APPENDIX A

EES PROGRAMS

EES, (Engineering Equation Solver) is a commercial software package which is in extensive use at the University of Wisconsin and other institutions. It is a well-suited platform, with its robust implicit solver, for numerical analysis, especially of energy applications. Design and optimization analyses are fascilitated with a parametric table capability. The program is available through the Solar Energy Laboratory.

EES Programs

Air Density Elevation Function

CLC Charging Model

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EES Lookup Tables

ACME 500 WT Lookup

Line Cluster Lookup

Random Cluster Lookup

Symmetric Cluster Lookup

Air Density Elevation Function

```
"Air Density Elevation Function"
"Inputs ____________________________________________________________"
T_o = 288.16 "reference sea level temperature-deg. K"
B = 0.0065 "lapse rate-K/m"
g = 9.80665 "gravitational constant-m/s2"
R = 287 "gas constant for air-kJ/kgK"
p_stp=101.350 "stp pressure-kPa"
"
Equations __________________________________________________________"
T_elev = T_o-B*Z_elev "temperature as a function of elevation"
p_elev = p_stp*(1-(B*Z_elev)/T_o)^gamma
gamma =g/(R*B) "pressure as a function of elevation"
"
Results ____________________________________________________________"
rho_elev = 999.9*p_elev/(R*T_elev) "ideal gas law"
percent = 100*rho_elev/1.225 "percent reduction in air density"
residual_rho = rho_std_elev-rho_elev "calulated error in rho"
```

CLC Charging Model

```
"Copetti/Lorenzo/Chenlo Battery Model: charging only
"Voltage Calculation _______________________________________________"
Procedure Voltage(I,C_10,SOC,temp,a,b:V)
If (I <= 0.0) Then "Discharge ______________________________________"
ev_dch = 2.085-0.12*(1-SOC)
r_dch1 = 1/C_10*4/(1+(abs(I))^1.3)*(1-0.007*(temp-25))
r_dch2 = 1/C_10*((0.27/SOC^1.5))*(1-0.007*(temp-25))
r_dch3 = 0.02/C_10*(1-0.007*(temp-25))
V_dch = ev_dch - abs(I)*(r_dch1 +r_dch2 +r_dch3)
V = V_dch
Else "Charge _______________________________________________________"
I_10 = C_10/10
C_adjusted =((1.67*C_10*(1+0.005*(temp-25)))/(1+0.67*(I/I_10)^0.9))
"(3)"
ev_ch = 2+0.16*SOC
r_ch1 =1/C_10*(6/(1+I^0.86))*(1-0.025*(temp-25))
r_ch2 =1/C_10*0.48/(1-SOC^1.2)*(1-0.025*(temp-25))
r_ch3 =0.036/C_10*(1-0.025*(temp-25))
V_ch = ev_ch + I*(r_ch1 +r_ch2 +r_ch3)
V_g = (2.24+1.97*ln(1+I/C_10))*(1-0.002*(temp-25))
If (V_g < V_ch) Then
eta_c = 1-exp(a/(I/I_10+b)*(SOC-1)) "(5)"
V = V_ch
Else "Overcharge ___________________________________________________"
V_ec = (2.45+2.011*ln(1+I/C_10))*(1-0.002*(temp-25))
tau = 17.3/(1+852*(I/C_10)^1.67)      "time constant"
I_10 = C_10/10
eta_c = 1-exp(a/(I/I_10+b)*(SOC-1)) "(5)"
Q_ovch = (1/eta_c)*SOC*C_adjusted
V_ovch = V_g+(V_ec-V_g)*(1-exp(-Q_ovch/(I*tau)))
```

```
V = V_ovch
EndIf
EndIf
end
"
Parameters ________________________________________________________"
a = 20.73; b = 0.55   "battery recharge constants"
C_10= 1500 "battery capacity (Ah)"
t_hr = 1 " time (hours)"
t_sec = t_hr*3600
temp = 25
SOC = .6 "state of charge (0 < SOC < 1)"
"I   (Amps), given in parametric table"
"
Calculations ______________________________________________________"
DOD = 1-SOC

Call Voltage(I,C_10,SOC,temp,a,b:V)
P_Watts = (V*I) "Watts"
P_kW = P_Watts/1000
E_kWh = P_kW*t_hr
```

Diesel Engine Model

```
"Diesel Generator Model
For each time step, determines output power, engine hours, fuel use,
fuel cost, and waste heat."
"
FUNCTION: Determine power output of diesel as a function of demand."
Function PowerOut_(Demand, Pmin, Pmax)
If (Demand <= 0) Then "no demand"
Power := 0
Else
If (Demand <  Pmin) Then "below minimum, then operate at minimum"
Power := Pmin
Else
If (Demand  < Pmax) Then " follow load"
Power := Demand
Else
Power := Pmax "max output"
EndIf; EndIf; EndIf
PowerOut_ := Power
end
"
FUNCTION: Determine fuel use as a function of demand"
Function FuelUse_(Demand, Pmin, Pmax, FuelRate)
If (Demand <= 0) Then "no demand"
Fuel := 0
Else
If (Demand <  Pmin) Then  "below minimum, then operate at minimum"
Fuel := Pmin*FuelRate
Else
If (Demand  < Pmax) Then " follow load"
Fuel := Demand*FuelRate
Else
```

```
Fuel := Pmax*FuelRate "max output"
EndIf; EndIf; EndIf
FuelUse_ :=Fuel
end
"
Inputs ___________________________________________________________"
Pmin=.3; FuelMin=.39 "First point on fuel consumption curve (kW,
kg/kWh)"
Pmax=2.3; FuelMax=.35 "Second point on fuel consumption curve (kW,
kg/kWh)"
FuelCost = .25 "25 cents per liter"
timeStep = 1 "hour"
SFC_fuel = .086 " kg/kWh (1/LHV, or equal to 1/42,000 kJ/kg)"
SpVol_fuel = 1.16 "liters/kg"
"Demand is in Parametric Table"
"
Determine Output Power and Fuel Use Rate __________________________"
Pdiesel = PowerOut_(Demand, Pmin, Pmax) "kWh/hr"
FuelRate = FuelMin +(Pdiesel-Pmin)*(FuelMax-FuelMin)/(Pmax-Pmin)
"kg/kWh"
FuelUse= FuelUse_(Demand, Pmin, Pmax, FuelRate) "kg/hr"
"
Outputs per time step _____________________________________________"
SpecificFuel=FuelUse/Pdiesel
Energy = Pdiesel*timeStep
Vol_fuel = FuelUse*SpVol_fuel
eta_thermal = SFC_fuel/SpecificFuel
Energy_WasteHeat = timeStep*(Pdiesel/eta_thermal-Pdiesel)
Costs = FuelCost*Vol_fuel
```

Power Conversion Model Comparisons

```
"Power Converter Models
Reference 1: Jennings, S.U. et al. 'RESIM: A Simulation Program for
Determining the Viability of Renewable Energy Power Supply Systems'.
draft paper. Murdoch University Energy Research Institute, Murdoch, WA
Australia.
Reference 2: Manwell, J., et al., 'Hybrid2 User's Guide Theory
Manual', Golden CO: NREL"
"
FUNCTION: Interpolate inverter efficiency value given efficiencies at
3 points on output curve "
Function InvEff(Load_Inv, MinLodEf, MinLod, MaxEfLod,
MaxEff,RatedLod,RatedEff)
If (Load_Inv < MinLod) Then "load is below cut-in for inverter"
InvEff := 0
Else
If (Load_Inv < MaxEfLod) Then
InvEff := MinLodEf+(((Load_Inv-MinLod)/(MaxEfLod-
MinLod))**(1/(Load_Inv**.5))*(MaxEff-MinLodEf))
Else
InvEff := MaxEff +((Load_Inv-MaxEfLod)/(RatedLod-MaxEfLod))*(RatedEff-
MaxEff)
EndIf
EndIf
```

```
end
"
FUNCTION: Interpolate rectifier efficiency value given efficiencies at
3 points on output curve "
Function RectEff(Load_T, MinLodEf, MinLod, MaxEfLod,
MaxEff,RatedLod,RatedEff)
Load_Rect := (-1)*Load_T
If (Load_Rect < MinLod) Then "load is below cut-in for rectifier"
RectEff := 0
Else
"NREL Inverter model"
PinRated :=RatedLod/RatedEff
B := ((RatedLod/RatedEff)-MinLod)/RatedLod
Pin := MinLod+(Load_Rect *B)
RectEff : = Load_Rect/Pin
EndIf
end
"
Inverter Inputs (DC to AC) ________________________________________"
MinInvLodEf =.05
MinInvLod = 1
MaxInvEfLod = 15
MaxInvEff = .90
RatedInvLod = 100
RatedInvEff = .85
InverterEff = InvEff(Load_T, MinInvLodEf, MinInvLod, MaxInvEfLod,
MaxInvEff,RatedInvLod,RatedInvEff)
"
Rectifier Inputs (AC to DC )_______________________________________"
MinRectLodEf =.05
MinRectLod = 2
MaxRectEfLod = 15
MaxRectEff = .92
RatedRectLod = 100
RatedRectEff = .96
RectifierEff = RectEff(Load_T, MinRectLodEf, MinRectLod, MaxRectEfLod,
MaxRectEff,RatedRectLod,RatedRectEff)
"
NREL Inverter Model _______________________________________________"
Load_Test=(-1)*Load_T
NRELEff = RectEff(Load_Test, MinInvLodEf, MinInvLod, MaxInvEfLod,
MaxInvEff,RatedInvLod,RatedInvEff)
```

Wind Turbine Model

```
"Input Data Stream ________________________________________________"
Hour = hr_t "parametric in prototype"
Wind = W_t "parametric in prototype"
alpha = alpha_t "parametric in prototype"
Temp = Temp_t "parametric in prototype"
Press = Press_t "parametric in prototype"
"
Parameter Data ___________________________________________________"
Input.units = 1 "SI"
Output.units = 1 "SI"
```

```
Rotor.diameter = 40 "meters"
Rotor.center.height = 40 "meters"
Site.elev = 500  "meters"
Site.data.height = 3 "meters"
Power.curve.mode = 1 "calls external file"
Air.density.mode = 1 "rho = rho(t)"
Wind.shear.mode = 1 " alpha = alpha(t)"
Air.density.curve = 1.23
"
Air Density Function _______________________________________________"
T_o = 288.16 "reference sea level temperature-deg. K"
B = 0.0065 "lapse rate-K/m"
g = 9.80665 "gravitational constant-m/s2"
R = 287 "gas constant for air-kJ/kgK"
p_stp = 101350 "stp pressure-kPa"
T_elev = Temp_t+273
"T_elev = Temp_t-B*Z_elev -temperature as a function of elevation, not
used in this example"
p_elev = p_stp*(1-(B*Site.elev)/T_o)^gamma; gamma =g/(R*B) "pressure
as a function of elevation"
rho_t = p_elev/(R*T_elev) "ideal gas law"
"
Shear Function _____________________________________________________"
W_hub = W_t*(Rotor.center.height/Site.data.height)^alpha
Speedup = W_hub /(W_t+.000001)
W_hub_SI = W_hub/2.237
"
Power Output function _______________________________________________"
Power = (rho_t/Air.density.curve)*lookup(((W_hub_SI)), #Acme500)
Power_fixedrho = lookup(((W_hub_SI)), #Acme500)
Power_delta = Power_fixedrho - Power
```

Rayleigh Function Model

```
"Rayleigh Probability Function Demonstration
Power_hh=lookup(U_hh, #Col2) "U_hh is parametric"
Duplicate i=5, 9; Ubar_hh[i] = i
Prob_hh[i]=((pi*U_hh)/(2*Ubar_hh[i]^2))*exp((-
pi*U_hh^2)/(4*Ubar_hh[i]^2))
End
```

Shear Sensitivity Analysis

```
"Wind Shear Power Law Exponant Sensitivity Analysis
Rayleigh Probability Function
"Input Assumptions __________________________________________________"
Z_hh in parametric table
Z_tmy in parametric table
Ubar in parametric table"
"Average Power =f(power-curve, mean-wind, hub-ht., sensor-ht., and
alpha)___"
```

```
N = 25 "m/s bins"
Ubar_hh = Ubar*(Z_hh/Z_tmy)^alpha "power law model for avg. wind speed
at hub height"
Duplicate i=1, N " for each wind speed integer"
U_tmy[i]=i " wind speed = index"
U_hh[i]=U_tmy[i]*(Z_hh/Z_tmy)^alpha "power law model for wind speed at
hub height"
Prob_hh[i]=((pi*U_hh[i])/(2*Ubar_hh^2))*exp((pi*(-
1)*U_hh[i]^2)/(4*Ubar_hh^2)) "Rayleigh function"
Power_hh[i]=lookup(U_hh[i], #Col2) "power curve"
End
Power_avg=sum(Power_hh[i]*Prob_hh[i],i=1,N) "weighted avg. power
calculation"
```

Thrust Coefficient Polynomial

```
"Polynomial Fit of CT to CP"
"
Equations from Wilson and Lissaman _________________________________"
C_p = 4*a*(1-a)^2 "from Wilson and Lissaman"
C_T = 4*a*(1-a) "from Wilson and Lissaman"
C_T_analytic = C_p/(1-a) "analytic solution for Ct = f(Cp)"
"
Polynomial Fit _____________________________________________________"
CT_poly =-1.453989e-2+1.473506*C_p-2.330823*C_p^2+3.885123*C_p^3
Residual = (CT_poly-C_T_analytic )/C_T_analytic
```

Wake Turbulence Model

```
"Wake Turbulence Model
"
fit ____________________________________________________________"
Delta1=0.1465587 -5.956977e-2 * ln(x\x)
"model _________________________________________________________"
Delta2=1/7*(1 -2/5* ln(x\x))
```

Wind Turbine Cluster

```
"Calculates the power output for each wind turbine in a fixed cluster
of wind turbines, as a function of wind speed and direction.
"
"Tables:
Lookup table: X,Y locations, and turbine performance data for four
turbines.
Array: t = turbine t, d = downwind turbine.
Parametric table: each run increments direction by 10 degrees, and
each column is a WT's wind speed."
"
Assumptions:
```

```
kW, meters, radii, radian measurement system used
Single free stream wind velocity (currently).
Wind direction, thetaRad, measured clockwise from '0 = Northeasterly'
direction.
Linear turbine performance model used to calculate thrust
coefficients."
"
Nomenclature:
Cs = crosswind transformed coordinates
D = distance between Rw and Rr
Dn = downwind transformed coordinates
Prated = nominal rating of generator
Rw = total wake radius
rrw = local wake radius
Rr = total rotor radius
theta = free-stream wind direction in degrees
thetaRad = free-stream wind direction in radians
Vcutin = lowest windspeed at which turbine produces energy
Vcutout = high wind speed at which turbine shuts down due to loads
Vo = free-stream wind speed
Vrated = wind speed at which the turbine generator operates at nominal
rating
X = physical east-west location of turbine, increasing to the east.
Y = physical north-south location of turbine, increasing to north"
"
FUNCTION: Interpolate power curve numbers _________________________"
Function WTPower(w,Vcutin,Vrated,Prated,Vcutout)
If (w<Vcutin) Then "Below rated"
WTPower := 0.0
Else
If (w<Vrated) Then "variable output operation"
WTPower := (w-Vcutin)/(Vrated-Vcutin)*Prated
Else
If (w<Vcutout) Then "constant output operation"
WTPower := Prated
Else
WTPower :=0.0 "Above cutout"
EndIf ; EndIf; EndIf;End
"
FUNCTION: Calculate wake radius at downwind distance X ___________"
Function WakeRadius(sigma, Ct, X_o, X)
If (X>X_o) Then "Use UT wake model"
WakeRadius := (abs(2*sigma^2*(X-X_o)^2*ln(4*sigma^2*(X-
X_o)^2/(1000*Ct))))^.5
Else
WakeRadius := 0 "no negative wakes"
EndIf; End
"
PROCEDURE: Map coordinate transformations to wind direction ______"
Procedure CoordTrans(X,Y,thetaRad: D,C) "ref: CRC Handbook"
thetaRad~ := thetaRad +(pi/2) "Using RADIANS, convert N convention to
X,Y data convention"
D := X*cos(thetaRad~)-Y*sin(thetaRad~) " note: northeasterly = FROM
North"
C := X*sin(thetaRad~)+Y*cos(thetaRad~); End
"
PROCEDURE: Offset Coordinates to first number quadrant ___________"
```

```
Procedure
Offset(D~[1],D~[2],D~[3],D~[4],C~[1],C~[2],C~[3],C~[4]:D'[1],D'[2],
D'[3],D'[4],C'[1],C'[2],C'[3],C'[4])
D_min1 := min(D~[1],D~[2]) "kludge to find min of 5 terms"
D_min2 := min(D~[3],D~[4]);
D_min := min(D_min1,D_min2)
C_min1 := min(C~[1],C~[2]) "kludge to find min of 5 terms"
C_min2 := min(C~[3],C~[4]);
C_min := min(C_min1,C_min2)
D_offset := 0-D_min; C_offset := 0-C_min
Duplicate j = 1,4
C'[j] :=  C~[j]+C_offset
D'[j] := D~[j]+D_offset
End; End
"
FUNCTION: Calculate wake-reduced wind speed deficit at rotor ______"
Function V_delta(Rw,Rr,D,Vo,Ct,sigma,X_o,X)
If (abs(D) > (Rw+Rr)) Then  "no intersection"
V_delta := 0
Else  "+++++++++++++++++++++++++"
V_deltai :=(Ct/(4*sigma^2*(X-X_o)^2))*exp(-(D+Rr)^2/(2*sigma^2*(X-
X_o)^2))
V_deltac :=(Ct/(4*sigma^2*(X-X_o)^2))*exp(-D^2/(2*sigma^2*(X-X_o)^2))
V_deltao :=(Ct/(4*sigma^2*(X-X_o)^2))*exp(-(D-Rr)^2/(2*sigma^2*(X-
X_o)^2))
V_delta := V_deltac {(V_deltai + V_deltac + V_deltac + V_deltao)/4}
EndIf;End
"
FUNCTION: Separation distance between wake and down wind rotor ____"
Function Separation(CrossRad_t, CrossRad_d, DownRad_t, DownRad_d,
HeightRad_t, HeightRad_d)
If (DownRad_t >DownRad_d) Then
Separation :=((CrossRad_t-CrossRad_d)^2+(HeightRad_t-
HeightRad_d)^2)^.5
Else
Separation := 9999
EndIf; end
"
FUNCTION: Intercept test and distance calculation _________________"
Function Intercept(WakeRad, DistApart) "radii"
If (WakeRad <> 9999) Then
IntercepTest := (WakeRad+1) - DistApart
If (IntercepTest > 0) Then
Intercept :=IntercepTest
Else
Intercept := 0.
EndIf
Else
Intercept := 0.
EndIf; End
"
FUNCTION: Calculate Final Wind Speed by Multiplying Deficits ______"
Function Vfinal(Vo, Vdelta1, Vdelta2, Vdelta3, Vdelta4) "wake
superposition"
Vfinal = Vo*(1-Vdelta1)*(1-Vdelta2)*(1-Vdelta3)*(1-Vdelta4)
end
"
```

```
Input values ______________________________________________________"
N =4 "number of turbines"
Vo = 6 "m/s set in table"
rho = 1.225 "air density"
sigma_u  = .12 " axial turbulence intensity -from data"
sigma = sigma_u "inferred lateral turbulence intensity-for wake
calculations"
"
Read in turbine data parameters __________________________________"
thetaRad = theta*pi/180
Duplicate t = 1,N
X[t] = lookup(t,#X-position) "meters"
Y[t] = lookup(t,#Y-position) "meters"
Hub[t] = lookup(t,#HubHeight) "meters"
Dia[t] = lookup(t,#Diameter) "meters"
Vcutin[t] = lookup(t,#Vcut-in) "meters"
Vrated[t] = lookup(t,#Vrated) "meters"
Prated[t] = lookup(t,#Prated) "kW"
Vcutout[t] = lookup(t,#Vcut-out) "meters"
End
"
Transform X' and Y' to Crosswind and Downwind Coordinates ________"
Duplicate u = 1,N
Call CoordTrans(X[u],Y[u],thetaRad:D~[u],C~[u])
End
Call
Offset(D~[1],D~[2],D~[3],D~[4],C~[1],C~[2],C~[3],C~[4]:Dn[1],Dn[2],
Dn[3],Dn[4],Cs[1],Cs[2],Cs[3],Cs[4])
"
Turbine spatial data _____________________________________________"
Duplicate t = 1,4
WtArea[t] = (pi/4)*Dia[t]^2 "m2"
WtRad[t]=1 "definition"
DownRad[t] = 2*Dn[t]/Dia[t] "downwind location of turbine"
CrossRad[t] = 2*Cs[t]/Dia[t]
HeightRad[t] = 2*Hub[t]/Dia[t]
"
Thrust coefficient estimation ____________________________________"
WindPower[t] = (rho*WtArea[t]*Vo^3)/1000 "kW"
WTOutput[t] = (rho/1.225)*WTPower(Vo,
Vcutin[t],Vrated[t],Prated[t],Vcutout[t]) "kW"
Cp[t] = WTOutput[t]/WindPower[t]
Ct[t] = 8.006291e-2+7.676590*Cp[t]-31.94685*Cp[t]^2+65.78295*Cp[t]^3-
50.23620*Cp[t]^4
End
"
Turbine cross wind separation distance estimation (radii) _________"
Duplicate t = 1,4
Duplicate d = 1,4
Separation[t,d] = Separation(CrossRad[t], CrossRad[d], DownRad[t],
DownRad[d], HeightRad[t], HeightRad[d])
End; End
"
Wake location estimation (radii)___________________________________"
Duplicate t = 1,4
Duplicate d = 1,4
WakeRad[t,d] = WakeRadius(sigma, Ct[t], DownRad[d], DownRad[t])
```

```
End; End
"
Calculate wind speed deficit in wake at distance downwind and radius
and r"
Duplicate t = 1,4
Duplicate d = 1,4
Vdelta[t,d] =
V_delta(WakeRad[t,d],WtRad[t],Separation[t,d],Vo,Ct[t],sigma,DownRad[d
], DownRad[t])
End; End
"
Overall wind speed at turbine location including all wakes ________"
Duplicate t = 1,4
Vfinal[t]= Vfinal(Vo, Vdelta[t,1], Vdelta[t,2], Vdelta[t,3],
Vdelta[t,4]) "wake superposition"
End
"
Wind Turbine kW at turbine location _______________________________"
Duplicate t = 1,4
WTkW[t] = (rho/1.225)*WTPower(Vfinal[t],
Vcutin[t],Vrated[t],Prated[t],Vcutout[t]) "kW"
End
"
Wind Cluster kW  _________________________________________________"
Duplicate t = 1,4
WtkWatVo[t] = (rho/1.225)*WTPower(Vo,
Vcutin[t],Vrated[t],Prated[t],Vcutout[t]) "kW"
End
ClusterkWatVo = sum(WtkWatVo[t], t = 1,4)
ClusterkWatVfinal = sum(WTkW[t], t = 1,4)

ClusterEff = 100*ClusterkWatVfinal/ClusterkWatVo
```

ACME500 WT Lookup

```
WindSpeed[m/s] PowerOutput[kW]

0 0.00
1 0.00
2 0.00
3 0.00
4 0.00
5 30.13
6 60.33
7 124.12
8 178.80
9 231.81
10 294.41
11 350.00
12 405.00
13 448.00
14 474.00
15 490.00
16 497.00
```

```
17 500.00
18 500.00
19 500.00
25 500.00
26 0.00
```

Line Cluster Lookup

WT #	X-pos. [m]	Y-pos. [m]	HubHeight [m]	Dia. [m]	Vcut-in [m/s]	Vrated [m/s]	Prated [kW]	Vcut-out [m/s]
1.0	0	0	25.3	26	5.0	15.6	275.0	23.0
2.0	0	78	25.3	26	5.0	15.6	275.0	23.0
3.0	0	156	25.3	26	5.0	15.6	275.0	23.0
4.0	0	234	25.3	26	5.0	15.6	275.0	23.0

Random Cluster Lookup

WT #	X-pos. [m]	Y-pos. [m]	HubHeight [m]	Dia. [m]	Vcut-in [m/s]	Vrated [m/s]	Prated [kW]	Vcut-out [m/s]
1.0	0	0	25.3	26	5.0	15.6	275.0	23.0
2.0	78	26	25.3	26	5.0	15.6	275.0	23.0
3.0	130	26	25.3	26	5.0	15.6	275.0	23.0
4.0	78	78	25.3	26	5.0	15.6	275.0	23.0

Symmetric Cluster Lookup

WT #	X-pos. [m]	Y-pos. [m]	HubHeight [m]	Dia. [m]	Vcut-in [m/s]	Vrated [m/s]	Prated [kW]	Vcut-out [m/s]
1.0	0	0	25.3	26	5.0	15.6	275.0	23.0
2.0	130	0	25.3	26	5.0	15.6	275.0	23.0
3.0	0	130	25.3	26	5.0	15.6	275.0	23.0
4.0	130	130	25.3	26	5.0	15.6	275.0	23.0

APPENDIX B

TRNSYS TYPES

TRNSYS Type 70: Storage Battery

TRNSYS Type 71: Power Converter

TRNSYS Type 85: Wind Turbine

TRNSYS Type 90: Diesel Engine

TRNSYS Type 92: Diesel Dispatcher

TRNSYS Type 70: Storage Battery

```
      SUBROUTINE TYPE70(TIME,XIN,OUT,T,DTDT,PAR,INFO,ICNTRL,*)
C
******************************************************************************
**
C  * TYPE 70: STORAGE BATTERY
*
C  *
*
C  * THIS TYPE 70 COMPONENT SIMULATES THE PERFORMANCE OF A LEAD-ACID
*
C  * STORAGE BATTERY. THE BASIC BATTERY MODEL IS THE MODEL RECOMMENDED IN THE
*
C  * BEST REPORT (THE HYMAN MODEL).  IT IS THE SHEPHERD MODEL MODIFIED BY
*
C  * THE ADDITION OF A ZIMMERMAN-PETERSEN DIODE IN BOTH THE CHARGE AND
*
C  * DISCHARGE EQUIVALENT CIRCUITS.IT IS DESIGNED TO OPERATE IN CONJUNCTION
*
C  * WITH A SOLAR CELL ARRAY AND A REGULATOR.
*
C  *
*
C  * THE MODEL HAS BEEN MODIFIED TO INCLUDE TEMPERATURE AND OVERCHARGING
*
C  * EFFECTS, BASED ON THE CLC MODEL FROM CIEMAT
*
C  *
*
C  * Last update August 1, 1996 by P.Quinlan, Solar Energy Lab-UW
*
C  *
*
C
******************************************************************************
**
C
C   Description of Parameters
*****************************************************
C
C   Q = STATE OF CHARGE [AH]
C   QM = RATED CAPACITY OF CELL [AH]
C   QC,QD = CAPACITY PARAMETERS ON CHARGE, DISCHARGE
C   F = FRACTIONAL STATE OF CHARGE = Q/QM (1.0 IS FULL CHARGE)
C   CP,CS = NUMBER OF CELLS IN PARALLEL, SERIES
C   P = POWER [WATTS]
C   IQ = CURRENT [AMPS]
C   IQMAX,IQMIN = MAXIMUM CURRENT (CHARGE), MINIMUM CURRENT (DISCHARGE)
C   V = VOLTAGE [VOLTS]
C   VC,IC = CUTOFF VOLTAGE ON CHARGE, CURRENT CORRESPONDING TO VC
C   ICTOL = PARAMETER FOR ITERATIVE CALCULATIONS
C   VD = CUTOFF VOLTAGE ON DISCHARGE
C   ED,RD = DATA USED TO CALCULATE VD WHEN VCONTR .LT. 0.
C   VCONTR =  SPECIFICATION OF VOLTAGE CONTROL ON DISCHARGE.
C   POSITIVE MEANS VD=VCONTR.  NEGATIVE MEANS VD=ED-ABS(IQ)*RD.
C   VDI = DIODE VOLTAGE FROM Z-P MODEL
C   VOC = OPEN CIRCUIT VOLTAGE AT FULL CHARGE
C   ESC,ESD = EXTRAPOLATED OPEN CIRCUIT VOLTAGES
C   GC,GD = COEFFICIENTS OF (1-F)IN V FORMULAS
C   RSC,RSD = INTERNAL RESISTANCES AT FULL CHARGE
C   MC,MD = CELL TYPE PARAMETERS WHICH DETERMINE THE SHAPES OF THE
```

```
C   I-V-Q CHARACTERISTICS
C   ICOUNT=COUNTS THE NUMBER OF ITERATIONS INVOLVED IN OBTAINING IC
C
      DIMENSION
     +    DTDT(1),       INFO(15),       OUT(9),       PAR(21),
     +    T(1),          XIN(2)
      DOUBLE PRECISION
     +    I1,           ICTOL,           IQ,           K1,
     +    MC,           MD,             I10,           Vc,
     +    zeta,          Vec,            DT,           Vg,
     +    Temp
C****************************************************************
      DOUBLE PRECISION XIN,OUT
      COMMON/SIM/ TIME0,TFINAL,DELT,IWARN
      COMMON/STORE/NSTORE,IAV,STORE(5000)
      INTEGER*4 INFO
C--------------------------------------------------------
C**** Initialization--first call of component
      IF (INFO(7).LT.0) THEN
  INFO(9)=1
  INFO(6)=9
  INFO(10)=1
  CALL TYPECK (1,INFO,2,21,1)
  RETURN 1
      ENDIF
  INDEX=INFO(10)
C****   Set parameters
  QM=PAR(1)
  CP=PAR(2)
  CS=PAR(3)
  EFF=PAR(4)
  VC=PAR(5)
  VCONTR=PAR(6)
  IF (VCONTR.GT.0) THEN
    VD=VCONTR
C****     Check on minimum discharge voltage
    IF (VD.GT.2.5.OR.VD.LT.1.5) CALL TYPECK (-4,INFO,0,0,0)
  ENDIF
  ICTOL=PAR(7)
  ESC=PAR(8)
  ESD=PAR(9)
  GC=PAR(10)
  GD=PAR(11)
  MC=PAR(12)
  MD=PAR(13)
  ED=PAR(14)
  RD=PAR(15)
  I1=PAR(16)
  K1=PAR(17)
  QC=PAR(18)
  QD=PAR(19)
  RSC=PAR(20)
  RSD=PAR(21)
C****   Check on maximum charge voltage
      IF (VC.GT.2.8.OR.VC.LT.1.8) CALL TYPECK (-4,INFO,0,0,0)
      IF(TIME.EQ.TIME0) STORE(INDEX)=T(1)
      IF(INFO(7).EQ.0) THEN
C****   computation of state of charge of battery from
C****   the previous time step
  Q=STORE(INDEX)
  F=Q/QM
  H=1.-F
      ENDIF
```

```
C****   set inputs
  IQ=XIN(1)
C****   current for one cell
  IQ=min(QM,(IQ/CP))
C****   temperature correction
        Temp=XIN(2)
        DT= Temp-25
        I10 = QM/10
C----------------------------------------------------------
C**** first and following calls in time step
C****   Modified Shepherd Model
  VOC=(ESC+ESD)/2.
  IF (IQ.GE.0.) THEN
C****     Charging
C----------------------------------------------------------
C***      adjust charge voltage to account for high overcharge, per CLC
          zeta = 17.3/(1+852*(abs(IQ/QM))**1.67)
          Vec  = (2.45+2.011*dlog(1+(abs(IQ))/QM))*(1-0.002*DT)
          Vg   = (2.24+1.970*dlog(1+(abs(IQ))/QM))*(1-0.002*DT)
          Vc   = Vg+(Vec-Vg)*(1-dexp(min(1,(abs(Q)-0.95*QM))))/
     +           (abs(IQ)*zeta)
C----------------------------------------------------------
          VDI=1./K1*ALOG(IQ/I1+1.)
    V=VOC+VDI-GC*H+Vc                          !modified per clc
C   V=VOC+VDI-GC*H+IQ*RSC*(1.+MC*H/(QC/QM-H))   !old model
    BB=IQ*EFF
    AA=0.
  ELSE
C****     Discharging
C----------------------------------------------------------
C****     adjust discharge capacity parameter by temperature,per CLC
          QD = QM*(1.67*(1.005*DT))/(1+1.065*(abs(IQ/QM)*0.9))
C----------------------------------------------------------
          VDI = 1./K1*DLOG(-IQ/I1+1.)
    V = VOC-VDI-GD*H+IQ*RSD*(1.+MD*H/(QD/QM-H))
    BB = IQ
    AA = 0.
  ENDIF
  CALL DIFFEQ(TIME,AA,BB,Q,Q1,QBAR)
C----------------------------------------------------------
      STORE(INDEX)=Q1
      P=IQ*V
C**** Output
      OUT(1)=Q1
      OUT(2)=Q1/QM
      OUT(3)=P*CP*CS
      OUT(4)=0.
      IF (P.GT.0.) OUT(4)=(1.-EFF)*P*CP*CS
      OUT(5)=IQ*CP
      OUT(6)=V*CS
      IF (VCONTR.LT.0.) VD=ED-ABS(IQ)*RD
      OUT(7)=VD*CS
      OUT(8)=VC*CS
      RETURN 1
      END
```

TRNSYS Type 71: Power Converter

```
      SUBROUTINE TYPE71(TIME,XIN,OUT,T,DTDT,PAR,INFO,ICNTRL,*)
C
******************************************************************************
**
C  * TYPE 71: Parametric Power Converter
*
C  *
*
C  * This TYPE 71 Power Converter is both a rectifier and an inverter. The
*
C  * rectifier uses the linear model used by NREL, and the inverter uses a
*
C  * modified Jennings model.
*
C  *
*
C  * The converter reads in minimum input, maximum efficiency, maximum
*
C  * output, and efficiency at maximum output. It then builds a math model of
*
C  * efficiency as a function of input/output. Model developed for TYPE 71 is
a   *
C  * modified version of Phillips et al model published in the reference
below.   *
C  * Improvements include variable decay and minimum load offset feature.
*
C  *
*
C  * Reference: Jennings, S.U., T.L. Pryor and D.P. Remmer, "RESIM: A
Simulation  *
C  * Program for Determining the Viability of Renewable Power Supply Systems",
*
C  * Murdoch University Energy Research Institute, Murdoch, WA 6150,
Australia.   *
C  * Journal of the International Solar Energy Society, draft manuscript no.
*
C  * 96-04-12-1894.
*
C  *
*
C  * Last update August 1, 1996 by P.Quinlan, Solar Energy Lab-UW
*
C  *
*
C
******************************************************************************
**
C
C  EXAMPLE INVERTER PARAMETERS
****************************************************
C
C  1      !time step, in fraction of hours
C  50     !Minimum rectifier load kW (ie., input at zero output)
C  20     !Minimum rectifier efficiency (percent)
C  96     !Maximum rectifier efficiency (percent)
C  1000   !Maximum continuous rectifier output to load
C  86     !Rectifier efficiency at maximum output to load
C  50     !Minimum inverter load kW (ie., input at zero output)
C  20     !Minimum inverter efficiency (percent)
```

```
C  96     !Maximum inverter efficiency (percent)
C  1000   !Maximum continuous inverter output to load
C  86     !Inverter efficiency at maximum output to load
C  1      !Control switch: 1 = on, 0 = off

*Declare TRNSYS Variables **********************************
       DOUBLE PRECISION XIN,OUT
       INTEGER*4 INFO
       DIMENSION XIN(1),OUT(4),PAR(12),INFO(15)
*Declare Type 77 Variables *********************************
       Double Precision step,MinLod,Minef,Maxef,MaxLod,MaxLodEf,InPwr,
     + decay,P,Pmin,ef,Powef,OutPwr,WastPwr,OnOff,Load_t,
     + MinRLod,MinRef,MaxRef,MaxRLod,MxRLodEf
       call typeck(1,INFO,1,12,0)
*PARAMETERS ************************************************
       Step      = par(1)
       MinRLod   = par(2)
       MinRef    = par(3)/100
       MaxRef    = par(4)/100
       MaxRLod   = par(5)
       MxRLodEf  = par(6)/100
       MinLod    = par(7)
       Minef     = par(8)/100
       Maxef     = par(9)/100
       MaxLod    = par(10)
       MaxLodEf  = par(11)/100
       OnOff     = par(12)
*INPUTS ****************************************************
       Load_T = XIN(1)  !kWh/hr timestep energy demanded by load
*CALCULATIONS **********************************************
       If (OnOff.lt.1.0) then
    ef      = 0.0
    InPwr   = 0.0
    OutPwr  = 0.0
    WastPwr = 0.0
   else if (Load_T.lt.0) then !rectifier
      Load_T= -Load_T
      If (Load_T.le.MinRLod) then
         ef  = 0.0
         InPwr   = MinRLod/MinREf
         OutPwr  = MinRLod
         WastPwr = InPwr-OutPwr
        else if (Load_T.lt.MaxRLod) then
     B = (MaxRlod/MxRLodef-MinRLod)/MaxRlod
     Pin = MinRLod+Load_T*B
     ef = max(0,(Load_T/Pin))
     InPwr   = Load_T/ef
     OutPwr  = Load_T
     WastPwr = InPwr-OutPwr
    else
       ef = MxRLodef
       InPwr  = MaxRLod/MxRLodef
       OutPwr = MaxRLod
       WastPwr = InPwr-OutPwr
      endif
   else If (Load_T.eq.0.0) then
      ef  = 0.0
      InPwr   = 0.00
      OutPwr  = 0.0
      WastPwr = 0.0
     else if (Load_T.le.MinLod) then !Inverter
        ef  = 0.0
        InPwr   = MinLod/Minef
```

```
         OutPwr  = MinLod
         WastPwr = InPwr-OutPwr
        else if (Load_T.lt.MaxLod) then
    Pmin = MinLod/MaxLod
    P = Load_T/MaxLod
    decay = (Maxef*(1-exp(-29*(1-Pmin)))-MaxLodEf)/(1-Pmin)
    ef = max(0,(Maxef*(1-exp(-29*(P-Pmin)))-decay*(P-Pmin)))
    Powef   = max(Minef,ef)
    InPwr   = Load_T/Powef
    OutPwr  = Load_T
    WastPwr = InPwr-OutPwr
          else
      ef  = MaxLodEf
      InPwr   = MaxLod/MaxLodEf
      OutPwr  = MaxLod
      WastPwr = InPwr-OutPwr
         end if
        deficit = max(0,abs(load_T-OutPwr))
*OUTPUTS ***************************************************
        OUT(1) = ef       !percent
        OUT(2) = InPwr    !kWh/hr
        OUT(3) = OutPwr   !kWh/hr
        OUT(4) = WastPwr  !kWh/hr
        OUT(5) = deficit  !kWh/hr

        RETURN 1
        END
```

TRNSYS Type 85: Wind Turbine

```
      SUBROUTINE TYPE85(TIME,XIN,OUT,T,DTDT, PAR,INFO,ICNTRL,*)
C  ***********************************************************************
C  *  TYPE 85: WIND TURBINE GENERATOR                                     *
C  *                                                                      *
C  *  This TYPE 85 calculates the power output of a wind turbine generator *
C  *  based on data from a table of power versus wind speed. The type     *
C  *  models the impacts of air density changes and wind speed increases  *
C  *  with height.                                                        *
C  *                                                                      *
C  *  Last update August 1, 1995, by P. Quinlan, Solar Energy Lab-UW      *
C  *                                                                      *
C  ***********************************************************************
C
C  EXAMPLE WECS DATA FILE *************************************************
C
C  Data files read by this type are space delimited text files with
C  the following format. There should be information in every field.
C
C  File_Nam BWC10KW.PWR    DOS file name
C  Test_Ref Brochure       Source of data
C  Rotor_Ht   30.00        Rotor center height, meters
C  Rotor_Di    1.00        Rotor diameter, meters
C  Sensr_Ht   30.00        Sensor Height for data, meters
C  Sher_Exp    0.14        Power-law exponant for speed-up calculation
C  Turb_Int    0.10        Turbulence intensity valid for this curve
C  Air_Dens    1.22        Power curve air density, kg/m3
C  Len_Unit       m        Length unit, m
C  Spd_Unit     m/s        Wind speed units m/s
C  Pwr_Unit     m/s        Power output units, kW
C  Ctl_mode       S        Control mode: S=stall; P=pitch; V=variable speed
C  Pwr_Ratd   10.00        Rated power of the turbine, kW
C  Spd_Ratd   12.00        Wind speed at rated power, m/s
C  Num_Pair      99        * The number of power vs. windspeed pairs
C      2.59    0.00        * power vs. windspeed pair no.1 -start at zero
C      3.31    0.21        * power vs. windspeed pair no.2
C      3.85    0.43        * power vs. windspeed pair no.2
C       ""      ""         ""
C       ""      ""         ""
C       ""      ""         ""
C     99.00    3.34        * power vs. windspeed pair no.N (100 pairs maximum)
C
*DECLARE TRNSYS VARIABLES ************************************************
      DOUBLE PRECISION XIN, OUT
      REAL T,DTDT,PAR
      INTEGER INFO, ICNTRL
      DIMENSION XIN(4),OUT(4),T(1),PAR(8),INFO(15)
*DECLARE TYPE 85 VARIABLES
*************************************************
      CHARACTER dum*8,File_Nam(60)*11,Test_Ref(60)*8,Spd_Unit(60)*3,
     +          Ctl_mode(60),Len_Unit(60)*3,Pwr_Unit(60)*2
      DOUBLE PRECISION Pwr_Ratd(60),Spd_Ratd(60),PC(60,100,2),Area,
     +                 Site_elv,Site_Ht,TimeStp,SiteRoHt,Lost,Num,
     +                 PWTIdeal,PWTNet,Cp,pi,PWECS,B,Bp_T,Bp_stp,
     +                 Rotor_Ht(60),Rotor_Di(60),Sensr_Ht(60),Pden,
     +                 Turb_Int(60),Air_Dens(60),Sher_Exp(60),alpha_T
      INTEGER Mode,Num_Pair(60),LU,q
*PARAMETERS **************************************************************
      Mode = PAR(1)              !0 = off, 1 = on
      Site_Elv = PAR(2)          !Site elevation, meters
```

```
       Site_Ht = PAR(3)           !Site data collection height, meters
       TimeStp = PAR(4)           !TimeStep used for energy calculations
       SiteRoHt = PAR(5)          !Hub height of WECS, as installed on site
       Lost = PAR(6)              !Miscellaneous losses
       Num = PAR(7)               !Number of exactly similar turbines
       LU = int(par(8)+.001)      !data file of power curve used
       PI = 3.412
*IS UNIT OFF? **************************************************************
       If (Mode.eq.0) then        !Unit is off
    OUT(1) = 0.0
    OUT(2) = 0.0
    OUT(3) = 0.0
    RETURN 1
       endif
*INPUTS ********************************************************************
       Vel_T   = XIN(1)           !Wind velocity, m/s
       TDB_T   = XIN(2)/10        !Dry bulb temperature*10, deg.C
       alpha_T = XIN(3)           !Site shear exponent, alpha
       BP_T    = XIN(4)           !Site barometric pressure,Pa
*AIR DENSITY AT HUB HEIGHT *************************************************
       T_STD = 288.16             !Standard reference temperature, deg.C
       B = 0.0065                 !Standard elevation lapse rate deg.C/m
       G = 9.8066                 !Gravitational constant
       R = 287.0                  !Universal gas constant
       BP_STP = 101350            !Standard sea-level pressure,Pa
       GAMMA = G/(R*B)            !Lapse Rate Manipulation
       T_ELV=TDB_T+273.15         !Convert temperatures to absolute, deg.K
       If(BP_T.lt.10000.0) then   !Not using real-time data; use model
    BP_T = BP_STP*(1-(B*Site_elv/T_STD))**GAMMA
       EndIf
       RHO_T = BP_T/(R*T_ELV)
*CORRECT SITE WIND SPEED TO ROTOR CENTER HEIGHT ****************************
       If (alpha_T.gt.1.0) then   !Not using real-time data: use model
   alpha_T = 1.0/7.0
       EndIf
       V_Hub = Vel_T*(SiteRoHt/Site_Ht)**alpha_T
*UNIT DETERMINATION (HANDLES MULTIPLE UNITS OF THIS TYPE) ******************
       If (info(7).eq.-1) then
        Do 17 k = 1,60
    If (k.eq.Info(1)) then
      q =int(k+.001)
      goto 18
    endif
 17          continue
 18       continue
*BACKSPACE (FOR CASE WHEN MORE THAN ONE ACCESS TO FILE) ********************
    Do L = 1,200
       backspace(LU)
    End do
*READ IN THE FILE DATA *****************************************************
    Read(lu,10) dum, File_Nam(q)
    Read(lu,13) dum, Test_Ref(q)
    Read(lu,11) dum, Rotor_Ht(q)
    Read(lu,11) dum, Rotor_Di(q)
    Read(lu,11) dum, Sensr_Ht(q)
    Read(lu,11) dum, Sher_Exp(q)
    Read(lu,11) dum, Turb_Int(q)
    Read(lu,11) dum, Air_Dens(q)
    Read(lu,14) dum, Len_Unit(q)
    Read(lu,14) dum, Spd_Unit(q)
    Read(lu,14) dum, Pwr_Unit(q)
    Read(lu,14) dum, Ctl_Mode(q)
    Read(lu,11) dum, Pwr_Ratd(q)
```

```
   Read(lu,11) dum, Spd_Ratd(q)
   Read(lu,12) dum, Num_Pair(q)
 10       Format (A8,1X,A11)
 11       Format (A8,1X,D7.2)
 12       Format (A8,1X,I7)
 13       Format (A8,1X,A8)
 14       Format (A8,1X,A5)
   Do 5 i = 1,Num_Pair(q)
       read(lu,*) PC(q,i,1),PC(q,i,2)
    5     continue
   endif
   Do L = 1,200
      backspace(LU)
   end do
   q = int(Info(1)+.001)
*POWER CALCULATION ****************************************
*Correct Power Curve Wind Speeds to Rotor Center Height _____________________
   If (Sensr_Ht(q).ne.Rotor_Ht(q)) then
     do 20 j=1,Num_Pair(q)
        PC(q,j,1) = PC(q,j,1)*(Rotor_Ht(q)/Sensr_Ht(q))
    +                     **Sher_Exp(q)
 20         continue
   endif
*Wind Turbine Output at Hub Height,Wind Speed _______________________________
   IF (V_Hub.LT.PC(q,1,1)) THEN
      PWECS = 0                    !Power is zero when winds are calm
   ELSEIF (V_HUB.LE.PC(q,Num_Pair(q),1)) THEN
      J=1
  15         IF (PC(q,J,1).LE.V_HUB) THEN  !Find first PCWIND<WIND
   J=J+1
   GO TO 15
      Endif
      PWECS = PC(q,(J-1),2)+(V_Hub-PC(q,(J-1),1))*(PC(q,J,2)-
    +        PC(q,(J-1),2))/(PC(q,J,1)-PC(q,(J-1),1)) !Linear interpolation
   ELSEIF (V_HUB.GT.PC(q,Num_Pair(q),1)) THEN
      PWECS = PC(q,Num_Pair(q),2)
   ENDIF
*Wind Turbine Output Corrected for Site Air Density _________________________
   PWECS = PWECS*RHO_T/Air_Dens(q)
   NEWVRAT=Spd_Ratd(q)*(RHO_T/Air_Dens(q))**(1.0/3.0)
   IF(Ctl_mode(q).EQ.'P'.OR.Ctl_mode(q).EQ.'p') then  !pitch control
      IF (PWECS.GT.Pwr_Ratd(q)) THEN
        PWECS = Pwr_Ratd(q)
      ELSEIF(V_HUB.GT.NEWVRAT) THEN
        PWECS = Pwr_Ratd(q)
      ELSE
        PWECS = PWECS*RHO_T/Air_Dens(q)
      ENDIF
   ELSE IF(Ctl_mode(q).EQ.'V'.OR. Ctl_mode(q).EQ.'v')  then !var. spd
      IF (PWECS.GT.Pwr_Ratd(q)) THEN
        PWECS = Pwr_Ratd(q)
      ELSE IF(V_HUB.GT.NEWVRAT) THEN
        PWECS = Pwr_Ratd(q)
      ELSE
        PWECS = PWECS*RHO_T/Air_Dens(q)
      ENDIF
   ENDIF                      !stall defaults to simple density ratio
*Hours, Cp, and Adjustments by Number of WTs and by Loss Coefficient *********
  If (PWECS.gt.0) then
     Hours = TimeStp
   Else
     Hours = 0.0
  Endif
```

```
  PWTIdeal = PWECS*Num
  PWTNet = PWTIdeal*(1.0-Lost/100.0)
  Pden   = 0.5*RHO_T*(V_Hub**3.0)
        Area   = (Pi/4.0)*(Rotor_di(q)**2.0)
  Cp     = (1000.0*PWTNet/Num)/(Pden*Area)
*OUTPUTS ***************************************************************
  OUT(1) = PWTNet*TimeStp
  OUT(2) = Hours
  OUT(3) = Cp
  RETURN 1
  END
```

TRNSYS Type 90: Diesel Engine

```
       SUBROUTINE TYPE90(TIME,XIN,OUT,T,DTDT, PAR,INFO,ICNTRL,*)
C
***************************************************************************
**
C  * TYPE 90: DIESEL GENERATOR
*
C  *
*
C  * This TYPE 90 Diesel Generator reads in parameters for a particular
diesel    *
C  * regarding minimum acceptable power, specific fuel consumption at that
power, *
C  * maximum power, specific fuel at that power, and calculates the fuel
*
C  * consumption for the engine at any load. The type outputs fuel
consumption,   *
C  * engine hours and waste heat for the timestep.
*
C  *
*
C  * Last update August 1, 1996    by P.Quinlan, Solar Energy Lab-UW
*
C  *
*
C
***************************************************************************
**
C
C  EXAMPLE DIESEL PARAMETERS
******************************************************
C
C  339.3              !Maximum electric power, kW
C  0.24               !Specific fuel consumption, kg/kWh at max power
C  135.72             !Mininum allowable electric power, kW
C  0.264              !Specific fuel consumption, kg/kWh at min power
C  0.9                !Generator efficiency

*Declare TRNSYS Variables *********************************
        DOUBLE PRECISION XIN,OUT
        REAL T,DTDT,PAR
        INTEGER INFO, ICNTRL
        DIMENSION TIME(1),XIN(1),OUT(5),T(1),PAR(3),INFO(1)
*Declare Type 90 Variables ********************************
        Double Precision MinPwr(40),MinSFC(40),MaxPwr(40),MaxSFC(40),
      +                  GenEff(40),kWh_T,Fuel_T,Hours_T,FulDr_T,TimeStp,
      +                  FuelCst,Load_T,QWast_T
        Integer q
*PARAMETERS ***********************************************
        q = int(Info(1)+.001)
        TimeStp = PAR(1)       !Timestep,fraction of hour,for fuel calcs
        FuelCst = PAR(2)       !Diesel fuel cost,per liter
        MaxPwr(q) = par(3)
        MaxSFC(q) = par(4)
        MinPwr(q) = par(5)
        MinSFC(q) = par(6)
        GenEff(q) = par(7)
*INPUTS ***************************************************
        Load_T = XIN(1)        !Customer load demand,kW
*ENGINE HOURS,ENERGY PRODUCTION,FUEL CONSUMPTION, AND FUEL DOLLARS
```

```
      Hours_T = TimeStp
      SFC_Ful = 0.0857    !kg/kWh of #2 fuel
      Ful_vol = 1.16      !liters per kg of #2 fuel
      If (MaxPwr(q).LE.0.0) then
          Hours_T = 0
          kWh_T   = 0
          Fuel_T  = 0
          QWast_T = 0
       Else IF (Load_T.LE.0) THEN
            Hours_T = 0
            kWh_T   = 0
            Fuel_T  = 0
            QWast_T = 0
         ELSE IF (Load_T.LE.MinPwr(q)) THEN
              kWh_T   = MinPwr(q)*Hours_T
              Fuel_T  = Ful_vol*MinSFC(q)*kWh_T
              Eff_T   = SFC_Ful/MinSFC(q)
              QWast_T = Hours_T*((MinPwr(q)/Eff_T)-MinPwr(q))
           ELSE IF (Load_T.LE.MaxPwr(q)) THEN
                kWh_T   = Load_T*Hours_T
                SFC_T   = MinSFC(q)+((Load_T-MinPwr(q))*(MinSFC(q)
    +                     -MaxSFC(q)))/(MinPwr(q)-MaxPwr(q))
                Fuel_T  = Ful_vol*SFC_T*kWh_T
                Eff_T   = SFC_Ful/SFC_T
                QWast_T = Hours_T*((Load_T/Eff_T)-Load_T)
              ELSE IF (Load_T.GT.MaxPwr(q)) THEN
                   kWh_T   = MaxPwr(q)*Hours_T
                   Fuel_T  = Ful_vol*MaxSFC(q)*kWh_T
                   Eff_T   = SFC_Ful/MaxSFC(q)
                   QWast_T = Hours_T*((MaxPwr(q)/Eff_T)-MaxPwr(q))
      end if
      FulDr_T = FuelCst*Fuel_T
*OUTPUTS ************************************************************
      OUT(1) = kWh_T
      OUT(2) = Hours_T
      OUT(3) = Fuel_T
      OUT(4) = FulDr_T
      OUT(5) = QWast_T
      RETURN 1
      END
```

TRNSYS Type 92: Diesel Dispatcher

```
       SUBROUTINE TYPE92(TIME,XIN,OUT,T,DTDT, PAR,INFO,ICNTRL,*)
*****************************************************************************
***
* TYPE 92: CONTROLLER FOR FIVE ARBITRARY DIESELS, WIND AND PV:QUASI-STEADY
*
*
*
* This TYPE 92 controller is used to manage the operation of a hybrid diesel
*
* wind and PV generator-set. This controller is designed to accept up to five
*
* wind turbine power curves, five sets of diesel parameters, and one PV
*
* input. The controller self programs itself by reading the performance
*
* parameters used by the units with which it is connected. Diesel dispatching
*
* is, in this version, optimized strictly for minimum cost.
*
*
*
 * Last update August 1, 1996    by P.Quinlan, Solar Energy Lab-UW
*
*
*
*****************************************************************************
***
C
C  EXAMPLE DIESEL PARAMETERS
****************************************************
C
C  339.3             !Maximum electric power, kW
C  0.24              !Specific fuel consumption, kg/kWh at max power
C  135.72            !Mininum allowable electric power, kW
C  0.264             !Specific fuel consumption, kg/kWh at min power
C  0.9               !Generator efficiency
C
*Declare TRNSYS Variables ********************************
       DOUBLE PRECISION XIN,OUT
       REAL T,DTDT,PAR
       INTEGER INFO, ICNTRL
       DIMENSION TIME(1),XIN(7),OUT(8),T(1),PAR(4),INFO(1)
*Declare Type 90 Variables ********************************
       Character        DiesNam(5)*20,DataRef(5)*20
       Double Precision MinPwr(5),MinSFC(5),MaxPwr(5),MaxSFC(5),
     +                  GenEff(5),TimeStp,FuelCst,Load_T,FuelTest,
     +                  Eff_Inv,Wir_Los,Wecs_T(5),PPV_T,PDump_T,
     +                  Demand_T,WECSum_T,PStor_T,PPVnet_T,PSysl_T,
     +                  Supply_T,Dump1_T,PGen(5),PDGtest(5),Dump2_T,
     +                  Totdgen
       Integer LU(5),FuelTyp(5),Cheap1,Cheap2,Cheap3,Cheap4,Cheap5
*PARAMETERS *********************************************
       TimeStp = par(1) !Timestep,fraction of hour,for fuel calcs
       FuelCst = par(2) !Diesel fuel cost,per liter
       Eff_inv = par(3) !Inverter efficiency
       Wir_los = par(4) !Wire Loss
       Do i = 1,5
       MaxPwr(i) = par(i*5)
```

```
□       MaxSFC(i) = par(i*5+1)
□       MinPwr(i) = par(i*5+2)
□       MinSFC(i) = par(i*5+3)
□       GenEff(i) = par(i*5+4)
□       end do
□*INPUTS ****************************************************
□       do j = 1,5
□       WECS_T(j) = Xin(j) !WECS #i energy production,kWh/hr
□       end do
□       PPV_T     = Xin(6) !PV energy production,kWh/hr
□       Demand_T  = Xin(7) !Load from demand,kWh/hr
□*RANK DIESELS BY FUEL ECONOMY ************************
□       if(info(7).eq.-1) then
□       CALL Rank(MinSFC,MaxSFC,Cheap1,Cheap2,Cheap3,
□      +               Cheap4,Cheap5)
□       endif
□*CONTROLLER CALCULATIONS ***********************************
□       WECSum_T = 0.0
□       Do i = 1,5
□       WECSum_T = WECSum_T + WECS_T(i)
□       end do
□       PStor_T  = 0                      !No storage
□       PPVnet_T = PPV_T*Eff_inv          !Determine inverter losses
□       PSysL_T  = Demand_T*Wir_los       !Calculate wire losses
□       Demand_T = Demand_T + PSysL_T
□       Supply_T = WECSum_T+PPVnet_T+PStor_T
□       If (Supply_T.gt.Demand_T) then    !Dump energy from oversupply
□        Load_T  = 0.00
□        Dump1_T = Supply_T-Demand_T
□       else
□        Load_T  = Demand_T-Supply_T
□        Dump1_T = 0.00
□       endif
□*DISPATCH DIESELS ******************************************
□       IF(Load_T.le.0.0) then                !zero load
□        Pgen(cheap1)=0.0
□        Pgen(cheap2)=0.0
□        Pgen(cheap3)=0.0
□        Pgen(cheap4)=0.0
□        Pgen(cheap5)=0.0
□       elseif(load_T.lt.MinPwr(cheap1))then  !between zero and min of
cheapest
□        Fuel= MinSFC(cheap1)*MinPwr(cheap1)
□        Pgen(cheap1)=MinPwr(cheap1)
□        Pgen(cheap2)=0.0
□        Pgen(cheap3)=0.0
□        Pgen(cheap4)=0.0
□        Pgen(cheap5)=0.0
□        If(Load_T.le.MaxPwr(cheap2))then     !test second best for fuel
savings
□         IF(Load_t.le.MinPwr(cheap2))then
□          Fueltest= MinSFC(cheap2)*MinPwr(cheap2)
□          Pdgtest(cheap2)=MinPwr(cheap2)
□         else
□          Fueltest= MinSFC(cheap2)*Load_T
□          Pdgtest(cheap2)=Load_T
□         endif
□         If(FuelTest.lt.Fuel)then
□          Fueltest=Fuel
□          Pgen(cheap1)=0.0
□          Pgen(cheap2)=Pdgtest(cheap2)
□          Pgen(cheap3)=0.0
□          Pgen(cheap4)=0.0
```

```
           Pgen(cheap5)=0.0
          endif
          endif
         If(Load_T.le.MaxPwr(cheap3))then     !test third best for fuel
savings
          IF(Load_t.le.MinPwr(cheap3))then
           Fueltest= MinSFC(cheap3)*MinPwr(cheap3)
           Pdgtest(cheap3)=MinPwr(cheap3)
          else
           Fueltest= MinSFC(cheap3)*Load_T
           Pdgtest(cheap3)=Load_T
          endif
          If(FuelTest.lt.Fuel)then
           Fueltest=Fuel
           Pgen(cheap1)=0.0
           Pgen(cheap2)=0.0
           Pgen(cheap3)=Pdgtest(cheap3)
           Pgen(cheap4)=0.0
           Pgen(cheap5)=0.0
          endif
          endif
         If(Load_T.le.MaxPwr(cheap4))then    !test fourth best for fuel
savings
          IF(Load_t.le.MinPwr(cheap4))then
           Fueltest= MinSFC(cheap3)*MinPwr(cheap4)
           Pdgtest(cheap4)=MinPwr(cheap3)
          else
           Fueltest= MinSFC(cheap4)*Load_T
           Pdgtest(cheap4)=Load_T
          endif
          If(FuelTest.lt.Fuel)then
           Fueltest=Fuel
           Pgen(cheap1)=0.0
           Pgen(cheap2)=0.0
           Pgen(cheap3)=0.0
           Pgen(cheap4)=Pdgtest(cheap4)
           Pgen(cheap5)=0.0
          endif
          endif
         If(Load_T.le.MaxPwr(cheap5))then    !test fifth best for fuel savings
          IF(Load_t.le.MinPwr(cheap5))then
           Fueltest= MinSFC(cheap3)*MinPwr(cheap5)
           Pdgtest(cheap5)=MinPwr(cheap5)
          else
           Fueltest= MinSFC(cheap5)*Load_T
           Pdgtest(cheap5)=Load_T
          endif
          If(FuelTest.lt.Fuel)then
           Fueltest=Fuel
           Pgen(cheap1)=0.0
           Pgen(cheap2)=0.0
           Pgen(cheap3)=0.0
           Pgen(cheap4)=0.0
           Pgen(cheap5)=Pdgtest(cheap3)
          endif
          endif
        elseif(load_T.le.MaxPwr(cheap1))then  !cheapest operation
         Pgen(cheap1)=Load_T
         Pgen(cheap2)=0
         Pgen(cheap3)=0
         Pgen(cheap4)=0
         Pgen(cheap5)=0
        elseif(load_T.le.(MaxPwr(cheap1)+MinPwr(cheap2)))then
```

```
         Pgen(cheap1)=Load_T-MinPwr(cheap2)    !mixing to meet load
         Pgen(cheap2)=MinPwr(cheap2)
         Pgen(cheap3)=0
         Pgen(cheap4)=0
         Pgen(cheap5)=0
        elseif(load_T.le.(MaxPwr(cheap1)+MaxPwr(cheap2)))then
         Pgen(cheap1)=MaxPwr(cheap1)           !second cheapest
         Pgen(cheap2)=Load_T-MaxPwr(cheap1)
         Pgen(cheap3)=0
         Pgen(cheap4)=0
         Pgen(cheap5)=0
        elseif(load_T.le.(MaxPwr(cheap1)+MaxPwr(cheap2)+MinPwr(cheap3)))
     +  then                                   !mixing to meet load
         Pgen(cheap1)=MaxPwr(cheap1)
         Pgen(cheap2)=Load_T-(MaxPwr(cheap1)+MinPwr(cheap3))
         Pgen(cheap3)=MinPwr(cheap3)
         Pgen(cheap4)=0
         Pgen(cheap5)=0
        elseif(load_T.le.(MaxPwr(cheap1)+MaxPwr(cheap2)+MaxPwr(cheap3)))
     +  then                                   !third cheapest
         Pgen(cheap1)=MaxPwr(cheap1)
         Pgen(cheap2)=MaxPwr(cheap2)
         Pgen(cheap3)=Load_T-(MaxPwr(cheap1)+MaxPwr(cheap2))
         Pgen(cheap4)=0
         Pgen(cheap5)=0
        elseif(load_T.le.(MaxPwr(cheap1)+MaxPwr(cheap2)+MaxPwr(cheap3)+
     +  MinPwr(cheap4)))then                   !mixing to meet load
         Pgen(cheap1)=MaxPwr(cheap1)
         Pgen(cheap2)=MaxPwr(cheap2)
         Pgen(cheap3)=Load_T-(MaxPwr(cheap1)+MaxPwr(cheap2)+
     +   MinPwr(cheap4))
         Pgen(cheap4)=MinPwr(cheap4)
         Pgen(cheap5)=0
        elseif(load_T.le.(MaxPwr(cheap1)+MaxPwr(cheap2)+MaxPwr(cheap3)+
     +  MaxPwr(cheap4)))then                   !fourth cheapest
         Pgen(cheap1)=MaxPwr(cheap1)
         Pgen(cheap2)=MaxPwr(cheap2)
         Pgen(cheap3)=MaxPwr(cheap3)
         Pgen(cheap4)=Load_T-(MaxPwr(cheap1)+MaxPwr(cheap2)+
     +   MaxPwr(cheap3))
         Pgen(cheap5)=0
        elseif(load_T.le.(MaxPwr(cheap1)+MaxPwr(cheap2)+MaxPwr(cheap3)+
     +  MaxPwr(cheap4)+MinPwr(cheap5)))then    !mixing to meet load
         Pgen(cheap1)=MaxPwr(cheap1)
         Pgen(cheap2)=MaxPwr(cheap2)
         Pgen(cheap3)=MaxPwr(cheap3)
         Pgen(cheap4)=Load_T-(MaxPwr(cheap1)+MaxPwr(cheap2)+
     +   MaxPwr(cheap3)+MinPwr(cheap5))
         Pgen(cheap5)=MinPwr(cheap5)
        elseif(load_T.le.(MaxPwr(cheap1)+MaxPwr(cheap2)+MaxPwr(cheap3)+
     +   MaxPwr(cheap4)+MaxPwr(cheap5)))then    !fifth cheapest
         Pgen(cheap1)=MaxPwr(cheap1)
         Pgen(cheap2)=MaxPwr(cheap2)
         Pgen(cheap3)=MaxPwr(cheap3)
         Pgen(cheap4)=MaxPwr(cheap4)
         Pgen(cheap5)=Load_T-(MaxPwr(cheap1)+MaxPwr(cheap2)+
     +   MaxPwr(cheap3)+MaxPwr(cheap4))
        elseif(load_T.gt.(MaxPwr(cheap1)+MaxPwr(cheap2)+MaxPwr(cheap3)+
     +   MaxPwr(cheap4)+MaxPwr(cheap5)))then    !overload
         Pgen(cheap1)=MaxPwr(cheap1)
         Pgen(cheap2)=MaxPwr(cheap2)
         Pgen(cheap3)=MaxPwr(cheap3)
         Pgen(cheap4)=MaxPwr(cheap4)
```

```
         Pgen(cheap5)=MaxPwr(cheap5)
        endif
*FINAL DUMP ENERGY CALCULATION ****************************
        TotDgen = 0.0
        do i = 1,5
        TotDgen = TotDgen + Pgen(i)       !Total diesel output
        end do
        Dump2_T = max(0,TotDgen - Load_T) !Dump from diesel over-output
        PDump_T = Dump1_T + Dump2_T       !Total dump energy
*OUTPUTS ********************************************
        OUT(1) = Pgen(1)
        OUT(2) = Pgen(2)
        OUT(3) = Pgen(3)
        OUT(4) = Pgen(4)
        OUT(5) = Pgen(5)
        OUT(6) = TotDgen
        OUT(7) = PDump_T
        OUT(8) = PSysL_T
        RETURN 1
        END
*****************************************************
*RANKING SUBROUTINE ***************************************
*       Ranks the indices of five sets of SFC values in ascending order
*
        SUBROUTINE Rank(min,max,Cheap1,Cheap2,Cheap3,Cheap4,Cheap5)
*
        double precision min(5),max(5),val(5),valtot,temp
        integer Cheap1,Cheap2,Cheap3,Cheap4,Cheap5
*
        Do 5 i = 1,5
        val(i) = (min(i)+max(i))/2
 5      continue
*
        valtot = 2*(val(1)+val(2)+val(3)+val(4)+val(5))
        Do 10 j = 1,5
           If(val(j).eq.(Dmin1(val(1),val(2),val(3),val(4),val(5)))) then
               cheap1 = j
               temp   = val(j)+valtot
               exit
           endif
 10     continue
        val(cheap1) = temp          !force to end of the que
        Do 20 k = 1,5
           If(val(k).eq.(dmin1(val(1),val(2),val(3),val(4),val(5))))then
               cheap2 = k
               temp   = val(k)+valtot
               exit
           endif
 20     continue
        val(cheap2) = temp          !force to end of the que
        Do 30 l = 1,5
           If(val(l).eq.(dmin1(val(1),val(2),val(3),val(4),val(5))))then
               cheap3 = l
               temp   = val(l)+valtot          !force to end of the que
               exit
           endif
 30     continue
        val(cheap3) = temp
        Do 40 m = 1,5
           If(val(m).eq.(dmin1(val(1),val(2),val(3),val(4),val(5))))then
               cheap4 = m
               temp = val(m)+valtot          !force to end of the que
               exit
```

```
           end if
 40     continue
        val(cheap4) = temp
        Do 50 n = 1,5
           If(val(n).eq.(dmin1(val(1),val(2),val(3),val(4),val(5))))then
               cheap5 = n
               exit
               end if
 50     continue

        return
        end
```

APPENDIX C

TRNSYS DECKS

Diesel Engine Performance Demonstrator

Diesel Dispatch Demonstrator

Power Converter Demonstrator

Storage Battery Demonstrator

Wind Turbine Demonstrator

UW-Hybrid 1.0

Diesel Engine Performance Demonstrator

```
*TRNSED
ASSIGN \Hybrid\Decks\Diesel.LST   6
□ASSIGN \Hybrid\Decks\Diesel.OUT  11
□
□WIDTH 120
□
□*|* _______________________________________________
□*|* Diesel Engine Performance Model
□*|* Type 90 Demonstrator
□*|*
□*|* University of Wisconsin  Solar Energy Laboratory
□*|*
□*|* Date:                |Aug 1, 1996
□*|* Prepared by:         |Patrick Quinlan
□*|*
□*|* _______________________________________________
□*|*
□
□Equations 8
□MaxPwr = 15.0
□*|< Diesel Generator:       |\hybrid\Diesels\Diesel.dat|2|3|99
□*|*
□Fuelcost =  2.0000E-0001
□*| Diesel Costs per Liter:  |$/liter|$/liter|0.0|0.0|0.0|1.0|99
□MaxSFC = .29
□*|<                         |\hybrid\Diesels\Diesel.dat|0|4|99
□MinPwr = 6.0
□*|<                         |\hybrid\Diesels\Diesel.dat|0|5|99
□MinSFC = .32
□*|<                         |\hybrid\Diesels\Diesel.dat|0|6|99
□GenEff = .90
□*|<                         |\hybrid\Diesels\Diesel.dat|0|7|99
□LOAD_T = time/10
□step = 1.0
□
□equations = 2
□maxplot = MaxPwr*3.0
□maxlen = MaxPwr*11.0
□
□SIMULATION 1 maxlen 1.0
□
□UNIT 19 TYPE 90 DIESEL ENGINE
□PARAMETERS 7
□*TIMESTP FUELCOST/LI MaxPwr MaxSFC MinPwr MinSFC GenEff
□ step    Fuelcost    MaxPwr MaxSFC MinPwr MinSFC GenEff
□INPUTS 1
□LOAD_T
□1
□
□UNIT 20 TYPE 25 HOURLY PRINTER
□PARAMETERS 4
□1 1 8760 11
□INPUTS 5
□19,1 19,2 19,3 19,4 19,5
□Diesel Hours Fuel Dollars Waste
□
□
□UNIT 21 TYPE 65 ONLINE PLOTTER
□*PRINT WIND AND POWER
□PARAMETERS 14
```

```
3 2 0 Maxplot 0 Maxplot 1 1 3 1 6 1 2 0
INPUTS 5
*kWh  Hours Fuel Dollars Waste
 19,1   19,2  19,3 19,4    19,5
 Diesel hours fuel Dollars Waste
LABELS 4
units units
kWh,_Hours,_and_Fuel
Dollars_and_Waste_Heat

END
```

Diesel Dispatch Demonstrator

```
*TRNSED
ASSIGN \Hybrid\Decks\Dispatch.LST    6
□ASSIGN \Hybrid\Decks\Dispatch.OUT   11
□
□*|* _________________________________________________________
□*|* Diesel Dispatch Controller Model
□*|* Type 92 Demonstrator
□*|*
□*|* University of Wisconsin  Solar Energy Laboratory
□*|*
□*|* Date:                  |Aug 1, 1996
□*|* Prepared by:           |Patrick Quinlan
□*|* _________________________________________________________
□
□WIDTH 120
□
□EQUATIONS 13
□Demand = time
□*|*
□*|* RENEWABLE GENERATORS AND SYSTEM EFFICIENCY _________
□*|*
□TotWind =  0.0000E+0000
□*| Constant Wind Power:                    |kW|kW|0.0|1|0.0|5000|99
□TotPV =  0.0000E+0000
□*| Constant PV Power:                      |kW|kW|0.0|1|0.0|5000|99
□Eff =  1.0000E+0002
□*| Inverter Efficiency:                    |percent|percent|0.0|1|0.0|100|99
□Wir =  0.0000E+0000
□*| Wire Losses:                            |percent|percent|0.0|1|0.0|100|99
□Eff_Inv = Eff/100
□WirLos =  Wir/100
□W1 = TotWind/5
□W2 = TotWind/5
□W3 = TotWind/5
□W4 = TotWind/5
□W5 = TotWind/5
□PV = TotPV
□
□*|*
□*|* DIESEL GENERATORS ____________________________________
□*|*
□Equations 6
□Fuelcost=  2.0000E-0001
□*| Diesel Fuel Costs per Liter:            |$/liter|$/liter|0.0|0.0|0.0|1.0|99
□MaxPwr1= 2.3
□*|< Diesel Generator No.1:                 |\hybrid\Diesels\Diesel1.dat|2|3|99
□MaxSFC1= .35
□*|<                                        |\hybrid\Diesels\Diesel1.dat|0|4|99
□MinPwr1= .90
□*|<                                        |\hybrid\Diesels\Diesel1.dat|0|5|99
□MinSFC1= .39
□*|<                                        |\hybrid\Diesels\Diesel1.dat|0|6|99
□GenEff1= .90
□*|<                                        |\hybrid\Diesels\Diesel1.dat|0|7|99
□Equations 5
□MaxPwr2= 16.4
□*|< Diesel Generator No.2:                 |\hybrid\Diesels\Diesel2.dat|2|3|99
□MaxSFC2= .28
□*|<                                        |\hybrid\Diesels\Diesel2.dat|0|4|99
□MinPwr2= 6.6
```

```
*|<                                    |\hybrid\Diesels\Diesel2.dat|0|5|99
MinSFC2= .31
*|<                                    |\hybrid\Diesels\Diesel2.dat|0|6|99
GenEff2= .90
*|<                                    |\hybrid\Diesels\Diesel2.dat|0|7|99
Equations 5
MaxPwr3= 100.0
*|< Diesel Generator No.3:             |\hybrid\Diesels\Diesel3.dat|2|3|99
MaxSFC3= .33
*|<                                    |\hybrid\Diesels\Diesel3.dat|0|4|99
MinPwr3= 40.0
*|<                                    |\hybrid\Diesels\Diesel3.dat|0|5|99
MinSFC3= .37
*|<                                    |\hybrid\Diesels\Diesel3.dat|0|6|99
GenEff3= .90
*|<                                    |\hybrid\Diesels\Diesel3.dat|0|7|99
Equations 5
MaxPwr4= 161.1
*|< Diesel Generator No.4:             |\hybrid\Diesels\Diesel4.dat|2|3|99
MaxSFC4= .23
*|<                                    |\hybrid\Diesels\Diesel4.dat|0|4|99
MinPwr4= 64.4
*|<                                    |\hybrid\Diesels\Diesel4.dat|0|5|99
MinSFC4= .25
*|<                                    |\hybrid\Diesels\Diesel4.dat|0|6|99
GenEff4= .90
*|<                                    |\hybrid\Diesels\Diesel4.dat|0|7|99
Equations 5
MaxPwr5= 252.9
*|< Diesel Generator No.5:             |\hybrid\Diesels\Diesel5.dat|2|3|99
MaxSFC5= .21
*|<                                    |\hybrid\Diesels\Diesel5.dat|0|4|99
MinPwr5= 101.2
*|<                                    |\hybrid\Diesels\Diesel5.dat|0|5|99
MinSFC5= .23
*|<                                    |\hybrid\Diesels\Diesel5.dat|0|6|99
GenEff5= .90
*|<                                    |\hybrid\Diesels\Diesel5.dat|0|7|99
*|*

equation 1
maxlen = 1.10*(MaxPwr1+MaxPwr2+MaxPwr3+MaxPwr4+MaxPwr5+TotWind+TotPV)
SIMULATION 1 maxlen 1.0

UNIT 22 TYPE 92 DIESEL ENGINE CONTROLLER
PARAMETERS 29
*TIMESTP FUELCOST/LI Eff_Inv WirLos
1.0      FuelCost    Eff_Inv WirLos
MaxPwr1 MaxSFC1 MinPwr1 MinSFC1 GenEff1
MaxPwr2 MaxSFC2 MinPwr2 MinSFC2 GenEff2
MaxPwr3 MaxSFC3 MinPwr3 MinSFC3 GenEff3
MaxPwr4 MaxSFC4 MinPwr4 MinSFC4 GenEff4
MaxPwr5 MaxSFC5 MinPwr5 MinSFC5 GenEff5
INPUTS 7
W1 W2 W3 W4 W5 PV Demand
3. 3. 3. 3. 3. 3. 10.0


UNIT 20 TYPE 25 HOURLY PRINTER
PARAMETERS 4
1 1 8760 11
INPUTS 7
DEMAND 22,1 22,2 22,3 22,4 22,5 22,6
```

```
Demand DSL1 DSL2 DSL3 DSL4 DSL5 TOT Fuel

equations 1
tot = [22,1]+[22,2]+[22,3]+[22,4]+[22,5]

UNIT 21 TYPE 65 ONLINE PLOTTER
*PRINT DIESEL OPERATION
PARAMETERS 14
5 2 0 Maxlen 0 Maxlen 1 1 3 1 7 1 2 0
INPUTS 7
*DSL1  DSL2  DSL3  DSL4  DSL5  TOT     DEMAND
 22,1  22,2  22,3  22,4  22,5  tot     Demand
 DSL_1 DSL_2 DSL_3 DSL_4 DSL_5 DSL_TOT DEMAND
LABELS 4
KW KW
DIESELS 1,2,3,4,5
TOTAL DIESEL,DEMAND

END
```

Power Converter Demonstrator

```
ASSIGN \Hybrid\Decks\Convrtr.LST    6
ASSIGN \Hybrid\Decks\Convrtr.OUT   11
ASSIGN \Hybrid\Decks\Convrtr.PLT   14

WIDTH 120

*|* _______________________________________________
*|* Power Converter Model
*|* Type 71 Demonstrator
*|*
*|* University of Wisconsin  Solar Energy Laboratory
*|*
*|* Date:        |May 26, 1996
*|* Prepared by: |Patrick Quinlan
*|*
Equations 17
InvType = 19
*|< Converter:       |\hybrid\Storage\ACDC.dat|2|1|99
MinRLod = .13
*|<             |\hybrid\Storage\ACDC.dat|0|3|99
MinREf = 20
*|<                  |\hybrid\Storage\ACDC.dat|0|4|99
MaxREf = 95
*|<                  |\hybrid\Storage\ACDC.dat|0|5|99
MaxRLod = 4.0
*|<                  |\hybrid\Storage\ACDC.dat|0|6|99
MxRLodEf = 85
*|<                  |\hybrid\Storage\ACDC.dat|0|7|99
MinLod = .13
*|<             |\hybrid\Storage\ACDC.dat|0|8|99
MinEf = 20
*|<                  |\hybrid\Storage\ACDC.dat|0|9|99
MaxEf = 95
*|<                  |\hybrid\Storage\ACDC.dat|0|10|99
MaxLod = 4.0
*|<                  |\hybrid\Storage\ACDC.dat|0|11|99
MaxLodEf = 85
*|<                  |\hybrid\Storage\ACDC.dat|0|12|99
OnOf = 1
*|<                  |\hybrid\Storage\ACDC.dat|0|13|99
Step = 1
plotlo = (-1*(MaxRLod/(MxRLodEf/100))*1.1)
plotht = (MaxLod/(MaxLodEf/100))*1.1
plotlen = (MaxRLod*100+MaxLod*100)*1.1
Load = (time/100)-MaxRLod*1.1

SIMULATION 0 plotlen 1.0

UNIT 33 TYPE 71 Power Converter
PARAMETERS 12
Step MinRLod MinREf MaxREf MaxRLod MxRLodEf
MinLod  MinEf  MaxEf  MaxLod  MaxLodEf OnOf
INPUTS 1
Load
 1.0

UNIT 19 TYPE 25 HOURLY PRINTER
PARAMETERS 4
1 1 8760 11
INPUTS 6
```

```
load  33,2     33,3     33,4    33,5     33,1
Load  InptPwr  OutPwr  WastPwr  Deficit  Eff

UNIT 20 TYPE 25 HOURLY PLOTTER
PARAMETERS 4
1 1 8760 14
INPUTS 6
load  33,2     33,3     33,4    33,5     33,1
Load  InptPwr  OutPwr  WastPwr  Deficit  Eff

UNIT 21 TYPE 65 ONLINE PLOTTER
PARAMETERS 14
5 1 plotlo plotht -.25 1.0 1 1 3 1 6 1 2 0
INPUTS 6
load  33,2     33,3     33,4    33,5     33,1
Load  Input  Output  Wasted  Deficit  Efficncy
Labels 4
a
b
Power_(kW)
Efficiency_(fraction)

END
```

Storage Battery Demonstrator

```
ASSIGN  \HYBRID\DECKS\BATTERY.LST                    6
ASSIGN  \HYBRID\DECKS\BATTERY.OUT                   11
ASSIGN  \HYBRID\DECKS\BATTERY.PLT                   12
WIDTH   120
*|* _______________________________________________
*|* Battery Performance Model
*|* Type 70 Demonstrator
*|*
*|* University of Wisconsin Solar Energy Laboratory
*|* Last Revision: August 1, 1996 by Patrick Quinlan
*|*
*|* Date:                   |August 1, 1996
*|* Prepared by:            |Patrick Quinlan
*|*
*|* Load Specification ___________________________________
*|*
EQUATIONS   4
LoLod = -1.0
*|< Load Profile:              |\hybrid\storage\demolod.dat|2|3|99
HiLod = 1.0
*|<                            |\hybrid\storage\demolod.dat|0|4|99
Rating =  1.0000E+0001
*| Maximum Load:               |Amps|Amps|0.0|1.0|0.0|100000|99
BatTemp =  2.5000E+0001
*| Battery Temperature:        |deg.C|deg.C|0.0|1.0|0.0|100000|99
EQUATIONS   8
minLod = Rating*min(LoLod,HiLod)
maxLod = Rating*max(LoLod,Hilod)
simlen = 2*rating
plothiL = maxlod*1.1
plotloL = min(0,(minLod*1.1))
plotloR = -5.0
plothiR = 5.0
cur = rating*LoLod+HiLod*Time
SIMULATION         0.000E+00    2.000E+01    1.000E+00
*|*
*|* Battery Specification ________________________________
*|*
Equations 21
QM=  1.7000E+0002
*| Battery Capacity:           |Ah|Ah|0.0|1.0|0.0|100000|99
CP= 1.0
*|< Battery Type:              |\hybrid\storage\bat.dat|2|3|99
CS= 1.0
*|< Cells in series:                    |\hybrid\storage\bat.dat|0|4|99
EFF= 1.0
*|< Efficiency of battery:              |\hybrid\storage\bat.dat|0|5|99
VC= 2.3
*|< Cutoff voltage on charge:           |\hybrid\storage\bat.dat|0|6|99
VCONTR= -1.0
*|< Discharge voltage control:          |\hybrid\storage\bat.dat|0|7|99
ICTOL= .01
*|< Iteration Parameter:                |\hybrid\storage\bat.dat|0|8|99
ESC= 2.25
*|< Extrapolated open circuit voltage:  |\hybrid\storage\bat.dat|0|9|99
ESD= 2.1
*|< Extrapolated open circuit voltage:  |\hybrid\storage\bat.dat|0|10|99
GC= .08
*|< GC coefficient in V formulas:       |\hybrid\storage\bat.dat|0|11|99
```

```
GD= .08
*|< GD coefficient in V formulas:       |\hybrid\storage\bat.dat|0|12|99
MC= .864
*|< MC coefficient in V formulas:       |\hybrid\storage\bat.dat|0|13|99
MD= 1.0
*|< MD cell type parameter:             |\hybrid\storage\bat.dat|0|14|99
ED= 1.8
*|< ED cell type parameter:             |\hybrid\storage\bat.dat|0|15|99
RD= .0024
*|< Rd data used when VCONTR < 0        |\hybrid\storage\bat.dat|0|16|99
I1= 2.5
*|< I1 data used when VCONTR < 0        |\hybrid\storage\bat.dat|0|17|99
K1= 29.3
*|< K1 data used when VCONTR < 0        |\hybrid\storage\bat.dat|0|18|99
QC=-0.035*QM
QD=QM/0.85
*capacity parameters on charge/discharge
RSC=3/QM
RSD=0.5/QM
*|*
*************************************************************************
UNIT 4 TYPE 70 Battery
Parameters 7
QM  CP  CS  EFF  VC  VCONTR  ICTOL
Parameters 7
ESC  ESD  GC  GD  MC  MD  ED
Parameters 7
RD  I1  K1  QC  QD  RSC  RSD
Inputs 2
* Cur BatTemp
  cur BatTemp
  -2  25
DERIVA 1
115
*************************************************************************
UNIT 19  TYPE 25  Plotting Data
PARAMETERS   4
1.000E+00    1.000E+00    8.760E+03    1.200E+01
INPUTS  7
4,1 4,5 4,3 4,4   4,2 4,6  4,7
Q   IB  P   PLOSS F   VBAT VD


UNIT 20     TYPE 25     HOURLY PRINTER
PARAMETERS   4
1.000E+00    1.000E+00    8.760E+03    1.100E+01
INPUTS  7
4,1 4,5 4,3 4,4   4,2 4,6  4,7
Q   IB  P   PLOSS F   VBAT VD


UNIT 21     TYPE 65     ONLINE PLOTTER
PARAMETERS  14
4 3 plotloL plothiL plotloR plothiR 1 1 3 1 6 1 2 0
INPUTS 7
4,1 4,5 4,3 4,4   4,2 4,6  4,7
Q   IB  P   PLOSS F   VBAT VD
LABELS 4
A
B
Q,Ibat,P,Ploss______________
F,Vbat,Vd_________________
```

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```
END
```

Wind Turbine Demonstrator

```
ASSIGN \Hybrid\Decks\wecs.LST    6
ASSIGN \Hybrid\Decks\wecs.OUT   11
Assign \HYBRID\WECS\JAC2KW.PWR  41
Assign \HYBRID\WECS\JAC3KW.PWR  42
Assign \HYBRID\WECS\WIS3KW.PWR  43
Assign \HYBRID\WECS\BWC10KW.PWR 44
Assign \HYBRID\WECS\JAC10KW.PWR 45
Assign \HYBRID\WECS\JAC20KW.PWR 46
Assign \HYBRID\WECS\AOC1550.PWR 47
Assign \HYBRID\WECS\AWT275.PWR  48
Assign \HYBRID\WECS\MHI275.PWR  49
Assign \HYBRID\WECS\CAR300.PWR  50
Assign \HYBRID\WECS\MHI300.PWR  51
Assign \HYBRID\WECS\VSTSV90.PWR 52
*Assign \HYBRID\WECS\TACK600.PWR 53

SIMULATION 0 30 1.0
WIDTH 80

*|* _______________________________________________
*|* Wind Turbine Performance Model
*|* Type 85 Demonstrator
*|*
*|* University of Wisconsin  Solar Energy Laboratory
*|*
*|* Date:            |August 1, 1996
*|* Prepared by:     |Patrick Quinlan
*|*
EQUATIONS 10
lu = 51
*|< Wind Energy System:  |\hybrid\WECS\WECS.dat|2|3|99
*|*
*|* Parameters _____________________________________
*|*
RatedPwr = 300.0
*|<                      |\hybrid\WECS\WECS.dat|0|6|99
HubHt =  2.6000E+0001
*| Hub Height:           |meters|feet|0.0|3.281|0.0|100.0|99
Alpha =  1.4000E-0001
*| Wind Shear Exponent:  |alpha| |0.000|0.000|-1.000|1.000|99
temp =  1.8000E+0001
*| Temperature:          |deg.C|deg.C|0|0.0|1.0|50.0|0
SiteElev =  2.5500E+0002
*| Site Elevation:       |meters|feet|0.0|3.281|-1000.0|10000.0|99
DataHt =  2.6000E+0001
*| Data Height:          |meters|feet|0.0|3.281|0.0|1000.0|99
Lost =  0.0000E+0000
*| Power Losses:         |percent|percent|0.0|1.0|0.0|100.0|99
WIND = time
plotht = RatedPwr*1.10

equations 2
alpha_t = 1.0
Bp = 1.0

UNIT 23 TYPE 85 Wind Turbine Generator
PARAMETERS 8
*Mode ELEV  DATAHT TimeStep HUBHT Lost Num PowerCurveLU
 1 SiteElev DATAHT 1.0      HubHt Lost 1.0 lu
```

```
INPUTS 4
*WND TDB  alpha_T BP
WIND temp alpha_T BP
 9.0 25.0   2.0   1.0

UNIT 20 TYPE 25 HOURLY PRINTER
PARAMETERS 4
1 1 8760 11
INPUTS 2
23,1 23,2
WECS HOURS

UNIT 21 TYPE 65 ONLINE PLOTTER
*PRINT WIND AND POWER
PARAMETERS 14
1 1 0 plotht 0 .6 1 1 3 1 6 1 2 0
INPUTS 2
*WECS
 23,1 23,3
Turbine Cp
LABELS 4
A
B
Power Output
Power Coefficient

END
```

UW-Hybrid 1.0

```
*TRNSED
ASSIGN \Hybrid\Decks\UWhybrid.LST   6
ASSIGN \Hybrid\Decks\UWhybrid.PLT  12
ASSIGN \Hybrid\Decks\UWhybrid.HIS  13
ASSIGN \Hybrid\Decks\UWhybrid.OUT  14
ASSIGN \Hybrid\Decks\WECS.OUT      15
ASSIGN \Hybrid\Decks\Econ.OUT      16
ASSIGN \Hybrid\Decks\Misc.OUT      17
Assign \HYBRID\WECS\WIS3KW.PWR     41
Assign \HYBRID\WECS\BWC10KW.PWR    42
Assign \HYBRID\WECS\JAC20KW.PWR    43
Assign \HYBRID\WECS\AOC1550.PWR    44
Assign \HYBRID\WECS\AWT275.PWR     45
*Assign \HYBRID\WECS\CAR300.PWR    46
*Assign \HYBRID\WECS\KVS33.PWR     47
*Assign \HYBRID\WECS\VSTSV90.PWR   48
*|* __________________________________________
*|* UW-HYBRID Wind/PV/Diesel Simulator
*|* Version 1.0
*|* University of Wisconsin  Solar Energy Laboratory
*|*
*|* Date:              |Feb 19, 1996
*|* Name of system:    |Micro-utility simulation
*|* Input Prepared by:|Patrick Quinlan
*|*
*|* SIMULATION PARAMETERS ____________________________
*|*
EQUATIONS 10
MONTH= 5088
*|< Month of the Simulation:           |\hybrid\Month1.dat|1|2|0
DAY1 =  2.9000E+0001
*| Day of Month for Simulation Start:  |||0|1|1|31|0
DAY = MONTH/24+DAY1
STEP =  1.0000E+0000
*| Timestep for Simulation:            |hour|hour|0|1|0.1|1.0|0
length = 1
*|< Length of Simulation:              |\hybrid\Length.dat|2|1|0
plotday = 7
*|< Plotting Period:                   |\hybrid\plotlen.dat|2|3|99
onplots = max(1,(length/plotday))
START = 24*(DAY-1)+1
STOP = START+LENGTH*24
WEEKS = INT(LENGTH/7+1)
*|*
SIMULATION START STOP STEP
WIDTH 132
LIMITS 50 50
TOLERANCES .01 .01

*|* WEATHER AND LOAD PROFILES  _______________________
*|*
ASSIGN \HYBRID\LOADS\WEPCO3.LOD 11
*|< Load Profile:                      |\hybrid\loads\Loads.dat|2|4|99
EQUATIONS 5
MAXPLT = 300
*|<                                    |\hybrid\loads\Loads.dat|0|3|99
DemFlag = 1
*|<                                    |\hybrid\loads\Loads.dat|0|5|99
Demand = [10,1]/step*DemFlag
```

```
Maxplt1 = max(1,maxplt)
MAXPLT2 = MAXPLT1*STEP*(STOP-START)
ASSIGN \HYBRID\WEATHER\WEPCOWE.THR 10
*|< Weather Profile:                    |\hybrid\weather\Weather.dat|2|4|99
Equations 1
Lat = 44.0
*|<                                     |\hybrid\weather\Weather.dat|0|3|99

*|*
*|* STORAGE ___________________________________________________
*|*
EQUATIONS 3
StorType = 2
*|< Storage Type:                       |\hybrid\storage\storage.dat|2|1|99
ChgCtl = 1
*|< Charge Control Mode:                |\hybrid\storage\ChgCtl.dat|2|3|99
StorCap =  0.0000E+0000
*| Total Storage Capacity:              |kWh|kWh|0.0|1.0|0.0|1000000|99
*|*
*|* POWER CONDITIONING ________________________________________
*|*
equations 6
InvType = 20
*|< Power Conditioner:                  |\hybrid\Storage\ACDC.dat|2|1|99
InvPar =  3.0000E+0000
*| Number of Units:                     |units|units|0.0|1.0|0.0|100000|99
wire =  0.0000E+0000
*| Wire Losses:                         |percent|percent |0.0|1.0|0.0|100.0|99
Invrtr = 93
Eff_inv = Invrtr/100.0
WirLos = wire/100.0

*|*
*|* PV ARRAY __________________________________________________
*|*
Equations 23
MODE = 2.0
pvnumb = 2
*|< PV Module Model:                    |\Hybrid\PV\PVMODUL2.DAT|2|1|0
SunRef= 1000.0
*|<                                     |\Hybrid\PV\PVMODUL2.DAT|0|3|0
Tcref = 298.0
*|< PV Module Model:                    |\Hybrid\PV\PVMODUL2.DAT|0|4|0
Iscref = 1.8
*|< PV Module Model:                    |\Hybrid\PV\PVMODUL2.DAT|0|5|0
Vocref = 55.5
*|< PV Module Model:                    |\Hybrid\PV\PVMODUL2.DAT|0|6|0
Imref = 1.32
*|< PV Module Model:                    |\Hybrid\PV\PVMODUL2.DAT|0|7|0
Vmref= 38.0
*|< PV Module Model:                    |\Hybrid\PV\PVMODUL2.DAT|0|8|0
Misc = 0.0015
*|< PV Module Model:                    |\Hybrid\PV\PVMODUL2.DAT|0|9|0
Mvoc = -0.19425
*|<                                     |\Hybrid\PV\PVMODUL2.DAT|0|10|0
T_a = 0.9
*|<                                     |\Hybrid\PV\PVMODUL2.DAT|0|11|0
EQ = 1.155
*|<                                     |\Hybrid\PV\PVMODUL2.DAT|0|12|0
NCS = 66.0
*|<                                     |\Hybrid\PV\PVMODUL2.DAT|0|13|0
WID = 0.8
*|<                                     |\Hybrid\PV\PVMODUL2.DAT|0|14|0
```

```
LEN = 1.525
*|<                                    |\Hybrid\PV\PVMODUL2.DAT|0|15|0
PV_On = 1.0
*|<                                    |\Hybrid\PV\PVMODUL2.DAT|0|16|0
NM = 1.0
NP =  4.9180E+0003
*| Number of Modules in Array:         |modules|modules|0|1|0|10000|108
Ns = Nm +.0001
DINRG = 100
* DINRG is the dynamic range required by the PV_TYPE
U_L = 10.0
beta =  9.0000E+0001
*| Array Tilt ( 0 = horizontal):       |degrees|degrees|0.0|1.0|0.0|90.0|99
gamma =  0.0000E+0000
*| Array Azimuth ( S=0, E="-", W="+"): |degrees|degrees|0.0|1.0|-90.0|90.0|99
*|*
EQUATIONS 2
PPV_T = 0.005*PV_On*MAX(0,[62,6])
WIND = [9,7]

*Inputs ***************************************************************
UNIT 9 TYPE 9 TMY WEATHER DATA READER
PARAMETERS 2
*MODE LU
 1    10
UNIT 10 TYPE 99 LOADS DATA READER
PARAMETERS 11
* MODE NUMVALS DT LOAD * + dUM * + LU FRMT
   -2     2     1   -1 1 0  -1 1 0 11 0
*OUTPUTS: 1)Demand

*Solar PV System ******************************************************

UNIT 16 TYPE 16 SOLAR RADIATION PROCESSOR
PARAMETERS 9
*RADMODE TRACKMOD N     LAT SC    SHFT SMOOTH IE
 7.      1.       1. 1. LAT 4871. 0.   2.     -1
INPUTS 7
*I  Idn  td1  td2  rhog beta gamma
 9,4 9,3 9,19 9,20 0,0  beta gamma
 0.  0.   0.  0.   0.2  40.  0.0

UNIT 62 TYPE 62 PV ARRAY
PARAMETERS 9
*MODE GTR    TCLR  ISCR   VOCR   IMPR  VMPR  MISC     MVOC
 2.0  Sunref Tcref Iscref Vocref Imref Vmref Misc     Mvoc
*  2.0  895.   323.  .3853  208.   .3417 16.63 .0025311 -.07781
PARAMETERS 8
*TAUALFA EQ    NCS WID LEN  NS NP DINRG
  T_a     EQ    NCS Wid len  Ns Np DINRG
*  .9      1.115 40. .4   1.0 1. 1. 100.
INPUTS 3
*SUN   TA   U_L
 16,6  9,5  U_L
 4921  24   10

*|* DIESEL GENERATORS _________________________________________
*|*
Equations 6
Fuelcost=  2.0000E-0001
*| Diesel Fuel Costs per Liter:        |$/liter|$/liter|0.0|0.0|0.0|1.0|99
MaxPwr1= 161.1
*|< Diesel Generator No.1:             |\hybrid\Diesels\Diesel1.dat|2|3|99
```

```
MaxSFC1= .23
*|<                                   |\hybrid\Diesels\Diesel1.dat|0|4|99
MinPwr1= 64.4
*|<                                   |\hybrid\Diesels\Diesel1.dat|0|5|99
MinSFC1= .25
*|<                                   |\hybrid\Diesels\Diesel1.dat|0|6|99
GenEff1= .90
*|<                                   |\hybrid\Diesels\Diesel1.dat|0|7|99
Equations 5
MaxPwr2= 161.1
*|< Diesel Generator No.2:            |\hybrid\Diesels\Diesel2.dat|2|3|99
MaxSFC2= .23
*|<                                   |\hybrid\Diesels\Diesel2.dat|0|4|99
MinPwr2= 64.4
*|<                                   |\hybrid\Diesels\Diesel2.dat|0|5|99
MinSFC2= .25
*|<                                   |\hybrid\Diesels\Diesel2.dat|0|6|99
GenEff2= .90
*|<                                   |\hybrid\Diesels\Diesel2.dat|0|7|99
Equations 5
MaxPwr3= 0
*|< Diesel Generator No.3:            |\hybrid\Diesels\Diesel3.dat|2|3|99
MaxSFC3= 0
*|<                                   |\hybrid\Diesels\Diesel3.dat|0|4|99
MinPwr3= 0
*|<                                   |\hybrid\Diesels\Diesel3.dat|0|5|99
MinSFC3= 0
*|<                                   |\hybrid\Diesels\Diesel3.dat|0|6|99
GenEff3= 0
*|<                                   |\hybrid\Diesels\Diesel3.dat|0|7|99
Equations 5
MaxPwr4= 0
*|< Diesel Generator No.4:            |\hybrid\Diesels\Diesel4.dat|2|3|99
MaxSFC4= 0
*|<                                   |\hybrid\Diesels\Diesel4.dat|0|4|99
MinPwr4= 0
*|<                                   |\hybrid\Diesels\Diesel4.dat|0|5|99
MinSFC4= 0
*|<                                   |\hybrid\Diesels\Diesel4.dat|0|6|99
GenEff4= 0
*|<                                   |\hybrid\Diesels\Diesel4.dat|0|7|99
Equations 5
MaxPwr5= 0
*|< Diesel Generator No.5:            |\hybrid\Diesels\Diesel5.dat|2|3|99
MaxSFC5= 0
*|<                                   |\hybrid\Diesels\Diesel5.dat|0|4|99
MinPwr5= 0
*|<                                   |\hybrid\Diesels\Diesel5.dat|0|5|99
MinSFC5= 0
*|<                                   |\hybrid\Diesels\Diesel5.dat|0|6|99
GenEff5= 0
*|<                                   |\hybrid\Diesels\Diesel5.dat|0|7|99
*|*

UNIT 21 TYPE 90 DIESEL ENGINE #1
PARAMETERS 7
*TIMESTP FUELCOST/LI MaxPwr  MaxSFC  MinPwr  MinSFC  GenEff
 step    FuelCost    MaxPwr1 MaxSFC1 MinPwr1 MinSFC1 GenEff1
INPUTS 1
26,1
1.0

UNIT 22 TYPE 90 DIESEL ENGINE #2
```

```
PARAMETERS 7
*TIMESTP FUELCOST/LI MaxPwr  MaxSFC  MinPwr  MinSFC  GenEff
 step    FuelCost    MaxPwr2 MaxSFC2 MinPwr2 MinSFC2 GenEff2
INPUTS 1
26,2
1.0

UNIT 23 TYPE 90 DIESEL ENGINE #3
PARAMETERS 7
*TIMESTP FUELCOST/LI MaxPwr  MaxSFC  MinPwr  MinSFC  GenEff
 step    FuelCost    MaxPwr3 MaxSFC3 MinPwr3 MinSFC3 GenEff3
INPUTS 1
26,3
1.0

UNIT 24 TYPE 90 DIESEL ENGINE #4
PARAMETERS 7
*TIMESTP FUELCOST/LI MaxPwr  MaxSFC  MinPwr  MinSFC  GenEff
 step    FuelCost    MaxPwr4 MaxSFC4 MinPwr4 MinSFC4 GenEff4
INPUTS 1
26,4
1.0

UNIT 25 TYPE 90 DIESEL ENGINE #5
PARAMETERS 7
*TIMESTP FUELCOST/LI MaxPwr  MaxSFC  MinPwr  MinSFC  GenEff
 step    FuelCost    MaxPwr5 MaxSFC5 MinPwr5 MinSFC5 GenEff5
INPUTS 1
26,5
1.0

*|* WIND ENERGY SYSTEMS _______________________________________
*|*
Equations = 3
SiteElev =  2.5500E+0002
*| Site Elevation:                     |meters|feet|0.0|3.281|-
1000.0|10000.0|99
DataHt =  1.0000E+0001
*| Site Data Height:                   |meters|feet|0.0|3.281|0.0|1000.0|99
Lost =  1.5000E+0001
*| Overall System Power Losses:        |percent|percent|0.0|1.0|0.0|100.0|99
*|*
EQUATIONS 5
lu41 = 45
*|< Wind Energy System No.1:           |\hybrid\WECS\WECS1.dat|2|3|99
HubHt41 =  2.6000E+0001
*|       Hub Height:                   |meters|feet|0.0|3.281|0.0|100.0|99
Alpha41 = .14
*|<       Wind Shear Exponent:         |\hybrid\WECS\shear1.dat|2|3|99
mode41 = 1
*|<                                    |\hybrid\WECS\WECS1.dat|0|4|99
Num41 =  1.0000E+0000
*|       Number of Turbines:           |turbines|turbines|0|1|0|10000|99
*|*
EQUATIONS 5
LU42 = 41
*|< Wind Energy System No.2:           |\hybrid\WECS\WECS2.dat|2|3|99
HubHt42 =  2.6000E+0001
*|       Hub Height:                   |meters|feet|0.0|3.281|0.0|100.0|99
Alpha42 = .14
*|<       Wind Shear Exponent:         |\hybrid\WECS\shear2.dat|2|3|99
mode42 = 0
*|<                                    |\hybrid\WECS\WECS2.dat|0|4|99
```

```
Num42 =  1.0000E+0000
*|       Number of Turbines:           |turbines|turbines|0|1|0|10000|99
*|*
EQUATIONS 5
LU43 = 41
*|< Wind Energy System No.3:           |\hybrid\WECS\WECS3.dat|2|3|99
HubHt43 =  2.7000E+0001
*|       Hub Height:                   |meters|feet|0.0|3.281|0.0|100.0|99
Alpha43 = .18
*|<       Wind Shear Exponent:         |\hybrid\WECS\shear3.dat|2|3|99
mode43 = 0
*|<                                    |\hybrid\WECS\WECS3.dat|0|4|99
Num43 =  1.0000E+0000
*|       Number of Turbines:           |turbines|turbines|0|1|0|10000|99
*|*
EQUATIONS 5
LU44 = 41
*|< Wind Energy System No.4:           |\hybrid\WECS\WECS4.dat|2|3|99
HubHt44 =  1.0000E+0001
*|       Hub Height:                   |meters|feet|0.0|3.281|0.0|100.0|99
Alpha44 = .14
*|<       Wind Shear Exponent:         |\hybrid\WECS\shear4.dat|2|3|99
mode44 = 0
*|<                                    |\hybrid\WECS\WECS4.dat|0|4|99
Num44 =  1.0000E+0000
*|       Number of Turbines:           |turbines|turbines|0|1|0|10000|99
*|*
EQUATIONS 5
LU45 = 41
*|< Wind Energy System No.5:           |\hybrid\WECS\WECS5.dat|2|3|99
HubHt45 =  1.4200E+0001
*|       Hub Height:                   |meters|feet|0.0|3.281|0.0|100.0|99
Alpha45 = .14
*|<       Wind Shear Exponent:         |\hybrid\WECS\shear5.dat|2|3|99
mode45 = 0
*|<                                    |\hybrid\WECS\WECS5.dat|0|4|99
Num45 =  1.0000E+0000
*|       Number of Turbines:           |turbines|turbines|0|1|0|10000|99
*|*

equations 1
BP = 1.0

UNIT 41 TYPE 85 Wind Turbine Generator #1
PARAMETERS 8
*Mode   ELEV     DATAHT  TimeStep HUBHT   Lost Num   PowerCurveLU
 mode41 SiteElev DataHt  Step     HubHt41 Lost Num41 LU41
INPUTS 4
*WND  TDB alpha_T BP
 WIND 9,5 alpha41 BP
 9.0 100. .14 1.0

UNIT 42 TYPE 85 Wind Turbine Generator #2
PARAMETERS 8
*Mode   ELEV     DATAHT  TimeStep HUBHT   Lost Num   PowerCurveLU
 mode42 SiteElev DataHt  Step     HubHt42 Lost Num42 LU42
INPUTS 4
*WND  TDB  alpha_T BP
 WIND 9,5 alpha42 BP
 9.0 100. .14 1.0

UNIT 43 TYPE 85 Wind Turbine Generator #3
PARAMETERS 8
```

```
*Mode   ELEV     DATAHT  TimeStep HUBHT   Lost Num   PowerCurveLU
 mode43 SiteElev DataHt  Step     HubHt43 Lost Num43 LU43
INPUTS 4
*WIND TDB  alpha_T BP
 WIND TDB alpha43 BP
 9.0 100. .14 1.0

UNIT 44 TYPE 85 Wind Turbine Generator #4
PARAMETERS 8
*Mode   ELEV     DATAHT  TimeStep HUBHT   Lost Num   PowerCurveLU
 mode44 SiteElev DataHt  Step     HubHt44 Lost Num44 LU44
INPUTS 4
*WiND TDB alpha_T BP
 WIND 9,5 alpha44 BP
 9.0 100. .14 1.0

UNIT 45 TYPE 85 Wind Turbine Generator #5
PARAMETERS
*Mode   ELEV     DATAHT  TimeStep HUBHT   Lost Num   PowerCurveLU
 mode45 SiteElev DataHt  Step     HubHt45 Lost Num45 LU45
INPUTS 4
*WND TDB alpha_T BP
WIND 9,5 alpha45 BP
 9.0 100. .14 1.0


UNIT 26 TYPE 92 DIESEL ENGINE CONTROLLER
PARAMETERS 29
*TIMESTP FUELCOST/LI Eff_Inv WirLos
 step    Fuelcost    Eff_Inv Wirlos
MaxPwr1  MaxSFC1 MinPwr1  MinSFC1 GenEff1
MaxPwr2  MaxSFC2 MinPwr2  MinSFC2 GenEff2
MaxPwr3  MaxSFC3 MinPwr3  MinSFC3 GenEff3
MaxPwr4  MaxSFC4 MinPwr4  MinSFC4 GenEff4
MaxPwr5  MaxSFC5 MinPwr5  MinSFC5 GenEff5
INPUTS 7
 41,1 42,1 43,1 44,1 45,1 PPV_T Demand
10.  10.  10.  10.  10.  10.    10.

*Outputs ***************************************************************

Equations 15
TotDsl  = [21,1]+[22,1]+[23,1]+[24,1]+[25,1]
DslHrs  = [21,2]+[22,2]+[23,2]+[24,2]+[25,2]
TotFuel = [21,3]+[22,3]+[23,3]+[24,3]+[25,3]
TotDoll = [21,4]+[22,4]+[23,4]+[24,4]+[25,4]
Qwaste  = [21,5]+[22,5]+[23,5]+[24,5]+[25,5]
TotWECS = [41,1]+[42,1]+[43,1]+[44,1]+[45,1]
PDeficit = max(0,(demand-(TotWECS+TotDsl+PPV_T)))
PDUMP = [26,7]
L1 = [21,1]
L2 = L1+[22,1]
L3 = L2+[23,1]
L4 = L3+[24,1]
L5 = L4+[25,1]
L6 = L5+PPV_T
L7 = L6+TotWecs

UNIT 60 TYPE 25 DATA FOR PLOTTING
PARAMETERS 4
1 1 8760 12
INPUTS 10
21,1 22,1 23,1 24,1 TotDsl TotWECS PPV_T 26,7 Demand PDeficit
```

```
Dsl1 Dsl2 Dsl3 Dsl4 TotDsl WECS    PV    Dump Demand Deficit

UNIT 61 TYPE 24 TOTAL SIMULATION DIESEL AND WECS INTEGRATOR
Inputs 10
*W1  W2   W3   W4   W5   DSL1 DSL2 DSL3 DSL4 DSL5
41,1 42,1 43,1 44,1 45,1 21,1 22,1 23,1 24,1 25,1
1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0  1.0

UNIT 71 TYPE 24 TOTAL SIMULATION ECONOMIC DATA INTEGRATOR
Inputs 8
*DEMAND PV    FUEL    TOTALDIESEL TOTALWIND DUMP DEFICIT  DOLLARS
 DEMAND PPV_T TotFuel TotDsl      TotWECS   26,7 PDeficit TotDoll
 1.0    1.0   1.0     1.0         1.0       1.0  1.0      1.0

* Diesel Output ________________________________________________

UNIT 63 TYPE 24 Monthly Diesel Power, Hours
PARAMETER 1
-1
Inputs 10
21,1 22,1 23,1 24,1 25,1 21,2 22,2 23,2 24,2 25,2
1. 1. 1. 1. 1. 1. 1. 1. 1. 1.

UNIT 64 TYPE 25 Print Diesel Power, Hours
PARAMETERS 4
*dtp ton toff lu
 -1  1 8760   14
INPUTS 10
63,1 63,2 63,3 63,4 63,5 63,6 63,7 63,8 63,9 63,10
1. 1. 1. 1. 1. 1. 1. 1. 1. 1.

* WECS Output ______________________________________________________

UNIT 65 TYPE 24 Wind Power, Hours
PARAMETERS 1
-1
Inputs 10
41,1 42,1 43,1 44,1 45,1 41,2 42,2 43,2 44,2 45,2
1. 1. 1. 1. 1. 1. 1. 1. 1. 1.

UNIT 66 TYPE 25 Print Wind Power, Hours
PARAMETERS 4
*dtp ton toff lu
 -1  1 8760   14
INPUTS 10
65,1 65,2 65,3 65,4 65,5 65,6 65,7 65,8 65,9 65,10
1. 1. 1. 1. 1. 1. 1. 1. 1. 1.

* Economic Output ______________________________________________________

UNIT 67 TYPE 24 Fuel and Dollars Summary
PARAMETERS 1
-1
Inputs 10
21,3 22,3 23,3 24,3 25,3 21,4 22,4 23,4 24,4 25,4
1. 1. 1. 1. 1. 1. 1. 1. 1. 1.

UNIT 68 TYPE 25 Print Fuel and Dollars Summary
PARAMETERS 4
*dtp ton toff lu
 -1  1 8760   14
INPUTS 10
67,1 67,2 67,3 67,4 67,5 67,6 67,7 67,8 67,9 67,10
```

```
1. 1. 1. 1. 1. 1. 1. 1. 1. 1.

UNIT 69 TYPE 24 Monthly Economic Data Summary
PARAMETERS 1
-1
Inputs 8
*DEMAND PV    FUEL    TOTALDIESEL TOTALWIND DUMP DEFICIT  DOLLARS
 DEMAND PPV_T TotFuel TotDsl      TotWECS   26,7 PDeficit TotDoll
 1.0    1.0   1.0     1.0         1.0       1.0  1.0      1.0

*UNIT 70 TYPE 25 Print Monthly Economic Data Summary
*PARAMETERS 4
**dtp ton toff lu
* -1  1 8760   14
*INPUTS 8
**DEMAND PV Fuel Dsl  WECS 26,7 Deficit TotDoll
*69,1 69,2 69,3 69,4 69,5 69,6 69,7    69,8
*1. 1. 1. 1. 1. 1. 1. 1.
*|*
*|* OUTPUT SPECIFICATIONS _______________________________________
*|*
UNIT 72 TYPE 65 ONLINE PLOTTER
*PRINT WIND AND POWER
PARAMETERS 14
5 5 0 maxplt1 0 maxplt1 1 1 3 onplots 6 1 2 0
INPUTS 10
L1  L2  L3  L4  L5 PPV_T TotWECS L7 Demand PDeficit
Dsl_1 +Dsl_2 +Dsl_3 +Dsl_4 All_Dsl PV Wind Totl_Gen Demand Deficit
LABELS 4
DIESEL
SYSTEM
DIESEL_OUTPUT,_(kWh/timestep)
SYSTEM_TOTALS,_(kWh/timestep)

*|* Histograms
equations 3
minwind =  0.0000E+0000
*|   Minimum Total Wind Output:
|kWh/timestep|kWh/timestep|0.000|0.000|0.000|100.00|99
maxwind =  1.0000E+0002
*|   Maximum Total Wind Output:
|kWh/timestep|kWh/timestep|0.000|0.000|0.000|100.00|99
binwind =  5.0000E+0000
*|   Number of Bins:                   |bins|bins|0|1|0|20|99
*|*
equations 3
mindsl =  0.0000E+0000
*|   Minimum Total Diesel Output:
|kWh/timestep|kWh/timestep|0.000|0.000|0.000|100.00|99
maxdsl =  1.0000E+0002
*|   Maximum Total Diesel Output:
|kWh/timestep|kWh/timestep|0.000|0.000|0.000|100.00|99
bindsl =  5.0000E+0000
*|   Number of Bins:                   |bins|bins|0|1|0|20|99
*|*
equations 3
minPV =  0.0000E+0000
*|   Minimum Total PV Output:
|kWh/timestep|kWh/timestep|0.000|0.000|0.000|100.00|99
maxPV =  1.0000E+0002
*|   Maximum Total PV Output:
|kWh/timestep|kWh/timestep|0.000|0.000|0.000|100.00|99
binPV =  5.0000E+0000
```

```
*|   Number of Bins:                    |bins|bins|0|1|0|20|99
*|*
equations 3
minDmp =  0.0000E+0000
*|   Minimum Total Dump Output:
|kWh/timestep|kWh/timestep|0.000|0.000|0.000|100.00|99
maxDmp =  1.0000E+0002
*|   Maximum Total Dump Output:
|kWh/timestep|kWh/timestep|0.000|0.000|0.000|100.00|99
binDmp =  5.0000E+0000
*|   Number of Bins:                    |bins|bins|0|1|0|20|99
*|*
equations 3
minDef =  0.0000E+0000
*|   Minimum Total Deficit:
|kWh/timestep|kWh/timestep|0.000|0.000|0.000|100.00|99
maxDef =  1.0000E+0002
*|   Maximum Total Deficit:
|kWh/timestep|kWh/timestep|0.000|0.000|0.000|100.00|99
binDef =  5.0000E+0000
*|   Number of Bins:                    |bins|bins|0|1|0|20|99
*|*
equations 3
minful =  0.0000E+0000
*|   Minimum Fuel Consumption:
|liters/timestep|liters/timestep|0.000|0.000|0.000|100.00|99
maxful =  1.0000E+0002
*|   Maximum Fuel Consumption:
|liters/timestep|liters/timestep|0.000|0.000|0.000|100.00|99
binful =  5.0000E+0000
*|   Number of Bins:                    |bins|bins|0|1|0|20|99
*|*
equations 3
minDmd =  0.0000E+0000
*|   Minimum Total Demand:
|kWh/timestep|kWh/timestep|0.000|0.000|0.000|100.00|99
maxDmd =  1.0000E+0002
*|   Maximum Total Demand:
|kWh/timestep|kWh/timestep|0.000|0.000|0.000|100.00|99
binDmd =  5.0000E+0000
*|   Number of Bins:                    |bins|bins|0|1|0|20|99
*|*

Unit 73 Type 27 Histogram Plotter
Parameters 27
*mode dtp dtr ton toff  rb1     re1     n1       rb2    re2    n2
 1    -1  -1  0   10000 minWind maxwind binwind  minDsl maxDsl binDsl
*rb3   re3   n3    rb4    re4    n4     rb5    re5    n5
 minPV maxPV binPV minDmp maxDmp binDmp minDef maxDef binDef
*rb6    re6    n6     rb7    re7    n7     LU
 minFul maxFul binFul minDmd maxDmd binDmd 13
Inputs 7
TotWECS TotDsl PPV_T 26,7 Pdeficit TotFuel Demand
WECS    Diesel PV    Dump Deficit  Fuel    Demand

END
```

APPENDIX D

UW-HYBRID INSTALLATION GUIDE

Introduction and Installation Guide:
UW-HYBRID PV WIND DIESEL HYBRID SIMULATOR
VERSION 1.0

University of Wisconsin Solar Energy Laboratory

July 1996
Prepared by P. Quinlan

Introduction

UW-Hybrid is a TRNSYS application implementing wind, PV and diesel engine models to simulate hybrid power systems.

Analytic Description

UW-HYBRID is a quasi-steady performance simulation tool. It calculates energy production and flows per timestep; totals are obtained by Euler integration over time. TRNSYS is an ideal software environment for the modeling of hybrid systems composed of various interconnected devices because TRNSYS itself is composed of linked modules. These modules are:

- A detailed multiple-unit wind turbine performance simulator with selectable hardware,
- A detailed diesel engine performance and fuel consumption model with selectable hardware,
- A detailed PV module array system and peak power tracker performance model with selectable hardware,
- A general diesel engine dispatch controller employing cost optimization algorithms,
- Selectable time series weather data,
- Selectable time series loads data, and
- Various output formats, diagnostic calculations, summaries and measures of performance.

UW-HYBRID 1.0 includes a wind turbine performance model which accurately calculates the performance of a real wind turbine, based on data read in from a power curve file. Up to five different types of turbines can be included in the current version. The model includes the effects of elevation wind shear and time varying temperature and wind speed to calculate the appropriate performance of the wind turbine over time. Cumulative loss factors can be incorporated as well.

The diesel engine performance model determines fuel output, fuel cost, power output, engine hours and waste heat delivered over time as a function of controller setpoints. These calculations are made subsequent to reading in power output and fuel consumption performance specifications from files describing actual diesel systems.

The PV performance model simulates the performance of a PV system at a user-specified array slope azimuth and module type. The calculations are based on data obtained from actual time series weather files for the location. The calculations of system performance utilize the methodologies developed at the Solar Energy Laboratory for calculating radiation on the tilted surface and net electrical power resulting from the system. A peak power tracker is included.

The diesel engine dispatch controller can accept up to five generators in any sequence or configuration. The controller determines the net load to be provided by the diesels, by subtracting renewables output from the demand. The controller programs itself by reading the performance specification data used by the diesels to describe their operational characteristics. Subsequently, the controller determines the least-cost ranking of the units, and dispatches the diesels in a sequence which satisfy the criteria of minimum cost to meet load. The controller also determines the amount of dump energy per timestep. This occurs because the diesels cannot operate at less than their minimum load, typically 40%.

Description of the Software

UW-HYBRID 1.0 provides a configurable user-interface, running under TRNSED. The user can specify the start, timestep, and length of the simulation period, as well as the load and weather profiles. Time steps of .1 hour to one hour are permitted. Pop-up menus are provided. The user selects the PV array tilt, azimuth and manufacturer. If desired, the user can elect to have no PV wind or diesel units simulated, in order to allow simulations of a wide variety of systems. The software permits the selection of identical diesels generators, if desired. A fuel cost is entered, per liter.
Finally, the wind characteristics are entered by the user. The site elevation and data height are entered in. For each turbine, the hub height and local wind shear are entered. Similar to the diesels, zero to five units as well as similar units are acceptable.

Outputs

After selecting “calculate” from the TRNSED menu, UW-HYBRID presents an on-screen plot as the simulation progresses. The plot shows the individual power output of each diesels, as well as the addition of PV power and wind turbine power to meet demand. Whenever demand is sufficiently met by the renewables, it can be seen that diesels are taken off line, in order of greatest to least cost. The lower plot shows the cumulative demand, as well as the output of the wind systems, cumulative diesels and PV. Also shown is the amount of dump energy and energy deficit. Energy deficit is defined as the amount of unserved demand during the simulation.

In addition to the on screen output, UW-HYBRID creates disk files of a number of parameters. Most can be plotted, without quitting UW-HYBRID, using the plot menu in TRNSED. Others, including histograms of data and time series outputs, are stored as text for viewing by other applications.

Support and Development

UW-HYBRID requires TRNSED. At minimum, a 486 microprocessor is recommended. Currently, approximately 10 load profiles, 10 weather files, 3 PV module, 15 diesels, and 10 wind turbines are included. The number of resource files is expected to increase significantly over the upcoming months.

Installing UW-Hybrid

The software contained on the UW-Hybrid disk has been compressed to allow it to fit onto a single 3-1/2” HD IBM PC-formatted floppy disk. The software has been designed to operate in a directory at the root level. In order to create this directory and load the UW-Hybrid files, complete the following steps:

1. Create a directory on the PC hard disk titled HYBRID.
2. Insert the UW-Hybrid disk into the floppy disk drive.

3 Navigate to the HYBRID directory on the PC hard disk in DOS.

4. Copy A: UWHYBRID.EXE to the C:\HYBRID directory.
5. In the HYBRID directory type in the following command:
   UWHYBRID.EXE -d

6. After installing, start Windows. Under File/Run, enter C:\HYBRID\TRNSHELW.EXE
7. Once TRNSHELW starts, choose File/Open and type: C:\HYBRID\DECKS\UWHYBRID.TRD Hit the return key.

To run a simulation select “Calculate” from the TRNSYS menu or press F8. The online plot of the progress of the software will indicate a successful simulation.

Notices and Information

UW-HYBRID is a research tool currently in development at the Solar Energy Laboratory, University of Wisconsin, Madison. Inquiries may be directed to Professor William Beckman, Solar Energy Laboratory, University of Wisconsin, 1500 Engineering Drive, Madison WI, 53706. telephone (608) 263-1590, fax (608) 262-8464. E-mail beckman@engr.wisc.edu. Visit the Solar Energy Laboratory web site at http://www.engr.wisc.edu/centers/sel/sel.html.

APPENDIX E

WIND TURBINE DATA

AOC 15-50

AWT-26

CARTER 300

BWC EXCEL

JACOBS LONG

JACOBS SHORT

JACOSBS 23-10

JACOBS 29-20

KVS-33

MHI 275

MHI 300

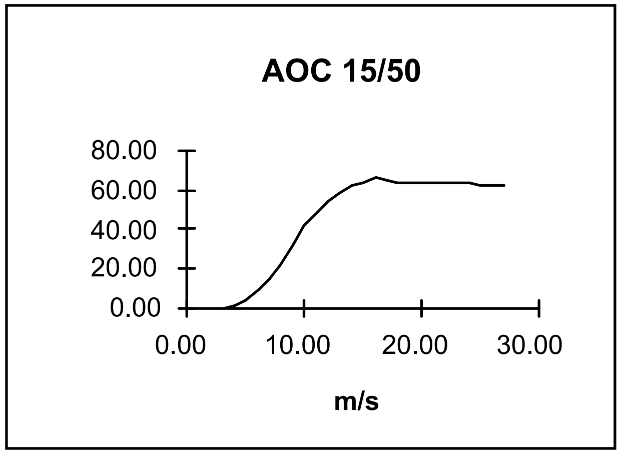
TACKE 600

WHISPER 300

VESTAS V-90

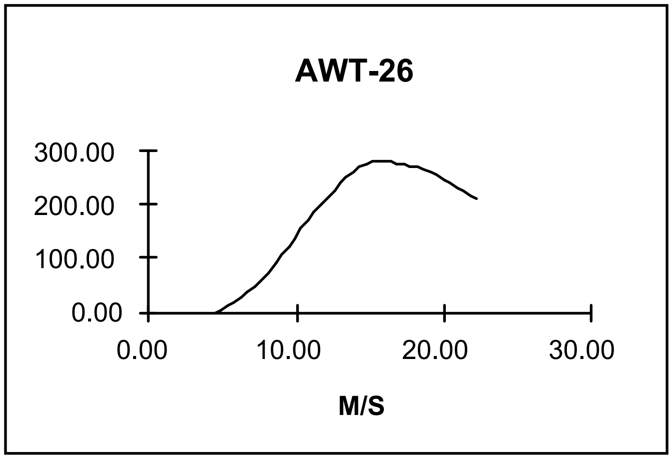
AOC-15/50 [50 KW]

Turbine Data File Name:	OAC1550.PWR
Test Reference:	Brochure
Rotor Center Height:	25.00
Rotor Diameter:	15.00
Sensor Height:	25.00
Wind Shear Exponent:	0.14
Turbulence Intensity:	0.10
Air Density:	1.22
Length Units:	m
Wind Units:	m/s
Power Units:	kW
Control:	S
Generator Rating:	50.00
3.00	0.00
4.00	1.10
5.00	4.20
6.00	9.50
7.00	14.40
8.00	21.90
9.00	31.90
10.00	41.00
11.00	49.00
12.00	54.20
13.00	58.20
14.00	62.10
15.00	64.00
16.00	65.80
17.00	64.7
18.00	63.90
19.00	63.90
20.00	63.80
21.00	63.40
22.00	63.30
23.00	63.00
24.00	62.90
25.00	62.10
26.00	62.00
27.00	62.00
99.00	62.00



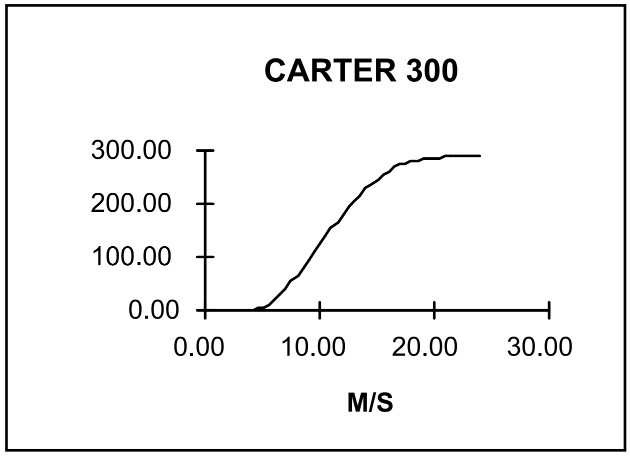
AWT-26 [275 KW]

Turbine Data File Name:	AWT275.PWR
Test Reference:	Brochure
Rotor Center Height:	47.30
Rotor Diameter:	26.20
Sensor Height:	47.30
Wind Shear Exponent:	0.14
Turbulence Intensity:	0.10
Air Density:	1.22
Length Units:	m
Wind Units:	m/s
Power Units:	kW
Control:	S
Generator Rating:	275.00
4.43	0.00
4.91	2.88
5.40	11.52
5.80	18.00
6.29	25.92
6.73	35.29
7.21	45.38
7.62	58.35
8.10	73.48
8.55	90.06
8.99	105.20
9.47	120.33
9.88	136.19
10.33	154.21
10.77	169.34
11.22	185.20
11.70	199.61
12.14	213.31
12.55	227.00
12.96	240.69
13.44	251.50
13.85	260.87
14.26	270.24
14.74	276.72
15.15	281.03
15.63	281.03
16.00	281.02
16.48	279.57
16.89	277.39
17.37	275.22
17.77	271.61
18.29	268.71
18.70	265.82
19.18	260.04
19.59	255.70
20.07	247.04
20.51	239.82
20.99	233.32
21.40	224.66
21.92	216.72
22.32	208.77



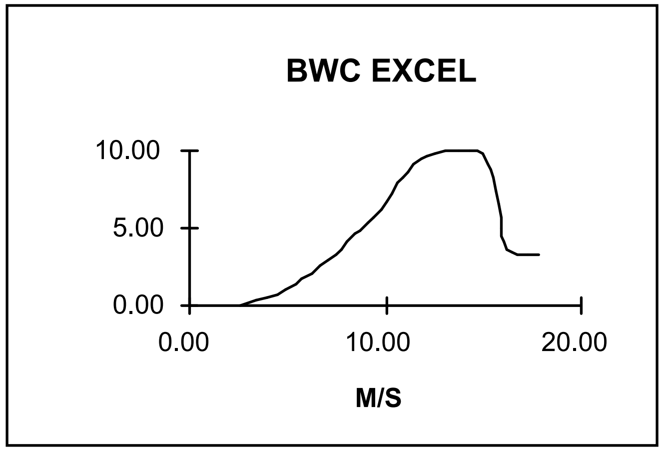
CARTER 300 [300 KW]

Turbine Data File Name:	CAR300.PWR
Test Reference:	Brochure
Rotor Center Height:	50.00
Rotor Diameter:	24.00
Sensor Height:	50.00
Wind Shear Exponent:	0.14
Turbulence Intensity:	0.10
Air Density:	1.22
Length Units:	m
Wind Units:	m/s
Power Units:	kW
Control:	S
Generator Rating:	300.00
4.00	0.00
4.50	0.80
5.00	4.60
5.50	10.50
6.00	18.80
6.50	28.70
7.00	40.00
7.50	52.30
8.00	65.30
8.50	78.80
9.00	92.80
9.50	107.40
10.00	122.20
10.50	137.10
11.00	151.7
11.50	165.90
12.00	179.50
12.50	192.40
13.00	204.70
13.50	216.50
14.00	227.30
14.50	236.80
15.00	245.30
15.50	253.70
16.00	261.30
16.50	267.80
17.00	272.90
17.50	276.70
18.00	279.60
18.50	282.00
19.00	284.00
19.50	285.00
20.00	286.00
20.50	287.00
21.00	288.20
21.50	288.60
22.00	288.90
23.00	289.30
24.00	289.70
99.00	289.00



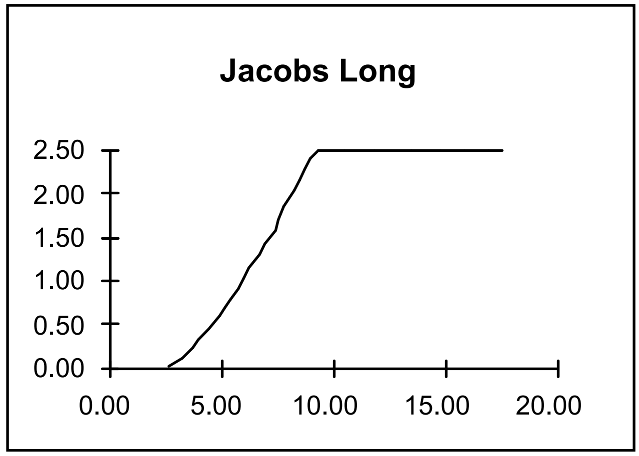
BWC EXCEL [10 KW]

Turbine Data File Name:	BWC10KW.PWR
Test Reference:	Home_Power
Rotor Center Height:	30.00
Rotor Diameter:	1.00
Sensor Height:	30.00
Wind Shear Exponent:	0.14
Turbulence Intensity:	0.10
Air Density:	1.22
Length Units:	m
Wind Units:	m/s
Power Units:	kW
Control:	S
Generator Rating:	10.00
2.59	0.00
3.31	0.21
3.85	0.43
4.46	0.70
4.88	0.92
5.36	1.24
5.72	1.63
6.27	2.06
6.69	2.50
7.11	2.93
7.41	3.26
7.72	3.64
8.02	4.02
8.44	4.51
8.74	4.84
9.05	5.22
9.35	5.61
9.77	6.21
10.01	6.59
10.26	7.13
10.62	7.84
10.86	8.28
11.10	8.61
11.47	9.04
11.77	9.37
12.13	9.64
12.55	9.80
13.09	10.00
13.76	10.00
14.30	10.00
14.66	9.85
14.96	9.69
15.20	9.14
15.32	8.65
15.50	8.27
15.61	7.34
15.73	6.46
15.85	5.70
15.91	4.99
15.97	4.50
16.03	4.06
16.21	3.62
16.45	3.35
16.75	3.24
17.29	3.24
17.77	3.29



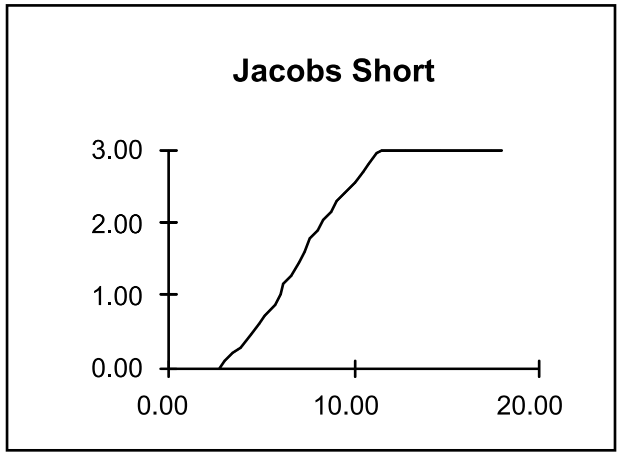
JACOBS LONG [2.5 KW]

Turbine Data File Name:	JAC2KW.PWR
Test Reference:	Home_Power
Rotor Center Height:	30.00
Rotor Diameter:	1.00
Sensor Height:	30.00
Wind Shear Exponent:	0.14
Turbulence Intensity:	0.10
Air Density:	1.22
Length Units:	m
Wind Units:	m/s
Power Units:	kW
Control:	P
Generator Rating:	2.50
2.58	0.01
3.16	0.12
3.62	0.23
3.96	0.34
4.42	0.46
4.89	0.59
5.12	0.70
5.35	0.78
5.70	0.91
5.99	1.03
6.22	1.15
6.62	1.29
6.86	1.42
7.32	1.58
7.55	1.71
7.79	1.86
8.19	2.04
8.42	2.17
8.66	2.29
8.95	2.42
9.23	2.50
10.44	2.50
11.81	2.50
13.48	2.50
14.79	2.50
15.88	2.50
16.91	2.50
17.60	2.50
99.00	2.50



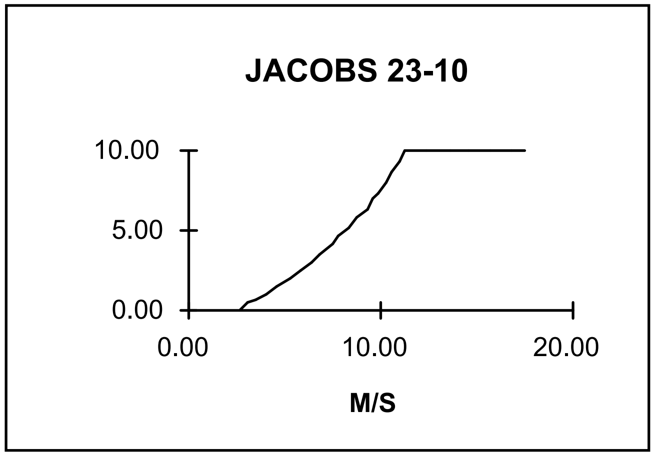
JACOBS SHORT [3 KW]

Turbine Data File Name:	WISP3K.PWR
Test Reference:	Home_Power
Rotor Center Height:	30.00
Rotor Diameter:	1.00
Sensor Height:	30.00
Wind Shear Exponent:	0.14
Turbulence Intensity:	0.10
Air Density:	1.22
Length Units:	m
Wind Units:	m/s
Power Units:	kW
Control:	P
Generator Rating:	3.00
2.64	0.00
3.04	0.09
3.39	0.19
3.85	0.29
4.37	0.45
4.83	0.60
5.18	0.73
5.70	0.88
5.99	1.01
6.22	1.15
6.62	1.29
6.97	1.44
7.32	1.59
7.61	1.77
7.96	1.91
8.31	2.04
8.71	2.16
9.06	2.29
9.52	2.42
10.04	2.55
10.44	2.70
10.79	2.82
11.14	2.95
11.43	3.00
12.86	3.00
14.69	3.00
16.30	3.00
17.39	3.00
17.96	3.00
99.00	3.00



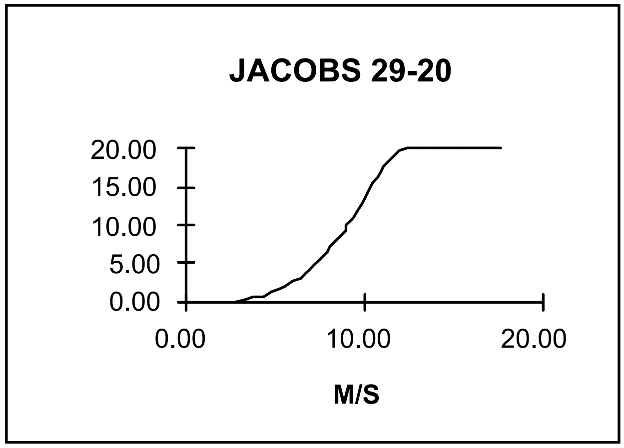
JACOBS 23-10 [10 KW]

Turbine Data File Name:	JAC10KW.PWR
Test Reference:	Home_Power
Rotor Center Height:	30.00
Rotor Diameter:	7.01
Sensor Height:	30.00
Wind Shear Exponent:	0.14
Turbulence Intensity:	0.10
Air Density:	1.22
Length Units:	m
Wind Units:	m/s
Power Units:	kW
Control:	P
Generator Rating:	10.00
2.53	0.00
3.01	0.38
3.43	0.66
3.98	0.98
4.58	1.42
5.18	1.92
5.79	2.41
6.33	2.97
6.75	3.46
7.42	4.12
7.78	4.61
8.26	5.11
8.75	5.88
9.23	6.38
9.59	6.92
9.77	7.31
10.20	7.97
10.50	8.58
10.98	9.40
11.17	10.00
12.37	10.00
13.64	10.00
14.60	10.00
15.74	10.00
16.77	10.00
17.49	10.00
99.00	10.00



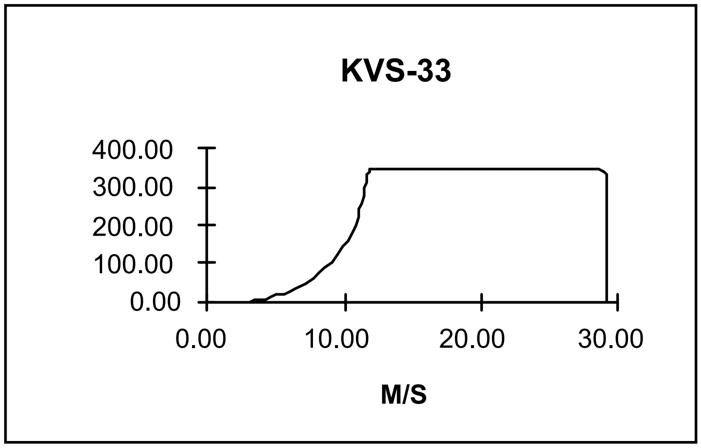
JACOBS 29-20 [20 KW]

Turbine Data File Name:	JAC20KW.PWR
Test Reference:	Home_Power
Rotor Center Height:	30.00
Rotor Diameter:	8.83
Sensor Height:	30.00
Wind Shear Exponent:	0.14
Turbulence Intensity:	0.10
Air Density:	1.22
Length Units:	m
Wind Units:	m/s
Power Units:	kW
Control:	P
Generator Rating:	20.00
2.71	0.00
3.19	0.16
3.73	0.43
4.28	0.75
4.70	1.14
5.12	1.52
5.54	2.06
5.97	2.72
6.33	3.10
6.63	3.64
6.88	4.25
7.18	4.79
7.48	5.50
7.72	6.16
7.85	6.65
8.09	7.25
8.27	7.79
8.63	8.61
8.88	9.24
9.00	9.86
9.30	10.58
9.43	11.23
9.61	11.94
9.85	12.87
10.03	13.53
10.16	14.24
10.34	14.89
10.46	15.49
10.71	16.37
10.89	17.02
11.07	17.84
11.31	18.50
11.56	19.04
11.92	19.64
12.34	20.00
13.18	20.00
14.09	20.00
15.41	20.00
16.13	20.00
16.98	20.00
17.58	20.00
99.00	20.00



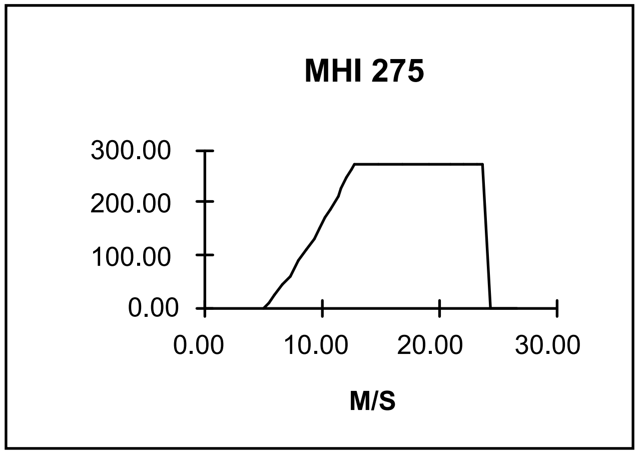
KVS-33 [275 KW]

Turbine Data File Name:	KVS33.PWR
Test Reference:	Brochure
Rotor Center Height:	33.00
Rotor Diameter:	33.00
Sensor Height:	33.00
Wind Shear Exponent:	0.14
Turbulence Intensity:	0.10
Air Density:	1.22
Length Units:	m
Wind Units:	m/s
Power Units:	kW
Control:	P
Generator Rating:	350.00
3.06	0.00
3.42	2.68
3.78	4.01
4.26	6.69
4.62	12.04
5.10	16.05
5.51	21.40
5.99	28.09
6.35	33.44
6.77	40.13
7.19	49.50
7.73	61.00
8.15	73.00
8.57	88.00
9.11	104.80
9.53	124.41
9.89	143.14
10.19	159.20
10.61	187.29
10.79	203.34
10.97	224.75
11.15	240.80
11.27	256.86
11.45	275.59
11.51	296.99
11.57	314.38
11.63	330.43
11.75	341.14
11.93	346.49
12.11	349.16
12.47	350.00
13.49	350.00
15.53	350.00
17.38	350.00
18.82	350.00
20.98	350.00
22.84	350.00
24.28	350.00
26.13	350.00
27.27	350.00
28.23	350.00
28.47	350.00
28.59	347.83
29.01	339.80
29.13	330.43
29.19	0.00



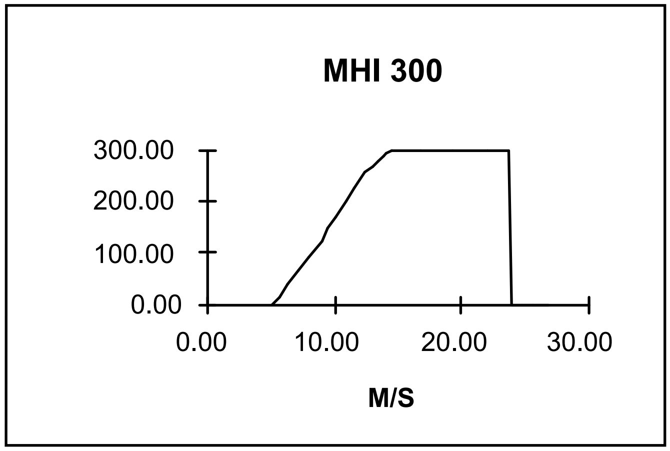
MHI 275 [275 KW]

Turbine Data File Name:	MHI275.PWR
Test Reference:	Brochure
Rotor Center Height:	40.00
Rotor Diameter:	30.00
Sensor Height:	40.00
Wind Shear Exponent:	0.14
Turbulence Intensity:	0.10
Air Density:	1.22
Length Units:	m
Wind Units:	m/s
Power Units:	kW
Control:	P
Generator Rating:	275.00
4.88	0.00
5.41	10.29
5.95	24.11
6.63	43.12
7.25	61.26
8.01	88.92
8.55	107.93
9.31	132.12
9.77	152.87
10.31	170.15
10.69	188.30
11.30	209.90
11.69	228.05
12.07	248.79
12.45	265.21
12.76	273.85
14.74	275.00
16.95	275.00
19.24	275.00
20.91	275.00
22.21	275.00
23.20	275.00
23.73	275.00
24.46	0.00
26.67	0.00
99.00	0.00

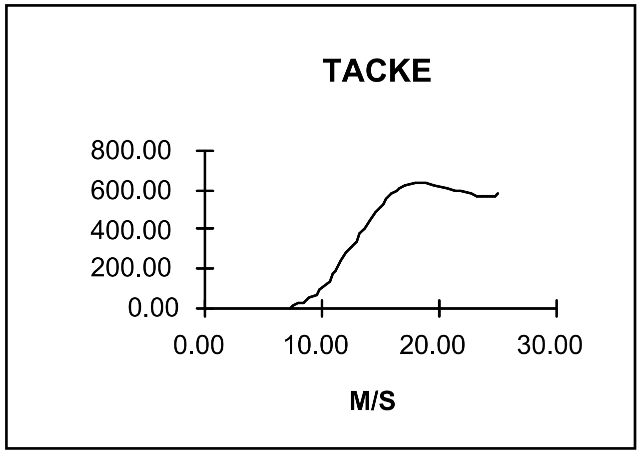


MHI 300 [300KW]

Turbine Data File Name:	MHI300.PWR
Test Reference:	Brochure
Rotor Center Height:	40.00
Rotor Diameter:	1.00
Sensor Height:	40.00
Wind Shear Exponent:	0.14
Turbulence Intensity:	0.10
Air Density:	1.22
Length Units:	m
Wind Units:	m/s
Power Units:	kW
Control:	P
Generator Rating:	300.00
4.96	0.00
5.66	14.98
6.28	39.11
7.14	63.23
7.99	92.38
8.93	121.53
9.47	145.66
10.10	168.78
10.80	200.95
11.50	226.08
12.35	254.22
12.90	267.29
13.36	278.34
13.83	286.38
14.14	292.41
14.37	297.43
14.53	300.00
16.78	300.00
19.33	300.00
21.97	300.00
23.75	300.00
23.87	0.00
24.80	0.00
25.58	0.00
26.82	0.00
99.00	0.00

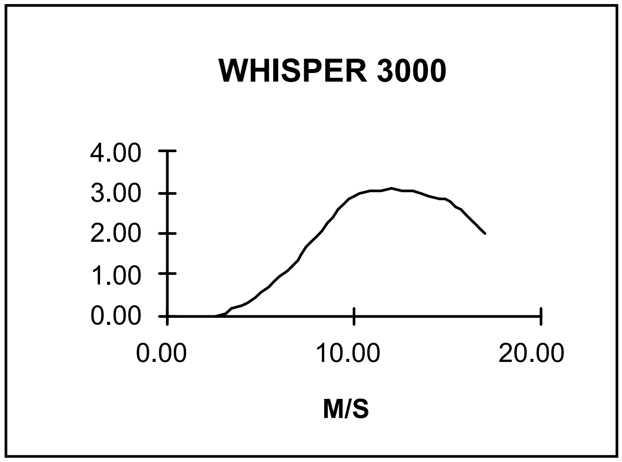


Tacke 600 [600 KW]	
Turbine Data File Name:	TACK600.PWR
Test Reference:	Brochure
Rotor Center Height:	40.00
Rotor Diameter:	1.00
Sensor Height:	40.00
Wind Shear Exponent:	0.14
Turbulence Intensity:	0.10
Air Density:	1.22
Length Units:	m
Wind Units:	m/s
Power Units:	kW
Control:	S
Generator Rating:	600.00
7.15	0.00
7.45	8.72
7.87	15.54
8.37	26.94
8.87	45.22
9.37	65.80
9.79	88.69
10.48	134.48
10.82	166.56
11.05	187.18
11.59	233.00
12.05	274.24
12.40	304.02
12.78	338.39
13.20	375.05
13.59	407.12
14.01	441.48
14.43	478.13
14.81	505.62
15.16	528.51
15.47	551.42
15.85	574.31
16.16	592.62
16.58	608.62
17.04	622.32
17.80	629.09
18.68	628.95
19.52	624.23
20.48	612.61
21.16	598.73
21.66	587.18
22.62	577.85
23.11	573.19
23.65	570.81
24.07	570.75
24.41	570.69
24.68	572.95
24.95	575.20
99.00	575.20



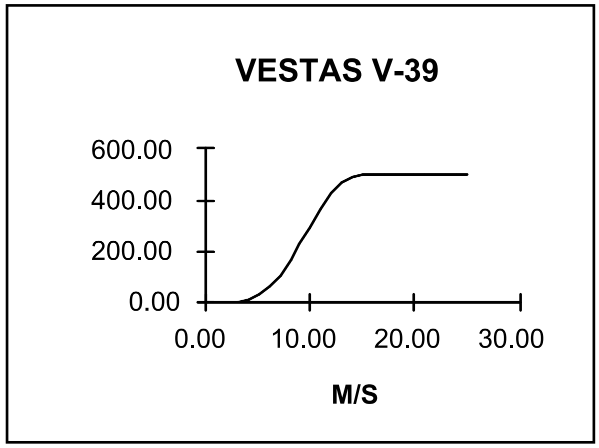
WHISPER 3000 [3 KW]

Turbine Data File Name:	WIS3KW.PWR
Test Reference:	BROCHURE
Rotor Center Height:	30.00
Rotor Diameter:	4.50
Sensor Height:	30.00
Wind Shear Exponent:	0.14
Turbulence Intensity:	0.10
Air Density:	1.22
Length Units:	m
Wind Units:	m/s
Power Units:	kW
Control:	S
Generator Rating:	3.00
2.58	0.00
3.04	0.06
3.44	0.15
3.90	0.22
4.25	0.30
4.65	0.40
5.00	0.53
5.35	0.66
5.64	0.79
5.98	0.94
6.33	1.09
6.68	1.23
6.91	1.37
7.09	1.49
7.44	1.67
7.73	1.81
8.02	1.94
8.19	2.06
8.60	2.27
8.83	2.40
9.12	2.55
9.47	2.72
9.70	2.81
9.99	2.89
10.33	2.94
10.91	3.02
11.43	3.06
11.94	3.07
12.57	3.05
13.20	3.03
13.54	2.98
14.06	2.93
14.52	2.86
14.86	2.82
15.09	2.77
15.43	2.66
15.77	2.56
16.05	2.45
16.34	2.31
16.56	2.20
16.73	2.12
16.96	2.02
99.00	0.00



VESTAS V-39 [500 KW]

Turbine Data File Name:	VSTSV39.PWR
Test Reference:	WIND_STATS
Rotor Center Height:	39.00
Rotor Diameter:	39.00
Sensor Height:	39.00
Wind Shear Exponent:	0.14
Turbulence Intensity:	0.10
Air Density:	1.22
Length Units:	m
Wind Units:	m/s
Power Units:	kW
Control:	P
Generator Rating:	500.00



3.00	0.00
4.00	6.90
5.00	29.40
6.00	62.90
7.00	106.70
8.00	160.90
9.00	224.20
10.00	293.10
11.00	362.10
12.00	423.40
13.00	466.80
14.00	489.20
15.00	497.40
16.00	499.50
17.00	499.50
18.00	500.00
19.00	500.00
20.00	500.00
21.00	500.00
22.00	500.00
23.00	500.00
24.00	500.00
25.00	500.00
45.00	500.00
46.00	0.00
99.00	0.00

APPENDIX F

DIESEL DATA

Diesel Engine Data

Engine	Petter AA1	Petter AB1	Petter AC1	Petter AC2	Generic 15 kW
Max_Pwr,gen	2.6	3.7	4.8	9.0	15.0
SFC at max	0.32	0.31	0.30	0.27	
Min_Pwr,gen	1.0	1.5	1.9	3.6	6.0
SFC at min	0.35	0.34	0.33	0.30	
motor eff.	0.90	0.90	0.90	0.90	0.90
Fuel Type	2	2	2	2	2
Reference	Lilly 24/14	Lilly 24/14	Lilly 24/14	Lilly 24/14	UMass

Genset Diesel Data

Engine	Petter AA1	Petter AB1	Petter AC1	Petter AC2	Generic 15 kW
Max_Power,elec	2.3	3.3	4.3	8.1	13.5
SFC@MaxPower,e	0.35	0.34	0.33	0.30	0.00
Min_Power,elec	0.9	1.3	1.7	3.2	5.4
SFC@MinPower,e	0.39	0.38	0.36	0.33	0.00
Gen_eff.	0.9	0.9	0.9	0.9	0.9
Fuel Type	2	2	2	2	2
Ref.	Lilly 24/14	Lilly 24/14	Lilly 24/14	Lilly 24/14	UMass

*Mirrlees Blackstone MB 190

Diesel Engine Data

Engine	Hatz 2_L30	Hatz 3_L30	Hatz 4_L30	Generic 100	Cummins D34
Max_Pwr,gen	18.2	27.3	36.4	111.1	179.0
SFC at max	0.25	0.25	0.25	0.30	0.20
Min_Pwr,gen	7.3	10.9	14.6	44.4	71.6
SFC at min	0.28	0.28	0.28	0.33	0.22
motor eff.	0.90	0.90	0.90	0.90	0.90
Fuel Type	2	2	2	2	2
Reference	Lilly 24/7	Lilly 24/7	Lilly 24/7	UMass	Cummins C-4815

Genset Diesel Data

Engine	Hatz 2_L30	Hatz 3_L30	Hatz 4_L30	Generic 100	Cummins D34
Max_Power,elec	16.4	24.6	32.8	100.0	161.1
SFC@MaxPower,e	0.28	0.28	0.28	0.33	0.23
Min_Power,elec	6.6	9.8	13.1	40.0	64.4
SFC@MinPower,e	0.31	0.31	0.31	0.37	0.25
Gen_eff.	0.9	0.9	0.9	0.9	0.9
Fuel Type	2	2	2	2	2
Ref.	Lilly 24/7	Lilly 24/7	Lilly 24/7	UMass	Cummins C-4815

*Mirrlees Blackstone MB 190

Diesel Engine Data

Engine	Cummins D35	Volvo TDF120	Cummins D09
Max_Pwr,gen	230.0	265.0	281.0
SFC at max	0.19	0.21	0.19
Min_Pwr,gen	92.0	106.0	112.4
SFC at min	0.21	0.21	0.21
motor eff.	0.90	0.90	0.90
Fuel Type	2	2	2
Reference	Cummins P-4934	Lilly, 22/36	Cummins C-4955

Genset Diesel Data

Engine	Cummins D35	Volvo TDF120	Cummins D09
Max_Power,elec	207.0	238.5	252.9
SFC@MaxPower,e	0.22	0.24	0.21
Min_Power,elec	82.8	95.4	101.2
SFC@MinPower,e	0.24	0.23	0.23
Gen_eff.	0.9	0.9	0.9
Fuel Type	2	2	2
Ref.	Cummins P-4934	Lilly, 22/36	Cummins C-4955

*Mirrlees Blackstone MB 190

Diesel Engine Data

Engine	Cummins KT 1150	6 MB 190*	Cummins KT 2300
Max_Pwr,gen	377.0	641.0	768.0
SFC at max	0.22	0.21	0.22
Min_Pwr,gen	150.8	256.4	307.2
SFC at min	0.24	0.24	0.24
motor eff.	0.90	0.90	0.90
Fuel Type	2	2	2
Reference	Lilly 24/5	Lilly 24/11	Lilly 24/5

Genset Diesel Data

Engine	Cummins KT 1150	6 MB 190*	Cummins KT 2300
Max_Power,elec	339.3	576.9	691.2
SFC@MaxPower,e	0.24	0.24	0.24
Min_Power,elec	135.7	230.8	276.5
SFC@MinPower,e	0.26	0.26	0.27
Gen_eff.	0.9	0.9	0.9
Fuel Type	2	2	2
Ref.	Lilly 24/5	Lilly 24/11	Lilly 24/5

*Mirrlees Blackstone MB 190

APPENDIX G

PHOTOVOLTAIC MODULE DATA

	EP-50	AEG PQ 10/40/01	F-SEC Module	Kyocera LA361J45V	MOBIL RA30-12	SHARP NT-11 H
Gt_ref	1000	1000	895	1000	1000	1000
Tc_ref	298	298	323.8	298	298	298
Isc_ref	1.8	2.41	0.3853	2.9	2.2	2.75
Voc_ref	55.5	22.4	20.8	20.7	18.9	21.6
Imp_ref	1.32	2.2	0.3417	2.74	1.94	2.55
Vmp_ref	38	17.45	16.63	16.7	15.5	17.5
MueIsc	0.0015	0.001495	0.002511	0.002	0.0016	0.001
MueVoc	-0.19425	-0.09009	-0.07781	-0.08	-0.00218	-0.067
tau_alfa	0.9	0.9	0.9	0.9	0.9	0.9
Eq	1.155	1.155	1.155	1.155	1.155	1.155
Ncs	66	40	40	40	36	36
Width	0.8	0.46	0.4	0.414	0.366	0.283
Length	1.525	1.076	1	1	1	1

APPENDIX H

POWER CONVERTER DATA

	Trace DR1512	Best M24-2500	Trace 2248	Trace DR3624	Best M48-5000	Generic 5000	Best M120-12000
Rectifier							
Max Rating	0	0	0	0	0	5000	0
Eff. at Max	0	0	0	0	0	90	0
Rating, Max Eff	0	0	0	0	0	250	0
Max Eff	0	0	0	0	0	90	0
Min Load	0	0	0	0	0	175	0
Inverter							
Max Rating	1500	2000	2200	3600	4000	5000	10000
Eff. at Max	85	90	87	85	90	90	90
Rating, Max Eff	50	200	250	50	200	250	1000
Max Eff	94	90	95	94	90	90	90
Min Load	8.4	48	50	60	96	175	240

Trace DR3624		Trace DR3424		Trace DR2412		TraceDR1524		Trace 1512		Trace 2248	
Watts	Eff.	Watts	Eff.	Watts	Eff.	Watts	Eff.	Watts	Eff.	Watts	Eff.
38	81.6	25	81.6	38	81.8	38	81.8	25	81.6	10	50.3
77	94.3	51	93.6	51	93.2	64	91.3	51	92.1	46	71.5
180	95.5	116	95.2	77	94.5	77	93.6	64	94.3	55	86.2
284	95.9	245	96.1	129	95.5	142	95.4	193	94.3	74	91.8
504	95.9	375	95.5	232	95.7	323	95.5	349	93.8	93	93.0
1010	94.6	997	93.0	375	95.5	504	94.5	530	92.3	112	94.0
1515	93.0	1515	91.1	517	95.0	971	91.3	997	88.4	141	94.6
1994	91.6	2007	89.1	1010	92.3	1515	87.7	1528	84.8	247	95.2
3497	87.3	2500	87.1	1515	90.2	2007	84.3	1994	80.9	538	94.3
3989	86.3	3005	85.0	1981	87.9	2500	80.9	2513	77.7	1389	90.7
4482	84.8	3497	83.0	2474	85.7	3018	77.9	3005	74.6	2008	88.3
4961	83.2	3989	80.9	2992	83.2					2675	85.8
		4482	78.9	3484	80.9					3197	83.5
		4974	77.1	3976	78.6					3488	82.4
				4482	76.3						
				4974	74.1						

APPENDIX I

PROOF: IRREDUCIBILITY OF THRUST COEFFICIENT FUNCTION

Given

$$C_T = 4(1-a) \tag{1}$$

and

$$Cp = 4(1-a)^2 \tag{2}$$

Solving for a in terms of C_T in equation 1 using the quadratic formula results in

$$a = \frac{1-\sqrt{1-C_T}}{2} \tag{3}$$

Substituting for a in equation 2 and simplifying results in

$$Cp = \tfrac{1}{2} C_T \left(1+\sqrt{1-C_T}\right) \tag{4}$$

Equation 4 can be rewritten as a cubic equation

$$C_T^3 - (4Cp)C_T + 4Cp^2 = 0 \tag{5}$$

The analytic solution of cubic equations is presented by Abramovitz (1972) for equations of the form

$$z^3 + a_2 z^2 + a_1 z + a_0 = 0 \tag{6}$$

so that for the Abramovitz solution

$$a_2 = 0; a_1 = (-4Cp); a_0 = (4Cp^2)$$

The Abramovitz solution then requires the creation of two interim parameters. The first solution is *q* where

$$q = \frac{1}{3}(a_1) - \frac{1}{9}(a_2)^2 \text{ which is } q = \frac{1}{3}(-4Cp) - \frac{1}{9}(0)^2 \text{ so that } q = -\frac{4}{3}Cp \tag{7}$$

The second parameter required by Abramovitz is r where

$$r = \frac{1}{6}(a_1 a_2 - 3a_0) - \frac{1}{27}a_2^3 \text{ which is } r = \frac{1}{6}((-4Cp)(0) - 3(4Cp^2)) - \frac{1}{27}0^3$$

so that $r = -2Cp^2$ (8)

The next step in the Abramovitz solution is to calculate the result of $q^3 + r^2$, which is

$$q^3 + r^2 = \left(\frac{-4}{3}Cp\right)^3 + \left(-2Cp^2\right)^2 = -\frac{64}{9}Cp^3 + 4Cp^4 \tag{9}$$

Evaluation of $-64/9\,Cp^3 + 4Cp^4$ over the range of possible Cp values (0 to .6) results in solutions which are always negative. According to Abramovitz, a cubic is *irreducible* when the solution to equation 9 is negative. Therefore, s numeric approach is appropriate. Figure 1 below shows the solutions to equation 9 as a function of *Cp*.

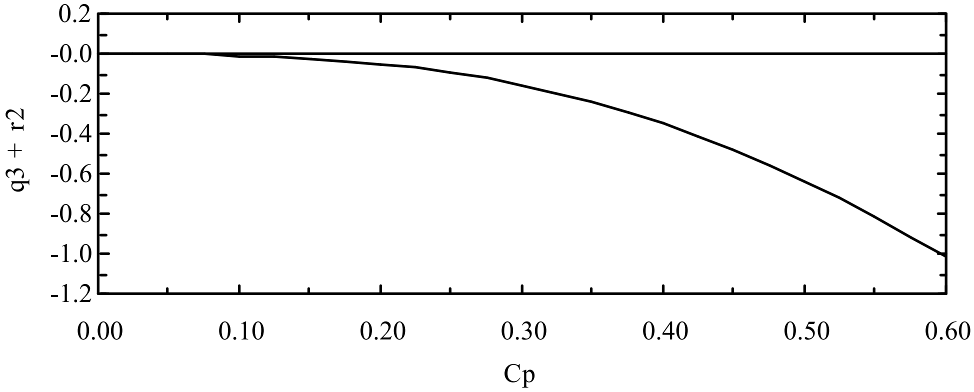


Figure 1 Solutions to equation 9 as a function of *Cp*.