarrow 60^\circ\text{C}$; LPG boiler η 82 %, $11,900 \text{ kcal/kg}$ ($\approx 49,823 \text{ kJ/kg}$), ₹ 100/kg; heat pump COP 3.8; ₹ 9.40/kWh.

Formula: Heat = $m \times C_p \times \Delta T$; LPG = $\text{heat}/(\eta \times \text{GCV})$; heat pump kWh = $\text{heat}/860/\text{COP}$.

Substitution: Heat = $28,000 \times 1 \times 32 = 8,96,000 \text{ kcal/day}$ ($\approx 3,751 \text{ MJ/day}$); LPG = $8,96,000/(0.82 \times 11,900) = 91.82 \text{ kg/day} \rightarrow ₹ 9,182/\text{day}$

Heat pump = $8,96,000/860/3.8 = 274.2 \text{ kWh/day} \rightarrow ₹ 2,577/\text{day}$; saving = ₹ 6,605/day $\times 365$

Result: Heat demand = $8,96,000 \text{ kcal/day}$ ($\approx 3,751 \text{ MJ/day}$); LPG cost ₹ 9,182/day; heat pump ₹ 2,577/day; annual saving = ₹ 24,10,816 (₹ 24.11 lakh).

d) Combined payback (3 marks)

Given: Investment = ₹ 18,50,000 + ₹ 24,00,000 = ₹ 42,50,000; savings = ₹ 8,67,494 + ₹ 24,10,816.

Formula: Simple payback = total investment / total annual saving.

Substitution: SPB = $42,50,000/(8,67,494 + 24,10,816) = 42,50,000/32,78,310$

Result: Combined simple payback = 1.30 years (stopping peak lopping is a zero-cost measure and adds ₹ 31,99,200 per year).

..... End of Section - III

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

Q	Code	Chapter	Answer
1	3P4CEA001	Chapter 1: Boilers	True
2	3P4CEA002	Chapter 2: Furnaces	False
3	3P4CEA003	Chapter 3: Cogeneration Systems	True
4	3P4CEA004	Chapter 4: Heat Exchangers	False
5	3P4CEA005	Chapter 5: Electric Motors and Variable Speed Drives	False
6	3P4CEA006	Chapter 6: Fans and Blowers	False
7	3P4CEA007	Chapter 7: Pumps	True
8	3P4CEA008	Chapter 15: Textile Industry	True
9	3P4CEA009	Chapter 9: HVAC Systems	True
10	3P4CEA010	Chapter 11: Thermal Power Station	False

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

Q	Code	Marks	Headline result
L-1	3P4CEA011	5	$\eta = 93.17\%$, i.e. 1.11 percentage point higher than with the IEEE stray value. Comment: the stray-loss assumption alone shifts the answer by more than 1 point, which is why field-test efficiencies (and name-plate slip) must be used with caution; the guidebook notes actual stray losses of motors up to
L-2	3P4CEA012	5	Water saved = $0.87 \text{ m}^3/\text{h} = 5,219 \text{ m}^3/\text{year}$, worth ₹ 4,43,627 (₹ 4.44 lakh) per year; only blow-down falls – evaporation is fixed by the heat load.
N-1	3P4CEA013	20	$\eta_{\text{new}} = 77.86\%$ (+2.36 points); husk saving = $92.5 \text{ kg/h} = 666.1 \text{ t/year}$, worth ₹ 25,31,126 (₹ 25.31 lakh) per year; heat recovered = $2,31,872 \text{ kcal/h} (\approx 270 \text{ kW})$; feed water leaves the economiser at about 80.4°C (rise 18.4°C); simple payback = 0.87 years. (Keep the stack above the acid dew point – lo
N-2	3P4CEA014	20	Oil saved = $6.23 \text{ kg/h} = 49,866 \text{ kg/year}$, worth ₹ 25,93,008 (₹ 25.93 lakh) per year; hot water available $\approx 1.48 \text{ m}^3/\text{h}$ at 68°C .
N-3	3P4CEA015	20	At ₹ 46 per Sm^3 the payback stretches to 10.73 years; the

			break-even NG price is ₹ 51.50 per Sm ³ . Gas-engine trigeneration is viable only with full use of exhaust and jacket heat and a firm gas-price contract.
N-4(a)	3P4CEA016a	20	Δ THR = 9.48 kcal/kWh ($\approx$ 39.7 kJ/kWh); Δ UHR = 10.95 kcal/kWh ($\approx$ 45.8 kJ/kWh); extra coal = 4,478 t/year costing ₹ 1,88,09,032 (₹ 1.88 crore) per year.
N-4(b)	3P4CEA016b	20	New SEC = 0.6097 toe/t ($\approx$ 25.5 GJ/t); ESCerts = 6,035 (3,087 more); total annual benefit = ₹ 16,91,96,500 (₹ 16.92 crore). The energy-cost saving dwarfs the ESCert value – PAT is a nudge, the real gain is the fuel and power bill.
N-4(c)	3P4CEA016c	20	Simple payback = 2.94 years; NPV = ₹ 1,25,30,42,084 (₹ 125.30 crore); discounted payback = 3.66 years – an attractive project.
N-4(d)	3P4CEA016d	20	Combined simple payback = 1.30 years (stopping peak lopping is a zero-cost measure and adds ₹ 31,99,200 per year).