SYSTEMATIC APPROACHES FOR SYNTHESIS, DESIGN AND OPERATION OF BIOMASS-BASED ENERGY SYSTEMS

VOLUME 2

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APPENDICES

A.1 CHAPTER 4

A.1.1 LINGO CODES

A.1.1.1 LINGO CODES (CASE 1)

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max = EP ;

! Q1 = Scenario 1, Q2 = Scenario 2, Q3 = Scenario 3;

!Economic Performance, EP;
EP = POC1*GP_Q1 + POC2*GP_Q2 + POC3*GP_Q3 - 0.13*CAP; ! in RM/year, whereby 1
USD=RM3.24, in 2013;
GPAVG = POC1*GP_Q1 + POC2*GP_Q2 + POC3*GP_Q3 ; ! in RM/year, whereby 1 USD=RM3.24, in
2013;

@free(EP);

! Fraction of Occurrence (POC1=Q1, POC2=Q2, POC3=Q3);
POC1 = 0.417;
POC2 = 0.333;
POC3 = 0.25;

! Process/Client Utility Demand;
FCoolW_Q1 = 11000; ! Cooling Water Demand in kg/h;
FChW_Q1 = 1000; ! Chilled Water in kg/h;
FLPS_Q1 = 20625; ! Low Pressure Steam (LPS) Demand in kg/h;
EDEMAND_Q1 = 632.5; ! Power Demand in kW;

! Process/Client Utility Demand;
FCoolW_Q2 = 13000; ! Cooling Water Demand in kg/h;
FChW_Q2 = 1000; ! Chilled Water in kg/h;
FLPS_Q2 = 24375; ! LPS Demand in kg/h;
EDEMAND_Q2 = 747.5; ! Power Demand in kW;

! Process/Client Utility Demand;
FCoolW_Q3 = 15000; ! Cooling Water Demand in kg/h;
FChW_Q3 = 1000; ! Chilled Water in kg/h;
FLPS_Q3 = 28125; ! LPS Demand in kg/h;
EDEMAND_Q3 = 862.5; ! Power Demand in kW;

! Price of Biomass Feedstock, assumed PKS=1, EFB=2, PMF=3, POME=4 ! RM/kg;
Price1 = 0.162;
Price2 = 0.02;
Price3 = 0.07;

! COD in mg/L for POME;
COD_Q1 = 50000;
COD_Q2 = 50000;
COD_Q3 = 50000;

! COD and POME in kg/m3;
COD2_Q1 = COD_Q1*0.001; ! mg/L to kgm3;
POME_Q1 = 1600;
COD2_Q2 = COD_Q2*0.001; ! mg/L to kgm3;
POME_Q2 = 1600;
COD2_Q3 = COD_Q3*0.001; ! mg/L to kgm3;
POME_Q3 = 1600;
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```
!Available Biomass Mass Flow: PKS=1, EFB=2, PMF=3, POME=4 (Please Input Data in
kg/h);
F1av_Q1 = 3437.5; F1_Q1 <= F1av_Q1;
F2av_Q1 = 12375; F2_Q1 <= F2av_Q1;
F3av_Q1 = 6875; F3_Q1 <= F3av_Q1;
F4av_Q1 = 40700; F4_Q1 <= F4av_Q1;

F1av_Q2 = 4062.5; F1_Q2 <= F1av_Q2;
F2av_Q2 = 14625; F2_Q2 <= F2av_Q2;
F3av_Q2 = 8125; F3_Q2 <= F3av_Q2;
F4av_Q2 = 48100; F4_Q2 <= F4av_Q2;

F1av_Q3 = 4687.5; F1_Q3 <= F1av_Q3;
F2av_Q3 = 16875; F2_Q3 <= F2av_Q3;
F3av_Q3 = 9375; F3_Q3 <= F3av_Q3;
F4av_Q3 = 55500; F4_Q3 <= F4av_Q3;

! Biomass Heating Values: Lignin=LHV1, Cellulose=LHV2, Hemi-Cellulose=LHV3 (Please
Input Data in kJ/kg);
LHV1_Q1 = 25000;
LHV2_Q1 = 17000;
LHV3_Q1 = 16000;
HvapW_Q1 = 2260;
CpW_Q1 = 4.2;
CpS_Q1 = 2.021;

LHV1_Q2 = 25000;
LHV2_Q2 = 17000;
LHV3_Q2 = 16000;
HvapW_Q2 = 2260;
CpW_Q2 = 4.2;
CpS_Q2 = 2.021;

LHV1_Q3 = 25000;
LHV2_Q3 = 17000;
LHV3_Q3 = 16000;
HvapW_Q3 = 2260;
CpW_Q3 = 4.2;
CpS_Q3 = 2.021;

! Biomass Composition: PKS=1, EFB=2, PMF=3 (Please Input Data);
XL1_Q1 = 0.39039;
XC1_Q1 = 0.16016;
XHC1_Q1 = 0.17479;
XW1_Q1 = 0.23;

XL2_Q1 = 0.07735;
XC2_Q1 = 0.13405;
XHC2_Q1 = 0.12355;
XW2_Q1 = 0.65;

XL3_Q1 = 0.1542;
XC3_Q1 = 0.207;
XHC3_Q1 = 0.1908;
XW3_Q1 = 0.40;

XL1_Q2 = 0.39039;
XC1_Q2 = 0.16016;
XHC1_Q2 = 0.17479;
XW1_Q2 = 0.23;

XL2_Q2 = 0.07735;
XC2_Q2 = 0.13405;
XHC2_Q2 = 0.12355;
XW2_Q2 = 0.65;

XL3_Q2 = 0.1542;
XC3_Q2 = 0.207;
XHC3_Q2 = 0.1908;
XW3_Q2 = 0.40;

XL1_Q3 = 0.39039;
XC1_Q3 = 0.16016;
XHC1_Q3 = 0.17479;
XW1_Q3 = 0.23;
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XL2_Q3 = 0.07735;
XC2_Q3 = 0.13405;
XHC2_Q3 = 0.12355;
XW2_Q3 = 0.65;

XL3_Q3 = 0.1542;
XC3_Q3 = 0.207;
XHC3_Q3 = 0.1908;
XW3_Q3 = 0.40;

! Scenario 1;

!Total Water in kg/h;
TotalWFree_Q1 = FChW_Q1 + FHPS_Q1 + CoolWCHILL_Q1 + CoolWECHILL_Q1 + FCoolW_Q1;
!Total Water in kg/s;
TotalWater_Q1 = TotalWFree_Q1*(1/3600);
! Power Demand in kWh;
EDEMAND_Q1*5000 = ECON_Q1;

! Component Mass Flow of Biomass: PKS=1, EFB=2, PMF=3;
FL_Q1 = XL1_Q1*F1_Q1 + XL2_Q1*F2_Q1 + XL3_Q1*F3_Q1;
FC_Q1 = XC1_Q1*F1_Q1 + XC2_Q1*F2_Q1 + XC3_Q1*F3_Q1;
FHC_Q1 = XHC1_Q1*F1_Q1 + XHC2_Q1*F2_Q1 + XHC3_Q1*F3_Q1;
FW_Q1 = XW1_Q1*F1_Q1 + XW2_Q1*F2_Q1 + XW3_Q1*F3_Q1;

! After Drying;
FW_Q1 = FW1_Q1 + FW2_Q1;
FT_Q1 = FL_Q1 + FC_Q1 + FHC_Q1 + FW1_Q1;

! Overall Moisture Composition of Boiler Feedstock (Input outlet composition for
drying);
XW_Q1 = 0.1;
XW_Q1*FT_Q1 = FW1_Q1;

! Heat Consumption of Dryer in kJ/h;
HeatDryer_Q1 = FW2_Q1*(CpW_Q1*75 + HvapW_Q1); !Heat required to vapourise moisture in
biomass in kJ/h;
HeatDryer_Q1 = FLPSDry_Q1*(ha3_Q1 - hf2_Q1); !LPS required (FLPSDry) for biomass
dryer in kJ/h;

! Dried Biomass in kg/h;
FT_Q1 = FT1_Q1;

! Heat from Water Tube Boiler Combustion in kJ/h;
HeatW_Q1 = FW1_Q1*CpW_Q1*(100-25) + FW1_Q1*HvapW_Q1 + FW1_Q1*CpS_Q1*(600-100); !Heat
required to vapourise water in kJ/h;
Qcomb_Q1 = LHV1_Q1*FL_Q1 + LHV2_Q1*FC_Q1 + LHV3_Q1*FHC_Q1 - (HeatW_Q1); !Heat
generated from biomass in kJ/h;
Beff_Q1 = 0.55; ! Efficiency of Water tube boiler;
Qcomb1_Q1 = Beff_Q1*Qcomb_Q1; !Heat generated after efficiency in kJ/h;
Qcomb_Q1 >= 0;

h1_Q1 = 2858; ! Enthalpy of Steam at 30 bar in kJ/kg;
hf1_Q1 = 104.92; ! Enthalpy of Water before steam production in kJ/kg;
hf2_Q1 = 146.64; ! Enthalpy of Water after drying biomass in kJ/kg;
ha2_Q1 = 2736; ! Enthalpy of Steam at 20 bar in kJ/kg;
ha3_Q1 = 2707; ! Enthalpy of Steam at 3 bar in kJ/kg;

! If water tube boiler is used;
Qcomb1_Q1 = FHPSt_Q1*(h1_Q1-hf1_Q1); !High pressure steam (HPS) produced from water
tube boiler;
FHPSkgs_Q1 = FHPSt_Q1*(1/3600); !HPS produced in kg/s;

! Biomethane Production;
!Biogas Plant and Methane Production ;
ADeff_Q1 = 0.23; ! Digester efficiency;
Sludgeeff_Q1 = 0.06; !Sludge conversion kg/kg POME;
CODremoval_Q1 = 0.80; !COD removal efficiency;

VolPOME_Q1*POME_Q1 = (F4_Q1*1000); ! Volume of POME;
CODin_Q1 = VolPOME_Q1*(COD2_Q1/1000);

Biogas_Q1 = CODin_Q1*CODremoval_Q1*ADeff_Q1; !Biogas produced from COD removal;
Sludge_Q1 = F4_Q1*Sludgeeff_Q1; !Sludge produced;
TreatedPOME_Q1 = F4_Q1 - Biogas_Q1 - Sludge_Q1; !Remainder as Treated POME;

! Biogas Upgrading (removal of CO2);
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Biogas_Q1 = Biogas1_Q1 + Biogas2_Q1 + Biogas3_Q1; !Biogas split into Biogas1=Amine
Scrubber, Biogas2_Q1=PSA, Biogas3_Q1=Membrane Sep;
Biogas1_Q1 <= Biogas_Q1;
Biogas2_Q1 <= Biogas_Q1;
Biogas3_Q1 <= Biogas_Q1;
Biomethane_Q1 = Biogas1_Q1*0.9994 + Biogas2_Q1*0.98 + Biogas3_Q1*0.99; !Conversions
of biogas into biomethane by
Biogas1=Amine Scrubber, Biogas2_Q1=PSA, Biogas3_Q1=Membrane Sep;
CARBRemoved_Q1 = CODin_Q1*CODremoval_Q1*0.124;

! Power Requirement for removal of CO2 in kW/(kg/h);
POWERASc_Q1 = 0.14*Biogas1_Q1; !Amine Scrubber;
POWERPSA_Q1 = 0.3*Biogas2_Q1; !PSA;
POWERMEMB_Q1 = 0.3*Biogas3_Q1; !Membrane Sep;

! Biomethane Split in kg/h (Gas Turbine =1, Gas Engine =2, FT Boiler =3);
Biomethane_Q1 = Biomethane1_Q1 + Biomethane2_Q1 + Biomethane3_Q1;

! If gas engine is used, Power in kW;
POWERICE_Q1 = Biomethane2_Q1*22000*(1/3600)*0.51*0.389;
! Biomethane Combustion in Gas Engine;

FWoutge_Q1 = Biomethane2_Q1*2.25; !kg/h H2O Produced from CH4 combustion;
Fcdoutge_Q1 = Biomethane2_Q1*2.75; !kg/h CO2 Produced from CH4 combustion;
Foxyinge_Q1 = Biomethane2_Q1*4; !kg/h O2 required for CH4 combustion;
FNinge_Q1 = (79/21)*Foxyinge_Q1; !kg/h N2 corresponding to O2 in air for CH4
combustion;
FNoutge_Q1 = FNinge_Q1;
Fairinge_Q1 = FNinge_Q1 + Foxyinge_Q1; !kg/h air used for CH4 combustion;
FFlueGGE_Q1 = FWoutge_Q1 + Fcdoutge_Q1 + FNoutge_Q1; !total flue gas produced in kg/h
from Gas engine;
FFlueGGE_Q1 = FFlueGE_Q1 + FFlueABS_Q1; !Flue gas split in kg/h, can be either used
for Absorption Chiller (ABS)
or release from gas engine;

! If fired tube boiler is used;
! Heat from Fired Tube Boiler Combustion in kJ/h;
QcombFTB_Q1 = 22000*Biomethane3_Q1; !Heat generated from biomethane in kJ/h;
FTBeff_Q1 = 0.60; ! Efficiency of Fired tube boiler;
Qcomb2_Q1 = FTBeff_Q1*QcombFTB_Q1; !Heat generated after efficiency in kJ/h;
Qcomb2_Q1 = MHPSt_Q1*(ha2_Q1-hf1_Q1); !Medium pressure steam (MPS) produced from
fired tube boiler;
FMPSkgs_Q1 = MHPSt_Q1*(1/3600); !MPS produced in kg/s;

! If gas turbine is used;
! Biomethane Combustion in Gas Turbine;

FWoutb_Q1 = Biomethane1_Q1*2.25; !kg/h H2O Produced from CH4 combustion;
Fcdoutb_Q1 = Biomethane1_Q1*2.75; !kg/h CO2 Produced from CH4 combustion;
Foxyinb_Q1 = Biomethane1_Q1*4; !kg/h O2 required for CH4 combustion;
FNinb_Q1 = (79/21)*Foxyinb_Q1; !kg/h N2 corresponding to O2 in air for CH4
combustion;
FNoutb_Q1 = FNinb_Q1;
Fairinb_Q1 = FNinb_Q1 + Foxyinb_Q1; !kg/h air used for CH4 combustion;
FFlueG_Q1 = FWoutb_Q1 + Fcdoutb_Q1 + FNoutb_Q1; !total flue gas produced in kg/h from
Gas turbine;
FFlueG_Q1 = FFlueGT_Q1 + FFlueGTABS_Q1; !Flue gas split in kg/h, can be either used
for Absorption Chiller (ABS)
or release from gas turbine;

! Gas Turbine Shaft Work;
@free(hg1_Q1);
@free(hg2_Q1);
@free(PowerGT_Q1);

hg1_Q1 = -1142*FFlueGT_Q1; ! Inlet Enthalpy of Flue gas kJ/kg x Mass flow of fluegas
in kg/h;
hg2_Q1 = 41.09*FFlueGT_Q1; ! Outlet Enthalpy of Flue gas kJ/kg x Mass flow of fluegas
in kg/h;
PowerGT_Q1 = (hg2_Q1 - hg1_Q1)*0.60; ! Power produced by Gas turbine in kJ/h;
PowerGTTariff_Q1 = PowerGT_Q1*(1/3600); ! Power produced by Gas turbine in kW;

!HRSG;
QHRSG_Q1 = FFlueGT_Q1*1.427*(1480 - 25); ! Heat from GT Combustion to HRSG in kJ/h;
QHRSG_Q1*0.35 = QHRSG1_Q1; ! Heat after efficiency of HRSG in kJ/h;
QHRSG1_Q1 = FStHRSG_Q1*(h1_Q1 - hf1_Q1); ! HPS produced from HRSG in kg/h;
FStHRSG_Q1*(1/3600) = FStHRSG_kgs_Q1; ! HPS produced from HRSG in kg/s;
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! Total HP Steam Produced by WT-Boiler and/or HRSG in kg/h;
FHPS_Q1 = FHPSt_Q1 + FStHRSG_Q1;

! HP Steam Turbine;
PowerHPS_Q1 = FHPS_Q1*(h1_Q1 - ha2_Q1)*0.98; ! HP Steam Turbine Power in kJ/h from 30
to 20 bar;
PowerHPSTariff_Q1 = PowerHPS_Q1*(1/3600); ! HP Steam Turbine Power in kW;

! HP Steam conversion to MP Steam in kg/h;
FHPS_Q1 = MHPSt2_Q1;

! Total MP Steam Produced in kg/h from HP Steam turbine and/or FT-Boiler;
FMPS_Q1 = MHPSt_Q1 + MHPSt2_Q1; !MHPSt is MPS from FT-boiler;

! MP Steam Turbine;
PowerMPS_Q1 = FMPS_Q1*(ha2_Q1 - ha3_Q1)*0.98; ! MP Steam Turbine in kJ/h from 20 to 3
bar;
PowerMPSTariff_Q1 = PowerMPS_Q1*(1/3600); ! MP Steam Turbine in kW;

! MP Steam conversion to LP Steam in kg/h;
FMPS_Q1 = FLPS_Q1 + FLPSDry_Q1; ! LPS Split to client (FLPS) and to biomass dryer
(FLPSDry);

! Absorption Chiller ;
COP_Q1 = 0.7; !Coefficient of Performace(COP);

! Heat in kW from gas engine (ABS), gas turbine (GTABS);
Qgen_Q1 = FFlueABS_Q1*1.427*(600 - 40)*(1/3600) + FFlueGTABS_Q1*1.427*(1480 -
25)*(1/3600);

Qchill_Q1 = Qgen_Q1*COP_Q1; !Cooling energy produced in kJ/h;
Qchill_Q1 = ChW_Q1*4.2*(40-7); !Chilled Water produced in kg/h;

! Mechanical Chiller;
COPEC_Q1 = 6.1; !Coefficient of Performace(COP);

QEC_Q1 = COPEC_Q1*POWEREC_Q1; !Cooling energy produced in kJ/h;
QEC_Q1 = ChWEC_Q1*4.2*(40-7); !Chilled Water produced in kg/h;

! Chilled Water in kg/h;
FChW_Q1 = ChW_Q1*3600 + ChWEC_Q1*3600; !Chilled Water produced in kg/h by Absorption
Chiller(ChW) and/or Mechanical Chiller(ChWEC);

! Cooling Water required for Chillers in kg/h;
CoolWCHILL_Q1 = 7.247*Qchill_Q1; !Absorption Chiller;
CoolWECHILL_Q1 = 7.247*QEC_Q1; !Mechanical Chiller;

! Cooling Tower;
ProcessW_Q1 = TotalWFree_Q1; !Total Water from client and other processes in kg/h;
CoolW_Q1 = TotalWFree_Q1*(1/3600); !Total Water in kg/s;

QCOOLT_Q1 = ProcessW_Q1*4.2*(40 - 30); ! Heat in kJ/h required to cool water
returning from client and other processes;
QCOOLT_Q1 = COOLAir_Q1*1.005*(50 - 30); !Cooling air required (COOLAir) to cool down
returning water in kJ/h;


! Site Power Balance in kWh;
! Internal Power Consumption in kWh;
IntCon_Power_Q1 = (POWERASc_Q1 + POWERPSA_Q1 + POWERMEMB_Q1 + POWEREC_Q1)*5000;

! Internal Power Generation in kWh;
IntGen_Power_Q1 = (PowerMPSTariff_Q1 + PowerHPSTariff_Q1 + PowerGTTariff_Q1 +
POWERICE_Q1)*5000;

! Internal Power Generation Split in kWh;
IntGen_Power_Q1 = IntCon_Power_Q1 + Export_Power_Q1 + Cust_Power_Q1;

! Power Demand from Client in kWh;
ECON_Q1 = Cust_Power_Q1 + External_Power_Q1;



! Gross Revenue in RM/year, whereby 1 USD=RM3.24, in 2013;
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GP_Q1 = Export_Power_Q1*0.3069 + Cust_Power_Q1*0.29 + FLPS_Q1*0.08*5000 +
FCoolW_Q1*0.0003*5000
+ FChW_Q1*0.002*5000 - External_Power_Q1*0.39 - F1_Q1*Price1*5000 - F2_Q1*Price2*5000
- F3_Q1*Price3*5000;

@free(GP_Q1);


! Scenario 2;

!Total Water in kg/h;
TotalWFree_Q2 = FChW_Q2 + FHPS_Q2 + CoolWCHILL_Q2 + CoolWECHILL_Q2 + FCoolW_Q2;
!Total Water in kg/s;
TotalWater_Q2 = TotalWFree_Q2*(1/3600);
! Power Demand in kWh;
EDEMAND_Q2*5000 = ECON_Q2;

! Component Mass Flow of Biomass: PKS=1, EFB=2, PMF=3;
FL_Q2 = XL1_Q2*F1_Q2 + XL2_Q2*F2_Q2 + XL3_Q2*F3_Q2;
FC_Q2 = XC1_Q2*F1_Q2 + XC2_Q2*F2_Q2 + XC3_Q2*F3_Q2;
FHC_Q2 = XHC1_Q2*F1_Q2 + XHC2_Q2*F2_Q2 + XHC3_Q2*F3_Q2;
FW_Q2 = XW1_Q2*F1_Q2 + XW2_Q2*F2_Q2 + XW3_Q2*F3_Q2;

! After Drying;
FW_Q2 = FW1_Q2 + FW2_Q2;
FT_Q2 = FL_Q2 + FC_Q2 + FHC_Q2 + FW1_Q2;

! Overall Moisture Composition of Boiler Feedstock (Input outlet composition for
drying);
XW_Q2 = 0.1;
XW_Q2*FT_Q2 = FW1_Q2;

! Heat Consumption of Dryer;
HeatDryer_Q2 = FW2_Q2*(CpW_Q2*75 + HvapW_Q2); !Heat required to vapourise moisture in
biomass in kJ/h;
HeatDryer_Q2 = FLPSDry_Q2*(ha3_Q2 - hf2_Q2); !LPS required (FLPSDry) for biomass
dryer in kJ/h;

! Dried Biomass in kg/h;
FT_Q2 = FT1_Q2;

! Heat from Water Tube Boiler Combustion in kJ/h;
HeatW_Q2 = FW1_Q2*CpW_Q2*(100-25) + FW1_Q2*HvapW_Q2 + FW1_Q2*CpS_Q2*(600-100); !Heat
required to vapourise water in kJ/h;
Qcomb_Q2 = LHV1_Q2*FL_Q2 + LHV2_Q2*FC_Q2 + LHV3_Q2*FHC_Q2 - (HeatW_Q2); !Heat
generated from biomass in kJ/h;
Beff_Q2 = 0.55; ! Efficiency of Water tube boiler;
Qcomb1_Q2 = Beff_Q2*Qcomb_Q2; !Heat generated after efficiency in kJ/h;
Qcomb_Q2 >= 0;

h1_Q2 = 2858; ! Enthalpy of Steam at 30 bar in kJ/kg;
hf1_Q2 = 104.92; ! Enthalpy of Water before steam production in kJ/kg;
hf2_Q2 = 146.64; ! Enthalpy of Water after drying biomass in kJ/kg;
ha2_Q2 = 2736; ! Enthalpy of Steam at 20 bar in kJ/kg;
ha3_Q2 = 2707; ! Enthalpy of Steam at 3 bar in kJ/kg;

! If water tube boiler is used;
Qcomb1_Q2 = FHPSt_Q2*(h1_Q2-hf1_Q2); !High pressure steam (HPS) produced from water
tube boiler;
FHPSkgs_Q2 = FHPSt_Q2*(1/3600); !HPS produced in kg/s;

! Biomethane Production;
!Biogas Plant and Methane Production ;
ADeff_Q2 = 0.23; ! Digester efficiency;
Sludgeeff_Q2 = 0.06; !Sludge conversion kg/kg POME;
CODremoval_Q2 = 0.80; !COD removal efficiency;

VolPOME_Q2*POME_Q2 = (F4_Q2*1000); ! Volume of POME;
CODin_Q2 = VolPOME_Q2*(COD2_Q2/1000);

Biogas_Q2 = CODin_Q2*CODremoval_Q2*ADeff_Q2; !Biogas produced from COD removal;
Sludge_Q2 = F4_Q2*Sludgeeff_Q2; !Sludge produced;
TreatedPOME_Q2 = F4_Q2 - Biogas_Q2 - Sludge_Q2; !Remainder as Treated POME;

! Biogas Upgrading (removal of CO2);
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Biogas_Q2 = Biogas1_Q2 + Biogas2_Q2 + Biogas3_Q2; !Biogas split into Biogas1=Amine
Scrubber, Biogas2_Q1=PSA, Biogas3_Q1=Membrane Sep;
Biogas1_Q2 <= Biogas_Q2;
Biogas2_Q2 <= Biogas_Q2;
Biogas3_Q2 <= Biogas_Q2;
Biomethane_Q2 = Biogas1_Q2*0.9994 + Biogas2_Q2*0.98 + Biogas3_Q2*0.99; !Conversions
of biogas into biomethane by
Biogas1=Amine Scrubber, Biogas2_Q1=PSA, Biogas3_Q1=Membrane Sep;
CARBRemoved_Q2 = CODin_Q2*CODremoval_Q2*0.124;

! Power Requirement for removal of CO2 in kW/(kg/h);
POWERASc_Q2 = 0.14*Biogas1_Q2; !Amine Scrubber;
POWERPSA_Q2 = 0.3*Biogas2_Q2; !PSA;
POWERMEMB_Q2 = 0.3*Biogas3_Q2; !Membrane Sep;

! Biomethane Split in kg/h (Gas Turbine =1, Gas Engine =2, FT Boiler =3);
Biomethane_Q2 = Biomethane1_Q2 + Biomethane2_Q2 + Biomethane3_Q2;

! If gas engine is used, Power in kW;
POWERICE_Q2 = Biomethane2_Q2*22000*(1/3600)*0.51*0.389;
! Biomethane Combustion in Gas Engine;

FWoutge_Q2 = Biomethane2_Q2*2.25; !kg/h H2O Produced from CH4 combustion;
Fcdoutge_Q2 = Biomethane2_Q2*2.75; !kg/h CO2 Produced from CH4 combustion;
Foxyinge_Q2 = Biomethane2_Q2*4; !kg/h O2 required for CH4 combustion;
FNinge_Q2 = (79/21)*Foxyinge_Q2; !kg/h N2 corresponding to O2 in air for CH4
combustion;
FNoutge_Q2 = FNinge_Q2;
Fairinge_Q2 = FNinge_Q2 + Foxyinge_Q2; !kg/h air used for CH4 combustion;
FFlueGGE_Q2 = FWoutge_Q2 + Fcdoutge_Q2 + FNoutge_Q2; !total flue gas produced in kg/h
from Gas engine;
FFlueGGE_Q2 = FFlueGE_Q2 + FFlueABS_Q2; !Flue gas split in kg/h, can be either used
for Absorption Chiller (ABS)
or release from gas engine;

! If fired tube boiler is used;
! Heat from Fired Tube Boiler Combustion in kJ/h;
QcombFTB_Q2 = 22000*Biomethane3_Q2;!Heat generated from biomethane in kJ/h;
FTBeff_Q2 = 0.60; ! Efficiency of Fired tube boiler;
Qcomb2_Q2 = FTBeff_Q2*QcombFTB_Q2; !Heat generated after efficiency in kJ/h;
Qcomb2_Q2 = MHPSt_Q2*(ha2_Q2-hf1_Q2); !Medium pressure steam (MPS) produced from
fired tube boiler;
FMPSkgs_Q2 = MHPSt_Q2*(1/3600); !MPS produced in kg/s;

! If gas turbine is used;
! Biomethane Combustion in Gas Turbine;

FWoutb_Q2 = Biomethane1_Q2*2.25; !kg/h H2O Produced from CH4 combustion;
Fcdoutb_Q2 = Biomethane1_Q2*2.75; !kg/h CO2 Produced from CH4 combustion;
Foxyinb_Q2 = Biomethane1_Q2*4; !kg/h O2 required for CH4 combustion;
FNinb_Q2 = (79/21)*Foxyinb_Q2; !kg/h N2 corresponding to O2 in air for CH4
combustion;
FNoutb_Q2 = FNinb_Q2;
Fairinb_Q2 = FNinb_Q2 + Foxyinb_Q2; !kg/h air used for CH4 combustion;
FFlueG_Q2 = FWoutb_Q2 + Fcdoutb_Q2 + FNoutb_Q2; !total flue gas produced in kg/h from
Gas turbine;
FFlueG_Q2 = FFlueGT_Q2 + FFlueGTABS_Q2; !Flue gas split in kg/h, can be either used
for Absorption Chiller (ABS)
or release from gas turbine;

! Gas Turbine Shaft Work;
@free(hg1_Q2);
@free(hg2_Q2);
@free(PowerGT_Q2);

hg1_Q2 = -1142*FFlueGT_Q2; ! Inlet Enthalpy of Flue gas kJ/kg x Mass flow of fluegas
in kg/h;
hg2_Q2 = 41.09*FFlueGT_Q2; ! Outlet Enthalpy of Flue gas kJ/kg x Mass flow of fluegas
in kg/h;
PowerGT_Q2 = (hg2_Q2 - hg1_Q2)*0.60; ! Power produced by Gas turbine in kJ/h;
PowerGTTariff_Q2 = PowerGT_Q2*(1/3600); ! Power produced by Gas turbine in kW;

!HRSG ;
QHRSG_Q2 = FFlueGT_Q2*1.427*(1480 - 25); ! Heat from GT Combustion to HRSG in kJ/h;
QHRSG_Q2*0.35 = QHRSG1_Q2; ! Heat after efficiency of HRSG in kJ/h;
QHRSG1_Q2 = FStHRSG_Q2*(h1_Q2 - hf1_Q2); ! HPS produced from HRSG in kg/h;
FStHRSG_Q2*(1/3600) = FStHRSG_kgs_Q2; ! HPS produced from HRSG in kg/s;
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! Total HP Steam Produced by WT-Boiler and/or HRSG in kg/h;
FHPS_Q2 = FHPSt_Q2 + FStHRSG_Q2;

! HP Steam Turbine Power;
PowerHPS_Q2 = FHPS_Q2*(h1_Q2 - ha2_Q2)*0.98; ! HP Steam Turbine Power in kJ/h from 30 to 20 bar;
PowerHPSTariff_Q2 = PowerHPS_Q2*(1/3600); ! HP Steam Turbine Power in kW;

! HP Steam conversion to MP Steam in kg/h;
FHPS_Q2 = MHPSt2_Q2;

! Total MP Steam Produced in kg/h from HP Steam turbine and/or FT-Boiler;
FMPS_Q2 = MHPSt_Q2 + MHPSt2_Q2; !MHPSt is MPS from FT-boiler;

! MP Steam Turbine;
PowerMPS_Q2 = FMPS_Q2*(ha2_Q2 - ha3_Q2)*0.98; ! MP Steam Turbine in kJ/h from 20 to 3 bar;
PowerMPSTariff_Q2 = PowerMPS_Q2*(1/3600); ! MP Steam Turbine in kW;

! MP Steam conversion to LP Steam in kg/h;
FMPS_Q2 = FLPS_Q2 + FLPSDry_Q2; ! LPS Split to client (FLPS) and to biomass dryer (FLPSDry);

! Absorption Chiller ;
COP_Q2 = 0.7; !Coefficient of Performace(COP);

! Heat in kW from gas engine (ABS), gas turbine (GTABS);
Qgen_Q2 = FFlueABS_Q2*1.427*(600 - 40)*(1/3600) + FFlueGTABS_Q2*1.427*(1480 - 25)*(1/3600);

Qchill_Q2 = Qgen_Q2*COP_Q2; !Cooling energy produced in kJ/h;
Qchill_Q2 = ChW_Q2*4.2*(40-7); !Chilled Water produced in kg/h;

! Mechanical Chiller;
COPEC_Q2 = 6.1; !Coefficient of Performace(COP);

QEC_Q2 = COPEC_Q2*POWEREC_Q2; !Cooling energy produced in kJ/h;
QEC_Q2 = ChWEC_Q2*4.2*(40-7); !Chilled Water produced in kg/h;

! Chilled Water in kg/h;
FChW_Q2 = ChW_Q2*3600 + ChWEC_Q2*3600; !Chilled Water produced in kg/h by Absorption Chiller(ChW) and/or Mechanical Chiller(ChWEC);

! Cooling Water for Chiller in kg/h;
CoolWCHILL_Q2 = 7.247*Qchill_Q2; !Absorption Chiller;
CoolWECHILL_Q2 = 7.247*QEC_Q2; !Mechanical Chiller;

! Cooling Tower;
ProcessW_Q2 = TotalWFree_Q2; !Total Water from client and other processes in kg/h;
CoolW_Q2 = TotalWFree_Q2*(1/3600); !Total Water in kg/s;

QCOOLT_Q2 = ProcessW_Q2*4.2*(40 - 30); ! Heat in kJ/h required to cool water returning from client and other processes;
QCOOLT_Q2 = COOLAir_Q2*1.005*(50 - 30); !Cooling air required (COOLAir) to cool down returning water in kJ/h;


! Site Power Balance in kWh;
! Internal BTS Consumption in kWh;
IntCon_Power_Q2 = (POWERASc_Q2 + POWERPSA_Q2 + POWERMEMB_Q2 + POWEREC_Q2)*5000;

! Internal BTS Generation in kWh;
IntGen_Power_Q2 = (PowerMPSTariff_Q2 + PowerHPSTariff_Q2 + PowerGTTariff_Q2 + POWERICE_Q2)*5000;

! Internal BTS Generation Split in kWh;
IntGen_Power_Q2 = IntCon_Power_Q2 + Export_Power_Q2 + Cust_Power_Q2;

! Power Demand from client in kWh;
ECON_Q2 = Cust_Power_Q2 + External_Power_Q2;



! Gross Revenue in RM/year, whereby 1 USD=RM3.24, in 2013;
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GP_Q2 = Export_Power_Q2*0.3069 + Cust_Power_Q2*0.29 + FLPS_Q2*0.08*5000 +
FCoolW_Q2*0.0003*5000
+ FChW_Q2*0.002*5000 - External_Power_Q2*0.39 - F1_Q2*Price1*5000 - F2_Q2*Price2*5000
- F3_Q2*Price3*5000;

@free(GP_Q2);


! Scenario 3;

!Total Water in kg/h;
TotalWFree_Q3 = FChW_Q3 + FHPS_Q3 + CoolWCHILL_Q3 + CoolWECHILL_Q3 + FCoolW_Q3;
!Total Water in kg/s;
TotalWater_Q3 = TotalWFree_Q3*(1/3600);
! Power Demand in kWh;
EDEMAND_Q3*5000 = ECON_Q3;

! Component Mass Flow of Biomass: PKS=1, EFB=2, PMF=3;
FL_Q3 = XL1_Q3*F1_Q3 + XL2_Q3*F2_Q3 + XL3_Q3*F3_Q3;
FC_Q3 = XC1_Q3*F1_Q3 + XC2_Q3*F2_Q3 + XC3_Q3*F3_Q3;
FHC_Q3 = XHC1_Q3*F1_Q3 + XHC2_Q3*F2_Q3 + XHC3_Q3*F3_Q3;
FW_Q3 = XW1_Q3*F1_Q3 + XW2_Q3*F2_Q3 + XW3_Q3*F3_Q3;

! After Drying;
FW_Q3 = FW1_Q3 + FW2_Q3;
FT_Q3 = FL_Q3 + FC_Q3 + FHC_Q3 + FW1_Q3;

! Overall Moisture Composition of Boiler Feedstock (Input outlet composition for
drying);
XW_Q3 = 0.1;
XW_Q3*FT_Q3 = FW1_Q3;

! Heat Consumption of Dryer in kJ/h;
HeatDryer_Q3 = FW2_Q3*(CpW_Q3*75 + HvapW_Q3); !Heat required to vapourise moisture in
biomass in kJ/h;
HeatDryer_Q3 = FLPSDry_Q3*(ha3_Q3 - hf2_Q3); !LPS required (FLPSDry) for biomass
dryer in kJ/h;

! Dried Biomass in kg.h;
FT_Q3 = FT1_Q3;

! Heat from Water Tube Boiler Combustion in kJ/h;
HeatW_Q3 = FW1_Q3*CpW_Q3*(100-25) + FW1_Q3*HvapW_Q3 + FW1_Q3*CpS_Q3*(600-100); !Heat
required to vapourise water in kJ/h;
Qcomb_Q3 = LHV1_Q3*FL_Q3 + LHV2_Q3*FC_Q3 + LHV3_Q3*FHC_Q3 - (HeatW_Q3); !Heat
generated from biomass in kJ/h;
Beff_Q3 = 0.55; ! Efficiency of Water tube boiler;
Qcomb1_Q3 = Beff_Q3*Qcomb_Q3; !Heat generated after efficiency in kJ/h;
Qcomb_Q3 >= 0;

h1_Q3 = 2858; ! Enthalpy of Steam at 30 bar in kJ/kg;
hf1_Q3 = 104.92; ! Enthalpy of Water before steam production in kJ/kg;
hf2_Q3 = 146.64; ! Enthalpy of Water after drying biomass in kJ/kg;
ha2_Q3 = 2736; ! Enthalpy of Steam at 20 bar in kJ/kg;
ha3_Q3 = 2707; ! Enthalpy of Steam at 3 bar in kJ/kg;

! If water tube boiler is used;
Qcomb1_Q3 = FHPSt_Q3*(h1_Q3-hf1_Q3); !High pressure steam (HPS) produced from water
tube boiler;
FHPSkgs_Q3 = FHPSt_Q3*(1/3600); !HPS produced in kg/s;

! Biomethane Production;
!Biogas Plant and Methane Production ;
ADeff_Q3 = 0.23; ! Digester efficiency;
Sludgeeff_Q3 = 0.06; !Sludge conversion kg/kg POME;
CODremoval_Q3 = 0.80; !COD removal efficiency;

VolPOME_Q3*POME_Q3 = (F4_Q3*1000); ! Volume of POME;
CODin_Q3 = VolPOME_Q3*(COD2_Q3/1000);

Biogas_Q3 = CODin_Q3*CODremoval_Q3*ADeff_Q3; !Biogas produced from COD removal;
Sludge_Q3 = F4_Q3*Sludgeeff_Q3; !Sludge produced;
TreatedPOME_Q3 = F4_Q3 - Biogas_Q3 - Sludge_Q3; !Remainder as Treated POME;

! Biogas Upgrading (removal of CO2);
Biogas_Q3 = Biogas1_Q3 + Biogas2_Q3 + Biogas3_Q3; !Biogas split into Biogas1=Amine
Scrubber, Biogas2_Q1=PSA, Biogas3_Q1=Membrane Sep;
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Biogas1_Q3 <= Biogas_Q3;
Biogas2_Q3 <= Biogas_Q3;
Biogas3_Q3 <= Biogas_Q3;
Biomethane_Q3 = Biogas1_Q3*0.9994 + Biogas2_Q3*0.98 + Biogas3_Q3*0.99; !Conversions
of biogas into biomethane by
Biogas1=Amine Scrubber, Biogas2_Q1=PSA, Biogas3_Q1=Membrane Sep;
CARBRemoved_Q3 = CODin_Q3*CODremoval_Q3*0.124;

! Power Requirement for removal of CO2 in kW/(kg/h);
POWERASc_Q3 = 0.14*Biogas1_Q3; !Amine Scrubber;
POWERPSA_Q3 = 0.3*Biogas2_Q3; !PSA;
POWERMEMB_Q3 = 0.3*Biogas3_Q3; !Membrane Sep;

! Biomethane Split in kg/h (Gas Turbine =1, Gas Engine =2, FT Boiler =3);
Biomethane_Q3 = Biomethane1_Q3 + Biomethane2_Q3 + Biomethane3_Q3;

! If gas engine is used, Power in kW;
POWERICE_Q3 = Biomethane2_Q3*22000*(1/3600)*0.51*0.389;
! Biomethane Combustion in Gas Engine;

FWoutge_Q3 = Biomethane2_Q3*2.25; !kg/h H2O Produced from CH4 combustion;
Fcdoutge_Q3 = Biomethane2_Q3*2.75; !kg/h CO2 Produced from CH4 combustion;
Foxyinge_Q3 = Biomethane2_Q3*4; !kg/h O2 required for CH4 combustion;
FNinge_Q3 = (79/21)*Foxyinge_Q3; !kg/h N2 corresponding to O2 in air for CH4
combustion;
FNoutge_Q3 = FNinge_Q3;
Fairinge_Q3 = FNinge_Q3 + Foxyinge_Q3;!kg/h air used for CH4 combustion;
FFlueGGE_Q3 = FWoutge_Q3 + Fcdoutge_Q3 + FNoutge_Q3; !total flue gas produced in kg/h
from Gas engine;
FFlueGGE_Q3 = FFlueGE_Q3 + FFlueABS_Q3; !Flue gas split in kg/h, can be either used
for Absorption Chiller (ABS)
or release from gas engine;

! If fired tube boiler is used;
! Heat from Fired Tube Boiler Combustion in kJ/h;
QcombFTB_Q3 = 22000*Biomethane3_Q3; !Heat generated from biomethane in kJ/h;
FTBeff_Q3 = 0.60; ! Efficiency of Fired tube boiler;
Qcomb2_Q3 = FTBeff_Q3*QcombFTB_Q3; !Heat generated after efficiency in kJ/h;
Qcomb2_Q3 = MHPSt_Q3*(ha2_Q3-hf1_Q3); !Medium pressure steam (MPS) produced from
fired tube boiler;
FMPSkgs_Q3 = MHPSt_Q3*(1/3600); !MPS produced in kg/s;

! If gas turbine is used, Power in kW;
! Biomethane Combustion in Gas Turbine;

FWoutb_Q3 = Biomethane1_Q3*2.25; !kg/h H2O Produced from CH4 combustion;
Fcdoutb_Q3 = Biomethane1_Q3*2.75; !kg/h CO2 Produced from CH4 combustion;
Foxyinb_Q3 = Biomethane1_Q3*4; !kg/h O2 required for CH4 combustion;
FNinb_Q3 = (79/21)*Foxyinb_Q3; !kg/h N2 corresponding to O2 in air for CH4
combustion;
FNoutb_Q3 = FNinb_Q3;
Fairinb_Q3 = FNinb_Q3 + Foxyinb_Q3; !kg/h air used for CH4 combustion;
FFlueG_Q3 = FWoutb_Q3 + Fcdoutb_Q3 + FNoutb_Q3; !total flue gas produced in kg/h from
Gas turbine;
FFlueG_Q3 = FFlueGT_Q3 + FFlueGTABS_Q3; !Flue gas split in kg/h, can be either used
for Absorption Chiller (ABS)
or release from gas turbine;

! Gas Turbine Shaft Work;
@free(hg1_Q3);
@free(hg2_Q3);
@free(PowerGT_Q3);

hg1_Q3 = -1142*FFlueGT_Q3;! Inlet Enthalpy of Flue gas kJ/kg x Mass flow of fluegas
in kg/h;
hg2_Q3 = 41.09*FFlueGT_Q3; ! Outlet Enthalpy of Flue gas kJ/kg x Mass flow of fluegas
in kg/h;
PowerGT_Q3 = (hg2_Q3 - hg1_Q3)*0.60; ! Power produced by Gas turbine in kJ/h;
PowerGTTariff_Q3 = PowerGT_Q3*(1/3600); ! Power produced by Gas turbine in kW;

!HRSG;
QHRSG_Q3 = FFlueGT_Q3*1.427*(1480 - 25); ! Heat from GT Combustion to HRSG in kJ/h;
QHRSG_Q3*0.35 = QHRSG1_Q3; ! Heat after efficiency of HRSG in kJ/h;
QHRSG1_Q3 = FStHRSG_Q3*(h1_Q3 - hf1_Q3); ! HPS produced from HRSG in kg/h;
FStHRSG_Q3*(1/3600) = FStHRSG_kgs_Q3; ! HPS produced from HRSG in kg/s;

! Total HP Steam Produced by WT-Boiler and/or HRSG in kg/h;
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FHPS_Q3 = FHPSt_Q3 + FStHRSG_Q3;

! HP Steam Turbine;
PowerHPS_Q3 = FHPS_Q3*(h1_Q3 - ha2_Q3)*0.98; ! HP Steam Turbine Power in kJ/h from 30
to 20 bar;
PowerHPSTariff_Q3 = PowerHPS_Q3*(1/3600); ! HP Steam Turbine Power in kW;

! HP Steam conversion to MP Steam in kg/h;
FHPS_Q3 = MHPSt2_Q3;

! Total MP Steam Produced in kg/h from HP Steam turbine and/or FT-Boiler;
FMPS_Q3 = MHPSt_Q3 + MHPSt2_Q3; !MHPSt is MPS from FT-boiler;

! MP Steam Turbine;
PowerMPS_Q3 = FMPS_Q3*(ha2_Q3 - ha3_Q3)*0.98; ! MP Steam Turbine in kJ/h from 20 to 3
bar;
PowerMPSTariff_Q3 = PowerMPS_Q3*(1/3600); ! MP Steam Turbine in kW;

! MP Steam conversion to LP Steam in kg/h;
FMPS_Q3 = FLPS_Q3 + FLPSDry_Q3; ! LPS Split to client (FLPS) and to biomass dryer
(FLPSDry);

! Absorption Chiller ;
COP_Q3 = 0.7; !Coefficient of Performace(COP);

! Heat in kW from gas engine (ABS), gas turbine (GTABS);
Qgen_Q3 = FFlueABS_Q3*1.427*(600 - 40)*(1/3600) + FFlueGTABS_Q3*1.427*(1480 -
25)*(1/3600);

Qchill_Q3 = Qgen_Q3*COP_Q3; !Cooling energy produced in kJ/h;
Qchill_Q3 = ChW_Q3*4.2*(40-7); !Chilled Water produced in kg/h;

! Mechanical Chiller;
COPEC_Q3 = 6.1; !Coefficient of Performace(COP);

QEC_Q3 = COPEC_Q3*POWEREC_Q3; !Cooling energy produced in kJ/h;
QEC_Q3 = ChWEC_Q3*4.2*(40-7); !Chilled Water produced in kg/h;

! Chilled Water in kg/h;
FChW_Q3 = ChW_Q3*3600 + ChWEC_Q3*3600; !Chilled Water produced in kg/h by Absorption
Chiller(ChW) and/or Mechanical Chiller(ChWEC);

! Cooling Water required for Chillers in kg/h;
CoolWCHILL_Q3 = 7.247*Qchill_Q3; !Absorption Chiller;
CoolWECHILL_Q3 = 7.247*QEC_Q3; !Mechanical Chiller;

! Cooling Tower;
ProcessW_Q3 = TotalWFree_Q3; !Total Water from client and other processes in kg/h;
CoolW_Q3 = TotalWFree_Q3*(1/3600); !Total Water in kg/s;

QCOOLT_Q3 = ProcessW_Q3*4.2*(40 - 30);! Heat in kJ/h required to cool water returning
from client and other processes;
QCOOLT_Q3 = COOLAir_Q3*1.005*(50 - 30);!Cooling air required (COOLAir) to cool down
returning water in kJ/h;


! Site Power Balance in kWh;
! Internal Power Consumption in kWh;
IntCon_Power_Q3 = (POWERASc_Q3 + POWERPSA_Q3 + POWERMEMB_Q3 + POWEREC_Q3)*5000;

! Internal Power Generation in kWh;
IntGen_Power_Q3 = (PowerMPSTariff_Q3 + PowerHPSTariff_Q3 + PowerGTTariff_Q3 +
POWERICE_Q3)*5000;

! Internal Power Generation Split in kWh;
IntGen_Power_Q3 = IntCon_Power_Q3 + Export_Power_Q3 + Cust_Power_Q3;

! Power Demand from client in kWh;
ECON_Q3 = Cust_Power_Q3 + External_Power_Q3;


! Gross Revenue in RM/year, whereby 1 USD=RM3.24, in 2013;

GP_Q3 = Export_Power_Q3*0.3069 + Cust_Power_Q3*0.29 + FLPS_Q3*0.08*5000 +
FCoolW_Q3*0.0003*5000
+ FChW_Q3*0.002*5000 - External_Power_Q3*0.39 - F1_Q3*Price1*5000 - F2_Q3*Price2*5000
- F3_Q3*Price3*5000 ;
```

```
@free(GP_Q3);

! Capital Cost Correlations;
CASc = 14657.5*700*N1A + 14657.5*500*N1B + 14657.5*200*N1C; !Capital cost for Amine
Scrubber;
CPSA = 10022*500*N2A + 10022*200*N2B + 10022*100*N2C; !Capital cost for PSA;
CMEMB = 9020*180*N3A + 9020*100*N3B + 9020*70*N3C; !Capital cost for Memb sep;
Cboiler2 = 3.24*1.5*94650*(12^0.7443)*N4A + 3.24*1.5*94650*(10^0.7443)*N4B +
3.24*1.5*94650*(6^0.7443)*N4C; !Capital cost for FT-Boiler;
Cboiler1 = 3.24*1.5*94650*(84^0.7443)*N5A + 3.24*1.5*94650*(70^0.7443)*N5B +
3.24*1.5*94650*(40^0.7443)*N5C; !Capital cost for WT-Boiler;
CSTT2 = 3.24*1.5*5478.3*(500^0.4346)*N6A + 3.24*1.5*5478.3*(250^0.4346)*N6B +
3.24*1.5*5478.3*(200^0.4346)*N6C; !Capital cost for MP Turbine;
CSTT1 = 3.24*1.5*5478.3*(1000^0.4346)*N7A + 3.24*1.5*5478.3*(500^0.4346)*N7B +
3.24*1.5*5478.3*(250^0.4346)*N7C; !Capital cost for HP Turbine;
CGT = 3.24*1.5*2652.1*(1000^0.6131)*N8A + 3.24*1.5*2652.1*(500^0.6131)*N8B +
3.24*1.5*2652.1*(250^0.6131)*N8C; !Capital cost for Gas Turbine;
CHRSG = 3.24*1.5*94650*(12^0.7443)*N9A + 3.24*1.5*94650*(40^0.7443)*N9B ; !Capital
cost for HRSG;
CAD = 38.5*(F4av_Q3); !Capital cost for Anaerobic Digester;
CICE = 3.24*1.5*451.05*(315^0.8232)*N11A + 3.24*1.5*451.05*(400^0.8232)*N11B;
!Capital cost for Gas Engine;
CDRY = 3.24*18*40000*N12A + 3.24*18*25000*N12B + 3.24*18*10000*N12C; !Capital cost
for Biomass Dryer;
CCHILL = 2128.9*1.5*(250^0.7414)*N13A + 2128.9*1.5*(300^0.7414)*N13B +
2128.9*1.5*(350^0.7414)*N13C; !Capital cost for Absoprtion Chiller;
CECHILL = 1308*1.5*(250^0.77)*N14A + 1308*1.5*(300^0.77)*N14B  +
1308*1.5*(400^0.77)*N14C; !Capital cost for Mechanical Chiller;
CCOOLTOWER = 3140*1.5*(50^0.7359)*N15A + 3140*1.5*(30^0.7359)*N15B +
3140*1.5*(25^0.7359)*N15C ; !Capital cost for Cooling Tower;

CAP = Cboiler1 + Cboiler2 + CSTT1 + CSTT2 + CGT + CICE + CDRY
+ CASc + CPSA + CMEMB + CHRSG + NAD*CAD + CCHILL + CECHILL + CCOOLTOWER;


! Design Capacity Selection;

Biogas1_Q1 <= N1A*700 + N1B*500 + N1C*200  ; !Capacities in kg/h;
Biogas1_Q2 <= N1A*700 + N1B*500 + N1C*200  ;
Biogas1_Q3 <= N1A*700 + N1B*500 + N1C*200  ;
@gin(N1A);
@gin(N1B);
@gin(N1C);

Biogas2_Q1 <= N2A*500 + N2B*200 + N2C*100  ; !Capacities in kg/h;
Biogas2_Q2 <= N2A*500 + N2B*200 + N2C*100  ;
Biogas2_Q3 <= N2A*500 + N2B*200 + N2C*100  ;
@gin(N2A);
@gin(N2B);
@gin(N2C);

Biogas3_Q1 <= N3A*180 + N3B*100 + N3C*70; !Capacities in kg/h;
Biogas3_Q2 <= N3A*180 + N3B*100 + N3C*70;
Biogas3_Q3 <= N3A*180 + N3B*100 + N3C*70;
@gin(N3A);
@gin(N3B);
@gin(N3C);

FMPSkgs_Q1 <= N4A*12 + N4B*10 + N4C*6; !Capacities in kg/s;
FMPSkgs_Q2 <= N4A*12 + N4B*10 + N4C*6;
FMPSkgs_Q3 <= N4A*12 + N4B*10 + N4C*6;
@gin(N4A);
@gin(N4B);
@gin(N4C);

FHPSkgs_Q1 <= N5A*84 + N5B*70 + N5C*40; !Capacities in kg/s;
FHPSkgs_Q2 <= N5A*84 + N5B*70 + N5C*40;
FHPSkgs_Q3 <= N5A*84 + N5B*70 + N5C*40;
@gin(N5A);
@gin(N5B);
@gin(N5C);

PowerMPSTariff_Q1 <= N6A*500 + N6B*250 + N6C*200; !Capacities in kW;
PowerMPSTariff_Q2 <= N6A*500 + N6B*250 + N6C*200;
PowerMPSTariff_Q3 <= N6A*500 + N6B*250 + N6C*200;
```

```
@gin(N6A);
@gin(N6B);
@gin(N6C);

PowerHPSTariff_Q1 <= N7A*1000 + N7B*500 + N7C*250; !Capacities in kW;
PowerHPSTariff_Q2 <= N7A*1000 + N7B*500 + N7C*250;
PowerHPSTariff_Q3 <= N7A*1000 + N7B*500 + N7C*250;
@gin(N7A);
@gin(N7B);
@gin(N7C);

PowerGTTariff_Q1 <= N8A*1000 + N8B*500 + N8C*250; !Capacities in kW;
PowerGTTariff_Q2 <= N8A*1000 + N8B*500 + N8C*250;
PowerGTTariff_Q3 <= N8A*1000 + N8B*500 + N8C*250;
@gin(N8A);
@gin(N8B);
@gin(N8C);

FStHRSG_kgs_Q1 <= N9A*12 + N9B*40; !Capacities in kg/s;
FStHRSG_kgs_Q2 <= N9A*12 + N9B*40;
FStHRSG_kgs_Q3 <= N9A*12 + N9B*40;
@gin(N9A);
@gin(N9B);

NAD = 1;

POWERICE_Q1 <= N11A*315 + N11B*400; !Capacities in kW;
POWERICE_Q2 <= N11A*315 + N11B*400;
POWERICE_Q3 <= N11A*315 + N11B*400;
@gin(N11A);
@gin(N11B);

FW2_Q1 <= N12A*40000 + N12B*25000 + N12C*10000; !Capacities in kg/h;
FW2_Q2 <= N12A*40000 + N12B*25000 + N12C*10000;
FW2_Q3 <= N12A*40000 + N12B*25000 + N12C*10000;
@gin(N12A);
@gin(N12B);
@gin(N12C);

Qchill_Q1 <= N13A*250 + N13B*300 + N13C*350; !Capacities in kW;
Qchill_Q2 <= N13A*250 + N13B*300 + N13C*350;
Qchill_Q3 <= N13A*250 + N13B*300 + N13C*350;
@gin(N13A);
@gin(N13B);
@gin(N13C);

QEC_Q1 <= N14A*250 + N14B*300 + N14C*350; !Capacities in kW;
QEC_Q2 <= N14A*250 + N14B*300 + N14C*350;
QEC_Q3 <= N14A*250 + N14B*300 + N14C*350;
@gin(N14A);
@gin(N14B);
@gin(N14C);

TotalWater_Q1 <= N15A*50 + N15B*30 + N15C*25; !Capacities in kg/s;
TotalWater_Q2 <= N15A*50 + N15B*30 + N15C*25;
TotalWater_Q3 <= N15A*50 + N15B*30 + N15C*25;
@gin(N15A);
@gin(N15B);
@gin(N15C);
```

A.1.1.2 LINGO CODES (CASE 2)

```
max = EP ;

! Q1 = Scenario 1, Q2 = Scenario 2, Q3 = Scenario 3;

!Economic Performance, EP;
EP = POC1*GP_Q1 + POC2*GP_Q2 + POC3*GP_Q3 - 0.13*CAP; ! in RM/year, whereby 1
USD=RM3.24, in 2013;
GPAVG = POC1*GP_Q1 + POC2*GP_Q2 + POC3*GP_Q3 ; ! in RM/year, whereby 1 USD=RM3.24, in
2013;
```

```
CAP <= 12000000;

@free(EP);

! Fraction of Occurence (POC1=Q1, POC2=Q2, POC3=Q3);
POC1 = 0.417;
POC2 = 0.333;
POC3 = 0.25;

! Process/Client Utility Demand;
FCoolW_Q1 = 11000; ! Cooling Water Demand in kg/h;
FChW_Q1 = 1000; ! Chilled Water in kg/h;
FLPS_Q1 = 20625; ! Low Pressure Steam (LPS) Demand in kg/h;
EDEMAND_Q1 = 632.5; ! Power Demand in kW;

! Process/Client Utility Demand;
FCoolW_Q2 = 13000; ! Cooling Water Demand in kg/h;
FChW_Q2 = 1000; ! Chilled Water in kg/h;
FLPS_Q2 = 24375; ! LPS Demand in kg/h;
EDEMAND_Q2 = 747.5; ! Power Demand in kW;

! Process/Client Utility Demand;
FCoolW_Q3 = 15000; ! Cooling Water Demand in kg/h;
FChW_Q3 = 1000; ! Chilled Water in kg/h;
FLPS_Q3 = 28125; ! LPS Demand in kg/h;
EDEMAND_Q3 = 862.5; ! Power Demand in kW;

! Price of Biomass Feedstock, assumed PKS=1, EFB=2, PMF=3, POME=4 ! RM/kg;
Price1 = 0.162;
Price2 = 0.02;
Price3 = 0.07;

! COD in mg/L for POME;
COD_Q1 = 50000;
COD_Q2 = 50000;
COD_Q3 = 50000;

! COD and POME in kg/m3;
COD2_Q1 = COD_Q1*0.001; ! mg/L to kgm3;
POME_Q1 = 1600;
COD2_Q2 = COD_Q2*0.001; ! mg/L to kgm3;
POME_Q2 = 1600;
COD2_Q3 = COD_Q3*0.001; ! mg/L to kgm3;
POME_Q3 = 1600;

!Available Biomass Mass Flow: PKS=1, EFB=2, PMF=3, POME=4 (Please Input Data in
kg/h);
F1av_Q1 = 3437.5; F1_Q1 <= F1av_Q1;
F2av_Q1 = 12375; F2_Q1 <= F2av_Q1;
F3av_Q1 = 6875; F3_Q1 <= F3av_Q1;
F4av_Q1 = 40700; F4_Q1 <= F4av_Q1;

F1av_Q2 = 4062.5; F1_Q2 <= F1av_Q2;
F2av_Q2 = 14625; F2_Q2 <= F2av_Q2;
F3av_Q2 = 8125; F3_Q2 <= F3av_Q2;
F4av_Q2 = 48100; F4_Q2 <= F4av_Q2;

F1av_Q3 = 4687.5; F1_Q3 <= F1av_Q3;
F2av_Q3 = 16875; F2_Q3 <= F2av_Q3;
F3av_Q3 = 9375; F3_Q3 <= F3av_Q3;
F4av_Q3 = 55500; F4_Q3 <= F4av_Q3;

! Biomass Heating Values: Lignin=LHV1, Cellulose=LHV2, Hemi-Cellulose=LHV3 (Please
Input Data in kJ/kg);
LHV1_Q1 = 25000;
LHV2_Q1 = 17000;
LHV3_Q1 = 16000;
HvapW_Q1 = 2260;
CpW_Q1 = 4.2;
CpS_Q1 = 2.021;

LHV1_Q2 = 25000;
LHV2_Q2 = 17000;
LHV3_Q2 = 16000;
HvapW_Q2 = 2260;
CpW_Q2 = 4.2;
CpS_Q2 = 2.021;
```

```
LHV1_Q3 = 25000;
LHV2_Q3 = 17000;
LHV3_Q3 = 16000;
HvapW_Q3 = 2260;
CpW_Q3 = 4.2;
CpS_Q3 = 2.021;

! Biomass Composition: PKS=1, EFB=2, PMF=3 (Please Input Data);
XL1_Q1 = 0.39039;
XC1_Q1 = 0.16016;
XHC1_Q1 = 0.17479;
XW1_Q1 = 0.23;

XL2_Q1 = 0.07735;
XC2_Q1 = 0.13405;
XHC2_Q1 = 0.12355;
XW2_Q1 = 0.65;

XL3_Q1 = 0.1542;
XC3_Q1 = 0.207;
XHC3_Q1 = 0.1908;
XW3_Q1 = 0.40;

XL1_Q2 = 0.39039;
XC1_Q2 = 0.16016;
XHC1_Q2 = 0.17479;
XW1_Q2 = 0.23;

XL2_Q2 = 0.07735;
XC2_Q2 = 0.13405;
XHC2_Q2 = 0.12355;
XW2_Q2 = 0.65;

XL3_Q2 = 0.1542;
XC3_Q2 = 0.207;
XHC3_Q2 = 0.1908;
XW3_Q2 = 0.40;

XL1_Q3 = 0.39039;
XC1_Q3 = 0.16016;
XHC1_Q3 = 0.17479;
XW1_Q3 = 0.23;

XL2_Q3 = 0.07735;
XC2_Q3 = 0.13405;
XHC2_Q3 = 0.12355;
XW2_Q3 = 0.65;

XL3_Q3 = 0.1542;
XC3_Q3 = 0.207;
XHC3_Q3 = 0.1908;
XW3_Q3 = 0.40;

! Scenario 1;

!Total Water in kg/h;
TotalWFree_Q1 = FChW_Q1 + FHPS_Q1 + CoolWCHILL_Q1 + CoolWECHILL_Q1 + FCoolW_Q1;
!Total Water in kg/s;
TotalWater_Q1 = TotalWFree_Q1*(1/3600);
! Power Demand in kWh;
EDEMAND_Q1*5000 = ECON_Q1;

! Component Mass Flow of Biomass: PKS=1, EFB=2, PMF=3;
FL_Q1 = XL1_Q1*F1_Q1 + XL2_Q1*F2_Q1 + XL3_Q1*F3_Q1;
FC_Q1 = XC1_Q1*F1_Q1 + XC2_Q1*F2_Q1 + XC3_Q1*F3_Q1;
FHC_Q1 = XHC1_Q1*F1_Q1 + XHC2_Q1*F2_Q1 + XHC3_Q1*F3_Q1;
FW_Q1 = XW1_Q1*F1_Q1 + XW2_Q1*F2_Q1 + XW3_Q1*F3_Q1;

! After Drying;
FW_Q1 = FW1_Q1 + FW2_Q1;
FT_Q1 = FL_Q1 + FC_Q1 + FHC_Q1 + FW1_Q1;

! Overall Moisture Composition of Boiler Feedstock (Input outlet composition for
drying);
XW_Q1 = 0.1;
XW_Q1*FT_Q1 = FW1_Q1;
```

```
! Heat Consumption of Dryer in kJ/h;
HeatDryer_Q1 = FW2_Q1*(CpW_Q1*75 + HvapW_Q1); !Heat required to vapourise moisture in
biomass in kJ/h;
HeatDryer_Q1 = FLPSDry_Q1*(ha3_Q1 - hf2_Q1); !LPS required (FLPSDry) for biomass
dryer in kJ/h;

! Dried Biomass in kg/h;
FT_Q1 = FT1_Q1;

! Heat from Water Tube Boiler Combustion in kJ/h;
HeatW_Q1 = FW1_Q1*CpW_Q1*(100-25) + FW1_Q1*HvapW_Q1 + FW1_Q1*CpS_Q1*(600-100); !Heat
required to vapourise water in kJ/h;
Qcomb_Q1 = LHV1_Q1*FL_Q1 + LHV2_Q1*FC_Q1 + LHV3_Q1*FHC_Q1 - (HeatW_Q1); !Heat
generated from biomass in kJ/h;
Beff_Q1 = 0.55; ! Efficiency of Water tube boiler;
Qcomb1_Q1 = Beff_Q1*Qcomb_Q1; !Heat generated after efficiency in kJ/h;
Qcomb_Q1 >= 0;

h1_Q1 = 2858; ! Enthalpy of Steam at 30 bar in kJ/kg;
hf1_Q1 = 104.92; ! Enthalpy of Water before steam production in kJ/kg;
hf2_Q1 = 146.64; ! Enthalpy of Water after drying biomass in kJ/kg;
ha2_Q1 = 2736; ! Enthalpy of Steam at 20 bar in kJ/kg;
ha3_Q1 = 2707; ! Enthalpy of Steam at 3 bar in kJ/kg;

! If water tube boiler is used;
Qcomb1_Q1 = FHPSt_Q1*(h1_Q1-hf1_Q1); !High pressure steam (HPS) produced from water
tube boiler;
FHPSkgs_Q1 = FHPSt_Q1*(1/3600); !HPS produced in kg/s;

! Biomethane Production;
!Biogas Plant and Methane Production ;
ADeff_Q1 = 0.23; ! Digester efficiency;
Sludgeeff_Q1 = 0.06; !Sludge conversion kg/kg POME;
CODremoval_Q1 = 0.80; !COD removal efficiency;

VolPOME_Q1*POME_Q1 = (F4_Q1*1000); ! Volume of POME;
CODin_Q1 = VolPOME_Q1*(COD2_Q1/1000);

Biogas_Q1 = CODin_Q1*CODremoval_Q1*ADeff_Q1; !Biogas produced from COD removal;
Sludge_Q1 = F4_Q1*Sludgeeff_Q1; !Sludge produced;
TreatedPOME_Q1 = F4_Q1 - Biogas_Q1 - Sludge_Q1; !Remainder as Treated POME;

! Biogas Upgrading (removal of CO2);
Biogas_Q1 = Biogas1_Q1 + Biogas2_Q1 + Biogas3_Q1; !Biogas split into Biogas1=Amine
Scrubber, Biogas2_Q1=PSA, Biogas3_Q1=Membrane Sep;
Biogas1_Q1 <= Biogas_Q1;
Biogas2_Q1 <= Biogas_Q1;
Biogas3_Q1 <= Biogas_Q1;
Biomethane_Q1 = Biogas1_Q1*0.9994 + Biogas2_Q1*0.98 + Biogas3_Q1*0.99; !Conversions
of biogas into biomethane by
Biogas1=Amine Scrubber, Biogas2_Q1=PSA, Biogas3_Q1=Membrane Sep;
CARBRemoved_Q1 = CODin_Q1*CODremoval_Q1*0.124;

! Power Requirement for removal of CO2 in kW/(kg/h);
POWERASc_Q1 = 0.14*Biogas1_Q1; !Amine Scrubber;
POWERPSA_Q1 = 0.3*Biogas2_Q1; !PSA;
POWERMEMB_Q1 = 0.3*Biogas3_Q1; !Membrane Sep;

! Biomethane Split in kg/h (Gas Turbine =1, Gas Engine =2, FT Boiler =3);
Biomethane_Q1 = Biomethane1_Q1 + Biomethane2_Q1 + Biomethane3_Q1;

! If gas engine is used, Power in kW;
POWERICE_Q1 = Biomethane2_Q1*22000*(1/3600)*0.51*0.389;
! Biomethane Combustion in Gas Engine;

FWoutge_Q1 = Biomethane2_Q1*2.25; !kg/h H2O Produced from CH4 combustion;
Fcdoutge_Q1 = Biomethane2_Q1*2.75; !kg/h CO2 Produced from CH4 combustion;
Foxyinge_Q1 = Biomethane2_Q1*4; !kg/h O2 required for CH4 combustion;
FNinge_Q1 = (79/21)*Foxyinge_Q1; !kg/h N2 corresponding to O2 in air for CH4
combustion;
FNoutge_Q1 = FNinge_Q1;
Fairinge_Q1 = FNinge_Q1 + Foxyinge_Q1; !kg/h air used for CH4 combustion;
FFlueGGE_Q1 = FWoutge_Q1 + Fcdoutge_Q1 + FNoutge_Q1; !total flue gas produced in kg/h
from Gas engine;
FFlueGGE_Q1 = FFlueGE_Q1 + FFlueABS_Q1; !Flue gas split in kg/h, can be either used
for Absorption Chiller (ABS)
```

```
or release from gas engine;

! If fired tube boiler is used;
! Heat from Fired Tube Boiler Combustion in kJ/h;
QcombFTB_Q1 = 22000*Biomethane3_Q1; !Heat generated from biomethane in kJ/h;
FTBeff_Q1 = 0.60; ! Efficiency of Fired tube boiler;
Qcomb2_Q1 = FTBeff_Q1*QcombFTB_Q1; !Heat generated after efficiency in kJ/h;
Qcomb2_Q1 = MHPSt_Q1*(ha2_Q1-hf1_Q1); !Medium pressure steam (MPS) produced from
fired tube boiler;
FMPSkgs_Q1 = MHPSt_Q1*(1/3600); !MPS produced in kg/s;

! If gas turbine is used;
! Biomethane Combustion in Gas Turbine;

FWoutb_Q1 = Biomethane1_Q1*2.25; !kg/h H2O Produced from CH4 combustion;
Fcdoutb_Q1 = Biomethane1_Q1*2.75; !kg/h CO2 Produced from CH4 combustion;
Foxyinb_Q1 = Biomethane1_Q1*4; !kg/h O2 required for CH4 combustion;
FNinb_Q1 = (79/21)*Foxyinb_Q1; !kg/h N2 corresponding to O2 in air for CH4
combustion;
FNoutb_Q1 = FNinb_Q1;
Fairinb_Q1 = FNinb_Q1 + Foxyinb_Q1; !kg/h air used for CH4 combustion;
FFlueG_Q1 = FWoutb_Q1 + Fcdoutb_Q1 + FNoutb_Q1; !total flue gas produced in kg/h from
Gas turbine;
FFlueG_Q1 = FFlueGT_Q1 + FFlueGTABS_Q1; !Flue gas split in kg/h, can be either used
for Absorption Chiller (ABS)
or release from gas turbine;

! Gas Turbine Shaft Work;
@free(hg1_Q1);
@free(hg2_Q1);
@free(PowerGT_Q1);

hg1_Q1 = -1142*FFlueGT_Q1; ! Inlet Enthalpy of Flue gas kJ/kg x Mass flow of fluegas
in kg/h;
hg2_Q1 = 41.09*FFlueGT_Q1; ! Outlet Enthalpy of Flue gas kJ/kg x Mass flow of fluegas
in kg/h;
PowerGT_Q1 = (hg2_Q1 - hg1_Q1)*0.60; ! Power produced by Gas turbine in kJ/h;
PowerGTTariff_Q1 = PowerGT_Q1*(1/3600); ! Power produced by Gas turbine in kW;

!HRSG;
QHRSG_Q1 = FFlueGT_Q1*1.427*(1480 - 25); ! Heat from GT Combustion to HRSG in kJ/h;
QHRSG_Q1*0.35 = QHRSG1_Q1; ! Heat after efficiency of HRSG in kJ/h;
QHRSG1_Q1 = FStHRSG_Q1*(h1_Q1 - hf1_Q1); ! HPS produced from HRSG in kg/h;
FStHRSG_Q1*(1/3600) = FStHRSG_kgs_Q1; ! HPS produced from HRSG in kg/s;

! Total HP Steam Produced by WT-Boiler and/or HRSG in kg/h;
FHPS_Q1 = FHPSt_Q1 + FStHRSG_Q1;

! HP Steam Turbine;
PowerHPS_Q1 = FHPS_Q1*(h1_Q1 - ha2_Q1)*0.98; ! HP Steam Turbine Power in kJ/h from 30
to 20 bar;
PowerHPSTariff_Q1 = PowerHPS_Q1*(1/3600); ! HP Steam Turbine Power in kW;

! HP Steam conversion to MP Steam in kg/h;
FHPS_Q1 = MHPSt2_Q1;

! Total MP Steam Produced in kg/h from HP Steam turbine and/or FT-Boiler;
FMPS_Q1 = MHPSt_Q1 + MHPSt2_Q1; !MHPSt is MPS from FT-boiler;

! MP Steam Turbine;
PowerMPS_Q1 = FMPS_Q1*(ha2_Q1 - ha3_Q1)*0.98; ! MP Steam Turbine in kJ/h from 20 to 3
bar;
PowerMPSTariff_Q1 = PowerMPS_Q1*(1/3600); ! MP Steam Turbine in kW;

! MP Steam conversion to LP Steam in kg/h;
FMPS_Q1 = FLPS_Q1 + FLPSDry_Q1; ! LPS Split to client (FLPS) and to biomass dryer
(FLPSDry);

! Absorption Chiller ;
COP_Q1 = 0.7; !Coefficient of Performace(COP);

! Heat in kW from gas engine (ABS), gas turbine (GTABS);
Qgen_Q1 = FFlueABS_Q1*1.427*(600 - 40)*(1/3600) + FFlueGTABS_Q1*1.427*(1480 -
25)*(1/3600);

Qchill_Q1 = Qgen_Q1*COP_Q1; !Cooling energy produced in kJ/h;
Qchill_Q1 = ChW_Q1*4.2*(40-7); !Chilled Water produced in kg/h;
```

```
! Mechanical Chiller;
COPEC_Q1 = 6.1; !Coefficient of Performace(COP);

QEC_Q1 = COPEC_Q1*POWEREC_Q1; !Cooling energy produced in kJ/h;
QEC_Q1 = ChWEC_Q1*4.2*(40-7); !Chilled Water produced in kg/h;

! Chilled Water in kg/h;
FChW_Q1 = ChW_Q1*3600 + ChWEC_Q1*3600; !Chilled Water produced in kg/h by Absorption
Chiller(ChW) and/or Mechanical Chiller(ChWEC);

! Cooling Water required for Chillers in kg/h;
CoolWCHILL_Q1 = 7.247*Qchill_Q1; !Absorption Chiller;
CoolWECHILL_Q1 = 7.247*QEC_Q1; !Mechanical Chiller;

! Cooling Tower;
ProcessW_Q1 = TotalWFree_Q1; !Total Water from client and other processes in kg/h;
CoolW_Q1 = TotalWFree_Q1*(1/3600); !Total Water in kg/s;

QCOOLT_Q1 = ProcessW_Q1*4.2*(40 - 30); ! Heat in kJ/h required to cool water
returning from client and other processes;
QCOOLT_Q1 = COOLAir_Q1*1.005*(50 - 30); !Cooling air required (COOLAir) to cool down
returning water in kJ/h;


! Site Power Balance in kWh;
! Internal Power Consumption in kWh;
IntCon_Power_Q1 = (POWERASc_Q1 + POWERPSA_Q1 + POWERMEMB_Q1 + POWEREC_Q1)*5000;

! Internal Power Generation in kWh;
IntGen_Power_Q1 = (PowerMPSTariff_Q1 + PowerHPSTariff_Q1 + PowerGTTariff_Q1 +
POWERICE_Q1)*5000;

! Internal Power Generation Split in kWh;
IntGen_Power_Q1 = IntCon_Power_Q1 + Export_Power_Q1 + Cust_Power_Q1;

! Power Demand from Client in kWh;
ECON_Q1 = Cust_Power_Q1 + External_Power_Q1;



! Gross Revenue in RM/year, whereby 1 USD=RM3.24, in 2013;

GP_Q1 = Export_Power_Q1*0.3069 + Cust_Power_Q1*0.29 + FLPS_Q1*0.08*5000 +
FCoolW_Q1*0.0003*5000
+ FChW_Q1*0.002*5000 - External_Power_Q1*0.39 - F1_Q1*Price1*5000 - F2_Q1*Price2*5000
- F3_Q1*Price3*5000;

@free(GP_Q1);



! Scenario 2;

!Total Water in kg/h;
TotalWFree_Q2 = FChW_Q2 + FHPS_Q2 + CoolWCHILL_Q2 + CoolWECHILL_Q2 + FCoolW_Q2;
!Total Water in kg/s;
TotalWater_Q2 = TotalWFree_Q2*(1/3600);
! Power Demand in kWh;
EDEMAND_Q2*5000 = ECON_Q2;

! Component Mass Flow of Biomass: PKS=1, EFB=2, PMF=3;
FL_Q2 = XL1_Q2*F1_Q2 + XL2_Q2*F2_Q2 + XL3_Q2*F3_Q2;
FC_Q2 = XC1_Q2*F1_Q2 + XC2_Q2*F2_Q2 + XC3_Q2*F3_Q2;
FHC_Q2 = XHC1_Q2*F1_Q2 + XHC2_Q2*F2_Q2 + XHC3_Q2*F3_Q2;
FW_Q2 = XW1_Q2*F1_Q2 + XW2_Q2*F2_Q2 + XW3_Q2*F3_Q2;

! After Drying;
FW_Q2 = FW1_Q2 + FW2_Q2;
FT_Q2 = FL_Q2 + FC_Q2 + FHC_Q2 + FW1_Q2;

! Overall Moisture Composition of Boiler Feedstock (Input outlet composition for
drying);
XW_Q2 = 0.1;
XW_Q2*FT_Q2 = FW1_Q2;

! Heat Consumption of Dryer;
```

```
HeatDryer_Q2 = FW2_Q2*(CpW_Q2*75 + HvapW_Q2); !Heat required to vapourise moisture in biomass in kJ/h;
HeatDryer_Q2 = FLPSDry_Q2*(ha3_Q2 - hf2_Q2); !LPS required (FLPSDry) for biomass dryer in kJ/h;

! Dried Biomass in kg/h;
FT_Q2 = FT1_Q2;

! Heat from Water Tube Boiler Combustion in kJ/h;
HeatW_Q2 = FW1_Q2*CpW_Q2*(100-25) + FW1_Q2*HvapW_Q2 + FW1_Q2*CpS_Q2*(600-100); !Heat required to vapourise water in kJ/h;
Qcomb_Q2 = LHV1_Q2*FL_Q2 + LHV2_Q2*FC_Q2 + LHV3_Q2*FHC_Q2 - (HeatW_Q2); !Heat generated from biomass in kJ/h;
Beff_Q2 = 0.55; ! Efficiency of Water tube boiler;
Qcomb1_Q2 = Beff_Q2*Qcomb_Q2; !Heat generated after efficiency in kJ/h;
Qcomb_Q2 >= 0;

h1_Q2 = 2858; ! Enthalpy of Steam at 30 bar in kJ/kg;
hf1_Q2 = 104.92; ! Enthalpy of Water before steam production in kJ/kg;
hf2_Q2 = 146.64; ! Enthalpy of Water after drying biomass in kJ/kg;
ha2_Q2 = 2736; ! Enthalpy of Steam at 20 bar in kJ/kg;
ha3_Q2 = 2707; ! Enthalpy of Steam at 3 bar in kJ/kg;

! If water tube boiler is used;
Qcomb1_Q2 = FHPSt_Q2*(h1_Q2-hf1_Q2); !High pressure steam (HPS) produced from water tube boiler;
FHPSkgs_Q2 = FHPSt_Q2*(1/3600); !HPS produced in kg/s;

! Biomethane Production;
!Biogas Plant and Methane Production ;
ADeff_Q2 = 0.23; ! Digester efficiency;
Sludgeeff_Q2 = 0.06; !Sludge conversion kg/kg POME;
CODremoval_Q2 = 0.80; !COD removal efficiency;

VolPOME_Q2*POME_Q2 = (F4_Q2*1000); ! Volume of POME;
CODin_Q2 = VolPOME_Q2*(COD2_Q2/1000);

Biogas_Q2 = CODin_Q2*CODremoval_Q2*ADeff_Q2; !Biogas produced from COD removal;
Sludge_Q2 = F4_Q2*Sludgeeff_Q2; !Sludge produced;
TreatedPOME_Q2 = F4_Q2 - Biogas_Q2 - Sludge_Q2; !Remainder as Treated POME;

! Biogas Upgrading (removal of CO2);
Biogas_Q2 = Biogas1_Q2 + Biogas2_Q2 + Biogas3_Q2; !Biogas split into Biogas1=Amine Scrubber, Biogas2_Q1=PSA, Biogas3_Q1=Membrane Sep;
Biogas1_Q2 <= Biogas_Q2;
Biogas2_Q2 <= Biogas_Q2;
Biogas3_Q2 <= Biogas_Q2;
Biomethane_Q2 = Biogas1_Q2*0.9994 + Biogas2_Q2*0.98 + Biogas3_Q2*0.99; !Conversions of biogas into biomethane by
Biogas1=Amine Scrubber, Biogas2_Q1=PSA, Biogas3_Q1=Membrane Sep;
CARBRemoved_Q2 = CODin_Q2*CODremoval_Q2*0.124;

! Power Requirement for removal of CO2 in kW/(kg/h);
POWERASc_Q2 = 0.14*Biogas1_Q2; !Amine Scrubber;
POWERPSA_Q2 = 0.3*Biogas2_Q2; !PSA;
POWERMEMB_Q2 = 0.3*Biogas3_Q2; !Membrane Sep;

! Biomethane Split in kg/h (Gas Turbine =1, Gas Engine =2, FT Boiler =3);
Biomethane_Q2 = Biomethane1_Q2 + Biomethane2_Q2 + Biomethane3_Q2;

! If gas engine is used, Power in kW;
POWERICE_Q2 = Biomethane2_Q2*22000*(1/3600)*0.51*0.389;
! Biomethane Combustion in Gas Engine;

FWoutge_Q2 = Biomethane2_Q2*2.25; !kg/h H2O Produced from CH4 combustion;
Fcdoutge_Q2 = Biomethane2_Q2*2.75; !kg/h CO2 Produced from CH4 combustion;
Foxyinge_Q2 = Biomethane2_Q2*4; !kg/h O2 required for CH4 combustion;
FNinge_Q2 = (79/21)*Foxyinge_Q2; !kg/h N2 corresponding to O2 in air for CH4 combustion;
FNoutge_Q2 = FNinge_Q2;
Fairinge_Q2 = FNinge_Q2 + Foxyinge_Q2; !kg/h air used for CH4 combustion;
FFlueGGE_Q2 = FWoutge_Q2 + Fcdoutge_Q2 + FNoutge_Q2; !total flue gas produced in kg/h from Gas engine;
FFlueGGE_Q2 = FFlueGE_Q2 + FFlueABS_Q2; !Flue gas split in kg/h, can be either used for Absorption Chiller (ABS)
or release from gas engine;
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! If fired tube boiler is used;
! Heat from Fired Tube Boiler Combustion in kJ/h;
QcombFTB_Q2 = 22000*Biomethane3_Q2;!Heat generated from biomethane in kJ/h;
FTBeff_Q2 = 0.60; ! Efficiency of Fired tube boiler;
Qcomb2_Q2 = FTBeff_Q2*QcombFTB_Q2; !Heat generated after efficiency in kJ/h;
Qcomb2_Q2 = MHPSt_Q2*(ha2_Q2-hf1_Q2); !Medium pressure steam (MPS) produced from
fired tube boiler;
FMPSkgs_Q2 = MHPSt_Q2*(1/3600); !MPS produced in kg/s;

! If gas turbine is used;
! Biomethane Combustion in Gas Turbine;

FWoutb_Q2 = Biomethane1_Q2*2.25; !kg/h H2O Produced from CH4 combustion;
Fcdoutb_Q2 = Biomethane1_Q2*2.75; !kg/h CO2 Produced from CH4 combustion;
Foxyinb_Q2 = Biomethane1_Q2*4; !kg/h O2 required for CH4 combustion;
FNinb_Q2 = (79/21)*Foxyinb_Q2; !kg/h N2 corresponding to O2 in air for CH4
combustion;
FNoutb_Q2 = FNinb_Q2;
Fairinb_Q2 = FNinb_Q2 + Foxyinb_Q2; !kg/h air used for CH4 combustion;
FFlueG_Q2 = FWoutb_Q2 + Fcdoutb_Q2 + FNoutb_Q2; !total flue gas produced in kg/h from
Gas turbine;
FFlueG_Q2 = FFlueGT_Q2 + FFlueGTABS_Q2; !Flue gas split in kg/h, can be either used
for Absorption Chiller (ABS)
or release from gas turbine;

! Gas Turbine Shaft Work;
@free(hg1_Q2);
@free(hg2_Q2);
@free(PowerGT_Q2);

hg1_Q2 = -1142*FFlueGT_Q2; ! Inlet Enthalpy of Flue gas kJ/kg x Mass flow of fluegas
in kg/h;
hg2_Q2 = 41.09*FFlueGT_Q2; ! Outlet Enthalpy of Flue gas kJ/kg x Mass flow of fluegas
in kg/h;
PowerGT_Q2 = (hg2_Q2 - hg1_Q2)*0.60; ! Power produced by Gas turbine in kJ/h;
PowerGTTariff_Q2 = PowerGT_Q2*(1/3600); ! Power produced by Gas turbine in kW;

!HRSG ;
QHRSG_Q2 = FFlueGT_Q2*1.427*(1480 - 25); ! Heat from GT Combustion to HRSG in kJ/h;
QHRSG_Q2*0.35 = QHRSG1_Q2; ! Heat after efficiency of HRSG in kJ/h;
QHRSG1_Q2 = FStHRSG_Q2*(h1_Q2 - hf1_Q2); ! HPS produced from HRSG in kg/h;
FStHRSG_Q2*(1/3600) = FStHRSG_kgs_Q2; ! HPS produced from HRSG in kg/s;

! Total HP Steam Produced by WT-Boiler and/or HRSG in kg/h;
FHPS_Q2 = FHPSt_Q2 + FStHRSG_Q2;

! HP Steam Turbine Power;
PowerHPS_Q2 = FHPS_Q2*(h1_Q2 - ha2_Q2)*0.98; ! HP Steam Turbine Power in kJ/h from 30
to 20 bar;
PowerHPSTariff_Q2 = PowerHPS_Q2*(1/3600); ! HP Steam Turbine Power in kW;

! HP Steam conversion to MP Steam in kg/h;
FHPS_Q2 = MHPSt2_Q2;

! Total MP Steam Produced in kg/h from HP Steam turbine and/or FT-Boiler;
FMPS_Q2 = MHPSt_Q2 + MHPSt2_Q2; !MHPSt is MPS from FT-boiler;

! MP Steam Turbine;
PowerMPS_Q2 = FMPS_Q2*(ha2_Q2 - ha3_Q2)*0.98; ! MP Steam Turbine in kJ/h from 20 to 3
bar;
PowerMPSTariff_Q2 = PowerMPS_Q2*(1/3600); ! MP Steam Turbine in kW;

! MP Steam conversion to LP Steam in kg/h;
FMPS_Q2 = FLPS_Q2 + FLPSDry_Q2; ! LPS Split to client (FLPS) and to biomass dryer
(FLPSDry);

! Absorption Chiller ;
COP_Q2 = 0.7; !Coefficient of Performace(COP);

! Heat in kW from gas engine (ABS), gas turbine (GTABS);
Qgen_Q2 = FFlueABS_Q2*1.427*(600 - 40)*(1/3600) + FFlueGTABS_Q2*1.427*(1480 -
25)*(1/3600);

Qchill_Q2 = Qgen_Q2*COP_Q2; !Cooling energy produced in kJ/h;
Qchill_Q2 = ChW_Q2*4.2*(40-7); !Chilled Water produced in kg/h;

! Mechanical Chiller;
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COPEC_Q2 = 6.1; !Coefficient of Performace(COP);

QEC_Q2 = COPEC_Q2*POWEREC_Q2; !Cooling energy produced in kJ/h;
QEC_Q2 = ChWEC_Q2*4.2*(40-7); !Chilled Water produced in kg/h;

! Chilled Water in kg/h;
FChW_Q2 = ChW_Q2*3600 + ChWEC_Q2*3600; !Chilled Water produced in kg/h by Absorption
Chiller(ChW) and/or Mechanical Chiller(ChWEC);

! Cooling Water for Chiller in kg/h;
CoolWCHILL_Q2 = 7.247*Qchill_Q2; !Absorption Chiller;
CoolWECHILL_Q2 = 7.247*QEC_Q2; !Mechanical Chiller;

! Cooling Tower;
ProcessW_Q2 = TotalWFree_Q2; !Total Water from client and other processes in kg/h;
CoolW_Q2 = TotalWFree_Q2*(1/3600); !Total Water in kg/s;

QCOOLT_Q2 = ProcessW_Q2*4.2*(40 - 30); ! Heat in kJ/h required to cool water
returning from client and other processes;
QCOOLT_Q2 = COOLAir_Q2*1.005*(50 - 30); !Cooling air required (COOLAir) to cool down
returning water in kJ/h;


! Site Power Balance in kWh;
! Internal BTS Consumption in kWh;
IntCon_Power_Q2 = (POWERASc_Q2 + POWERPSA_Q2 + POWERMEMB_Q2 + POWEREC_Q2)*5000;

! Internal BTS Generation in kWh;
IntGen_Power_Q2 = (PowerMPSTariff_Q2 + PowerHPSTariff_Q2 + PowerGTTariff_Q2 +
POWERICE_Q2)*5000;

! Internal BTS Generation Split in kWh;
IntGen_Power_Q2 = IntCon_Power_Q2 + Export_Power_Q2 + Cust_Power_Q2;

! Power Demand from client in kWh;
ECON_Q2 = Cust_Power_Q2 + External_Power_Q2;



! Gross Revenue in RM/year, whereby 1 USD=RM3.24, in 2013;

GP_Q2 = Export_Power_Q2*0.3069 + Cust_Power_Q2*0.29 + FLPS_Q2*0.08*5000 +
FCoolW_Q2*0.0003*5000
+ FChW_Q2*0.002*5000 - External_Power_Q2*0.39 - F1_Q2*Price1*5000 - F2_Q2*Price2*5000
- F3_Q2*Price3*5000;

@free(GP_Q2);


! Scenario 3;

!Total Water in kg/h;
TotalWFree_Q3 = FChW_Q3 + FHPS_Q3 + CoolWCHILL_Q3 + CoolWECHILL_Q3 + FCoolW_Q3;
!Total Water in kg/s;
TotalWater_Q3 = TotalWFree_Q3*(1/3600);
! Power Demand in kWh;
EDEMAND_Q3*5000 = ECON_Q3;

! Component Mass Flow of Biomass: PKS=1, EFB=2, PMF=3;
FL_Q3 = XL1_Q3*F1_Q3 + XL2_Q3*F2_Q3 + XL3_Q3*F3_Q3;
FC_Q3 = XC1_Q3*F1_Q3 + XC2_Q3*F2_Q3 + XC3_Q3*F3_Q3;
FHC_Q3 = XHC1_Q3*F1_Q3 + XHC2_Q3*F2_Q3 + XHC3_Q3*F3_Q3;
FW_Q3 = XW1_Q3*F1_Q3 + XW2_Q3*F2_Q3 + XW3_Q3*F3_Q3;

! After Drying;
FW_Q3 = FW1_Q3 + FW2_Q3;
FT_Q3 = FL_Q3 + FC_Q3 + FHC_Q3 + FW1_Q3;

! Overall Moisture Composition of Boiler Feedstock (Input outlet composition for
drying);
XW_Q3 = 0.1;
XW_Q3*FT_Q3 = FW1_Q3;

! Heat Consumption of Dryer in kJ/h;
HeatDryer_Q3 = FW2_Q3*(CpW_Q3*75 + HvapW_Q3); !Heat required to vapourise moisture in
biomass in kJ/h;
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HeatDryer_Q3 = FLPSDry_Q3*(ha3_Q3 - hf2_Q3); !LPS required (FLPSDry) for biomass
dryer in kJ/h;

! Dried Biomass in kg.h;
FT_Q3 = FT1_Q3;

! Heat from Water Tube Boiler Combustion in kJ/h;
HeatW_Q3 = FW1_Q3*CpW_Q3*(100-25) + FW1_Q3*HvapW_Q3 + FW1_Q3*CpS_Q3*(600-100); !Heat
required to vapourise water in kJ/h;
Qcomb_Q3 = LHV1_Q3*FL_Q3 + LHV2_Q3*FC_Q3 + LHV3_Q3*FHC_Q3 - (HeatW_Q3); !Heat
generated from biomass in kJ/h;
Beff_Q3 = 0.55; ! Efficiency of Water tube boiler;
Qcomb1_Q3 = Beff_Q3*Qcomb_Q3; !Heat generated after efficiency in kJ/h;
Qcomb_Q3 >= 0;

h1_Q3 = 2858; ! Enthalpy of Steam at 30 bar in kJ/kg;
hf1_Q3 = 104.92; ! Enthalpy of Water before steam production in kJ/kg;
hf2_Q3 = 146.64; ! Enthalpy of Water after drying biomass in kJ/kg;
ha2_Q3 = 2736; ! Enthalpy of Steam at 20 bar in kJ/kg;
ha3_Q3 = 2707; ! Enthalpy of Steam at 3 bar in kJ/kg;

! If water tube boiler is used;
Qcomb1_Q3 = FHPSt_Q3*(h1_Q3-hf1_Q3); !High pressure steam (HPS) produced from water
tube boiler;
FHPSkgs_Q3 = FHPSt_Q3*(1/3600); !HPS produced in kg/s;

! Biomethane Production;
!Biogas Plant and Methane Production ;
ADeff_Q3 = 0.23; ! Digester efficiency;
Sludgeeff_Q3 = 0.06; !Sludge conversion kg/kg POME;
CODremoval_Q3 = 0.80; !COD removal efficiency;

VolPOME_Q3*POME_Q3 = (F4_Q3*1000); ! Volume of POME;
CODin_Q3 = VolPOME_Q3*(COD2_Q3/1000);

Biogas_Q3 = CODin_Q3*CODremoval_Q3*ADeff_Q3; !Biogas produced from COD removal;
Sludge_Q3 = F4_Q3*Sludgeeff_Q3; !Sludge produced;
TreatedPOME_Q3 = F4_Q3 - Biogas_Q3 - Sludge_Q3; !Remainder as Treated POME;

! Biogas Upgrading (removal of CO2);
Biogas_Q3 = Biogas1_Q3 + Biogas2_Q3 + Biogas3_Q3; !Biogas split into Biogas1=Amine
Scrubber, Biogas2_Q1=PSA, Biogas3_Q1=Membrane Sep;
Biogas1_Q3 <= Biogas_Q3;
Biogas2_Q3 <= Biogas_Q3;
Biogas3_Q3 <= Biogas_Q3;
Biomethane_Q3 = Biogas1_Q3*0.9994 + Biogas2_Q3*0.98 + Biogas3_Q3*0.99; !Conversions
of biogas into biomethane by
Biogas1=Amine Scrubber, Biogas2_Q1=PSA, Biogas3_Q1=Membrane Sep;
CARBRemoved_Q3 = CODin_Q3*CODremoval_Q3*0.124;

! Power Requirement for removal of CO2 in kW/(kg/h);
POWERASc_Q3 = 0.14*Biogas1_Q3; !Amine Scrubber;
POWERPSA_Q3 = 0.3*Biogas2_Q3; !PSA;
POWERMEMB_Q3 = 0.3*Biogas3_Q3; !Membrane Sep;

! Biomethane Split in kg/h (Gas Turbine =1, Gas Engine =2, FT Boiler =3);
Biomethane_Q3 = Biomethane1_Q3 + Biomethane2_Q3 + Biomethane3_Q3;

! If gas engine is used, Power in kW;
POWERICE_Q3 = Biomethane2_Q3*22000*(1/3600)*0.51*0.389;
! Biomethane Combustion in Gas Engine;

FWoutge_Q3 = Biomethane2_Q3*2.25; !kg/h H2O Produced from CH4 combustion;
Fcdoutge_Q3 = Biomethane2_Q3*2.75; !kg/h CO2 Produced from CH4 combustion;
Foxyinge_Q3 = Biomethane2_Q3*4; !kg/h O2 required for CH4 combustion;
FNinge_Q3 = (79/21)*Foxyinge_Q3; !kg/h N2 corresponding to O2 in air for CH4
combustion;
FNoutge_Q3 = FNinge_Q3;
Fairinge_Q3 = FNinge_Q3 + Foxyinge_Q3;!kg/h air used for CH4 combustion;
FFlueGGE_Q3 = FWoutge_Q3 + Fcdoutge_Q3 + FNoutge_Q3; !total flue gas produced in kg/h
from Gas engine;
FFlueGGE_Q3 = FFlueGE_Q3 + FFlueABS_Q3; !Flue gas split in kg/h, can be either used
for Absorption Chiller (ABS)
or release from gas engine;

! If fired tube boiler is used;
! Heat from Fired Tube Boiler Combustion in kJ/h;
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QcombFTB_Q3 = 22000*Biomethane3_Q3; !Heat generated from biomethane in kJ/h;
FTBeff_Q3 = 0.60; ! Efficiency of Fired tube boiler;
Qcomb2_Q3 = FTBeff_Q3*QcombFTB_Q3; !Heat generated after efficiency in kJ/h;
Qcomb2_Q3 = MHPSt_Q3*(ha2_Q3-hf1_Q3); !Medium pressure steam (MPS) produced from
fired tube boiler;
FMPSkgs_Q3 = MHPSt_Q3*(1/3600); !MPS produced in kg/s;

! If gas turbine is used, Power in kW;
! Biomethane Combustion in Gas Turbine;

FWoutb_Q3 = Biomethane1_Q3*2.25; !kg/h H2O Produced from CH4 combustion;
Fcdoutb_Q3 = Biomethane1_Q3*2.75; !kg/h CO2 Produced from CH4 combustion;
Foxyinb_Q3 = Biomethane1_Q3*4; !kg/h O2 required for CH4 combustion;
FNinb_Q3 = (79/21)*Foxyinb_Q3; !kg/h N2 corresponding to O2 in air for CH4
combustion;
FNoutb_Q3 = FNinb_Q3;
Fairinb_Q3 = FNinb_Q3 + Foxyinb_Q3; !kg/h air used for CH4 combustion;
FFlueG_Q3 = FWoutb_Q3 + Fcdoutb_Q3 + FNoutb_Q3; !total flue gas produced in kg/h from
Gas turbine;
FFlueG_Q3 = FFlueGT_Q3 + FFlueGTABS_Q3; !Flue gas split in kg/h, can be either used
for Absorption Chiller (ABS)
or release from gas turbine;

! Gas Turbine Shaft Work;
@free(hg1_Q3);
@free(hg2_Q3);
@free(PowerGT_Q3);

hg1_Q3 = -1142*FFlueGT_Q3;! Inlet Enthalpy of Flue gas kJ/kg x Mass flow of fluegas
in kg/h;
hg2_Q3 = 41.09*FFlueGT_Q3; ! Outlet Enthalpy of Flue gas kJ/kg x Mass flow of fluegas
in kg/h;
PowerGT_Q3 = (hg2_Q3 - hg1_Q3)*0.60; ! Power produced by Gas turbine in kJ/h;
PowerGTTariff_Q3 = PowerGT_Q3*(1/3600); ! Power produced by Gas turbine in kW;

!HRSG;
QHRSG_Q3 = FFlueGT_Q3*1.427*(1480 - 25); ! Heat from GT Combustion to HRSG in kJ/h;
QHRSG_Q3*0.35 = QHRSG1_Q3; ! Heat after efficiency of HRSG in kJ/h;
QHRSG1_Q3 = FStHRSG_Q3*(h1_Q3 - hf1_Q3); ! HPS produced from HRSG in kg/h;
FStHRSG_Q3*(1/3600) = FStHRSG_kgs_Q3; ! HPS produced from HRSG in kg/s;

! Total HP Steam Produced by WT-Boiler and/or HRSG in kg/h;
FHPS_Q3 = FHPSt_Q3 + FStHRSG_Q3;

! HP Steam Turbine;
PowerHPS_Q3 = FHPS_Q3*(h1_Q3 - ha2_Q3)*0.98; ! HP Steam Turbine Power in kJ/h from 30
to 20 bar;
PowerHPSTariff_Q3 = PowerHPS_Q3*(1/3600); ! HP Steam Turbine Power in kW;

! HP Steam conversion to MP Steam in kg/h;
FHPS_Q3 = MHPSt2_Q3;

! Total MP Steam Produced in kg/h from HP Steam turbine and/or FT-Boiler;
FMPS_Q3 = MHPSt_Q3 + MHPSt2_Q3; !MHPSt is MPS from FT-boiler;

! MP Steam Turbine;
PowerMPS_Q3 = FMPS_Q3*(ha2_Q3 - ha3_Q3)*0.98; ! MP Steam Turbine in kJ/h from 20 to 3
bar;
PowerMPSTariff_Q3 = PowerMPS_Q3*(1/3600); ! MP Steam Turbine in kW;

! MP Steam conversion to LP Steam in kg/h;
FMPS_Q3 = FLPS_Q3 + FLPSDry_Q3; ! LPS Split to client (FLPS) and to biomass dryer
(FLPSDry);

! Absorption Chiller ;
COP_Q3 = 0.7; !Coefficient of Performance(COP);

! Heat in kW from gas engine (ABS), gas turbine (GTABS);
Qgen_Q3 = FFlueABS_Q3*1.427*(600 - 40)*(1/3600) + FFlueGTABS_Q3*1.427*(1480 -
25)*(1/3600);

Qchill_Q3 = Qgen_Q3*COP_Q3; !Cooling energy produced in kJ/h;
Qchill_Q3 = ChW_Q3*4.2*(40-7); !Chilled Water produced in kg/h;

! Mechanical Chiller;
COPEC_Q3 = 6.1; !Coefficient of Performace(COP);
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QEC_Q3 = COPEC_Q3*POWEREC_Q3; !Cooling energy produced in kJ/h;
QEC_Q3 = ChWEC_Q3*4.2*(40-7); !Chilled Water produced in kg/h;

! Chilled Water in kg/h;
FChW_Q3 = ChW_Q3*3600 + ChWEC_Q3*3600; !Chilled Water produced in kg/h by Absorption
Chiller(ChW) and/or Mechanical Chiller(ChWEC);

! Cooling Water required for Chillers in kg/h;
CoolWCHILL_Q3 = 7.247*Qchill_Q3; !Absorption Chiller;
CoolWECHILL_Q3 = 7.247*QEC_Q3; !Mechanical Chiller;

! Cooling Tower;
ProcessW_Q3 = TotalWFree_Q3; !Total Water from client and other processes in kg/h;
CoolW_Q3 = TotalWFree_Q3*(1/3600); !Total Water in kg/s;

QCOOLT_Q3 = ProcessW_Q3*4.2*(40 - 30);! Heat in kJ/h required to cool water returning
from client and other processes;
QCOOLT_Q3 = COOLAir_Q3*1.005*(50 - 30);!Cooling air required (COOLAir) to cool down
returning water in kJ/h;


! Site Power Balance in kWh;
! Internal Power Consumption in kWh;
IntCon_Power_Q3 = (POWERASc_Q3 + POWERPSA_Q3 + POWERMEMB_Q3 + POWEREC_Q3)*5000;

! Internal Power Generation in kWh;
IntGen_Power_Q3 = (PowerMPSTariff_Q3 + PowerHPSTariff_Q3 + PowerGTTariff_Q3 +
POWERICE_Q3)*5000;

! Internal Power Generation Split in kWh;
IntGen_Power_Q3 = IntCon_Power_Q3 + Export_Power_Q3 + Cust_Power_Q3;

! Power Demand from client in kWh;
ECON_Q3 = Cust_Power_Q3 + External_Power_Q3;


! Gross Revenue in RM/year, whereby 1 USD=RM3.24, in 2013;

GP_Q3 = Export_Power_Q3*0.3069 + Cust_Power_Q3*0.29 + FLPS_Q3*0.08*5000 +
FCoolW_Q3*0.0003*5000
+ FChW_Q3*0.002*5000 - External_Power_Q3*0.39 - F1_Q3*Price1*5000 - F2_Q3*Price2*5000
- F3_Q3*Price3*5000 ;

@free(GP_Q3);


! Capital Cost Correlations;
CASc = 14657.5*700*N1A + 14657.5*500*N1B + 14657.5*200*N1C; !Capital cost for Amine
Scrubber;
CPSA = 10022*500*N2A + 10022*200*N2B + 10022*100*N2C; !Capital cost for PSA;
CMEMB = 9020*180*N3A + 9020*100*N3B + 9020*70*N3C; !Capital cost for Memb sep;
Cboiler2 = 3.24*1.5*94650*(12^0.7443)*N4A + 3.24*1.5*94650*(10^0.7443)*N4B +
3.24*1.5*94650*(6^0.7443)*N4C; !Capital cost for FT-Boiler;
Cboiler1 = 3.24*1.5*94650*(84^0.7443)*N5A + 3.24*1.5*94650*(70^0.7443)*N5B +
3.24*1.5*94650*(40^0.7443)*N5C; !Capital cost for WT-Boiler;
CSTT2 = 3.24*1.5*5478.3*(500^0.4346)*N6A + 3.24*1.5*5478.3*(250^0.4346)*N6B +
3.24*1.5*5478.3*(200^0.4346)*N6C; !Capital cost for MP Turbine;
CSTT1 = 3.24*1.5*5478.3*(1000^0.4346)*N7A + 3.24*1.5*5478.3*(500^0.4346)*N7B +
3.24*1.5*5478.3*(250^0.4346)*N7C; !Capital cost for HP Turbine;
CGT = 3.24*1.5*2652.1*(1000^0.6131)*N8A + 3.24*1.5*2652.1*(500^0.6131)*N8B +
3.24*1.5*2652.1*(250^0.6131)*N8C; !Capital cost for Gas Turbine;
CHRSG = 3.24*1.5*94650*(12^0.7443)*N9A + 3.24*1.5*94650*(40^0.7443)*N9B ; !Capital
cost for HRSG;
CAD = 38.5*(F4av_Q3); !Capital cost for Anaerobic Digester;
CICE = 3.24*1.5*451.05*(315^0.8232)*N11A + 3.24*1.5*451.05*(400^0.8232)*N11B;
!Capital cost for Gas Engine;
CDRY = 3.24*18*40000*N12A + 3.24*18*25000*N12B + 3.24*18*10000*N12C; !Capital cost
for Biomass Dryer;
CCHILL = 2128.9*1.5*(250^0.7414)*N13A + 2128.9*1.5*(300^0.7414)*N13B +
2128.9*1.5*(350^0.7414)*N13C; !Capital cost for Absoprtion Chiller;
CECHILL = 1308*1.5*(250^0.77)*N14A + 1308*1.5*(300^0.77)*N14B  +
1308*1.5*(400^0.77)*N14C; !Capital cost for Mechanical Chiller;
CCOOLTOWER = 3140*1.5*(50^0.7359)*N15A + 3140*1.5*(30^0.7359)*N15B +
3140*1.5*(25^0.7359)*N15C ; !Capital cost for Cooling Tower;

CAP = Cboiler1 + Cboiler2 + CSTT1 + CSTT2 + CGT + CICE + CDRY
+ CASc + CPSA + CMEMB + CHRSG + NAD*CAD + CCHILL + CECHILL + CCOOLTOWER;
```

```
! Design Capacity Selection;

Biogas1_Q1 <= N1A*700 + N1B*500 + N1C*200  ; !Capacities in kg/h;
Biogas1_Q2 <= N1A*700 + N1B*500 + N1C*200  ;
Biogas1_Q3 <= N1A*700 + N1B*500 + N1C*200  ;
@gin(N1A);
@gin(N1B);
@gin(N1C);

Biogas2_Q1 <= N2A*500 + N2B*200 + N2C*100  ; !Capacities in kg/h;
Biogas2_Q2 <= N2A*500 + N2B*200 + N2C*100  ;
Biogas2_Q3 <= N2A*500 + N2B*200 + N2C*100  ;
@gin(N2A);
@gin(N2B);
@gin(N2C);

Biogas3_Q1 <= N3A*180 + N3B*100 + N3C*70; !Capacities in kg/h;
Biogas3_Q2 <= N3A*180 + N3B*100 + N3C*70;
Biogas3_Q3 <= N3A*180 + N3B*100 + N3C*70;
@gin(N3A);
@gin(N3B);
@gin(N3C);

FMPSkgs_Q1 <= N4A*12 + N4B*10 + N4C*6; !Capacities in kg/s;
FMPSkgs_Q2 <= N4A*12 + N4B*10 + N4C*6;
FMPSkgs_Q3 <= N4A*12 + N4B*10 + N4C*6;
@gin(N4A);
@gin(N4B);
@gin(N4C);

FHPSkgs_Q1 <= N5A*84 + N5B*70 + N5C*40; !Capacities in kg/s;
FHPSkgs_Q2 <= N5A*84 + N5B*70 + N5C*40;
FHPSkgs_Q3 <= N5A*84 + N5B*70 + N5C*40;
@gin(N5A);
@gin(N5B);
@gin(N5C);

PowerMPSTariff_Q1 <= N6A*500 + N6B*250 + N6C*200; !Capacities in kW;
PowerMPSTariff_Q2 <= N6A*500 + N6B*250 + N6C*200;
PowerMPSTariff_Q3 <= N6A*500 + N6B*250 + N6C*200;
@gin(N6A);
@gin(N6B);
@gin(N6C);

PowerHPSTariff_Q1 <= N7A*1000 + N7B*500 + N7C*250; !Capacities in kW;
PowerHPSTariff_Q2 <= N7A*1000 + N7B*500 + N7C*250;
PowerHPSTariff_Q3 <= N7A*1000 + N7B*500 + N7C*250;
@gin(N7A);
@gin(N7B);
@gin(N7C);

PowerGTTariff_Q1 <= N8A*1000 + N8B*500 + N8C*250; !Capacities in kW;
PowerGTTariff_Q2 <= N8A*1000 + N8B*500 + N8C*250;
PowerGTTariff_Q3 <= N8A*1000 + N8B*500 + N8C*250;
@gin(N8A);
@gin(N8B);
@gin(N8C);

FStHRSG_kgs_Q1 <= N9A*12 + N9B*40; !Capacities in kg/s;
FStHRSG_kgs_Q2 <= N9A*12 + N9B*40;
FStHRSG_kgs_Q3 <= N9A*12 + N9B*40;
@gin(N9A);
@gin(N9B);

NAD = 1;

POWERICE_Q1 <= N11A*315 + N11B*400; !Capacities in kW;
POWERICE_Q2 <= N11A*315 + N11B*400;
POWERICE_Q3 <= N11A*315 + N11B*400;
@gin(N11A);
@gin(N11B);

FW2_Q1 <= N12A*40000 + N12B*25000 + N12C*10000; !Capacities in kg/h;
FW2_Q2 <= N12A*40000 + N12B*25000 + N12C*10000;
FW2_Q3 <= N12A*40000 + N12B*25000 + N12C*10000;
```

```
@gin(N12A);
@gin(N12B);
@gin(N12C);

Qchill_Q1 <= N13A*250 + N13B*300 + N13C*350; !Capacities in kW;
Qchill_Q2 <= N13A*250 + N13B*300 + N13C*350;
Qchill_Q3 <= N13A*250 + N13B*300 + N13C*350;
@gin(N13A);
@gin(N13B);
@gin(N13C);

QEC_Q1 <= N14A*250 + N14B*300 + N14C*350; !Capacities in kW;
QEC_Q2 <= N14A*250 + N14B*300 + N14C*350;
QEC_Q3 <= N14A*250 + N14B*300 + N14C*350;
@gin(N14A);
@gin(N14B);
@gin(N14C);

TotalWater_Q1 <= N15A*50 + N15B*30 + N15C*25; !Capacities in kg/s;
TotalWater_Q2 <= N15A*50 + N15B*30 + N15C*25;
TotalWater_Q3 <= N15A*50 + N15B*30 + N15C*25;
@gin(N15A);
@gin(N15B);
@gin(N15C);
```

A.1.1.3 LINGO CODES (CASE 3)

```
max = EP ;

! Q1 = Scenario 1, Q2 = Scenario 2, Q3 = Scenario 3;

!Economic Performance, EP;
EP = POC1*GP_Q1 + POC2*GP_Q2 + POC3*GP_Q3 - 0.13*CAP; ! in RM/year, whereby 1
USD=RM3.24, in 2013;
GPAVG = POC1*GP_Q1 + POC2*GP_Q2 + POC3*GP_Q3 ; ! in RM/year, whereby 1 USD=RM3.24, in
2013;

@free(EP);

! Fraction of Occurence (POC1=Q1, POC2=Q2, POC3=Q3);
POC1 = 0.417;
POC2 = 0.333;
POC3 = 0.25;

! Process/Client Utility Demand;
FCoolW_Q1 = 11000; ! Cooling Water Demand in kg/h;
FChW_Q1 = 1000; ! Chilled Water in kg/h;
FLPS_Q1 = 20625; ! Low Pressure Steam (LPS) Demand in kg/h;
EDEMAND_Q1 = 632.5; ! Power Demand in kW;

! Process/Client Utility Demand;
FCoolW_Q2 = 13000; ! Cooling Water Demand in kg/h;
FChW_Q2 = 1000; ! Chilled Water in kg/h;
FLPS_Q2 = 24375; ! LPS Demand in kg/h;
EDEMAND_Q2 = 747.5; ! Power Demand in kW;

! Process/Client Utility Demand;
FCoolW_Q3 = 15000; ! Cooling Water Demand in kg/h;
FChW_Q3 = 1000; ! Chilled Water in kg/h;
FLPS_Q3 = 28125; ! LPS Demand in kg/h;
EDEMAND_Q3 = 862.5; ! Power Demand in kW;

! Price of Biomass Feedstock, assumed PKS=1, EFB=2, PMF=3, POME=4 ! RM/kg;
Price1 = 0.162;
Price2 = 0.02;
Price3 = 0.07;

! COD in mg/L for POME;
COD_Q1 = 50000;
COD_Q2 = 50000;
COD_Q3 = 50000;
```

```
! COD and POME in kg/m3;
COD2_Q1 = COD_Q1*0.001; ! mg/L to kgm3;
POME_Q1 = 1600;
COD2_Q2 = COD_Q2*0.001; ! mg/L to kgm3;
POME_Q2 = 1600;
COD2_Q3 = COD_Q3*0.001; ! mg/L to kgm3;
POME_Q3 = 1600;

!Available Biomass Mass Flow: PKS=1, EFB=2, PMF=3, POME=4 (Please Input Data in
kg/h);
F1av_Q1 = 3437.5; F1_Q1 <= F1av_Q1;
F2av_Q1 = 12375; F2_Q1 <= F2av_Q1;
F3av_Q1 = 6875; F3_Q1 <= F3av_Q1;
F4av_Q1 = 40700; F4_Q1 <= F4av_Q1;

F1av_Q2 = 4062.5; F1_Q2 <= F1av_Q2;
F2av_Q2 = 14625; F2_Q2 <= F2av_Q2;
F3av_Q2 = 8125; F3_Q2 <= F3av_Q2;
F4av_Q2 = 48100; F4_Q2 <= F4av_Q2;

F1av_Q3 = 4687.5; F1_Q3 <= F1av_Q3;
F2av_Q3 = 16875; F2_Q3 <= F2av_Q3;
F3av_Q3 = 9375; F3_Q3 <= F3av_Q3;
F4av_Q3 = 55500; F4_Q3 <= F4av_Q3;

! Biomass Heating Values: Lignin=LHV1, Cellulose=LHV2, Hemi-Cellulose=LHV3 (Please
Input Data in kJ/kg);
LHV1_Q1 = 25000;
LHV2_Q1 = 17000;
LHV3_Q1 = 16000;
HvapW_Q1 = 2260;
CpW_Q1 = 4.2;
CpS_Q1 = 2.021;

LHV1_Q2 = 25000;
LHV2_Q2 = 17000;
LHV3_Q2 = 16000;
HvapW_Q2 = 2260;
CpW_Q2 = 4.2;
CpS_Q2 = 2.021;

LHV1_Q3 = 25000;
LHV2_Q3 = 17000;
LHV3_Q3 = 16000;
HvapW_Q3 = 2260;
CpW_Q3 = 4.2;
CpS_Q3 = 2.021;

! Biomass Composition: PKS=1, EFB=2, PMF=3 (Please Input Data);
XL1_Q1 = 0.41;
XC1_Q1 = 0.17;
XHC1_Q1 = 0.18;
XW1_Q1 = 0.21;

XL2_Q1 = 0.05;
XC2_Q1 = 0.10;
XHC2_Q1 = 0.11;
XW2_Q1 = 0.72;

XL3_Q1 = 0.1542;
XC3_Q1 = 0.207;
XHC3_Q1 = 0.1908;
XW3_Q1 = 0.40;

XL1_Q2 = 0.41;
XC1_Q2 = 0.17;
XHC1_Q2 = 0.18;
XW1_Q2 = 0.21;

XL2_Q2 = 0.05;
XC2_Q2 = 0.10;
XHC2_Q2 = 0.11;
XW2_Q2 = 0.72;

XL3_Q2 = 0.1542;
XC3_Q2 = 0.207;
XHC3_Q2 = 0.1908;
```

```
XW3_Q2 = 0.40;

XL1_Q3 = 0.41;
XC1_Q3 = 0.17;
XHC1_Q3 = 0.18;
XW1_Q3 = 0.21;

XL2_Q3 = 0.05;
XC2_Q3 = 0.10;
XHC2_Q3 = 0.11;
XW2_Q3 = 0.72;

XL3_Q3 = 0.1542;
XC3_Q3 = 0.207;
XHC3_Q3 = 0.1908;
XW3_Q3 = 0.40;

! Scenario 1;

!Total Water in kg/h;
TotalWFree_Q1 = FChW_Q1 + FHPS_Q1 + CoolWCHILL_Q1 + CoolWECHILL_Q1 + FCoolW_Q1;
!Total Water in kg/s;
TotalWater_Q1 = TotalWFree_Q1*(1/3600);
! Power Demand in kWh;
EDEMAND_Q1*5000 = ECON_Q1;

! Component Mass Flow of Biomass: PKS=1, EFB=2, PMF=3;
FL_Q1 = XL1_Q1*F1_Q1 + XL2_Q1*F2_Q1 + XL3_Q1*F3_Q1;
FC_Q1 = XC1_Q1*F1_Q1 + XC2_Q1*F2_Q1 + XC3_Q1*F3_Q1;
FHC_Q1 = XHC1_Q1*F1_Q1 + XHC2_Q1*F2_Q1 + XHC3_Q1*F3_Q1;
FW_Q1 = XW1_Q1*F1_Q1 + XW2_Q1*F2_Q1 + XW3_Q1*F3_Q1;

! After Drying;
FW_Q1 = FW1_Q1 + FW2_Q1;
FT_Q1 = FL_Q1 + FC_Q1 + FHC_Q1 + FW1_Q1;

! Overall Moisture Composition of Boiler Feedstock (Input outlet composition for
drying);
XW_Q1 = 0.1;
XW_Q1*FT_Q1 = FW1_Q1;

! Heat Consumption of Dryer in kJ/h;
HeatDryer_Q1 = FW2_Q1*(CpW_Q1*75 + HvapW_Q1); !Heat required to vapourise moisture in
biomass in kJ/h;
HeatDryer_Q1 = FLPSDry_Q1*(ha3_Q1 - hf2_Q1); !LPS required (FLPSDry) for biomass
dryer in kJ/h;

! Dried Biomass in kg/h;
FT_Q1 = FT1_Q1;

! Heat from Water Tube Boiler Combustion in kJ/h;
HeatW_Q1 = FW1_Q1*CpW_Q1*(100-25) + FW1_Q1*HvapW_Q1 + FW1_Q1*CpS_Q1*(600-100); !Heat
required to vapourise water in kJ/h;
Qcomb_Q1 = LHV1_Q1*FL_Q1 + LHV2_Q1*FC_Q1 + LHV3_Q1*FHC_Q1 - (HeatW_Q1); !Heat
generated from biomass in kJ/h;
Beff_Q1 = 0.55; ! Efficiency of Water tube boiler;
Qcomb1_Q1 = Beff_Q1*Qcomb_Q1; !Heat generated after efficiency in kJ/h;
Qcomb_Q1 >= 0;

h1_Q1 = 2858; ! Enthalpy of Steam at 30 bar in kJ/kg;
hf1_Q1 = 104.92; ! Enthalpy of Water before steam production in kJ/kg;
hf2_Q1 = 146.64; ! Enthalpy of Water after drying biomass in kJ/kg;
ha2_Q1 = 2736; ! Enthalpy of Steam at 20 bar in kJ/kg;
ha3_Q1 = 2707; ! Enthalpy of Steam at 3 bar in kJ/kg;

! If water tube boiler is used;
Qcomb1_Q1 = FHPSt_Q1*(h1_Q1-hf1_Q1); !High pressure steam (HPS) produced from water
tube boiler;
FHPSkgs_Q1 = FHPSt_Q1*(1/3600); !HPS produced in kg/s;

! Biomethane Production;
!Biogas Plant and Methane Production ;
ADeff_Q1 = 0.23; ! Digester efficiency;
Sludgeeff_Q1 = 0.06; !Sludge conversion kg/kg POME;
CODremoval_Q1 = 0.80; !COD removal efficiency;

VolPOME_Q1*POME_Q1 = (F4_Q1*1000); ! Volume of POME;
```

```
CODin_Q1 = VolPOME_Q1*(COD2_Q1/1000);

Biogas_Q1 = CODin_Q1*CODremoval_Q1*ADeff_Q1; !Biogas produced from COD removal;
Sludge_Q1 = F4_Q1*Sludgeeff_Q1; !Sludge produced;
TreatedPOME_Q1 = F4_Q1 - Biogas_Q1 - Sludge_Q1; !Remainder as Treated POME;

! Biogas Upgrading (removal of CO2);
Biogas_Q1 = Biogas1_Q1 + Biogas2_Q1 + Biogas3_Q1; !Biogas split into Biogas1=Amine
Scrubber, Biogas2_Q1=PSA, Biogas3_Q1=Membrane Sep;
Biogas1_Q1 <= Biogas_Q1;
Biogas2_Q1 <= Biogas_Q1;
Biogas3_Q1 <= Biogas_Q1;
Biomethane_Q1 = Biogas1_Q1*0.9994 + Biogas2_Q1*0.98 + Biogas3_Q1*0.99; !Conversions
of biogas into biomethane by
Biogas1=Amine Scrubber, Biogas2_Q1=PSA, Biogas3_Q1=Membrane Sep;
CARBRemoved_Q1 = CODin_Q1*CODremoval_Q1*0.124;

! Power Requirement for removal of CO2 in kW/(kg/h);
POWERASc_Q1 = 0.14*Biogas1_Q1; !Amine Scrubber;
POWERPSA_Q1 = 0.3*Biogas2_Q1; !PSA;
POWERMEMB_Q1 = 0.3*Biogas3_Q1; !Membrane Sep;

! Biomethane Split in kg/h (Gas Turbine =1, Gas Engine =2, FT Boiler =3);
Biomethane_Q1 = Biomethane1_Q1 + Biomethane2_Q1 + Biomethane3_Q1;

! If gas engine is used, Power in kW;
POWERICE_Q1 = Biomethane2_Q1*22000*(1/3600)*0.51*0.389;
! Biomethane Combustion in Gas Engine;

FWoutge_Q1 = Biomethane2_Q1*2.25; !kg/h H2O Produced from CH4 combustion;
Fcdoutge_Q1 = Biomethane2_Q1*2.75; !kg/h CO2 Produced from CH4 combustion;
Foxyinge_Q1 = Biomethane2_Q1*4; !kg/h O2 required for CH4 combustion;
FNinge_Q1 = (79/21)*Foxyinge_Q1; !kg/h N2 corresponding to O2 in air for CH4
combustion;
FNoutge_Q1 = FNinge_Q1;
Fairinge_Q1 = FNinge_Q1 + Foxyinge_Q1; !kg/h air used for CH4 combustion;
FFlueGGE_Q1 = FWoutge_Q1 + Fcdoutge_Q1 + FNoutge_Q1; !total flue gas produced in kg/h
from Gas engine;
FFlueGGE_Q1 = FFlueGE_Q1 + FFlueABS_Q1; !Flue gas split in kg/h, can be either used
for Absorption Chiller (ABS)
or release from gas engine;

! If fired tube boiler is used;
! Heat from Fired Tube Boiler Combustion in kJ/h;
QcombFTB_Q1 = 22000*Biomethane3_Q1; !Heat generated from biomethane in kJ/h;
FTBeff_Q1 = 0.60; ! Efficiency of Fired tube boiler;
Qcomb2_Q1 = FTBeff_Q1*QcombFTB_Q1; !Heat generated after efficiency in kJ/h;
Qcomb2_Q1 = MHPSt_Q1*(ha2_Q1-hf1_Q1); !Medium pressure steam (MPS) produced from
fired tube boiler;
FMPSkgs_Q1 = MHPSt_Q1*(1/3600); !MPS produced in kg/s;

! If gas turbine is used;
! Biomethane Combustion in Gas Turbine;

FWoutb_Q1 = Biomethane1_Q1*2.25; !kg/h H2O Produced from CH4 combustion;
Fcdoutb_Q1 = Biomethane1_Q1*2.75; !kg/h CO2 Produced from CH4 combustion;
Foxyinb_Q1 = Biomethane1_Q1*4; !kg/h O2 required for CH4 combustion;
FNinb_Q1 = (79/21)*Foxyinb_Q1; !kg/h N2 corresponding to O2 in air for CH4
combustion;
FNoutb_Q1 = FNinb_Q1;
Fairinb_Q1 = FNinb_Q1 + Foxyinb_Q1; !kg/h air used for CH4 combustion;
FFlueG_Q1 = FWoutb_Q1 + Fcdoutb_Q1 + FNoutb_Q1; !total flue gas produced in kg/h from
Gas turbine;
FFlueG_Q1 = FFlueGT_Q1 + FFlueGTABS_Q1; !Flue gas split in kg/h, can be either used
for Absorption Chiller (ABS)
or release from gas turbine;

! Gas Turbine Shaft Work;
@free(hg1_Q1);
@free(hg2_Q1);
@free(PowerGT_Q1);

hg1_Q1 = -1142*FFlueGT_Q1; ! Inlet Enthalpy of Flue gas kJ/kg x Mass flow of fluegas
in kg/h;
hg2_Q1 = 41.09*FFlueGT_Q1; ! Outlet Enthalpy of Flue gas kJ/kg x Mass flow of fluegas
in kg/h;
PowerGT_Q1 = (hg2_Q1 - hg1_Q1)*0.60; ! Power produced by Gas turbine in kJ/h;
```

```
PowerGTTariff_Q1 = PowerGT_Q1*(1/3600); ! Power produced by Gas turbine in kW;

!HRSG;
QHRSG_Q1 = FFlueGT_Q1*1.427*(1480 - 25); ! Heat from GT Combustion to HRSG in kJ/h;
QHRSG_Q1*0.35 = QHRSG1_Q1; ! Heat after efficiency of HRSG in kJ/h;
QHRSG1_Q1 = FStHRSG_Q1*(h1_Q1 - hf1_Q1); ! HPS produced from HRSG in kg/h;
FStHRSG_Q1*(1/3600) = FStHRSG_kgs_Q1; ! HPS produced from HRSG in kg/s;

! Total HP Steam Produced by WT-Boiler and/or HRSG in kg/h;
FHPS_Q1 = FHPSt_Q1 + FStHRSG_Q1;

! HP Steam Turbine;
PowerHPS_Q1 = FHPS_Q1*(h1_Q1 - ha2_Q1)*0.98; ! HP Steam Turbine Power in kJ/h from 30
to 20 bar;
PowerHPSTariff_Q1 = PowerHPS_Q1*(1/3600); ! HP Steam Turbine Power in kW;

! HP Steam conversion to MP Steam in kg/h;
FHPS_Q1 = MHPSt2_Q1;

! Total MP Steam Produced in kg/h from HP Steam turbine and/or FT-Boiler;
FMPS_Q1 = MHPSt_Q1 + MHPSt2_Q1; !MHPSt is MPS from FT-boiler;

! MP Steam Turbine;
PowerMPS_Q1 = FMPS_Q1*(ha2_Q1 - ha3_Q1)*0.98; ! MP Steam Turbine in kJ/h from 20 to 3
bar;
PowerMPSTariff_Q1 = PowerMPS_Q1*(1/3600); ! MP Steam Turbine in kW;

! MP Steam conversion to LP Steam in kg/h;
FMPS_Q1 = FLPS_Q1 + FLPSDry_Q1; ! LPS Split to client (FLPS) and to biomass dryer
(FLPSDry);

! Absorption Chiller ;
COP_Q1 = 0.7; !Coefficient of Performace(COP);

! Heat in kW from gas engine (ABS), gas turbine (GTABS);
Qgen_Q1 = FFlueABS_Q1*1.427*(600 - 40)*(1/3600) + FFlueGTABS_Q1*1.427*(1480 -
25)*(1/3600);

Qchill_Q1 = Qgen_Q1*COP_Q1; !Cooling energy produced in kJ/h;
Qchill_Q1 = ChW_Q1*4.2*(40-7); !Chilled Water produced in kg/h;

! Mechanical Chiller;
COPEC_Q1 = 6.1; !Coefficient of Performace(COP);

QEC_Q1 = COPEC_Q1*POWEREC_Q1; !Cooling energy produced in kJ/h;
QEC_Q1 = ChWEC_Q1*4.2*(40-7); !Chilled Water produced in kg/h;

! Chilled Water in kg/h;
FChW_Q1 = ChW_Q1*3600 + ChWEC_Q1*3600; !Chilled Water produced in kg/h by Absorption
Chiller(ChW) and/or Mechanical Chiller(ChWEC);

! Cooling Water required for Chillers in kg/h;
CoolWCHILL_Q1 = 7.247*Qchill_Q1; !Absorption Chiller;
CoolWECHILL_Q1 = 7.247*QEC_Q1; !Mechanical Chiller;

! Cooling Tower;
ProcessW_Q1 = TotalWFree_Q1; !Total Water from client and other processes in kg/h;
CoolW_Q1 = TotalWFree_Q1*(1/3600); !Total Water in kg/s;

QCOOLT_Q1 = ProcessW_Q1*4.2*(40 - 30); ! Heat in kJ/h required to cool water
returning from client and other processes;
QCOOLT_Q1 = COOLAir_Q1*1.005*(50 - 30); !Cooling air required (COOLAir) to cool down
returning water in kJ/h;


! Site Power Balance in kWh;
! Internal Power Consumption in kWh;
IntCon_Power_Q1 = (POWERASc_Q1 + POWERPSA_Q1 + POWERMEMB_Q1 + POWEREC_Q1)*5000;

! Internal Power Generation in kWh;
IntGen_Power_Q1 = (PowerMPSTariff_Q1 + PowerHPSTariff_Q1 + PowerGTTariff_Q1 +
POWERICE_Q1)*5000;

! Internal Power Generation Split in kWh;
IntGen_Power_Q1 = IntCon_Power_Q1 + Export_Power_Q1 + Cust_Power_Q1;

! Power Demand from Client in kWh;
```

```
ECON_Q1 = Cust_Power_Q1 + External_Power_Q1;


! Gross Revenue in RM/year, whereby 1 USD=RM3.24, in 2013;

GP_Q1 = Export_Power_Q1*0.3069 + Cust_Power_Q1*0.29 + FLPS_Q1*0.08*5000 +
FCoolW_Q1*0.0003*5000
+ FChW_Q1*0.002*5000 - External_Power_Q1*0.39 - F1_Q1*Price1*5000 - F2_Q1*Price2*5000
- F3_Q1*Price3*5000;

@free(GP_Q1);


! Scenario 2;

!Total Water in kg/h;
TotalWFree_Q2 = FChW_Q2 + FHPS_Q2 + CoolWCHILL_Q2 + CoolWECHILL_Q2 + FCoolW_Q2;
!Total Water in kg/s;
TotalWater_Q2 = TotalWFree_Q2*(1/3600);
! Power Demand in kWh;
EDEMAND_Q2*5000 = ECON_Q2;

! Component Mass Flow of Biomass: PKS=1, EFB=2, PMF=3;
FL_Q2 = XL1_Q2*F1_Q2 + XL2_Q2*F2_Q2 + XL3_Q2*F3_Q2;
FC_Q2 = XC1_Q2*F1_Q2 + XC2_Q2*F2_Q2 + XC3_Q2*F3_Q2;
FHC_Q2 = XHC1_Q2*F1_Q2 + XHC2_Q2*F2_Q2 + XHC3_Q2*F3_Q2;
FW_Q2 = XW1_Q2*F1_Q2 + XW2_Q2*F2_Q2 + XW3_Q2*F3_Q2;

! After Drying;
FW_Q2 = FW1_Q2 + FW2_Q2;
FT_Q2 = FL_Q2 + FC_Q2 + FHC_Q2 + FW1_Q2;

! Overall Moisture Composition of Boiler Feedstock (Input outlet composition for
drying);
XW_Q2 = 0.1;
XW_Q2*FT_Q2 = FW1_Q2;

! Heat Consumption of Dryer;
HeatDryer_Q2 = FW2_Q2*(CpW_Q2*75 + HvapW_Q2); !Heat required to vapourise moisture in
biomass in kJ/h;
HeatDryer_Q2 = FLPSDry_Q2*(ha3_Q2 - hf2_Q2); !LPS required (FLPSDry) for biomass
dryer in kJ/h;

! Dried Biomass in kg/h;
FT_Q2 = FT1_Q2;

! Heat from Water Tube Boiler Combustion in kJ/h;
HeatW_Q2 = FW1_Q2*CpW_Q2*(100-25) + FW1_Q2*HvapW_Q2 + FW1_Q2*CpS_Q2*(600-100); !Heat
required to vapourise water in kJ/h;
Qcomb_Q2 = LHV1_Q2*FL_Q2 + LHV2_Q2*FC_Q2 + LHV3_Q2*FHC_Q2 - (HeatW_Q2); !Heat
generated from biomass in kJ/h;
Beff_Q2 = 0.55; ! Efficiency of Water tube boiler;
Qcomb1_Q2 = Beff_Q2*Qcomb_Q2; !Heat generated after efficiency in kJ/h;
Qcomb_Q2 >= 0;

h1_Q2 = 2858; ! Enthalpy of Steam at 30 bar in kJ/kg;
hf1_Q2 = 104.92; ! Enthalpy of Water before steam production in kJ/kg;
hf2_Q2 = 146.64; ! Enthalpy of Water after drying biomass in kJ/kg;
ha2_Q2 = 2736; ! Enthalpy of Steam at 20 bar in kJ/kg;
ha3_Q2 = 2707; ! Enthalpy of Steam at 3 bar in kJ/kg;

! If water tube boiler is used;
Qcomb1_Q2 = FHPSt_Q2*(h1_Q2-hf1_Q2); !High pressure steam (HPS) produced from water
tube boiler;
FHPSkgs_Q2 = FHPSt_Q2*(1/3600); !HPS produced in kg/s;

! Biomethane Production;
!Biogas Plant and Methane Production ;
ADeff_Q2 = 0.23; ! Digester efficiency;
Sludgeeff_Q2 = 0.06; !Sludge conversion kg/kg POME;
CODremoval_Q2 = 0.80; !COD removal efficiency;

VolPOME_Q2*POME_Q2 = (F4_Q2*1000); ! Volume of POME;
CODin_Q2 = VolPOME_Q2*(COD2_Q2/1000);
```

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Biogas_Q2 = CODin_Q2*CODremoval_Q2*ADeff_Q2; !Biogas produced from COD removal;
Sludge_Q2 = F4_Q2*Sludgeeff_Q2; !Sludge produced;
TreatedPOME_Q2 = F4_Q2 - Biogas_Q2 - Sludge_Q2; !Remainder as Treated POME;

! Biogas Upgrading (removal of CO2);
Biogas_Q2 = Biogas1_Q2 + Biogas2_Q2 + Biogas3_Q2; !Biogas split into Biogas1=Amine
Scrubber, Biogas2_Q1=PSA, Biogas3_Q1=Membrane Sep;
Biogas1_Q2 <= Biogas_Q2;
Biogas2_Q2 <= Biogas_Q2;
Biogas3_Q2 <= Biogas_Q2;
Biomethane_Q2 = Biogas1_Q2*0.9994 + Biogas2_Q2*0.98 + Biogas3_Q2*0.99; !Conversions
of biogas into biomethane by
Biogas1=Amine Scrubber, Biogas2_Q1=PSA, Biogas3_Q1=Membrane Sep;
CARBRemoved_Q2 = CODin_Q2*CODremoval_Q2*0.124;

! Power Requirement for removal of CO2 in kW/(kg/h);
POWERASc_Q2 = 0.14*Biogas1_Q2; !Amine Scrubber;
POWERPSA_Q2 = 0.3*Biogas2_Q2; !PSA;
POWERMEMB_Q2 = 0.3*Biogas3_Q2; !Membrane Sep;

! Biomethane Split in kg/h (Gas Turbine =1, Gas Engine =2, FT Boiler =3);
Biomethane_Q2 = Biomethane1_Q2 + Biomethane2_Q2 + Biomethane3_Q2;

! If gas engine is used, Power in kW;
POWERICE_Q2 = Biomethane2_Q2*22000*(1/3600)*0.51*0.389;
! Biomethane Combustion in Gas Engine;

FWoutge_Q2 = Biomethane2_Q2*2.25; !kg/h H2O Produced from CH4 combustion;
Fcdoutge_Q2 = Biomethane2_Q2*2.75; !kg/h CO2 Produced from CH4 combustion;
Foxyinge_Q2 = Biomethane2_Q2*4; !kg/h O2 required for CH4 combustion;
FNinge_Q2 = (79/21)*Foxyinge_Q2; !kg/h N2 corresponding to O2 in air for CH4
combustion;
FNoutge_Q2 = FNinge_Q2;
Fairinge_Q2 = FNinge_Q2 + Foxyinge_Q2; !kg/h air used for CH4 combustion;
FFlueGGE_Q2 = FWoutge_Q2 + Fcdoutge_Q2 + FNoutge_Q2; !total flue gas produced in kg/h
from Gas engine;
FFlueGGE_Q2 = FFlueGE_Q2 + FFlueABS_Q2; !Flue gas split in kg/h, can be either used
for Absorption Chiller (ABS)
or release from gas engine;

! If fired tube boiler is used;
! Heat from Fired Tube Boiler Combustion in kJ/h;
QcombFTB_Q2 = 22000*Biomethane3_Q2;!Heat generated from biomethane in kJ/h;
FTBeff_Q2 = 0.60; ! Efficiency of Fired tube boiler;
Qcomb2_Q2 = FTBeff_Q2*QcombFTB_Q2; !Heat generated after efficiency in kJ/h;
Qcomb2_Q2 = MHPSt_Q2*(ha2_Q2-hf1_Q2); !Medium pressure steam (MPS) produced from
fired tube boiler;
FMPSkgs_Q2 = MHPSt_Q2*(1/3600); !MPS produced in kg/s;

! If gas turbine is used;
! Biomethane Combustion in Gas Turbine;

FWoutb_Q2 = Biomethane1_Q2*2.25; !kg/h H2O Produced from CH4 combustion;
Fcdoutb_Q2 = Biomethane1_Q2*2.75; !kg/h CO2 Produced from CH4 combustion;
Foxyinb_Q2 = Biomethane1_Q2*4; !kg/h O2 required for CH4 combustion;
FNinb_Q2 = (79/21)*Foxyinb_Q2; !kg/h N2 corresponding to O2 in air for CH4
combustion;
FNoutb_Q2 = FNinb_Q2;
Fairinb_Q2 = FNinb_Q2 + Foxyinb_Q2; !kg/h air used for CH4 combustion;
FFlueG_Q2 = FWoutb_Q2 + Fcdoutb_Q2 + FNoutb_Q2; !total flue gas produced in kg/h from
Gas turbine;
FFlueG_Q2 = FFlueGT_Q2 + FFlueGTABS_Q2; !Flue gas split in kg/h, can be either used
for Absorption Chiller (ABS)
or release from gas turbine;

! Gas Turbine Shaft Work;
@free(hg1_Q2);
@free(hg2_Q2);
@free(PowerGT_Q2);

hg1_Q2 = -1142*FFlueGT_Q2; ! Inlet Enthalpy of Flue gas kJ/kg x Mass flow of fluegas
in kg/h;
hg2_Q2 = 41.09*FFlueGT_Q2; ! Outlet Enthalpy of Flue gas kJ/kg x Mass flow of fluegas
in kg/h;
PowerGT_Q2 = (hg2_Q2 - hg1_Q2)*0.60; ! Power produced by Gas turbine in kJ/h;
PowerGTTariff_Q2 = PowerGT_Q2*(1/3600); ! Power produced by Gas turbine in kW;
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!HRSG ;
QHRSG_Q2 = FFlueGT_Q2*1.427*(1480 - 25); ! Heat from GT Combustion to HRSG in kJ/h;
QHRSG_Q2*0.35 = QHRSG1_Q2; ! Heat after efficiency of HRSG in kJ/h;
QHRSG1_Q2 = FStHRSG_Q2*(h1_Q2 - hf1_Q2); ! HPS produced from HRSG in kg/h;
FStHRSG_Q2*(1/3600) = FStHRSG_kgs_Q2; ! HPS produced from HRSG in kg/s;

! Total HP Steam Produced by WT-Boiler and/or HRSG in kg/h;
FHPS_Q2 = FHPSt_Q2 + FStHRSG_Q2;

! HP Steam Turbine Power;
PowerHPS_Q2 = FHPS_Q2*(h1_Q2 - ha2_Q2)*0.98; ! HP Steam Turbine Power in kJ/h from 30
to 20 bar;
PowerHPSTariff_Q2 = PowerHPS_Q2*(1/3600); ! HP Steam Turbine Power in kW;

! HP Steam conversion to MP Steam in kg/h;
FHPS_Q2 = MHPSt2_Q2;

! Total MP Steam Produced in kg/h from HP Steam turbine and/or FT-Boiler;
FMPS_Q2 = MHPSt_Q2 + MHPSt2_Q2; !MHPSt is MPS from FT-boiler;

! MP Steam Turbine;
PowerMPS_Q2 = FMPS_Q2*(ha2_Q2 - ha3_Q2)*0.98; ! MP Steam Turbine in kJ/h from 20 to 3
bar;
PowerMPSTariff_Q2 = PowerMPS_Q2*(1/3600); ! MP Steam Turbine in kW;

! MP Steam conversion to LP Steam in kg/h;
FMPS_Q2 = FLPS_Q2 + FLPSDry_Q2; ! LPS Split to client (FLPS) and to biomass dryer
(FLPSDry);

! Absorption Chiller ;
COP_Q2 = 0.7; !Coefficient of Performace(COP);

! Heat in kW from gas engine (ABS), gas turbine (GTABS);
Qgen_Q2 = FFlueABS_Q2*1.427*(600 - 40)*(1/3600) + FFlueGTABS_Q2*1.427*(1480 -
25)*(1/3600);

Qchill_Q2 = Qgen_Q2*COP_Q2; !Cooling energy produced in kJ/h;
Qchill_Q2 = ChW_Q2*4.2*(40-7); !Chilled Water produced in kg/h;

! Mechanical Chiller;
COPEC_Q2 = 6.1; !Coefficient of Performace(COP);

QEC_Q2 = COPEC_Q2*POWEREC_Q2; !Cooling energy produced in kJ/h;
QEC_Q2 = ChWEC_Q2*4.2*(40-7); !Chilled Water produced in kg/h;

! Chilled Water in kg/h;
FChW_Q2 = ChW_Q2*3600 + ChWEC_Q2*3600; !Chilled Water produced in kg/h by Absorption
Chiller(ChW) and/or Mechanical Chiller(ChWEC);

! Cooling Water for Chiller in kg/h;
CoolWCHILL_Q2 = 7.247*Qchill_Q2; !Absorption Chiller;
CoolWECHILL_Q2 = 7.247*QEC_Q2; !Mechanical Chiller;

! Cooling Tower;
ProcessW_Q2 = TotalWFree_Q2; !Total Water from client and other processes in kg/h;
CoolW_Q2 = TotalWFree_Q2*(1/3600); !Total Water in kg/s;

QCOOLT_Q2 = ProcessW_Q2*4.2*(40 - 30); ! Heat in kJ/h required to cool water
returning from client and other processes;
QCOOLT_Q2 = COOLAir_Q2*1.005*(50 - 30); !Cooling air required (COOLAir) to cool down
returning water in kJ/h;


! Site Power Balance in kWh;
! Internal BTS Consumption in kWh;
IntCon_Power_Q2 = (POWERASc_Q2 + POWERPSA_Q2 + POWERMEMB_Q2 + POWEREC_Q2)*5000;

! Internal BTS Generation in kWh;
IntGen_Power_Q2 = (PowerMPSTariff_Q2 + PowerHPSTariff_Q2 + PowerGTTariff_Q2 +
POWERICE_Q2)*5000;

! Internal BTS Generation Split in kWh;
IntGen_Power_Q2 = IntCon_Power_Q2 + Export_Power_Q2 + Cust_Power_Q2;

! Power Demand from client in kWh;
ECON_Q2 = Cust_Power_Q2 + External_Power_Q2;
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```
! Gross Revenue in RM/year, whereby 1 USD=RM3.24, in 2013;

GP_Q2 = Export_Power_Q2*0.3069 + Cust_Power_Q2*0.29 + FLPS_Q2*0.08*5000 +
FCoolW_Q2*0.0003*5000
+ FChW_Q2*0.002*5000 - External_Power_Q2*0.39 - F1_Q2*Price1*5000 - F2_Q2*Price2*5000
- F3_Q2*Price3*5000;

@free(GP_Q2);


! Scenario 3;

!Total Water in kg/h;
TotalWFree_Q3 = FChW_Q3 + FHPS_Q3 + CoolWCHILL_Q3 + CoolWECHILL_Q3 + FCoolW_Q3;
!Total Water in kg/s;
TotalWater_Q3 = TotalWFree_Q3*(1/3600);
! Power Demand in kWh;
EDEMAND_Q3*5000 = ECON_Q3;

! Component Mass Flow of Biomass: PKS=1, EFB=2, PMF=3;
FL_Q3 = XL1_Q3*F1_Q3 + XL2_Q3*F2_Q3 + XL3_Q3*F3_Q3;
FC_Q3 = XC1_Q3*F1_Q3 + XC2_Q3*F2_Q3 + XC3_Q3*F3_Q3;
FHC_Q3 = XHC1_Q3*F1_Q3 + XHC2_Q3*F2_Q3 + XHC3_Q3*F3_Q3;
FW_Q3 = XW1_Q3*F1_Q3 + XW2_Q3*F2_Q3 + XW3_Q3*F3_Q3;

! After Drying;
FW_Q3 = FW1_Q3 + FW2_Q3;
FT_Q3 = FL_Q3 + FC_Q3 + FHC_Q3 + FW1_Q3;

! Overall Moisture Composition of Boiler Feedstock (Input outlet composition for
drying);
XW_Q3 = 0.1;
XW_Q3*FT_Q3 = FW1_Q3;

! Heat Consumption of Dryer in kJ/h;
HeatDryer_Q3 = FW2_Q3*(CpW_Q3*75 + HvapW_Q3); !Heat required to vapourise moisture in
biomass in kJ/h;
HeatDryer_Q3 = FLPSDry_Q3*(ha3_Q3 - hf2_Q3); !LPS required (FLPSDry) for biomass
dryer in kJ/h;

! Dried Biomass in kg.h;
FT_Q3 = FT1_Q3;

! Heat from Water Tube Boiler Combustion in kJ/h;
HeatW_Q3 = FW1_Q3*CpW_Q3*(100-25) + FW1_Q3*HvapW_Q3 + FW1_Q3*CpS_Q3*(600-100); !Heat
required to vapourise water in kJ/h;
Qcomb_Q3 = LHV1_Q3*FL_Q3 + LHV2_Q3*FC_Q3 + LHV3_Q3*FHC_Q3 - (HeatW_Q3); !Heat
generated from biomass in kJ/h;
Beff_Q3 = 0.55; ! Efficiency of Water tube boiler;
Qcomb1_Q3 = Beff_Q3*Qcomb_Q3; !Heat generated after efficiency in kJ/h;
Qcomb_Q3 >= 0;

h1_Q3 = 2858; ! Enthalpy of Steam at 30 bar in kJ/kg;
hf1_Q3 = 104.92; ! Enthalpy of Water before steam production in kJ/kg;
hf2_Q3 = 146.64; ! Enthalpy of Water after drying biomass in kJ/kg;
ha2_Q3 = 2736; ! Enthalpy of Steam at 20 bar in kJ/kg;
ha3_Q3 = 2707; ! Enthalpy of Steam at 3 bar in kJ/kg;

! If water tube boiler is used;
Qcomb1_Q3 = FHPSt_Q3*(h1_Q3-hf1_Q3); !High pressure steam (HPS) produced from water
tube boiler;
FHPSkgs_Q3 = FHPSt_Q3*(1/3600); !HPS produced in kg/s;

! Biomethane Production;
!Biogas Plant and Methane Production ;
ADeff_Q3 = 0.23; ! Digester efficiency;
Sludgeeff_Q3 = 0.06; !Sludge conversion kg/kg POME;
CODremoval_Q3 = 0.80; !COD removal efficiency;

VolPOME_Q3*POME_Q3 = (F4_Q3*1000); ! Volume of POME;
CODin_Q3 = VolPOME_Q3*(COD2_Q3/1000);

Biogas_Q3 = CODin_Q3*CODremoval_Q3*ADeff_Q3; !Biogas produced from COD removal;
Sludge_Q3 = F4_Q3*Sludgeeff_Q3; !Sludge produced;
TreatedPOME_Q3 = F4_Q3 - Biogas_Q3 - Sludge_Q3; !Remainder as Treated POME;
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! Biogas Upgrading (removal of CO2);
Biogas_Q3 = Biogas1_Q3 + Biogas2_Q3 + Biogas3_Q3; !Biogas split into Biogas1=Amine
Scrubber, Biogas2_Q1=PSA, Biogas3_Q1=Membrane Sep;
Biogas1_Q3 <= Biogas_Q3;
Biogas2_Q3 <= Biogas_Q3;
Biogas3_Q3 <= Biogas_Q3;
Biomethane_Q3 = Biogas1_Q3*0.9994 + Biogas2_Q3*0.98 + Biogas3_Q3*0.99; !Conversions
of biogas into biomethane by
Biogas1=Amine Scrubber, Biogas2_Q1=PSA, Biogas3_Q1=Membrane Sep;
CARBRemoved_Q3 = CODin_Q3*CODremoval_Q3*0.124;

! Power Requirement for removal of CO2 in kW/(kg/h);
POWERASc_Q3 = 0.14*Biogas1_Q3; !Amine Scrubber;
POWERPSA_Q3 = 0.3*Biogas2_Q3; !PSA;
POWERMEMB_Q3 = 0.3*Biogas3_Q3; !Membrane Sep;

! Biomethane Split in kg/h (Gas Turbine =1, Gas Engine =2, FT Boiler =3);
Biomethane_Q3 = Biomethane1_Q3 + Biomethane2_Q3 + Biomethane3_Q3;

! If gas engine is used, Power in kW;
POWERICE_Q3 = Biomethane2_Q3*22000*(1/3600)*0.51*0.389;
! Biomethane Combustion in Gas Engine;

FWoutge_Q3 = Biomethane2_Q3*2.25; !kg/h H2O Produced from CH4 combustion;
Fcdoutge_Q3 = Biomethane2_Q3*2.75; !kg/h CO2 Produced from CH4 combustion;
Foxyinge_Q3 = Biomethane2_Q3*4; !kg/h O2 required for CH4 combustion;
FNinge_Q3 = (79/21)*Foxyinge_Q3; !kg/h N2 corresponding to O2 in air for CH4
combustion;
FNoutge_Q3 = FNinge_Q3;
Fairinge_Q3 = FNinge_Q3 + Foxyinge_Q3;!kg/h air used for CH4 combustion;
FFlueGGE_Q3 = FWoutge_Q3 + Fcdoutge_Q3 + FNoutge_Q3; !total flue gas produced in kg/h
from Gas engine;
FFlueGGE_Q3 = FFlueGE_Q3 + FFlueABS_Q3; !Flue gas split in kg/h, can be either used
for Absorption Chiller (ABS)
or release from gas engine;

! If fired tube boiler is used;
! Heat from Fired Tube Boiler Combustion in kJ/h;
QcombFTB_Q3 = 22000*Biomethane3_Q3; !Heat generated from biomethane in kJ/h;
FTBeff_Q3 = 0.60; ! Efficiency of Fired tube boiler;
Qcomb2_Q3 = FTBeff_Q3*QcombFTB_Q3; !Heat generated after efficiency in kJ/h;
Qcomb2_Q3 = MHPSt_Q3*(ha2_Q3-hf1_Q3); !Medium pressure steam (MPS) produced from
fired tube boiler;
FMPSkgs_Q3 = MHPSt_Q3*(1/3600); !MPS produced in kg/s;

! If gas turbine is used, Power in kW;
! Biomethane Combustion in Gas Turbine;

FWoutb_Q3 = Biomethane1_Q3*2.25; !kg/h H2O Produced from CH4 combustion;
Fcdoutb_Q3 = Biomethane1_Q3*2.75; !kg/h CO2 Produced from CH4 combustion;
Foxyinb_Q3 = Biomethane1_Q3*4; !kg/h O2 required for CH4 combustion;
FNinb_Q3 = (79/21)*Foxyinb_Q3; !kg/h N2 corresponding to O2 in air for CH4
combustion;
FNoutb_Q3 = FNinb_Q3;
Fairinb_Q3 = FNinb_Q3 + Foxyinb_Q3; !kg/h air used for CH4 combustion;
FFlueG_Q3 = FWoutb_Q3 + Fcdoutb_Q3 + FNoutb_Q3; !total flue gas produced in kg/h from
Gas turbine;
FFlueG_Q3 = FFlueGT_Q3 + FFlueGTABS_Q3; !Flue gas split in kg/h, can be either used
for Absorption Chiller (ABS)
or release from gas turbine;

! Gas Turbine Shaft Work;
@free(hg1_Q3);
@free(hg2_Q3);
@free(PowerGT_Q3);

hg1_Q3 = -1142*FFlueGT_Q3;! Inlet Enthalpy of Flue gas kJ/kg x Mass flow of fluegas
in kg/h;
hg2_Q3 = 41.09*FFlueGT_Q3; ! Outlet Enthalpy of Flue gas kJ/kg x Mass flow of fluegas
in kg/h;
PowerGT_Q3 = (hg2_Q3 - hg1_Q3)*0.60; ! Power produced by Gas turbine in kJ/h;
PowerGTTariff_Q3 = PowerGT_Q3*(1/3600); ! Power produced by Gas turbine in kW;

!HRSG;
QHRSG_Q3 = FFlueGT_Q3*1.427*(1480 - 25); ! Heat from GT Combustion to HRSG in kJ/h;
QHRSG_Q3*0.35 = QHRSG1_Q3; ! Heat after efficiency of HRSG in kJ/h;
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QHRSG1_Q3 = FStHRSG_Q3*(h1_Q3 - hf1_Q3); ! HPS produced from HRSG in kg/h;
FStHRSG_Q3*(1/3600) = FStHRSG_kgs_Q3; ! HPS produced from HRSG in kg/s;

! Total HP Steam Produced by WT-Boiler and/or HRSG in kg/h;
FHPS_Q3 = FHPSt_Q3 + FStHRSG_Q3;

! HP Steam Turbine;
PowerHPS_Q3 = FHPS_Q3*(h1_Q3 - ha2_Q3)*0.98; ! HP Steam Turbine Power in kJ/h from 30
to 20 bar;
PowerHPSTariff_Q3 = PowerHPS_Q3*(1/3600); ! HP Steam Turbine Power in kW;

! HP Steam conversion to MP Steam in kg/h;
FHPS_Q3 = MHPSt2_Q3;

! Total MP Steam Produced in kg/h from HP Steam turbine and/or FT-Boiler;
FMPS_Q3 = MHPSt_Q3 + MHPSt2_Q3; !MHPSt is MPS from FT-boiler;

! MP Steam Turbine;
PowerMPS_Q3 = FMPS_Q3*(ha2_Q3 - ha3_Q3)*0.98; ! MP Steam Turbine in kJ/h from 20 to 3
bar;
PowerMPSTariff_Q3 = PowerMPS_Q3*(1/3600); ! MP Steam Turbine in kW;

! MP Steam conversion to LP Steam in kg/h;
FMPS_Q3 = FLPS_Q3 + FLPSDry_Q3; ! LPS Split to client (FLPS) and to biomass dryer
(FLPSDry);

! Absorption Chiller ;
COP_Q3 = 0.7; !Coefficient of Performace(COP);

! Heat in kW from gas engine (ABS), gas turbine (GTABS);
Qgen_Q3 = FFlueABS_Q3*1.427*(600 - 40)*(1/3600) + FFlueGTABS_Q3*1.427*(1480 -
25)*(1/3600);

Qchill_Q3 = Qgen_Q3*COP_Q3; !Cooling energy produced in kJ/h;
Qchill_Q3 = ChW_Q3*4.2*(40-7); !Chilled Water produced in kg/h;

! Mechanical Chiller;
COPEC_Q3 = 6.1; !Coefficient of Performace(COP);

QEC_Q3 = COPEC_Q3*POWEREC_Q3; !Cooling energy produced in kJ/h;
QEC_Q3 = ChWEC_Q3*4.2*(40-7); !Chilled Water produced in kg/h;

! Chilled Water in kg/h;
FChW_Q3 = ChW_Q3*3600 + ChWEC_Q3*3600; !Chilled Water produced in kg/h by Absorption
Chiller(ChW) and/or Mechanical Chiller(ChWEC);

! Cooling Water required for Chillers in kg/h;
CoolWCHILL_Q3 = 7.247*Qchill_Q3; !Absorption Chiller;
CoolWECHILL_Q3 = 7.247*QEC_Q3; !Mechanical Chiller;

! Cooling Tower;
ProcessW_Q3 = TotalWFree_Q3; !Total Water from client and other processes in kg/h;
CoolW_Q3 = TotalWFree_Q3*(1/3600); !Total Water in kg/s;

QCOOLT_Q3 = ProcessW_Q3*4.2*(40 - 30);! Heat in kJ/h required to cool water returning
from client and other processes;
QCOOLT_Q3 = COOLAir_Q3*1.005*(50 - 30);!Cooling air required (COOLAir) to cool down
returning water in kJ/h;


! Site Power Balance in kWh;
! Internal Power Consumption in kWh;
IntCon_Power_Q3 = (POWERASc_Q3 + POWERPSA_Q3 + POWERMEMB_Q3 + POWEREC_Q3)*5000;

! Internal Power Generation in kWh;
IntGen_Power_Q3 = (PowerMPSTariff_Q3 + PowerHPSTariff_Q3 + PowerGTTariff_Q3 +
POWERICE_Q3)*5000;

! Internal Power Generation Split in kWh;
IntGen_Power_Q3 = IntCon_Power_Q3 + Export_Power_Q3 + Cust_Power_Q3;

! Power Demand from client in kWh;
ECON_Q3 = Cust_Power_Q3 + External_Power_Q3;


! Gross Revenue in RM/year, whereby 1 USD=RM3.24, in 2013;
```

```
GP_Q3 = Export_Power_Q3*0.3069 + Cust_Power_Q3*0.29 + FLPS_Q3*0.08*5000 +
FCoolW_Q3*0.0003*5000
+ FChW_Q3*0.002*5000 - External_Power_Q3*0.39 - F1_Q3*Price1*5000 - F2_Q3*Price2*5000
- F3_Q3*Price3*5000 ;

@free(GP_Q3);


! Capital Cost Correlations;
CASc = 14657.5*700*N1A + 14657.5*500*N1B + 14657.5*200*N1C; !Capital cost for Amine
Scrubber;
CPSA = 10022*500*N2A + 10022*200*N2B + 10022*100*N2C; !Capital cost for PSA;
CMEMB = 9020*180*N3A + 9020*100*N3B + 9020*70*N3C; !Capital cost for Memb sep;
Cboiler2 = 3.24*1.5*94650*(12^0.7443)*N4A + 3.24*1.5*94650*(10^0.7443)*N4B +
3.24*1.5*94650*(6^0.7443)*N4C; !Capital cost for FT-Boiler;
Cboiler1 = 3.24*1.5*94650*(84^0.7443)*N5A + 3.24*1.5*94650*(70^0.7443)*N5B +
3.24*1.5*94650*(40^0.7443)*N5C; !Capital cost for WT-Boiler;
CSTT2 = 3.24*1.5*5478.3*(500^0.4346)*N6A + 3.24*1.5*5478.3*(250^0.4346)*N6B +
3.24*1.5*5478.3*(200^0.4346)*N6C; !Capital cost for MP Turbine;
CSTT1 = 3.24*1.5*5478.3*(1000^0.4346)*N7A + 3.24*1.5*5478.3*(500^0.4346)*N7B +
3.24*1.5*5478.3*(250^0.4346)*N7C; !Capital cost for HP Turbine;
CGT = 3.24*1.5*2652.1*(1000^0.6131)*N8A + 3.24*1.5*2652.1*(500^0.6131)*N8B +
3.24*1.5*2652.1*(250^0.6131)*N8C; !Capital cost for Gas Turbine;
CHRSG = 3.24*1.5*94650*(12^0.7443)*N9A + 3.24*1.5*94650*(40^0.7443)*N9B ; !Capital
cost for HRSG;
CAD = 38.5*(F4av_Q3); !Capital cost for Anaerobic Digester;
CICE = 3.24*1.5*451.05*(315^0.8232)*N11A + 3.24*1.5*451.05*(400^0.8232)*N11B;
!Capital cost for Gas Engine;
CDRY = 3.24*18*40000*N12A + 3.24*18*25000*N12B + 3.24*18*10000*N12C; !Capital cost
for Biomass Dryer;
CCHILL = 2128.9*1.5*(250^0.7414)*N13A + 2128.9*1.5*(300^0.7414)*N13B +
2128.9*1.5*(350^0.7414)*N13C; !Capital cost for Absoprtion Chiller;
CECHILL = 1308*1.5*(250^0.77)*N14A + 1308*1.5*(300^0.77)*N14B  +
1308*1.5*(400^0.77)*N14C; !Capital cost for Mechanical Chiller;
CCOOLTOWER = 3140*1.5*(50^0.7359)*N15A + 3140*1.5*(30^0.7359)*N15B +
3140*1.5*(25^0.7359)*N15C ; !Capital cost for Cooling Tower;

CAP = Cboiler1 + Cboiler2 + CSTT1 + CSTT2 + CGT + CICE + CDRY
+ CASc + CPSA + CMEMB + CHRSG + NAD*CAD + CCHILL + CECHILL + CCOOLTOWER;


! Design Capacity Selection;

Biogas1_Q1 <= N1A*700 + N1B*500 + N1C*200  ; !Capacities in kg/h;
Biogas1_Q2 <= N1A*700 + N1B*500 + N1C*200  ;
Biogas1_Q3 <= N1A*700 + N1B*500 + N1C*200  ;
@gin(N1A);
@gin(N1B);
@gin(N1C);

Biogas2_Q1 <= N2A*500 + N2B*200 + N2C*100  ; !Capacities in kg/h;
Biogas2_Q2 <= N2A*500 + N2B*200 + N2C*100  ;
Biogas2_Q3 <= N2A*500 + N2B*200 + N2C*100  ;
@gin(N2A);
@gin(N2B);
@gin(N2C);

Biogas3_Q1 <= N3A*180 + N3B*100 + N3C*70; !Capacities in kg/h;
Biogas3_Q2 <= N3A*180 + N3B*100 + N3C*70;
Biogas3_Q3 <= N3A*180 + N3B*100 + N3C*70;
@gin(N3A);
@gin(N3B);
@gin(N3C);

FMPSkgs_Q1 <= N4A*12 + N4B*10 + N4C*6; !Capacities in kg/s;
FMPSkgs_Q2 <= N4A*12 + N4B*10 + N4C*6;
FMPSkgs_Q3 <= N4A*12 + N4B*10 + N4C*6;
@gin(N4A);
@gin(N4B);
@gin(N4C);

FHPSkgs_Q1 <= N5A*84 + N5B*70 + N5C*40; !Capacities in kg/s;
FHPSkgs_Q2 <= N5A*84 + N5B*70 + N5C*40;
FHPSkgs_Q3 <= N5A*84 + N5B*70 + N5C*40;
@gin(N5A);
@gin(N5B);
@gin(N5C);
```

```
PowerMPSTariff_Q1 <= N6A*500 + N6B*250 + N6C*200; !Capacities in kW;
PowerMPSTariff_Q2 <= N6A*500 + N6B*250 + N6C*200;
PowerMPSTariff_Q3 <= N6A*500 + N6B*250 + N6C*200;
@gin(N6A);
@gin(N6B);
@gin(N6C);

PowerHPSTariff_Q1 <= N7A*1000 + N7B*500 + N7C*250; !Capacities in kW;
PowerHPSTariff_Q2 <= N7A*1000 + N7B*500 + N7C*250;
PowerHPSTariff_Q3 <= N7A*1000 + N7B*500 + N7C*250;
@gin(N7A);
@gin(N7B);
@gin(N7C);

PowerGTTariff_Q1 <= N8A*1000 + N8B*500 + N8C*250; !Capacities in kW;
PowerGTTariff_Q2 <= N8A*1000 + N8B*500 + N8C*250;
PowerGTTariff_Q3 <= N8A*1000 + N8B*500 + N8C*250;
@gin(N8A);
@gin(N8B);
@gin(N8C);

FStHRSG_kgs_Q1 <= N9A*12 + N9B*40; !Capacities in kg/s;
FStHRSG_kgs_Q2 <= N9A*12 + N9B*40;
FStHRSG_kgs_Q3 <= N9A*12 + N9B*40;
@gin(N9A);
@gin(N9B);

NAD = 1;

POWERICE_Q1 <= N11A*315 + N11B*400; !Capacities in kW;
POWERICE_Q2 <= N11A*315 + N11B*400;
POWERICE_Q3 <= N11A*315 + N11B*400;
@gin(N11A);
@gin(N11B);

FW2_Q1 <= N12A*40000 + N12B*25000 + N12C*10000; !Capacities in kg/h;
FW2_Q2 <= N12A*40000 + N12B*25000 + N12C*10000;
FW2_Q3 <= N12A*40000 + N12B*25000 + N12C*10000;
@gin(N12A);
@gin(N12B);
@gin(N12C);

Qchill_Q1 <= N13A*250 + N13B*300 + N13C*350; !Capacities in kW;
Qchill_Q2 <= N13A*250 + N13B*300 + N13C*350;
Qchill_Q3 <= N13A*250 + N13B*300 + N13C*350;
@gin(N13A);
@gin(N13B);
@gin(N13C);

QEC_Q1 <= N14A*250 + N14B*300 + N14C*350; !Capacities in kW;
QEC_Q2 <= N14A*250 + N14B*300 + N14C*350;
QEC_Q3 <= N14A*250 + N14B*300 + N14C*350;
@gin(N14A);
@gin(N14B);
@gin(N14C);

TotalWater_Q1 <= N15A*50 + N15B*30 + N15C*25; !Capacities in kg/s;
TotalWater_Q2 <= N15A*50 + N15B*30 + N15C*25;
TotalWater_Q3 <= N15A*50 + N15B*30 + N15C*25;
@gin(N15A);
@gin(N15B);
@gin(N15C);
```

A.1.2 RESULTS

A.1.2.1 RESULTS (CASE 1)

```
Global optimal solution found.
Objective value:                              6377207.
Objective bound:                              6377207.
Infeasibilities:                            0.2980232E-07
Extended solver steps:                             63
Total solver iterations:                         1388
Elapsed runtime seconds:                         1.54

Model Class:                                     MILP

Total variables:                   336
Nonlinear variables:                 0
Integer variables:                  40

Total constraints:                 333
Nonlinear constraints:               0

Total nonzeros:                    922
Nonlinear nonzeros:                  0
```

Variable	Value	Reduced Cost
EP	6377207.	0.000000
POC1	0.4170000	0.000000
GP_Q1	7690965.	0.000000
POC2	0.3330000	0.000000
GP_Q2	9089265.	0.000000
POC3	0.2500000	0.000000
GP_Q3	0.1048756E+08	0.000000
CAP	0.1906570E+08	0.000000
GPAVG	8855749.	0.000000
FCOOLW_Q1	11000.00	0.000000
FCHW_Q1	1000.000	0.000000
FLPS_Q1	20625.00	0.000000
EDEMAND_Q1	632.5000	0.000000
FCOOLW_Q2	13000.00	0.000000
FCHW_Q2	1000.000	0.000000
FLPS_Q2	24375.00	0.000000
EDEMAND_Q2	747.5000	0.000000
FCOOLW_Q3	15000.00	0.000000
FCHW_Q3	1000.000	0.000000
FLPS_Q3	28125.00	0.000000
EDEMAND_Q3	862.5000	0.000000
PRICE1	0.1620000	0.000000
PRICE2	0.2000000E-01	0.000000
PRICE3	0.7000000E-01	0.000000
COD_Q1	50000.00	0.000000
COD_Q2	50000.00	0.000000
COD_Q3	50000.00	0.000000
COD2_Q1	50.00000	0.000000
POME_Q1	1600.000	0.000000
COD2_Q2	50.00000	0.000000
POME_Q2	1600.000	0.000000
COD2_Q3	50.00000	0.000000
POME_Q3	1600.000	0.000000
F1AV_Q1	3437.500	0.000000
F1_Q1	132.4281	0.000000
F2AV_Q1	12375.00	0.000000
F2_Q1	12375.00	0.000000
F3AV_Q1	6875.000	0.000000
F3_Q1	6875.000	0.000000
F4AV_Q1	40700.00	0.000000
F4_Q1	40700.00	0.000000
F1AV_Q2	4062.500	0.000000
F1_Q2	156.5059	0.000000
F2AV_Q2	14625.00	0.000000
F2_Q2	14625.00	0.000000
F3AV_Q2	8125.000	0.000000
F3_Q2	8125.000	0.000000
F4AV_Q2	48100.00	0.000000

F4_Q2	48100.00	0.000000
F1AV_Q3	4687.500	0.000000
F1_Q3	180.5838	0.000000
F2AV_Q3	16875.00	0.000000
F2_Q3	16875.00	0.000000
F3AV_Q3	9375.000	0.000000
F3_Q3	9375.000	0.000000
F4AV_Q3	55500.00	0.000000
F4_Q3	55500.00	0.000000
LHV1_Q1	25000.00	0.000000
LHV2_Q1	17000.00	0.000000
LHV3_Q1	16000.00	0.000000
HVAPW_Q1	2260.000	0.000000
CPW_Q1	4.200000	0.000000
CPS_Q1	2.021000	0.000000
LHV1_Q2	25000.00	0.000000
LHV2_Q2	17000.00	0.000000
LHV3_Q2	16000.00	0.000000
HVAPW_Q2	2260.000	0.000000
CPW_Q2	4.200000	0.000000
CPS_Q2	2.021000	0.000000
LHV1_Q3	25000.00	0.000000
LHV2_Q3	17000.00	0.000000
LHV3_Q3	16000.00	0.000000
HVAPW_Q3	2260.000	0.000000
CPW_Q3	4.200000	0.000000
CPS_Q3	2.021000	0.000000
XL1_Q1	0.3903900	0.000000
XC1_Q1	0.1601600	0.000000
XHC1_Q1	0.1747900	0.000000
XW1_Q1	0.2300000	0.000000
XL2_Q1	0.7735000E-01	0.000000
XC2_Q1	0.1340500	0.000000
XHC2_Q1	0.1235500	0.000000
XW2_Q1	0.6500000	0.000000
XL3_Q1	0.1542000	0.000000
XC3_Q1	0.2070000	0.000000
XHC3_Q1	0.1908000	0.000000
XW3_Q1	0.4000000	0.000000
XL1_Q2	0.3903900	0.000000
XC1_Q2	0.1601600	0.000000
XHC1_Q2	0.1747900	0.000000
XW1_Q2	0.2300000	0.000000
XL2_Q2	0.7735000E-01	0.000000
XC2_Q2	0.1340500	0.000000
XHC2_Q2	0.1235500	0.000000
XW2_Q2	0.6500000	0.000000
XL3_Q2	0.1542000	0.000000
XC3_Q2	0.2070000	0.000000
XHC3_Q2	0.1908000	0.000000
XW3_Q2	0.4000000	0.000000
XL1_Q3	0.3903900	0.000000
XC1_Q3	0.1601600	0.000000
XHC1_Q3	0.1747900	0.000000
XW1_Q3	0.2300000	0.000000
XL2_Q3	0.7735000E-01	0.000000
XC2_Q3	0.1340500	0.000000
XHC2_Q3	0.1235500	0.000000
XW2_Q3	0.6500000	0.000000
XL3_Q3	0.1542000	0.000000
XC3_Q3	0.2070000	0.000000
XHC3_Q3	0.1908000	0.000000
XW3_Q3	0.4000000	0.000000
TOTALWFREE_Q1	42892.11	0.000000
FHPS_Q1	30613.10	0.000000
COOLWCHILL_Q1	0.000000	0.000000
COOLWECHILL_Q1	279.0095	0.000000
TOTALWATER_Q1	11.91447	0.000000
ECON_Q1	3162500.	0.000000
FL_Q1	2069.030	0.000000
FC_Q1	3103.203	0.000000
FHC_Q1	2863.828	0.000000
FW_Q1	10824.21	0.000000
FW1_Q1	892.8957	0.000000
FW2_Q1	9931.313	0.000000
FT_Q1	8928.957	0.000000
XW_Q1	0.1000000	0.000000

HEATDRYER_Q1	0.2557313E+08	0.000000
FLPSDRY_Q1	9988.099	0.000000
HA3_Q1	2707.000	0.000000
HF2_Q1	146.6400	0.000000
FT1_Q1	8928.957	0.000000
HEATW_Q1	3201478.	0.000000
QCOMB_Q1	0.1471000E+09	0.000000
BEFF_Q1	0.5500000	0.000000
QCOMB1_Q1	0.8090499E+08	0.000000
H1_Q1	2858.000	0.000000
HF1_Q1	104.9200	0.000000
HA2_Q1	2736.000	0.000000
FHPST_Q1	29387.08	0.000000
FHPSKGS_Q1	8.163079	0.000000
ADEFF_Q1	0.2300000	0.000000
SLUDGEEFF_Q1	0.6000000E-01	0.000000
CODREMOVAL_Q1	0.8000000	0.000000
VOLPOME_Q1	25437.50	0.000000
CODIN_Q1	1271.875	0.000000
BIOGAS_Q1	234.0250	0.000000
SLUDGE_Q1	2442.000	0.000000
TREATEDPOME_Q1	38023.97	0.000000
BIOGAS1_Q1	0.000000	0.000000
BIOGAS2_Q1	0.000000	31.50520
BIOGAS3_Q1	234.0250	0.000000
BIOMETHANE_Q1	231.6848	0.000000
CARBREMOVED_Q1	126.1700	0.000000
POWERASC_Q1	0.000000	0.000000
POWERPSA_Q1	0.000000	0.000000
POWERMEMB_Q1	70.20750	0.000000
BIOMETHANE1_Q1	231.6848	0.000000
BIOMETHANE2_Q1	0.000000	0.000000
BIOMETHANE3_Q1	0.000000	0.000000
POWERICE_Q1	0.000000	958.5757
FWOUTGE_Q1	0.000000	0.000000
FCDOUTGE_Q1	0.000000	0.000000
FOXYINGE_Q1	0.000000	0.000000
FNINGE_Q1	0.000000	0.000000
FNOUTGE_Q1	0.000000	0.000000
FAIRINGE_Q1	0.000000	0.000000
FFLUEGGE_Q1	0.000000	0.000000
FFLUEGE_Q1	0.000000	60.48456
FFLUEABS_Q1	0.000000	0.000000
QCOMBFTB_Q1	0.000000	0.000000
FTBEFF_Q1	0.6000000	0.000000
QCOMB2_Q1	0.000000	0.000000
MHPST_Q1	0.000000	0.000000
FMPSKGS_Q1	0.000000	1914722.
FWOUTB_Q1	521.2907	0.000000
FCDOUTB_Q1	637.1331	0.000000
FOXYINB_Q1	926.7390	0.000000
FNINB_Q1	3486.304	0.000000
FNOUTB_Q1	3486.304	0.000000
FAIRINB_Q1	4413.043	0.000000
FFLUEG_Q1	4644.728	0.000000
FFLUEGT_Q1	4644.728	0.000000
FFLUEGTABS_Q1	0.000000	0.000000
HG1_Q1	-5304279.	0.000000
HG2_Q1	190851.9	0.000000
POWERGT_Q1	3297078.	0.000000
POWERGTTARIFF_Q1	915.8551	0.000000
QHRSG_Q1	9643778.	0.000000
QHRSG1_Q1	3375322.	0.000000
FSTHRSG_Q1	1226.017	0.000000
FSTHRSG_KGS_Q1	0.3405602	0.000000
POWERHPS_Q1	3660102.	0.000000
POWERHPSTARIFF_Q1	1016.695	0.000000
MHPST2_Q1	30613.10	0.000000
FMPS_Q1	30613.10	0.000000
POWERMPS_Q1	870024.3	0.000000
POWERMPSTARIFF_Q1	241.6734	0.000000
COP_Q1	0.7000000	0.000000
QGEN_Q1	0.000000	0.000000
QCHILL_Q1	0.000000	284.3581
CHW_Q1	0.000000	0.000000
COPEC_Q1	6.100000	0.000000
QEC_Q1	38.50000	0.000000

POWEREC_Q1	6.311475	0.000000
CHWEC_Q1	0.2777778	0.000000
PROCESSW_Q1	42892.11	0.000000
COOLW_Q1	11.91447	0.000000
QCOOLT_Q1	1801469.	0.000000
COOLAIR_Q1	89625.30	0.000000
INTCON_POWER_Q1	382594.9	0.000000
INTGEN_POWER_Q1	0.1087112E+08	0.000000
EXPORT_POWER_Q1	7326023.	0.000000
CUST_POWER_Q1	3162500.	0.000000
EXTERNAL_POWER_Q1	0.000000	0.1555827
TOTALWFREE_Q2	50458.13	0.000000
FHPS_Q2	36179.12	0.000000
COOLWCHILL_Q2	0.000000	0.000000
COOLWECHILL_Q2	279.0095	0.000000
TOTALWATER_Q2	14.01615	0.000000
ECON_Q2	3737500.	0.000000
FL_Q2	2445.217	0.000000
FC_Q2	3667.422	0.000000
FHC_Q2	3384.524	0.000000
FW_Q2	12792.25	0.000000
FW1_Q2	1055.240	0.000000
FW2_Q2	11737.01	0.000000
FT_Q2	10552.40	0.000000
XW_Q2	0.1000000	0.000000
HEATDRYER_Q2	0.3022279E+08	0.000000
FLPSDRY_Q2	11804.12	0.000000
HA3_Q2	2707.000	0.000000
HF2_Q2	146.6400	0.000000
FT1_Q2	10552.40	0.000000
HEATW_Q2	3783565.	0.000000
QCOMB_Q2	0.1738454E+09	0.000000
BEFF_Q2	0.5500000	0.000000
QCOMB1_Q2	0.9561499E+08	0.000000
H1_Q2	2858.000	0.000000
HF1_Q2	104.9200	0.000000
HA2_Q2	2736.000	0.000000
FHPST_Q2	34730.19	0.000000
FHPSKGS_Q2	9.647275	0.000000
ADEFF_Q2	0.2300000	0.000000
SLUDGEEFF_Q2	0.6000000E-01	0.000000
CODREMOVAL_Q2	0.8000000	0.000000
VOLPOME_Q2	30062.50	0.000000
CODIN_Q2	1503.125	0.000000
BIOGAS_Q2	276.5750	0.000000
SLUDGE_Q2	2886.000	0.000000
TREATEDPOME_Q2	44937.43	0.000000
BIOGAS1_Q2	0.000000	0.000000
BIOGAS2_Q2	0.000000	25.15883
BIOGAS3_Q2	276.5750	0.000000
BIOMETHANE_Q2	273.8093	0.000000
CARBREMOVED_Q2	149.1100	0.000000
POWERASC_Q2	0.000000	0.000000
POWERPSA_Q2	0.000000	0.000000
POWERMEMB_Q2	82.97250	0.000000
BIOMETHANE1_Q2	273.8093	0.000000
BIOMETHANE2_Q2	0.000000	0.000000
BIOMETHANE3_Q2	0.000000	0.000000
POWERICE_Q2	0.000000	765.4813
FWOUTGE_Q2	0.000000	0.000000
FCDOUTGE_Q2	0.000000	0.000000
FOXYINGE_Q2	0.000000	0.000000
FNINGE_Q2	0.000000	0.000000
FNOUTGE_Q2	0.000000	0.000000
FAIRINGE_Q2	0.000000	0.000000
FFLUEGGE_Q2	0.000000	0.000000
FFLUEGE_Q2	0.000000	48.30062
FFLUEABS_Q2	0.000000	0.000000
QCOMBFTB_Q2	0.000000	0.000000
FTBEFF_Q2	0.6000000	0.000000
QCOMB2_Q2	0.000000	0.000000
MHPST_Q2	0.000000	0.000000
FMPSKGS_Q2	0.000000	1529023.
FWOUTB_Q2	616.0708	0.000000
FCDOUTB_Q2	752.9754	0.000000
FOXYINB_Q2	1095.237	0.000000
FNINB_Q2	4120.177	0.000000

FNOUTB_Q2	4120.177	0.000000
FAIRINB_Q2	5215.414	0.000000
FFLUEG_Q2	5489.224	0.000000
FFLUEGT_Q2	5489.224	0.000000
FFLUEGTABS_Q2	0.000000	0.000000
HG1_Q2	-6268693.	0.000000
HG2_Q2	225552.2	0.000000
POWERGT_Q2	3896547.	0.000000
POWERGTTARIFF_Q2	1082.374	0.000000
QHRSG_Q2	0.1139719E+08	0.000000
QHRSG1_Q2	3989017.	0.000000
FSTHRSG_Q2	1448.929	0.000000
FSTHRSG_KGS_Q2	0.4024803	0.000000
POWERHPS_Q2	4325575.	0.000000
POWERHPSTARIFF_Q2	1201.549	0.000000
MHPST2_Q2	36179.12	0.000000
FMPS_Q2	36179.12	0.000000
POWERMPS_Q2	1028211.	0.000000
POWERMPSTARIFF_Q2	285.6140	0.000000
COP_Q2	0.7000000	0.000000
QGEN_Q2	0.000000	0.000000
QCHILL_Q2	0.000000	227.0773
CHW_Q2	0.000000	0.000000
COPEC_Q2	6.100000	0.000000
QEC_Q2	38.50000	0.000000
POWEREC_Q2	6.311475	0.000000
CHWEC_Q2	0.2777778	0.000000
PROCESSW_Q2	50458.13	0.000000
COOLW_Q2	14.01615	0.000000
QCOOLT_Q2	2119241.	0.000000
COOLAIR_Q2	105434.9	0.000000
INTCON_POWER_Q2	446419.9	0.000000
INTGEN_POWER_Q2	0.1284768E+08	0.000000
EXPORT_POWER_Q2	8663765.	0.000000
CUST_POWER_Q2	3737500.	0.000000
EXTERNAL_POWER_Q2	0.000000	0.1242423
TOTALWFREE_Q3	58024.15	0.000000
FHPS_Q3	41745.14	0.000000
COOLWCHILL_Q3	0.000000	0.000000
COOLWECHILL_Q3	279.0095	0.000000
TOTALWATER_Q3	16.11782	0.000000
ECON_Q3	4312500.	0.000000
FL_Q3	2821.404	0.000000
FC_Q3	4231.641	0.000000
FHC_Q3	3905.220	0.000000
FW_Q3	14760.28	0.000000
FW1_Q3	1217.585	0.000000
FW2_Q3	13542.70	0.000000
FT_Q3	12175.85	0.000000
XW_Q3	0.1000000	0.000000
HEATDRYER_Q3	0.3487245E+08	0.000000
FLPSDRY_Q3	13620.14	0.000000
HA3_Q3	2707.000	0.000000
HF2_Q3	146.6400	0.000000
FT1_Q3	12175.85	0.000000
HEATW_Q3	4365651.	0.000000
QCOMB_Q3	0.2005909E+09	0.000000
BEFF_Q3	0.5500000	0.000000
QCOMB1_Q3	0.1103250E+09	0.000000
H1_Q3	2858.000	0.000000
HF1_Q3	104.9200	0.000000
HA2_Q3	2736.000	0.000000
FHPST_Q3	40073.29	0.000000
FHPSKGS_Q3	11.13147	0.000000
ADEFF_Q3	0.2300000	0.000000
SLUDGEEFF_Q3	0.6000000E-01	0.000000
CODREMOVAL_Q3	0.8000000	0.000000
VOLPOME_Q3	34687.50	0.000000
CODIN_Q3	1734.375	0.000000
BIOGAS_Q3	319.1250	0.000000
SLUDGE_Q3	3330.000	0.000000
TREATEDPOME_Q3	51850.88	0.000000
BIOGAS1_Q3	0.000000	0.000000
BIOGAS2_Q3	0.000000	18.88801
BIOGAS3_Q3	319.1250	0.000000
BIOMETHANE_Q3	315.9338	0.000000
CARBREMOVED_Q3	172.0500	0.000000

POWERASC_Q3	0.000000	0.000000
POWERPSA_Q3	0.000000	0.000000
POWERMEMB_Q3	95.73750	0.000000
BIOMETHANE1_Q3	315.9338	0.000000
BIOMETHANE2_Q3	0.000000	0.000000
BIOMETHANE3_Q3	0.000000	0.000000
POWERICE_Q3	0.000000	574.6857
FWOUTGE_Q3	0.000000	0.000000
FCDOUTGE_Q3	0.000000	0.000000
FOXYINGE_Q3	0.000000	0.000000
FNINGE_Q3	0.000000	0.000000
FNOUTGE_Q3	0.000000	0.000000
FAIRINGE_Q3	0.000000	0.000000
FFLUEGGE_Q3	0.000000	0.000000
FFLUEGE_Q3	0.000000	36.26173
FFLUEABS_Q3	0.000000	0.000000
QCOMBFTB_Q3	0.000000	0.000000
FTBEFF_Q3	0.6000000	0.000000
QCOMB2_Q3	0.000000	0.000000
MHPST_Q3	0.000000	0.000000
FMPSKGS_Q3	0.000000	1147915.
FWOUTB_Q3	710.8509	0.000000
FCDOUTB_Q3	868.8178	0.000000
FOXYINB_Q3	1263.735	0.000000
FNINB_Q3	4754.051	0.000000
FNOUTB_Q3	4754.051	0.000000
FAIRINB_Q3	6017.786	0.000000
FFLUEG_Q3	6333.719	0.000000
FFLUEGT_Q3	6333.719	0.000000
FFLUEGTABS_Q3	0.000000	0.000000
HG1_Q3	-7233108.	0.000000
HG2_Q3	260252.5	0.000000
POWERGT_Q3	4496016.	0.000000
POWERGTTARIFF_Q3	1248.893	0.000000
QHRSG_Q3	0.1315061E+08	0.000000
QHRSG1_Q3	4602712.	0.000000
FSTHRSG_Q3	1671.841	0.000000
FSTHRSG_KGS_Q3	0.4644003	0.000000
POWERHPS_Q3	4991048.	0.000000
POWERHPSTARIFF_Q3	1386.402	0.000000
MHPST2_Q3	41745.14	0.000000
FMPS_Q3	41745.14	0.000000
POWERMPS_Q3	1186397.	0.000000
POWERMPSTARIFF_Q3	329.5547	0.000000
COP_Q3	0.7000000	0.000000
QGEN_Q3	0.000000	0.000000
QCHILL_Q3	0.000000	170.4785
CHW_Q3	0.000000	0.000000
COPEC_Q3	6.100000	0.000000
QEC_Q3	38.50000	0.000000
POWEREC_Q3	6.311475	0.000000
CHWEC_Q3	0.2777778	0.000000
PROCESSW_Q3	58024.15	0.000000
COOLW_Q3	16.11782	0.000000
QCOOLT_Q3	2437014.	0.000000
COOLAIR_Q3	121244.5	0.000000
INTCON_POWER_Q3	510244.9	0.000000
INTGEN_POWER_Q3	0.1482425E+08	0.000000
EXPORT_POWER_Q3	0.1000151E+08	0.000000
CUST_POWER_Q3	4312500.	0.000000
EXTERNAL_POWER_Q3	0.000000	0.9327500E-01
CASC	0.000000	0.000000
N1A	0.000000	1112255.
N1B	0.000000	794468.0
N1C	0.000000	317787.2
CPSA	0.000000	0.000000
N2A	0.000000	651430.0
N2B	0.000000	260572.0
N2C	0.000000	130286.0
CMEMB	2886400.	0.000000
N3A	1.000000	211068.0
N3B	0.000000	117260.0
N3C	2.000000	82082.00
CBOILER2	0.000000	0.000000
N4A	0.000000	380132.4
N4B	0.000000	331894.6
N4C	0.000000	226922.8

CBOILER1	7164240.	0.000000
N5A	0.000000	1617861.
N5B	0.000000	1412559.
N5C	1.000000	931351.2
CSTT2	396510.3	0.000000
N6A	1.000000	51546.34
N6B	0.000000	38139.08
N6C	0.000000	34614.10
CSTT1	932408.2	0.000000
N7A	1.000000	69666.73
N7B	1.000000	51546.34
N7C	0.000000	38139.08
CGT	1270822.	0.000000
N8A	1.000000	115736.3
N8B	0.000000	75667.26
N8C	1.000000	49470.53
CHRSG	2924095.	0.000000
N9A	1.000000	380132.4
N9B	0.000000	931351.2
CAD	2136750.	0.000000
CICE	0.000000	0.000000
N11A	0.000000	32464.86
N11B	0.000000	39520.29
CDRY	1166400.	0.000000
N12A	0.000000	303264.0
N12B	0.000000	189540.0
N12C	2.000000	75816.00
CCHILL	0.000000	0.000000
N13A	0.000000	24889.87
N13B	0.000000	28492.30
N13C	0.000000	31941.99
CECHILL	137756.7	0.000000
N14A	1.000000	17908.37
N14B	0.000000	20607.52
N14C	0.000000	25717.49
CCOOLTOWER	50322.82	0.000000
N15A	0.000000	10895.23
N15B	0.000000	7481.312
N15C	1.000000	6541.966
NAD	1.000000	0.000000

A.1.2.2 RESULTS (CASE 2)

```
Global optimal solution found.
Objective value:                              5406293.
Objective bound:                              5406293.
Infeasibilities:                             0.1192093E-06
Extended solver steps:                              1
Total solver iterations:                          316
Elapsed runtime seconds:                         0.55

Model Class:                                     MILP

Total variables:                    336
Nonlinear variables:                  0
Integer variables:                   40

Total constraints:                  334
Nonlinear constraints:                0

Total nonzeros:                     923
Nonlinear nonzeros:                   0
```

Variable	Value	Reduced Cost
EP	5406293.	0.000000
POC1	0.4170000	0.000000
GP_Q1	6048272.	0.000000
POC2	0.3330000	0.000000
GP_Q2	7147901.	0.000000
POC3	0.2500000	0.000000
GP_Q3	8247530.	0.000000

CAP	0.1198439E+08	0.000000
GPAVG	6964263.	0.000000
FCOOLW_Q1	11000.00	0.000000
FCHW_Q1	1000.000	0.000000
FLPS_Q1	20625.00	0.000000
EDEMAND_Q1	632.5000	0.000000
FCOOLW_Q2	13000.00	0.000000
FCHW_Q2	1000.000	0.000000
FLPS_Q2	24375.00	0.000000
EDEMAND_Q2	747.5000	0.000000
FCOOLW_Q3	15000.00	0.000000
FCHW_Q3	1000.000	0.000000
FLPS_Q3	28125.00	0.000000
EDEMAND_Q3	862.5000	0.000000
PRICE1	0.1620000	0.000000
PRICE2	0.2000000E-01	0.000000
PRICE3	0.7000000E-01	0.000000
COD_Q1	50000.00	0.000000
COD_Q2	50000.00	0.000000
COD_Q3	50000.00	0.000000
COD2_Q1	50.00000	0.000000
POME_Q1	1600.000	0.000000
COD2_Q2	50.00000	0.000000
POME_Q2	1600.000	0.000000
COD2_Q3	50.00000	0.000000
POME_Q3	1600.000	0.000000
F1AV_Q1	3437.500	0.000000
F1_Q1	563.4543	0.000000
F2AV_Q1	12375.00	0.000000
F2_Q1	12375.00	0.000000
F3AV_Q1	6875.000	0.000000
F3_Q1	6875.000	0.000000
F4AV_Q1	40700.00	0.000000
F4_Q1	0.000000	0.000000
F1AV_Q2	4062.500	0.000000
F1_Q2	665.9006	0.000000
F2AV_Q2	14625.00	0.000000
F2_Q2	14625.00	0.000000
F3AV_Q2	8125.000	0.000000
F3_Q2	8125.000	0.000000
F4AV_Q2	48100.00	0.000000
F4_Q2	0.000000	0.000000
F1AV_Q3	4687.500	0.000000
F1_Q3	768.3468	0.000000
F2AV_Q3	16875.00	0.000000
F2_Q3	16875.00	0.000000
F3AV_Q3	9375.000	0.000000
F3_Q3	9375.000	0.000000
F4AV_Q3	55500.00	0.000000
F4_Q3	0.000000	0.000000
LHV1_Q1	25000.00	0.000000
LHV2_Q1	17000.00	0.000000
LHV3_Q1	16000.00	0.000000
HVAPW_Q1	2260.000	0.000000
CPW_Q1	4.200000	0.000000
CPS_Q1	2.021000	0.000000
LHV1_Q2	25000.00	0.000000
LHV2_Q2	17000.00	0.000000
LHV3_Q2	16000.00	0.000000
HVAPW_Q2	2260.000	0.000000
CPW_Q2	4.200000	0.000000
CPS_Q2	2.021000	0.000000
LHV1_Q3	25000.00	0.000000
LHV2_Q3	17000.00	0.000000
LHV3_Q3	16000.00	0.000000
HVAPW_Q3	2260.000	0.000000
CPW_Q3	4.200000	0.000000
CPS_Q3	2.021000	0.000000
XL1_Q1	0.3903900	0.000000
XC1_Q1	0.1601600	0.000000
XHC1_Q1	0.1747900	0.000000
XW1_Q1	0.2300000	0.000000
XL2_Q1	0.7735000E-01	0.000000
XC2_Q1	0.1340500	0.000000
XHC2_Q1	0.1235500	0.000000
XW2_Q1	0.6500000	0.000000
XL3_Q1	0.1542000	0.000000

XC3_Q1	0.2070000	0.000000
XHC3_Q1	0.1908000	0.000000
XW3_Q1	0.4000000	0.000000
XL1_Q2	0.3903900	0.000000
XC1_Q2	0.1601600	0.000000
XHC1_Q2	0.1747900	0.000000
XW1_Q2	0.2300000	0.000000
XL2_Q2	0.7735000E-01	0.000000
XC2_Q2	0.1340500	0.000000
XHC2_Q2	0.1235500	0.000000
XW2_Q2	0.6500000	0.000000
XL3_Q2	0.1542000	0.000000
XC3_Q2	0.2070000	0.000000
XHC3_Q2	0.1908000	0.000000
XW3_Q2	0.4000000	0.000000
XL1_Q3	0.3903900	0.000000
XC1_Q3	0.1601600	0.000000
XHC1_Q3	0.1747900	0.000000
XW1_Q3	0.2300000	0.000000
XL2_Q3	0.7735000E-01	0.000000
XC2_Q3	0.1340500	0.000000
XHC2_Q3	0.1235500	0.000000
XW2_Q3	0.6500000	0.000000
XL3_Q3	0.1542000	0.000000
XC3_Q3	0.2070000	0.000000
XHC3_Q3	0.1908000	0.000000
XW3_Q3	0.4000000	0.000000
TOTALWFREE_Q1	42956.88	0.000000
FHPS_Q1	30677.87	0.000000
COOLWCHILL_Q1	0.000000	0.000000
COOLWECHILL_Q1	279.0095	0.000000
TOTALWATER_Q1	11.93247	0.000000
ECON_Q1	3162500.	0.000000
FL_Q1	2237.298	0.000000
FC_Q1	3172.237	0.000000
FHC_Q1	2939.167	0.000000
FW_Q1	10923.34	0.000000
FW1_Q1	927.6336	0.000000
FW2_Q1	9995.711	0.000000
FT_Q1	9276.336	0.000000
XW_Q1	0.1000000	0.000000
HEATDRYER_Q1	0.2573896E+08	0.000000
FLPSDRY_Q1	10052.87	0.000000
HA3_Q1	2707.000	0.000000
HF2_Q1	146.6400	0.000000
FT1_Q1	9276.336	0.000000
HEATW_Q1	3326030.	0.000000
QCOMB_Q1	0.1535611E+09	0.000000
BEFF_Q1	0.5500000	0.000000
QCOMB1_Q1	0.8445862E+08	0.000000
H1_Q1	2858.000	0.000000
HF1_Q1	104.9200	0.000000
HA2_Q1	2736.000	0.000000
FHPST_Q1	30677.87	0.000000
FHPSKGS_Q1	8.521629	0.000000
ADEFF_Q1	0.2300000	0.000000
SLUDGEEFF_Q1	0.6000000E-01	0.000000
CODREMOVAL_Q1	0.8000000	0.000000
VOLPOME_Q1	0.000000	0.000000
CODIN_Q1	0.000000	0.000000
BIOGAS_Q1	0.000000	0.000000
SLUDGE_Q1	0.000000	0.000000
TREATEDPOME_Q1	0.000000	0.000000
BIOGAS1_Q1	0.000000	89.58411
BIOGAS2_Q1	0.000000	191.9659
BIOGAS3_Q1	0.000000	191.9659
BIOMETHANE_Q1	0.000000	0.000000
CARBREMOVED_Q1	0.000000	0.000000
POWERASC_Q1	0.000000	0.000000
POWERPSA_Q1	0.000000	0.000000
POWERMEMB_Q1	0.000000	0.000000
BIOMETHANE1_Q1	0.000000	0.000000
BIOMETHANE2_Q1	0.000000	0.000000
BIOMETHANE3_Q1	0.000000	0.000000
POWERICE_Q1	0.000000	0.000000
FWOUTGE_Q1	0.000000	0.000000
FCDOUTGE_Q1	0.000000	0.000000

FOXYINGE_Q1	0.000000	0.000000
FNINGE_Q1	0.000000	0.000000
FNOUTGE_Q1	0.000000	0.000000
FAIRINGE_Q1	0.000000	0.000000
FFLUEGGE_Q1	0.000000	0.000000
FFLUEGE_Q1	0.000000	0.000000
FFLUEABS_Q1	0.000000	0.000000
QCOMBFTB_Q1	0.000000	0.000000
FTBEFF_Q1	0.6000000	0.000000
QCOMB2_Q1	0.000000	0.000000
MHPST_Q1	0.000000	0.000000
FMPSKGS_Q1	0.000000	0.000000
FWOUTB_Q1	0.000000	0.000000
FCDOUTB_Q1	0.000000	0.000000
FOXYINB_Q1	0.000000	0.000000
FNINB_Q1	0.000000	0.000000
FNOUTB_Q1	0.000000	0.000000
FAIRINB_Q1	0.000000	0.000000
FFLUEG_Q1	0.000000	0.000000
FFLUEGT_Q1	0.000000	0.000000
FFLUEGTABS_Q1	0.000000	0.000000
HG1_Q1	0.000000	0.000000
HG2_Q1	0.000000	0.000000
POWERGT_Q1	0.000000	0.000000
POWERGTTARIFF_Q1	0.000000	0.000000
QHRSG_Q1	0.000000	0.000000
QHRSG1_Q1	0.000000	0.000000
FSTHRSG_Q1	0.000000	0.000000
FSTHRSG_KGS_Q1	0.000000	0.000000
POWERHPS_Q1	3667846.	0.000000
POWERHPSTARIFF_Q1	1018.846	0.000000
MHPST2_Q1	30677.87	0.000000
FMPS_Q1	30677.87	0.000000
POWERMPS_Q1	871864.9	0.000000
POWERMPSTARIFF_Q1	242.1847	0.000000
COP_Q1	0.7000000	0.000000
QGEN_Q1	0.000000	0.000000
QCHILL_Q1	0.000000	0.000000
CHW_Q1	0.000000	0.000000
COPEC_Q1	6.100000	0.000000
QEC_Q1	38.50000	0.000000
POWEREC_Q1	6.311475	0.000000
CHWEC_Q1	0.2777778	0.000000
PROCESSW_Q1	42956.88	0.000000
COOLW_Q1	11.93247	0.000000
QCOOLT_Q1	1804189.	0.000000
COOLAIR_Q1	89760.64	0.000000
INTCON_POWER_Q1	31557.38	0.000000
INTGEN_POWER_Q1	6305154.	0.000000
EXPORT_POWER_Q1	3111096.	0.000000
CUST_POWER_Q1	3162500.	0.000000
EXTERNAL_POWER_Q1	0.000000	0.1555827
TOTALWFREE_Q2	50534.67	0.000000
FHPS_Q2	36255.66	0.000000
COOLWCHILL_Q2	0.000000	0.000000
COOLWECHILL_Q2	279.0095	0.000000
TOTALWATER_Q2	14.03741	0.000000
ECON_Q2	3737500.	0.000000
FL_Q2	2644.080	0.000000
FC_Q2	3749.007	0.000000
FHC_Q2	3473.562	0.000000
FW_Q2	12909.41	0.000000
FW1_Q2	1096.294	0.000000
FW2_Q2	11813.11	0.000000
FT_Q2	10962.94	0.000000
XW_Q2	0.1000000	0.000000
HEATDRYER_Q2	0.3041877E+08	0.000000
FLPSDRY_Q2	11880.66	0.000000
HA3_Q2	2707.000	0.000000
HF2_Q2	146.6400	0.000000
FT1_Q2	10962.94	0.000000
HEATW_Q2	3930763.	0.000000
QCOMB_Q2	0.1814813E+09	0.000000
BEFF_Q2	0.5500000	0.000000
QCOMB1_Q2	0.9981473E+08	0.000000
H1_Q2	2858.000	0.000000
HF1_Q2	104.9200	0.000000

HA2_Q2	2736.000	0.000000
FHPST_Q2	36255.66	0.000000
FHPSKGS_Q2	10.07102	0.000000
ADEFF_Q2	0.2300000	0.000000
SLUDGEEFF_Q2	0.6000000E-01	0.000000
CODREMOVAL_Q2	0.8000000	0.000000
VOLPOME_Q2	0.000000	0.000000
CODIN_Q2	0.000000	0.000000
BIOGAS_Q2	0.000000	0.000000
SLUDGE_Q2	0.000000	0.000000
TREATEDPOME_Q2	0.000000	0.000000
BIOGAS1_Q2	0.000000	71.53839
BIOGAS2_Q2	0.000000	153.2965
BIOGAS3_Q2	0.000000	153.2965
BIOMETHANE_Q2	0.000000	0.000000
CARBREMOVED_Q2	0.000000	0.000000
POWERASC_Q2	0.000000	0.000000
POWERPSA_Q2	0.000000	0.000000
POWERMEMB_Q2	0.000000	0.000000
BIOMETHANE1_Q2	0.000000	0.000000
BIOMETHANE2_Q2	0.000000	0.000000
BIOMETHANE3_Q2	0.000000	0.000000
POWERICE_Q2	0.000000	0.000000
FWOUTGE_Q2	0.000000	0.000000
FCDOUTGE_Q2	0.000000	0.000000
FOXYINGE_Q2	0.000000	0.000000
FNINGE_Q2	0.000000	0.000000
FNOUTGE_Q2	0.000000	0.000000
FAIRINGE_Q2	0.000000	0.000000
FFLUEGGE_Q2	0.000000	0.000000
FFLUEGE_Q2	0.000000	0.000000
FFLUEABS_Q2	0.000000	0.000000
QCOMBFTB_Q2	0.000000	0.000000
FTBEFF_Q2	0.6000000	0.000000
QCOMB2_Q2	0.000000	0.000000
MHPST_Q2	0.000000	0.000000
FMPSKGS_Q2	0.000000	0.000000
FWOUTB_Q2	0.000000	0.000000
FCDOUTB_Q2	0.000000	0.000000
FOXYINB_Q2	0.000000	0.000000
FNINB_Q2	0.000000	0.000000
FNOUTB_Q2	0.000000	0.000000
FAIRINB_Q2	0.000000	0.000000
FFLUEG_Q2	0.000000	0.000000
FFLUEGT_Q2	0.000000	0.000000
FFLUEGTABS_Q2	0.000000	0.000000
HG1_Q2	0.000000	0.000000
HG2_Q2	0.000000	0.000000
POWERGT_Q2	0.000000	0.000000
POWERGTTARIFF_Q2	0.000000	0.000000
QHRSG_Q2	0.000000	0.000000
QHRSG1_Q2	0.000000	0.000000
FSTHRSG_Q2	0.000000	0.000000
FSTHRSG_KGS_Q2	0.000000	0.000000
POWERHPS_Q2	4334727.	0.000000
POWERHPSTARIFF_Q2	1204.091	0.000000
MHPST2_Q2	36255.66	0.000000
FMPS_Q2	36255.66	0.000000
POWERMPS_Q2	1030386.	0.000000
POWERMPSTARIFF_Q2	286.2183	0.000000
COP_Q2	0.7000000	0.000000
QGEN_Q2	0.000000	0.000000
QCHILL_Q2	0.000000	0.000000
CHW_Q2	0.000000	0.000000
COPEC_Q2	6.100000	0.000000
QEC_Q2	38.50000	0.000000
POWEREC_Q2	6.311475	0.000000
CHWEC_Q2	0.2777778	0.000000
PROCESSW_Q2	50534.67	0.000000
COOLW_Q2	14.03741	0.000000
QCOOLT_Q2	2122456.	0.000000
COOLAIR_Q2	105594.8	0.000000
INTCON_POWER_Q2	31557.38	0.000000
INTGEN_POWER_Q2	7451545.	0.000000
EXPORT_POWER_Q2	3682488.	0.000000
CUST_POWER_Q2	3737500.	0.000000
EXTERNAL_POWER_Q2	0.000000	0.1242423

TOTALWFREE_Q3	58112.46	0.000000
FHPS_Q3	41833.45	0.000000
COOLWCHILL_Q3	0.000000	0.000000
COOLWECHILL_Q3	279.0095	0.000000
TOTALWATER_Q3	16.14235	0.000000
ECON_Q3	4312500.	0.000000
FL_Q3	3050.861	0.000000
FC_Q3	4325.777	0.000000
FHC_Q3	4007.956	0.000000
FW_Q3	14895.47	0.000000
FW1_Q3	1264.955	0.000000
FW2_Q3	13630.51	0.000000
FT_Q3	12649.55	0.000000
XW_Q3	0.1000000	0.000000
HEATDRYER_Q3	0.3509858E+08	0.000000
FLPSDRY_Q3	13708.45	0.000000
HA3_Q3	2707.000	0.000000
HF2_Q3	146.6400	0.000000
FT1_Q3	12649.55	0.000000
HEATW_Q3	4535496.	0.000000
QCOMB_Q3	0.2094015E+09	0.000000
BEFF_Q3	0.5500000	0.000000
QCOMB1_Q3	0.1151708E+09	0.000000
H1_Q3	2858.000	0.000000
HF1_Q3	104.9200	0.000000
HA2_Q3	2736.000	0.000000
FHPST_Q3	41833.45	0.000000
FHPSKGS_Q3	11.62040	0.000000
ADEFF_Q3	0.2300000	0.000000
SLUDGEEFF_Q3	0.6000000E-01	0.000000
CODREMOVAL_Q3	0.8000000	0.000000
VOLPOME_Q3	0.000000	0.000000
CODIN_Q3	0.000000	0.000000
BIOGAS_Q3	0.000000	0.000000
SLUDGE_Q3	0.000000	0.000000
TREATEDPOME_Q3	0.000000	0.000000
BIOGAS1_Q3	0.000000	53.70750
BIOGAS2_Q3	0.000000	115.0875
BIOGAS3_Q3	0.000000	115.0875
BIOMETHANE_Q3	0.000000	0.000000
CARBREMOVED_Q3	0.000000	0.000000
POWERASC_Q3	0.000000	0.000000
POWERPSA_Q3	0.000000	0.000000
POWERMEMB_Q3	0.000000	0.000000
BIOMETHANE1_Q3	0.000000	0.000000
BIOMETHANE2_Q3	0.000000	0.000000
BIOMETHANE3_Q3	0.000000	0.000000
POWERICE_Q3	0.000000	0.000000
FWOUTGE_Q3	0.000000	0.000000
FCDOUTGE_Q3	0.000000	0.000000
FOXYINGE_Q3	0.000000	0.000000
FNINGE_Q3	0.000000	0.000000
FNOUTGE_Q3	0.000000	0.000000
FAIRINGE_Q3	0.000000	0.000000
FFLUEGGE_Q3	0.000000	0.000000
FFLUEGE_Q3	0.000000	0.000000
FFLUEABS_Q3	0.000000	0.000000
QCOMBFTB_Q3	0.000000	0.000000
FTBEFF_Q3	0.6000000	0.000000
QCOMB2_Q3	0.000000	0.000000
MHPST_Q3	0.000000	0.000000
FMPSKGS_Q3	0.000000	0.000000
FWOUTB_Q3	0.000000	0.000000
FCDOUTB_Q3	0.000000	0.000000
FOXYINB_Q3	0.000000	0.000000
FNINB_Q3	0.000000	0.000000
FNOUTB_Q3	0.000000	0.000000
FAIRINB_Q3	0.000000	0.000000
FFLUEG_Q3	0.000000	0.000000
FFLUEGT_Q3	0.000000	0.000000
FFLUEGTABS_Q3	0.000000	0.000000
HG1_Q3	0.000000	0.000000
HG2_Q3	0.000000	0.000000
POWERGT_Q3	0.000000	0.000000
POWERGTTARIFF_Q3	0.000000	0.000000
QHRSG_Q3	0.000000	0.000000
QHRSG1_Q3	0.000000	0.000000

FSTHRSG_Q3	0.000000	0.000000
FSTHRSG_KGS_Q3	0.000000	0.000000
POWERHPS_Q3	5001608.	0.000000
POWERHPSTARIFF_Q3	1389.335	0.000000
MHPST2_Q3	41833.45	0.000000
FMPS_Q3	41833.45	0.000000
POWERMPS_Q3	1188907.	0.000000
POWERMPSTARIFF_Q3	330.2519	0.000000
COP_Q3	0.7000000	0.000000
QGEN_Q3	0.000000	0.000000
QCHILL_Q3	0.000000	0.000000
CHW_Q3	0.000000	0.000000
COPEC_Q3	6.100000	0.000000
QEC_Q3	38.50000	0.000000
POWEREC_Q3	6.311475	0.000000
CHWEC_Q3	0.2777778	0.000000
PROCESSW_Q3	58112.46	0.000000
COOLW_Q3	16.14235	0.000000
QCOOLT_Q3	2440723.	0.000000
COOLAIR_Q3	121429.0	0.000000
INTCON_POWER_Q3	31557.38	0.000000
INTGEN_POWER_Q3	8597937.	0.000000
EXPORT_POWER_Q3	4253879.	0.000000
CUST_POWER_Q3	4312500.	0.000000
EXTERNAL_POWER_Q3	0.000000	0.9327500E-01
CASC	0.000000	0.000000
N1A	0.000000	1333832.
N1B	0.000000	952737.5
N1C	0.000000	381095.0
CPSA	0.000000	0.000000
N2A	0.000000	651430.0
N2B	0.000000	260572.0
N2C	0.000000	130286.0
CMEMB	0.000000	0.000000
N3A	0.000000	211068.0
N3B	0.000000	117260.0
N3C	0.000000	82082.00
CBOILER2	0.000000	0.000000
N4A	0.000000	-9576351.
N4B	0.000000	-7965175.
N4C	0.000000	-4751319.
CBOILER1	7164240.	0.000000
N5A	0.000000	1617861.
N5B	0.000000	1412559.
N5C	1.000000	931351.2
CSTT2	396510.3	0.000000
N6A	1.000000	51546.34
N6B	0.000000	38139.08
N6C	0.000000	34614.10
CSTT1	932408.2	0.000000
N7A	1.000000	69666.73
N7B	1.000000	51546.34
N7C	0.000000	38139.08
CGT	0.000000	0.000000
N8A	0.000000	-1418764.
N8B	0.000000	-691582.7
N8C	0.000000	-334154.5
CHRSG	0.000000	0.000000
N9A	0.000000	-0.1177793E+08
N9B	0.000000	-0.3959552E+08
CAD	2136750.	0.000000
CICE	0.000000	0.000000
N11A	0.000000	-450902.6
N11B	0.000000	-574279.7
CDRY	1166400.	0.000000
N12A	0.000000	303264.0
N12B	0.000000	189540.0
N12C	2.000000	75816.00
CCHILL	0.000000	0.000000
N13A	0.000000	-37999.48
N13B	0.000000	-46974.91
N13C	0.000000	-56103.10
CECHILL	137756.7	0.000000
N14A	1.000000	17908.37
N14B	0.000000	20607.52
N14C	0.000000	25717.49
CCOOLTOWER	50322.82	0.000000

N15A	0.000000	10895.23
N15B	0.000000	7481.312
N15C	1.000000	6541.966
NAD	1.000000	0.000000

A.1.2.3 RESULTS (CASE 3)

```
Global optimal solution found.
Objective value:                              5130922.
Objective bound:                              5130922.
Infeasibilities:                              0.2980232E-07
Extended solver steps:                             67
Total solver iterations:                         1325
Elapsed runtime seconds:                         1.42

Model Class:                                     MILP

Total variables:                    336
Nonlinear variables:                  0
Integer variables:                   40

Total constraints:                  333
Nonlinear constraints:                0

Total nonzeros:                     922
Nonlinear nonzeros:                   0
```

Variable	Value	Reduced Cost
EP	5130922.	0.000000
POC1	0.4170000	0.000000
GP_Q1	6539050.	0.000000
POC2	0.3330000	0.000000
GP_Q2	7717848.	0.000000
POC3	0.2500000	0.000000
GP_Q3	8893652.	0.000000
CAP	0.1837937E+08	0.000000
GPAVG	7520240.	0.000000
FCOOLW_Q1	11000.00	0.000000
FCHW_Q1	1000.000	0.000000
FLPS_Q1	20625.00	0.000000
EDEMAND_Q1	632.5000	0.000000
FCOOLW_Q2	13000.00	0.000000
FCHW_Q2	1000.000	0.000000
FLPS_Q2	24375.00	0.000000
EDEMAND_Q2	747.5000	0.000000
FCOOLW_Q3	15000.00	0.000000
FCHW_Q3	1000.000	0.000000
FLPS_Q3	28125.00	0.000000
EDEMAND_Q3	862.5000	0.000000
PRICE1	0.1620000	0.000000
PRICE2	0.2000000E-01	0.000000
PRICE3	0.7000000E-01	0.000000
COD_Q1	50000.00	0.000000
COD_Q2	50000.00	0.000000
COD_Q3	50000.00	0.000000
COD2_Q1	50.00000	0.000000
POME_Q1	1600.000	0.000000
COD2_Q2	50.00000	0.000000
POME_Q2	1600.000	0.000000
COD2_Q3	50.00000	0.000000
POME_Q3	1600.000	0.000000
F1AV_Q1	3437.500	0.000000
F1_Q1	1756.673	0.000000
F2AV_Q1	12375.00	0.000000
F2_Q1	10781.34	0.000000
F3AV_Q1	6875.000	0.000000
F3_Q1	6875.000	0.000000
F4AV_Q1	40700.00	0.000000
F4_Q1	40700.00	0.000000
F1AV_Q2	4062.500	0.000000
F1_Q2	2275.356	0.000000
F2AV_Q2	14625.00	0.000000
F2_Q2	10074.57	0.000000

F3AV_Q2	8125.000	0.000000
F3_Q2	8125.000	0.000000
F4AV_Q2	48100.00	0.000000
F4_Q2	48100.00	0.000000
F1AV_Q3	4687.500	0.000000
F1_Q3	2853.346	0.000000
F2AV_Q3	16875.00	0.000000
F2_Q3	8574.116	0.000000
F3AV_Q3	9375.000	0.000000
F3_Q3	9375.000	0.000000
F4AV_Q3	55500.00	0.000000
F4_Q3	55500.00	0.000000
LHV1_Q1	25000.00	0.000000
LHV2_Q1	17000.00	0.000000
LHV3_Q1	16000.00	0.000000
HVAPW_Q1	2260.000	0.000000
CPW_Q1	4.200000	0.000000
CPS_Q1	2.021000	0.000000
LHV1_Q2	25000.00	0.000000
LHV2_Q2	17000.00	0.000000
LHV3_Q2	16000.00	0.000000
HVAPW_Q2	2260.000	0.000000
CPW_Q2	4.200000	0.000000
CPS_Q2	2.021000	0.000000
LHV1_Q3	25000.00	0.000000
LHV2_Q3	17000.00	0.000000
LHV3_Q3	16000.00	0.000000
HVAPW_Q3	2260.000	0.000000
CPW_Q3	4.200000	0.000000
CPS_Q3	2.021000	0.000000
XL1_Q1	0.4100000	0.000000
XC1_Q1	0.1700000	0.000000
XHC1_Q1	0.1800000	0.000000
XW1_Q1	0.2100000	0.000000
XL2_Q1	0.5000000E-01	0.000000
XC2_Q1	0.1000000	0.000000
XHC2_Q1	0.1100000	0.000000
XW2_Q1	0.7200000	0.000000
XL3_Q1	0.1542000	0.000000
XC3_Q1	0.2070000	0.000000
XHC3_Q1	0.1908000	0.000000
XW3_Q1	0.4000000	0.000000
XL1_Q2	0.4100000	0.000000
XC1_Q2	0.1700000	0.000000
XHC1_Q2	0.1800000	0.000000
XW1_Q2	0.2100000	0.000000
XL2_Q2	0.5000000E-01	0.000000
XC2_Q2	0.1000000	0.000000
XHC2_Q2	0.1100000	0.000000
XW2_Q2	0.7200000	0.000000
XL3_Q2	0.1542000	0.000000
XC3_Q2	0.2070000	0.000000
XHC3_Q2	0.1908000	0.000000
XW3_Q2	0.4000000	0.000000
XL1_Q3	0.4100000	0.000000
XC1_Q3	0.1700000	0.000000
XHC1_Q3	0.1800000	0.000000
XW1_Q3	0.2100000	0.000000
XL2_Q3	0.5000000E-01	0.000000
XC2_Q3	0.1000000	0.000000
XHC2_Q3	0.1100000	0.000000
XW2_Q3	0.7200000	0.000000
XL3_Q3	0.1542000	0.000000
XC3_Q3	0.2070000	0.000000
XHC3_Q3	0.1908000	0.000000
XW3_Q3	0.4000000	0.000000
TOTALWFREE_Q1	42961.19	0.000000
FHPS_Q1	30682.18	0.000000
COOLWCHILL_Q1	0.000000	0.000000
COOLWECHILL_Q1	279.0095	0.000000
TOTALWATER_Q1	11.93366	0.000000
ECON_Q1	3162500.	0.000000
FL_Q1	2319.428	0.000000
FC_Q1	2799.894	0.000000
FHC_Q1	2813.899	0.000000
FW_Q1	10881.47	0.000000
FW1_Q1	881.4690	0.000000

FW2_Q1	10000.00	0.000000
FT_Q1	8814.690	0.000000
XW_Q1	0.1000000	0.000000
HEATDRYER_Q1	0.2575000E+08	0.000000
FLPSDRY_Q1	10057.18	0.000000
HA3_Q1	2707.000	0.000000
HF2_Q1	146.6400	0.000000
FT1_Q1	8814.690	0.000000
HEATW_Q1	3160507.	0.000000
QCOMB_Q1	0.1474458E+09	0.000000
BEFF_Q1	0.5500000	0.000000
QCOMB1_Q1	0.8109517E+08	0.000000
H1_Q1	2858.000	0.000000
HF1_Q1	104.9200	0.000000
HA2_Q1	2736.000	0.000000
FHPST_Q1	29456.16	0.000000
FHPSKGS_Q1	8.182267	0.000000
ADEFF_Q1	0.2300000	0.000000
SLUDGEEFF_Q1	0.6000000E-01	0.000000
CODREMOVAL_Q1	0.8000000	0.000000
VOLPOME_Q1	25437.50	0.000000
CODIN_Q1	1271.875	0.000000
BIOGAS_Q1	234.0250	0.000000
SLUDGE_Q1	2442.000	0.000000
TREATEDPOME_Q1	38023.97	0.000000
BIOGAS1_Q1	0.000000	0.000000
BIOGAS2_Q1	0.000000	31.17261
BIOGAS3_Q1	234.0250	0.000000
BIOMETHANE_Q1	231.6848	0.000000
CARBREMOVED_Q1	126.1700	0.000000
POWERASC_Q1	0.000000	0.000000
POWERPSA_Q1	0.000000	0.000000
POWERMEMB_Q1	70.20750	0.000000
BIOMETHANE1_Q1	231.6847	0.000000
BIOMETHANE2_Q1	0.000000	0.000000
BIOMETHANE3_Q1	0.000000	0.000000
POWERICE_Q1	0.000000	941.7010
FWOUTGE_Q1	0.000000	0.000000
FCDOUTGE_Q1	0.000000	0.000000
FOXYINGE_Q1	0.000000	0.000000
FNINGE_Q1	0.000000	0.000000
FNOUTGE_Q1	0.000000	0.000000
FAIRINGE_Q1	0.000000	0.000000
FFLUEGGE_Q1	0.000000	0.000000
FFLUEGE_Q1	0.000000	59.84604
FFLUEABS_Q1	0.000000	0.000000
QCOMBFTB_Q1	0.000000	0.000000
FTBEFF_Q1	0.6000000	0.000000
QCOMB2_Q1	0.000000	0.000000
MHPST_Q1	0.000000	0.000000
FMPSKGS_Q1	0.000000	1913483.
FWOUTB_Q1	521.2907	0.000000
FCDOUTB_Q1	637.1331	0.000000
FOXYINB_Q1	926.7390	0.000000
FNINB_Q1	3486.304	0.000000
FNOUTB_Q1	3486.304	0.000000
FAIRINB_Q1	4413.043	0.000000
FFLUEG_Q1	4644.728	0.000000
FFLUEGT_Q1	4644.728	0.000000
FFLUEGTABS_Q1	0.000000	0.000000
HG1_Q1	-5304279.	0.000000
HG2_Q1	190851.9	0.000000
POWERGT_Q1	3297078.	0.000000
POWERGTTARIFF_Q1	915.8551	0.000000
QHRSG_Q1	9643778.	0.000000
QHRSG1_Q1	3375322.	0.000000
FSTHRSG_Q1	1226.017	0.000000
FSTHRSG_KGS_Q1	0.3405602	0.000000
POWERHPS_Q1	3668361.	0.000000
POWERHPSTARIFF_Q1	1018.989	0.000000
MHPST2_Q1	30682.18	0.000000
FMPS_Q1	30682.18	0.000000
POWERMPS_Q1	871987.5	0.000000
POWERMPSTARIFF_Q1	242.2188	0.000000
COP_Q1	0.7000000	0.000000
QGEN_Q1	0.000000	0.000000
QCHILL_Q1	0.000000	280.2487

CHW_Q1	0.000000	0.000000
COPEC_Q1	6.100000	0.000000
QEC_Q1	38.50000	0.000000
POWEREC_Q1	6.311475	0.000000
CHWEC_Q1	0.2777778	0.000000
PROCESSW_Q1	42961.19	0.000000
COOLW_Q1	11.93366	0.000000
QCOOLT_Q1	1804370.	0.000000
COOLAIR_Q1	89769.65	0.000000
INTCON_POWER_Q1	382594.9	0.000000
INTGEN_POWER_Q1	0.1088532E+08	0.000000
EXPORT_POWER_Q1	7340221.	0.000000
CUST_POWER_Q1	3162500.	0.000000
EXTERNAL_POWER_Q1	0.000000	0.1555827
TOTALWFREE_Q2	48711.19	0.000000
FHPS_Q2	34432.18	0.000000
COOLWCHILL_Q2	0.000000	0.000000
COOLWECHILL_Q2	279.0095	0.000000
TOTALWATER_Q2	13.53089	0.000000
ECON_Q2	3737500.	0.000000
FL_Q2	2689.500	0.000000
FC_Q2	3076.143	0.000000
FHC_Q2	3068.017	0.000000
FW_Q2	10981.52	0.000000
FW1_Q2	981.5177	0.000000
FW2_Q2	10000.00	0.000000
FT_Q2	9815.177	0.000000
XW_Q2	0.1000000	0.000000
HEATDRYER_Q2	0.2575000E+08	0.000000
FLPSDRY_Q2	10057.18	0.000000
HA3_Q2	2707.000	0.000000
HF2_Q2	146.6400	0.000000
FT1_Q2	9815.177	0.000000
HEATW_Q2	3519232.	0.000000
QCOMB_Q2	0.1651010E+09	0.000000
BEFF_Q2	0.5500000	0.000000
QCOMB1_Q2	0.9080553E+08	0.000000
H1_Q2	2858.000	0.000000
HF1_Q2	104.9200	0.000000
HA2_Q2	2736.000	0.000000
FHPST_Q2	32983.25	0.000000
FHPSKGS_Q2	9.162014	0.000000
ADEFF_Q2	0.2300000	0.000000
SLUDGEEFF_Q2	0.6000000E-01	0.000000
CODREMOVAL_Q2	0.8000000	0.000000
VOLPOME_Q2	30062.50	0.000000
CODIN_Q2	1503.125	0.000000
BIOGAS_Q2	276.5750	0.000000
SLUDGE_Q2	2886.000	0.000000
TREATEDPOME_Q2	44937.43	0.000000
BIOGAS1_Q2	0.000000	0.000000
BIOGAS2_Q2	0.000000	24.89323
BIOGAS3_Q2	276.5750	0.000000
BIOMETHANE_Q2	273.8093	0.000000
CARBREMOVED_Q2	149.1100	0.000000
POWERASC_Q2	0.000000	0.000000
POWERPSA_Q2	0.000000	0.000000
POWERMEMB_Q2	82.97250	0.000000
BIOMETHANE1_Q2	273.8093	0.000000
BIOMETHANE2_Q2	0.000000	0.000000
BIOMETHANE3_Q2	0.000000	0.000000
POWERICE_Q2	0.000000	752.0059
FWOUTGE_Q2	0.000000	0.000000
FCDOUTGE_Q2	0.000000	0.000000
FOXYINGE_Q2	0.000000	0.000000
FNINGE_Q2	0.000000	0.000000
FNOUTGE_Q2	0.000000	0.000000
FAIRINGE_Q2	0.000000	0.000000
FFLUEGGE_Q2	0.000000	0.000000
FFLUEGE_Q2	0.000000	47.79072
FFLUEABS_Q2	0.000000	0.000000
QCOMBFTB_Q2	0.000000	0.000000
FTBEFF_Q2	0.6000000	0.000000
QCOMB2_Q2	0.000000	0.000000
MHPST_Q2	0.000000	0.000000
FMPSKGS_Q2	0.000000	1528033.
FWOUTB_Q2	616.0708	0.000000

FCDOUTB_Q2	752.9754	0.000000
FOXYINB_Q2	1095.237	0.000000
FNINB_Q2	4120.177	0.000000
FNOUTB_Q2	4120.177	0.000000
FAIRINB_Q2	5215.414	0.000000
FFLUEG_Q2	5489.224	0.000000
FFLUEGT_Q2	5489.224	0.000000
FFLUEGTABS_Q2	0.000000	0.000000
HG1_Q2	-6268693.	0.000000
HG2_Q2	225552.2	0.000000
POWERGT_Q2	3896547.	0.000000
POWERGTTARIFF_Q2	1082.374	0.000000
QHRSG_Q2	0.1139719E+08	0.000000
QHRSG1_Q2	3989017.	0.000000
FSTHRSG_Q2	1448.929	0.000000
FSTHRSG_KGS_Q2	0.4024803	0.000000
POWERHPS_Q2	4116711.	0.000000
POWERHPSTARIFF_Q2	1143.531	0.000000
MHPST2_Q2	34432.18	0.000000
FMPS_Q2	34432.18	0.000000
POWERMPS_Q2	978562.5	0.000000
POWERMPSTARIFF_Q2	271.8229	0.000000
COP_Q2	0.7000000	0.000000
QGEN_Q2	0.000000	0.000000
QCHILL_Q2	0.000000	223.7958
CHW_Q2	0.000000	0.000000
COPEC_Q2	6.100000	0.000000
QEC_Q2	38.50000	0.000000
POWEREC_Q2	6.311475	0.000000
CHWEC_Q2	0.2777778	0.000000
PROCESSW_Q2	48711.19	0.000000
COOLW_Q2	13.53089	0.000000
QCOOLT_Q2	2045870.	0.000000
COOLAIR_Q2	101784.6	0.000000
INTCON_POWER_Q2	446419.9	0.000000
INTGEN_POWER_Q2	0.1248864E+08	0.000000
EXPORT_POWER_Q2	8304721.	0.000000
CUST_POWER_Q2	3737500.	0.000000
EXTERNAL_POWER_Q2	0.000000	0.1242423
TOTALWFREE_Q3	53917.02	0.000000
FHPS_Q3	37638.01	0.000000
COOLWCHILL_Q3	0.000000	0.000000
COOLWECHILL_Q3	279.0095	0.000000
TOTALWATER_Q3	14.97695	0.000000
ECON_Q3	4312500.	0.000000
FL_Q3	3044.203	0.000000
FC_Q3	3283.105	0.000000
FHC_Q3	3245.505	0.000000
FW_Q3	10522.57	0.000000
FW1_Q3	1063.646	0.000000
FW2_Q3	9458.920	0.000000
FT_Q3	10636.46	0.000000
XW_Q3	0.1000000	0.000000
HEATDRYER_Q3	0.2435672E+08	0.000000
FLPSDRY_Q3	9513.006	0.000000
HA3_Q3	2707.000	0.000000
HF2_Q3	146.6400	0.000000
FT1_Q3	10636.46	0.000000
HEATW_Q3	3813702.	0.000000
QCOMB_Q3	0.1800322E+09	0.000000
BEFF_Q3	0.5500000	0.000000
QCOMB1_Q3	0.9901773E+08	0.000000
H1_Q3	2858.000	0.000000
HF1_Q3	104.9200	0.000000
HA2_Q3	2736.000	0.000000
FHPST_Q3	35966.16	0.000000
FHPSKGS_Q3	9.990601	0.000000
ADEFF_Q3	0.2300000	0.000000
SLUDGEEFF_Q3	0.6000000E-01	0.000000
CODREMOVAL_Q3	0.8000000	0.000000
VOLPOME_Q3	34687.50	0.000000
CODIN_Q3	1734.375	0.000000
BIOGAS_Q3	319.1250	0.000000
SLUDGE_Q3	3330.000	0.000000
TREATEDPOME_Q3	51850.88	0.000000
BIOGAS1_Q3	0.000000	0.000000
BIOGAS2_Q3	0.000000	18.68861

BIOGAS3_Q3	319.1250	0.000000
BIOMETHANE_Q3	315.9338	0.000000
CARBREMOVED_Q3	172.0500	0.000000
POWERASC_Q3	0.000000	0.000000
POWERPSA_Q3	0.000000	0.000000
POWERMEMB_Q3	95.73750	0.000000
BIOMETHANE1_Q3	315.9338	0.000000
BIOMETHANE2_Q3	0.000000	0.000000
BIOMETHANE3_Q3	0.000000	0.000000
POWERICE_Q3	0.000000	564.5690
FWOUTGE_Q3	0.000000	0.000000
FCDOUTGE_Q3	0.000000	0.000000
FOXYINGE_Q3	0.000000	0.000000
FNINGE_Q3	0.000000	0.000000
FNOUTGE_Q3	0.000000	0.000000
FAIRINGE_Q3	0.000000	0.000000
FFLUEGGE_Q3	0.000000	0.000000
FFLUEGE_Q3	0.000000	35.87892
FFLUEABS_Q3	0.000000	0.000000
QCOMBFTB_Q3	0.000000	0.000000
FTBEFF_Q3	0.6000000	0.000000
QCOMB2_Q3	0.000000	0.000000
MHPST_Q3	0.000000	0.000000
FMPSKGS_Q3	0.000000	1142220.
FWOUTB_Q3	710.8509	0.000000
FCDOUTB_Q3	868.8178	0.000000
FOXYINB_Q3	1263.735	0.000000
FNINB_Q3	4754.051	0.000000
FNOUTB_Q3	4754.051	0.000000
FAIRINB_Q3	6017.786	0.000000
FFLUEG_Q3	6333.719	0.000000
FFLUEGT_Q3	6333.719	0.000000
FFLUEGTABS_Q3	0.000000	0.000000
HG1_Q3	-7233108.	0.000000
HG2_Q3	260252.5	0.000000
POWERGT_Q3	4496016.	0.000000
POWERGTTARIFF_Q3	1248.893	0.000000
QHRSG_Q3	0.1315061E+08	0.000000
QHRSG1_Q3	4602712.	0.000000
FSTHRSG_Q3	1671.841	0.000000
FSTHRSG_KGS_Q3	0.4644003	0.000000
POWERHPS_Q3	4500000.	0.000000
POWERHPSTARIFF_Q3	1250.000	0.000000
MHPST2_Q3	37638.01	0.000000
FMPS_Q3	37638.01	0.000000
POWERMPS_Q3	1069672.	0.000000
POWERMPSTARIFF_Q3	297.1311	0.000000
COP_Q3	0.7000000	0.000000
QGEN_Q3	0.000000	0.000000
QCHILL_Q3	0.000000	168.0148
CHW_Q3	0.000000	0.000000
COPEC_Q3	6.100000	0.000000
QEC_Q3	38.50000	0.000000
POWEREC_Q3	6.311475	0.000000
CHWEC_Q3	0.2777778	0.000000
PROCESSW_Q3	53917.02	0.000000
COOLW_Q3	14.97695	0.000000
QCOOLT_Q3	2264515.	0.000000
COOLAIR_Q3	112662.4	0.000000
INTCON_POWER_Q3	510244.9	0.000000
INTGEN_POWER_Q3	0.1398012E+08	0.000000
EXPORT_POWER_Q3	9157378.	0.000000
CUST_POWER_Q3	4312500.	0.000000
EXTERNAL_POWER_Q3	0.000000	0.9327500E-01
CASC	0.000000	0.000000
N1A	0.000000	1112780.
N1B	0.000000	794842.9
N1C	0.000000	317937.2
CPSA	0.000000	0.000000
N2A	0.000000	651430.0
N2B	0.000000	260572.0
N2C	0.000000	130286.0
CMEMB	2886400.	0.000000
N3A	1.000000	211068.0
N3B	0.000000	117260.0
N3C	2.000000	82082.00
CBOILER2	0.000000	0.000000

```
        N4A       0.000000        380132.4
        N4B       0.000000        331894.6
        N4C       0.000000        226922.8
   CBOILER1       7164240.        0.000000
        N5A       0.000000        1617861.
        N5B       0.000000        1412559.
        N5C       1.000000        931351.2
      CSTT2       396510.3        0.000000
        N6A       1.000000        51546.34
        N6B       0.000000        38139.08
        N6C       0.000000        34614.10
      CSTT1       829275.4        0.000000
        N7A       1.000000        28244.27
        N7B       0.000000        30835.11
        N7C       1.000000        27783.46
        CGT       1270822.        0.000000
        N8A       1.000000        115736.3
        N8B       0.000000        75667.26
        N8C       1.000000        49470.53
      CHRSG       2924095.        0.000000
        N9A       1.000000        380132.4
        N9B       0.000000        931351.2
        CAD       2136750.        0.000000
       CICE       0.000000        0.000000
       N11A       0.000000        32464.86
       N11B       0.000000        39520.29
       CDRY       583200.0        0.000000
       N12A       0.000000        137237.8
       N12B       0.000000        85773.60
       N12C       1.000000        34309.44
     CCHILL       0.000000        0.000000
       N13A       0.000000        24889.87
       N13B       0.000000        28492.30
       N13C       0.000000        31941.99
    CECHILL       137756.7        0.000000
       N14A       1.000000        17908.37
       N14B       0.000000        20607.52
       N14C       0.000000        25717.49
  CCOOLTOWER      50322.82        0.000000
       N15A       0.000000        10895.23
       N15B       0.000000        7481.312
       N15C       1.000000        6541.966
        NAD       1.000000        0.000000
```

A.2 CHAPTER 5

A.2.1 LINGO CODES

A.2.1.1 LINGO CODES (CASE STUDY 1)

```
DATA:
 UB1 = 5; !maximum units per line;
 UB2 = 5; !maximum units per line;
 UB3 = 5; !maximum units per line;
 Rmina = 0.94; !Minimum reliability level;
 prb1 = 0.90; !Reliability of 250 kW unit;
 prb2 = 0.91; !Reliability of 500 kW unit;
 prb3 = 0.92; !Reliability of 1000 kW unit;
ENDDATA

max = EP;

EP = GP - TAC; ! Economic Performance in USD/yr;

CapCost = m1a*(90549) + m2a*(122380) + m3a*(165395); !Capital Costs in USD;
OpCost = m1a*(5000*1) + m2a*(10000*1) + m3a*(20000*1); !Operating Costs in USD/yr;
```

```
TAC = 0.13*CapCost + OpCost; !Total Annualised Costs (Annualised Capital costs +
Operating Costs) in USD/yr;
GP = (P1a*5000*0.0926)*0.417 + (P2a*5000*0.0926)*0.333 + (P3a*5000*0.0926)*0.25;
!Gross revenue in USD/yr;
! with AOT = 5000 h/yr and export power = 0.0926 USD/kWh;

! Power Demand in Scenario 1;
P1a = 489;
! Power Demand in Scenario 2;
P2a = 225;
! Power Demand in Scenario 3;
P3a = 289;

!Design capacity selection;
P1a <= n1aa*250 + n2aa*500 + n3aa*1000; !Capacities in kW;
P2a <= n1ab*250 + n2ab*500 + n3ab*1000;
P3a <= n1ac*250 + n2ac*500 + n3ac*1000;

!m is number of installed units, n is number of operating units for a given scenario;
@gin(n1aa); !number of 250 kW units operating in Scenario 1;
@gin(n1ab); !number of 250 kW units operating in Scenario 2;
@gin(n1ac); !number of 250 kW units operating in Scenario 3;

@gin(n2aa); !number of 500 kW units operating in Scenario 1;
@gin(n2ab); !number of 500 kW units operating in Scenario 2;
@gin(n2ac); !number of 500 kW units operating in Scenario 3;

@gin(n3aa); !number of 1000 kW units operating in Scenario 1;
@gin(n3ab); !number of 1000 kW units operating in Scenario 2;
@gin(n3ac); !number of 1000 kW units operating in Scenario 3;

@BND(0, m1a, UB1);
@BND(0, m2a, UB2);
@BND(0, m3a, UB3);

@gin(m1aa); @gin(m2aa); @gin(m3aa);
@gin(m1ab); @gin(m2ab); @gin(m3ab);
@gin(m1ac); @gin(m2ac); @gin(m3ac);

m1a >= m1aa; !m1a is number of installed 250 kW units;
m1a >= m1ab;
m1a >= m1ac;

m2a >= m2aa; !m2a is number of installed 250 kW units;
m2a >= m2ab;
m2a >= m2ac;

m3a >= m3aa; !m3a is number of installed 250 kW units;
m3a >= m3ab;
m3a >= m3ac;


! Use a disjunctive formulation;
! Disjunction 1;
@bin(I1aa);
m1aa >= (n1aa + 1)*I1aa;
m1aa <= UB1*I1aa;
n1aa <= UB1*I1aa;

@bin(I1ab);
m1ab >= (n1ab + 1)*I1ab;
m1ab <= UB1*I1ab;
n1ab <= UB1*I1ab;

@bin(I1ac);
m1ac >= (n1ac + 1)*I1ac;
m1ac <= UB1*I1ac;
n1ac <= UB1*I1ac;

! Disjunction 2;
@bin(I2aa);
m2aa >= (n2aa + 1)*I2aa;
m2aa <= UB2*I2aa;
n2aa <= UB2*I2aa;

@bin(I2ab);
```

```
m2ab >= (n2ab + 1)*I2ab;
m2ab <= UB2*I2ab;
n2ab <= UB2*I2ab;

@bin(I2ac);
m2ac >= (n2ac + 1)*I2ac;
m2ac <= UB2*I2ac;
n2ac <= UB2*I2ac;

! Disjunction 3;
@bin(I3aa);
m3aa >= (n3aa + 1)*I3aa;
m3aa <= UB3*I3aa;
n3aa <= UB3*I3aa;

@bin(I3ab);
m3ab >= (n3ab + 1)*I3ab;
m3ab <= UB3*I3ab;
n3ab <= UB3*I3ab;

@bin(I3ac);
m3ac >= (n3ac + 1)*I3ac;
m3ac <= UB3*I3ac;
n3ac <= UB3*I3ac;

! Tie the disjunctions together;
I1aa + I2aa + I3aa = 1;
ng1 = n1aa + n2aa + n3aa;
mg1 = m1aa + m2aa + m3aa;
prb11 = prb1*I1aa + prb2*I2aa + prb3*I3aa;

! Tie the disjunctions together;
I1ab + I2ab + I3ab = 1;
ng2 = n1ab + n2ab + n3ab;
mg2 = m1ab + m2ab + m3ab;
prb22 = prb1*I1ab + prb2*I2ab + prb3*I3ab;

! Tie the disjunctions together;
I1ac + I2ac + I3ac = 1;
ng3 = n1ac + n2ac + n3ac;
mg3 = m1ac + m2ac + m3ac;
prb33 = prb1*I1ac + prb2*I2ac + prb3*I3ac;

! Reliability and redundancy Allocation;
! Compute two Binomial probabilities;
Rcg1 = @EXP( @LGM( mg1 + 1) - @LGM( ng1 + 1)     - @LGM( mg1 - ng1 +1)       +
ng1*@LOG(prb11)     + (mg1-ng1)*@LOG((1-prb11)))
    + @EXP( @LGM( mg1 + 1) - @LGM( ng1 + 1 + 1) - @LGM( mg1 - (ng1 +1) +1) + (ng1
+1)*@LOG(prb11) + (mg1-(ng1 +1))*@LOG((1-prb11)));

Rcg1 >= Rmina; ! Minimum reliability level;

! Compute two Binomial probabilities;
Rcg2 = @EXP( @LGM( mg2 + 1) - @LGM( ng2 + 1)     - @LGM( mg2 - ng2 +1)       +
ng2*@LOG(prb22)     + (mg2-ng2)*@LOG((1-prb22)))
    + @EXP( @LGM( mg2 + 1) - @LGM( ng2 + 1 + 1) - @LGM( mg2 - (ng2 +1) +1) + (ng2
+1)*@LOG(prb22) + (mg2-(ng2 +1))*@LOG((1-prb22)));

Rcg2 >= Rmina; ! Minimum reliability level;

! Compute two Binomial probabilities;
Rcg3 = @EXP( @LGM( mg3 + 1) - @LGM( ng3 + 1)     - @LGM( mg3 - ng3 +1)       +
ng3*@LOG(prb33)     + (mg3-ng3)*@LOG((1-prb33)))
    + @EXP( @LGM( mg3 + 1) - @LGM( ng3 + 1 + 1) - @LGM( mg3 - (ng3 +1) +1) + (ng3
+1)*@LOG(prb33) + (mg3-(ng3 +1))*@LOG((1-prb33)));

Rcg3 >= Rmina; ! Minimum reliability level;
```

A.2.1.2 LINGO CODES (CASE STUDY 2)

A.2.2 RESULTS

A.2.2.1 RESULTS (CASE STUDY 1)

```
Global optimal solution found.
Objective value:                              112239.6
Objective bound:                              112239.6
Infeasibilities:                              0.000000
Extended solver steps:                               5
Total solver iterations:                          3378
Elapsed runtime seconds:                          4.11

Model Class:                                     MINLP

Total variables:                    46
Nonlinear variables:                27
Integer variables:                  27

Total constraints:                  62
Nonlinear constraints:              12

Total nonzeros:                    164
Nonlinear nonzeros:                 27
```

Variable	Value	Reduced Cost
UB1	5.000000	0.000000
UB2	5.000000	0.000000
UB3	5.000000	0.000000
RMINA	0.9400000	0.000000
PRB1	0.9000000	0.000000
PRB2	0.9100000	0.000000
PRB3	0.9200000	0.000000
EP	112239.6	0.000000
GP	162553.7	0.000000
TAC	50314.11	0.000000
CAPCOST	271647.0	0.000000
M1A	3.000000	0.000000
M2A	0.000000	0.000000
M3A	0.000000	15591.95
OPCOST	15000.00	0.000000
P1A	489.0000	0.000000
P2A	225.0000	0.000000
P3A	289.0000	0.000000
N1AA	2.000000	8636.470
N2AA	0.000000	0.000000
N3AA	0.000000	0.000000
N1AB	2.000000	0.000000
N2AB	0.000000	0.000000
N3AB	0.000000	0.000000
N1AC	2.000000	0.000000
N2AC	0.000000	0.000000
N3AC	0.000000	0.000000
M1AA	3.000000	8134.900
M2AA	0.000000	0.000000
M3AA	0.000000	0.000000
M1AB	3.000000	0.000000
M2AB	0.000000	0.000000
M3AB	0.000000	0.000000
M1AC	3.000000	0.000000
M2AC	0.000000	0.000000
M3AC	0.000000	0.000000
I1AA	1.000000	0.000000
I1AB	1.000000	0.000000
I1AC	1.000000	0.000000
I2AA	0.000000	0.000000
I2AB	0.000000	0.000000

I2AC	0.000000	0.000000
I3AA	0.000000	0.000000
I3AB	0.000000	0.000000
I3AC	0.000000	0.000000
NG1	2.000000	0.000000
MG1	3.000000	0.000000
PRB11	0.9000000	0.000000
NG2	2.000000	0.000000
MG2	3.000000	0.000000
PRB22	0.9000000	0.000000
NG3	2.000000	0.000000
MG3	3.000000	0.000000
PRB33	0.9000000	0.000000
RCG1	0.9720000	0.000000
RCG2	0.9720000	0.000000
RCG3	0.9720000	0.000000

A.2.2.2 RESULTS (CASE STUDY 2)

```
Global optimal solution found.
Objective value:                              5768516.
Objective bound:                              5768516.
Infeasibilities:                              0.000000
Extended solver steps:                           10851
Total solver iterations:                       1965424
Elapsed runtime seconds:                       1799.21

Model Class:                                     MINLP

Total variables:                 426
Nonlinear variables:              43
Integer variables:                94

Total constraints:               455
Nonlinear constraints:            19

Total nonzeros:                 1162
Nonlinear nonzeros:               43
```

Variable	Value	Reduced Cost
EP	5768516.	0.000000
POC1	0.4170000	0.000000
GP_Q1	7803958.	0.000000
POC2	0.3330000	0.000000
GP_Q2	9221041.	0.000000
POC3	0.2500000	0.000000
GP_Q3	0.1063812E+08	0.000000
CAP	0.2193594E+08	0.000000
MAC	364200.0	0.000000
FCOOLW_Q1	11000.00	0.000000
FCHW_Q1	1000.000	0.000000
FLPS_Q1	20625.00	0.000000
EDEMAND_Q1	632.5000	0.000000
FCOOLW_Q2	13000.00	0.000000
FCHW_Q2	1000.000	0.000000
FLPS_Q2	24375.00	0.000000
EDEMAND_Q2	747.5000	0.000000
FCOOLW_Q3	15000.00	0.000000
FCHW_Q3	1000.000	0.000000
FLPS_Q3	28125.00	0.000000
EDEMAND_Q3	862.5000	0.000000
PRICE1	0.1620000	0.000000
PRICE2	0.2000000E-01	0.000000
PRICE3	0.7000000E-01	0.000000
COD_Q1	50000.00	0.000000
COD_Q2	50000.00	0.000000
COD_Q3	50000.00	0.000000

COD2_Q1	50.00000	0.000000
POME_Q1	1600.000	0.000000
COD2_Q2	50.00000	0.000000
POME_Q2	1600.000	0.000000
COD2_Q3	50.00000	0.000000
POME_Q3	1600.000	0.000000
F1AV_Q1	3437.500	0.000000
F1_Q1	0.000000	105.6263
F2AV_Q1	12375.00	0.000000
F2_Q1	12375.00	0.000000
F3AV_Q1	6875.000	0.000000
F3_Q1	6779.887	0.000000
F4AV_Q1	40700.00	0.000000
F4_Q1	40700.00	0.000000
F1AV_Q2	4062.500	0.000000
F1_Q2	0.000000	84.34906
F2AV_Q2	14625.00	0.000000
F2_Q2	14625.00	0.000000
F3AV_Q2	8125.000	0.000000
F3_Q2	8012.593	0.000000
F4AV_Q2	48100.00	0.000000
F4_Q2	48100.00	0.000000
F1AV_Q3	4687.500	0.000000
F1_Q3	0.000000	63.32512
F2AV_Q3	16875.00	0.000000
F2_Q3	16875.00	0.000000
F3AV_Q3	9375.000	0.000000
F3_Q3	9245.300	0.000000
F4AV_Q3	55500.00	0.000000
F4_Q3	55500.00	0.000000
LHV1_Q1	25000.00	0.000000
LHV2_Q1	17000.00	0.000000
LHV3_Q1	16000.00	0.000000
HVAPW_Q1	2260.000	0.000000
CPW_Q1	4.200000	0.000000
CPS_Q1	2.021000	0.000000
LHV1_Q2	25000.00	0.000000
LHV2_Q2	17000.00	0.000000
LHV3_Q2	16000.00	0.000000
HVAPW_Q2	2260.000	0.000000
CPW_Q2	4.200000	0.000000
CPS_Q2	2.021000	0.000000
LHV1_Q3	25000.00	0.000000
LHV2_Q3	17000.00	0.000000
LHV3_Q3	16000.00	0.000000
HVAPW_Q3	2260.000	0.000000
CPW_Q3	4.200000	0.000000
CPS_Q3	2.021000	0.000000
XL1_Q1	0.3903900	0.000000
XC1_Q1	0.1601600	0.000000
XHC1_Q1	0.1747900	0.000000
XW1_Q1	0.2300000	0.000000
XL2_Q1	0.7735000E-01	0.000000
XC2_Q1	0.1340500	0.000000
XHC2_Q1	0.1235500	0.000000
XW2_Q1	0.6500000	0.000000
XL3_Q1	0.1542000	0.000000
XC3_Q1	0.2070000	0.000000
XHC3_Q1	0.1908000	0.000000
XW3_Q1	0.4000000	0.000000
XL1_Q2	0.3903900	0.000000
XC1_Q2	0.1601600	0.000000
XHC1_Q2	0.1747900	0.000000
XW1_Q2	0.2300000	0.000000
XL2_Q2	0.7735000E-01	0.000000
XC2_Q2	0.1340500	0.000000
XHC2_Q2	0.1235500	0.000000
XW2_Q2	0.6500000	0.000000
XL3_Q2	0.1542000	0.000000
XC3_Q2	0.2070000	0.000000
XHC3_Q2	0.1908000	0.000000
XW3_Q2	0.4000000	0.000000
XL1_Q3	0.3903900	0.000000
XC1_Q3	0.1601600	0.000000
XHC1_Q3	0.1747900	0.000000
XW1_Q3	0.2300000	0.000000
XL2_Q3	0.7735000E-01	0.000000

XC2_Q3	0.1340500	0.000000
XHC2_Q3	0.1235500	0.000000
XW2_Q3	0.6500000	0.000000
XL3_Q3	0.1542000	0.000000
XC3_Q3	0.2070000	0.000000
XHC3_Q3	0.1908000	0.000000
XW3_Q3	0.4000000	0.000000
TOTALWFREE_Q1	42301.59	0.000000
FHPS_Q1	30022.58	0.000000
COOLWCHILL_Q1	0.000000	50.34880
COOLWECHILL_Q1	279.0095	0.000000
TOTALWATER_Q1	11.75044	0.000000
ECON_Q1	3162500.	0.000000
FL_Q1	2002.665	0.000000
FC_Q1	3062.305	0.000000
FHC_Q1	2822.534	0.000000
FW_Q1	10755.70	0.000000
FW1_Q1	876.3893	0.000000
FW2_Q1	9879.315	0.000000
FT_Q1	8763.893	0.000000
XW_Q1	0.1000000	0.000000
HEATDRYER_Q1	0.2543924E+08	0.000000
FLPSDRY_Q1	9397.576	0.000000
HA3_Q1	2707.000	0.000000
HF2_Q1	146.6400	186.6589
FT1_Q1	8763.893	0.000000
HEATW_Q1	3142294.	0.000000
QCOMB_Q1	0.1441441E+09	0.000000
BEFF_Q1	0.5500000	0.000000
QCOMB1_Q1	0.7927923E+08	0.000000
H1_Q1	2858.000	0.000000
HF1_Q1	104.9200	0.000000
HA2_Q1	2736.000	0.000000
FHPST_Q1	28796.56	0.000000
FHPSKGS_Q1	7.999044	0.000000
ADEFF_Q1	0.2300000	0.000000
SLUDGEEFF_Q1	0.6000000E-01	0.000000
CODREMOVAL_Q1	0.8000000	0.000000
VOLPOME_Q1	25437.50	0.000000
CODIN_Q1	1271.875	0.000000
BIOGAS_Q1	234.0250	0.000000
SLUDGE_Q1	2442.000	0.000000
TREATEDPOME_Q1	38023.98	0.000000
BIOGAS1_Q1	0.000000	0.000000
BIOGAS2_Q1	0.000000	0.000000
BIOGAS3_Q1	234.0250	0.000000
BIOMETHANE_Q1	231.6848	0.000000
CARBREMOVED_Q1	126.1700	0.000000
POWERASC_Q1	0.000000	0.000000
POWERPSA_Q1	0.000000	98.43997
POWERMEMB_Q1	70.20750	0.000000
BIOMETHANE1_Q1	231.6848	0.000000
BIOMETHANE2_Q1	0.000000	0.000000
BIOMETHANE3_Q1	0.000000	2658.106
POWERICE_Q1	0.000000	858.4619
FWOUTGE_Q1	0.000000	0.000000
FCDOUTGE_Q1	0.000000	0.000000
FOXYINGE_Q1	0.000000	0.000000
FNINGE_Q1	0.000000	0.000000
FNOUTGE_Q1	0.000000	0.000000
FAIRINGE_Q1	0.000000	0.000000
FFLUEGGE_Q1	0.000000	0.000000
FFLUEGE_Q1	0.000000	56.69633
FFLUEABS_Q1	0.000000	0.000000
QCOMBFTB_Q1	0.000000	0.000000
FTBEFF_Q1	0.6000000	0.000000
QCOMB2_Q1	0.000000	0.000000
MHPST_Q1	0.000000	0.000000
FMPSKGS_Q1	0.000000	0.000000
FWOUTB_Q1	521.2907	0.000000
FCDOUTB_Q1	637.1331	0.000000
FOXYINB_Q1	926.7390	0.000000
FNINB_Q1	3486.304	0.000000
FNOUTB_Q1	3486.304	0.000000
FAIRINB_Q1	4413.043	0.000000
FFLUEG_Q1	4644.728	0.000000
FFLUEGT_Q1	4644.728	0.000000

FFLUEGTABS_Q1	0.000000	0.000000
HG1_Q1	-5304279.	0.000000
HG2_Q1	190851.9	0.000000
POWERGT_Q1	3297078.	0.000000
POWERGTTARIFF_Q1	915.8551	0.000000
QHRSG_Q1	9643778.	0.000000
QHRSG1_Q1	3375322.	0.000000
FSTHRSG_Q1	1226.017	0.000000
FSTHRSG_KGS_Q1	0.3405602	0.000000
POWERHPS_Q1	3589499.	0.000000
POWERHPSTARIFF_Q1	997.0831	0.000000
MHPST2_Q1	30022.58	0.000000
FMPS_Q1	30022.58	0.000000
POWERMPS_Q1	853241.6	0.000000
POWERMPSTARIFF_Q1	237.0116	0.000000
COP_Q1	0.7000000	0.000000
QGEN_Q1	0.000000	0.000000
QCHILL_Q1	0.000000	0.000000
CHW_Q1	0.000000	0.000000
COPEC_Q1	6.100000	0.000000
QEC_Q1	38.50000	0.000000
POWEREC_Q1	6.311475	0.000000
CHWEC_Q1	0.2777778	0.000000
PROCESSW_Q1	42301.59	0.000000
COOLW_Q1	11.75044	0.000000
QCOOLT_Q1	1776667.	0.000000
COOLAIR_Q1	88391.37	0.000000
INTCON_POWER_Q1	351037.5	0.000000
INTGEN_POWER_Q1	0.1074975E+08	0.000000
EXPORT_POWER_Q1	7236211.	0.000000
CUST_POWER_Q1	3162500.	0.000000
EXTERNAL_POWER_Q1	0.000000	0.1555827
TOTALWFREE_Q2	49760.24	0.000000
FHPS_Q2	35481.23	0.000000
COOLWCHILL_Q2	0.000000	40.20660
COOLWECHILL_Q2	279.0095	0.000000
TOTALWATER_Q2	13.82229	0.000000
ECON_Q2	3737500.	0.000000
FL_Q2	2366.786	0.000000
FC_Q2	3619.088	0.000000
FHC_Q2	3335.722	0.000000
FW_Q2	12711.29	0.000000
FW1_Q2	1035.733	0.000000
FW2_Q2	11675.55	0.000000
FT_Q2	10357.33	0.000000
XW_Q2	0.1000000	0.000000
HEATDRYER_Q2	0.3006455E+08	0.000000
FLPSDRY_Q2	11106.23	0.000000
HA3_Q2	2707.000	0.000000
HF2_Q2	146.6400	176.1601
FT1_Q2	10357.33	0.000000
HEATW_Q2	3713620.	0.000000
QCOMB_Q2	0.1703521E+09	0.000000
BEFF_Q2	0.5500000	0.000000
QCOMB1_Q2	0.9369364E+08	0.000000
H1_Q2	2858.000	0.000000
HF1_Q2	104.9200	0.000000
HA2_Q2	2736.000	0.000000
FHPST_Q2	34032.30	0.000000
FHPSKGS_Q2	9.453416	0.000000
ADEFF_Q2	0.2300000	0.000000
SLUDGEEFF_Q2	0.6000000E-01	0.000000
CODREMOVAL_Q2	0.8000000	0.000000
VOLPOME_Q2	30062.50	0.000000
CODIN_Q2	1503.125	0.000000
BIOGAS_Q2	276.5750	0.000000
SLUDGE_Q2	2886.000	0.000000
TREATEDPOME_Q2	44937.43	0.000000
BIOGAS1_Q2	0.000000	0.000000
BIOGAS2_Q2	0.000000	0.000000
BIOGAS3_Q2	276.5750	0.000000
BIOMETHANE_Q2	273.8093	0.000000
CARBREMOVED_Q2	149.1100	0.000000
POWERASC_Q2	0.000000	0.000000
POWERPSA_Q2	0.000000	78.61033
POWERMEMB_Q2	82.97250	0.000000
BIOMETHANE1_Q2	273.8093	0.000000

BIOMETHANE2_Q2	0.000000	0.000000
BIOMETHANE3_Q2	0.000000	2122.660
POWERICE_Q2	0.000000	685.5343
FWOUTGE_Q2	0.000000	0.000000
FCDOUTGE_Q2	0.000000	0.000000
FOXYINGE_Q2	0.000000	0.000000
FNINGE_Q2	0.000000	0.000000
FNOUTGE_Q2	0.000000	0.000000
FAIRINGE_Q2	0.000000	0.000000
FFLUEGGE_Q2	0.000000	0.000000
FFLUEGE_Q2	0.000000	45.27549
FFLUEABS_Q2	0.000000	0.000000
QCOMBFTB_Q2	0.000000	0.000000
FTBEFF_Q2	0.6000000	0.000000
QCOMB2_Q2	0.000000	0.000000
MHPST_Q2	0.000000	0.000000
FMPSKGS_Q2	0.000000	0.000000
FWOUTB_Q2	616.0708	0.000000
FCDOUTB_Q2	752.9754	0.000000
FOXYINB_Q2	1095.237	0.000000
FNINB_Q2	4120.177	0.000000
FNOUTB_Q2	4120.177	0.000000
FAIRINB_Q2	5215.414	0.000000
FFLUEG_Q2	5489.224	0.000000
FFLUEGT_Q2	5489.224	0.000000
FFLUEGTABS_Q2	0.000000	0.000000
HG1_Q2	-6268693.	0.000000
HG2_Q2	225552.2	0.000000
POWERGT_Q2	3896547.	0.000000
POWERGTTARIFF_Q2	1082.374	0.000000
QHRSG_Q2	0.1139719E+08	0.000000
QHRSG1_Q2	3989017.	0.000000
FSTHRSG_Q2	1448.929	0.000000
FSTHRSG_KGS_Q2	0.4024803	0.000000
POWERHPS_Q2	4242135.	0.000000
POWERHPSTARIFF_Q2	1178.371	0.000000
MHPST2_Q2	35481.23	0.000000
FMPS_Q2	35481.23	0.000000
POWERMPS_Q2	1008376.	0.000000
POWERMPSTARIFF_Q2	280.1046	0.000000
COP_Q2	0.7000000	0.000000
QGEN_Q2	0.000000	0.000000
QCHILL_Q2	0.000000	0.000000
CHW_Q2	0.000000	0.000000
COPEC_Q2	6.100000	0.000000
QEC_Q2	38.50000	0.000000
POWEREC_Q2	6.311475	0.000000
CHWEC_Q2	0.2777778	0.000000
PROCESSW_Q2	49760.24	0.000000
COOLW_Q2	13.82229	0.000000
QCOOLT_Q2	2089930.	0.000000
COOLAIR_Q2	103976.6	0.000000
INTCON_POWER_Q2	414862.5	0.000000
INTGEN_POWER_Q2	0.1270425E+08	0.000000
EXPORT_POWER_Q2	8551886.	0.000000
CUST_POWER_Q2	3737500.	0.000000
EXTERNAL_POWER_Q2	0.000000	0.1242423
TOTALWFREE_Q3	57218.89	0.000000
FHPS_Q3	40939.88	0.000000
COOLWCHILL_Q3	0.000000	30.18513
COOLWECHILL_Q3	279.0095	0.000000
TOTALWATER_Q3	15.89413	0.000000
ECON_Q3	4312500.	0.000000
FL_Q3	2730.907	0.000000
FC_Q3	4175.871	0.000000
FHC_Q3	3848.910	0.000000
FW_Q3	14666.87	0.000000
FW1_Q3	1195.076	0.000000
FW2_Q3	13471.79	0.000000
FT_Q3	11950.76	0.000000
XW_Q3	0.1000000	0.000000
HEATDRYER_Q3	0.3468987E+08	0.000000
FLPSDRY_Q3	12814.88	0.000000
HA3_Q3	2707.000	0.000000
HF2_Q3	146.6400	152.5988
FT1_Q3	11950.76	0.000000
HEATW_Q3	4284946.	0.000000

QCOMB_Q3	0.1965601E+09	0.000000
BEFF_Q3	0.5500000	0.000000
QCOMB1_Q3	0.1081080E+09	0.000000
H1_Q3	2858.000	0.000000
HF1_Q3	104.9200	0.000000
HA2_Q3	2736.000	0.000000
FHPST_Q3	39268.03	0.000000
FHPSKGS_Q3	10.90779	0.000000
ADEFF_Q3	0.2300000	0.000000
SLUDGEEFF_Q3	0.6000000E-01	0.000000
CODREMOVAL_Q3	0.8000000	0.000000
VOLPOME_Q3	34687.50	0.000000
CODIN_Q3	1734.375	0.000000
BIOGAS_Q3	319.1250	0.000000
SLUDGE_Q3	3330.000	0.000000
TREATEDPOME_Q3	51850.87	0.000000
BIOGAS1_Q3	0.000000	0.000000
BIOGAS2_Q3	0.000000	0.000000
BIOGAS3_Q3	319.1250	0.000000
BIOMETHANE_Q3	315.9337	0.000000
CARBREMOVED_Q3	172.0500	0.000000
POWERASC_Q3	0.000000	0.000000
POWERPSA_Q3	0.000000	59.01677
POWERMEMB_Q3	95.73750	0.000000
BIOMETHANE1_Q3	315.9337	0.000000
BIOMETHANE2_Q3	0.000000	0.000000
BIOMETHANE3_Q3	0.000000	1593.589
POWERICE_Q3	0.000000	514.6654
FWOUTGE_Q3	0.000000	0.000000
FCDOUTGE_Q3	0.000000	0.000000
FOXYINGE_Q3	0.000000	0.000000
FNINGE_Q3	0.000000	0.000000
FNOUTGE_Q3	0.000000	0.000000
FAIRINGE_Q3	0.000000	0.000000
FFLUEGGE_Q3	0.000000	0.000000
FFLUEGE_Q3	0.000000	33.99061
FFLUEABS_Q3	0.000000	0.000000
QCOMBFTB_Q3	0.000000	0.000000
FTBEFF_Q3	0.6000000	0.000000
QCOMB2_Q3	0.000000	0.000000
MHPST_Q3	0.000000	0.000000
FMPSKGS_Q3	0.000000	0.000000
FWOUTB_Q3	710.8509	0.000000
FCDOUTB_Q3	868.8178	0.000000
FOXYINB_Q3	1263.735	0.000000
FNINB_Q3	4754.051	0.000000
FNOUTB_Q3	4754.051	0.000000
FAIRINB_Q3	6017.786	0.000000
FFLUEG_Q3	6333.719	0.000000
FFLUEGT_Q3	6333.719	0.000000
FFLUEGTABS_Q3	0.000000	0.000000
HG1_Q3	-7233108.	0.000000
HG2_Q3	260252.5	0.000000
POWERGT_Q3	4496016.	0.000000
POWERGTTARIFF_Q3	1248.893	0.000000
QHRSG_Q3	0.1315061E+08	0.000000
QHRSG1_Q3	4602712.	0.000000
FSTHRSG_Q3	1671.841	0.000000
FSTHRSG_KGS_Q3	0.4644003	0.000000
POWERHPS_Q3	4894772.	0.000000
POWERHPSTARIFF_Q3	1359.659	0.000000
MHPST2_Q3	40939.88	0.000000
FMPS_Q3	40939.88	0.000000
POWERMPS_Q3	1163511.	0.000000
POWERMPSTARIFF_Q3	323.1976	0.000000
COP_Q3	0.7000000	0.000000
QGEN_Q3	0.000000	0.000000
QCHILL_Q3	0.000000	0.000000
CHW_Q3	0.000000	0.000000
COPEC_Q3	6.100000	0.000000
QEC_Q3	38.50000	0.000000
POWEREC_Q3	6.311475	0.000000
CHWEC_Q3	0.2777778	0.000000
PROCESSW_Q3	57218.89	0.000000
COOLW_Q3	15.89413	0.000000
QCOOLT_Q3	2403193.	0.000000
COOLAIR_Q3	119561.8	0.000000

INTCON_POWER_Q3	478687.5	0.000000
INTGEN_POWER_Q3	0.1465875E+08	0.000000
EXPORT_POWER_Q3	9867561.	0.000000
CUST_POWER_Q3	4312500.	0.000000
EXTERNAL_POWER_Q3	0.000000	0.9327500E-01
NAD	1.000000	0.000000
CAD	2136750.	0.000000
M61	0.000000	83946.34
M62	3.000000	54339.08
M71	0.000000	134466.7
M72	4.000000	83946.34
M81	0.000000	196736.3
M82	4.000000	116167.3
M51	0.000000	971351.2
M52	2.000000	392132.4
N91	1.000000	0.000000
N92	0.000000	931351.2
N111	0.000000	32464.86
N112	0.000000	39520.29
N121	0.000000	303264.0
N122	0.000000	189540.0
N123	2.000000	0.000000
N131	0.000000	24889.87
N132	0.000000	28492.30
N141	0.000000	17908.37
N142	0.000000	20607.52
N151	0.000000	10895.23
N152	1.000000	0.000000
N41	0.000000	380132.4
N42	0.000000	331894.6
M11	0.000000	172510.2
M21	0.000000	651430.0
M31	3.000000	211068.0
N161	1.000000	0.000000
N162	0.000000	20607.52
TPOME	55500.00	0.000000
RMINBG	0.9400000	0.000000
PRB11	0.9200000	0.000000
PRB21	0.9100000	0.000000
PRB31	0.9000000	0.000000
N11	0.000000	0.000000
N21	0.000000	0.000000
N31	2.000000	0.000000
UB1	5.000000	0.000000
UB2	5.000000	0.000000
UB3	5.000000	0.000000
I11	0.000000	0.000000
I21	0.000000	0.000000
I31	1.000000	0.000000
NGBG	2.000000	0.000000
MGBG	3.000000	0.000000
PRBBG	0.9000000	0.000000
RCGBG	0.9720000	0.000000
N41A	0.000000	0.000000
N42A	0.000000	0.000000
N41B	0.000000	0.000000
N42B	0.000000	0.000000
N41C	0.000000	0.000000
N42C	0.000000	0.000000
N131A	0.000000	0.000000
N132A	0.000000	0.000000
N131B	0.000000	0.000000
N132B	0.000000	0.000000
N131C	0.000000	0.000000
N132C	0.000000	0.000000
N161A	1.000000	17908.37
N162A	0.000000	0.000000
N161B	1.000000	0.000000
N162B	0.000000	0.000000
N161C	1.000000	0.000000
N162C	0.000000	0.000000
N111A	0.000000	0.000000
N112A	0.000000	0.000000
N111B	0.000000	0.000000
N112B	0.000000	0.000000
N111C	0.000000	0.000000
N112C	0.000000	0.000000

N121A	0.000000	0.000000
N122A	0.000000	0.000000
N123A	1.000000	0.000000
N121B	0.000000	0.000000
N122B	0.000000	0.000000
N123B	2.000000	0.000000
N121C	0.000000	0.000000
N122C	0.000000	0.000000
N123C	2.000000	75816.00
N91A	1.000000	380132.4
N92A	0.000000	0.000000
N91B	1.000000	0.000000
N92B	0.000000	0.000000
N91C	1.000000	0.000000
N92C	0.000000	0.000000
RMIN5	0.9400000	0.000000
PRB51	0.9200000	0.000000
PRB52	0.9000000	0.000000
N51A	0.000000	0.000000
N52A	1.000000	0.000000
N51B	0.000000	0.000000
N52B	1.000000	0.000000
N51C	0.000000	0.000000
N52C	1.000000	0.000000
N51	0.000000	0.000000
N52	1.000000	0.000000
I51	0.000000	0.000000
I52	1.000000	0.000000
NG5	1.000000	0.000000
MG5	2.000000	0.000000
PRB5	0.9000000	0.000000
RCG5	0.9900000	0.000000
RMIN6	0.9400000	0.000000
PRB61	0.9200000	0.000000
PRB62	0.9100000	0.000000
N61A	0.000000	0.000000
N62A	2.000000	0.000000
N61B	0.000000	0.000000
N62B	2.000000	0.000000
N61C	0.000000	0.000000
N62C	2.000000	0.000000
N61	0.000000	0.000000
N62	2.000000	0.000000
I61	0.000000	0.000000
I62	1.000000	0.000000
NG6	2.000000	0.000000
MG6	3.000000	0.000000
PRB6	0.9100000	0.000000
RCG6	0.9771580	0.000000
RMIN7	0.9400000	0.000000
PRB71	0.9200000	0.000000
PRB72	0.9100000	0.000000
N71A	0.000000	0.000000
N72A	3.000000	0.000000
N71B	0.000000	0.000000
N72B	3.000000	0.000000
N71C	0.000000	0.000000
N72C	3.000000	0.000000
N71	0.000000	0.000000
N72	3.000000	0.000000
I71	0.000000	0.000000
I72	1.000000	0.000000
NG7	3.000000	0.000000
MG7	4.000000	0.000000
PRB7	0.9100000	0.000000
RCG7	0.9570352	0.000000
RMIN8	0.9400000	0.000000
PRB81	0.9200000	0.000000
PRB82	0.9100000	0.000000
N81A	0.000000	0.000000
N82A	3.000000	0.000000
N81B	0.000000	0.000000
N82B	3.000000	0.000000
N81C	0.000000	0.000000
N82C	3.000000	0.000000
N81	0.000000	0.000000
N82	3.000000	0.000000

I81	0.000000	0.000000
I82	1.000000	0.000000
NG8	3.000000	0.000000
MG8	4.000000	0.000000
PRB8	0.9100000	0.000000
RCG8	0.9570353	0.000000
N151A	0.000000	0.000000
N152A	1.000000	7481.312
N151B	0.000000	0.000000
N152B	1.000000	0.000000
N151C	0.000000	0.000000
N152C	1.000000	0.000000

A.3 CHAPTER 6

A.3.1 LINGO CODES

A.3.1.1 LINGO CODES (SCENARIO 1)

```
! Turbine Configuration Selection;
FBav_t2 = 6875; !Biomass (PMF) availability in kg/h;
h0_t2 = 104.9; !Enthalpy of water at 25C;
h1_t2 = 3137.5; !Enthalpy of steam at 20 bar;
h2_t2 = 2901.6; !Enthalpy of steam at 10 bar;
h3_t2 = 2855.8; !Enthalpy of steam at 5 bar;
e0_t2 = 0.75; !Efficiency of Boiler;
e1_t2 = 0.7; !Efficiency of Turbine 1;
e2_t2 = 0.7; !Efficiency of Turbine 2;
e3_t2 = 0.7; !Efficiency of Turbine 3;
CV_t2 = 19000; !Calorific Value of Biomass (PMF) in kJ/kg;
CpW_t2 = 4.2; !Heat Capacity of Water in kJ/kgC;
CpSt_t2 = 2.021; !Heat Capacity of steam in kJ/kgC;
Xw_t2 = 0.10; !Moisture Content in Biomass (after drying);
Rmin_t2 = 0.92; !Mininum Reliability level for Turbine Config;
CWTB_t2 = 2000000; !Cap Cost for Boiler in USD for 40kg/s;
Caux_t2 = 1000000; !Cap Cost for Auxilliary Boiler in USD for 40kg/s;
CFB_t2 = 0.022; !Cost of Biomass in USD/kg;
CFt_t2 = 0.0023; !Cost of External Water Supply in USD/kg;
PDemand_t2 = 850; !Power Demand in kW;
HDemand_t2 = 13631.35; !Heat Demand in kW (assumming P level not specific);

!Data obtained from Turbine 3 Config (FEL) Optimisation;
mT1_t2 = 3; !Number of installed units;
RT1_t2 = 0.9771580; !Reliability of configuration;
CT1_t2 = 465000; !Capital cost of configuration;

!Data obtained from Turbine 1a and 1b Config(FEL) Optimisation;
mT2_t2 = 6; !Number of installed units;
RT2_t2 = 0.938223; !Reliability of configuration;
CT2_t2 = 680000; !Capital cost of configuration;

!Data obtained from Turbine 2 Config (FEL) Optimisation;
mT3_t2 = 3; !Number of installed units;
RT3_t2 = 0.9771580; !Reliability of configuration;
CT3_t2 = 465000; !Capital cost of configuration;

min = TAC_t2;

!Biomass flow rate between Boiler (FB) and Auxilliary Boiler (FBaux);
FBav_t2 >= FB_t2 + FBaux_t2;

!Boiler energy balance;
        !Heat to vapourise moisture in Biomass (kJ/h);
        HeatW_t2 = FB_t2*Xw_t2*CpW_t2*(100-30) + FB_t2*Xw_t2*2260 + FB_t2*CpSt_t2*(600
- 100);

        !Heat Exchange between biomass and incoming water supply (kJ/h);
        (FB_t2*(1 - Xw_t2)*CV_t2 - HeatW_t2)*e0_t2 = Ft_t2*(h1_t2 - h0_t2);

        !Steam flow rate from kg/h to kg/s;
        Fts_t2 = Ft_t2*(1/3600);

!Steam Flowrate Split in kg/s;
Fts_t2 = F1_t2 + F2_t2 + F3_t2;

!Turbine Energy Balance;
        !Turbine 3 Power Output in kW;
        P1_t2 = F1_t2*e1_t2*(h1_t2 - h2_t2);

        !Turbine 1a and 1b Power Output in kW;
        P2_t2 = F2_t2*e1_t2*(h1_t2 - h2_t2) + F2_t2*e2_t2*(h2_t2 - h3_t2);

        !Turbine 2 Power Output in kW;
        P3_t2 = F3_t2*e3_t2*(h1_t2 - h3_t2);

!Power Balance in kW;
```

```
PDemand_t2 = P1_t2 + P2_t2 + P3_t2;

!Auxilliary Boiler energy balance;
        !Heat to vapourise moisture in Biomass (kJ/h);
        HeatWaux_t2 = FBaux_t2*Xw_t2*CpW_t2*(100-30) + FBaux_t2*Xw_t2*2260 +
FBaux_t2*CpSt_t2*(600 - 100);

        !Heat Exchange between biomass and incoming water supply (kJ/h);
        (FBaux_t2*(1 - Xw_t2)*CV_t2 - HeatWaux_t2)*e0_t2 = Faux_t2*(h3_t2 - h0_t2);

        !Auxilliary Steam flow rate from kg/h to kg/s;
        Ftaux_t2 = Faux_t2*(1/3600);

!Heat Balance in kW with excess heat (Hextra);
HDemand_t2 + Hextra_t2 = F3_t2*h3_t2 + F2_t2*h3_t2 + F1_t2*h2_t2 + Ftaux_t2*h3_t2;

!Configuration Selection;
F1_t2 <= 1000000*I1_t2;
F2_t2 <= 1000000*I2_t2;
F3_t2 <= 1000000*I3_t2;
Fts_t2 <= 1000000*Its_t2;
Faux_t2 <= 1000000*Iaux_t2;


        I1_t2 + I2_t2 + I3_t2 = 1;
        @bin(I1_t2);
        @bin(I2_t2);
        @bin(I3_t2);
        @bin(Its_t2);
        @bin(Iaux_t2);

        RT1_t2*I1_t2 + RT2_t2*I2_t2 + RT3_t2*I3_t2 >= Rmin_t2;

!Capital Cost;
CAP_t2 = CT1_t2*I1_t2 + CT2_t2*I2_t2 + CT3_t2*I3_t2 + CWTB_t2*Its_t2 +
Caux_t2*Iaux_t2;

!Maintenance Cost;
MAC_t2 = 30000*I1_t2 + 30000*I2_t2 + 30000*I3_t2;

!Operating Cost;
OP_t2 = (FB_t2*CFB_t2 + Ft_t2*CFt_t2 + FBaux_t2*CFB_t2)*5000;

!Total Annualised Costs;
TAC_t2 = CAP_t2*0.13 + OP_t2 + MAC_t2;
```

A.3.1.2 LINGO CODES (SCENARIO 2)

```
! Turbine Configuration Selection;
FBav_t1 = 6875; !Biomass (PMF) availability in kg/h;
h0_t1 = 104.9; !Enthalpy of water at 25C;
h1_t1 = 3137.5; !Enthalpy of steam at 20 bar;
h2_t1 = 2901.6; !Enthalpy of steam at 10 bar;
h3_t1 = 2855.8; !Enthalpy of steam at 5 bar;
e0_t1 = 0.75; !Efficiency of Boiler;
e1_t1 = 0.7; !Efficiency of Turbine 1;
e2_t1 = 0.7; !Efficiency of Turbine 2;
e3_t1 = 0.7; !Efficiency of Turbine 3;
CV_t1 = 19000; !Calorific Value of Biomass (PMF) in kJ/kg;
CpW_t1 = 4.2; !Heat Capacity of Water in kJ/kgC;
CpSt_t1 = 2.021; !Heat Capacity of steam in kJ/kgC;
Xw_t1 = 0.10; !Moisture Content in Biomass (after drying);
Rmin_t1 = 0.92; !Mininum Reliability level for Turbine Config;
CWTB_t1 = 2000000; !Cap Cost for Boiler in USD of 40kg/s;
CFB_t1 = 0.022; !Cost of Biomass in USD/kg;
CFt_t1 = 0.0023; !Cost of External Water Supply in USD/kg;
Cgrid_t1 = 0.12; !Cost of Import Power from Grid in USD/kWh;
PDemand_t1 = 850; !Power Demand in kW;
HDemand_t1 = 13631.35; !Heat Demand in kW;

!Data obtained from Turbine 1a and b (FTL) Optimisation;
```

```
mT1_t1 = 5; !Number of installed units;
RT1_t1 = 0.9673864; !Reliability of configuration;
CT1_t1 = 665000; !Capital cost of configuration;

!Data obtained from Turbine 3 Config (FTL) Optimisation;
mT1a_t1 = 3; !Number of installed units;
RT1a_t1 = 0.9771580; !Reliability of configuration;
CT1a_t1 = 465000; !Capital cost of configuration;

!Data obtained from Turbine 2 Config (FTL) Optimisation;
mT3_t1 = 3; !Number of installed units;
RT3_t1 = 0.9771580; !Reliability of configuration;
CT3_t1 = 465000; !Capital cost of configuration;

min = TAC_t1;

!Biomass flow rate;
FBav_t1 >= FB_t1;

!Boiler energy balance;
        !Heat to vapourise moisture in Biomass (kJ/h);
        HeatW_t1 = FB_t1*Xw_t1*CpW_t1*(100-30) + FB_t1*Xw_t1*2260 + FB_t1*CpSt_t1*(600
- 100);

        !Heat Exchange between biomass and incoming water supply (kJ/h);
        (FB_t1*(1 - Xw_t1)*CV_t1 - HeatW_t1)*e0_t1 = Ft_t1*(h1_t1 - h0_t1);

        !Steam flow rate from kg/h to kg/s;
        Fts_t1 = Ft_t1*(1/3600);

!Steam Flowrate Split in kg/s;
Fts_t1 = F1_t1 + F1a_t1 + F3_t1;

!Turbine Energy Balance for Turbine 1a and 1b in kW;
        !Turbine 1a Power Output in kW;
        P1_t1 = F1_t1*e1_t1*(h1_t1 - h2_t1);

        !Steam Flowrate Split from Turbine 1a to Turbine 1b (F2) or Process (F1ext) in
kg/s;
        F1_t1 = F2_t1 + F1ext_t1;

        !Turbine 1b Power Output in kW;
        P2_t1 = F2_t1*e2_t1*(h2_t1 - h3_t1);

        !Steam Flowrate Split from Turbine 1b (F2) to Process (F2ext) in kg/s;
        F2_t1 = F2ext_t1;

!Turbine Energy Balance for Turbine 3 in kW;
        !Turbine 3 Power Output in kW;
        P1a_t1 = F1a_t1*e1_t1*(h1_t1 - h2_t1);

        !Steam Flowrate Split from Turbine 3 to Process (F1aext) in kg/s;
        F1a_t1 = F1aext_t1;

!Turbine Energy Balance for Turbine 2 in kW;
        !Turbine 2 Power Output in kW;
        P3_t1 = F3_t1*e3_t1*(h1_t1 - h3_t1);

        !Steam Flowrate Split from Turbine 2 to Process (F3ext) in kg/s;
        F3_t1 = F3ext_t1;

!Power Balance in kW with excess power (PEXTRA);
PDemand_t1 + PEXTRA_t1 = P1_t1 + P2_t1 + P1a_t1 + P3_t1 + PGrid_t1;

!Heat Balance in kW;
        !Heat Output for T1a and T1b in kW;
        Heat1_t1 = F1ext_t1*h2_t1 + F2ext_t1*h3_t1;

        !Heat Output for T3 in kW;
        Heat1a_t1 = F1aext_t1*h2_t1;

        !Heat Output for T2 in kW;
        Heat3_t1 = F3ext_t1*h3_t1;

        !Total Heat in kW;
        HDemand_t1 = Heat1_t1 + Heat1a_t1 + Heat3_t1;
```

```
!Configuration Selection;
F1_t1 <= 1000000*I1_t1;
F1a_t1 <= 1000000*I1a_t1;
F3_t1 <= 1000000*I3_t1;
Fts_t1 <= 1000000*Its_t1;

!whereby;
        I1_t1 + I1a_t1 + I3_t1 = 1;
        @bin(I1_t1);
        @bin(I1a_t1);
        @bin(I3_t1);
        @bin(Its_t1);

        RT1_t1*I1_t1 + RT1a_t1*I1a_t1 + RT3_t1*I3_t1 >= Rmin_t1;

!Capital Cost;
CAP_t1 = CT1_t1*I1_t1 + CT1a_t1*I1a_t1 + CT3_t1*I3_t1 + CWTB_t1*Its_t1;

!Maintenance Cost;
MAC_t1 = 40000*I1_t1 + 30000*I1a_t1 + 30000*I3_t1;

!Operating Cost;
OP_t1 = (FB_t1*CFB_t1 + Ft_t1*CFt_t1 + PGrid_t1*Cgrid_t1)*5000;

!Total Annualised Costs;
TAC_t1 = CAP_t1*0.13 + OP_t1 + MAC_t1;
```

A.3.1.3 LINGO CODES (SCENARIO 3)

```
FBav_t1 = 6875; !Biomass availability in kg/h;
h0 = 104.9; !Enthalpy of water at 25C;
h1 = 3137.5; !Enthalpy of steam at 20 bar;
h2 = 2901.6; !Enthalpy of steam at 10 bar;
h3 = 2855.8; !Enthalpy of steam at 5 bar;
e0 = 0.75; !Efficiency of Boiler;
e1 = 0.7; !Efficiency of Turbine 1;
e2 = 0.7; !Efficiency of Turbine 2;
e3 = 0.7; !Efficiency of Turbine 3;
CV = 19000; !Calorific Value of Biomass in kJ/kg;
CpW = 4.2; !Heat Capacity of Water in kJ/kgC;
CpSt = 2.021; !Heat Capacity of steam in kJ/kgC;
Xw = 0.10; !Moisture Content in Biomass;
Prb11 = 0.90; !Reliability of Design Capacity n11;
Prb12 = 0.91; !Reliability of Design Capacity n12;
Prb21 = 0.90; !Reliability of Design Capacity n21;
Prb22 = 0.91; !Reliability of Design Capacity n22;
Rmin = 0.92; !Mininum Reliability level for Turbine Config;
C11 = 120000; !Cap Cost for Design Capacity n11 in USD;
C12 = 155000; !Cap Cost for Design Capacity n12 in USD;
C21 = 100000; !Cap Cost for Design Capacity n21 in USD;
C22 = 130000; !Cap Cost for Design Capacity n22 in USD;
CWTB = 2000000; !Cap Cost for Boiler in USD for 12kg/s;
CFB = 0.022; !Cost of Biomass in USD/kg;
CFt = 0.0023; !Cost of External Water Supply in USD/kg;
Cgrid = 0.12; !Cost of Import Power from Grid in USD/kWh;
PDemand_t1 = 850; !Power Demand in kW;
HDemand_t1 = 13631.35;!Heat Demand in kW;
PDemand_t2 = 850; !Power Demand in kW;
HDemand_t2 = 13631.35;!Heat Demand in kW;

!min = CAP;
min = TAC;

! For FTL => _t1;
!Biomass flow rate;
FBav_t1 >= FB_t1;

!Boiler energy balance;
        !Heat to vapourise moisture in Biomass (kJ/h);
        HeatW_t1 = FB_t1*Xw*CpW*(100-30) + FB_t1*Xw*2260 + FB_t1*CpSt*(600 - 100);

        !Heat Exchange between biomass and incoming water supply (kJ/h);
```

```
        (FB_t1*(1 - Xw)*CV - HeatW_t1)*e0 = Ft_t1*(h1 - h0);

        !Steam flow rate from kg/h to kg/s;
        Fts_t1 = Ft_t1*(1/3600);

!Turbine 1a Energy Balance;
        !Turbine 1a Power Output in kW;
        P1a_t1 = Fts_t1*e1*(h1 - h2);

        !Design Capacity Selection;
        P1a_t1 <= n11_t1*250 + n12_t1*500;
        ! whereby;
        @gin(n11_t1);
        @gin(n12_t1);

!Steam Flowrate Split from Turbine 1a to Turbine 1b (F2) or Process (F1ext) in kg/s;
Fts_t1 = F2_t1 + F1ext_t1;
!F1ext = 0.5*Fts;

!Turbine 1b Energy Balance;
        !Turbine 1b Power Output in kW;
        P1b_t1 = F2_t1*e2*(h2 - h3);

        !Design Capacity Selection;
        P1b_t1 <= n21_t1*250 + n22_t1*500;
        ! whereby;
        @gin(n21_t1);
        @gin(n22_t1);

!Steam Flowrate Split from Turbine 1 to Process (F2ext);
F2_t1 = F2ext_t1;

!Total Power Generated in kW;
Ptotal_t1 = P1a_t1 + P1b_t1;

!Power Balance in kW with excess power (PEXTRA);
!Ptotal_t1 + PGrid_t1 = PDemand_t1 + PEXTRA_t1;
Ptotal_t1 = PDemand_t1 + PEXTRA_t1;

!Heat Demand in kW;
HDemand_t1 = F1ext_t1*h2 + F2ext_t1*h3;

! For FEL => _t2;
!Biomass flow rate;
FBav_t2 >= FB_t2;

!Boiler energy balance;
        !Heat to vapourise moisture in Biomass (kJ/h);
        HeatW_t2 = FB_t2*Xw*CpW*(100-30) + FB_t2*Xw*2260 + FB_t2*CpSt*(600 - 100);

        !Heat Exchange between biomass and incoming water supply (kJ/h);
        (FB_t2*(1 - Xw)*CV - HeatW_t2)*e0 = Ft_t2*(h1 - h0);

        !Steam flow rate from kg/h to kg/s;
        Fts_t2 = Ft_t2*(1/3600);

!Turbine 1a Energy Balance;
        !Turbine 1a Power Output in kW;
        P1a_t2 = Fts_t2*e1*(h1 - h2);

        !Design Capacity Selection;
        P1a_t2 <= n11_t2*250 + n12_t2*500;
        ! whereby;
        @gin(n11_t2);
        @gin(n12_t2);

!Steam Flowrate Split from Turbine 1a to Turbine 1b (F2) or Process (F1ext) in kg/s;
Fts_t2 = F2_t2 + F1ext_t2;
!F2_t2 = 0;

!Steam Flowrate Split from Turbine 1 to Process (F2ext);
F2_t2 = F2ext_t2;

!Turbine 1b Energy Balance;
        !Turbine 1b Power Output in kW;
        P1b_t2 = F2_t2*e2*(h2 - h3);
```

```
        !Design Capacity Selection;
        P1b_t2 <= n21_t2*250 + n22_t2*500;
        ! whereby;
        @gin(n21_t2);
        @gin(n22_t2);

!Power Demand in kW;
PDemand_t2 = P1a_t2 + P1b_t2;

!Heat Demand in kW;
Houtput_t2 = F1ext_t2*h2 + F2ext_t2*h3;
Houtput_t2 = HDemand_t2 + Hexcess_t2;


n11_t1 <= n11;
n11_t2 <= n11;
n12_t1 <= n12;
n12_t2 <= n12;
n21_t1 <= n21;
n21_t2 <= n21;
n22_t1 <= n22;
n22_t2 <= n22;

@gin(n11);
@gin(n12);
@gin(n21);
@gin(n22);

!Capital Cost;
CAP = m11*C11 + m12*C12 + m21*C21 + m22*C22 + nwtb*CWTB; !n11*C11 + n12*C12 + n21*C21
+ n22*C22;

!Reliability/Redundancy Allocation;
        m11 >= (n11 + 1)*I11;
        m11 <= 5*I11;
        n11 <= 5*I11;

        m12 >= (n12 + 1)*I12;
        m12 <= 5*I12;
        n12 <= 5*I12;

        !whereby;
        I11 + I12 = 1;
        @gin(m11);
        @gin(m12);
        @bin(I11);
        @bin(I12);

        mg = m11 + m12;
        ng = n11 + n12;
        PrbBG = Prb11*I11 + Prb12*I12;

        RT = @EXP( @LGM( mg + 1) - @LGM( ng + 1)      - @LGM( mg - ng +1)        +
ng*@LOG(prbBG)      + (mg-ng)*@LOG((1-prbBG)))
        + @EXP( @LGM( mg + 1) - @LGM( ng + 1 + 1) - @LGM( mg - (ng +1) +1) + (ng
+1)*@LOG(prbBG) + (mg-(ng +1))*@LOG((1-prbBG)));

        RT >= Rmin;

!Reliability/Redundancy Allocation;
        m21 >= (n21 + 1)*I21;
        m21 <= 5*I21;
        n21 <= 5*I21;

        m22 >= (n22 + 1)*I22;
        m22 <= 5*I22;
        n22 <= 5*I22;

        !whereby;
        I21 + I22 = 1;
        @gin(m21);
        @gin(m22);
        @bin(I21);
        @bin(I22);

        mg2 = m21 + m22;
        ng2 = n21 + n22;
```

```
        PrbBG2 = Prb21*I21 + Prb22*I22;

        RT2 = @EXP( @LGM( mg2 + 1) - @LGM( ng2 + 1)      - @LGM( mg2 - ng2 +1)        +
ng2*@LOG(prbBG2)      + (mg2-ng2)*@LOG((1-prbBG2)))
        + @EXP( @LGM( mg2 + 1) - @LGM( ng2 + 1 + 1) - @LGM( mg2 - (ng2 +1) +1) + (ng2
+1)*@LOG(prbBG2) + (mg2-(ng2 +1))*@LOG((1-prbBG2)));

        RT2 >= Rmin;

        RT2*RT = RTO;

!Boiler Capacity Selection;

Fts_t1 <= nwtb_t1*12;
Fts_t2 <= nwtb_t2*12;

nwtb_t1 <= nwtb;
nwtb_t2 <= nwtb;

@gin(nwtb_t1);
@gin(nwtb_t2);
@gin(nwtb);

!Maintenance Cost;
MAC = m11*5000 + m12*10000 + m21*5000 + m22*10000;

!Operating Cost;
OP = (FB_t1*CFB*0.50 + Ft_t1*CFt*0.50  + FB_t2*CFB*0.50  + Ft_t2*CFt*0.50)*5000;

!Annualised Operating Costs;
TAC = CAP*0.13 + OP + MAC;
```

A.3.2 RESULTS

A.3.2.1 RESULTS (SCENARIO 1)

```
  Global optimal solution found.
  Objective value:                              1084088.
  Objective bound:                              1084088.
  Infeasibilities:                             0.7450581E-08
  Extended solver steps:                              0
  Total solver iterations:                            0
  Elapsed runtime seconds:                         0.16

  Model Class:                                     MILP

  Total variables:                 24
  Nonlinear variables:              0
  Integer variables:                5

  Total constraints:               25
  Nonlinear constraints:            0

  Total nonzeros:                  69
  Nonlinear nonzeros:               0


                                Variable           Value        Reduced Cost
                                 FBAV_T2        6875.000            0.000000
                                   H0_T2        104.9000            0.000000
                                   H1_T2        3137.500            0.000000
                                   H2_T2        2901.600            0.000000
                                   H3_T2        2855.800            0.000000
                                   E0_T2       0.7500000            0.000000
                                   E1_T2       0.7000000            0.000000
                                   E2_T2       0.7000000            0.000000
                                   E3_T2       0.7000000            0.000000
                                   CV_T2        19000.00            0.000000
                                  CPW_T2        4.200000            0.000000
                                 CPST_T2        2.021000            0.000000
                                   XW_T2       0.1000000            0.000000
```

```
         RMIN_T2       0.9200000           0.000000
         CWTB_T2        2000000.           0.000000
         CAUX_T2        1000000.           0.000000
          CFB_T2       0.2200000E-01       0.000000
          CFT_T2       0.2300000E-02       0.000000
      PDEMAND_T2        850.0000           0.000000
      HDEMAND_T2        13631.35           0.000000
          MT1_T2        3.000000           0.000000
          RT1_T2       0.9771580           0.000000
          CT1_T2        465000.0           0.000000
          MT2_T2        6.000000           0.000000
          RT2_T2       0.9382230           0.000000
          CT2_T2        680000.0           0.000000
          MT3_T2        3.000000           0.000000
          RT3_T2       0.9771580           0.000000
          CT3_T2        465000.0           0.000000
          TAC_T2        1084088.           0.000000
           FB_T2        4732.122           0.000000
        FBAUX_T2        0.000000           0.000000
        HEATW_T2        5990393.           0.000000
           FT_T2        18530.85           0.000000
          FTS_T2        5.147460           0.000000
           F1_T2        5.147460           0.000000
           F2_T2        0.000000           0.000000
           F3_T2        0.000000           0.000000
           P1_T2        850.0000           0.000000
           P2_T2        0.000000           0.000000
           P3_T2        0.000000           0.000000
     HEATWAUX_T2        0.000000           0.000000
         FAUX_T2        0.000000           25.48079
        FTAUX_T2        0.000000           0.000000
       HEXTRA_T2        1304.519           0.000000
           I1_T2        1.000000           90450.00
           I2_T2        0.000000         -0.2767099E+11
           I3_T2        0.000000         -0.2767102E+11
          ITS_T2        1.000000           260000.0
         IAUX_T2        0.000000           130000.0
          CAP_T2        2465000.           0.000000
          MAC_T2        30000.00           0.000000
           OP_T2        733638.2           0.000000
```

A.3.2.2 RESULTS (SCENARIO 2)

```
Global optimal solution found.
Objective value:                              1030749.
Objective bound:                              1030749.
Infeasibilities:                             0.7450581E-08
Extended solver steps:                              0
Total solver iterations:                            2
Elapsed runtime seconds:                         0.17

Model Class:                                     MILP

Total variables:                   29
Nonlinear variables:                0
Integer variables:                  4

Total constraints:                 29
Nonlinear constraints:              0

Total nonzeros:                    77
Nonlinear nonzeros:                 0


                        Variable           Value        Reduced Cost
                         FBAV_T1        6875.000            0.000000
                           H0_T1        104.9000            0.000000
                           H1_T1        3137.500            0.000000
                           H2_T1        2901.600            0.000000
                           H3_T1        2855.800            0.000000
                           E0_T1       0.7500000            0.000000
                           E1_T1       0.7000000            0.000000
                           E2_T1       0.7000000            0.000000
                           E3_T1       0.7000000            0.000000
```

CV_T1	19000.00	0.000000
CPW_T1	4.200000	0.000000
CPST_T1	2.021000	0.000000
XW_T1	0.1000000	0.000000
RMIN_T1	0.9200000	0.000000
CWTB_T1	2000000.	0.000000
CFB_T1	0.2200000E-01	0.000000
CFT_T1	0.2300000E-02	0.000000
CGRID_T1	0.1200000	0.000000
PDEMAND_T1	850.0000	0.000000
HDEMAND_T1	13631.35	0.000000
MT1_T1	5.000000	0.000000
RT1_T1	0.9673864	0.000000
CT1_T1	665000.0	0.000000
MT1A_T1	3.000000	0.000000
RT1A_T1	0.9771580	0.000000
CT1A_T1	465000.0	0.000000
MT3_T1	3.000000	0.000000
RT3_T1	0.9771580	0.000000
CT3_T1	465000.0	0.000000
TAC_T1	1030749.	0.000000
FB_T1	4388.075	0.000000
HEATW_T1	5554864.	0.000000
FT_T1	17183.58	0.000000
FTS_T1	4.773216	0.000000
F1_T1	0.000000	0.000000
F1A_T1	0.000000	0.000000
F3_T1	4.773216	0.000000
P1_T1	0.000000	0.000000
F2_T1	0.000000	2285.739
F1EXT_T1	0.000000	0.000000
P2_T1	0.000000	0.000000
F2EXT_T1	0.000000	0.000000
P1A_T1	0.000000	0.000000
F1AEXT_T1	0.000000	0.000000
P3_T1	941.2304	0.000000
F3EXT_T1	4.773216	0.000000
PEXTRA_T1	91.23045	0.000000
PGRID_T1	0.000000	600.0000
HEAT1_T1	0.000000	0.000000
HEAT1A_T1	0.000000	0.000000
HEAT3_T1	13631.35	0.000000
I1_T1	0.000000	-0.2285613E+10
I1A_T1	0.000000	-0.2285649E+10
I3_T1	1.000000	90450.00
ITS_T1	1.000000	260000.0
CAP_T1	2465000.	0.000000
MAC_T1	30000.00	0.000000
OP_T1	680299.4	0.000000

A.3.2.3 RESULTS (SCENARIO 3)

```
Global optimal solution found.
Objective value:                              1060829.
Objective bound:                              1060829.
Infeasibilities:                              0.000000
Extended solver steps:                               1
Total solver iterations:                           142
Elapsed runtime seconds:                          0.69

Model Class:                                     MINLP

Total variables:                   59
Nonlinear variables:               16
Integer variables:                 23

Total constraints:                 68
Nonlinear constraints:              7

Total nonzeros:                   169
Nonlinear nonzeros:                16
```

Variable	Value	Reduced Cost
FBAV_T1	6875.000	0.000000
H0	104.9000	0.000000
H1	3137.500	0.000000
H2	2901.600	0.000000
H3	2855.800	0.000000
E0	0.7500000	0.000000
E1	0.7000000	0.000000
E2	0.7000000	0.000000
E3	0.7000000	0.000000
CV	19000.00	0.000000
CPW	4.200000	0.000000
CPST	2.021000	0.000000
XW	0.1000000	0.000000
PRB11	0.9000000	0.000000
PRB12	0.9100000	0.000000
PRB21	0.9000000	0.000000
PRB22	0.9100000	0.000000
RMIN	0.9200000	0.000000
C11	120000.0	0.000000
C12	155000.0	0.000000
C21	100000.0	0.000000
C22	130000.0	0.000000
CWTB	2000000.	0.000000
CFB	0.2200000E-01	0.000000
CFT	0.2300000E-02	0.000000
CGRID	0.1200000	0.000000
PDEMAND_T1	850.0000	0.000000
HDEMAND_T1	13631.35	0.000000
PDEMAND_T2	850.0000	0.000000
HDEMAND_T2	13631.35	0.000000
TAC	1060829.	0.000000
FB_T1	4349.888	0.000000
HEATW_T1	5506523.	0.000000
FT_T1	17034.04	0.000000
FTS_T1	4.731677	0.000000
P1A_T1	781.3418	0.000000
N11_T1	0.000000	0.000000
N12_T1	2.000000	0.000000
F2_T1	2.141554	0.000000
F1EXT_T1	2.590123	0.000000
P1B_T1	68.65822	0.000000
N21_T1	1.000000	0.000000
N22_T1	0.000000	0.000000
F2EXT_T1	2.141554	0.000000
PTOTAL_T1	850.0000	0.000000
PEXTRA_T1	0.000000	32.44720
FBAV_T2	4349.888	0.000000
FB_T2	4349.888	0.000000
HEATW_T2	5506523.	0.000000
FT_T2	17034.04	0.000000
FTS_T2	4.731677	0.000000
P1A_T2	781.3418	0.000000
N11_T2	0.000000	0.000000
N12_T2	2.000000	0.000000
F2_T2	2.141554	0.000000
F1EXT_T2	2.590123	0.000000
F2EXT_T2	2.141554	0.000000
P1B_T2	68.65822	0.000000
N21_T2	1.000000	0.000000
N22_T2	0.000000	0.000000
HOUTPUT_T2	13631.35	0.000000
HEXCESS_T2	0.000000	22.71304
N11	0.000000	0.000000
N12	2.000000	0.000000
N21	1.000000	0.000000
N22	0.000000	0.000000
CAP	2665000.	0.000000
M11	0.000000	20600.00
M12	3.000000	30150.00
M21	2.000000	18000.00
M22	0.000000	26900.00
NWTB	1.000000	260000.0
I11	0.000000	0.000000

I12	1.000000	0.000000
MG	3.000000	0.000000
NG	2.000000	0.000000
PRBBG	0.9100000	0.000000
RT	0.9771580	0.000000
I21	1.000000	0.000000
I22	0.000000	0.000000
MG2	2.000000	0.000000
NG2	1.000000	0.000000
PRBBG2	0.9000000	0.000000
RT2	0.9900000	0.000000
RTO	0.9673864	0.000000
NWTB_T1	1.000000	0.000000
NWTB_T2	1.000000	0.000000
MAC	40000.00	0.000000
OP	674379.1	0.000000

A.4 CHAPTER 7

A.4.1 LINGO CODES

```
! Biomass-based Tri-generation System Input-Output Model;

Min = OPCost; ! Operational Costs in USD/yr;

OPCost = -(b1*c1 + b7*c7 + b10*c10 + b11*c11)*5000;
! Optional to include Annualised CAP Payment; ! + 0.13*6770352;
@free(OPCost);

c1 = 0;
c7 = 0;
c10 = 0.006; !USD/kg of EFB;
c11 = 0.022; !USD/kg of PMF;

! IO Model - Mass and Energy Balance;

!POME (kg/h);                 b1 = -55500*x0;
!Biogas (kg/h);               b2 = 319.13*x0 - 159.565*x1 - 159.565*x2 - 159.565*x3;
!Biomethane (kg/h);           b3 = 157.965*x1 + 157.965*x2 + 157.965*x3 - 105.31*x4 -
                              105.31*x5 - 105.31*x6 - 105.31*x7;
!Power (kW);                  b4 = -47.87*x1 - 47.87*x2 - 47.87*x3 + 416.3*x4 +
                              416.3*x5 + 416.3*x6 + 416.3*x7 -6.31*x13 + 453.22*x14
                              + 453.22*x15 + 453.22*x16 + 453.22*x17 + 161.6*x18 +
                              161.6*x19 + 161.6*x20;
!Flue gas (kg/h);             b5 = 526.57*x4 + 526.57*x5 + 526.57*x6 + 526.57*x7 -
1579.71*x8;
!Released flue gas (kg/h);    b6 = 1579.71*x8 + 32558.01*x9 + 32558.01*x10;
!Return/Fresh Water (kg/h);   b7 = -57218*x12;
!Cooling Water (kg/h);        b8 = -1671.84*x8 - 39268.05*x9 - 39268.05*x10 +
                              56218*x12 - 279*x13;
!Chilled Water (kg/h);        b9 = 1000*x13;
!EFB (kg/h);                  b10 = -16875*x11;
!PMF (kg/h);                  b11 = -9245.3*x11;
!Dried Biomass (kg/h);        b12 = -11950.8*x9 - 11950.8*x10 + 11950.8*x11;
!HPS (kg/h);                  b13 = 1671.84*x8 + 39268.05*x9 + 39268.05*x10 -
                              13646.63*x14 - 13646.63*x15 - 13646.63*x16 -
                              13646.63*x17;
!MPS (kg/h);                  b14 = 13646.63*x14 + 13646.63*x15 + 13646.63*x16 +
                              13646.63*x17 - 20469.945*x18 - 20469.945*x19 -
                              20469.945*x20;
!LPS (kg/h);                  b15 = -12814.88*x11 + 20469.945*x18 + 20469.945*x19 +
                              20469.945*x20;

@bin(I0);@bin(I1);@bin(I2);@bin(I3);@bin(I4);@bin(I5);@bin(I6);@bin(I7);@bin(I8);@bin
(I9);@bin(I10);
@bin(I11);@bin(I12);@bin(I13);@bin(I14);@bin(I15);@bin(I16);@bin(I17);@bin(I18);@bin(
I19);@bin(I20);

@free(b1);
@free(b7);
@free(b10);
@free(b11);

! High Season Energy Demands;
b8 = 13000;
b9 = 1000;
b15 = 24375;

! Assumming Net Flow of Intermediates are zero;
b2 = 0;
b3 = 0;
b5 = 0;
b12 = 0;
b13 = 0;
b14 = 0;

! Failure or Partial Load Analysis for HST3;
x16 = 0;

! Feasible Operating Range for each Equipment;

! AD; x0 >= 0.60*I0; x0 <= 1*I0;
```

```
! MM1; x1 >= 0.60*I1; x1 <= 1.12*I1;
! MM2; x2 >= 0.60*I2; x2 <= 1.12*I2;
! MM3; x3 >= 0.60*I3; x3 <= 1.12*I3;
! GT1; x4 >= 0.60*I4; x4 <= 1.20*I4;
! GT2; x5 >= 0.60*I5; x5 <= 1.20*I5;
! GT3; x6 >= 0.60*I6; x6 <= 1.20*I6;
! GT4; x7 >= 0.60*I7; x7 <= 1.20*I7;
! HRSG; x8 >= 0.10*I8; x8 <= 27.35*I8;
! WTB1; x9 >= 0.05*I9; x9 <= 1.10*I9;
! WTB2; x10 >= 0.05*I10; x10 <= 1.10*I10;
! DR; x11 >= 0.10*I11; x11 <= 1.30*I11;
! CT; x12 >= 0.10*I12; x12 <= 1.88*I12;
! MCH; x13 >= 0.60*I13; x13 <= 39.6*I13;
! HST1; x14 >= 0.55*I14; x14 <= 1.10*I14;
! HST2; x15 >= 0.55*I15; x15 <= 1.10*I15;
! HST3; x16 >= 0.55*I16; x16 <= 1.10*I16;
! HST1; x17 >= 0.55*I17; x17 <= 1.10*I17;
! MST1; x18 >= 0.77*I18; x18 <= 1.54*I18;
! MST2; x19 >= 0.77*I19; x19 <= 1.54*I19;
! MST3; x20 >= 0.77*I20; x20 <= 1.54*I20;
```

A.4.2 RESULTS

```
Global optimal solution found.
  Objective value:                              1307299.
  Objective bound:                              1307299.
  Infeasibilities:                              0.000000
  Extended solver steps:                               0
  Total solver iterations:                            59
  Elapsed runtime seconds:                          0.18

  Model Class:                                      MILP

  Total variables:                   47
  Nonlinear variables:                0
  Integer variables:                 21

  Total constraints:                 58
  Nonlinear constraints:              0

  Total nonzeros:                   149
  Nonlinear nonzeros:                 0
```

Variable	Value	Reduced Cost
OPCOST	1307299.	0.000000
B1	-55500.00	0.000000
C1	0.000000	0.000000
B7	-49517.66	0.000000
C7	0.000000	0.000000
B10	-14482.79	0.000000
C10	0.6000000E-02	0.000000
B11	-7934.683	0.000000
C11	0.2200000E-01	0.000000
X0	1.000000	0.000000
B2	0.000000	0.000000
X1	1.120000	0.000000
X2	0.8800000	0.000000
X3	0.000000	0.000000
B3	0.000000	0.000000
X4	0.000000	0.000000
X5	0.6000000	0.000000
X6	1.200000	0.000000
X7	1.200000	0.000000
B4	2600.889	0.000000
X13	1.000000	0.000000
X14	1.100000	0.000000
X15	0.9420860	0.000000
X16	0.000000	0.000000
X17	0.5500000	0.000000
X18	0.7700000	0.000000
X19	0.000000	0.000000

X20	0.9580573	0.000000
B5	0.000000	0.000000
X8	1.000000	0.000000
B6	29522.29	0.000000
X9	0.000000	0.000000
X10	0.8582397	0.000000
X12	0.8654210	0.000000
B8	13000.00	0.000000
B9	1000.000	0.000000
X11	0.8582397	0.000000
B12	0.000000	0.000000
B13	0.000000	0.000000
B14	0.000000	0.000000
B15	24375.00	0.000000
I0	1.000000	-96268.31
I1	1.000000	0.000000
I2	1.000000	0.000000
I3	0.000000	0.000000
I4	0.000000	0.000000
I5	1.000000	0.000000
I6	1.000000	0.000000
I7	1.000000	0.000000
I8	1.000000	0.000000
I9	0.000000	-0.1024455E-08
I10	1.000000	0.000000
I11	1.000000	0.000000
I12	1.000000	0.000000
I13	1.000000	0.000000
I14	1.000000	0.000000
I15	1.000000	0.000000
I16	0.000000	0.000000
I17	1.000000	0.000000
I18	1.000000	0.000000
I19	0.000000	0.000000
I20	1.000000	0.000000

A.5 CHAPTER 8

A.5.1 LINGO CODES

```
! Biomass-based Tri-generation System Input-Output Model;

Min = OPCost; ! Operational Costs in USD/yr;

OPCost = -(b1*c1 + b7*c7 + b10*c10 + b11*c11)*5000; ! Optional to include Annualised
CAP Payment; ! + 0.13*6770352;
@free(OPCost);

c1 = 0;
c7 = 0;
c10 = 0.006; !USD/kg of EFB;
c11 = 0.022; !USD/kg of PMF;

! IO Model - Mass and Energy Balance;

!POME (kg/h);                 b1 = -55500*x0;
!Biogas (kg/h);               b2 = 319.13*x0 - 159.565*x1 - 159.565*x2 - 159.565*x3;
!Biomethane (kg/h);           b3 = 157.965*x1 + 157.965*x2 + 157.965*x3 - 105.31*x4 -
                              105.31*x5 - 105.31*x6 - 105.31*x7;
!Power (kW);                  b4 = -47.87*x1 - 47.87*x2 - 47.87*x3 + 416.3*x4 +
                              416.3*x5 + 416.3*x6 + 416.3*x7 -6.31*x13 + 453.22*x14
                              + 453.22*x15 + 453.22*x16 + 453.22*x17 + 161.6*x18 +
                              161.6*x19 + 161.6*x20;
!Flue gas (kg/h);             b5 = 526.57*x4 + 526.57*x5 + 526.57*x6 + 526.57*x7 -
1579.71*x8;
!Released flue gas (kg/h);    b6 = 1579.71*x8 + 32558.01*x9 + 32558.01*x10;
!Return/Fresh Water (kg/h);   b7 = -57218*x12;
!Cooling Water (kg/h);        b8 = -1671.84*x8 - 39268.05*x9 - 39268.05*x10 +
                              56218*x12 - 279*x13;
!Chilled Water (kg/h);        b9 = 1000*x13;
!EFB (kg/h);                  b10 = -16875*x11;
!PMF (kg/h);                  b11 = -9245.3*x11;
!Dried Biomass (kg/h);        b12 = -11950.8*x9 - 11950.8*x10 + 11950.8*x11;
!HPS (kg/h);                  b13 = 1671.84*x8 + 39268.05*x9 + 39268.05*x10 -
                              13646.63*x14 - 13646.63*x15 - 13646.63*x16 -
                              13646.63*x17;
!MPS (kg/h);                  b14 = 13646.63*x14 + 13646.63*x15 + 13646.63*x16 +
                              13646.63*x17 - 20469.945*x18 - 20469.945*x19 -
                              20469.945*x20;
!LPS (kg/h);                  b15 = -12814.88*x11 + 20469.945*x18 + 20469.945*x19 +
                              20469.945*x20;

@bin(I0);@bin(I1);@bin(I2);@bin(I3);@bin(I4);@bin(I5);@bin(I6);@bin(I7);@bin(I8);@bin
(I9);@bin(I10);
@bin(I11);@bin(I12);@bin(I13);@bin(I14);@bin(I15);@bin(I16);@bin(I17);@bin(I18);@bin(
I19);@bin(I20);

@free(b1);
@free(b7);
@free(b10);
@free(b11);

! High Season Energy Demands;
b8 = 13000;
b9 = 1000;
b15 = 24375;

! Assumming Net Flow of Intermediates are zero;
b2 = 0;
b3 = 0;
b5 = 0;
b12 = 0;
b13 = 0;
b14 = 0;

! Failure or Partial Load Analysis;
x2 = 0.60;

! Feasible Operating Range for each Equipment;

! AD; x0 >= 0.60*I0; x0 <= 1*I0;
```

```
! MM1; x1 >= 0.60*I1; x1 <= 1.12*I1;
! MM2; x2 >= 0.60*I2; x2 <= 1.12*I2;
! MM3; x3 >= 0.60*I3; x3 <= 1.12*I3;
! GT1; x4 >= 0.60*I4; x4 <= 1.20*I4;
! GT2; x5 >= 0.60*I5; x5 <= 1.20*I5;
! GT3; x6 >= 0.60*I6; x6 <= 1.20*I6;
! GT4; x7 >= 0.60*I7; x7 <= 1.20*I7;
! HRSG; x8 >= 0.10*I8; x8 <= 27.35*I8;
! WTB1; x9 >= 0.05*I9; x9 <= 1.10*I9;
! WTB2; x10 >= 0.05*I10; x10 <= 1.10*I10;
! DR; x11 >= 0.10*I11; x11 <= 1.30*I11;
! CT; x12 >= 0.10*I12; x12 <= 1.88*I12;
! MCH; x13 >= 0.60*I13; x13 <= 39.6*I13;
! HST1; x14 >= 0.55*I14; x14 <= 1.10*I14;
! HST2; x15 >= 0.55*I15; x15 <= 1.10*I15;
! HST3; x16 >= 0.55*I16; x16 <= 1.10*I16;
! HST1; x17 >= 0.55*I17; x17 <= 1.10*I17;
! MST1; x18 >= 0.77*I18; x18 <= 1.54*I18;
! MST2; x19 >= 0.77*I19; x19 <= 1.54*I19;
! MST3; x20 >= 0.77*I20; x20 <= 1.54*I20;
```

A.5.2 RESULTS

```
 Global optimal solution found.
 Objective value:                              1307299.
 Objective bound:                              1307299.
 Infeasibilities:                              0.000000
 Extended solver steps:                               0
 Total solver iterations:                            44
 Elapsed runtime seconds:                          0.12

 Model Class:                                      MILP

 Total variables:                    47
 Nonlinear variables:                 0
 Integer variables:                  21

 Total constraints:                  58
 Nonlinear constraints:               0

 Total nonzeros:                    149
 Nonlinear nonzeros:                  0


                                Variable           Value        Reduced Cost
                                  OPCOST        1307299.            0.000000
                                      B1       -55500.00            0.000000
                                      C1        0.000000            0.000000
                                      B7       -49517.66            0.000000
                                      C7        0.000000            0.000000
                                     B10       -14482.79            0.000000
                                     C10       0.6000000E-02        0.000000
                                     B11       -7934.683            0.000000
                                     C11       0.2200000E-01        0.000000
                                      X0        1.000000            0.000000
                                      B2        0.000000            0.000000
                                      X1       0.6000000            0.000000
                                      X2       0.6000000            0.000000
                                      X3       0.8000000            0.000000
                                      B3        0.000000            0.000000
                                      X4        0.000000            0.000000
                                      X5        1.200000            0.000000
                                      X6        1.200000            0.000000
                                      X7       0.6000000            0.000000
                                      B4        2600.889            0.000000
                                     X13        1.000000            0.000000
                                     X14        1.100000            0.000000
                                     X15       0.9420860            0.000000
                                     X16        0.000000            0.000000
                                     X17       0.5500000            0.000000
                                     X18       0.7700000            0.000000
                                     X19        0.000000            0.000000
```

X20	0.9580573	0.000000
B5	0.000000	0.000000
X8	1.000000	0.000000
B6	29522.29	0.000000
X9	0.000000	0.000000
X10	0.8582397	0.000000
X12	0.8654210	0.000000
B8	13000.00	0.000000
B9	1000.000	0.000000
X11	0.8582397	0.000000
B12	0.000000	0.000000
B13	0.000000	0.000000
B14	0.000000	0.000000
B15	24375.00	0.000000
I0	1.000000	-96268.31
I1	1.000000	0.000000
I2	1.000000	0.000000
I3	1.000000	0.000000
I4	0.000000	0.000000
I5	1.000000	0.000000
I6	1.000000	0.000000
I7	1.000000	0.000000
I8	1.000000	0.000000
I9	0.000000	-0.1024455E-08
I10	1.000000	0.000000
I11	1.000000	0.000000
I12	1.000000	0.000000
I13	1.000000	0.000000
I14	1.000000	0.000000
I15	1.000000	0.000000
I16	0.000000	0.000000
I17	1.000000	0.000000
I18	1.000000	0.000000
I19	0.000000	0.000000
I20	1.000000	0.000000

A.6 CHAPTER 9

A.6.1 MATHEMATICAL FORMULATION

A.6.1.1 Material and Energy Balance

A.6.1.1.1 Palm Oil Mill (POM)

Fresh fruit bunches (FFBs) with flow rate F^{FFB} is sent to the POM and converted to crude palm oil (CPO) *o* and palm-based biomass *i* at the conversion of $\mathrm{X}_o^{\mathrm{OIL}}$ and $\mathrm{X}_i^{\mathrm{BIO}}$ respectively.

$$F_o^{\mathrm{OIL}} = F^{\mathrm{FFB}}\mathrm{X}_o^{\mathrm{OIL}} \qquad \forall o \qquad \text{(A.1)}$$

$$F_i^{\mathrm{BIO}} = F^{\mathrm{FFB}}\mathrm{X}_i^{\mathrm{BIO}} \qquad \forall i \qquad \text{(A.2)}$$

Each palm-based biomass *i* with flow rate F_i^{BIO} can distributed between the potential technology *j* in the biomass-based tri-generation system with flow rate F_{ij}^{I} and potential technology *g* in the palm-based biorefinery with flow rate F_{ig}^{I} .

$$F_i^{\mathrm{BIO}} \geq \sum_{j=1}^{J} F_{ij}^{\mathrm{I}} + \sum_{g=1}^{G} F_{ig}^{\mathrm{I}} \qquad \forall i \qquad \text{(A.3)}$$

Apart from material conversions, POM would consume energy in order to operate. The total energy consumption of POM is determined based on the energy requirement per unit FFB processed ($\mathrm{Y}_e^{\mathrm{Con\text{-}POM}}$). The total energy consumption is shown in Equation A.4;

$$E_e^{\mathrm{Con\text{-}POM}} = F^{\mathrm{FFB}}\mathrm{Y}_e^{\mathrm{Con\text{-}POM}} \qquad \forall e \qquad \text{(A.4}$$

The total energy consumption of POM ($E_e^{\text{Con-POM}}$) is met either by importing energy from BTS ($E_e^{\text{BTS-POM}}$) or importing from an external facility ($E_e^{\text{Imp-POM}}$) as shown in Equation A.5;

$$E_e^{\text{Con-POM}} = E_e^{\text{BTS-POM}} + E_e^{\text{Imp-POM}} \qquad \forall e \qquad \text{(A.5}$$

A.6.1.1.2 Biomass Tri-generation System (BTS)

In technology *j*, the flow rate of component *q* (with fraction of composition θ_{iq}) in biomass *i* is given by Equation A.6

$$f_{qj}^{\text{I}} = \sum_{i=1}^{I} F_{ij}^{\text{I}} \theta_{iq} \qquad \forall q \forall j \qquad \text{(A.6}$$

where

$$\sum_{q=1}^{Q} \theta_{iq} \leq 1 \qquad \forall i \qquad \text{(A.7}$$

Component *q* is then converted to primary products *p* with the conversion of $\text{X}_{qjp}^{\text{I}}$ respectively as shown in Equation A.8.

$$F_{jp}^{\text{I}} = \sum_{q=1}^{Q} f_{qj}^{\text{I}} \text{X}_{qjp}^{\text{I}} \qquad \forall p \forall j \qquad \text{(A.8}$$

The total production rate of primary product *p* for all technologies *j* is given as F_p in Equation A.9;

$$F_p = \sum_{j=1}^{J} F_{jp}^{\text{I}} \qquad \forall p \qquad \text{(A.9}$$

Next, primary product p can be distributed to potential technology j' for further processing to produce product p'. The splitting of primary product p is given by flow rate $F_{pj'}^{\mathrm{II}}$ (as shown in Equation A.10).

$$F_p = \sum_{j'=1}^{J'} F_{pj'}^{\mathrm{II}} \qquad \forall p \qquad \text{(A.10}$$

Additionally, flow rate $F_{pj'}^{\mathrm{II}}$ contains components q'. Each component q' has a composition $\theta_{pq'}$ and flow rate $f_{q'j'}^{\mathrm{II}}$ as shown in Equation A.11

$$f_{q'j'}^{\mathrm{II}} = \sum_{p=1}^{P} F_{pj'}^{\mathrm{II}} \theta_{pq'} \qquad \forall j' \forall q' \qquad \text{(A.11}$$

where

$$\sum_{q'=1}^{Q'} \theta_{pq'} \leq 1 \qquad \forall p \qquad \text{(A.12}$$

Component q' is then converted to final product p' with conversion $\mathrm{X}_{q'j'p'}^{\mathrm{II}}$ (Equation A.13).

$$F_{j'p'}^{\mathrm{II}} = \sum_{q'=1}^{Q'} f_{q'j'}^{\mathrm{II}} \mathrm{X}_{q'j'p'}^{\mathrm{II}} \qquad \forall j' \forall p' \qquad \text{(A.13}$$

The total production rate of product p' for all technologies j' is written as;

$$F_{p'} = \sum_{j'=1}^{J'} F_{j'p'}^{\mathrm{II}} \qquad \forall p' \qquad \text{(A.14}$$

However, in the case where a single or no technology is required to produce the final product p', biomass i and primary product p are allowed to bypass technology j and j'

via a "blank" technology (where no conversion takes place). It is important to note that the representation of final product *p'* is applicable in cases where BTS outputs (e.g. steam, cooling water, etc.) are sold or exported to the end user as raw materials (e.g., in reactions). Hence, Equation A.15 indicates the splitting of product *p'* to either POM or PBB.

$$F_{p'} = F_{p'}^{\mathrm{POM}} + F_{p'}^{\mathrm{PBB}} \qquad \forall p' \qquad \text{(A.15}$$

Alternatively, BTS outputs can be sold or exported as utilities (e.g., for heating, cooling, power, etc.). Components *q* in biomass *i* can also be converted into energy *e* via technology *j* with conversion of $\mathrm{V}_{qje}^{\mathrm{I}}$. Moreover, components *q'* in product *p* can also be converted into energy *e* via technology *j'* with conversion of $\mathrm{V}_{q'j'e}^{\mathrm{II}}$. Total energy generated by technologies *j* and *j'* is shown in Equation A.16.

$$E_e^{\text{Gen-BTS}} = \sum_{q=1}^{Q}\sum_{j=1}^{J} f_{qj}^{\mathrm{I}}\mathrm{V}_{qje}^{\mathrm{I}} + \sum_{q'=1}^{Q'}\sum_{j'=1}^{J'} f_{q'j'}^{\mathrm{II}}\mathrm{V}_{q'j'e}^{\mathrm{II}} \qquad \forall e \qquad \text{(A.16}$$

Apart from generating energy, some technologies in the BTS may consume energy. The total energy consumption of BTS is determined based on the energy requirement in all technologies *j* and *j'* that are used to convert biomass *i* to products *p* and *p'* as well as energy *e*. The total energy consumption is shown in Equation A.17

$$E_e^{\text{Con-BTS}} = \sum_{p=1}^{P}\sum_{j=1}^{J} F_{jp}^{\mathrm{I}}\mathrm{Y}_{pje}^{\mathrm{I}} + \sum_{p'=1}^{P'}\sum_{j'=1}^{J'} F_{j'p'}^{\mathrm{II}}\mathrm{Y}_{p'j'e}^{\mathrm{II}} \qquad \forall e \qquad \text{(A.17}$$

where $\mathrm{Y}_{pje}^{\mathrm{I}}$ and $\mathrm{Y}_{p'j'e}^{\mathrm{II}}$ are specific energy consumption for technologies *j* and *j'* respectively. The specific energy consumption for each technology is determined by obtaining the amount of energy required in each technology per unit of its respective main product basis. In the case where energy generated by BTS exceeds the total energy consumption and energy demand from process or customer $\left(E_e^{\text{Gen-BTS}} > E_e^{\text{Con-BTS}} + E_e^{\text{BTS-POM}} + E_e^{\text{BTS-PBB}}\right)$, excess energy $E_e^{\text{Exp-BTS}}$ can be sold or exported to the power grid. In contrast, import of external energy is required if the total energy consumption of BTS is more than the energy generated ($E_e^{\text{Gen-BTS}} < E_e^{\text{Con-BTS}} + E_e^{\text{BTS-POM}} + E_e^{\text{BTS-PBB}}$). The overall energy correlation for the BTS can be written as

$$E_e^{\text{Gen-BTS}} = E_e^{\text{Con-BTS}} + E_e^{\text{BTS-POM}} + E_e^{\text{BTS-PBB}} + E_e^{\text{Exp-BTS}} \qquad \forall e \qquad \text{(A.18}$$

A.6.1.1.3 Palm-Based Biorefinery (PBB)

In technology *g*, the flow rate of component *q* (with fraction of composition θ_{iq}) in biomass *i* is given by Equation A.19:

$$f_{qg}^{\text{I}} = \sum_{i=1}^{I} F_{ig}^{\text{I}} \theta_{iq} \qquad \forall q \forall g \qquad \text{(A.19}$$

where

$$\sum_{q=1}^{Q} \theta_{iq} \leq 1 \qquad \forall i \qquad \text{(A.20}$$

Component *q* is then converted to primary products *h* with the conversion of $\text{X}_{qgh}^{\text{I}}$ respectively as shown in Equation A.21.

$$F_{gh}^{\text{I}} = \sum_{q=1}^{Q} f_{qh}^{\text{I}} \text{X}_{qgh}^{\text{I}} \qquad \forall h \forall g \qquad \text{(A.21}$$

The total production rate of primary product h for all technologies g is given as F_h in Equation A.22;

$$F_h = \sum_{g=1}^{G} F_{gh}^{\mathrm{I}} \qquad \forall h \qquad \text{(A.22}$$

Next, primary product h can be distributed to potential technology g' for further processing to produce product h'. The splitting of primary product h is given by flow rate $F_{hg'}^{\mathrm{II}}$ (as shown in Equation A.23).

$$F_h = \sum_{g'=1}^{G'} F_{hg'}^{\mathrm{II}} \qquad \forall h \qquad \text{(A.23}$$

Additionally, flow rate $F_{hg'}^{\mathrm{II}}$ contains components q''. Each component q'' has a composition $\theta_{hq''}$ and flow rate $f_{q''g'}^{\mathrm{II}}$ as shown in Equation A.24.

$$f_{q''g'}^{\mathrm{II}} = \sum_{h=1}^{H} F_{hg'}^{\mathrm{II}} \theta_{hq''} \qquad \forall g' \forall q'' \qquad \text{(A.24}$$

where

$$\sum_{q''=1}^{Q''} \theta_{hq''} \leq 1 \qquad \forall h \qquad \text{(A.25}$$

Components q'' are then converted to final product h' with conversion $\mathrm{X}_{q''g'h'}^{\mathrm{II}}$ (see Equation A.26).

$$F_{g'h'}^{\mathrm{II}} = \sum_{q''=1}^{Q''} f_{q''g'}^{\mathrm{II}} \mathrm{X}_{q''g'h'}^{\mathrm{II}} \qquad \forall g' \forall h' \qquad \text{(A.26}$$

The total production rate of product h' for all technologies g' is written as;

$$F_{h'} = \sum_{g'=1}^{G'} F_{g'h'}^{\text{II}} \qquad \forall h' \qquad \text{(A.27}$$

Similar to the previous section, if a single or no technology is required to produce the final product *h'*, biomass *i* and primary product *h* are allowed to bypass technology *g* and *g'* via a "blank" technology (where no conversion takes place).

Apart from material conversions, technologies *g* and *g'* in the PBB may consume energy. The total energy consumption of PBB is determined based on the energy requirement in all technologies *g* and *g'* that are used to convert biomass *i* to products *p* and *p'* as well as energy *e*. The total energy consumption is shown in Equation A.28.

$$E_e^{\text{Con-PBB}} = \sum_{h=1}^{H}\sum_{g=1}^{G} F_{gh}^{\text{I}} \Upsilon_{hge}^{\text{I}} + \sum_{h'=1}^{H'}\sum_{g'=1}^{G'} F_{g'h'}^{\text{II}} \Upsilon_{h'g'e}^{\text{II}} \qquad \forall e \qquad \text{(A.28}$$

where $\Upsilon_{hge}^{\text{I}}$ and $\Upsilon_{h'g'e}^{\text{II}}$ are specific energy consumption for technologies *g* and *g'* respectively. The specific energy consumption for each technology is determined by obtaining the amount of energy required in each technology per unit of its respective main product basis. The total energy consumption of the PBB ($E_e^{\text{Con-PBB}}$) is met either by importing energy from the BTS ($E_e^{\text{BTS-PBB}}$) or importing from an external facility ($E_e^{\text{Imp-PBB}}$) as shown in Equation A.29;

$$E_e^{\text{Con-PBB}} = E_e^{\text{BTS-PBB}} + E_e^{\text{Imp-PBB}} \qquad \forall e \qquad \text{(A.29}$$

A.6.1.2 Economic Analysis

The economic performance of POM is analysed by determining the gross profit (GP^{POM}) of the system, as shown in Equation A.30. Note that AOT in Equation A.30

represents the annual operating time (in terms of 5000 hours/year). Meanwhile, C_o^{OIL} is the selling price of crude palm oil *o*, C_{ij}^{I} is the selling price of palm-based biomass *i* to BTS, C_{ig}^{I} is the selling price of palm-based biomass *i* to PBB, $C_e^{BTS\text{-}POM}$ is the cost of importing energy *e* from the BTS, $C_e^{Imp\text{-}POM}$ is the cost of importing energy *e* from an external facility and C^{FFB} is cost of FBB.

$$GP^{POM} = AOT \times \begin{pmatrix} \sum_{o=1}^{O} F_o^{OIL} C_o^{OIL} + \sum_{j=1}^{J}\sum_{i=1}^{I} F_{ij}^{I} C_{ij}^{I} + \sum_{g=1}^{G}\sum_{i=1}^{I} F_{ig}^{I} C_{ig}^{I} - \sum_{e=1}^{E} E_e^{BTS\text{-}POM} C_e^{BTS\text{-}POM} \\ -\sum_{e=1}^{E} E_e^{Imp\text{-}POM} C_e^{Imp\text{-}POM} - \sum F^{FFB} C^{FFB} \end{pmatrix} \quad (A$$

As for BTS, the economic performance is determined by the gross profit (GP^{BTS}) as shown in Equation A.31. $C_{p'}^{POM}$ is the selling price of products *p'* to POM, $C_{p'}^{PBB}$ is the selling price of products *p'* to PBB, $C_e^{Exp\text{-}BTS}$ is the selling price of exporting excess energy *e*, C_{ij}^{I} is the cost of palm-based biomass *i*.

$$GP^{BTS} = AOT \times \begin{pmatrix} \sum_{p'=1}^{P'} F_{p'}^{POM} C_{p'}^{POM} + \sum_{p'=1}^{P'} F_{p'}^{PBB} C_{p'}^{PBB} + \sum_{e=1}^{E} E_e^{Exp\text{-}BTS} C_e^{Exp\text{-}BTS} + \\ \sum_{e=1}^{E} E_e^{BTS\text{-}POM} C_e^{BTS\text{-}POM} + \sum_{e=1}^{E} E_e^{BTS\text{-}PBB} C_e^{BTS\text{-}PBB} - \sum_{j=1}^{J}\sum_{i=1}^{I} F_{ij}^{I} C_{ij}^{I} \end{pmatrix} \quad (A.31$$

On the other hand, the economic performance of PBB is analysed by determining the gross profit (GP^{PBB}) as shown in Equation A.32. $C_{h'}$ is the selling price of products *h'*, $C_e^{BTS\text{-}PBB}$ is the cost of importing energy *e* from the BTS, $C_e^{Imp\text{-}PBB}$

is the cost of importing energy *e* from an external facility and C^{I}_{ig} is the cost of palm-based biomass *i*.

$$GP^{PBB} = AOT \times \left(\sum_{h'=1}^{H'} F_{h'} C_{h'} - \sum_{e=1}^{E} E_e^{Imp\text{-}PBB} C_e^{Imp\text{-}PBB} - \sum_{e=1}^{E} E_e^{BTS\text{-}PBB} C_e^{BTS\text{-}PBB} - \sum_{g=1}^{G} \sum_{i=1}^{I} F^{I}_{ig} C^{I}_{ig} \right)$$

Following the proposed approach, the optimal EIP configuration is determined by maximising the overall economic performance ($GP^{OVERALL}$) as shown in Equation A.33.

$$\text{Maximise } GP^{OVERALL} = GP^{POM} + GP^{BTS} + GP^{PBB} \quad \text{(A.33}$$

A.6.1.3 Cost Savings Allocation

As shown in Equation A.34, C^{Disp}_{ij} represents the disposal cost of the biomass produced by the POM, while C^{Ext}_{ij} represents the purchasing cost of the biomass produced from an external facility. In Equation A.36, C^{Ext}_{ig} represents the purchasing cost of the biomass for the PBB from an external facility.

$$CS^{POM} = AOT \times \left(\begin{array}{l} \sum_{j=1}^{J} \sum_{i=1}^{I} F^{I}_{ij} C^{I}_{ij} + \sum_{g=1}^{G} \sum_{i=1}^{I} F^{I}_{ig} C^{I}_{ig} - \sum_{j=1}^{J} \sum_{i=1}^{I} F^{I}_{ij} C^{Disp}_{ij} - \sum_{g=1}^{G} \sum_{i=1}^{I} F^{I}_{ig} C^{Disp}_{ig} \\ \sum_{e=1}^{E} E_e^{BTS\text{-}POM} C_e^{BTS\text{-}POM} - \sum_{e=1}^{E} E_e^{Imp\text{-}POM} C_e^{Imp\text{-}POM} \end{array} \right) \quad \text{(A.34}$$

$$CS^{\mathrm{BTS}} = \mathrm{AOT} \times \left(\sum_{j=1}^{J} \sum_{i=1}^{I} F_{ij}^{\mathrm{I}} \mathrm{C}_{ij}^{\mathrm{I}} - \sum_{j=1}^{J} \sum_{i=1}^{I} F_{ij}^{\mathrm{I}} \mathrm{C}_{ij}^{\mathrm{Ext}} \right) \quad \text{(A.35}$$

$$CS^{\mathrm{PBB}} = \mathrm{AOT} \times \left(\sum_{g=1}^{G} \sum_{i=1}^{I} F_{ig}^{\mathrm{I}} \mathrm{C}_{ig}^{\mathrm{I}} - \sum_{g=1}^{G} \sum_{i=1}^{I} F_{ig}^{\mathrm{I}} \mathrm{C}_{ig}^{\mathrm{Ext}} + \sum_{e=1}^{E} E_{e}^{\mathrm{BTS\text{-}PBB}} \mathrm{C}_{e}^{\mathrm{BTS\text{-}PBB}} - \sum_{e=1}^{E} E_{e}^{\mathrm{Imp\text{-}PBB}} \mathrm{C}_{e}^{\mathrm{Imp\text{-}PBB}} \right) \quad \text{(A.36}$$

A.6.1.4 Nomenclature

Abbreviations

BTS	Biomass Tri-generation System
PBB	Palm-based Biorefinery
POM	Palm Oil Mill
CPO	Crude Palm Oil
FFB	Fresh Fruit Bunch
EFB	Empty Fruit Bunch
PKS	Palm Kernel Shell
PMF	Palm Mesocarp Fiber
POME	Palm Oil Mill Effluent
LPS	Low Pressure Steam
MPS	Medium Pressure Steam
HPS	High Pressure Steam

Indices

o	Index for palm oil
i	Index for biomass
j, j'	Index for technologies in BTS

g, g'	Index for technologies in PBB
p	Index for primary products in BTS
p'	Index for final products in BTS
h	Index for primary products in PBB
h'	Index for final products in PBB
q	Index for component balance of biomass *i*
q'	Index for component balance of primary product *p* in BTS
q''	Index for component balance of primary product *h* in PBB
e	Index for energy

Variables

F_i^{OIL}	Flow rate of palm oil *o*
F_i^{BIO}	Flow rate of biomass *i*
F_{ij}^{I}	Flow rate of biomass *i* to technology *j*
f_{qj}^{I}	Flow rate of component *q* in biomass to technology *j*
F_{jp}^{I}	Production rate of primary product *p* at technology *j*
F_p	Total production rate of primary product *p* at technology *j*
$F_{pj'}^{\mathrm{II}}$	Flow rate of primary product *p* to technology *j'*
$f_{q'j'}^{\mathrm{II}}$	Flow rate of component *q'* in product *p* to technology *j'*
$F_{j'p'}^{\mathrm{II}}$	Production rate of final product *p'* at technology *j'*
$F_{p'}$	Total production rate of final product *p'* at technology *j'*

$F_{p'}^{\text{POM}}$	Total production rate of final product *p'* sent to POM
$F_{p'}^{\text{PBB}}$	Total production rate of final product *p'* sent to PBB
F_{ig}^{I}	Flow rate of biomass *i* to technology *g*
f_{qg}^{I}	Flow rate of component *q* in biomass to technology *g*
F_{gh}^{I}	Production rate of primary product *h* at technology *g*
F_{h}	Total production rate of primary product *h* at technology *g*
$F_{hg'}^{\text{II}}$	Flow rate of primary product *h* to technology *g'*
$f_{q''g'}^{\text{II}}$	Flow rate of component *q''* in product *p* to technology *g'*
$F_{g'h'}^{\text{II}}$	Production rate of final product *h'* at technology *g'*
$F_{h'}$	Total production rate of final product *h'* at technology *g'*
$E_{e}^{\text{Con-POM}}$	Total energy consumed by POM
$E_{e}^{\text{BTS-POM}}$	Total energy imported from BTS by POM
$E_{e}^{\text{Imp-POM}}$	Total energy imported from external facility by POM
$E_{e}^{\text{Gen-BTS}}$	Total energy generated by BTS
$E_{e}^{\text{Con-BTS}}$	Total energy consumed by BTS
$E_{e}^{\text{BTS-POM}}$	Total external energy exported to POM by BTS
$E_{e}^{\text{BTS-PBB}}$	Total external energy exported to POM by PBB
$E_{e}^{\text{Exp-BTS}}$	Total excess energy exported to grid by BTS
$E_{e}^{\text{Con-PBB}}$	Total energy consumed by PBB
$E_{e}^{\text{BTS-PBB}}$	Total energy imported from BTS by PBB

$E_e^{\text{Imp-PBB}}$	Total energy imported from external facility by PBB
GP^{POM}	Total gross profit of POM
GP^{BTS}	Total gross profit of BTS
GP^{PBB}	Total gross profit of PBB
CS^{POM}	Total cost savings of POM
CS^{BTS}	Total cost savings of BTS
CS^{PBB}	Total cost savings of PBB

Parameters

θ_{iq}	Fraction of composition q in biomass i
$\theta_{pq'}$	Fraction of composition q' in primary product p
$\theta_{hq''}$	Fraction of composition q'' in primary product h
$\mathrm{X}_o^{\text{OIL}}$	Mass conversion of fresh fruit bunches to palm oil o
$\mathrm{X}_i^{\text{BIO}}$	Mass conversion of fresh fruit bunches to biomass i
$\mathrm{X}_{qjp}^{\text{I}}$	Conversion of biomass i to primary product p via technology j
$\mathrm{X}_{q'j'p'}^{\text{II}}$	Conversion of p to final product p' via technology j'
$\mathrm{X}_{qgh}^{\text{I}}$	Conversion of biomass i to primary product h via technology g
$\mathrm{X}_{q''g'h'}^{\text{II}}$	Conversion of h to final product h' via technology g'
$\mathrm{V}_{qje}^{\text{I}}$	Conversion of component q to energy e via technology j
$\mathrm{V}_{q'j'e}^{\text{II}}$	Conversion of component q' to energy e via technology j'

$Y_e^{\text{Con-POM}}$	Specific energy consumption of POM
Y_{pje}^{I}	Specific energy consumption of technology *j*
$Y_{p'j'e}^{\text{II}}$	Specific energy consumption of technology *j'*
Y_{hge}^{I}	Specific energy consumption of technology *g*
$Y_{h'g'e}^{\text{II}}$	Specific energy consumption of technology *g'*
AOT	Annual operating time in h/y
C_{ij}^{I}	Cost of biomass *i* for technology *j*
C_{ig}^{I}	Cost of biomass *i* for technology *g*
$C_{p'}^{\text{POM}}$	Cost of final product *p'* from BTS to POM
$C_{p'}^{\text{PBB}}$	Cost of final product *p'* from BTS to PBB
$C_{h'}$	Cost of final product *h'*
C_o^{OIL}	Revenue from palm oil *o*
C^{FFB}	Cost of fresh fruit bunches
$C_e^{\text{Imp-POM}}$	Cost of importing energy from external facility to POM
C_{ij}^{Disp}	Cost of disposing biomass *i*
C_{ij}^{Ext}	Cost of purchasing biomass *i* from external facility for BTS
C_{ig}^{Disp}	Cost of disposing biomass *i*
C_{ig}^{Ext}	Cost of purchasing biomass *i* from external facility for PBB in USD/kg
$C_e^{\text{BTS-POM}}$	Cost of energy from BTS to POM

$C_e^{BTS\text{-}PBB}$	Cost of energy from BTS to PBB
$C_e^{Imp\text{-}POM}$	Cost of importing energy from external facility to POM
$C_e^{Imp\text{-}PBB}$	Cost of importing energy from external facility to PBB
$C_e^{Exp\text{-}BTS}$	Selling cost of exporting excess energy from BTS to grid

A.6.2 LINGO CODES (COST SAVINGS ALLOCATION)

```
! Costs Savings Allocation via Maali's Method;
max = lambda; !Arbitary Variable;

GP1 = 400000; !Cost savings of Plant 1 in USD/yr;
GP2 = 200000; !Cost savings of Plant 2 in USD/yr;
GP3 = 900000; !Cost savings of Plant 3 in USD/yr;
GP13 = 4100000; !Cost savings of Coalition between Plant 1 and 3 in USD/yr;
GP23 = 1600000; !Cost savings of Coalition between Plant 2 and 3 in USD/yr;
GP12 = 1200000; !Cost savings of Coalition between Plant 1 and 2 in USD/yr;
GP123 = 5400000; !Cost savings of Coalition between Plant 1, 2 and 3 in USD/yr;

x1 + x2 + x3 = GP123;
x1 >= GP1;
x2 >= GP2;
x3 >= GP3;

x1/C1 >= lambda;

C1 = (GP123 + GP1 + GP12 + GP13 - (GP23 + GP2 + GP3))/(GP123); !Weighting for Plant
1;
InverseC1 = 1/C1;

x2/C2 >= lambda;

C2 = (GP123 + GP2 + GP12 + GP23 - (GP13 + GP1 + GP3))/(GP123); !Weighting for Plant
2;
InverseC2 = 1/C2;

x3/C3 >= lambda;

C3 = (GP123 + GP3 + GP13 + GP23 - (GP12 + GP1 + GP2))/(GP123); !Weighting for Plant
3;
InverseC3 = 1/C3;
```

A.6.3 RESULTS

```
  Global optimal solution found.
  Objective value:                              1350000.
  Infeasibilities:                              0.000000
  Total solver iterations:                             4
  Elapsed runtime seconds:                          0.08

  Model Class:                                        LP

  Total variables:                      4
  Nonlinear variables:                  0
  Integer variables:                    0

  Total constraints:                    8
  Nonlinear constraints:                0
```

```
Total nonzeros:                    13
Nonlinear nonzeros:                 0
```

Variable	Value	Reduced Cost
LAMBDA	1350000.	0.000000
GP1	400000.0	0.000000
GP2	200000.0	0.000000
GP3	900000.0	0.000000
GP13	4100000.	0.000000
GP23	1600000.	0.000000
GP12	1200000.	0.000000
GP123	5400000.	0.000000
X1	2100000.	0.000000
X2	750000.0	0.000000
X3	2550000.	0.000000
C1	1.555556	0.000000
INVERSEC1	0.6428571	0.000000
C2	0.5555556	0.000000
INVERSEC2	1.800000	0.000000
C3	1.888889	0.000000
INVERSEC3	0.5294118	0.000000