THERMO-ECONOMIC ANALYSIS

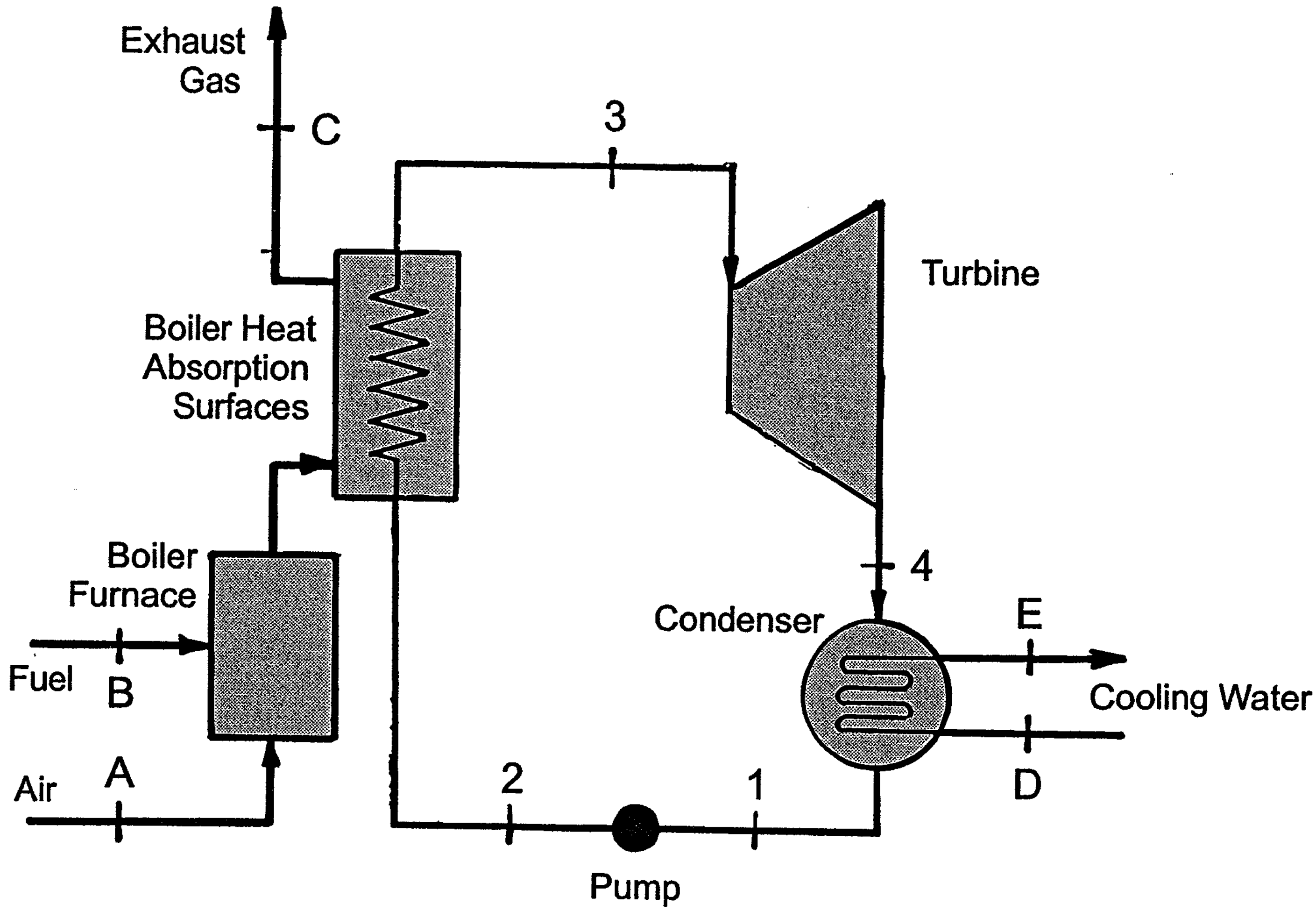
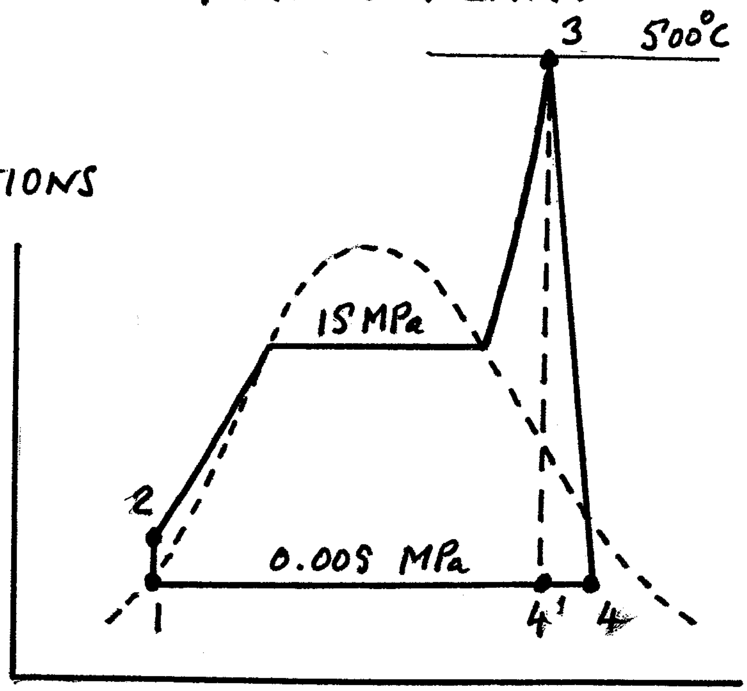


Figure 16 Simple steam cycle for a fossil fuel fired plant

EXERGY FLOW DIAGRAM

FOSSIL FUEL FIRED POWER PLANT



STEAM CYCLE CONDITIONS

p_1 = 0.005 MPa SAT
h_1 = 138 kJ/kg
s_1 = 0.4764 kJ/kg °K

s_2 = 0.4764 kJ/kg °K
p_2 = 15 MPa
h_2 = 153 kJ/kg

p_3 = 15 MPa
t_3 = 500 °C
h_3 = 3309 kJ/kg
s_3 = 6.3443 kJ/kg °K

$\eta_{PUMP} = 100\%$ $\eta_{TURBINE} = 80\%$

s_4' = 6.3443 kJ/kg °K
p_4' = 0.005 MPa
$6.3443 = 0.4764 + x_4' \, 7.9187$
$x_4' = (6.3443 - 0.4764) / 7.9187 = 0.741$
$h_4' = 137.87 + 0.741\,(2423.7) = 1934$ kJ/kg

$\eta_{TURBINE} = (h_3 - h_4) / (h_3 - h_4')$
$3309 - h_4 = 0.80\,(3309 - 1934)$
$h_4 = 3309 - 1100 = 2209$ kJ/kg

h_4 = 2209 kJ/kg
p_4 = 0.005 MPa
$2209 = 137.87 + x_4 \, 2423.7$
$x_4 = (2209 - 137.87) / 2423.7 = 0.854$
$s_4 = 0.4764 + 0.854\,(7.9187) = 7.2433$ kJ/kg °K

POWER OUTPUT CONDITIONS

$$P_{OUT} = 500 \text{ MW}$$

$$CV_{COAL} = 34\,000 \text{ kJ/kg}$$

WORK DONE BY TURBINE

$$
\begin{aligned}
W_{OUT} &= (h_3 - h_4) - (h_2 - h_1) \\
&= (3309 - 2209) - (153 - 138) \\
&= 1100 - 15 \\
&= 1085 \text{ kJ/kg}
\end{aligned}
$$

MASS FLOW RATE OF STEAM

$$
\begin{aligned}
P_{OUT} &= 1085 \times M_{STEAM} \\
500\,000 &= 1085 \times M_{STEAM} \\
M_{STEAM} &= 500\,000 / 1085 = 461 \text{ kg/s}
\end{aligned}
$$

MASS FLOW RATE OF COOLING WATER

$$
\begin{aligned}
q_{REJ} &= h_4 - h_1 \\
&= 2209 - 138 = 2071 \text{ kJ/kg}
\end{aligned}
$$

$$
\begin{aligned}
\Omega_{REJ} &= 2071 \times M_{STEAM} \\
&= 2071 \times 461 = 955\,000 \text{ kJ/s}
\end{aligned}
$$

$$
\begin{aligned}
t_{INLET} &= 10 °C \\
t_{OUTLET} &= 20 °C
\end{aligned}
$$

$$
\begin{aligned}
h_D &= 42 \text{ kJ/kg} \\
h_E &= 84 \text{ kJ/kg} \\
S_D &= 0.151 \text{ kJ/kg °K} \\
S_E &= 0.297 \text{ kJ/kg °K}
\end{aligned}
$$

$$
\begin{aligned}
\Omega_{REJ} &= (h_E - h_D)\, M_{CW} \\
M_{CW} &= 955\,000 / (84 - 42) = 22700 \text{ kg/s}
\end{aligned}
$$

AVAILABILITIES

TEMPERATURE OF HEAT REJECTION = CW TEMPERATURE

$t_0 = 10°C$
$T_0 = 283\ °K$
$h_0 = 42\ kJ/kg$
$s_0 = 0.151\ kJ/kg\ °K$

$a = (h - h_0) - T_0 (s - s_0)$

$a_1 = (138 - 42) - 283 (0.476 - 0.151)$
$= 96 - 92 = 4\ kJ/kg$

$a_2 = (153 - 42) - 283 (0.476 - 0.151)$
$= 111 - 92 = 19\ kJ/kg$

$a_3 = (3309 - 42) - 283 (6.344 - 0.151)$
$= 3267 - 1753 = 1514\ kJ/kg$

$a_4 = (2709 - 42) - 283 (7.243 - 0.151)$
$= 2167 - 2007 = 160\ kJ/kg$

$a_D = (42 - 42) - 283 (0.151 - 0.151)$
$= 0 - 0 = 0\ kJ/kg$

$a_E = (84 - 42) - 283 (0.297 - 151)$
$= 42 - 41 = 1\ kJ/kg$

EXERGY FLOWS

$A = a \times M / 1000$

$A_1 = 4 \times 461 / 1000$
$= 2\ MW$

$A_2 = 19 \times 461 / 1000$
$= 9$ MW

$A_3 = 1514 \times 461 / 1000$
$= 699$ MW

$A_4 = 160 \times 461 / 1000$
$= 74$ MW

$A_D = 0 \times 22700 / 1000$
$= 0$ MW

$A_E = 1 \times 22700 / 1000$
$= 23$ MW

MASS FLOW RATES IN COAL FIRED BOILER

AIR INLET TEMPERATURE AND CONDITIONS
$t_A = 10°C$
$h_A = 283$ kJ/kg
$s_A = 2.4567$ kJ/kg °K

COAL INLET TEMPERATURE
$t_B = 10°C$

GAS OUTLET TEMPERATURE AND CONDITIONS
$t_C = 200°C$
$h_C = 475$ kJ/kg
$s_C = 2.9758$ kJ/kg °K

AVAILABLE ENERGY IN COAL IS ASSUMED TO BE EQUAL TO ITS HIGHER CALORIFIC VALUE (IT IS ACTUALLY ABOUT 4% HIGHER)

AIR/FUEL RATIO $= M_{AIR} / M_{COAL} = 12$

$$\Omega_{STEAM} = M_{STEAM}(h_3 - h_2)$$
$$= 461\ (3309 - 153)$$
$$= 1454\,900 \ \text{kJ/s}$$

$$\Omega_{LOST} = M_{GAS}\ (h_C - h_A)$$
$$= M_{GAS}\ (475 - 283)$$
$$= M_{GAS}\ 192$$

$$\Omega_{COAL} = \Omega_{STEAM} + \Omega_{LOST}$$
$$M_{COAL}\ CV_{COAL} = 1454\,900 + (M_{AIR} + M_{COAL})\ 192$$
$$M_{COAL}\ 34000 = 1454\,900 + 13\ M_{COAL}\ 192$$
$$M_{COAL}\ (34000 - 2496) = 1454\,900$$
$$M_{COAL} = 1454\,900 / 31504 = 46 \ \text{kg/s}$$

$$M_{AIR} = 12\ M_{COAL} = 12 \times 46 = 552 \ \text{kg/s}$$

$$M_{GAS} = M_{AIR} + M_{COAL} = 46 + 552 = 598 \ \text{kg/s}$$

AVAILABILITIES

$$a = (h - h_0) - T_0\,(s - s_0)$$

$$a_B = (283 - 283) - 283\,(2.4567 - 2.4567)$$
$$= 0 \ \text{kJ/kg}$$

$$a_C = (475 - 283) - 283\,(2.9758 - 2.4567)$$
$$= 192 - 147 = 45 \ \text{kJ/kg}$$

$$a_A = CV_{COAL} = 34\,000 \ \text{kJ/kg}$$

EXERGY FLOWS

$$A = a \times M / 1000$$

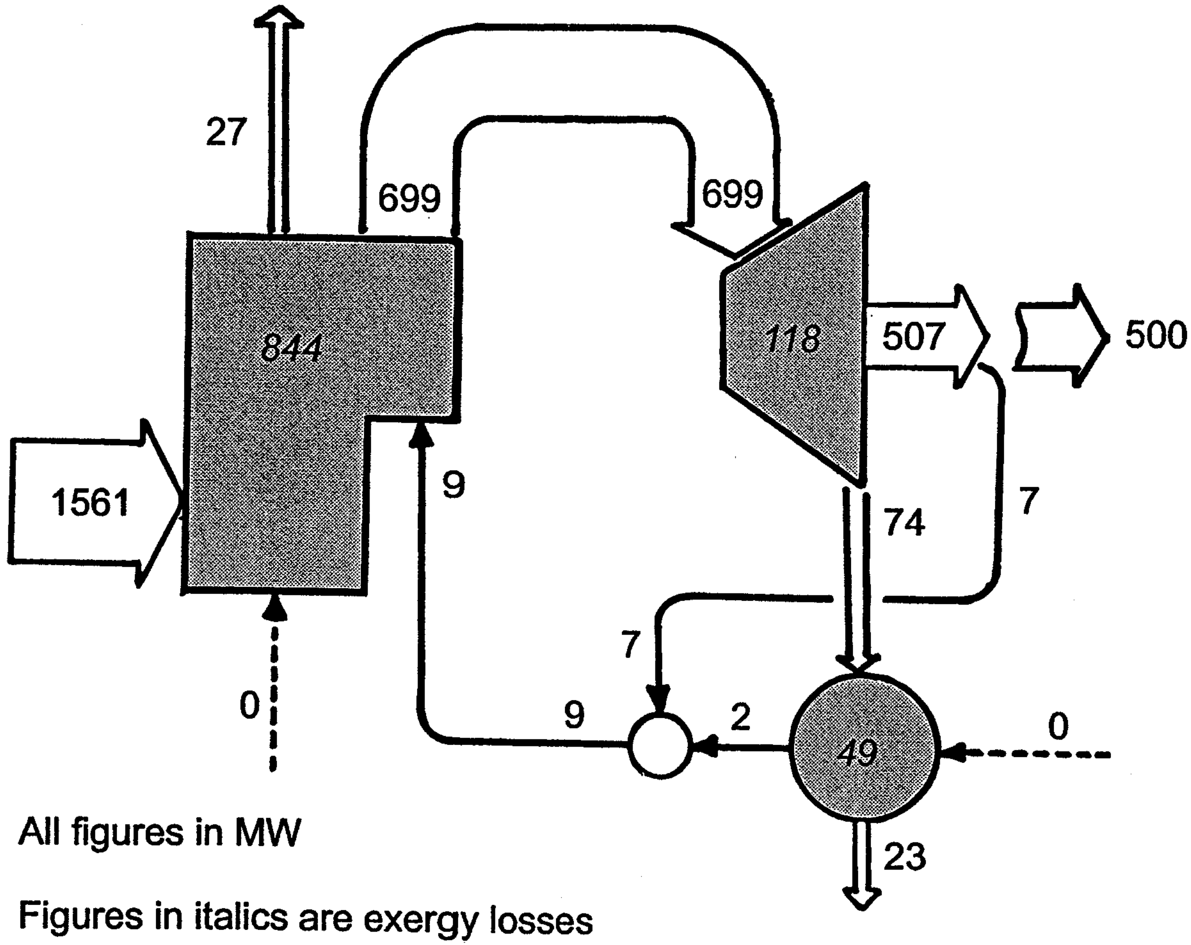


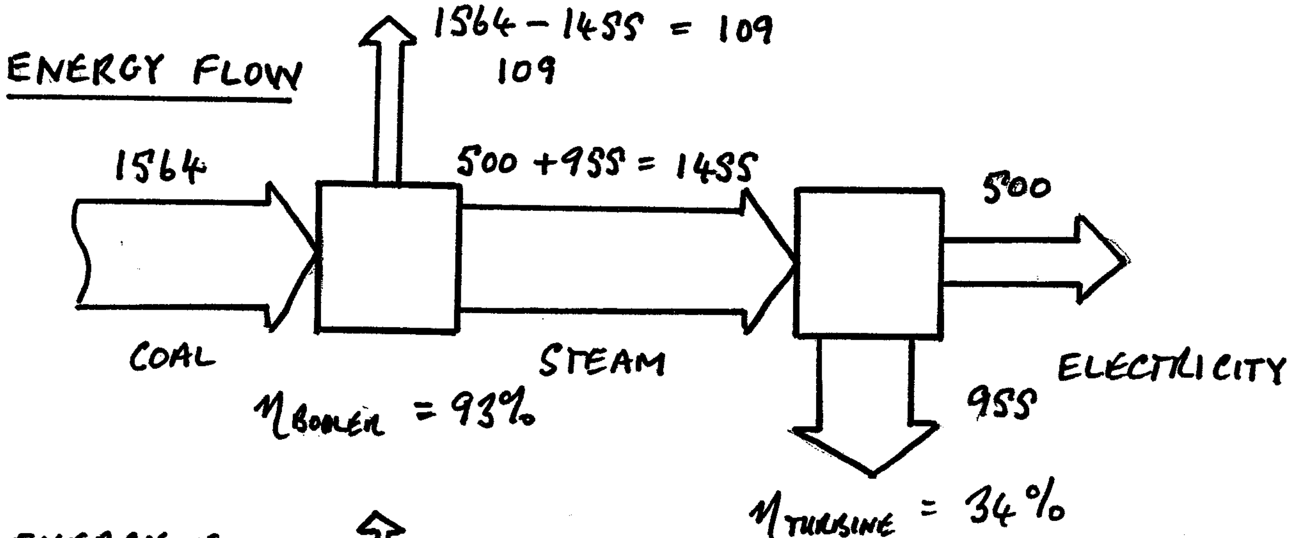
Figure 17 Exergy flow diagram for simple steam plant (fossil fuel)

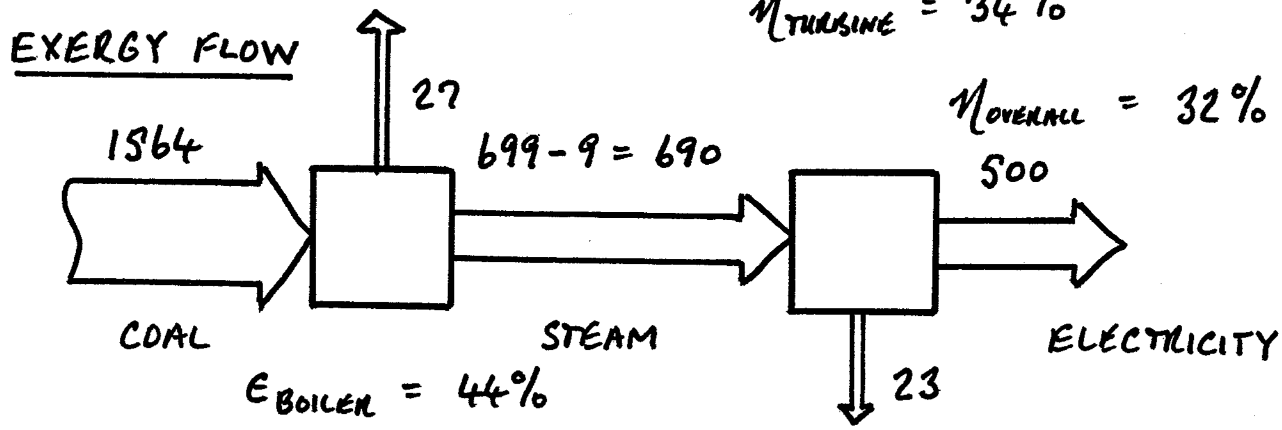
$A_A = 34\,000 \times 46 / 1000$
$= 1564$ MW

$A_B = 0 \times 552 / 1000$
$= 0$ MW

$A_C = 45 \times 598 / 1000$
$= 27$ MW

UNIDIRECTIONAL ENERGY AND EXERGY FLOWS





$\epsilon_{TURBINE}$ = 72%

$\epsilon_{OVERALL}$ = 32%

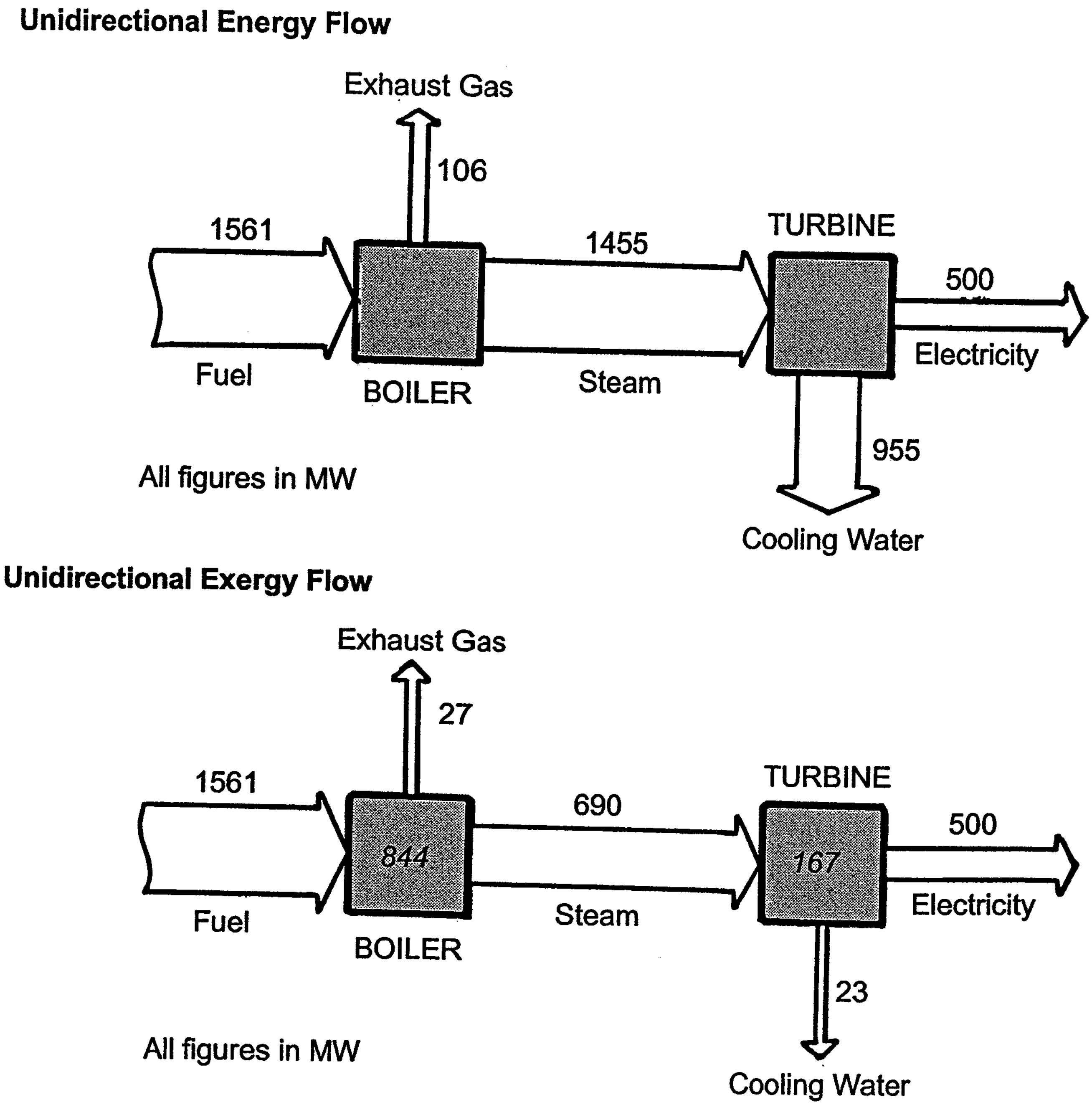


Figure 18 Unidirectional flow of energy and exergy

THERMO-ECONOMIC ANALYSIS

FOSSIL FUEL FIRED POWER PLANT

BASIC COST DATA

COAL COST	\$100 / tonne	(10 c / kg)
CALORIFIC VALUE	34 000 kJ / kg	

ENERGY VALUE OF COAL

$$E_{COAL} = 10 / 34\,000 = 0.00029 \text{ c/kJ} = 0.29 \text{ c/MJ}$$

ENERGY VALUE OF ELECTRICITY

$$E_{ELEC} = 0.29 / 0.32 = 0.92 \text{ c/MJ}$$

$$\text{UNIT OF ELECTRICITY} = 1 \text{ kWh} = 1 \text{ kJ/s} \times 3600 \text{ s} = 3.6 \text{ MJ}$$

$$E_{ELEC} = 0.92 \times 3.6 = 3.31 \text{ c/kWh}$$ (BASED ON FUEL ONLY)

CAPITAL COST (INCLUDING OPERATING COSTS)

ASSUME CAPITAL COST IS EQUAL TO FUEL COST AVERAGED OVER LIFE OF PLANT

$$E_{ELEC} = \text{FUEL COST} + \text{CAPITAL COST}$$

$$E_{ELEC} = 0.92 + 0.92 = 1.84 \text{ c/MJ}$$

$$E_{ELEC} = 3.31 + 3.31 = 6.62 \text{ c/kWh}$$

COST FLOW RATE OF USEFUL (AVAILABLE) ENERGY

COAL FLOW AND COSTS

$$E_{COAL} = 0.29 \text{ c/MJ}$$
$$A_{COAL} = 1564 \text{ MJ/s}$$

COST FLOW : $C_{COAL} = 0.29 \times 1564$
$= 454 \text{ c/s}$

CONVERSION EFFECTIVENESS REDUCES AMOUNT OF AVAILABLE ENERGY SO ITS VALUE IN THE STEAM INCREASES BY THE INVERSE OF EFFECTIVENES

$$E_{STEAM} = 0.29 / 0.44$$
$$= 0.66 \text{ c/MJ}$$
$$A_{STEAM} = 1564 \times 0.44$$
$$= 690 \text{ MJ/s}$$
$$C_{STEAM} = 0.66 \times 690$$
$$= 455 \text{ c/s}$$

SIMILARLY THE CONVERSION EFFECTIVENESS IN THE TURBINE GENERATOR REDUCES THE AMOUNT OF AVAILABLE ENERGY. THE VALUE OF THE ELECTRICITY IS INCREASED BY THE INVERSE OF THE EFFECTIVENESS.

$$E_{ELEC} = 0.66 / 0.72$$
$$= 0.92 \text{ c/MJ}$$
$$A_{ELEC} = 690 \times 0.72$$
$$= 500 \text{ MJ/s (MW)}$$
$$C_{ELEC} = 0.92 \times 500$$
$$= 460 \text{ c/s}$$

MONETARY FLOW RATE IS CONSTANT EXCEPT FOR ROUNDING OFF ERRORS AS WOULD BE EXPECTED.

COST FLOW RATE OF USEFUL ENERGY WHEN CAPITAL (AND OPERATING) COSTS ARE TAKEN INTO ACCOUNT

ASSUME OVER LIFE OF PLANT

CAPITAL COST = FUEL COST

HENCE TOTAL ELECTRICITY COST

$$
\begin{aligned}
E_{ELEC} &= (\text{FUEL COST}) + (\text{CAPITAL COST}) \\
&= 0.92 \text{ c/MJ} + 0.92 \text{ c/MJ} \\
&= 1.84 \text{ c/MJ} \\
&= 1.84 \times 3.6 \text{ c/kWh} \\
&= 6.62 \text{ c/kWh}
\end{aligned}
$$

THIS NOW GIVES A MORE CORRECT VALUE FOR THE COST OF ELECTRICITY. ALSO THE COST FLOW RATE IN c/s INCREASES THROUGH THE PLANT REFLECTING THE COST OF BUILDING AND OPERATING THE PLANT TO PRODUCE POWER.

TO OBTAIN THE VALUE OF STEAM FLOWING BETWEEN THE BOILER AND THE TURBINE IT IS NECESSARY TO CONSIDER THE COST OF THE BOILER PLANT AND THAT OF THE TURBINE PLANT AND THEIR RESPECTIVE CONTRIBUTIONS TO THE INCREASE IN THE VALUE OF AVAILABLE ENERGY

ASSUME THE FOLLOWING RELATIVE COSTS

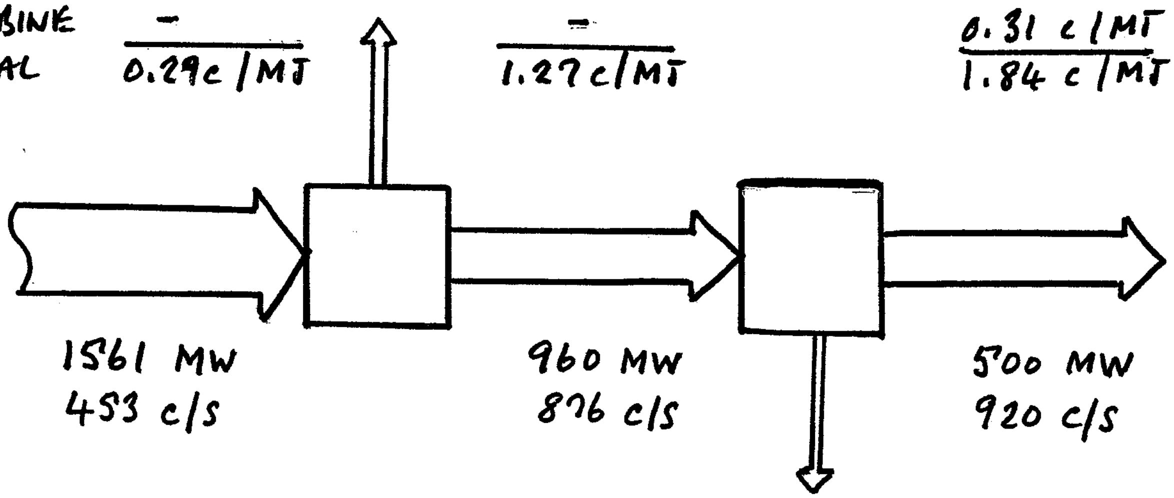
BOILER PLANT COST = 2 (TURBINE PLANT COST)

TOTAL CAPITAL COST CONTRIBUTION TO ELECTRICITY COST = 0.92 c/MJ

BOILER PLANT CONTRIBUTION = 0.61 c/MJ
TURBINE PLANT CONTRIBUTION = 0.31 c/MJ

COMBINING THESE COSTS WITH ENERGY COST GIVES THE FOLLOWING :

FUEL	0.29 c/MJ	0.66 c/MJ	0.92 c/MJ
BOILER	-	0.61 c/MJ	0.61 c/MJ
TURBINE	-	-	0.31 c/MJ
TOTAL	0.29 c/MJ	1.27 c/MJ	1.84 c/MJ



NOTE THAT MONETARY FLOW INCREASES THROUGH THE PLANT AS MORE CAPITAL EQUIPMENT IS REQUIRED TO PRODUCE THE ENERGY

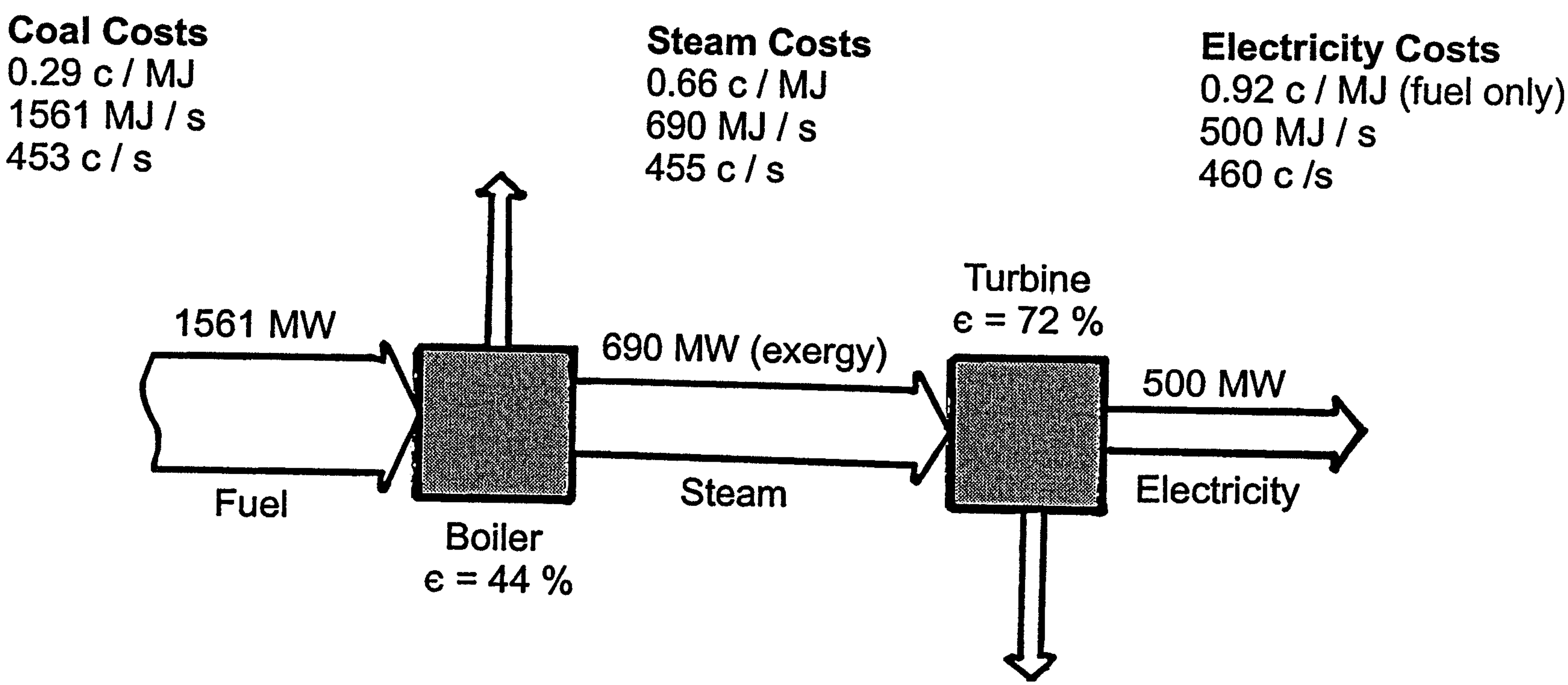


Figure 20 Steam cost based on conversion efficiency and fuel cost

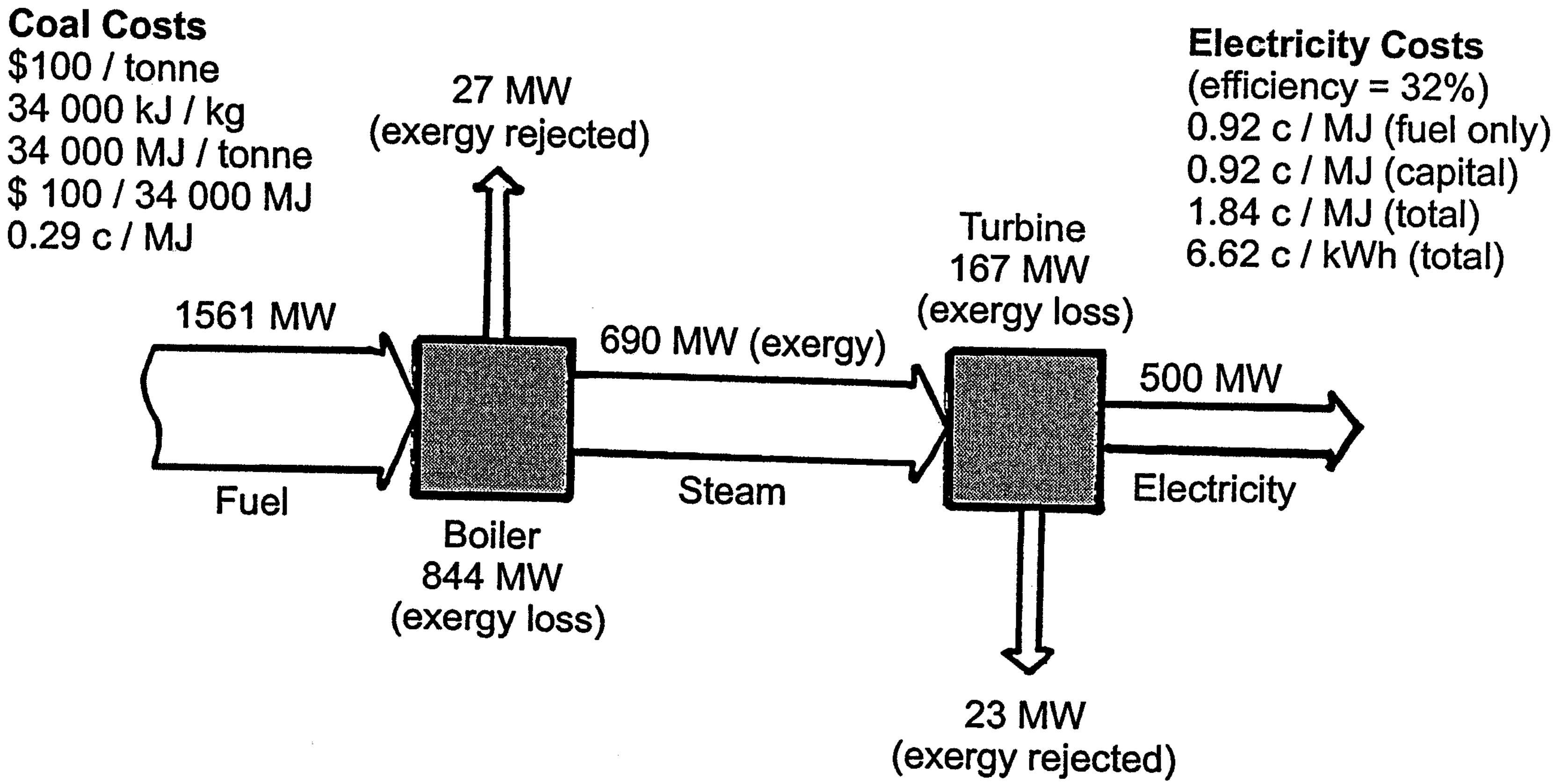


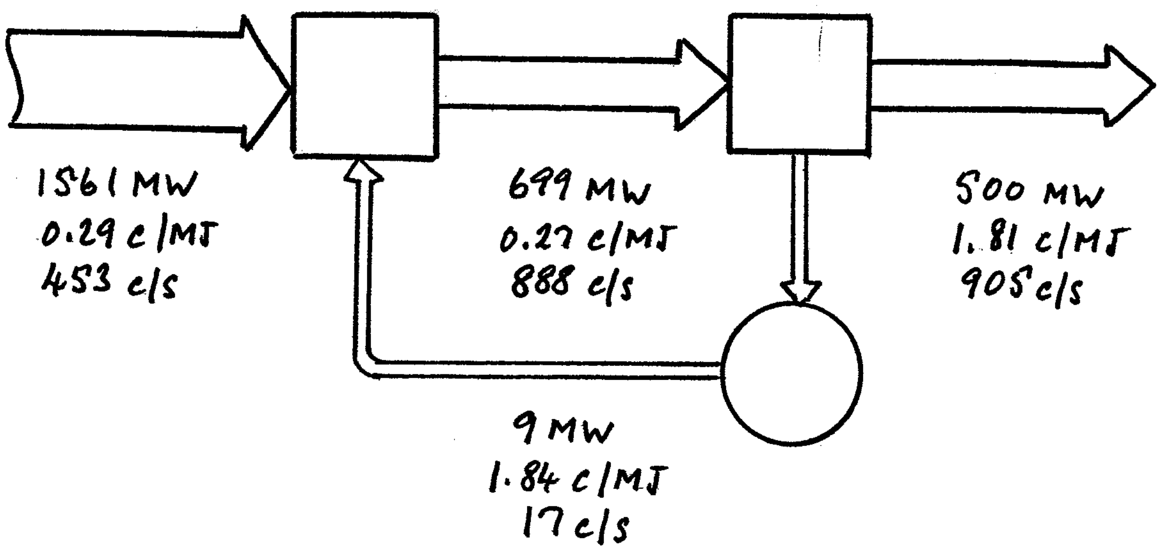
Figure 19 Monetary input and output flows based on conversion efficiency

THIS PRINCIPLE CAN BE EXTENDED TO ACCOMMODATE FEEDWATER FLOW BACK TO THE BOILER

ASSUME A CONDENSER COST IN ADDITION TO THAT OF THE BOILER AND TURBINE SUCH THAT:

BOILER COST CONTRIBUTION	67%	0.61 c/MJ
TURBINE COST CONTRIBUTION	30%	0.28 c/MJ
CONDENSER COST CONTRIBUTION	3%	0.03 c/MJ
TOTAL CAPITAL COST	100%	0.92 c/MJ

FUEL	0.29 c/MJ	0.66 c/MJ	0.92 c/MJ	0.92 c/MJ
BOILER	-	0.61 c/MJ	0.61 c/MJ	0.61 c/MJ
TURBINE	-	-	0.28 c/MJ	0.28 c/MJ
CONDENSER	-	-	-	0.03 c/MJ
TOTAL	0.29 c/MJ	0.27 c/MJ	1.81 c/MJ	1.84 c/MJ



HENCE THE VALUE OF THE ENERGY IN ANY FLOW STREAM CAN BE ESTABLISHED. THIS IS OF PARTICULAR USE WHEN, IN A CO-GENERATION PLANT, SOME STEAM IS TAKEN FROM THE POWER CYCLE FOR PROCESS HEATING.

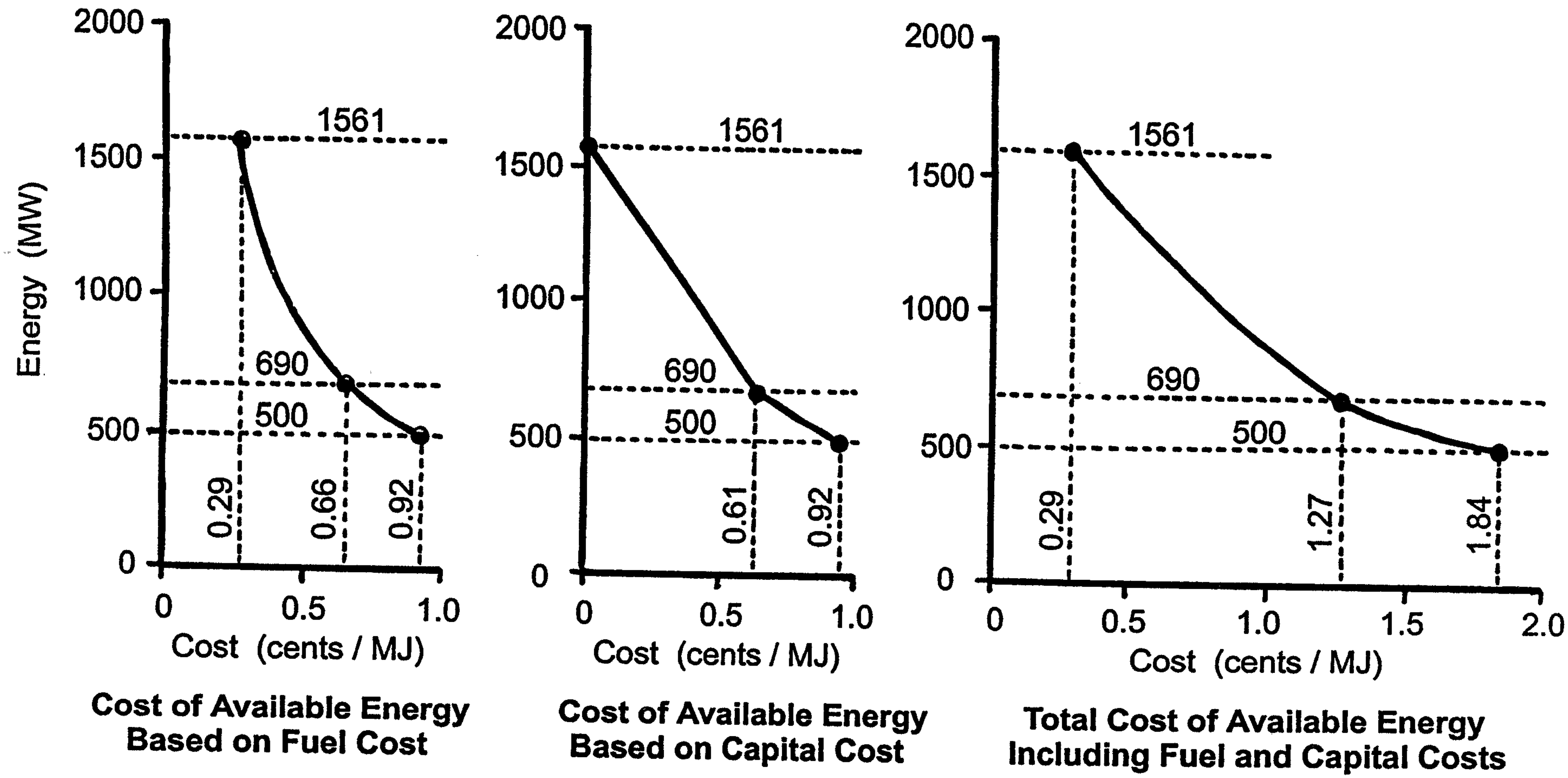


Figure 21 Cost of available energy at key points in the plant

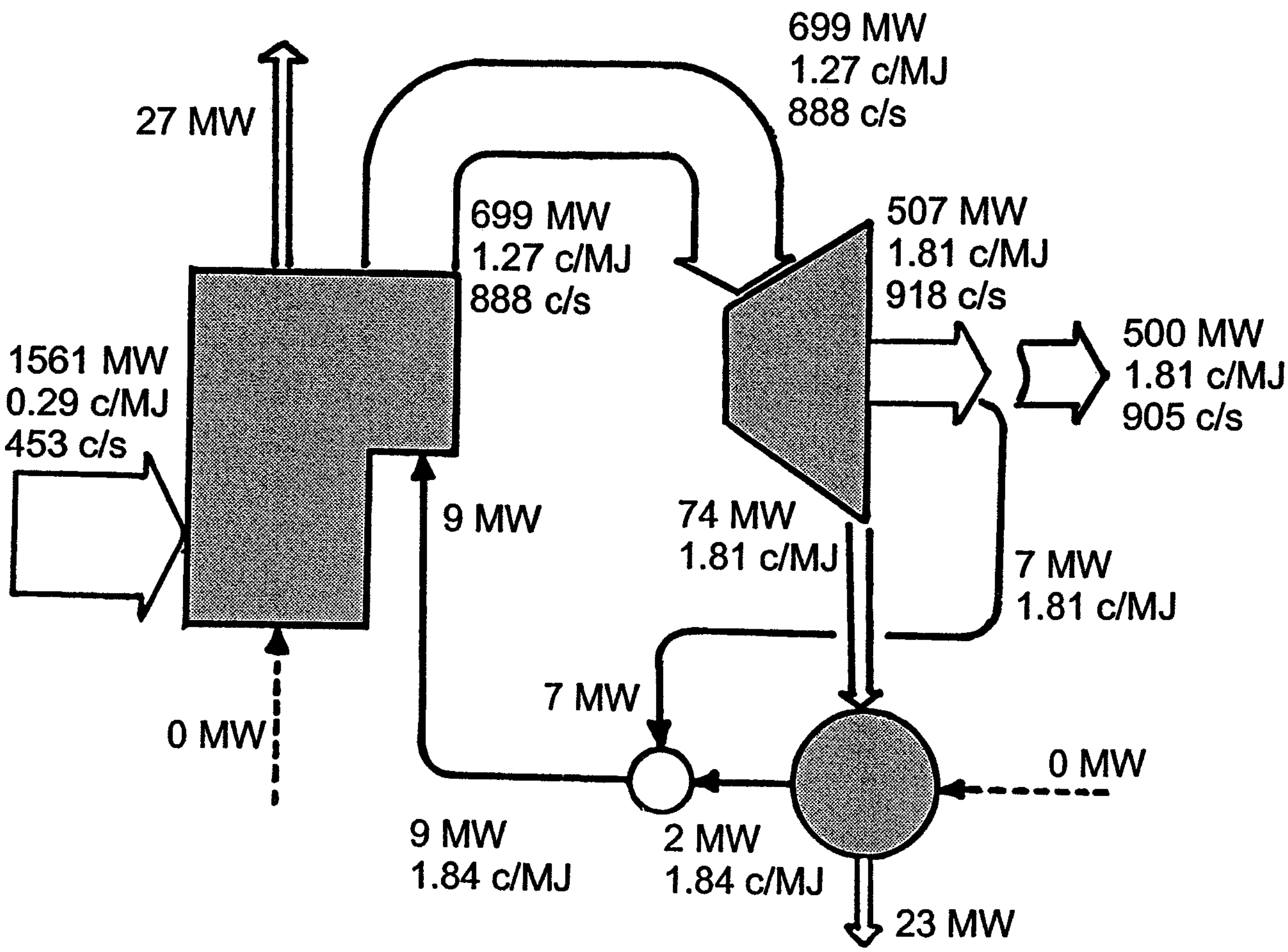


Figure 22 Monetary values for simple steam plant (fossil fuel)