HYBRID2- A HYBRID SYSTEM SIMULATION MODEL

THEORY MANUAL

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Abstract

This report describes the theoretical basis for Hybrid2, a computer simulation model for hybrid power systems. Hybrid power systems are designed for the generation and use of electrical power. They are independent of a large, centralized electricity grid and incorporate more than one type of power source. They may range in size from relatively large island grids to individual household power supplies.

This hybrid system computer model, developed at the University of Massachusetts and the National Renewable Energy Laboratory, is a comprehensive, flexible, user friendly model that allows a wide range of choices of system components and operating strategies. In general, a hybrid system might contain alternating current (AC) diesel generators, direct current (DC) diesel generators, an AC distribution system, a DC distribution system, loads, renewable power sources, energy storage, power converters, rotary converters, coupled diesel systems, dump loads, load management options, or a supervisory control system. Each of these can be modeled with the Hybrid2 code with a structure designed to mirror as closely as possible the structure of actual hybrid power systems. The code itself is based on a combined time series/probabilistic method.

This manual describes the operation of hybrid power systems and describes the theory behind the Hybrid2 computer code. It is intended to allow the user to understand the details of the calculations and considerations involved in the modeling process. This theory manual is a companion volume to the Hybrid2 User Manual (NREL/TP-440-21272), which describes the practical aspects of using the model. In addition to providing a detailed description of the structure of Hybrid2, this work discusses the principles of the model, including the details of the governing energy balance relationships. The individual module algorithms in the code(including power system, loads, renewable resource characterization, and economics) are described. In addition, major sections of the report are devoted to detailed summaries and documentation of the code component and subsystem algorithms.

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Nomenclature

This is a partial listing of symbols used in this report. It is divided according to Chapter.

Chapter 4

$D_{I,I}$	= Deferrable inventory input, kW
$D_{I,O}$	= Deferrable inventory output, kW
DL	= Power delivered from the diesel generator(s) (either bus), kW
DP	= Power dissipated in dump load, kW
DP_{Ex}	= Extra power in excess of dump load capacity, kW
erf(.)	= Error function.
F_{WPT}	= Wind power turbulence correction factor
LS	= Losses (both buses), kW
L_D	= Power delivered to the deferrable load (both buses), kW
L_O	= Power delivered to the optional load (both buses), kW
L_P	= Power delivered to the primary load (both buses), kW
$\overline{L}$	= Mean load, kW
N	= Instantaneous value of net load, kW.
N_{max}	= Maximum acceptable value of the net load, kW
$\overline{N}$	= Mean net load, kW
P_{DNL}	= Disregarded net load probability, -
PV	= Power supplied by PV array (either bus), kW
S_I	= Storage input, kW
S_O	= Storage output, kW
$\overline{S}$	= Mean photovoltaic power, kW
U	= Unmet load, kW
$\overline{V}$	= Mean wind speed, m/s
W	= Power delivered from all the wind turbine(s) (both buses), kW
$\overline{W}$	= Mean wind power, kW.
$\overline{W}_1$	= Mean power of one wind machine, kW
y	= Argument of error function, -
σ_L	= Standard deviation of load, kW
σ_N	= Standard deviation of the net load, kW
σ_W	= Standard deviation of the wind power, kW
σ_V	= Standard deviation of wind speed, m/s

Chapter 5, Sections 5.2 Power System and 5.3 Loads

a	= Constant limiting range of integration
L_i	= Sampled load, kW
$L_{transfer}$	= Converter loss during transfer, kW.
$\overline{L}$	= Average load over time step, kW
n	= Number of measured values for the load within the time step
N_1	= Instantaneous net load on bus 1, kW
N_2	= Instantaneous net load on bus 2, kW

$N_{1,at}$ = Net load on bus 1 after transfer, kW
$N_{1,bt}$ = Net load on bus 1 before transfer, kW
$N_{2,at}$ = Net load on bus 2 after transfer, kW
$N_{2,bt}$ = Net load on bus 2 before transfer, kW
$\overline{N}_1$ = Mean net load on bus 1, kW
$\overline{N}_2$ = Mean net load on bus 2, kW
p(.) = Probability density functions, assumed to be Gaussian, -
$\overline{P}_{1\to 2}$ = Average power transferred from bus 1 to bus 2, kW
$\overline{P}_{2\to 1}$ = Average power transferred from bus 2 to bus 1, kW
$P_{2\to 1,new}$ = Average power transferred after converter size limit is considered, kW
R_c = Rated power of converter, kW
x = Random variable; net load on bus 1
y(= Random variable; net load on bus 2; argument of error function
$\overline{y}$ = Mean value of y
$\overline{y}_{y<a}$ = Fractional mean value of y when y less than "a"
$\overline{y}_{y\geq a}$ = Fractional mean value of y when y equal to or greater than "a"
z = Random variable; argument of probability density function; net load after transfer of power between buses.
$\overline{z}$ = Mean value of z
u = Variable of integration
σ_L = Standard deviation of load, kW
σ_x = Standard deviation of x
σ_1 = Standard deviation of net load on bus 1, kW
σ_2 = Standard deviation of net load on bus 2, kW

Chapter 5, Section 5.5 Economics

C(n) = System operating costs in year n, $/year
C_A = Annual payment on loan for equipment, $/year
$C_{A,B}$ = Annual payment on loan for equipment (base case), $/year
$C_{A,L}$ = Levelized annual payment for equipment, $/year
$C_{A,L,B}$ = Levelized annual payment for equipment (base case), $/year
C_{Admin} = Annual administrative cost, $/year
$C_{Admin,B}$ = Annual administrative costs (base case), $/year
$C_B(n)$ = System operating costs in year n (base case), $/year
C_{Bat} = Battery bank capital costs, $
C_{BatI} = Battery installation costs, $
C_{BOS} = Balance of system costs, $
C_C = Power converters capital costs, $
$C_{Cap}(n)$ = Payment for equipment capital costs in year n, $/year
$C_{Cap,B}(n)$ = Payment for equipment capital costs in year n (base case), $/year
C_{CI} = Power converters installation costs, $
C_D = Diesel capital costs, $
$C_{D,B}$ = Diesel capital costs (base case), $

c_{Def} = Cost of energy to deferrable load, $/kWh
C_{DI} = Diesel installation costs, $
$C_{DI,B}$ = Diesel installation costs (base case), $
C_{dp} = Down payment, $
$C_{dp,B}$ = Down payment, base case, $
C_{Dump} = Dump load capital costs, $
C_{DumpI} = Dump load installation costs, $
C_E = Equipment related costs, $
C_{Ext} = Installed cost of line extension to existing grid, $
c_F = Cost of fuel, $/unit
$C_F(n)$ = Cost of fuel in year n, $/year
$C_{F,B}(n)$ = Cost of fuel in year n (base case), $/year
$C_{F,L}$ = Levelized cost of fuel, $/year
$C_{F,L,B}$ = Levelized cost of fuel (base case), $/year
C_I = Total installation costs, $
c_I = System installation overhead cost fraction,-
$C_M(n)$ = Total non-fuel operation and maintenance cost in year n, $/year
$C_{M,B}(n)$ = Total non-fuel operation and maintenance cost in year n (base case), $/year
$c_{M,Bat}$ = Battery annual operation and maintenance costs, fraction of capital cost
$c_{M,D}$ = Diesel related operation and maintenance costs, $/kWh
$C_{M,L}$ = Total levelized non-fuel operation and maintenance cost, $/year
$C_{M,L,B}$ = Total levelized non-fuel operation and maintenance cost (base case), $/year
$C_{M,Sys}$ = General system operation and maintenance cost, $/year
$C_{M,Sys,B}$ = General system operation and maintenance costs (base case), $/year
$c_{M,W}$ = Wind turbine operation and maintenance costs, $/kWh
C_{MPPT} = Capital cost of maximum power point tracker, $
C_O = Installed cost of optional load equipment, $
COE = Levelized cost of energy, $/kWh
COE' = Levelized cost of energy, modified for direct comparisons, $/kWh
COE_B = Levelized cost of energy, (base case) $/kWh
COE_R = Levelized cost of energy difference in retrofit system, $/kWh
COE'_R = Levelized cost of energy difference in retrofit system, modified for direct comparisons, $/kWh
c_{Opt} = Cost of energy to optional load, $/kWh
c_{Prim} = Cost of energy to primary load, $/kWh
C_{PV} = Capital cost of photovoltaics, $
C_{PVI} = Installation cost of photovoltaics, $
C_{PVR} = Capital cost of photovoltaics racks and/or trackers, $
$C_R(n)$ = Total yearly replacement costs, $/year
$C_{R,B}(n)$ = Yearly replacement cost for diesels (base case), $/year
$C_{R,Di}$ = Diesel overhaul costs, $
$C_{R,L}$ = Levelized diesel overhaul costs, $
$C_{R,L,B}$ = Levelized diesel overhaul costs (base case), $
$C_{R,Wi}$ = Total overhaul cost for i^{th} wind turbine, $

$C_{R,X}(n)$ = Yearly replacement cost for component "X", $/year
C_S = System installed capital cost, $
$C_{S,B}$ = System installed capital cost (base case), $
C_{Sh} = Shipping costs, $
C_T = Tariff costs, $
C_W = Total wind turbine capital cost, $
$C_{WD,AC}$ = Capital cost of domestically purchased AC wind turbines, $
$C_{WD,DC}$ = Capital cost of domestically purchased DC wind turbines, $
$C_{WF,AC}$ = Capital cost of internationally purchased AC wind turbines, $
$C_{WF,DC}$ = Capital cost of internationally purchased DC wind turbines, $
$C_{WI,AC}$ = Installation cost of AC wind turbines, $
$C_{WI,DC}$ = Installation cost of DC wind turbines, $
$C_{WT,AC}$ = Capital cost of tower for AC wind turbines, $
$C_{WT,DC}$ = Capital cost of tower for DC wind turbines, $
d = Discount rate, fraction/year
D(n) = Depreciation in year n, $
$D_B(n)$ = Depreciation in year n (base case), $
DPP = Discounted payback period, years
$\bar{F}$ = Average hourly total diesel fuel consumption, units/hr
$\bar{F}_B$ = Average hourly total diesel fuel consumption (base case), fuel units/hr
f = Fuel inflation rate, fraction/year
f_{dp} = Capital cost down payment fraction, -
f_s = Fractional salvage value of system equipment, -
g = General inflation rate, fraction/year
i = Loan interest rate, fraction/year
I(n) = Revenue in year n, $/year
$I_B(n)$ = Revenue in year n (base case), $/year
$I_{net}(n)$ = Net revenue in year n, $/year
$I_{net,B}(n)$ = Net revenue in year n (base case), $/year
$I_{Net,R}(n)$ = Net revenue difference in year n (retrofit), $/year
$I_R(n)$ = Retrofit system revenue difference in year n, $/year
N = Financial life of system, years
N_D = Number of diesel generator sets
$N_{D,B}$ = Number of diesel generator sets (base case)
N_W = Number of wind turbines
Pr(n) = Profit from retrofit system in year n, $/year
$P_{R,AC}$ = Total rated power of AC connected WTGs, kW
$P_{R,Bat}$ = Nominal battery capacity, kW
$P_{R,C}$ = Rated power of the converters, kW
$P_{R,D}$ = Rated power of diesels, kW
$P_{R,DC}$ = Total rated power of DC connected WTGs, kW
$P_{R,Dump}$ = Rated power of dump load, kW
$P_{R,PV}$ = Rated power of photovoltaics, kW
$Pr_B(n)$ = Profit from base case system in year n, $/year
Pr_L = Levelized system profit, $

$Pr_{L,R}(n)$ = Levelized profit difference in retrofit system in year n, $/year
$Pr_R(n)$ = Retrofit system profit difference in year n, $
$\overline{P}_D$ = Average power from diesels, kW
$\overline{P}_{Def}$ = Average power to deferrable load, kW
$\overline{P}_{Over}$ = Average overload power, kW
$\overline{P}_{Over,B}$ = Average overload power (base case), kW
$\overline{P}_{Opt}$ = Average power to optional load, kW
$\overline{P}_{Prim}$ = Average power to primary load, kW
$\overline{P}_{PV}$ = Average power from photovoltaics, kW
$\overline{P}_W$ = Average wind power, kW
r = Rate of return on investment, fraction/year
S = Salvage value of system equipment, $
S_B = Salvage value of system equipment (base case), $
S_L = Levelized salvage value of system equipment, $
$S_{L,B}$ = Levelized salvage value of system equipment (base case), $
SPP = Simple payback period, years
SPP_R = Simple payback period for retrofit, years
t = Corporate tax rate, -
T_{Bat} = Battery life, years
t_C = Renewable energy production tax credit rate, $/kWh
T_{Di} = Operating time of diesel engine i, hrs
T_E = Equipment depreciation time, years
T_G = Loan grace period, years
T_L = Loan period, years
$T_{R,C}$ = Period between power converter replacements, years
$T_{R,Di}$ = Diesel overhaul interval, years
$t_{R,Di}$ = Period between diesel overhauls, hrs
$T_{R,Dump}$ = Period between dump load replacements, years
$T_{R,PV}$ = Time between photovoltaics replacements, years
$T_{R,Wi}$ = Time between overhauls for wind turbine i
T_{Sim} = Simulation length, hours
Tx(n) = Tax payment in year n, $
$Tx_B(n)$ = Tax payment in year n (base case), $
X = Arbitrary cost or income, $
X(n) = Arbitrary system cost in year n, $
X_L = Levelized cost or income, $
X_{NPW} = Net present worth of cost or income, $
$X_{PW}(n)$ = Present worth of cost or income in year n, $
Δ_{Bat} = Battery size scale factor, -
$\Delta_{W,AC}$ = Scale factor for AC connected wind turbines, -
$\Delta_{W,DC}$ = Scale factor for DC connected wind turbines, -
ϕ = Ratio used in finding discounted payback period, -

Chapter 5, Section 5.8 Gap Filler

$[C_{j,k}]$	= Cumulative transition probability matrix
j	= Index ranging from 1 to N
k	= Index ranging from 1 to N
N	= Number of bins
Nj	= Total transitions from bin j
Nj,k	= Number of transitions from bin j to bin k
r	= Random number between 0 and 1, -
Tj,k	= Probability of making a transition from bin j to bin k
$[T_{j,k}]$	= Transition Probability Matrix
X_{high}	= Greatest value of data
x_i	= Time series data, i^{th} value
X_{low}	= Lowest value of data
$\{x\}$	= Set of time series data
Δ .	= Bin width

Chapter 6, Section 6.1 Wind Turbines

f	= Frequency, Hz
f_{lo}	= Lower limit of integration of power spectral density, Hz
$f_{lo,1}$	= Frequency corresponding to $1/\Delta t_1$, Hz
$f_{lo,2}$	= Frequency corresponding to $1/\Delta t_2$, Hz
f_{up}	= Upper limit of integration of power spectral density, Hz
F_{WPT}	= Wind power turbulence factor, -
Fv	= Fraction of variance, -
H	= Height above ground level, m
H_{site}	= Site altitude, m
H_1,H_2	= Heights above ground level used adjustment of wind speed, m
L	= Turbulence integral length scale, m
lapse	= Adiabatic lapse rate, -0.00638 K/m.
P	= Power, kW
P_i	= Sampled value of power, kW
$p_1(V)$	= Probability density function of wind speed based on averaging times Δt_2 long, -
$p_2(V)$	= Probability density function of wind speed based on averaging times Δt_1 long, -
$P_{\Delta t_1}(.)$	= Power curve based on averaging times Δt_1 long, kW
$P_{\Delta t_2}(.)$	= Power curve based on averaging times Δt_2 long, kW
$\overline{P}$	= Mean wind power over time step, kW
Pr_{site}	= Mean atmospheric pressure at site, mm Hg
$Pr_{SL,0}$	= Atmospheric pressure at standard conditions, 760 mm Hg.
S(f)	= Power spectral density of turbulent wind speed, $(m/s)^2$/Hz
T_{SL}	= Sea level temperature, K
$T_{SL,0}$	= Temperature at standard conditions, K

T_{site} = Site mean temperature, K
TI = Turbulence intensity of wind speed, -
V = Wind speed, m/s
V_i = Sampled value of wind speed, m/s
V_1, V_2 = Wind speed at heights 1 and 2, m/s
$\overline{V}$ = Mean wind speed over time step, m/s.
$\overline{V}_1$ = Wind speed averaged over time period Δt_1.
Z_0 = Surface roughness height, m
α = Power law exponent, -.
Δt_1 = Averaging time step used in power curve estimate, sec
Δt_2 = Averaging time step to which power curve is adjusted, sec
ρ = Air density at site, kg/m^2
ρ_0 = Air density at standard conditions (293 K), kg/m^2
σ_P = Standard deviation of wind power, kW
σ_V = Standard deviation of wind speed, m/s
σ_{V_1} = Standard deviation of wind speed based on averaging times Δt_1. long, m/s

Chapter 6, Section 6.2 Photovoltaic Panels

A = PV panel curve fitting parameter.
A_C = Area of photovoltaic panel, m^2
A_{ref} = PV panel curve Fitting Parameter at Reference Conditions
$G_{T,NOCT}$ = Solar irradiance at normal operating conditions, W/m^2
$G_{T,SOC}$ = Solar irradiance at standard conditions, W/m^2
$\overline{G}$ = Average solar irradiance on a horizontal surface, W/m^2
$\overline{G}_T$ = Average solar irradiance incident on the PV panel, W/m^2,
I = Current, A
I_0 = Diode reverse saturation current
$I_{0,ref}$ = Current at Reference Conditions, A
I_D = Diode current, A
I_L = Light current, A
$I_{L,ref}$ = Light current at reference conditions, W/m^2
I_{mp} = Maximum power point current, A
$I_{mp,ref}$ = Maximum power point current at reference conditions, A
I_{sc} = PV panel short circuit current, A
N_S = Number of cells in series in photovoltaic panel, -
R_S = Series resistance in PV cell, Ohms
R_{sh} = Shunt resistance in PV cell, Ohms
T_a = Ambient temperature, K
$T_{c,NOCT}$ = PV cell temperature at normal operating conditions, K
V_{mp} = Maximum power point voltage, V
T_1, T_2 = Temperatures near the reference temperature
$T_{c,SOC}$ = PV panel temperature at standard conditions, K

T_c = PV panel temperature, K
$T_{c,ref}$ = PV panel temperature at reference conditions, K
U_L = PV panel loss coefficient, W/C m^2
V = Voltage, V
$V_{mp,ref}$ = Maximum power point voltage at reference conditions, V
V_{oc} = Open circuit voltage, V
$V_{oc,ref}$ = Open circuit voltage at reference conditions, V
α = Absorbed radiation fraction on the panel surface, -
η_c = Efficiency of the panel in converting sunlight to electricity
$\mu_{I,sc}$ = Short circuit current temperature coefficient, A/C
$\mu_{V,oc}$ = Open circuit voltage temperature coefficient, V/C
τ = Transmittance of covers over the cells, -

Chapter 6, Section 6.3 Diesel Generators

a = No load fuel consumption, fuel units/hr
b = Slope of fuel vs. power curve, fuel units/kWh
F = Fuel consumption, fuel units/hr

Chapter 6, Section 6.4 Batteries

A = Constant relating internal battery voltage to state of charge, V
a1,...,a5 = Constants used in fit of cycles to failure vs. cycle depth of discharge
c = Kinetic Battery Model capacity ratio, -
C = Constant relating internal battery voltage to state of charge, V
C_F = Battery cycles to failure, -
D = (i) Constant relating internal battery voltage to state of charge, -
D = (ii) Damage done to battery due to charge/discharge cycles, -
E = Battery internal voltage, V
E_0 = Fully charged internal battery voltage, V
I = Battery current, A
I_c = Charging current, A
$I_{c,max}$ = Maximum charging current, A
I_d = Discharge current, A
$I_{d,max}$ = Maximum discharge current, A
k = Kinetic Battery Model rate constant, -
L_{chg} = Power loss in charging, W
N_i = Number of cycles corresponding to specified fractional depth of discharge, -
P_{Need} = Power required from battery in time step, W
q_{max} = Maximum battery capacity, Ah
q_0 = Total battery charge at beginning of time step, Ah
q_1 = Kinetic Battery Model "available" charge, Ah
$q_{1,0}$ = Available charge at the beginning of time step, Ah
q_2 = Kinetic Battery Model "bound" charge, A
$q_{2,0}$ = Bound charge at the beginning of time step, Ah
R = Fractional depth of discharge, -
R_0 = Kinetic Battery Model internal resistance, Ω

V	= Battery terminal voltage, V
$V(q,I)$	= Voltage (as function of state of charge and current), V
V_{nom}	= Nominal battery voltage, V
X	= Non-dimensional state of charge of battery, -
Δt	= Length of time step of model, hr

Chapter 6, Section 6.6 Power Converters

B	= Constant relating input to output of power converter
B_{in}	= Constant relating input to output of power converter (referred to input)
B_{out}	= Constant relating input to output of power converter (referred to output)
L_{nl}	= No load loss of power converter, kW
P_{in}	= Input power, kW
P_{NL}	= No load power, kW
P_{out}	= Output power, kW
P_R	= Rated input or output power of converter, kW
η_R	= Rated efficiency of power converter, -

Chapter 7, Section 7.1 Multiple Wind Turbines

a	= Coherence decay constant, taken to be 50
k	= Constant relating wind speed to wind turbine power (assuming linearity), kW/(m/s)
L	= Integral length scale of turbulence, m
N	= Number of wind turbines in array, -
$\overline{P}_1$	= Mean power from 1 wind turbine, kW
$\overline{P}_N$	= Mean power from N wind turbines, kW
$S_1(f)$	= Power spectra of fluctuating wind at one point, $(m/s)^2/Hz$
$S_N(f)$	= Power spectra of fluctuating wind at N points, $(m/s)^2/Hz$
$\overline{V}$	= Mean wind speed, m/s.
x_{ij}	= Spacing between points i and j, m
$\gamma_{ij}^2(f)$	= Coherence, -
$\sigma_{P,1}$	= Standard deviation of power from one wind turbine, kW
$\sigma_{P,N}$	= Standard deviation of power from N wind turbines, kW
σ_V	= Standard deviation of wind speed, m/s

Chapter 7, Section 7.2 Photovoltaic Array

A_i	= Anisotropy index, given by $A_i = \overline{G}_b / \overline{G}_o$, -
B	= Term in Equation of Time, given by B = (n-1) 360/365, -
$C_1,...,C_5$	= Constants used in calculation of solar or surface azimuth, -
E	= Correction for the Equation of Time, hrs.
f	= Modulating factor $(\overline{G}_b / \overline{G})^{1/2}$, –

$\overline{G}_o$ = Average solar irradiance on horizontal surface outside earth's atmosphere, W/m^2

G_{sc} = Solar constant (1367 W/m^2)

$\overline{G}$ = Average (over time step) of total solar irradiance on horizontal surface, W/m^2

$\overline{G}_b$ = Average (over time step) of beam component of solar irradiance, W/m^2

$\overline{G}_d$ = Average (over time step) of diffuse component of solar irradiance, W/m^2

$\overline{G}_T$ = Average (over time step) of total solar irradiance on tilted surface, W/m^2

k_T = Average (over time step) of clearness index, given by $k_T = \overline{G} / \overline{G}_0$, -

L = Longitude of the site under analysis, deg

L_{st} = Standard meridian for the local time zone, deg

n = Julian day

R_b = Ratio of beam radiation on slope to that on horizontal, -

t_{sol} = Solar time, hrs

t_{std} = Standard time, hrs

β = PV array slope, deg

γ = PV array surface azimuth angle, deg

γ_s = Solar azimuth angle, deg

δ = Declination angle of sun, deg

θ = Angle of incidence of beam radiation on surface, deg

θ_z = Zenith angle (the angle between the sun's rays and a line perpendicular to the earth's surface), deg

ρ_g = Ground reflectance, -

ϕ = Site latitude, deg

ω = Hour angle, deg

ω_{es} = Sunrise hour angle, deg

ω_2 = Hour angle at the end of a time step, deg

ω_1 = Hour angle at the start of a time step, deg

Chapter 7, Section 7.4 Dispatch, 7.5 Diesel Fuel Use

a_1 = No load fuel consumption of 1st diesel, fuel units/hr

$a_{i,k}$ = No load fuel consumption of the kth diesel in the ith configuration, fuel units/hr

b_1 = Incremental fuel consumption of 1st diesel, fuel units/kWh

$b_{i,k}$ = Slope of fuel vs. power curve for the kth diesel in the ith configuration, fuel units/kWh

$F_{i,m}$ = Minimum allowed fuel consumption for configuration, fuel units/hr

$F_m(L)$ = Minimum fuel consumption at power level L in configuration, fuel units/hr

i = Configuration number, -

j = Ordered index of states, -

k = Dummy index, -

L = Load on diesels, kW

N_d = Number of diesels, -

p(N) = Probability density function of net load, -.

$P_{lo,j}$ = Lower power level of the jth state, kW

$P_{m,i,k}$ = Minimum allowed power level of the k^{th}diesel in the i_{th} configuration, kW

$P_{m,k}$ = Minimum allowed power level of the k^{th}diesel, kW

P_{min} = Total minimum power of ith configuration, kW

$P_{min,1}$ = Minimum power level of 1st diesel, kW

$P_{R,1}$ = Rated power level of 1st diesel, kW

$P_{R,k}$ = Ordered rated diesel power, kW

$P_{up,j}$ = Upper power level of the jth state, kW

1. Introduction

1.1 Overview

Hybrid power systems are designed for the generation and use of electrical power. They are independent of a large centralized electricity grid, incorporate more than one type of power source, and are typically found in remote locations. Diesel generators are portable, modular, and have a high power-to-weight ratio, which makes them an ideal power source for these hybrid power systems. In an effort to conserve expensive diesel fuel, hybrid systems often include some other power source such as wind, solar, or hydropower. To maximize the use of the renewable resource, the size and operation of the hybrid system components need to be matched to the load and the available renewable resource. This is best accomplished by using computer models.

These models of hybrid systems allow the user to easily consider a number of system configurations and operating strategies to optimize the system design. Hybrid2, a hybrid system computer model designed at the University of Massachusetts and the National Renewable Energy Laboratory, is a comprehensive, flexible, user-friendly model that allows a wide range of choices of system components and operating strategies. A hybrid system might contain alternating current (AC) diesel generators, direct current (DC) diesel generators, an AC distribution system, a DC distribution system, loads, renewable power sources (wind turbines or photovoltaic power sources), energy storage, power converters, rotary converters, coupled diesel systems, dump loads, load management options, or a supervisory control system. Each of these can be modeled with the Hybrid2 code.

The Hybrid2 model has been developed to assist a designer in sizing hybrid power system hardware and in selecting operating options on the basis of overall system performance and economics when site specific conditions and load profiles are known. It cannot, however, tell the designer how to implement the necessary system controls and to provide for adequate voltage or frequency regulation. Other analytical tools may be needed for the detailed design of the hybrid power system. Nonetheless, Hybrid2 can be of great value in narrowing the options and reducing the need for more detailed analysis.

This manual describes the operation of hybrid power systems and describes the theory behind the Hybrid2 computer code. It is intended to allow the user to understand the details of the calculations and considerations involved in the modeling process. This theory manual is a companion volume to the user manual, which describes the practical aspects of using the model. Each chapter of this theory manual begins with an executive summary summarizing the contents of the chapter. This is followed with more detailed information. In Chapters 6 and 7, the executive summary is followed by an overview of the inputs needed for the section of the model being discussed, details of model inputs, and finally, the theory behind the section of the model under consideration.

1.2 How to Use the Manual

Each of the main features of the Hybrid2 model is described in the following chapters. The chapters and major sections begin with an executive summary. They then describe the various aspects of the model in more depth. For an overview of the model, it is suggested that the user read only the executive summaries. The user who is interested in the details may wish to bypass the executive summaries and read the remainder of the chapters instead. Chapter 2 describes all of the components and the component features that are included in the hybrid systems modeled on Hybrid2. Chapter 3 describes the overall model structure as it is implemented in the code.

Chapter 4 includes an explanation of the principles behind the modeling method used on Hybrid2. Chapter 5 details calculations and inputs used in the code to determine power flows in the system, to handle the various types of loads, and to calculate system economics. Chapter 6 describes the models used to model each system component (such as wind turbines, photovoltaic cells, or diesels) and the inputs to those models. Chapter 7 includes the algorithms used to model the operation of multiple individual components that are grouped into subsystems (such as wind farms or PV panels).

2. Background

2.1 Executive Summary

This manual describes the theory behind the Hybrid2 computer code, which analyzes the operation of hybrid power systems. The Hybrid2 computer code structure was designed to mirror as closely as possible the structure of actual hybrid power systems. Before proceeding, it is useful to review the main features of hybrid power systems and to put this model into the context of ongoing hybrid power system modeling efforts.

Hybrid power systems are designed for the generation and use of electrical power. They are independent of a large, centralized electricity grid and incorporate more than one type of power source. They may range in size from relatively large island grids of many megawatts to individual household power supplies on the order of one kilowatt (kW). Larger, systems (greater than 100 kW nominal capacity) are normally based on alternating current (AC) of fixed frequency. Larger isolated AC systems include at least the following: conventional AC generators, an electrical distribution system, and distributed AC loads. A hybrid system of this size could also include additional power sources such as renewables (wind turbines, photovoltaic panels, hydroelectric generators) and storage. Medium-size systems (greater than 10 kW nominal capacity) may also be based primarily on AC, as are the larger systems. They may also include a significant direct current (DC) component. The DC side could include diesel generators, renewable generators, and storage. Small systems may be all or primarily DC systems. The DC components would be of the same type as those used in the medium-size systems.

A hybrid power system might contain AC diesel generators, DC diesel generators, an AC distribution system, a DC distribution system, loads, renewable power sources (wind turbines, or photovoltaic power sources), energy storage, power converters, rotary converters, coupled diesel systems, dump loads, load management options, or a supervisory control system. Each of these can be modeled with the Hybrid2 code. Hybrid systems might also include biomass or hydroelectric generators, but these are not specifically included in Hybrid2 at this time.

In recent times, many simulation models have been developed for hybrid power systems. Generally, one can classify these models into two broad categories: logistical models and dynamic models. Logistical models are used primarily for long-term performance predictions, for component sizing, and for providing input to economic analyses. Dynamic models are used primarily for component design, assessment of system stability, and determination of power quality. They are generally used for hybrid power systems with no storage capability, or systems with minimal storage, such as a flywheel. The work to be presented here is based on the application of a new logistical model, Hybrid2. Hybrid2 is the result of a number of years of work at the University of Massachusetts and the National Renewable Energy Laboratory. The model includes both a time series and a statistical approach to determining the operation of the hybrid system. This allows the model to determine long-term system performance while taking into consideration the effect of the short term variability of the renewable resources. The rest of this manual describes the theory behind the calculations in Hybrid2.

2.2 What is a Hybrid Power System?

This manual describes the theory behind the Hybrid2 computer code, which analyzes the operation of hybrid power systems. The Hybrid2 computer code structure was designed to mirror as closely as possible the structure of actual hybrid power systems. Before addressing the

structure of the code and the principles and theory behind the code, the key facets of typical hybrid power systems need to be understood.

2.2.1 Hybrid Power Systems

Hybrid power systems are designed for the generation and use of electrical power. They are independent of a large, centralized electricity grid and incorporate more than one type of power source. They may range in size from relatively large island grids of many megawatts to individual household power supplies on the order of one kilowatt.

Hybrid power systems that deliver alternating current of fixed frequency are an emerging technology for supplying electric power in remote locations. They can take advantage of the ease of transforming the AC power to higher voltages to minimize power loss in transferring the power over relatively long distances. Isolated AC systems include at least the following: conventional AC diesel generators, an electrical distribution system, and distributed AC loads. A hybrid system could also include additional power sources such as renewables (wind turbines, photovoltaic panels) and storage. (Note that storage is actually both a source and a load).

Larger systems, nominally above 100 kW, typically consist of AC-connected diesel generators, renewable sources, loads, and occasionally include energy storage subsystems. Below 100 kW, combinations of both AC and DC-connected components are common as is use of energy storage. The DC components could include diesel generators, renewable sources, and storage. Small hybrid systems serving only DC loads, typically less than 5 kW, have been used commercially for many years at remote sites for telecommunications repeater stations and other low power applications.

In general a hybrid system might contain AC diesel generators, DC diesel generators, an AC distribution system, a DC distribution system, loads, renewable power sources (wind turbines, or photovoltaic power sources), energy storage, power converters, rotary converters, coupled diesel systems, dump loads, load management options, or a supervisory control system. Each of these can be modeled with the Hybrid2 code. Hybrid systems might also include biomass or hydroelectric generators, but these are not specifically included in Hybrid2 at this time. A schematic of the possibilities for hybrid systems is illustrated in Figure 2.1. The operation of each of these components and the interactions between components is described below.

2.2.2 AC Diesel Generators

Conventional generators are normally diesel engines directly coupled to synchronous generators. The frequency of the AC power is maintained by a governor on one of the engines. The governor functions by adjusting the flow of fuel to the engine to keep the engine speed and the generator speed essentially constant. The grid frequency is directly related to the speed of the generator, and is, therefore, maintained at the desired level. In most of the western hemisphere, the grid frequency is 60 Hz. In Europe and many other parts of the world, the frequency is 50 Hz.

AC networks supply two types of power to their loads: real and reactive. Real power is power that is actually consumed, such as in a space heater. Reactive power supplies the magnetic fields used in motors. It is not actually consumed, but the currents associated with reactive power do increase losses in the system. The reactive power in a conventional AC system is supplied by the synchronous generator (as is the real power). This is done in conjunction with the voltage regulator on the generator.

From the preceding discussion it is apparent that, in a conventional AC power system, there must always be at least one diesel generator connected to the network. It is required to set the grid frequency and to supply the reactive power. It is possible to modify the system so that the diesel generator is not always required, but in that case other components must be added. These other components could include an inverter, a rotary converter or a synchronous condenser. An inverter is a device (typically a solid-state electronic device) that provides AC power from a DC source. A rotary converter is essentially an electromechanical inverter. It requires a separate controller to set the frequency. A synchronous condenser is a synchronous generator connected to the network and allowed to spin at a speed determined by the grid frequency. Operating in conjunction with a voltage regulator, it supplies reactive power to the network.

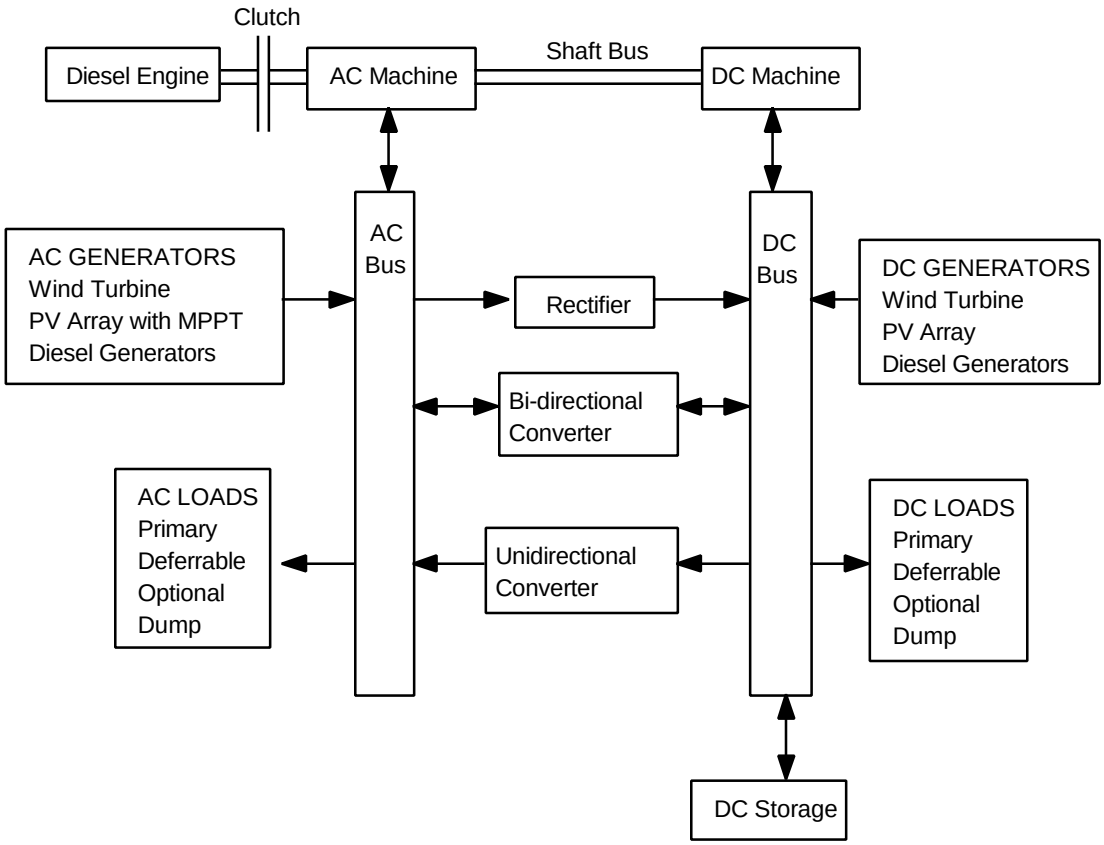


Figure 2.1. Hybrid Power System Configuration.

There may be more than one diesel generator supplying power to the network. These are normally connected to an AC bus in the power house where the diesels are located. This bus provides power to the distribution network. When there is more than one diesel generator, a control system must be employed to properly allocate the power from the diesels. These control systems may take a variety of forms, especially as computerized control systems become more widespread. One approach is to use one lead diesel to set the grid frequency and to set the others to run at fixed throttle. In traditional systems, the fixed throttle is set manually by an operator. With modern controllers, the "fixed" throttle position may be adjusted as often as desired to optimize fuel use.

2.2.3 DC Diesel Generators

Diesel generators may be used to supply DC loads directly. In practical terms, a DC diesel generator would be an AC diesel generator with a dedicated rectifier. It is possible to have multiple DC diesel generators, but that situation would probably be relatively rare. If multiple diesels were used, they would be connected together via a DC bus.

2.2.4 Distribution System

The distribution system carries the power generated at the power house to the consumers. A conventional AC distribution system consists primarily of transformers, conductors, and utility poles. Step-up transformers at the power house convert the voltage of the generators (typically 480 V or 120-240 V in smaller systems) to much higher levels (for example, 13,400 V). This reduces the current in the conductors, and hence the losses. The conductors, which carry the current, are copper or aluminum wire. They are normally carried in the air by utility poles, although they are sometimes buried. Adjacent to the loads, step-down transformers convert the AC voltage to a lower level again. This is typically 480 V for industrial or commercial users, or 120-240 V for residential or other smaller loads.

Larger networks may also include a transmission system that is separate from the distribution system. Its voltage is higher than that of the distribution system and is used when large amounts of current must be transmitted over longer distances.

2.2.5 DC Distribution

Direct current is seldom used when the load is very far from the generators because, historically, it has been more difficult to change the voltage of DC power than to change the voltage of the AC power. Sending low voltage current long distances results in high losses or requires the use of very large diameter conductors. With advances in power electronics, it is now possible to "transform" DC power within certain limits. Accordingly, it is possible that there will be a greater use of DC distribution systems in the future.

2.2.6 Loads

Electrical loads convert the electrical power into a useful form. AC loads are primarily of two types: resistive and inductive. Resistive loads include incandescent light bulbs, space and water heaters, etc. Devices with electric motors are both resistive and inductive. They are a major cause of the need for a source of reactive power. DC sources can only supply resistive loads. DC loads may have an inductive component, but this only causes transient voltage and current fluctuations during changes in system operation.

2.2.7 Renewable Power Sources

Wind Turbines

Larger isolated AC electrical systems can use wind turbines of the type connected to large central grids. The turbines are typically 10 kW to 500 kW. Most of the wind turbines larger than 50 kW use induction generators. They turn at a nearly fixed speed (based on the frequency of the AC network to which they are connected). They also require an external source to supply their reactive power requirements. Thus, in hybrid power systems they operate only when at least one diesel generator is operating. Some larger wind turbines use synchronous generators. With

suitable controls, they may control grid frequency and provide reactive power. In such cases, these turbines could operate without any diesel generators on line. Other turbines operate directly with power electronic converters. Such machines may also be able to run without the presence of a diesel generator.

There are a number of wind turbines that supply DC power as the principal output. These machines are typically in the smaller size range (10 kW or less). With suitable controls or converters they may operate in conjunction with AC or DC loads.

Photovoltaic Panels

Sunlight may be used to generate electricity directly via photovoltaic cells. Photovoltaic panels are inherently a DC power source. As such, they usually operate in conjunction with storage and a separate DC bus. In larger systems, they may be coupled with a dedicated inverter and thus act as a de facto AC power source.

Other Renewable Power Sources

Hydroelectric turbines have historically been used with synchronous generators and are primary sources of power in many isolated areas. They may also be incorporated into hybrid power systems in ways very similar to those with wind turbines. In the future, renewable sources such as biomass or solar thermal may also be used in hybrid power systems for remote areas. (None of these other renewable sources is dealt with in the present version of Hybrid2.)

2.2.8 Storage

The use of energy storage is very common with smaller hybrid power systems. Storage is also sometimes used with larger, isolated AC networks, although this is less common. When storage is used with AC networks, it is most likely to be used for smoothing of short term power fluctuations. This is in contrast to its use in smaller systems where the generation and use of relatively large amounts of energy may be shifted from one time to another. Energy storage is most commonly accomplished through the use of batteries. Batteries are usually of the lead-acid type, although nickel-cadmium batteries are also occasionally used. Assuming batteries to be the storage medium, it should be noted that they are inherently DC devices. Sometimes storage is accomplished via pumped water storage or flywheels, but this is not as common.

2.2.9 Power Converters

For storage or other DC components to be used in conjunction with AC networks or AC loads, some type of power conversion capability is required. There are two types of power conversion functions of particular significance for hybrid power systems: rectifying and inverting. Sometimes these functions are incorporated into a single device or assembly; other times they are not. Rectifiers convert AC power to DC. They are commonly used to charge batteries from an AC source. They are relatively simple, inexpensive, and efficient devices. Inverters convert DC power to AC power. They are used to supply individual AC loads from a DC source or battery bank. Inverters are electronic devices. The most modern ones are based on switching power transistors at high frequency. There is rapid development is this area, but inverters are still relatively complex and expensive. They are also susceptible to voltage and current irregularities.

Most inverters are of one of two types: line-commutated or self-commutated. Line-commutated inverters require the presence of an external AC line. Thus they cannot set the grid frequency if,

for example, all of the diesel generators are turned off. Self-commutated inverters control frequency themselves. They do not normally operate together with another device that also sets the grid frequency. In this case they are sometimes known as "switched mode" inverters. There are inverters that can operate either independently or in parallel with another generator. These are the most versatile, but presently they are also the most expensive.

2.2.10 Rotary Converters

A rotary converter is essentially an electromechanical rectifier/inverter. It consists of an AC synchronous machine directly coupled to a DC machine. Both electrical machines can act as either a motor or a generator. When one machine is a motor, the other is a generator and vice versa. Some advantages of a rotary converter are that it is well developed piece of equipment and is normally quite rugged. The main disadvantage is that the efficiency is less than that of a solid state power converter.

2.2.11 Synchronous Condensers

A synchronous condenser is an electromechanical device whose function is to provide reactive power to the rest of the network in an AC power system. Synchronous condensers are commonly used in those hybrid power systems where all the diesel generators may be disconnected, but where there are large requirements for reactive power. The latter include conventional wind turbines with induction generators. The role of the synchronous condenser is typically provided by a synchronous motor which is electrically connected to the grid, but which is not connected to a mechanical load. A voltage regulator on the synchronous motor regulates the provision of reactive power.

2.2.12 Coupled Diesel Systems

A variant on the typical hybrid power system is known as the "coupled diesel" system. In this system there are both AC and DC generators and loads. The AC and DC networks are connected together via the AC and DC generators that constitute a rotary converter. A single diesel engine is coupled via a clutch to the rotary converter (See Figure 2.1). The advantage of this concept is that it provides a more efficient means of incorporating a rotary converter than would be the case if the diesel engine were associated only with its own generator. It also offers a convenient way to shut down the diesel when it is not needed, while still providing a means of supplying reactive power to the AC bus.

2.2.13 Dump Load

One component that may be required in hybrid power systems but is uncommon in conventional isolated systems, is a dump load. A dump load is used to protect against an excess of power in the network. Such an excess could arise during times of high renewable contribution and low load. Excess energy could lead to grid instability. The dump load may be a real device, based on power electronics or switchable resistors. In some cases, dissipation of excess power may be accomplished without the use of a dump load. An example is the dissipation of excess wind power by furling the rotor or blade pitch control.

2.2.14 Load Management

Many power systems, whether small or large, employ some form of load management. This is sometimes referred to as demand side management (DSM). Load management can be of even

greater use in hybrid power systems that include renewable energy sources. The load management can augment or take the place of storage. In the context of Hybrid2, manageable loads are referred to as deferrable or optional. Deferrable loads are those that must be supplied at some time, but for which the exact time is flexible. An example of a deferrable load is water pumping for a water storage tank that must be refilled at least once a day. Optional loads are those that provide a use for surplus power that would otherwise go to waste.

One example of deferrable load DSM in conventional utilities (isolated as well as central) is the use of water-heater switches. The switches are turned on and off by a signal that is sent over the power lines from the utility power plant. These are commonly used to diminish peak loads during the day by shifting the load to the night instead.

2.2.15 Supervisory Control System

Most hybrid power systems incorporate some form of control. Residential-scale battery chargers often include some form of control to prevent overcharging the batteries or letting their state of charge drop too low. Larger multi-diesel grids may use relatively sophisticated methods for dispatching diesel generators and regulating the flow of power.

Sometimes the control function is carried out by a dedicated controller that is integral with the component. Typical examples include the governor on a diesel, the voltage regulator on a synchronous generator, or the furling mechanism and charge controller on a wind turbine.

Other times control is accomplished by a separate controller known as the supervisory control. The supervisory control might control some or all of the components indicated in Figure 2.2. This control is usually thought of as automatic, but in reality some of the functions may be carried out by an operator. Specific functions of the supervisory controller may include turning diesel generators on and off, adjusting their power set points, charging batteries, and allocating power to a deferrable, optional, or dump load. In the following chapters, Hybrid2 includes a variety of supervisory control functions, at the component, subsystem, and module level. For many of the functions, an explicit system dispatch model is used (see Chapter 7).

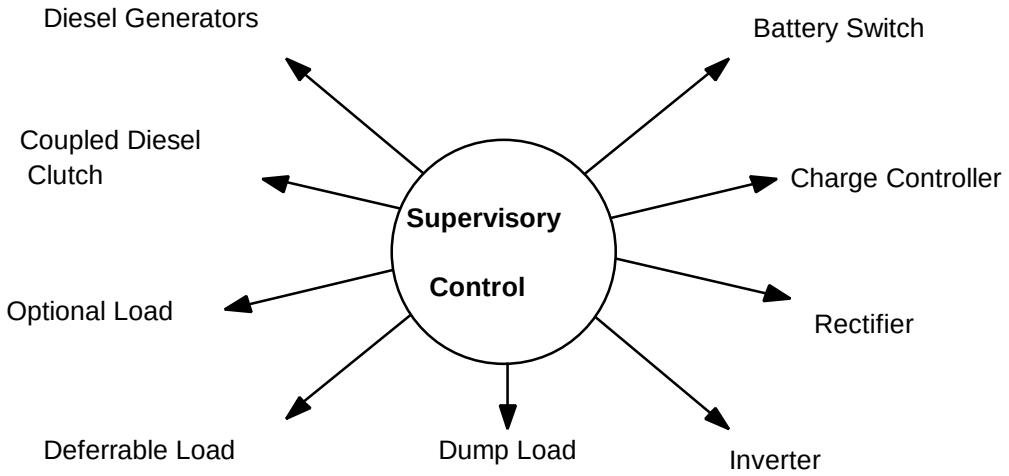


Figure 2.2. Functions of Supervisory Control.

2.2.16 Hybrid Power Systems - Renewable Sources and Fuel Savings

In trying to predict the performance of a hybrid power system, it is worth considering the limiting possibilities. In an ideal diesel grid, the diesel fuel consumption would be exactly proportional to power generated. Thus, the fuel use would be proportional to the load. When renewables are added, the effect would be to reduce the load that must be served by the diesel generators. If there were a perfect match between the load and renewable power, the diesel load could be reduced to zero. All the renewable power produced up to the amount of the load would be used, but any power produced in excess of that would have to be dumped or otherwise dissipated. If there were a temporal mismatch between the load and the available renewable power, even less of the latter would be used. This gives rise to the following rules:

1. The maximum renewable energy that can be used is limited by the load.
2. The use of renewable energy will be further limited by a temporal mismatch between the load and the renewables.

   Corollary: The maximum possible gain in the use of renewable energy afforded by the use of storage is limited by the mismatch between its availability and the load.

In practice, the fuel use of diesel generators never varies in exact proportion to the load. Diesel generator efficiency virtually always decreases with decreasing load. This gives rise to two more rules:

3. The maximum fuel savings realized from using renewables is never greater than the proportional reduction in the diesel-served load resulting from their use.
4. The maximum possible benefit with improved controls or operating strategies is a system approaching the fuel use of the ideal diesel generator - fuel use proportional to the diesel-served load.

Those who design hybrid power systems and wish to understand Hybrid2 modeling results will find it useful to keep these rules in mind.

2.3 Hybrid Power System Modeling

In recent times, many simulation models have been developed for hybrid power systems. For example, European researchers have developed numerous analytical models of varying sophistication and general use for wind/diesel systems (Hunter and Elliot, 1994; Infield, et al., 1990). Similarly, work at the University of Massachusetts (UMass) has produced a number of system models for wind/diesel/hybrid power systems. Generally, one can classify these models into two broad categories: logistical and dynamic models.

Logistical models (Infield, et al., 1990) are used primarily for long-term performance predictions, component sizing, and for providing input to economic analyses. Generally, they can be divided into the following three categories:

- Time series (or quasi-steady state): This type of model requires the long-term time series input of variables such as wind speed, solar insolation, and load.
- Probabilistic: Models of this type generally require long term load and resource data (e.g., monthly or seasonal) as inputs. The analytical model is based on the use of statistical modeling techniques.
- Time series/probabilistic: As their name implies, models in this category are based on the use of a combined time series and statistical approach. These

models use a time series approach to account for load and resource variations over intervals typically ranging from 10 minutes to one hour. Shorter term fluctuations within those intervals are dealt with by means of statistical techniques.

Dynamic models are used primarily for component design, assessment of system stability, and determination of power quality. They are generally used for hybrid power systems with no storage capability, or systems with minimal storage, such as a flywheel. Depending on the time step size and the number of modeled components, they can be divided into the following three categories:

- Dynamic Mechanical Model: This type of model is based on the mechanical equations of motion and power balances. It can be used to get a first approximation of the dynamic behavior of a system and to find such long term effects as the start-stop behavior of the diesel engine component. Such a model is of particular value for studying systems with very little or no storage.
- Dynamic Mechanical, Steady-State Electrical Model: This class of model is based on the mechanical equations of motion and the steady-state equations of the electrical components of the system. It can give a first approximation of the electrical behavior of the system.
- Dynamic Mechanical and Electrical Model: Models of this type are based on the dynamic equations of motion of the mechanical and electrical components of the system. They are intended to investigate the electrical stability of the system (millisecond scale) and mechanical vibrations.

Although hybrid power system modeling at UMass has focused on both dynamic and logistical models, the work to be presented here is based on the application of a logistical model. The first logistical models were based on the time series type and could be classified as quasi-steady state. In their most detailed form, they require long-term data sets, typically of wind speed and load, in order to be used. Also, they generally require the inclusion of some type of energy storage component into the system. At UMass initial wind/diesel/hybrid modeling efforts were directed toward the development of long-term models of this type. Initially, this work produced the UMLTM time series model (Manwell, et al., 1990).

Following this work, a combined time series/probabilistic model resulted. This model resulted in the HYBRID1 code (Manwell and McGowan, 1994; Manwell, et al., 1994a). This detailed hybrid simulation code has allowed the simulation of a variety of no-storage as well as storage-based hybrid power systems. In addition, the analytical modeling techniques developed for the components in this hybrid power system model have formed the basis for screening level models (probabilistic type) for wind/diesel systems. These models (WNDSCREEN: Manwell and McGowan, 1993a; WNDSCREEN2: Manwell, et al., 1994b) are generally intended for a designer's use as a quick overview of the appropriateness of a wind/diesel system and to indicate whether or not a more detailed analysis would be of use.

Based on the HYBRID1 code, a new model called Hybrid2 was developed that greatly extends the hybrid system modeling capabilities beyond that of HYBRID1, and also features a user-friendly windows-based interface (Baring-Gould et. al., 1996). This report details the analytical basis of the Hybrid2 code.

3. Structure of Hybrid2 Model

3.1 Executive Summary

The structure of Hybrid2 was designed to parallel as closely as possible the structure of actual hybrid power systems. As described in Chapter 2, actual hybrid power systems consist of a number of readily identifiable components. Many of these can in turn be grouped into subsystems.

The primary division is into AC and DC sides. The AC side contains all the AC power sources and loads, while the DC side contains all the DC power sources, loads and the storage. The concept of "bus" has been adopted as the focal point for all the power generated and consumed on each of the two sides. The two sides (or buses) are connected together via power converters. In Hybrid2 the buses implicitly include the electrical distribution system.

The Hybrid2 model of a generalized hybrid power system is composed of a number of main parts. Each bus includes subsystems associated with each of the power generators and with storage devices: diesel generators, wind power, solar power, and batteries. The subsystems include individual components such as individual diesel generators, wind turbines, photovoltaic panels, and batteries. On the subsystem level these components are grouped together, such as a collection of diesel generators, wind turbine clusters, photovoltaic arrays, or batteries on the DC bus.

The generalized hybrid power system also includes power converters that are not included in any subsystem. Converters connect the two buses and are components independent of the storage subsystem or either bus. Similarly, the dump load synchronous condenser are considered as a separate components.

Loads are not actually components, but they are considered in logical groupings: primary loads and secondary loads. The secondary loads include the deferrable and optional loads. Like the components, loads are considered for each bus.

For each component, subsystem, and logical grouping in the system an individual mathematical model has been constructed. These models are all linked to create a model of the entire system. The components explicitly modeled in Hybrid2 include diesel generators, wind turbines, photovoltaic panels, batteries, and various types of power converters. The power converters include rectifiers, inverters, bi-directional converters, rotary converters, maximum power point trackers, dump loads, and synchronous condensers.

Finally, the Hybrid2 code is structured in a modular manner to facilitate 1) preparing a simulation, 2) performing the simulation, and 3) assessing the results of the simulation.

3.2 Structure of Hybrid2

The structure of Hybrid2 was designed to parallel as closely as possible the structure of actual hybrid power systems. As described previously, actual hybrid power systems are composed of a number of readily identifiable components. Many of these can in turn be grouped into subsystems.

Hybrid2 was created to provide a consistent platform for assessing the performance of a wide variety of hybrid power systems. Figure 3.1 depicts the structure of the code and illustrates the

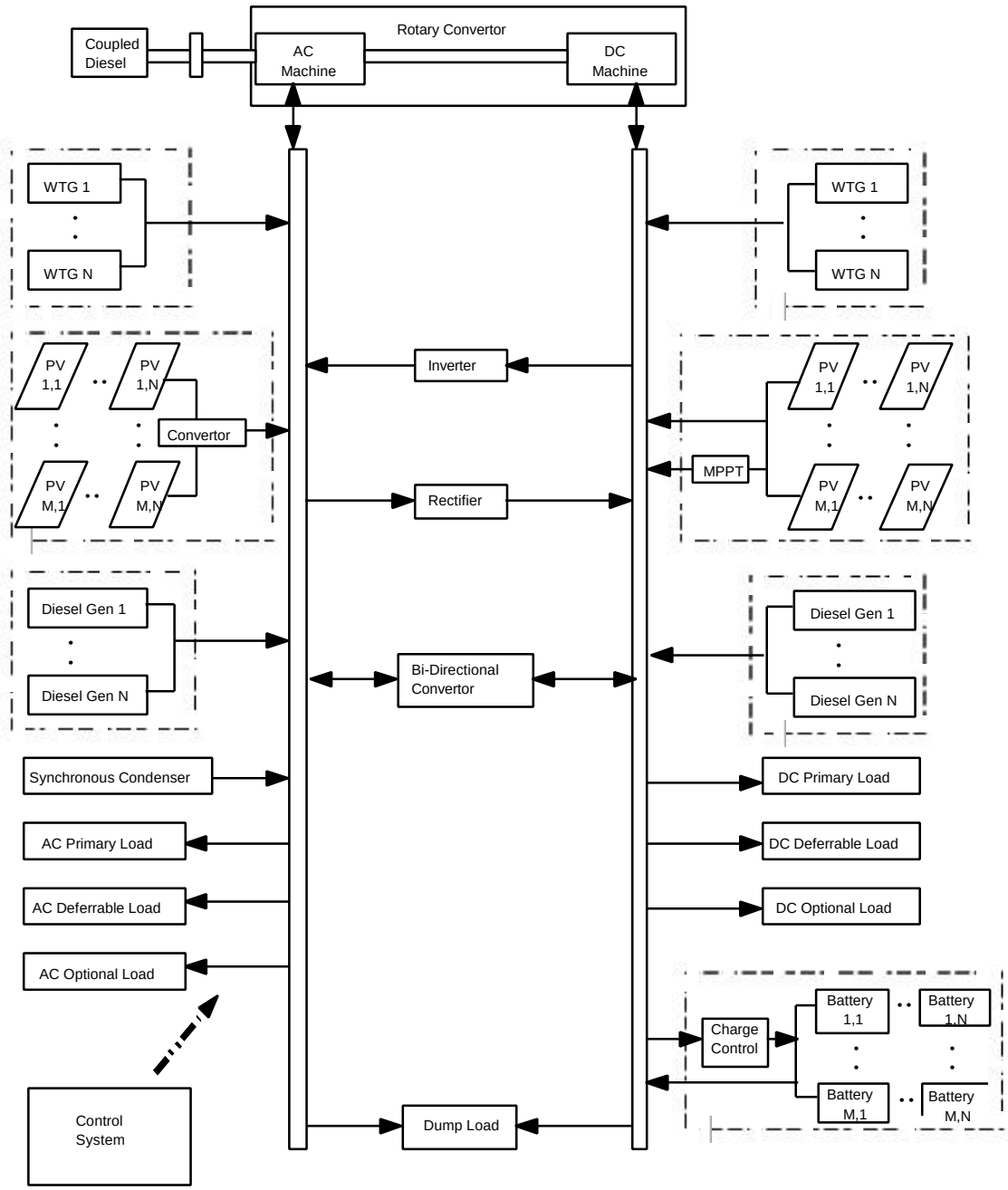


Figure 3.1. Schematic of Components and Subsystems in Hybrid2.

variety of components and subsystems that may be considered. Note that components are represented by solid boxes and subsystems by dotted boxes. The control system is not, strictly speaking, a component, but it is represented as such in the figure. Multiple components are denoted 1 through N (e.g. wind turbines). When there are multiples in series and parallel, they are denoted by 1 to N and 1 to M.

The primary division is into AC and DC sides. The AC side contains all the AC power sources and loads, while the DC side contains all the DC power sources, loads and the storage. The concept of "bus" has been adopted as the focal point for all the power generated and consumed on each of the two sides. The two sides (or buses) are connected together via power converters. In Hybrid2, the buses implicitly include the electrical distribution system.

The Hybrid2 model of a generalized hybrid power system is comprised of a number of main parts. Each bus includes subsystems associated with each of the power generators: diesel generators, wind power, and solar power. The subsystems include individual components such as individual diesel generators, wind turbines, photovoltaic panels, batteries grouped together into collections of diesel generators, wind turbine clusters, photovoltaic arrays, and battery banks. The generalized hybrid power system also includes power converters that are not included in any subsystem. Converters connect the two buses and are components independent of the storage subsystem or either bus. Similarly, the dump load and synchronous condenser are considered as a separate components. Loads are not actually components, but they are considered in logical groupings: primary loads and secondary loads. The secondary loads include the deferrable and optional loads. Like the components, loads are considered for each bus.

For each component, subsystem and logical grouping in the system, an individual mathematical model has been constructed. These models are all linked to create a model of the entire system. The components explicitly modeled in Hybrid2 include diesel generators, wind turbines, photovoltaic panels, batteries, and various types of power converters. The power converters include rectifiers, inverters, bi-directional converters, rotary converters, maximum power point trackers, dump loads, and synchronous condensers. Hybrid2 also includes control/dispatch capability, which is described in detail in Chapter 7.

The Hybrid2 code is structured in a modular manner to facilitate 1) preparing a simulation, 2) performing the simulation, and 3) assessing the results of the simulation. Preparing and running a simulation is accomplished via a Graphical User Interface. The interface provides the starting point for the rest of the simulation.

3.2.1 Simulation Preparation

The main simulation engine is file-based. The input files have been designed to correspond to the logical groupings discussed above. The user interface facilitates the input of the information that will be recorded in the files. This information is usually available from manufacturer's data and an assessment of the proposed site. The information is organized internally to form a library of components and resource data. Subsequent simulations can draw from pre-existing library files.

Sometimes readily available data is not in the form that is most appropriate for storing directly into data files. In this case, for example, preliminary calculations may be carried out before the files are actually created. This is done in preparing the photovoltaic and battery component files and in ensuring that certain of the data files are complete. Thus the Graphical User Interface relieves the user from much of the effort associated with the actual creation of the files by taking

advantage of information stored in the database library and performing many of the preliminary calculations.

There are three major levels of files used by the simulation engine. The first level gathers the basic information needed in the simulation. The second level of detail includes information about the site, resource data, and the configuration of the hybrid power system. The final level of detail is associated with the individual loads and resource files and components.

The first level, the project file, gathers the basic information needed in the simulation. It includes pointers to other files that contain more details.

The second level of detail includes 1) site and resource data, and 2) the configuration of the hybrid power system. The site and resource file consists of general information about the site and contains load and resource information. The hybrid power system file describes the basic configuration of the electrical generating system. It includes data specific to the various subsystems and pointers to the component files.

The third level of detail is associated with the individual load and resource files and component files. The load data files include: primary, deferrable, and optional loads. The resource data files include wind speed, solar radiation, and temperature. The component data files include diesel generators, wind turbines, photovoltaic panels, batteries, power converters, system control and dump load.

3.2.2 Simulation Engine

The first phase of the simulation involves accessing the necessary data and making preliminary calculations. This is done first by reading in the project file, thus, defining the project. This is followed by defining the power system and the site and resource characteristics. These steps include defining the power system control and dispatch and defining the components. The load files and resource files are also accessed. The final step in this phase is preparing of the output data files.

The main part of the simulation engine involves time series calculations. The principles of the approach used are described in Chapter 4, but the essence of it is that the entire simulation period (for example, a year) is broken into smaller time steps (such as an hour). The performance of the system is modeled every time step, based on the current inputs, and the state of the system at that time. Within each time step, the following actions take place.

Calculation of the per bus net load. First, the primary load data is read in. The renewable resource data is read in, and the renewable power is calculated. Based on the load data and renewable power, the net load is determined. This is the load minus the renewable power. These calculations are done for both buses.

Calculations for a diesel only system. At this point calculations are also performed for a diesel-only system ("base case"). These are used in comparisons between alternatives.

Calculation of energy transfer between buses. If the hybrid power system includes storage and multiple buses, the next step is to determine if one bus has an excess of power while the other has a deficit. If this is the case, then some or all of the excess power on the one bus is transferred to the other to reduce its net load.

Distribution of energy to storage and from diesels. After transferring the power between the buses, calculations are performed to address the remaining net load. Whether or not the system includes diesels, the next step is to determine the possible contribution of the battery. If there are diesels included, the way in which storage is used will be affected by the state of the system and the dispatch strategy used. At this juncture, the generation and fuel use (if there are diesels), and excess power, power into storage, losses, and power deficits will be calculated. If there is no storage included in the hybrid system but there are diesels, then calculations are performed to assess the contribution of the diesel generator(s) to supply the net load. These calculations predict the actual diesel generation and fuel use, as well as any excess or deficit. If there is neither storage nor diesels included in the hybrid system, then any excess or deficit is found directly.

Distribution of energy to secondary and dump loads. If there is excess power remaining after the load has been met and the storage has been filled, the next step is to attempt to supply the secondary loads. First the deferrable load is addressed, then the optional load. If there is still excess power remaining in the system after the secondary loads have been met, then the remaining excess is sent to the dump load. Supplying the dump load is the last significant power calculation in the time step. At this point various outputs from the calculations are printed to a detailed output file, or summed to provide a basis for subsequent determination of totals and averages. This ends the operations in the time step. The entire sequence of events is then repeated for the next and all succeeding time steps until the end of the simulation period.

When the end of the simulation period has been reached, a number of summary calculations are performed. These include finding averages of the various outputs (such as power, and fuel use) and totals of others (such as diesel run time). Battery life, as affected by charge-discharge cycles, is also found. Summary values are printed to output file. A number of files are created. One file is intended to provide a complete overall view of the simulation. Another is used to provide input to the economic module. After these actions, the program flow returns to the main interface.

Once the simulation has been completed, a number of options are available. The summary output file may be opened and read in a convenient editor available in Hybrid2 or any other word processor. The detailed output file may be viewed in a built-in graphics package, or in an external spreadsheet program. Economic calculations may be performed based on the outputs of the simulation and user supplied economic parameters. Finally, the simulation may be repeated with the same or modified inputs.

3.2.3 Overview of Program Flow

An overview of the program flow follows. The overview proceeds in the order that the code executes the various calculations and decisions. Each major program subtask is indicated with an Italics title. The description of the code in that subtask follows. Each of these subtask descriptions corresponds to a flow chart in the Appendices. The overall program flow is summarized in the flow charts in Figures 3.2 to 3.4.

Project Definition

Defining the project first involves initializing a number of code parameters. The project file is then opened and read. A number of project-specific parameters are initialized, and the project file is closed. This is illustrated in Flow Chart 2 in the Appendices.

Hybrid2 Simulation Engine

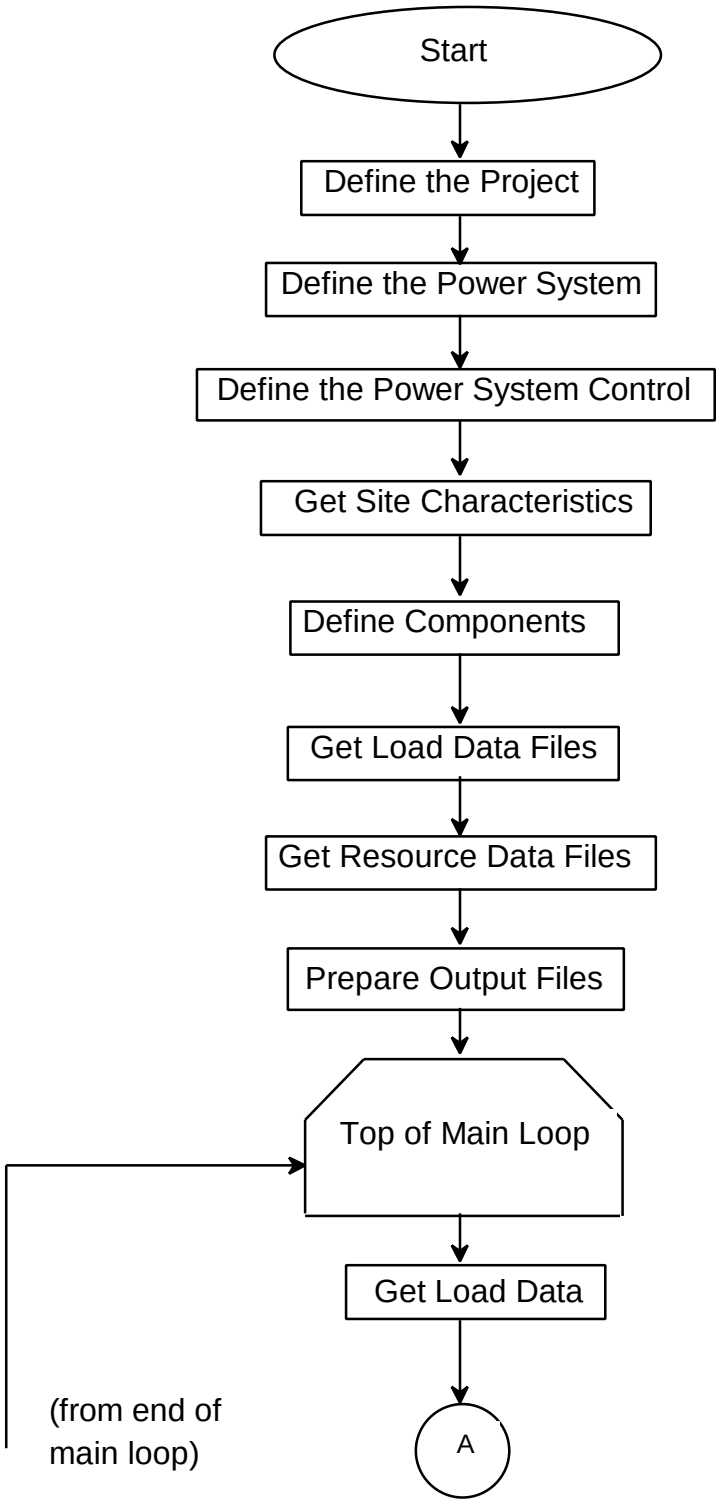


Figure 3.2. Hybrid2 Engine Flow Chart (1 of 3).

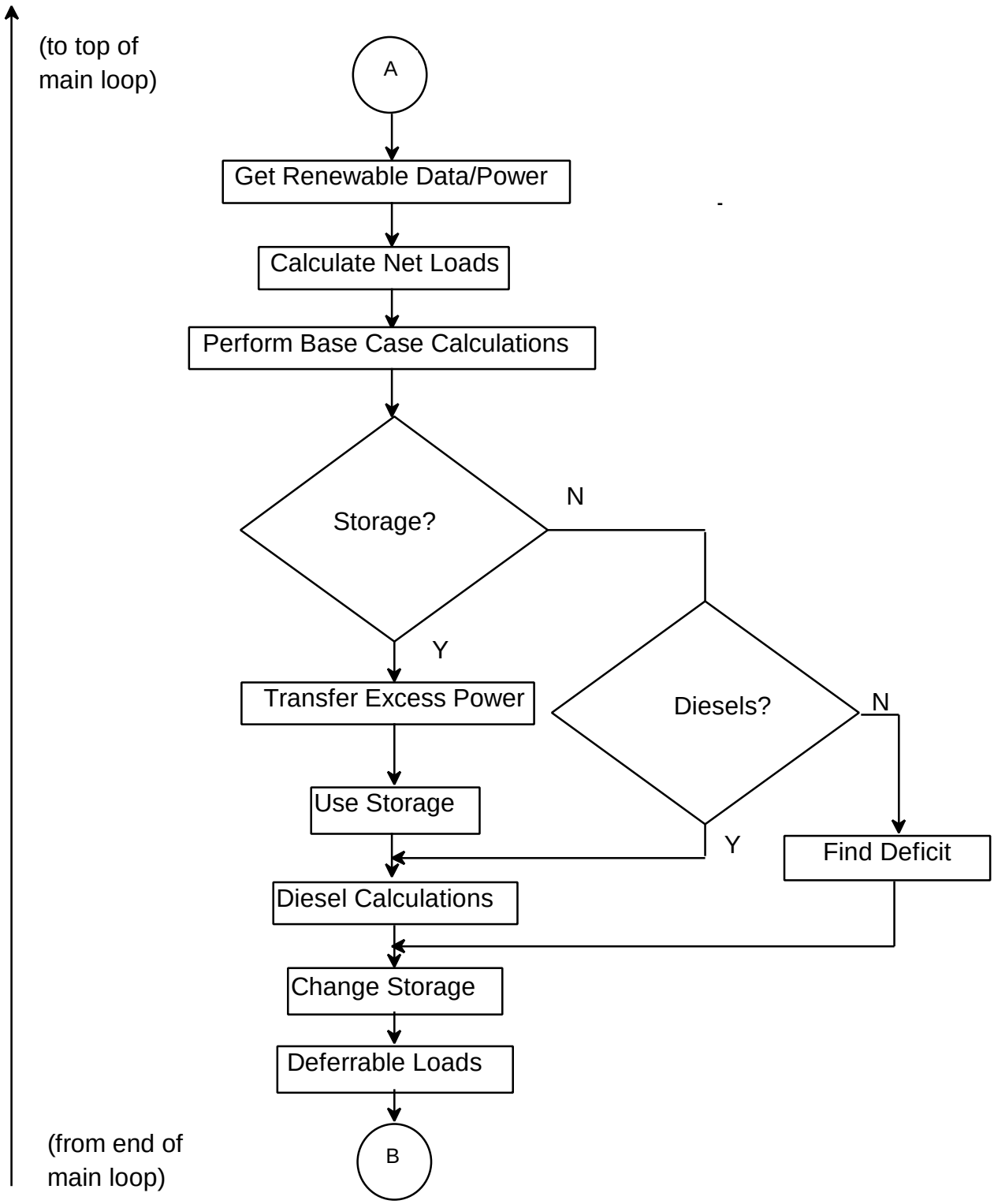


Figure 3.3. Continuation of Hybrid2 Engine Flow Chart (2 of 3).

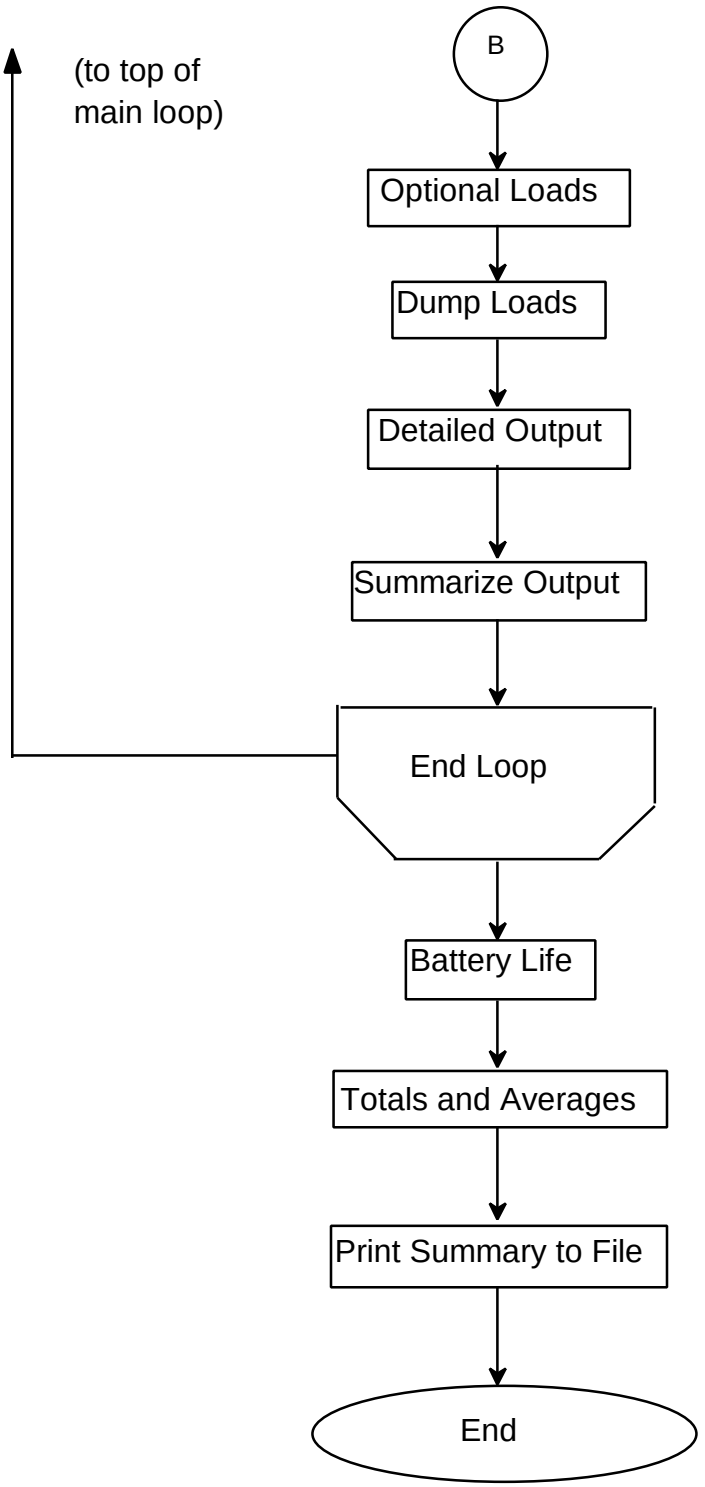


Figure 3.4. Continuation of Hybrid2 Engine Flow Chart (3 of 3).

Power System Definition

Defining the power system involves opening the power system file, reading it, initializing a variety of power system parameters, and closing the file. This is illustrated in Flow Chart 3 in the Appendices.

Power System Control Definition

Defining the power system control involves opening the power system control file, reading it, initializing a variety of control parameters, and closing the file. This is illustrated in Flow Chart 4 in the Appendices.

Site/Resource Characteristics Definition

Defining the site/resource characteristics involves opening the site/resource file, reading it, initializing a variety of site/resource parameters, and closing the file. This is illustrated in Flow Chart 5 in the Appendices.

Power System Components Definition

Wind Turbines/Wind Power Subsystem. Wind power subsystem parameters are read from the power system file. Individual wind turbine characteristics are found in component files. They are obtained by opening a wind turbine file, reading it, and closing it. The wind turbine power curve is filled in by interpolation if points are spaced too far apart. The filled in power curve is then adjusted (as explained in Chapter 6) if the averaging time used when the power curve was created is significantly different than the time step of the simulation. The process is repeated if there is more than one wind turbine on the bus. In that case, a wind-farm power fluctuation reduction factor is calculated. The entire process is done for each bus, if appropriate. This is illustrated in Flow Charts 6-10 in the Appendices. More details are provided in Chapter 6.

Storage/Storage Sub System. Storage subsystem parameters are read from the power system file. Parameters associated with the control of the storage are contained in the control file. The battery characteristics are found in the battery component file. Only one type of battery is allowed in a battery bank. The voltage constants are checked for reasonableness, and then various parameters applicable to the entire bank of storage batteries are calculated. The battery bank voltage is given by the voltage of an individual battery times the number of batteries in series. The capacity is given by the capacity of an individual battery times the number of battery strings in parallel. The resistance of the bank is the resistance of an individual battery string divided by the number of battery strings in parallel. The battery state of charge is initialized in accordance with specifications in the control file. This is illustrated in Flow Charts 6 and 11 in the Appendices.

Power Converters. Power converter characteristics are obtained from power converter files. The converters may include 1) a rectifier, 2) an inverter, 3) a bi-directional converter, or 4) a rotary converter. In all cases the file is opened, the data is read in and the file is closed. In the case of the rotary converter, some additional calculations are performed. This is illustrated in Flow Charts 6 and 12 in the Appendices.

Photovoltaic Panels. Photovoltaic subsystem parameters are read in the power system file. Photovoltaic panel characteristics are obtained from the photovoltaic panel file. The file is opened, the data read in, and the file is closed. Only one type of photovoltaic panel is allowed in

a photovoltaic array. The reasonableness of the array voltage in comparison with that of the battery bank is assessed and a number of photovoltaic array parameters are calculated. This is illustrated in Flow Charts 6 and 13 in the Appendices.

Diesels. The number and types of diesel generators are specified in the power system file. The method of dispatch of diesels is specified in the control file. For each type of diesel, a file is opened, the data is read in, and the file is closed. Various diesel parameters are calculated or initialized. The process is repeated for each diesel type. Note that there may be diesels on only one bus in any given power system. This is illustrated in Flow Charts 6 and 14 in the Appendices.

Dump Load. The dump load rated power is determined from the dump load file, if applicable. This is illustrated in Flow Charts 6 and 15 in the Appendices.

Initialize Load Data Files

Primary Load Data Files. The primary load data file for each bus is prepared by opening the file and reading in some initial parameters. Consistency of the data file time step with that of the simulation is checked. The file is left open to allow the time series input to be used.

Deferrable and Optional Load Data Files. The deferrable and optional load data files for each bus are prepared by opening the file and reading in some initial parameters. Consistency of the data file time step with that of the simulation is checked. When the block average deferrable and optional loads (q. v.) are used, the files are left open to allow for time series input. Otherwise the files are closed. This is illustrated in Flow Chart 16 in the Appendices.

Initialize Resource Data Files

Wind Speed Data File. The wind speed data file is prepared by opening the file and reading in some initial parameters. Consistency of the data file time step with that of the simulation is checked and some initial calculations are carried out. The wind speed data file is left open to allow the time series input to be used.

Solar Data File. The solar data file is prepared by opening the file and reading in some initial parameters. Consistency of the data file time step with that of the simulation is checked and some initial calculations are carried out. The file is left open to allow the time series input to be used.

Temperature Data File. Time series temperature data may be used in the calculation of power from photovoltaic panels. The temperature data file is prepared by opening the file and reading in some initial parameters. Consistency of the data file time step with that of the simulation is checked. The file is left open to allow the time series input to be used. This is illustrated in Flow Chart 17 in the Appendices.

Prepare Output Load Files

The next step is an internal bookkeeping function, in which the output files are initialized and given the proper headers.

Input Load Data

Primary load data for each time step is obtained by reading in values from the primary load data file. Deferrable and load data are read in a similar manner (except in the case of running average deferrable load data, which are read in only once, at the beginning of the simulation.) The base case primary load is also adjusted to account for deferrable loads. This is illustrated in Flow Chart 18 in the Appendices.

Calculate Renewable Power

Wind Power. Wind power is found by reading in the wind speed data from the data file. The power from each turbine is calculated based on the power curve. The power may also be adjusted for site conditions, if applicable. Total mean wind power is found from the sum of powers from individual turbines. Fluctuations in wind power are found in accordance with characteristics of the turbines and the site, and the spacing between the turbines.

Photovoltaic Power. Photovoltaic power is found by first reading in the solar insolation data from the data file. The solar data is adjusted to the slope of the PV panels. The photovoltaic power is then found, based on the characteristics of the panels, the solar data, and the battery bank voltage. This is illustrated in Flow Chart 19 in the Appendices.

Calculate Net Loads

The net loads are found on the AC bus and then on the DC bus. The mean net load is the primary load minus the renewable power. Fluctuations in mean net load are found by statistical methods, as described in Chapter 4. When the project includes a deferrable load, the deferrable load may have been converted to a primary load at the end of the previous time step if the deferrable load cannot be supplied by renewables within the specified period. If this happens the normal primary load will be increased by that amount before the calculation of the net load. This is illustrated in Flow Chart 20 in the Appendices.

Diesel Only ("Base Case") Calculations

Supply of the primary load by a diesel-only system is estimated next. For each time step the configuration of diesels to supply the load is ascertained. The total power actually produced and the fuel consumed is calculated. The possibility of overload is also addressed. This is illustrated in Flow Chart 20 in the Appendices.

Storage/No Storage

At this point there are two significant branches that the program flow may take. The choice of branch depends on whether or not the power system contains storage. The storage branch includes the possible transfer of power from one bus to another. Various sub-branches are associated with the number and types of diesel generators that the system may contain. The other branch involves systems where there are one or more diesels, but no storage. Both branches merge just before the requirements of any secondary loads (deferrable or optional) are addressed.

Transfer of Excess Power

When there is excess power on at least one of the buses, at least some of the excess is transferred from one bus to the other. This serves to reduce the net load, and also allows for some of the

excess to go immediately to storage. This is illustrated in Flow Charts 21 and 22 in the Appendices.

If there is excess on both buses, all of the AC excess is transferred directly to the DC bus where it may be stored. The rectifier losses are calculated. If there is some deficit of power on the AC bus (based on a statistical analysis, as described later in this report) that positive net load is left on the AC bus. The power fluctuations on both buses are adjusted and the ranges of net loads are recalculated.

If there is excess only on the AC bus, some or all of that excess is transferred directly to the DC bus to reduce the positive net load on that bus. The amount of power transferred is constrained by both the positive DC load and the rated capacity of the rectifier. The code also ensures that the transferred power and losses do not exceed the available excess. If there is some deficit of power on the AC bus (based on the statistics), that positive net load is left on the AC bus. The rectifier losses are determined. The most appropriate statistical model for the resulting net loads is selected. The power fluctuations on both buses are adjusted and the mean and ranges of net loads are recalculated.

If there is excess only on the DC bus, some or all of that excess is transferred directly to the AC bus to reduce the positive net load on that bus. The amount of power transferred is constrained by both the positive AC load and the rated capacity of the inverter. The code also ensures that the transferred power and losses do not exceed the available excess. If there is some deficit of power on the AC bus (based on the statistics), that positive net load is left on the AC bus. The inverter losses are determined. The most appropriate statistical model for the resulting net loads is selected. The power fluctuations on both buses are adjusted and the mean and ranges of net loads are recalculated.

Storage/Diesel Calculations

Storage/AC Diesel Calculations. If there is excess power on the DC bus after all primary loads have been filled, then it is sent to storage directly, and the state of charge is updated. If there is a positive net load on the DC bus, then it is ascertained whether the diesel must be on for charging purposes. If the diesel need not be on, then power is taken from storage, if possible, to supply the net load, and the state of charge is updated. If the diesel must be on or the diesel is required to supply the net load, then nothing is taken immediately from storage. The amount of power supplied by the AC diesel is calculated, as are the losses associated with the transfer of this power to the DC bus. The AC net load on the diesel is adjusted to account for the total additional power it is to supply.

The AC net load may in general be supplied from either the storage or the diesels. The code checks to see how much power the batteries could accept, as well as which diesels must be on, and the battery charging mode. The dispatch mode for the diesels and batteries is identified. The batteries may be used for 1) transient peaks, or 2) supplying part or all of the net load. The system may be in charge up mode (3), or the diesels must be off (4).

Assuming the diesels are running, the diesel production and fuel use is calculated. If there is any excess or deficit that is also determined. If there is excess, the excess is directed to the storage. The total amount of power that goes into the storage is determined, as are the corresponding losses and the amount of excess power that may still remain.

If there are storage and diesels in the system, but if the diesels must be off, then the code will first try to supply any positive AC net load from storage. It will then seek to supply the DC net load from storage. If there is a deficit, it will be determined. This is illustrated in Flow Charts 23 and 24 in the Appendices.

Storage/DC Diesel Calculations. The storage/DC diesel calculations are analogous in form to the Storage/AC diesel calculations except that the losses associated with power conversion may not be relevant. This is illustrated in Flow Charts 25 and 26 in the Appendices.

Storage/Coupled Diesel (Shaft Bus)

The coupled diesel calculations begin in a way similar to that for diesels on the AC or DC buses. In particular, if there is an excess of power (negative net load) on one bus, and a deficit on the other, then power is transferred from the former to the latter to reduce the deficit before storage is either used or charged. If any excess remains on the AC bus, it will later be used to supply storage, to supply a secondary load, or be dumped. If there is any excess on the DC bus, it is sent directly to storage (if possible). If there is initially excess power on both buses, it is sent to storage immediately if there is room. Otherwise it may go to a secondary load or be dumped.

If the batteries are to be charged from the AC bus, the additional losses associated with transferring excess power from the AC to the DC bus through two electrical machines are calculated. The state of charge of the battery is then updated. Any remaining net load on the AC bus is referred to the shaft bus. That is, a certain amount of power would have to be present at the input shaft of the rotary converter in order to supply the desired AC net load and the associated losses. In finding the required power on the shaft bus, the portion of the net load on the AC bus is found up to the rating of the AC machine. The corresponding losses are determined, and an appropriate corresponding total is determined for the shaft. Any load in excess of the AC machines rating is also found. This will be unmet load. Similar calculations are performed for load on the DC bus. The total net load on the shaft is found from the two derived from each of the AC and DC buses. The expected range of the net load is then determined by assuming the two net loads are uncorrelated. The net load may be supplied by storage, or by the shaft diesel, as when there are diesels on either the AC or DC buses. There may be differences, however, in the losses depending on whether the power supplied comes from the diesel or storage. These are accounted for here.

Storage / No Diesel Calculations

If the hybrid power system includes storage but no diesels, the code first seeks to supply any positive AC net load from storage. It begins by checking the effect of an inverter size limit to see what power cannot be met. Then it is determined whether all the required power plus the accompanying losses can come from the storage. If so, then all the required power is taken; if not, but if the storage can supply some power, then it does so. If there is no available power in the storage, the storage is not used. If there is either excess power or a power deficit, those values are determined. The same process is applied to the DC bus, but the inverter size limit does not apply. If there is excess power, some or all of it may be stored, supplied to a secondary load, or be dumped in that order. This is illustrated in Flow Charts 27 and 28 in the Appendices.

AC Diesel /No Storage Calculations

If there is no storage (and thus no DC bus), but there are AC diesel generator(s), the code identifies the configuration of diesels that can meet the maximum net load. The production and

fuel use from that/those diesel(s) are calculated. Any excess or overload is also determined. If there is excess power, it may be supplied to a secondary load or be dumped. This is illustrated in Flow Chart 29 in the Appendices.

Deferrable Loads

At this point, the primary load has been met, if possible. Any excess power has been identified. As noted above, if there is storage in the system, then as much as possible of the excess has already been used to charge the batteries. If there is still excess power on either bus, then the code will address the secondary loads - first the deferrable, then the optional loads. This is illustrated in Flow Chart 30 in the Appendices.

If there are secondary loads only on the AC bus, then any excess on the DC bus is transferred to the AC bus. Similarly, if there are secondary loads only on the DC bus, then any excess on the AC bus is transferred to the DC bus. In the case where there are secondary loads on both buses, however, there is no transfer of any excess energy from one bus to another. The code next seeks to supply the AC deferrable loads (if any). At this point the type of deferrable load (block average or running average) is considered. The analogous procedure is applied to the DC deferrable loads.

Optional Loads

Any excess power still remaining after the deferrable loads have been supplied may go to the optional loads. First the AC optional loads are considered, then the DC optional loads. This is illustrated in Flow Chart 31 in the Appendices.

Dump Load

If there is still excess power after the secondary loads have been met, then the excess is sent to the dump load. First AC excess is dumped, then the DC excess. The code also ensures that the total dumped power does not exceed the dump load rated capacity. Any dumped power over the dump load rated capacity is treated as excess dump load. If no dump load has been specified, all dumped power will be treated as excess dump load. This is illustrated in Flow Chart 32 in the Appendices.

Detailed Output

At this point a number of values used or calculated in the time step are printed out to the detailed output file. The energy balance in the time step is also calculated here. This is the sum of all the sources and sinks. Its value should be very close to zero, but may not be identically equal to zero due to round off error. It is printed to the output file, if specified by the user at the start of the simulation, where it is accessible for verifying that the analysis is internally consistent. This is illustrated in Flow Chart 33 in the Appendices.

Summaries

Important outputs from the time step are added to running sums. These will later be used for finding averages and totals over the entire run. The state of charge of the battery is checked to see if it has reached a peak or valley. The latter are used in the battery life calculations. When complete cycles occur they are binned and counted. This is illustrated in Flow Chart 33 in the Appendices.

Next Time Step

The model then moves on to the next time step. It returns to the top of the main loop, reads in more load and resource data, and repeats the required calculations. After all the time steps have been analyzed, the model exits from the main loop and completes the summary calculations described below.

Battery Life

Estimation of battery life first requires determining the number of cycles to failure for various depths of discharge of the battery. A "cycle" refers to discharging the battery from one state of charge to a lower one, and then charging it back to the same level. The depth of discharge of the cycle is the difference between the maximum and minimum state of charge during the cycle. The number of cycles at the specified depths of discharge are used to the find the damage due to battery cycling at that depth of discharge. From all the damages the total damage is found. This damage is then used to predict the expected life of the battery. This is illustrated in Flow Chart 34 in the Appendices. More details are provided in Chapter 6.

Totals and Averages

The total run hours are determined, based on the length of the time step and the number of time steps run. A number of other totals are calculated, such as run hours for each diesel. Averages for a wide variety of outputs are also determined from the running totals obtained during the simulation. This is illustrated in Flow Chart 34 in the Appendices.

Summary Output

A wide variety of averages and totals from the entire run are printed to a summary output file. A number of the resource and load inputs are averaged as well. The file also contains summaries of the key inputs to the project simulation.

4. Principles of Hybrid2 Code

4.1 Executive Summary

Hybrid2 uses a combined time series/probabilistic method. The time series approach is useful for long term predictions, but, to account for the correct dispatch diesels in a multiple diesel system, it is crucial to also account for short term fluctuations in the wind and load power. To include the effect of short term fluctuations in wind power or load, a probabilistic approach is applied within each time step. The time series/probabilistic method is based on an energy balance approach within each time step. This assures that energy is conserved throughout the entire simulation, and that the model is internally consistent.

4.2 Background - Hybrid System Operation

Before discussing the principles behind the Hybrid2 software, it is worthwhile to review briefly how a real hybrid power system operates. In a conventional diesel grid, the mean load on the diesels changes relatively slowly, although there are generally distinct diurnal and seasonal patterns. Short-term fluctuations in load are usually small relative to the mean. Diesel generators are turned on in anticipation of increasing loads. In multiple-diesel systems, some of the diesels may run at fixed throttle, while one follows the remaining load and sets the grid frequency. The lead diesel governor takes care of short-term fluctuations in the load. Voltage regulators keep the voltage within a narrow range.

When a fluctuating renewable power source such as a wind turbine is added to the network, the net load on the diesels will be considerably more variable, especially if the wind power is relatively large in comparison to the total load. There will likely be much more governor action, but the response of diesel generators is such that the frequency and voltage can normally be kept within acceptable limits. On the other hand, the variability of the net load may be such that the total diesel capacity on line might not be able to be reduced as much as expected based on the mean net load. The opportunity presents itself for more sophisticated controls on the diesel to take full advantage of the renewable power source. By adding controls to the diesels and power converters, a wide variety of system operation modes are possible. For example, appropriate controls could allow any of the diesels in a multi diesel system to run independently or together to both meet the average load and to maintain reserve capacity for compensating for drops in wind power. Alternatively, some storage, either short term or long term, could be used in conjunction with power converters to provide additional flexibility in meeting fluctuating loads. The addition of storage may even allow all of the diesels to be turned off.

The following example illustrates the behavior of one possible hybrid power system with a fluctuating load and wind power contribution. The system includes wind and a 3 kW and a 7 kW diesel generator. In Figure 4.1, a time series of a hypothetical load, wind power, and the resulting net load are shown. Superimposed on the same figure are mean values (dotted lines) and the rated power for a single 7 kW diesel and for the combined rated power of a 7 kW and 3 kW diesel (dashed lines). The load has a mean of 20 kW with a standard deviation of 0.2 kW (coefficient of variation = 0.01) and the wind power has a mean of 15 kW and a standard deviation of 2 kW (coefficient of variation = 0.133.) The net load has a mean of 5 kW and a standard deviation of 2.01 (coefficient of variation = 0.402.) Using a quasi-steady model, only the mean values would be used. That would imply that only the 7 kW diesel need be on. The fluctuations in the net load are such that the power is frequently more than 7 kW, so, in the absence of storage, both diesels would have to be on. With the use of a small amount of storage, those transients peaks could be met, and the second diesel kept off.

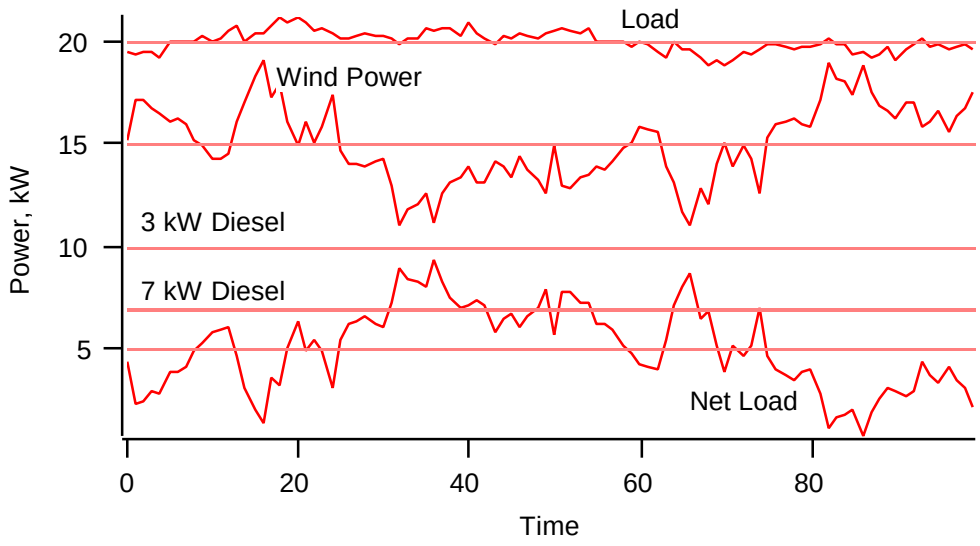


Figure 4.1. Sample Fluctuating Load, Wind Power and Net Load.

Small hybrid power systems may include only a renewable source, a load, and battery storage. In these cases there may be significant variations in voltage, but the effect of fluctuations may be reduced. In the absence of sophisticated control, the current flows to the lowest impedance. Thus when there is large load (low impedance), renewable power will preferentially go to the load, bypassing or even draining the batteries. When the load is less, the voltage at the battery terminals will tend to rise, and they will be charged.

In order to model the behavior of a hybrid power system, a model which could simulate the behavior at a very high frequency might at first seem to be most desirable. Time series data on the order of minutes or even seconds could, in principle be used. Systems with a wide variety of time constants could in principle be modeled. There are some problems with this method for long term performance assessments, however. First of all, obtaining high frequency input load and resource data may be very difficult, if not impossible. Second, a high frequency model running a year's worth of data would take a very long time with a conventional micro computer. Third, for many situations, this approach would be overkill - there would be few benefits to be gained over a model using much longer time steps.

The alternative chosen for Hybrid2 is the characterization of hybrid system behavior with a combination of average behavior over a series of time intervals and statistical (or "probabilistic") measures of the high frequency variability during those time intervals. This combination of a times series and a probabilistic approach can model both long term system behavior and also system behavior based on the effects of the short term system fluctuations.

It should also be noted, however, that the times series/probabilistic approach cannot address all situations that might possibly be of interest. Any action that may take place multiple times in one time step or that has a significant short term "memory" effect can only be approximated with this method. Examples of such actions are multiple diesel starts and stops, diesel start up periods, and alternate battery charging and discharging to meet a transient load all during one time step. If highly accurate modeling of such actions were required, a time series model with very short time steps would need to be used.

4.3 Overview of Principles of Hybrid2 Code

The time series/probabilistic method in Hybrid2 uses a time series approach for long term predictions. To include the effect of short term fluctuations in wind power or load, a statistical or "probabilistic" approach is applied within each time step. (The name of the method is based on its use of probability density functions for addressing the statistics of short term fluctuations.) Using the time series/probabilistic method, the prime considerations during each time step are the mean values of the various inputs and internally calculated values. It is assumed that they are randomly distributed about the mean value, and furthermore that the distribution of values can be described by a probability density function. In most cases, the normal (Gaussian) probability density function is used, although in a few situations the Weibull is applied. The probability density function is used within the time step to find: 1) the expected maximum or minimum value of various parameters, 2) the fraction of time that values may be within a certain range, and 3) the amount of energy that may be required (or may be available) within certain ranges.

The primary function of the probabilistic part of the method is in the characterization of the net load on each bus in each time step. In this process it is assumed that, over each time step: 1) the wind speed and load are all normally distributed, 2) the wind speed (and wind power) are uncorrelated with the load, 3) the variability of the wind power from a single machine can be estimated from that of the wind speed, 4) the variability of multiple machines can be derived from that of a single machine by taking into account correlation limits, 5) the mean net load is the mean load less the mean wind power and 6) the variance of the net load is equal to the variance of the wind power plus that of the load.

An essential feature of the time series method is that it employs an energy balance approach within each time step. This assures that energy is conserved throughout the entire simulation, and that the model is internally consistent. The sum of all energy sources (diesel, wind, photovoltaic panels, storage output) must equal the sum of all the sinks (storage input, loads, losses, unmet load, dump, and excess dump). An energy balance is also required in the statistical approach to fluctuations within the time step.

4.4 Principles of Hybrid2 Code

4.4.1 Time Series/Probabilistic Method

The time series/probabilistic method in Hybrid2 uses a time series approach for long term predictions. To include the effect of short term fluctuations in wind power or load, a probabilistic approach is applied within each time step. At the present time short term fluctuations in photovoltaic output are not included. As denoted above, short term fluctuations in wind power or load can have a significant effect on the performance of a hybrid power system. This is particularly likely when: 1) there is no or minimal storage and 2) the available renewable power is of the same order of magnitude as the load. Generally speaking, large amounts of storage, the use of multiple wind turbines and multiple diesel generators will all serve to reduce the magnitude of any short term fluctuations. Most hybrid power systems which include photovoltaic panels also incorporate significant amounts of storage. In these cases, the present inability of Hybrid2 to consider short term fluctuations in photovoltaic output should not appreciably affect the predictions.

The time series/probabilistic method is based on an energy balance approach within each time step. This assures that energy is conserved throughout the entire simulation, and that the model is internally consistent.

Details of the Time Series/Probabilistic Method

The following discussion focuses on the wind power and the load, since, as noted above, short term fluctuations in the photovoltaic power are not considered in this version of Hybrid2. When photovoltaic power is included, the method is the same, except that wherever the mean wind power is used, the mean photovoltaic power would be added in. As previously indicated, most hybrid power systems which include photovoltaic panels also incorporate significant amounts of storage. In these cases, Hybrid2's present inability to consider short term fluctuations in photovoltaic output should not appreciably affect the predictions. In situations where photovoltaic panels are a major contributor to the power supply, and the amount of storage is minimal, Hybrid2 could overpredict the contribution from the panels.

Using the time series/probabilistic method, the prime considerations during each time step are the mean values of the various inputs and internally calculated values. To account for the short fluctuations, it is assumed that they are randomly distributed about the mean value, and furthermore that the distribution of values can be described by a probability density function. In most cases, the normal (Gaussian) probability density function is used. In a few situations (such as when, for physical reasons, a distribution can only be positive) a Weibull distribution is applied. The use of the Weibull distribution for these cases is discussed in Chapter 5.

The probability density function is used within the time step to find: 1) the expected maximum or minimum value of various parameters, 2) the fraction of time that values may be within a certain range, and 3) the amount of energy that may be required (or may be available) within certain ranges.

The primary function of the probabilistic part of the method is in the characterization of the net load on each bus in each time step. In this process it is assumed that, over each time step: 1) the wind speed and load are all normally distributed, 2) the wind speed (and wind power) are uncorrelated with the load, 3) the variability of the wind power from a single machine can be estimated from that of the wind speed, 4) the variability in power of multiple wind turbines can be derived from that of a single wind turbine by taking into account correlation limits, 5) the mean net load is the mean load less the mean wind power and 6) the variance of the net load is equal to the variance of the wind power plus that of the load. The basis for some of these assumptions is described below.

Hybrid2 assumes that the wind speed, wind power, and load are all normally distributed over the time step. The basis for this assumption is previous work at the University of Massachusetts (Manwell, Jeffries, and McGowan, 1991; Manwell, et al., 1991) that showed that the wind and wind power are approximately normally distributed around the mean value over time intervals of approximately 10 minutes. In addition, other work at the University of Massachusetts (using data from Cuttyhunk Island) indicates that the electrical load for an autonomous diesel grid is also approximately normally distributed over a short time interval.

The variability of the wind power from a single machine is estimated from that of the wind speed. The work noted above has also shown that a reasonable first order approach to estimating the variability of the wind power is to base it on the variability of the wind. In particular it appears that the wind power variability should be at least as great as that of the wind and may be up to three times as much. A wind power turbulence response factor of typically between 1.0 and 3.0 can be used to multiply the wind speed turbulence intensity (standard deviation divided by the mean) to give an estimate of the wind turbine power variability. Determination of a wind power turbulence factor for the full range of wind speeds may be quite problematic, however. Its value

could well change with mean wind speed, turbulence intensity, and depends on the design of the machine. In particular, its value may decrease at higher wind speeds, in either stall or pitch regulated turbines. Thus, it may be useful to perform a sensitivity analysis in which different values of the turbulence response factor are used.

The variability of power from multiple wind turbines is derived from that of a single machine by taking into account correlation limits. When multiple wind turbines are used the variability of the total wind power will be influenced by the correlation between the various machines. When a spatial correlation relation is assumed such as described by McNerney and Richardson, 1992, the resultant variability can be described in the frequency domain. Within the limits of complete correlation or lack thereof, the relatively simple relations that apply to normally distributed random variables may be used. If the turbines are completely correlated they behave as one large turbine, so the standard deviations are additive and the variability of the combined power is the same as that of a single machine. If they are completely uncorrelated the variances are additive (Papoulis, 1984). This causes the variability of the total power to decrease as the square root of the number of machines. Details of the "wind farm filter" are discussed in Chapter 7.

Variability of the Net Load. The mean net load is the mean load less the mean power from renewables. The net load is of primary importance. This is what the diesel and/or storage must supply in order to support the grid. The key aspects of the net load are its mean, variance, and its maximum value. In order to estimate these, one must consider both the renewable power and the load itself. The important parameters for these are the mean and the variance (for wind power and load). Making the reasonable assumption that the load and wind power are uncorrelated over the time step (normally one hour or less), the variance of the net load is given by that of the load plus that of the wind turbine power. This is also consistent with observations on Block Island (Manwell, Jeffries, and McGowan, 1991; Jeffries, 1991) where the variability of the net load did show this type of behavior. The limits of the net load are found by selecting an acceptable fraction of the net load which need not be met. This is used together with the net load standard deviation and the assumption of normality to estimate the minimum and maximum powers that may be expected. In particular, the disregarded net load probability is used in determining the maximum expected value of the net load, which in turn is later used in determining the required diesel or power converter rated power that will be needed to supply the net load. To be most accurate, the model requires as input, both standard deviations of wind speed and loads, as well as the mean values for each time step. When they are not available, typical values must be assumed. In equation form, some of the key steps are summarized below. In this case, the only renewable power is from the wind.

The limits of the net load are found by selecting an acceptable fraction of the net load that will not necessarily be met. This is referred to as "disregarded net load probability" and is denoted by P_{DNL}.

The mean net load is

$$\overline{N} = \overline{L} - \overline{W} \tag{4.4.1}$$

where

$\overline{N}$ = Mean net load

$\overline{L}$ = Mean load

$\overline{W}$ = Mean wind power.

Note that if photovoltaic power is used, then the net load would be

$$\overline{N} = \overline{L} - \overline{W} - \overline{S} \tag{4.4.2}$$

where $\overline{S}$ = mean photovoltaic power.

The variability of the net load is

$$\frac{\sigma_N}{\overline{N}} = \frac{\sqrt{\sigma_W^2 + \sigma_L^2}}{\overline{N}} \tag{4.4.3}$$

where

σ_N = Standard deviation of the net load

σ_W = Standard deviation of the wind power

σ_L = Standard deviation of the load.

For a single wind machine:

$$\frac{\sigma_W}{\overline{W}_1} = F_{WPT} \frac{\sigma_V}{\overline{V}} \tag{4.4.4}$$

where

F_{WPT} = Wind power turbulence correction factor (See Chapter 6)

σ_V = Standard deviation of wind speed, kW

$\overline{V}$ = Mean wind speed, m/s

$\overline{W}_1$ = Mean power of one wind machine, kW.

The power smoothing effect of multiple wind machines, which affects the variability of the net load, is discussed in Chapter 7.

The maximum net load during the interval is found in terms of the disregarded net load probability as follows. The net load, which is calculated before the possibility of supplying part or all of it from storage is addressed, is assumed to be normally distributed. The probability density function of the net load is therefore given by

$$p(N) = \frac{1}{\sigma_N \sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{N-\overline{N}}{\sigma_N}\right)^2} \tag{4.4.5}$$

where

N = Instantaneous value of net load.

The disregarded net load probability, P_{DNL}, during the interval is given by the integral

$$P_{DNL} = \int_{N_{max}}^{\infty} p(N)dN = \frac{1-\mathrm{erf}(y)}{2} \qquad (4.4.6)$$

where

y = Argument of error function, given by $y = \frac{N_{max} - \overline{N}}{\sigma_N \cdot \sqrt{2}}$

N_{max} = Maximum acceptable value of the net load, kW

erf(y) = Error function.

Given a P_{DNL} it is then possible to calculate a maximum net load. (To do this it is convenient to use an approximation for the error function as explained in Chapter 5.)

For example, suppose a wind/diesel system is planned which will have ten 10 kW wind turbines. Over a 10 minute period the mean load is 100 kW and has a standard deviation of 5 kW. At the same time the mean wind speed is measured to be 8 m/s with standard deviation 2 m/s.

According to a power curve, the mean power of each turbine will be 5 kW. Assuming a wind power turbulence factor (F_{WPT}) of 1.5 the standard deviation of the wind power will be 5 x 1.5 x (2/8) =1.875 kW. The wind turbines are assumed to be uncorrelated. The total mean wind power will then be 10 x 5 = 50 kW, with a standard deviation of $\sqrt{10}$ x 1.875 = 5.93 kW. The mean net diesel load will be 100 - 50 = 50 kW, with a standard deviation of $\sqrt{5.93^2 + 5^2} = 7.76$ kW. Using a disregarded net load probability of .0015 (corresponding to 3 standard deviations from the mean) the maximum and minimum values of the net load should be 26.7 and 73.2 kW respectively.

Application of Statistics in Hybrid2

Statistics of short term fluctuations are dealt with explicitly in a number of situations in the Hybrid2 code. Table 4.1 provides a summary overview of the most important situations where statistics are used. The table includes an indication of what specifically is affected, what it is affected by, and what it affects subsequently. All of these are discussed in detail elsewhere in this report.

Theoretical Basis for Time Series/Probabilistic Method

The physical behavior of a hybrid power system consists of a continuous process in which power is being simultaneously generated, consumed, and perhaps stored, together with other actions which affect that process. Hybrid2 breaks down these continuous processes into time steps for analysis. The approach is based on the eight fundamental assumptions described below.

<u>1. Continuous Operation is Representable by a Series of Sampled Events</u>. The first fundamental assumption of Hybrid2 is that the continuous operation of a hybrid power system can be represented by a sequential series of sampled events. This breaks the simulation period into a finite number of steps or "instants." These instants could be of very short duration (less than one second). This assumption corresponds to representing an analog signal in digital form. The overall performance of a hybrid power system is found by combining the samples over the simulation period.

Table 4.1. Applications of Statistics in Hybrid2

Situation Components	Power Affected	Affected by	Effects
Wind turbines	Power fluctuations	Wind speed variability; Wind power turbulence factor; Number of turbines	Average net load and variability
Diesel generator	Power generated	Power rating;Fuel curve; Maximum net load; Average net load in various ranges	Operational state; Fuel use; Unmet load
Loads			
Primary loads	Primary load mean and variability	Primary load input mean and variability; Deferrable load converted to primary	Average net load and variability
Net loads	Maximum net load; Average in various ranges	Average primary load and renewable power; Fluctuations in primary load and wind power	Power and fuel use from diesels; Power to or from batteries
Dump loads	Average surplus power above and below rating of dump load	Power in excess of all possible loads; Dump load rating	Dumped power; Power in excess of dump load capacity
Net Load Transfer			
Excess power on AC bus	Average DC power in excess of AC load	Rectifier rating; Size of load on DC bus	Final average net load and variability on both buses
Excess power on DC bus	Average AC power in excess of DC load	Inverter rating; Size of load on AC bus	Final average net load and variability on both buses
Excess power on AC and DC bus	Average power on one bus in excess of that on other	Rectifier and Inverter rating; Relative size of excess; Sizes of loads on opposite bus	Final average net load and variability on both buses
Batteries			
Energy in	Average power in excess of primary load	Rectifier rating; Battery capacity	Battery state of charge; Power available for secondary loads or to de dumped
Energy out/Cycle Charge dispatch	Average power required	Average net load; Diesel rating; Inverter rating; Battery capacity; Dispatch strategy	Battery state of charge; Diesel power, Unmet load
Energy out/Transient Peak dispatch	Power required to meet peaks in net load	Net load fluctuations; Diesel rating; Inverter rating; Battery capacity; Dispatch strategy	Battery state of charge; Diesel power, Unmet load

2. Events are Combinable into Time Steps. The second assumption is that the performance of the system may be found by considering individual time steps which are significantly longer than the sampled events would be. These time steps could have lengths of minutes to hours. Many parameters of interest change very little from one moment to the next, and would be relatively constant over the time step. Other parameters, such as wind speed, may vary over the time step, but may be characterized by mean values (or other summary measures) over the time step. It is further assumed that the time step is long enough i) that there are sufficient samples in the step that they may be characterized by statistical measures and ii) that any given variable (detrended, with mean removed) has negligible correlation with its value at the beginning of the time step.

3. Simultaneous Events are Representable by Sequences. The third assumption is that the simultaneous process of generation and use of power may be represented by a sequence of different types of processes over the time step. For example, in a simple wind/diesel system there would be a continuously varying load and wind power over any time interval. The net load on the diesels (which is here the load less the wind power) would also vary continuously, and hence so would the power and fuel use. This third assumption implies that the effect at the end of the time steps would be the same if the load were found first, the wind power next, the net load third, the diesel power fourth, and the fuel use last.

4. Correlations may Exist Within Periods Longer than Allowed Time Steps. A fourth assumption is that for periods longer than the time step, there may be correlations (either positive or negative) between or among the various inputs (such as the resource and the load). This effectively puts an upper limit on the length of simulation time steps. For example, if one wished to use a time step of a day, the predictions could be adversely affected, since typically loads and resources have diurnal patterns.

5. Quasi-Steady Model is Appropriate, but has Some Limitations. A "quasi-steady" model is one in which i) the output of the various model elements is algebraically related to the inputs and ii) the variance within each time step is assumed to be zero. For example, in a conventional diesel grid, mean loads normally change relatively slowly over time periods up to approximately one hour. Fluctuations within those time periods usually have minimal trends and are essentially random. When using time steps of an hour or less, the assumption of quasi-steadiness may be applied. That is, mean values over the time step are considered adequate to describe the process. There is no further subdivision of the time step. The quasi-steady assumption may also be appropriate for many other parameters of interest in hybrid systems as well. The quasi-steady assumption also has some limitations, as described below.

6. Statistical Methods Extend Time Series Method beyond Quasi-Steady. In some cases, there is significant variability of certain parameters within time periods of otherwise desirable length. In these cases, the quasi-steady assumption may not be completely appropriate. When the variations are random and uncorrelated, the next assumption is that statistical methods may be applied to account for certain types of operational characteristics. This results in the transformation of the quasi-steady method into the "time series/probabilistic" method. This method, as applied in Hybrid2, specifically affects: 1) diesel operation, and 2) power flows through converters and into and out of storage. For other parameters, such as dispatch/control, the quasi-steady assumption of events happening once per time step still applies.

7. System Performance is Characterizable by Power Flows. The next assumption is that the performance of the system is ultimately describable by power flows. In particular, for an AC system, real power flow is the parameter of primary interest. Reactive power, grid frequency, and

voltage are not considered. For a DC system, real power is also the parameter of primary interest. Voltage variation is also considered, but the effects are referenced to power.

8. Energy is Conserved. The final fundamental assumption is that energy in conserved. In particular there must be a balance between power into and out of the system (including storage) in each time step.

As noted in Section 4.2, the times series/probabilistic approach cannot address all situations that might possibly be of interest. These include, in particular, actions that may take place multiple times in one time step or that have a significant short term "memory." These effects can often only be approximated with the times series/probabilistic method. Examples of such actions are multiple diesel starts and stops, diesel start up periods, and alternate battery charging and discharging to meet transient load. In general, Hybrid2 does not consider multiple events within a time step. It also does not consider the effect of sequential events. Such effects are dealt with, however, through averages wherever possible. For example, alternate battery charging and discharging within a time step is considered through two averages, as discussed in Chapter 6.

4.4.2 Energy Balance

Energy Balance Overview

An essential feature of the time series method is that it employs an energy balance approach within each time step. This assures that energy is conserved throughout the entire simulation, and that the model is internally consistent. In particular the sum of all energy sources (diesel, wind, photovoltaic panels, storage output) must equal the sum of all the sinks (storage input, loads, losses, unmet load, dump, and excess). The approach has been schematically represented in Figure 4.2. The various sources and sinks are calculated independently. They are summed at the end of each time step to a value which should equal zero. The results are available to the user to check the consistency of the simulation. (Note that any significant difference from zero would indicate an internal programming error.)

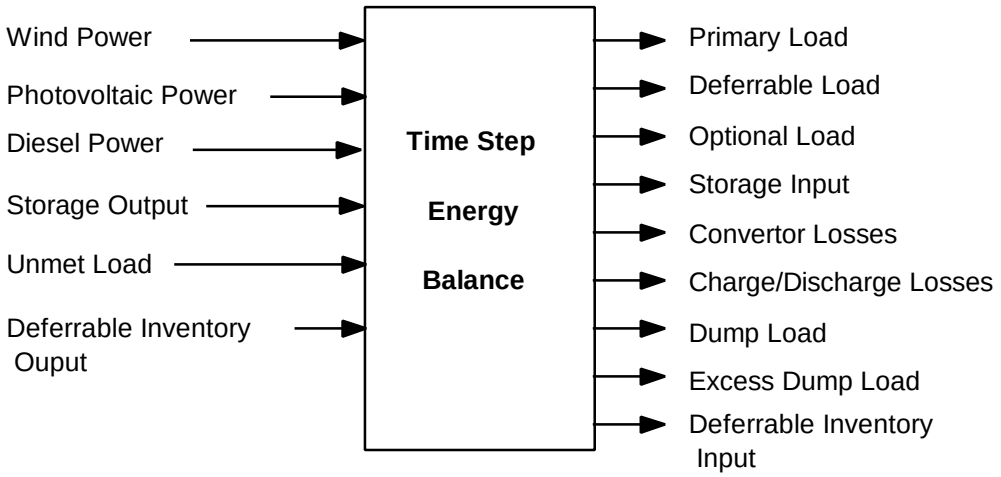


Figure 4.2. Schematic of Energy Balance.

Theory of Energy Balance

If the energy in the system is to be balanced, the sum of all energy sources (diesel, wind, photovoltaic panels, storage output) must equal the sum of all the energy sinks (storage input, loads, losses, unmet load). The energy balance may be described by an equation. In its simplest form, the energy balance relation can be written as follows:

$$W + PV + DL + S_O + U + D_{I,O} - L_P - S_I - L_D - L_O - D_{I,I} - DP - DP_{Ex} - LS = 0 \quad (4.4.7)$$

where

W	= Power delivered from all the wind turbine(s) (both buses)
PV	= Power supplied by PV array (either bus)
DL	= Power delivered from the diesel generator(s) (either bus)
S_O	= Storage output
U	= Unmet load
$D_{I,O}$	= Deferrable inventory output
L_P	= Power delivered to the primary load (both buses)
S_I	= Storage input
L_D	= Power delivered to the deferrable load (both buses)
L_O	= Power delivered to the optional load (both buses)
$D_{I,I}$	= Deferrable inventory input
DP	= Power dissipated in dump load
DP_{Ex}	= Extra power in excess of dump load capacity
LS	= Losses (both buses)

4.4.3 Time Step

The model is designed to allow for a range of time steps. A constant time step is used throughout the simulation. The typical value for long term simulations is one hour, but either shorter or longer values may be used. The recommended range is between 5 minutes and 2 hours. Time steps of longer than three hours should be avoided, since the fluctuations in wind speed could incorporate factors other than turbulence, such as diurnal or synoptic effects. The assumption of lack of correlation between wind speed and load within the time step would also not necessarily hold true. In principle, very short time steps could be used, but to do so would not take full advantage of the probabilistic method. In these cases, the model would, in effect, converge to a more conventional "quasi-steady" model, in which short term fluctuations within the time step would be less significant. In addition, short time steps would implicitly represent relatively few samples, and the applicability of the statistical method would be diminished. For very short time steps (on the order of seconds) dynamic effects could become important, and the use of the Hybrid2 code would be inappropriate. Potentially important factors in these time scales include diesel or wind turbine accelerations, and battery charging/discharging characteristics.

5. Module Algorithms and Program Output

5.1 Executive Summary

A Hybrid2 Project consists of a description of the key characteristics and associated data of the hybrid power system to be simulated. The Hybrid2 engine takes this information and uses it to define and direct the course of the simulation. The project is based around five modules, which relate to distinct aspects of the system.

The five modules include the power system module, the loads module, the site resource module, the economics module, and the base case module. These modules, in turn, rely on calculations undertaken in component and subsystem sections of the code. The power system module involves the power generation subsystems of the hybrid power system. These include the diesel generators, the wind turbine subsystem, the photovoltaic panels subsystem, the battery bank, and the overall system controller. Each of these subsystems is composed of individual components. The loads module deals with all data related to the loads to be supplied. These include the primary load, deferrable loads and optional loads. The site resource module is concerned with renewable resource aspects of the system that are specifically related to the actual location being considered. These include specifically the wind and solar resource. The economics module deals with the costs of the various components and the economic parameters that are used to evaluate the economic performance of the system. Economic calculations also reflect the calculations from the main part of the simulation engine. The base case module allows comparisons between a diesel-only system and a hybrid system in which the same primary load is supplied.

The main modules are described in this chapter. Subsequent chapters discuss the components and subsystems.

5.2 Power System Module

5.2.1 Executive Summary

Hybrid2 is configured such that many different types of hybrid autonomous energy power systems can be modeled, including AC systems, DC systems, or systems with components on both an AC and a DC bus. As shown schematically in Figure 5.1, Hybrid2 allows a large number of configurations (including systems with both AC and DC buses) in which energy transfer can occur between buses.

The overall intent of the Hybrid2 code is to allow each of the loads, components, or power conversion devices that are shown in Figure 5.1 to be included in a simulation at the user's discretion. As shown in the above-mentioned figure, the hardware configuration can be divided into the following parts: loads, power conversion, and components. Both AC and DC connected loads are possible and the deferrable and optional load categories allow users to investigate the value of load management methods. Hybrid2 is designed so that the user will be able to choose from a range of power conversion devices between the AC and DC buses of the power system. Finally, the power-producing components include any or all of the following: multiple non-identical wind turbines, multiple non-identical diesel generator sets, and PV arrays.

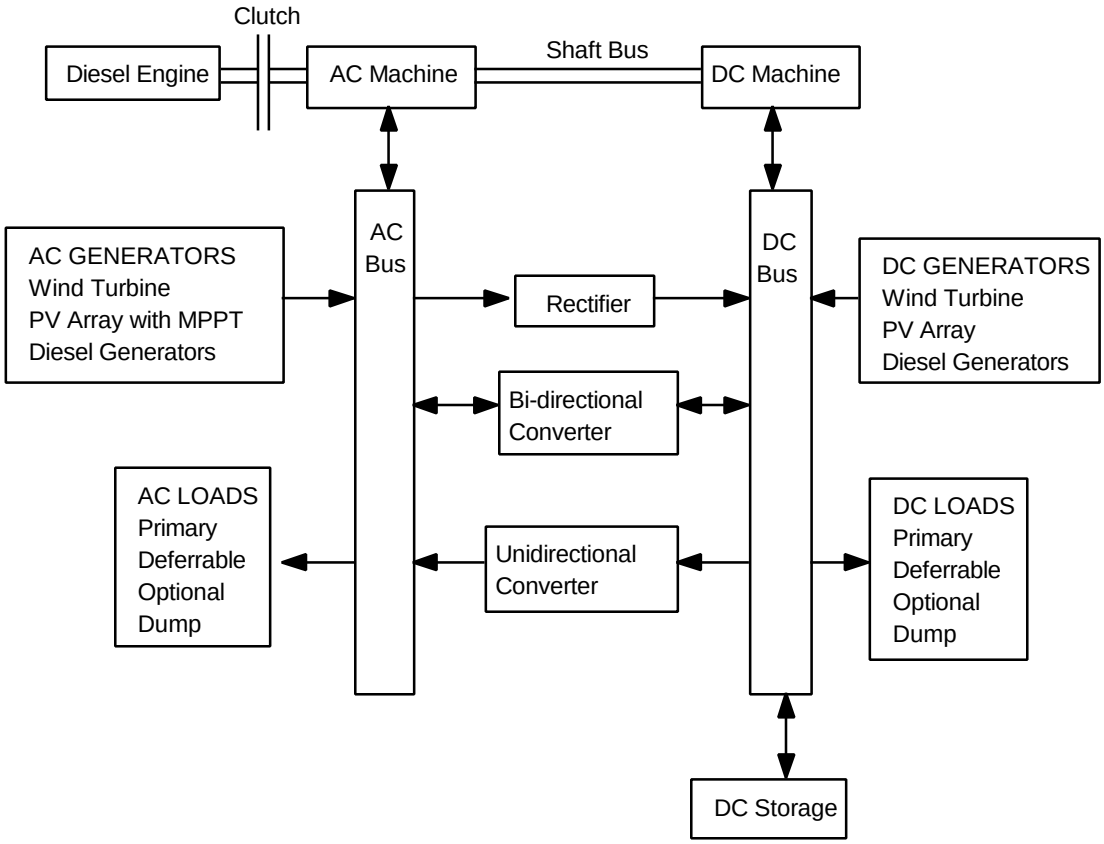


Figure 5.1. Power System Configurations in Hybrid2

5.2.2 Description of Bus System

Hybrid2 is configured such that many different types of hybrid autonomous energy power systems can be modeled, including AC systems with AC or DC loads and DC systems with DC or AC loads. As shown schematically in Figure 5.1, Hybrid2 allows a large number of configurations (including systems with both AC and DC buses) in which energy transfer can occur between buses. The overall intent of the Hybrid2 code is to allow each of the loads, components, or power conversion devices to be included in a simulation at the user's discretion. As shown in the above figure, the hardware configuration can be divided into the following parts: loads, power conversion, and power components.

Loads. The user selects either AC or DC connected loads, or both. The categories "deferrable" and "optional" are provided to allow users to investigate the value of load management methods. Primary loads are time series based and must be met. A deferrable load is defined as one that can be deferred for either a fixed period of time or until a renewable energy input is available. An optional load is one that has economic value but will be served only with surplus energy. Each of these load types is discussed in detail in the Hybrid2 users manual.

Power Conversion. Hybrid2 is designed so that the user will be able to choose from a range of power conversion devices between the AC and DC buses of the power system. Various types of static converters are possible: unidirectional, bi-directional, and bimodal. Also provided

(implicitly) are options for line-commutated or self-commutated inverter operation, or both. A rotary converter may also be used.

Components. Hybrid2 was designed to maximize flexibility and minimize limitations for the user in selecting components to include in a given power system. For example, multiple wind turbines are an option on one or both buses. The user is able to select multiple non-identical diesel generator sets (although these may be only on one bus at a time). At the user's discretion, the generator sets may be capable of "back-drive" operation - absorbing power from the system. Like the generator sets, a PV array will be allowed on only one of the two buses for a given simulation.

Dump Loads. The Hybrid2 engine allows excess power to be dumped from either bus. In practice, dump loads are typically used only on AC buses. What would otherwise be excess power on a DC bus, is usually spilled from the power generator (for example, by the furling of a wind turbine). For that reason the Graphical User Interface only shows a dump load on the AC bus.

System Restrictions. Restrictions that apply to the power system configurations are: 1) PV and diesel can only be used on one bus at a time, 2) if a coupled diesel is used, no additional diesel may be used, 3) if there is no storage, there can be no DC bus, and 4) there can be no more than one converter that allows power flow between buses in any given direction. These restrictions apply because the systems to which they would correspond are expected to be relatively uncommon, and it was not considered worth adding to the model the additional complexity that would be required.

5.2.3 Overview of Power Transfer Between Buses

Power can be transferred from one bus to the other when there is excess power on one bus, and a positive net load on the other bus. This takes place after the calculation of the net loads on each bus. The purpose is to allow the excess to be used directly by a primary load, albeit on a different bus, rather than going to storage or to a secondary load. The basic principle is that power may be transferred up to the amount that is required on the other bus. If there is still excess on the first bus then it remains there and is dealt with subsequently. In that case it would either go to storage, serve a secondary load, or be dumped. The calculations to determine the division of the excess power are complicated, but some examples will make the principles clear.

Power Transfer with No Net Load Variability

If there is no variability in the net load on either bus, and if we ignore losses for now, then the situation is fairly simple. Suppose that the net load on buses 1 and 2 are represented by N_1 and N_2. Suppose further that $N_1 > 0$ and $N_2 < 0$. In other words, bus 1 requires some power and bus 2 has excess power available. In this case, if $|N_2| < N_1$ then all the excess power from bus 2 is transferred. The new net load on bus 1 is $N_1 + N_2$. (Note that N_2 is negative.) The new net load on bus 2 is zero. Suppose next that $|N_2| > N_1$. Now there is more excess on bus 2 than can be used. After the transfer, the net load on bus 1 will be zero, and the net load on bus 2 will be $N_1 + N_2$. This value will be less than zero, so there will still be an excess on bus 2.

Power Transfer with Net Load Variability

When there is variability in the net load on either bus, the situation can get much more complicated. There may be times during the simulation interval, for example, that the one bus

has an excess and the other a deficit, while at other times the opposite may be the case. In order to deal with the various situations that may present themselves, and to do so in a consistent manner, the following criterion is used.

Power may be transferred from one bus ("2") to another ("1") when:

- Bus 2 power is negative
- Bus 1 power is positive
- When bus 2 power exceeds the net load on bus 1, the bus 1 net load is reduced to zero.
- When bus 2 is less than the net load on bus 1, all the bus 2 power is used to reduce the load.

To illustrate this, consider the following examples:

Example 1. In the first example, there is a positive net load on bus 1 with mean and standard deviation of $N_1 = 30$ and $\sigma_1 = 2$. On bus 2 there is a negative mean net load with $N_2 = -10$ and $\sigma_2 = 2$. In this case all the excess power in bus is 2 is transferred to bus 1, so the new net load on bus 1 is decreased to 20. The standard deviation of the power should be increased to be $2\sqrt{2}$.

To illustrate this, two time series were created and a code was written to apply the rules listed above in a time series manner. Each time series consists of 5000 points with essentially zero autocorrelation, and which are uncorrelated with the other time series. The histograms for the two time series, and that of the resultant, are shown in Figure 5.2. Analysis of the data indicate that the results were as expected. Note that the standard deviation of the resultant was 2.81525. This example behaves similarly to the cases with no standard deviation.

Example 2. In the next example the net load on bus 1 is the same as in Example 1. The mean $N_1 = 30$ and $\sigma_1 = 2$. Bus 2 has no mean net excess, however. Sometimes it is positive, sometimes negative. The standard deviation of the net load on bus 2 is $\sigma_2 = 2$. That means that some of the power will be transferred, and some will not. This will decrease the net load on bus 1 somewhat, and leave a positive net load on bus 2. Analysis of the resulting data shows a new net load of 29.23 on bus 1, and a standard deviation of $\sigma = 2.346$. The resulting histograms for the original net loads and the new net load on bus 1 are shown in Figure 5.3. Note that the new net load on bus 1 is no longer quite Gaussian.

Example 3. The possibility of non-Gaussian results is shown even more dramatically in the last example. In this case bus 1 has a positive net load of $N_1 = 10$ and $\sigma_1 = 1$ while bus 2 has a negative net load of $N_2 = -10$ and $\sigma_2 = 1$. The resulting net load on bus 1 is now $N_1 = 0.568977$ while $\sigma_1 = 0.809049$. The results are shown in Figure 5.4.

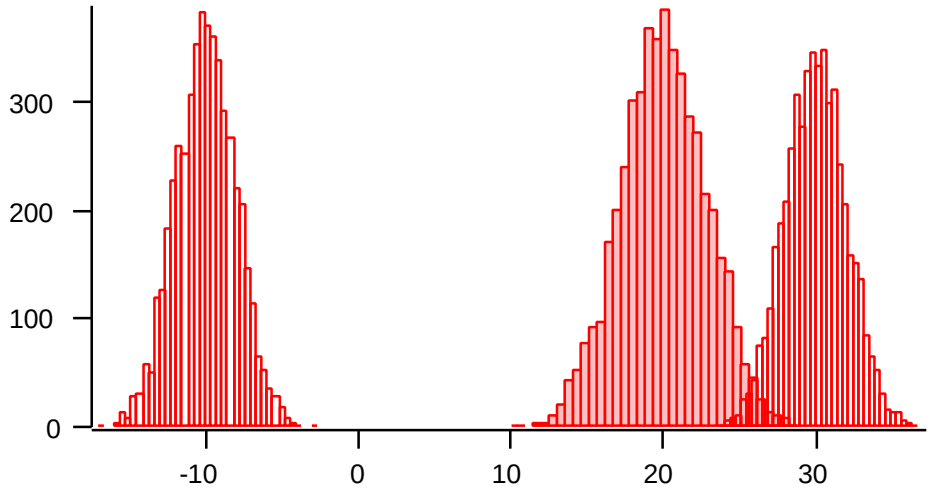


Figure 5.2. Histograms of Bus Power before and after Power Transfer (Example 1).

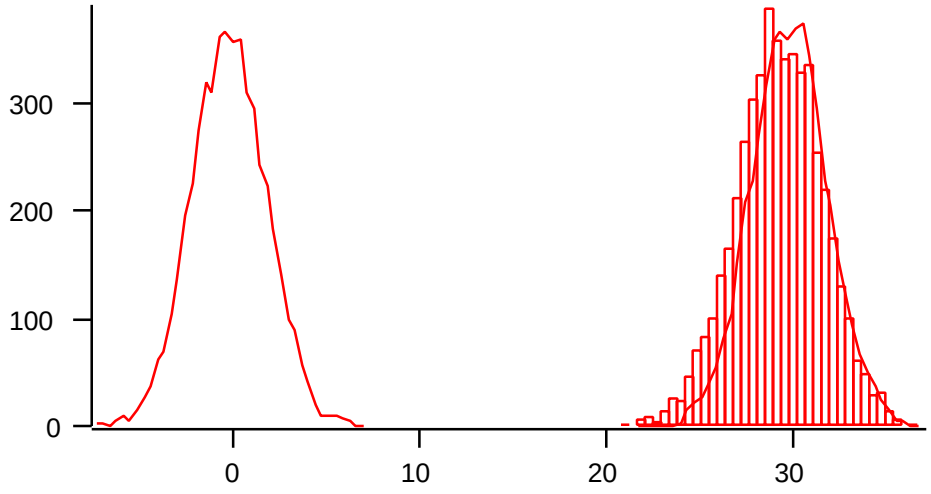


Figure 5.3. Histograms of Bus Power before and after Power Transfer (Example 2).

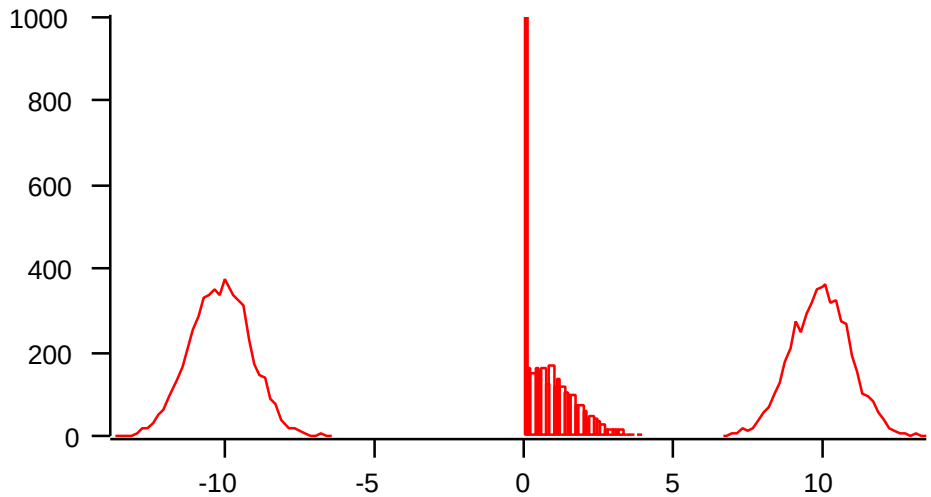


Figure 5.4. Histograms of Bus Power before and after Power Transfer (Example 3).

5.2.4 Theory of Power Transfer Between Buses Losses

The analytical basis of the bus transfer code is described below. It should be noted that all distributions on both buses are assumed to be Gaussian (normal) before power is transferred. The transfer process may be non-linear, and the resulting distributions may not be completely normal in all time steps. The code makes provisions to minimize the adverse effects of non-normality in those situations, and experience to date has not indicated any problems. The method is outlined starting with the simplest (and most nearly Gaussian) situations.

<u>Case 1: Large Positive Net Load on One Bus, Small Excess on Other Bus</u>

If all the net load on bus 1 is greater than 0 and greater than the opposite of the net load on bus 2 then all of the power on bus 2 (N_2) is transferred to bus 1. Thus:

$$\overline{P}_{2\to1} = \overline{N}_2 \tag{5.2.1}$$

where

$\overline{P}_{2\to1}$ = Average power transferred from bus 2 to bus 1, kW

The contribution to the variance of the net load on bus 1 is σ_2^2.

<u>Case 2: Small Positive Net Load on One Bus, Large Excess on Other Bus</u>

If all the net load on bus 1 is greater than 0 and less than the opposite of the net load on bus 2 then an amount equal to the net load on bus 1 is transferred (N_1).

$$\overline{P}_{2\to1} = \overline{N}_1 \tag{5.2.2}$$

The contribution to the variance of the net load on bus 2 is σ_1^2.

Case 3: Constant Net Load on One Bus, Variable Excess on Other Bus

Suppose there is a positive and essentially constant net load on bus 1, N_1, and that there is variable excess power on the other bus, the absolute value of whose mean is close to N_1. Then sometimes the absolute value of the excess on bus 2 may be less than N_1, while at other times it may greater than N_1. In this case the average power transferred is:

$$\overline{P}_{2\to 1} = N_1 \int_{-\infty}^{-N_1} p(y)\,dy - \int_{-N_1}^{0} y\,p(y)\,dy \tag{5.2.3}$$

where

N_1	= Net load (positive and constant) on bus 1, kW
y	= Net load (negative) on bus 2, kW.
p(y)	= Probability density function (assumed to be Gaussian), -

The rationale behind Eq. 5.2.3 may be best understood by considering the implications of its two integrals separately. The first integral gives the probability (and thus fraction of time step) that there is more power available on bus 2 than can be used on bus 1. Since too much power is available, only an amount equal in magnitude to that required on bus 1 (that is, N_1) will be transferred during that portion of the time step. For the second integral, first recall that the average of a random variable y(t) is given by the following integral:

$$\overline{y} = \int_{-\infty}^{\infty} y\,p(y)\,dy \tag{5.2.4}$$

This integral can be expressed in terms of two "fractional averages", which may be obtained by breaking the integral into two parts at value "a." Then:

$$\overline{y} = \overline{y}_{y<a} + \overline{y}_{y\geq a} \tag{5.2.5}$$

where

$$\overline{y}_{y<a} = \int_{-\infty}^{a} y\,p(y)\,dy \text{ , kW}$$

$$\overline{y}_{y\geq a} = \int_{a}^{\infty} y\,p(y)\,dy \text{, kW}$$

The first of these fractional averages gives the fractional contribution to the overall average when y is less than "a." The second integral gives the remaining contribution. In terms of the power transferred from bus 2 to bus 1, when the absolute value of excess power bus 2 is less than that needed on bus 1 (N_1), then all of it can be transferred. Thus the second of the above two integrals indicates the fractional contribution of power during this remaining fraction of the time step. (Note that since y is less than zero, the signs and limits of integration are adjusted accordingly.)

In both cases the net loads are assumed to be normally distributed. The contribution to the variance is found from the weighted squared value of power on bus 2 between 0 and N_1.

Case 4: Variable Net Load on One Bus, Constant Excess on Other Bus

If there is an essentially constant excess of power (negative net load) on bus 2, while the net load on bus 1 is always positive with some of it being less than the opposite of the net load on bus 2, and some of it being more, then the average power transferred is

$$P_{2\to 1} = \int_{0}^{-N_2} x\, p(x)\, dx - N_2 \int_{-N_2}^{\infty} p(x)\, dx \tag{5.2.6}$$

where

N_2	= Net load on bus 2 (negative and constant), kW
x	= Net load (positive) on bus 1, kW
p(x)	= Probability density function, assumed to be Gaussian

The contribution to variance is found from the integral of x^2.

Case 5: Variable Net Load on One Bus, Variable Excess on Other Bus

In the general case that both bus 1 and bus 2 net loads are not constant, there may be overlap in the distributions of the absolute values of the net loads on the two buses. In this case the average power transferred is given by

$$P_{2\to 1} = \int_{0}^{\infty} \left[x \int_{-\infty}^{-x} p(y)\, dy - \int_{-x}^{0} y\, p(y)\, dy \right] p(x)\, dx \tag{5.2.7}$$

Eq. 5.2.7 can be considered to be an extension of Eq. 5.2.6 by incorporation of Eq. 5.2.3.

The contribution to variance is found from

$$\int_{0}^{\infty} \left[(x - \overline{N}_1)^2 \int_{-\infty}^{-x} p(y)\, dy + \int_{-x}^{0} (y - \overline{N}_2)^2\, p(y)\, dy \right] p(x)\, dx \tag{5.2.8}$$

In the implementation of the above formulae in the Hybrid2 code, all distributions are assumed to be normal. That is to say, their probability density function is given by:

$$p(z) = \frac{1}{\sigma_z \sqrt{2\pi}}\, e^{-\frac{1}{2}\left(\frac{z-\bar{z}}{\sigma_z}\right)^2} \tag{5.2.9}$$

Where appropriate, the limits of integration are set to realistic values (such as the maximum net load, based on the disregarded net load probability). The integrals of the normal distribution are

found according to commonly used approximations. For example, the integral from a finite limit, "a", to infinity is related to the error function as follows:

$$\int_a^{\infty} p(z)\,dz = \frac{1 \pm \operatorname{erf}(y)}{2} \tag{5.2.10}$$

where

y = Argument of error function, given by $y = \frac{|a - \bar{z}|}{\sigma_z \sqrt{2}}$

$\bar{z}$ = Mean of z, kW. Note: $\bar{z} = \int_{-\infty}^{\infty} z\,p(z)\,dz$.

σ_z^2 = Variance of z, kW^2

The minus sign is used with the error function when $a \geq 0$ and the plus sign is used when $a < 0$.

The error function itself is defined by:

$$\operatorname{erf}(y) = \int_0^y e^{-w^2} dw \tag{5.2.11}$$

It is approximated by (Spanier and Oldham, 1987):

$$\operatorname{erf}(y) = \frac{3.372\,y}{3 + y^2} \quad \text{for } y < 1.5 \tag{5.2.12}$$

$$\operatorname{erf}(y) = 1 - 1.132\,y\,\frac{e^{-y^2}}{2\,y^2 + 1} \quad \text{for } 1.5 < y < 5 \tag{5.2.13}$$

$$\operatorname{erf}(y) = 1 \text{ for } y = 5 \tag{5.2.14}$$

The weighted normal distribution is found from

$$\int_a^{\infty} z\,p(z)\,dz = \sigma_z \sqrt{\frac{1}{2\pi}}\; e^{-y^2} + \bar{z}\left(1 \pm \operatorname{erf}(y)\right)/2 \tag{5.2.15}$$

where the minus sign is used with the error function when $a \geq \bar{z}$ and the plus sign is used when $a < \bar{z}$. Eq. 5.2.15 may be found by substitution of Eq. 5.2.9 into $\int_a^{\infty} z\,p(z)\,dz$ to give:

$$\int_x^{\infty} z\,p(z)\,dz = \int_x^{\infty} z\,\frac{1}{\sigma_z \sqrt{2\pi}}\,e^{-\frac{1}{2}\left(\frac{z-\bar{z}}{\sigma_z}\right)^2} dz \tag{5.2.16}$$

By defining a variable of integration, $u = \frac{z - \bar{z}}{\sigma_z \sqrt{2}}$, such that $du = \frac{dz}{\sigma_z \sqrt{2}}$, adding and subtracting $\int_x^{\infty} \frac{1}{\sigma_z \sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{z-\bar{z}}{\sigma_z}\right)^2} dz$, rearranging and completing the integration gives the final result.

Converter Rated Power Limit

The transfer of power between buses is limited by the size of the power converters. These are the rectifier when the transfer is from the AC bus to the DC bus, and the inverter when the transfer is in the other direction. The code checks to see that the average transferred power plus three times the standard deviation does not exceed the rating of the appropriate converter. If it does then the amount of power transferred is limited.

$$P_{2\to1,new} = P_{2\to1} - \int_{R_c}^{\infty} (z - R_c)\, p(z)\, dz \qquad (5.2.17)$$

where

$P_{2\to1,new}$	= Average power transferred after the limit is considered, kW
$P_{2\to1}$	= Average power transferred before the limit is considered, kW
z	= Net load after original transfer (random variable), kW
R_c	= Rated power of converter, kW

The reduction in variance is approximated by the original calculated value times the ratio $P_{2\to1,new} / P_{2\to1}$.

Converter No Load Limit

If the average power to be transferred does not exceed the no load loss of the converter, it is assumed that no power is transferred.

Transfer Losses

The losses through the converter are calculated on the basis of the average power transferred. The method of calculating converter losses is described elsewhere in this report. The losses are assumed to reduce the amount of power transferred. In the case where less power is available on bus 2 than is needed on bus 1, the amount of power transferred is reduced by the calculated loss, and the loss is recalculated. An iterative loop in the code is used to ensure that as much as possible of the power is transferred. In cases where additional constraints (such as the rated power of the converter) would limit the amount of power transferred, the losses are reduced to reflect only the power actually transferred. The following discussion of transfer losses deals with the simpler situation, where the rated power of the converter is not exceeded.

Bus Net Loads After Transfer

In general, the net load on bus 1 is positive so any power transfer will reduce it. The net load on bus 2 is negative so power transfer from it will make it less negative. The net loads on both buses are adjusted after the converter limits and losses are considered.

The mean net load on bus 1 (a positive value) is reduced by the power transfer and so given by:

$$N_{1,at} = N_{1,bt} - P_{2\rightarrow 1} \tag{5.2.18}$$

where

$N_{1,at}$ = Net load on bus 1 after transfer, kW

$N_{1,bt}$ = Net load on bus 1 before transfer, kW

The mean net load on bus 2 (a negative value), is made less negative by having excess power transferred from it and so it is given by:

$$N_{2,at} = N_{2,bt} + P_{2\rightarrow 1} + L_{transfer} \tag{5.2.19}$$

where

$N_{2,at}$ = Net load on bus 2 after transfer, kW

$N_{2,bt}$ = Net load on bus 2 before transfer, kW

$L_{transfer}$ = Converter loss during transfer, kW

Note that in this method the loss is assigned to bus 2, that is, the bus which is providing the power. There are some cases, such as when the transferred power would be very small or the losses relatively high, that a "phantom load" could appear if the method were applied exactly as shown. The code has been configured to eliminate that possibility. For example, if the losses plus the power to be transferred were to exceed the power available, then both would be reduced as mentioned above. In addition, if the no load losses were to exceed the power available, then there would be no transfer at all.

Special Conditions

A variety of different conditions are possible, and they are treated differently from one another.

If there is a negative mean net load on both buses, then all of the excess on the AC bus is transferred directly to the DC bus. This excess power can then go to storage. The remaining net load on the AC bus will in general be close to zero. In fact, it will only be non-zero in the case that some of the time during the interval the available AC power is less than the no load rating of the rectifier. For simplicity's sake, this remaining AC net load is taken to be constant (no variability). The new net load on the DC bus will have a variability calculated in the normal way for uncorrelated random variables. Note that in this model, secondary loads on the AC bus would not receive excess AC power except by a return from the DC bus. When secondary loads are considered, they are always assumed to be constant over the interval.

If there is a negative mean net load on the AC bus and a positive mean net load on the DC bus, then excess power is transferred to the DC bus to try to meet that load. Additional excess remains on the AC bus.

If there is a negative mean net load on the DC bus and a positive mean net load on the AC bus, then excess power is transferred to the AC bus to try to meet that load. Additional excess remains on the DC bus.

The possibility of non-Gaussian net loads on the two buses after the transfer can complicate the situation. In some cases it is preferable to use a one-sided distribution. For this situation Hybrid2 employs the Weibull distribution, which is a commonly used one-sided distribution. In one case, if all of the net load on one of the buses is negative, then it must also be negative (or zero) after the transfer. Using a normal distribution could imply some positive net load. Thus the Weibull distribution is used for that bus. Similarly, if all of the original net load on one bus is positive, then it must remain so after the transfer. Again, the Weibull distribution is used. The decision as to which type of distribution is used is made in the transfer section of the code. The result is applied subsequently. It should be noted that using the Weibull distribution as described here is an approximation. A more exact method could have been used, but it would have been computationally much more intensive and the expected benefits would have been minimal.

5.3 Loads Module

5.3.1 Executive Summary

Hybrid2 incorporates four different classes of loads: 1) primary, 2) deferrable, 3) optional and 4) dump loads. The effectiveness of hybrid power systems depends strongly on the correlation between power production and consumption. The code includes a detailed load management strategy that allows the hybrid system to meet load requirements that differ from the conventional "primary" load profile. Deferrable and optional loads are categorized as "secondary" loads. Deferrable loads need to be met but can be delayed until the system has an excess of power, whereas optional loads do not necessarily need to be met and can be supplied at any time. When an energy excess cannot be used by the secondary loads and is also not required to charge the battery, it goes to a dump load (see Figure 5.5). Thus, a dump load is not really a load in the conventional sense.

Whenever there is excess of energy produced by the system (from the renewables and the diesels), the program first checks if the battery is able to accept a charge. If, after charging the battery, there is still excess energy, then Hybrid2 supplies the deferrable loads and, finally, the optional loads. The dump load is the last sink and it is used when it is not possible to use the excess energy produced to fulfill other requirements.

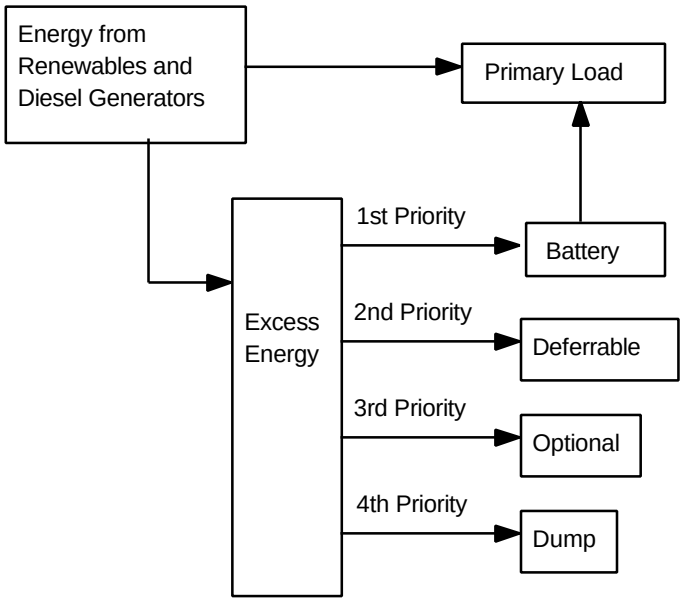


Figure 5.5. Diagram of Load Priority

5.3.2 Overview of Loads

Primary Loads

The primary load must be met at all times. It may not be postponed. The code characterizes the primary load based on the average load during the time step and its standard deviation, if it is known, or, otherwise, a specified variability about the average.

Deferrable Loads

Deferrable loads are loads which must be supplied, but for which there is some flexibility as to when. The advantage of deferrable loads is that by using them it may be possible to utilize some renewable energy which would otherwise be wasted. This could occur when there is a temporal mismatch between the primary load and the renewables. Deferrable loads are those loads that can be postponed, if possible, until there is excess of energy from renewable sources. If no renewables are available, then the deferrable loads will eventually be supplied by the diesel(s). Deferrable loads are categorized as secondary loads.

Hybrid2 allows the use of two methods for modeling deferrable loads. They are referred to as "block average" and "running average." These are described below.

Optional Loads

Optional loads are treated similarly to deferrable loads, except that they need never be met. Optional loads are addressed after the deferrable loads are supplied. Optional loads, together with deferrable loads, are categorized as secondary loads.

Dump Load

Dump loads are used to absorb any excess energy that the system produces that cannot be used by the secondary loads. The only necessary input parameter is the rated power that the dump load is able to draw. Note that if the dump load capacity is sometimes less than the power that must be dissipated to keep the power flows in balance, then a value of power in excess of the dump load capacity will be reported in the output as excess dump energy.

In AC systems the dump load is normally an actual device, although in certain cases some of the excess power may be dissipated by other means, such as wind turbine blade pitch regulation. In DC systems, on the other hand, the function of the dump load is normally accomplished by intrinsic power regulation of the wind turbine or photovoltaic panels. Hybrid2 calculations make no distinction among the various possible methods of power dissipation. The presumption, however, as reflected in the program user interface, is that an AC dump load is a device, while a DC dump load is not.

Unmet Load

In some situations it may not be possible for the hybrid power system to always supply all of the required primary load. If this happens Hybrid2 reports the portion of load which is not supplied. This is known as an "unmet load."

5.3.3 Details of Loads

Primary Loads

The primary load must be met during each time step. It may not be postponed. The code characterizes the primary load based on the average load during the time step and its standard deviation, if it is known, or, otherwise, a specified variability (percentage of the load) about the average.

The primary load is based on a time series input by the user, either in the form of an input file or one created using the primary load matrix. For more information about creating a primary load, please see the Hybrid2 users manual.

Inputs

The inputs defining the behavior of the primary loads are as follows:

Data time step: The time interval over which the average load values were obtained. This should be the same as the time step used in the simulation as a whole.

Mean: The mean value of the primary load, based on averaging frequent samples during the simulation time step. If the load data within the time step were based on n measured value the mean value would be

$$\bar{L} = \frac{1}{n}\sum_{i=1}^{n} L_i \qquad (5.3.1)$$

where

L_i = Measured load, kW

$\bar{L}$ = Average load within specified time step, kW

n = Number of measured values for the load within the time step

Standard deviation: Assuming the load data to have been based on n measured values, then the standard deviation would be calculated as follows:

$$\sigma_L = \sqrt{\frac{\sum_{i=1}^{n}\left(L_i - \bar{L}\right)^2}{n-1}} \tag{5.3.2}$$

Variability ($\sigma_L / \bar{L}$): In case the standard deviation is not available for each time step, the user can specify the load variability as a percentage of the average load. The code calculates the standard deviation as the variability multiplied by the average load within each specific time step.

Deferrable Loads

Deferrable loads are loads which must be supplied, but for which there is some flexibility as to when. The advantage of deferrable loads is that by using them it may be possible to utilize some renewable energy which would otherwise be wasted. This could occur when there is a temporal mismatch between the primary load and the renewables. Deferrable loads are those loads that can be postponed until there is excess of energy from renewable sources. Deferrable loads are categorized as secondary loads. A typical deferrable load is water pumping when there is a storage tank available. If the tank can hold water for a day's use, then pumping could take place at any time during the day when power was available, as long as the tank was not full. As long as there was sufficient renewable energy available at sometime during the day, the pumping load would always be supplied by renewables, and it would never become primary load. If the renewables were insufficient, then some of the water pumping would become a primary load, and thus might require the use of the diesel generator(s). Other examples include water heating, especially in cold climates, or production of some product which could be stored. This latter category could include sawing lumber, grinding corn, etc.

Hybrid2 allows the use of two methods for modeling deferrable loads. They are referred to as "block average" and "running average." In both methods, the deferrable load is characterized by: 1) a rated power, 2) a duty cycle, 3) a deferral period, and 4) a flexibility. The rated power is the maximum power that can be used by the deferrable load. The duty cycle relates the average power required by the load to the rated power. Specifically the average power is equal to the rated power times the duty cycle. The deferral period is a measure of time over which the load may be deferred. The flexibility determines whether the load is to be supplied at rated or can be supplied at part load. The two methods treat the deferral period somewhat differently, as described below.

Inputs

The inputs to the model for the deferrable loads are:

Type of deferrable load: This specifies the type of deferrable load. It may be either Block Average or Running Average

Rated power: Maximum rated power of the deferrable load

Duty cycle: Average power to be delivered to deferrable load divided by the rated power. This is the fraction of time over which the power is required. The duty cycle is used to calculate the total energy required to meet the deferrable load. For example: If the duty cycle is 0.5, the deferral period is 20 hours, and the rated power is 10 kW, then the total energy required from the deferrable load during the deferral period is 100 kWh.

Deferral period**:** Length of time the deferrable load can be neglected. After that the deferrable load becomes a primary load and needs to be met.

Flexibility: Specification determining whether deferrable load must be at full power or may be supplied at part load. The full power specification could apply, for example, to a pump operating at a constant head and flow rate. The part load specification could apply when the load is a composite of individual, switchable loads, or is an otherwise adjustable load. The user has two options:

1. Rated power only: The power available (excess) within specific time step must be at least the same magnitude as the rated power.
2. Part load acceptable: The power available (excess) can be any value up to the rated power of the device.

Block Average Deferrable Loads

In the block average method, the deferral period specifies a time period during which a certain amount of energy must be supplied. This energy is defined by the average deferrable load times the time period. The deferral period is assumed to be constant for the entire simulation. For example, consider a deferrable load with a rated power of 10 kW, a duty cycle of 0.1 and a deferral period of 100 hr. Over the deferral period, a total of 100 kWh would need to be supplied to the load. Part of the energy could be supplied at any time, subject to the limitation that the rated power of 10 kW not be exceeded. There may be multiple deferral periods in a simulation. The number of deferral periods is the total simulation length divided by the deferral period (as an integer).

The method gives preference to excess renewable energy. In general, the deferrable load will not be supplied unless there is excess renewable power available. Each time step the code checks to see if the total required deferrable energy can conceivably be supplied, given what has already been supplied, and subject to the limitation that the load cannot be supplied at a rate greater than its rated capacity. If it becomes apparent that renewables will not be able to supply the required energy, then the deferrable load becomes a primary load. Subsequently, and until the beginning of the next deferral period, the full rated power of the deferrable load is added to the original primary load. The resulting primary load can then be supplied by renewables, storage, or diesels in the usual manner.

If the amount of excess power is less than the rated power of the deferrable load, one of two conditions will apply depending on the "flexibility" specification:

1. The deferrable load may be designated as always operating at rated power. In this case, none of the excess power would be directed to this deferrable load. It could go to other deferrable loads, or to an optional load, or it could be dumped.

2. The deferrable load may be designated as being capable of part load operation. In this case, any excess power is available could be used by the load.

The block average method has been designed to facilitate assessing the performance of hybrid power systems with seasonally varying loads. These could be, for example, heating loads in the Arctic or irrigation loads in arid lands.

Running Average Deferrable Loads

The running average method assumes that the load is supplied at a constant rate, but uses a deferrable load time inventory as an implicit form of storage. The deferral period specifies a time during which the re-supply of the inventory can be deferred if there is no excess renewable power available. This method has been designed to facilitate the evaluation of systems which incorporate multiple deferrable loads with possibly different deferral periods.

The method works as follows: At every time step a constant power is assumed to be supplied to the load from the deferrable load inventory. This corresponds to the average power required over the deferral period. That is, the power supplied is the product of the duty cycle and the rated power. For example, if the load is rated at 20 kW and the duty cycle is 0.1, then 2 kWh would be supplied every hour.

As long as the storage inventory is not empty, it can be used to supply the deferrable load. If the storage inventory is empty, the load becomes a primary load. When power is withdrawn from the storage inventory, the time remaining before the load must become a primary one decreases. Suppose that the capacity of the inventory was 50 hours and that it was full at the start of the simulation. At the end of 50 hours, in the absence of any renewable power, the inventory would be empty. The load would become a primary one.

When a deferrable load becomes a primary load, an amount of load normally equal to the rated power of the deferrable load is added to the regular primary load in the subsequent time step of the simulation. The total primary load will be dealt with in the usual way: If there is sufficient renewable power, the load will be supplied by the renewable source. If there is excess renewable power, it may go to storage, or it may augment the deferrable load storage inventory. It may even be dumped. If there is a deficit, the load may be supplied by the diesel(s).

Suppose that there is enough excess power available to supply the deferrable load at its rated capacity for one time step of the simulation. The effect of this would be to add to the inventory an amount equal to the time step of the simulation divided by the duty cycle. Thus, if the time step of the simulation is 1 hour and the duty cycle is 0.1, 10 hours would be added to storage reservoir. Adding time to the storage reservoir increases the time remaining before the deferrable load becomes a primary load.

If the amount of excess power is less than the rated power the discussion of flexibility given for the block average method applies here as well.

If the amount of excess power is greater than the rated power and if sufficient capacity remains in the inventory, then the full time increment (i.e., time step divided by duty cycle) will be added to the inventory. If the inventory is limited, then only a proportionally smaller amount will be used. When there is still excess power available, it could go to other deferrable loads, or to an optional load, or it could be dumped.

One adjustment to the above procedure is needed in the case of small duty cycles. In particular this adjustment applies when the time step divided by duty cycle is greater than the deferral period. An example of this could be a lightly loaded water pump, which is nonetheless needed on a regular basis. In this situation it is necessary to calculate a reduction factor and apply it to two of the parameters. The factor is given by the product of the deferral period times the duty cycle divided by the time step. The reduction factor is applied (by multiplying) to the time increment which is added to the storage inventory. It also is used to adjust the decrease in excess power (to be used by subsequent deferrable or optional loads) and the power added to the primary load in subsequent time steps (when required).

For example, consider a 1 kW water pump with a duty cycle of 0.1 operating in conjunction with a storage tank (deferral period) of 5 hr capacity. The reduction factor for a simulation using 1 hr time steps would be 0.5. This means that in any one time step a maximum of 0.5 kWh could be supplied to this load from the excess power.

The running average method also includes a check to ensure that the power dedicated to the deferrable loads in the rated power case does not violate the disregarded net load probability criterion of the simulation.

Once the calculations for one deferrable load are completed, similar calculations are performed for the remaining deferrable loads.

Comparison of Block Average and Running Average Deferrable Loads

A summary of the differences between the block average and running average deferrable loads is helpful in understanding their application.

The <u>block average</u> deferrable load has the following features:

1. Only one deferrable load may be used at a time on each bus.
2. The deferrable load may have different values (rated deferrable power and duty cycle) in successive blocks during the simulation.
3. Blocks all have the same length.
4. The energy corresponding to the rated deferrable power times the duty cycle times the block length will be supplied to the deferrable load during the block
5. Surplus renewable energy is given preference during each block.
6. The deferrable load becomes primary when it is apparent that, to supply the required load, the load must be supplied at its rated power until the end of the block.

The block average method is most appropriate when there is a single dominant deferrable load, which varies over the year.

The <u>running average</u> deferrable load has the following features:

1. Multiple deferrable loads may be used simultaneously.
2. The various deferrable loads may have different values (rated deferrable power, duty cycle, and deferrable time period.)
3. The deferrable load parameters do not change over the simulation.
4. Power is supplied to each deferrable load at a constant rate.

5. The inventory for each deferrable load is preferentially re-supplied with surplus renewable energy.
6. When the inventory is depleted, a deferrable load is converted to a primary load (at the rated power level).
7. When converted to a primary load, a deferrable load remains a primary load until the inventory can supply that load for at least one time step.

Use of the running average deferrable load is most appropriate when there are multiple deferrable loads whose characteristics do not vary greatly over the year. More discussion of the running average method can be found in Barley (1994.)

Optional Loads

Optional loads are treated similarly to deferrable loads, except that they need never be met. A typical optional load is normally supplied by another primary source of energy (such as fuel oil) but can also use excess electricity from the hybrid power system when it is available. Due to the expected intermittency and unregulated nature of the excess power at this point optional loads are most commonly heating loads. Examples include heating of fuel oil before it is pumped to diesel engines in very cold climates and electric heating used in conjunction with wood or oil fired space or domestic hot water heaters. Optional loads are addressed after the deferrable loads have been considered.

Inputs

The inputs to the model for the optional loads are:

Type of optional load: This specifies the type of optional load. It may be either block average or running average. The type of optional load is specified implicitly. If a block average is used, separate files are created. If a running average is used, optional loads are specified in the same way as deferrable loads. The difference is that the deferral period must be longer than the simulation period.

Rated power: Maximum rated power of the optional load.

Duty cycle: Average power to be delivered to optional load divided by the rated power. The duty cycle is used to calculate the total energy required to meet the optional load. For example: Let the duty cycle be 0.5. If the total optional period is 20 hours and the rated power is 10 kW, then the total energy in that time period is 100 kWh.

Option/Deferral period: In the running average type, this is the capacity of optional load storage inventory. This must be longer than the simulation period. In the block average method this is used as the basis for determining how much energy can be used by the optional load over the time period.

Flexibility: Specification determining whether optional load must run at full power or may run at part load. The user has two options:

1. Rated power only: The power available (excess) within specific time step must be at least the same magnitude as the rated power.
2. Part load acceptable: The power available (excess) can be any value.

Block Average Optional Loads

In the block average method, different optional loads may be specified for different seasons of the year. As with the block average deferrable load, the total energy that may be absorbed over the deferral period is calculated based on the rated power and duty cycle. Any excess power will go to the optional load until the total allowed optional energy over that period is supplied. The process will begin again after the next period starts.

Running Average Optional Loads

In the running average method, optional loads are types of deferrable loads. The only difference is that the deferral period must be longer than the simulation period.

Comparison of Block Average and Running Average Optional Loads

A summary of the differences between the block average and running average optional loads is helpful in understanding their application.

The <u>block average</u> optional load has the following features:

1. Only one optional load may be used at a time on each bus.
2. The optional load may have different values (rated deferrable power and duty cycle) in successive blocks during the simulation.
3. Blocks all have the same length.
4. Only surplus renewable energy goes to supply the optional load.
5. The optional load never becomes primary.

The block average method is most appropriate when there is a single dominant optional load, which varies over the year.

The <u>running average</u> optional load has the following features:

1. Multiple optional loads may be used simultaneously.
2. The various optional loads may have different values (rated optional power and duty cycle.)
3. The optional time period may have any value greater than the length of the simulation.
4. The optional load parameters do not change over the simulation.
5. Only surplus renewable energy goes to supply the optional load.
6. The optional load never becomes primary.

Use of the running average optional load is most appropriate when there are one or more optional loads whose characteristics do not vary greatly over the year. This type of optional load should be used when running average deferrable loads are also used.

Dump Load

Dump loads are used to absorb any excess energy that the system produces that cannot be used by the secondary loads. In this context, a dump load is a device as well as a load. The only necessary input parameter is the rated power that the dump load is able to draw. Any power in excess of the dump load capacity is reported as such. Reporting of excess dump power may indicate that the system has been incorrectly designed (by incorporating too small a dump load.) On the other hand, it may reflect the possibility of using controllable (dispatchable) renewable generators. As discussed in Chapter 7, Hybrid2 assumes that the renewable generators are not dispatchable, but they sometimes can be. For example, pitch regulated or furling wind turbines may be able to reduce their output if it is not required by the load. Using such turbines, dump loads may still be needed to maintain grid frequency, but they may not need to be sized as large as if the turbines were completely non-dispatchable. In modeling these systems, the excess dump load would correspond to power dissipated in the wind rather than being converted by the wind turbine.

Unmet Load

In some situations it may not be possible for the hybrid power system to always supply all of the required primary load. If this happens Hybrid2 reports the portion of load which is not supplied. This is known as an "unmet load." Circumstances which, individually or in combination, could result in unmet load include: no diesels at all in the system, diesels too small for the load, insufficient energy in the storage, power converters sized too small for the load, or a high load at times of forced diesel shut-off.

5.4 Renewable Resource Module

5.4.1 Executive Summary

Hybrid2 assumes two possible renewable power resources: wind and sun. The characterization of each of these resources requires the basic data on the available resource plus, as appropriate, information on the measurement of the resource data, variability of the data, and geographic factors that affect the determination of the actual available renewable resource.

5.4.2 Overview of Renewable Resource Characterization

The wind resource is characterized by a number of parameters, including site-specific geographic factors, information about the wind speed data collection and averaging time, and the speed and variability of the wind. The specific parameters are detailed below.

The wind resource and the necessary information about its measurement are defined by the following parameters: the units used for the wind speed, the measured average wind speed for each time interval, the data time step, the anemometer height used for measuring the wind, and the variability of the wind speed. The wind speed variability can be characterized by either 1) the standard deviation of the wind speed during each time interval, 2) a fixed ratio of the standard deviation of the wind speed to the average wind speed. Finally, a wind speed scale factor can be applied to measured mean data and the standard deviation of the wind speed.

A number of factors related to the site geography also affect the nature of the local wind resource, including the nature of the turbulence at the site and the local air density. The site power law exponent, turbulence length scale, reference wind velocity for the turbulence length scale, and the

turbulence intensity all may be required to determine the wind power at a given site. The local air density is defined by two parameters whose values depend on the approach taken to defining the air density. The air density can be determined from 1) a fixed air density, 2) the local temperature and pressure using the ideal gas law, or 3) the site elevation and the adiabatic lapse rate.

The solar resource is characterized by measured insolation data and parameters related to the site. The site-related parameters include geographic information (site latitude and longitude, and ground reflectivity) and temperature information (the nominal ambient temperature or a time series of ambient temperature). The solar resource itself is defined by the insolation time series data, the data time interval, and the time used to define the collection of the data (standard time, local solar time, etc.). Solar data is assumed to be taken on a horizontal surface.

5.4.3 Details of Renewable Resource Characterization

Wind Resource Characterization

The wind resource is characterized by a number of parameters, including geographic factors at the site under consideration that affect the renewable resource, information about the wind speed data collection and averaging time, and the speed and variability of the wind. The specific parameters are detailed below.

Inputs

Wind Speed Scale Factor: A scale factor may be used to adjust the input wind speed. This is a multiplier which applies to all wind speed inputs from the data file. The scale factor applies to interval standard deviations as well as mean wind speeds. The wind speed scale factor is normally set to 1.

Power Law Exponent: Wind speed increases with height from the ground. Thus, the wind speed that a wind turbine experiences at hub height will be different from that measured by an anemometer at a different height. The power law exponent is used to correct the wind speed measured at one height to determine the wind speed at another height. The change in wind speed as a function of height is typically modeled as the ratio of the new height to the measured height raised to some power. The value of the exponent used in the power law depends on the terrain of the site under consideration. The allowed values for the power law exponent is between 0.1 and 1.0. A value of 0 would represent no change with height. A value of 1.0 would represent a two fold increase in wind speed with an increase in height by a factor of two. A typical value used is 1/7 = 0.143 for flat terrain like fields or ocean.

Turbulence Length Scale: Determination of the behavior of multiple wind turbines and determination of the power fluctuations from any single wind turbine are a function of the averaging time used to determine the turbine power curve and changes in the wind characteristics across a site with multiple turbines. The required calculations require some knowledge about the typical turbulence characteristics at the site. The Turbulence Length Scale, typically between 10 and 1000 meters, is a measure of the distance over which the wind speed remains correlated. It may be estimated from the surface roughness of the site (Freris, 1990), or from measurements and calculations using the autocorrelation function and the mean wind speed (Fordham, 1985.)

Reference Wind Velocity for Turbulence Length Scale: The Reference Wind Velocity is used in conjunction with the turbulence length scale. In Hybrid2, calculations using the turbulence length

scale are done only once in the run to find representative values. Accordingly, the most appropriate Reference Wind Velocity to use is the site mean wind speed.

Nominal Turbulence Intensity: Hybrid2 takes into account the fluctuations in wind power due to wind speed fluctuations about the average value during each time interval. It does this in a number of ways. In correcting the wind turbine power curve from one averaging time to another and in deriving a wind farm filter, the site nominal turbulence intensity referred to here is used. The Nominal Turbulence Intensity is the nominal ratio of the standard deviation of the wind to the mean wind speed. The value of the nominal turbulence intensity is normally between 0.01 and 0.5. A value of zero indicates that there are no fluctuations in the wind over each time interval. A value of 0.5 indicates that the standard deviation of the wind over each time step is half of the average wind speed.

If the wind speed time series data file includes the standard deviation of the wind during each time interval, then that standard deviation is used to determine fluctuations in wind power. If the wind speed time series data file does not include the standard deviation of wind speed during each time interval, then a nominal turbulence intensity may also be used. In that case the two values should be the same. See Wind Speed Fluctuations below.

Air Density: The power captured from the wind depends not only on the wind turbine and the wind speed, but also on the air density, which changes with temperature and air pressure. Wind power is first determined from the power curve, which is assumed to be based on standard atmospheric conditions. Actual power is then determined by multiplying by the ratio of the actual air density to the air density at standard conditions. Hybrid2 allows for three different approaches to determine air density:

Density ratio: Application of a constant ratio of site density to standard density, input by the user.

Ideal gas law : Using the Ideal Gas Law and the site mean temperature and pressure.

Adiabatic lapse rate: Calculating a value based on mean temperature and elevation above sea level, assuming the standard adiabatic lapse rate.

Data Time Step: This is the data time step in minutes. It is the period over which the data is assumed to be averaged. The data time step must have the same length as that used in the simulation. Values should be between 5 minutes and 2 hours. It is assumed that all data is originally sampled at a much higher rate, and then averaged to obtain mean values (and standard deviations where applicable) for each time step.

Anemometer Height: This is the height of the anemometer used to measure the wind data. Anemometer height is typically 10 m above ground level, although other values are also common. Wind turbine hub height, however, is normally 20 m or more, and the winds are usually much stronger at higher elevations. The wind speed should therefore be adjusted to take into account the height differences. This is discussed in more detail in Chapter 6.

Wind Speed Fluctuations. When short term standard deviation of the wind speed data is available for each time step, then that value may be included in the data file along with the mean. When the short term standard deviation time series are not available, a representative site turbulence intensity may be used. Turbulence intensity is the ratio of the short term standard deviation of the wind to the short term mean (corresponding to a typical time step in Hybrid2). In this case, the code multiplies the mean each time step by the turbulence intensity to estimate the short term standard deviation.

Wind Data: The wind data file must include at least the mean wind speed for each time of the simulation. When short term standard deviation is available, it may be included as well.

Solar Resource Characterization

The solar resource is characterized by measured insolation data and parameters related to the site. The site related parameters include geographic information (site latitude and longitude, and ground reflectivity) and temperature information (the nominal ambient temperature or a time series of ambient temperature). The solar resource itself is defined by the insolation time series data, the data time interval, and the time used to define the collection of the data (standard time, local solar time, etc.). The specific parameters are detailed below.

Inputs

Ground Reflectivity: Solar power depends not only on direct and diffuse sky solar radiation, but also on radiation reflected from the ground. Ground reflectivity ranges from 0 to 1.0, with typical values about 0.2.

Ambient Temperature: Ambient temperature is used in estimating the solar photovoltaic cell panel temperature. When time series data is available, it may be used by Hybrid2 in a manner similar to that of wind speed. When such data is not available, a representative site mean ambient temperature should be used. The value selected should be a daytime temperature, corresponding to the times of highest productivity from the panels.

Latitude: The site latitude is used in solar angle calculations. These calculations are done since solar data is usually taken on a horizontal surface (and assumed to be such by Hybrid2) whereas photovoltaic panels are normally installed on a slope. The slope surface generally face south in the northern hemisphere and north in the southern hemisphere. Sometimes panels are installed on adjustable tracking devices. Solar angle calculations are also needed in those cases.

Longitude: The site longitude is used in solar angle calculations to ensure that the data is converted to solar time. If the solar time is not properly accounted for, errors in the results will appear.

Initial Julian Day of Data: Solar resource calculations require knowledge of the day during which the data was taken. Specification of the Julian day of the first data point allows the data to begin on any day of the year.

Insolation Data: Solar insolation data is used in time series form in a manner similar to that of wind speed. The data is assumed to be taken on the horizontal. Hybrid2 corrects the data, if necessary, to the plane of the photovoltaic array. Data is in Watts per square meter.

5.5 Economics Module

5.5.1 Executive Summary

The economics section of the Hybrid2 model is based on the use of conventional life cycle costing economics. That is, the Hybrid2 economic routine performs a first level economic evaluation of a hybrid power system. This includes yearly cash flows, the present value of system costs and incomes, levelized annual costs, payback periods, and the internal rate of return.

In addition, the analysis has been designed to allow for a side-by-side comparison of the economics of a hybrid power system with those of a diesel-only powered system. Another aspect of Hybrid2 economics is the ability to examine the potential economic advantage (or disadvantage) of adding renewable energy sources to a pre-existing diesel-powered system. This economic analysis is performed at the completion of a Hybrid2 simulation, or any time thereafter. The analysis uses results of the simulation, such as fuel usage, power supplied to the various types of loads, diesel operating hours and battery life. It also considers economic parameters such as component costs, fuel costs, interest rates, inflation rates, etc.

The economic analysis that is completed by Hybrid2, although an in-depth analysis, was designed only to provide a reasonable estimate of system cash flow and an even comparison to an all-diesel power system alternative. Due to the complex nature of project economics, Hybrid2 was not intended to conduct a complete economic analysis. It is assumed that the user will use the Hybrid2 economics package to obtain a desired system design and then will perform an independent economic analysis using the methods and software of his or her choice.

5.5.2 Model Overview

Major Input

Modeling Input: The following inputs (and their symbols) are supplied to the economics part of the Hybrid2 program by direct user input:

Capital cost of domestically purchased AC WTG components ($C_{WD,AC}$)

Capital cost of internationally purchased AC WTG components ($C_{WF,AC}$)

Capital cost of tower equipment for AC WTGs ($C_{WT,AC}$)

Installation cost of AC WTGs ($C_{WI,AC}$)

Capital cost of domestically purchased DC WTG components ($C_{WD,DC}$)

Capital cost of internationally purchased DC WTG components ($C_{WF,DC}$)

Capital cost of tower equipment for DC WTGs ($C_{WT,DC}$)

Installation cost of DC WTGs ($C_{WI,DC}$)

Total overhaul cost for WTGi (C_{R,W_i})

Time between overhauls for turbine i (T_{R,W_i})

Wind turbine related operation and maintenance costs (om_W)

Capital cost of photovoltaic panels (C_{PV})

Installation cost of photovoltaic panels (C_{PVI})

Capital cost of photovoltaic racks and/or trackers (C_{PVR})

Capital cost of maximum power point tracker (C_{MPPT})

Time between photovoltaic panel replacements ($T_{R,PV}$)

Diesel capital costs (C_D)

Diesel installation costs (C_{DI})

Diesel capital costs (base case) ($C_{D,B}$)

Diesel installation costs (base case) ($C_{DI,B}$)

Diesel overhaul costs (C_{R,D_i})

Period between diesel overhauls (t_{R,D_i}

Diesel related operation and maintenance costs (om_D)

Battery bank capital costs (C_{Bat})

Battery installation costs (C_{BatI})

Battery operation and maintenance costs (om_{Bat})

Power converters capital costs (C_C)

Power converters installation costs (C_{CI})

Period between power converter replacements ($T_{R,C}$)

Dump load capital costs (C_{Dump})

Dump load installation costs (C_{DumpI})

Period between dump load replacements ($T_{R,Dump}$)

Unit cost of fuel (c_F)

Balance of system costs (C_{BOS})

Installed cost of optional load equipment (C_O)

Installed cost of line extension to existing grid (C_{Ext})

System installation overhead percentage (c_I)

Tariff costs (C_T)

Shipping costs (C_{sh})

General system operation and maintenance cost (OM_{Sys})

Annual administrative costs (C_{Admin})

General system operation and maintenance costs (base case) ($OM_{Sys,B}$)

Annual administrative costs (base case) ($C_{Admin,B}$)

Financial life of system (N)

Salvage value of system equipment (S)

General inflation rate (g)

Discount rate (d)

Fuel inflation rate (f)

Loan interest rate (i)

Fraction of installed capital cost which must be paid up front (f_{dp})

Loan period (T_L)

Loan grace period (T_G)

Cost of energy to primary load (c_{Prim})

Cost of energy to deferrable load (c_{Def})

Cost of energy to optional load (c_{Opt})

Corporate tax rate (t)

Renewables production tax credit (t_c)

Equipment depreciation time (T_E)

<u>Simulation Input</u>: The following inputs (and their symbols) are supplied to the economics module of the Hybrid2 program from an input file created by the performance module of the Hybrid2 program:

Number of wind turbines in system (N_W)

Total rated power of AC connected WTGs ($P_{R,AC}$)

Total rated power of DC connected WTGs ($P_{R,DC}$)

Average power to primary load ($\overline{P}_{Prim}$)

Average power to deferrable load ($\overline{P}_{Def}$)

Average power to optional load ($\overline{P}_{Opt}$)

Average power from WTGs ($\overline{P}_W$)

Average power from diesels ($\overline{P}_D$)

Average power from photovoltaic panels ($\overline{P}_{PV}$)

Average overload power ($\overline{P}_{Over}$) ("Load not met")

Average overload power (base case) ($\overline{P}_{Over,B}$) ("Load not met")

Average hourly total diesel fuel consumption (F_h)

Average hourly total diesel fuel consumption (base case) ($F_{h,B}$)

Simulation length in hours (T_{Sim})

Rated power of photovoltaic panels ($P_{R,PV}$)

Rated power of the diesels ($P_{R,D}$)

Rated power of the converters ($P_{R,C}$)

Nominal battery capacity ($P_{R,Bat}$)

Number of diesel generator sets (N_D)

Number of diesel generator sets (base case) ($N_{D,B}$)

Rated power of dump load ($P_{R,Dump}$)

Battery life (T_{Bat})

Operating time of diesel engine i (T_{D_i})

Battery size scale factor (Δ_{Bat})

Scale factor for AC connected wind turbines ($\Delta_{W,AC}$)

Scale factor for DC connected wind turbines ($\Delta_{W,DC}$)

Output

Based on the user inputs, the Hybrid2 economic analysis result is in the following output: present worth, levelized cost, simple payback period, discounted payback period, rate of return and various cash flows.

5.5.3 Economic Model Theory

Overall Model Basis and Overview

The economic analysis that is completed by Hybrid2, although an in-depth analysis, was designed only to provide a reasonable estimate of system cash flow and an even comparison to an all-diesel power system alternative. Due to the very complex nature of project economics, which varies from country to country, and even region to region, the economic calculations conducted in Hybrid2 are not meant to be complete. An example of this is the determination of the cost of energy. Finding the true cost of energy may be very difficult. Hybrid2 compares the costs to produce power from a diesel plant to that of a hybrid system. This is simpler because issues like system administrative costs, distribution expenses, and local labor rates are very hard to determine accurately. With this in mind, the authors of the economics module tried to maximize accuracy and flexibility without making the software too complex to be used efficiently. It is assumed that the user will use the Hybrid2 economics package to obtain a desired system design and then will perform an independent economic analysis using the methods and software of his or her choice.

Like most conventional life cycle costing economic analyses, Hybrid2 has to predict and reduce all lifetime or future costs to a standard time cost basis, usually defined via the present value of a particular cost component. For Hybrid2, the model assumes that the period of simulation is typical of the system lifetime performance. With this assumption, a 24-hour simulation of a hybrid system could in principle be used to analyze its lifetime economics. Normally, a longer period, such as a season or a year should be used, however. Inherent to the generality assumption is the assumption that power demand, and therefore production, remains constant throughout the lifetime of the system. Additionally, the power mix of the system remains constant, i.e., the ratio of wind energy to diesel energy is fixed.

Due to the time-dependent nature of the value of money, any economic analysis must define the relation between the present value of money and the value of money at any point within the time frame of the analysis. To this end, Hybrid2 uses constant inflation, interest, and discount rates. For instance, the cost of diesel fuel is increased yearly according to a constant fuel inflation rate. Also, all user input costs must be in terms of the present value of money. It should also be noted that in the Hybrid2 economics model, for the cash flow analysis, all revenues and disbursements occur at the end of the period (year).

The economic analysis is driven by a set of user-defined inputs. These inputs include detailed component-by-component costs, financing rates, loan period, fuel prices, etc. One of these inputs also determines the nature of the economic analysis: 1) a new hybrid system whose economics are compared to a diesel only system, 2) a pre-existing diesel system which is retrofitted to use renewable energy resources. After the completion of a Hybrid2 simulation of the system under examination, the economics module combines the simulation performance results file with the user-provided parameters to perform the economic analysis. First, a year-by-year cash flow of the system disbursements and revenues is completed. Next, the net present value of these costs and incomes is determined. These net present values are in turn used to calculate annualized

values. Finally, the economic indicators of simple payback period, discounted payback period, levelized cost of energy, and internal rate of return are determined. The results of these calculations are stored in two output files. The first summarizes the economic indicators and the configuration of the hybrid system. The second details the cash flow analysis.

The following sections will define the basis of the economics model for a new hybrid system whose economics are compared to a diesel only system, and a pre-existing diesel system which is retrofitted to use renewable energy resources.

Economics of New Hybrid Power Systems

The economic analysis of a new hybrid power system includes two parallel paths. The first is the determination of the hybrid system economic performance during the financial lifetime of the system. The second path calculates the economics of a diesel-only power system of comparable generating capacity (base case) during the same financial period. The specifics of these calculations are detailed below. If the user does not wish to compare the hybrid system with a base case, then the program outputs zeroes for the second path.

Cash Flow Analysis

As detailed below, the cash flow analysis produces year-by-year detailed figures for project incomes and disbursements. The disbursements are separated into the following categories: installed capital costs/annuity payments, fuel costs, operation and maintenance expenses, equipment replacement costs.

Installed Capital Cost. The initial venture capital for a hybrid power system includes equipment costs, installation expenses, tariffs, shipping costs, and possibly the cost of extending a distribution network from the hybrid power system to the consumer loads. While every effort has been made to identify the major capital costs, Hybrid2 uses a 'balance of system' term , C_{BOS}, in order to account for any capital costs which are unique to the user's application. Therefore the system installed capital cost, C_S, is given by

$$C_S = C_E + C_I(1 + c_I) + C_O + C_{BOS} + C_T + C_{Sh} + C_{Ext} \tag{5.5.1}$$

where

C_I = Total installation costs, $

c_I = System installation overhead cost fraction,-

C_O = Installed cost of optional load equipment, $

C_{BOS} = Balance of system costs, $

C_T = Tariff costs, $

C_{Sh} = Shipping costs, $

C_{Ext} = Installed cost of line extension or grid installation, $

C_E is the equipment-related costs:

$$C_E = C_W + C_{PV} + C_{PVR} + C_{MPPT} + C_D + \Delta_{Bat} C_{Bat} + C_C + C_{Dump} \tag{5.5.2}$$

where

C_W = Total wind turbine capital cost, $

C_{PV} = Capital cost of photovoltaic panels, $

C_{PVR} = Capital cost of photovoltaic racks and/or trackers, $

C_{MPPT} = Capital cost of maximum power point tracker, $

C_D = Diesel capital costs, $

Δ_{Bat} = Battery size scale factor, -

C_{Bat} = Battery bank capital costs, $

C_C = Power converters capital costs, $

C_{Dump} = Dump load capital costs, $

The wind turbine equipment costs are broken down according to whether the machines are connected to an AC or a DC bus.

$$C_W = \Delta_{W,AC}\left(C_{WD,AC} + C_{WF,AC} + C_{WT,AC}\right) + \Delta_{W,DC}\left(C_{WD,DC} + C_{WF,DC} + C_{WT,DC}\right) \quad (5.5.3)$$

where

$\Delta_{W,AC}$ = Scale factor for AC connected wind turbines

$C_{WD,AC}$ = Capital cost of domestically purchased AC wind turbines, $

$C_{WF,AC}$ = Capital cost of internationally purchased AC wind turbines, $

$C_{WT,AC}$ = Capital cost of tower for AC wind turbines, $

$\Delta_{W,DC}$ = Scale factor for DC connected wind turbines

$C_{WD,DC}$ = Capital cost of domestically purchased DC wind turbines, $

$C_{WF,DC}$ = Capital cost of internationally purchased DC wind turbines, $

$C_{WT,DC}$ = Capital cost of tower for DC wind turbines, $

The installation costs are given by

$$C_I = \left(\Delta_{W,AC}C_{WI,AC} + \Delta_{W,DC}C_{WI,DC} + C_{PVI} + C_{DI} + \Delta_{Bat}C_{BatI} + C_{CI} + C_{DumpI}\right) \quad (5.5.4)$$

where

$C_{WI,AC}$ = Installation cost of AC wind turbines, $

$C_{WI,DC}$ = Installation cost of DC wind turbines, $

C_{PVI} = Installation cost of photovoltaic panels, $

C_{DI} = Diesel installation costs, $

C_{BatI} = Battery installation costs, $

C_{CI} = Power converters installation costs, $

C_{DumpI} = Dump load installation costs, $

Δ_{Bat}, $\Delta_{W,AC}$, and $\Delta_{W,DC}$ in the equations above reflect factors which are used to linearly scale the costs associated with the battery bank components and the wind turbine components. These scale factors and their impact on the simulation of a system are discussed in chapter 6 and 7.

The base case installed capital costs, $C_{S,B}$, are similarly computed as

$$C_{S,B} = C_{D,B} + C_{DI,B}(1 + c_I) + C_{BOS} + C_{Ext} \tag{5.5.5}$$

where

$C_{D,B}$ = Diesel capital costs (base case), $

$C_{DI,B}$ = Diesel installation costs (base case), $

The initial down payment, C_{dp}, and loan annuity, C_A, are then determined using the standard annuity formula with interest rate, i, and loan period, T_L. The down payment is some fraction, f_{dp}, of the installed cost.

$$C_{dp} = f_{dp}\, C_S \tag{5.5.6}$$

$$C_A = C_S(1 - f_{dp})\left[\frac{i(1+i)^{T_L}}{(1+i)^{T_L} - 1}\right] \text{ for } i > 0 \tag{5.5.7}$$

$$C_A = \frac{C_S(1 - f_{dp})}{T_L} \text{ for } i = 0 \tag{5.5.8}$$

For the base case, the down payment, $C_{dp,B}$, and annuity, $C_{A,B}$, are

$$C_{dp,B} = f_{dp}\, C_{S,B} \tag{5.5.9}$$

$$C_{A,B} = C_{S,B}(1 - f_{dp})\left[\frac{i(1+i)^{T_L}}{(1+i)^{T_L} - 1}\right] \text{ for } i > 0 \tag{5.5.10}$$

$$C_{A,B} = \frac{C_{S,B}(1 - f_{dp})}{T_L} \text{ for } i = 0 \tag{5.5.11}$$

Therefore, the yearly disbursement associated with the capital costs, $C_{Cap}(n)$, are given by

$$C_{Cap}(n) = \left[C_{dp}\right|_{n=1} + \left[C_A\right|_{1+T_G \le n \le T_G + T_L} \tag{5.5.12}$$

where T_G = Loan grace period

n = year

and the half bracket annotation, $Y(n) = [X|_{n=i}$, is

$$Y(n) = X \text{ if } n = i$$

$$Y(n) = 0 \text{ if } n \neq i$$

and for the base case, the yearly payment for capital costs, $C_{Cap,B}(n)$, is

$$C_{Cap,B}(n) = [C_{dp,B}|_{n=1} + [C_{A,B}|_{1+T_G \leq n \leq T_G + T_L} \tag{5.5.13}$$

Here, T_G is the grace loan period.

The bracketed costs (and salvage revenue) are included only for the years indicated by the evaluation criteria. For example, if

$$C_{dp} = \$50{,}000,\ C_A = \$10{,}000,\ T_G = 2,\ T_L = 5, \text{ and } N = 20, \text{ then}$$

$$C_{Cap}(4) = \$10{,}000 \text{ and } C_{Cap}(8) = \$0.$$

<u>Fuel Costs</u>. Annual fuel costs, $C_F(n)$, are determined using the value of the average hourly diesel fuel consumption, $\bar{F}$. This value is an output from the Hybrid2 simulation engine. The annual cost is found by multiplying this value by the number of hours in a year and the unit cost of diesel fuel, c_F. This cost is also inflated for year n using a constant fuel inflation rate, f.

$$C_F(n) = \left(8760\,\bar{F}\ c_F\right)(1+f)^n \tag{5.5.14}$$

The base case fuel costs , $C_{F,B}(n)$, are found in a similar manner.

$$C_{F,B}(n) = \left(8760\,\bar{F}_B\ c_F\right)(1+f)^n \tag{5.5.15}$$

<u>Operation and Maintenance Expenses.</u> The annual O&M expense, $C_M(n)$, is the sum of the individual O&M costs for the wind turbines, diesels, battery bank, a general system O&M cost, $C_{M,sys}$, and an annual administrative fee, C_{Admin}. The yearly operation and maintenance costs for the battery bank, the general system O&M and the annual administrative fee are set by the user for the first year of the project and increase according to a general inflation rate, g. The O&M costs for the wind turbine(s) and diesel(s) are based on the total annual energy production from the wind turbines and hours of diesel operation, respectively.

$$C_M(n) = \left\{8760\left(\bar{P}_W\ c_{M,W}\right) + h_D\ c_{M,D} + \Delta_{Bat}\ C_{Bat}\ c_{M,Bat} + C_{M,sys} + C_{Admin}\right\}(1+g)^n \tag{5.5.16}$$

where

$\bar{P}_W$ = Average wind power, kW

$c_{M,W}$ = Wind turbine operation and maintenance costs, \$/kWh

h_D = Total diesel yearly operating hours ($h_D = \sum_{i=1}^{N_D} T_{D_i}$), h

$c_{M,D}$ = Diesel related operation and maintenance costs, \$/kWh

$c_{M,Bat}$ = Battery annual operation and maintenance costs, fraction of capital cost , -

For the Base Case,

$$C_{M,B}(n) = \left[h_{D,B}\ c_{M,D} + C_{sys,B} + C_{Admin,B}\right](1+g)^n \tag{5.5.17}$$

where

$C_{M,B}(n)$ = Total non-fuel O & M cost in year n (base case), \$/year

$h_{D,B}$ = Total diesel base case yearly operating hours ($h_{D,B} = \sum_{i=1}^{N_{D,B}} T_{D,B_i}$), h

<u>Equipment Replacement Expenses</u>. These costs reflect the need to overhaul or completely replace components in the hybrid power system at various intervals throughout its financial lifetime. The total replacement cost in a given year, n, is simply the sum of the replacement costs of all the components which must be renewed during the year.

$$C_R(n) = \sum_{j=1}^{N_W} C_{R,W_j}(n) + C_{R,PV}(n) + \sum_{j=1}^{N_D} C_{R,D_j}(n) + C_{R,Bat}(n) + C_{R,C}(n) + C_{R,Dump}(n) \tag{5.5.18}$$

where

$C_R(n)$ = Total yearly replacement costs, \$/year

N_D = Number of diesel generator sets, -

N_W = Number of wind turbines, -

Here, $C_{R,X}(n)$ is the replacement cost for component X during year n. This cost is zero for the years in which component X is not replaced. The equation accounts for N_W AC or DC connected wind turbines, $C_{R,W_j}(n)$, a photovoltaic array, $C_{R,PV}(n)$, N_D diesel generator sets, $C_{R,D_j}(n)$, a battery bank, $C_{R,Bat}(n)$, power converters, $C_{R,C}(n)$, and dump load equipment, $C_{R,Dump}(n)$.

The replacement cost for a component, X, in year n is found by

$$C_{R,X}(n) = (1+g)^n C_{R,X}\Big|_{m\,T_R = n} \tag{5.5.19}$$

where $m = \mathrm{int}\left[\frac{n}{T_{R,X}}\right]$ and $T_{R,X}$ is the replacement period (in years) input by the user. All components except the diesels are replaced or overhauled every $T_{R,X}$ years as specified by the user. Diesels are overhauled after a specified number of operating hours. Therefore, for each diesel generator set T_{R,D_j} is actually a derived quantity. It is a function of the operation time

fraction, $\frac{T_{D_j}}{T_{Sim}}$, and the user input, t_{R,D_j} ; the number of operating hours between overhauls, so that

$$T_{R,D_j} = t_{R,D_j} \frac{T_{Sim}}{8760\ T_{D_j}} \tag{5.5.20}$$

Equation 5.5.19 shows that the replacement cost for year n is inflated using a constant general inflation rate, g.

For the base case, only diesel generator sets are overhauled. The replacement cost for all diesels, $C_{R,B}(n)$, in the years they are replaced is

$$C_{R,B}(n) = \sum_{j=1}^{N_D} \left[(1+g)^n C_{R,D_{jB}} \right|_{m\,T_{R,D_{jB}} = n} \tag{5.5.21}$$

<u>System Revenue</u>**.** Hybrid2 calculates annual revenue, I(n), by determining the annual energy supplied to each of the three load types: primary, deferrable, and optional. The value of energy to each load varies so that the total revenue equals

$$I(n) = 8760 \left[\left(\overline{P}_{Prim} - \overline{P}_{Over} \right) c_{Prim} + \overline{P}_{Def}\ c_{Def} + \overline{P}_{Opt}\ c_{Opt} \right] (1+f)^n \tag{5.5.22}$$

where

$\overline{P}_{Over}$ = Average overload power (which the system is incapable of supplying), kW

c_{Prim} = Cost of energy to primary load, \$/kWh

c_{Def} = Cost of energy to deferrable load, \$/kWh

c_{Opt} = Cost of energy to optional load, \$/kWh

The revenue for year n is inflated using a constant fuel inflation rate, f.

The base case system does not include optional load equipment; therefore the annual revenue is

$$I_B(n) = 8760 \left[\left(\overline{P}_{Prim} + \overline{P}_{Def} - \overline{P}_{Over,B} \right) c_{Prim} \right] (1+f)^n \tag{5.5.23}$$

where

$\overline{P}_{Over,B}$ = Average overload power (base case), kW

Note that in the base case conventional system, as modeled by Hybrid2, there is no distinction between primary and deferrable loads and they are both valued the same. See Section 5.3 for more discussion on the distinctions among the various types of loads.

Hybrid2 also calculates, on a yearly basis, the following, more global, economic quantities: total system expenses, net revenue, and profit (deficit).

Total System Expense. The total system expense for year n, C(n), is merely a sum of the individual disbursements defined in the above sections. Note that this quantity includes the annuity disbursements.

$$C(n) = C_F(n) + C_R(n) + C_M(n) + C_A(n) \tag{5.5.24}$$

where

$C_F(n)$ = Cost of fuel in year n, $/year

$C_M(n)$ = Total non-fuel O & M cost in year n, $/year

$C_R(n)$ = Total replacement and overhaul costs in year n, $year

$C_A(n)$ = Annuity in year n, $/year

Likewise, the total system cost for the base case is

$$C_B(n) = C_{F,B}(n) + C_{R,B}(n) + C_{M,B}(n) + C_{A,B}(n) \tag{5.5.25}$$

Net Revenue. The yearly net revenue, $I_{Net}(n)$, is defined as the revenue minus the total system expense.

$$I_{Net}(n) = I(n) - C(n) + [S|_{n=N} \tag{5.5.26}$$

And for the base case,

$$I_{Net,B}(n) = I_B(n) - C_B(n) + [S_B|_{n=N} \tag{5.5.27}$$

where

S = Equipment salvage value at the end of the system's financial life

The salvage values for both the hybrid system and the base case, S_B, are related to the equipment cost as follows:

$$S = f_s\ C_E \tag{5.5.28}$$

$$S_B = f_s\ C_{D,B} \tag{5.5.29}$$

where

f_S = Fraction of the installed capital cost

System Profit. Hybrid2 defines the system's profit as the net revenue minus any taxes. The yearly taxes are calculated for years in which the net revenue is positive, and are a function of capital depreciation, D(n), the renewable energy tax credit rate, t_c, and the tax rate, t. The depreciation of the system's equipment capital is modeled using a linear depreciation over the period, T_E, such that

$$D(n) = \left\lceil \frac{C_S}{T_E} \right\rceil_{1 \le n \le T_E} \tag{5.5.30}$$

and, for the base case the depreciation, $D_B(n)$, is given by

$$D_B(n) = \left\lceil \frac{C_{S,B}}{T_E} \right\rceil_{1 \le n \le T_E} \tag{5.5.31}$$

The renewables production tax credit is equal to the energy produced by renewables multiplied by the tax credit rate. The yearly tax, Tx(n), is therefore given by:

$$Tx(n) = t\left[I_{Net}(n) - D(n)\right] - 8760\left(\overline{P}_W + \overline{P}_{PV}\right)t_c \tag{5.5.32}$$

where

$\overline{P}_{PV}$ = Average power from photovoltaic panels, kW

Taxes for the base case, $Tx_B(n)$, obviously, do not include the renewables tax credit.

$$Tx_B(n) = t\left[I_{Net,B}(n) - D_B(n)\right] \tag{5.5.33}$$

Using the above relations, the yearly profit for the hybrid system, Pr(n), is given by

$$Pr(n) = I_{Net}(n) - \left[Tx(n)\right|_{I_{Net}(n)>0} \tag{5.5.34}$$

And finally, the base case profit, $Pr_B(n)$, is given by:

$$Pr_B(n) = I_{Net,B}(n) - \left[Tx_B(n)\right|_{I_{NetB}(n)>0} \tag{5.5.35}$$

Although many possible calculations of equipment deprecation could be used in an economic analysis, only one, linear depreciation, was selected for inclusion in this version of the Hybrid2 software. Linear depreciation was used due to its simple nature and common global use.

Present Worth

In order to compare the economics of two systems whose disbursements are spread out over the life of the system, the future worth must be discounted back to the present worth (year 0). The present worth is obtained using a constant discount rate, d. For an arbitrary cost or income, X, in year n, the present worth, X_{PW}, is:

$$X_{PW}(n) = \frac{X(n)}{(1+d)^n} \tag{5.5.36}$$

The net or lifetime present worth of a disbursement, X_{NPW}, is a summation of the yearly present worths.

$$X_{NPW} = \sum_{n=1}^{N} \frac{X(n)}{(1+d)^n} \tag{5.5.37}$$

In the Hybrid2 economics, the present worth of the project is determined from summing the yearly profit less the initial capital expenses.

$$Pr_{NPW}(n) = \frac{Pr(n)}{(1+d)^n} - C_{dp} \tag{5.5.38}$$

For the base case:

$$Pr_{NPW,B}(n) = \frac{Pr_B(n)}{(1+d)^n} - C_{dp,B} \tag{5.5.39}$$

Levelized Cost

Once the net present worth of a cost has been determined, Hybrid2 calculates the levelized annual cost, X_L. This is the annuity one would pay out yearly given the constant discount rate, d.

$$X_L = X_{NPW} \frac{d\,(1+d)^N}{(1+d)^N - 1} \tag{5.5.40}$$

Cost of Energy

Another levelized calculation concerns the cost of energy, COE. The total levelized cost of energy is given by

$$COE = \frac{C_{M,L} + C_{F,L} + C_{R,L} + C_{dp} + C_{A,L} - S_L}{8760\left(\overline{P}_{Prim} + \overline{P}_{Def} + \overline{P}_{Opt}\right)} \tag{5.5.41}$$

where

$C_{M,L}$ = Total levelized non-fuel operation and maintenance cost, \$/year

$C_{F,L}$ = Levelized cost of fuel, \$/year

$C_{R,L}$ = Levelized replacement and overhaul costs, \$/year

C_{dp} = Initial capital (down payment), \$

$C_{A,L}$ = Levelized annual payment for equipment, \$/year

S_L = Levelized salvage value of system equipment, \$

Since the base case does not account for optional loads, the levelized cost of energy, COE_B, is

$$COE_B = \frac{C_{M,L,B} + C_{F,L,B} + C_{R,L,B} + C_{dp,B} + C_{A,L,B} - S_{L,B}}{8760\left(\overline{P}_{Prim} + \overline{P}_{Def}\right)} \tag{5.5.42}$$

where

$C_{M,L,B}$ = Total levelized non-fuel O & M cost (base case), $/year

$C_{F,L,B}$ = Levelized cost of fuel (base case), $/year

$C_{R,L,B}$ = Levelized diesel overhaul costs (base case), $

$C_{A,L,B}$ = Levelized annual payment for equipment (base case), $/year

$S_{L,B}$ = Levelized salvage value of system equipment (base case), $

In order to directly compare the COE of the hybrid power system and the base case system, a modified COE is used: the real power, levelized COE.

$$COE' = \frac{C_{M,L} + C_{F,L} + C_{R,L} + C_{dp} + C_{A,L} - S_L}{8760\left(\overline{P}_{Prim} + \overline{P}_{Def}\right)} \tag{5.5.43}$$

Note that Hybrid2 calculates the cost of energy based on the amount of energy used in primary, deferrable, or optional loads. It should be clear that the cost to produce this energy should be used to devise a payment strategy that covers this expense. The COE only indicates the expense that must be incurred to produce that energy. In the software, it has no bearing on the price that is charged a user for that energy.

Simple Payback Period

The simple payback period, SPP, is calculated from the following expression,

$$SPP = \frac{C_S}{Pr_L} \tag{5.5.44}$$

where

Pr_L = Levelized system profit, $

Discounted Payback Period

The discounted payback period, DPP, is calculated from the following expression when the fuel inflation rate, f, is less than the general inflation rate, g.

$$DPP = \frac{\ln\left(1 + SPP\,\frac{\phi - 1}{\phi}\right)}{\ln(\phi)} \tag{5.5.45}$$

where

$$\phi = \frac{1+f}{1+g}$$

Rate of Return

The project rate of return, r, is a measure of the projected return of an investment. In the Hybrid2 code, it is the projected return on the investment of installing a hybrid power system. This represents the rate at which the initial capital expense could be invested to obtain the same return over the project life. The calculation of the project rate of return is an iterative process in which the yearly cash flows of the project are discounted back to the present using varying discount rates. The method used in Hybrid2 for this calculation is taken from the equity owner's perspective. This means that the rate of return of the yearly cash flow is compared to the investment made at the beginning of the project. This method was selected because it is one of the primary methods used for the consideration of small systems where the owner of the plant will also be the operator. It should be noted that a different calculation is needed if the project is being considered from the perspective of a financial institution that is interested in the return on the initial and subsequent investments. The equation used in determining the rate of return is the following:

$$C_S = \sum_{n=1}^{N} \frac{Pr(n)}{(1+r)^n} \tag{5.5.46}$$

The discount rate is adjusted until the present value of the project, represented by the right side of equation (5.5.46), equals the installation cost of the project.

Economics of Retrofit Systems

The economics of a system retrofit as compared to a new system differ in a number of ways. A new project is assumed to start with no debt for equipment or outside expenses. On the other hand, a retrofit system could already have outstanding debt as well as other plant associated expenses. Since it is beyond the scope of this analysis to allow for the numerous possibilities of preexisting expenses, loans of different rates, etc., the Hybrid2 model conducts a comparison between the system and its all diesel counterpart. This comparison quantifies the cash flows associated with the savings and expenses of the renewables added to the diesel only system. Thus, differences in O&M, fuel, replacement costs, and any difference in revenues due to the sale of power for deferrable and optional use are compared to the capital expenses of the retrofit components. This difference is then subject to taxes, depreciation, and equipment salvage. The present worth, internal rate of return and cash flow are then calculated to reflect the change associated with the installation of renewables. In this case, changing the value of energy may increase or decrease the profitability of the complete system, but it will not change the economics of installing renewables in the power system.

The economic analysis for a retrofit hybrid power system assumes that the system to be replaced includes only diesel generator sets and not other wind or PV sources. If the system under retrofit consideration already contains renewables, it would have to be modeled independently and referenced to a base case diesel-only system. Furthermore, since the definition of retrofit used in this analysis consists of adding renewables to an existing diesel system, it is not possible to conduct a retrofit analysis that consists just of replacing diesels in an existing system. It is possible to account for modifications to existing diesels through the Balance of System costs and to remove diesels from the retrofit system, but new diesels must not be added.

Cash Flow Analysis

The cash flow analysis for a retrofitted system closely follows the calculations performed for a new hybrid system. Note however, that the "base case" system refers to the original, diesel-only system and that these costs and revenues are compared with those for the retrofitted system.

Installed Capital Costs. The installed capital costs for a retrofitted hybrid system are computed in the same manner as for a new system, except that the diesel cost terms are zero and there is no cost for extending the grid to the system. These costs are incurred only for new systems.

Fuel Costs. The fuel cost calculations are identical to those for a new system.

Operation and Maintenance Expenses. The operation and maintenance cost calculations are identical to those for a new system.

Equipment Replacement Expenses. These costs are also determined in the same manner as those for a new system. One assumption is made, however, regarding the diesel replacements. The existing diesels are assumed to have been replaced or overhauled at the start of the economic simulation. In other words, Hybrid2 does not allow for an initial overhaul period that is different from the standard diesel overhaul period, which is used throughout the system's financial lifetime.

System Revenue. Hybrid2 computes the increased (or decreased) revenue of the retrofitted system as compared with the original diesel-only system. This revenue difference, $I_R(n)$ is given by

$$I_R(n) = I(n) - I_B(n) \tag{5.5.47}$$

where I(n) is the revenue for the retrofitted system and $I_B(n)$ is the revenue for the diesel-only system. These individual revenues are calculated using the same equations as in the section for new systems. There may be a difference in revenue streams between a conventional diesel system and one which has been converted to a hybrid power system. In a conventional system, as modeled by Hybrid2, there is no distinction between primary and deferrable loads. They are both valued the same. In a hybrid system, power to a deferrable load would normally be sold at a lower rate than would primary load power. This would tend to decrease system hybrid power system revenues relative to that of the diesel-only system. Conversely, any excess power delivered to an optional load would generate revenues which would not appear in a diesel-only system. This would tend to increase hybrid power system revenues relative to that of the diesel-only system.

The logic behind this approach is as follows. In diesel-only power plants, load management is typically not used. This is because there is only a little economic benefit to be gained from shifting energy use patterns to different times of the day. In hybrid systems, however, there is potentially a large economic benefit to be gained by shifting energy use to times when renewable power is abundant and away from times when renewable power is limited. Thus Hybrid2 includes the option of using load management (in the form of deferrable loads.) The use of such loads can reduce or eliminate the need for storage, which is normally quite costly. As a way of encouraging the acceptance of deferrable loads, Hybrid2 assumes that the energy supplied to them could be valued less than would energy to primary loads. Although higher rates could, in principle, be charged for primary load energy in load managed hybrid power systems versus all energy in the diesel-only base case, Hybrid2 does not allow that option. This is because it would appear to be unlikely that a potential installer of a hybrid power system would seriously consider raising the rates for primary load energy.

Total System Expense. The expense calculations are the same as for new systems.

Net Revenue. The net revenue difference is similar to the system revenue calculations. The difference in net revenue is determined by

$$I_{Net,R}(n) = I_{Net}(n) - I_{Net,B} \tag{5.5.48}$$

System Profit. For the retrofitted system, Hybrid2 calculates the difference in system profit, $Pr_R(n)$, between the diesel-only system and the retrofitted hybrid system. This profit calculation is given by

$$Pr_R(n) = Pr(n) - Pr_B(n) \tag{5.5.49}$$

Note that Hybrid2 assumes there are no depreciation costs associated with a diesel-only system in the analysis of a retrofit system. This is because it is assumed that a separate economic analysis was conducted for the original equipment and any change relative to a system retrofit will have no impact on the original system economics. Depreciation is considered for all equipment in the analysis of a new system.

Net Present Worth

The net present worth calculations are the same as for a new system.

Cost of Energy

The levelized cost of energy, COE_R and modified cost of energy $COE_R^{'}$, calculations for a retrofitted system differs from the new system calculations so that

$$COE_R = \frac{Pr_{L,R}}{8760\left(\overline{P}_{Prim} + \overline{P}_{Def} + \overline{P}_{Opt}\right)} \tag{5.5.50}$$

$$COE_R^{'} = \frac{Pr_{L,R,B}}{8760\left(\overline{P}_{Prim} + \overline{P}_{Def}\right)} \tag{5.5.51}$$

Therefore, the COE calculations for retrofitted systems determines the additional cost of energy as compared with the original diesel-only system.

Simple Payback Period

The simple payback period, SPP_R, is given by

$$SPP_R = \frac{C_S}{Pr_{L,R}} \tag{5.5.52}$$

Discounted Payback Period

The discounted payback period calculation is the same as for a new system.

Rate of Return

The internal rate of return is found in the same manner as for new systems, except that the return to be matched is the yearly profit of the retrofit system over the profit of the original diesel-only system.

5.6 Base Case Module

A base case module is provided to allow comparisons between a diesel-only system and a hybrid system in which the same primary load is supplied. Diesels in the base case system may be the same as or different from those in the hybrid system. The diesels may also use the same or different operating strategies. The base case system includes no renewable energy sources, storage, or power converters.

5.7 Program Output

5.7.1 Executive Summary

Hybrid2 provides three kinds of output. Performance summary files provide a summary of the cumulative energy flows and fuel consumption during the simulation run. They also provide a record for the information used for the run, the input file names, and site and modeling information. Economics summary files provide a summary of the input to and output from the economic analysis. Files of detailed information include values of a number of system variables for each time step.

The following sections describe the output included in the summary files and a description of the variables included in the detailed files.

5.7.2 Performance Summary Files

Hybrid2 provides both summaries and detailed information on the results of the simulation for the modeling period. An example of the performance summary output is included in the following pages. More detail is provided in the Hybrid2 users' manual.

Sample Performance Summary Output

```
**************************************************
*    RESULTS OF THE SIMULATION: OVERALL PERFORMANCE
**************************************************
```

* Project
Sample Simulation

* General

- simulation program	Hybrid2
- date of run	03-18-1996
- Time of run	14:24:00

* Run specifications

- start value of the simulation period (h)	1
- duration of the simulation period (h)	720
- simulation time step (min)	60

* HYBRID SYSTEM

ENERGY FLOWS	kWh	% load		kWh	% load
Total production	7802.14	52.8	Total sinks	15002.23	101.5
Load demand	14783.24	100.0	Load coverage	12479.76	84.4
AC primary load	3801.62	25.7	AC primary load	3209.26	21.7
AC deferrable load	3590	24.3	AC deferrable load	3030.62	20.5
DC primary load	3801.62	25.7	DC primary load	3209.26	21.7
DC deferrable load	3590	24.3	DC deferrable load	3030.62	20.5
			Unmet load	2303.47	15.6
Production			Optional load	0	0
- from wind (AC)	0	0	- AC optional load	0	0
- from wind (DC)	3414.98	23.1	- DC optional load	0	0
- from PV (AC/DC)	483.39	3.3			
- from diesel (AC/DC)	1071.37	7.2			
Storage			Excess energy 0	0	
- into storage	410.53	2.8	- spilled	0	0
- from storage	528.92	3.6	- dump load	0	0
			- excess dump load	0	0
Energy losses	-7391.54	-50			
Fuel consumed (liters)	366.67				

* RESULTS OF THE SIMULATION: PERFORMANCE PER COMPONENT **********

* AC primary load
(scale factor of 2 included)

- average (kW)	5.28
- standard deviation (kW)	.02
- minimum (kW)	5.28
- maximum (kW)	5.28

* DC primary load
(scale factor of 2 included)

- average (kW)	5.28
- standard deviation (kW)	.02
- minimum (kW)	5.28
- maximum (kW)	5.28

* Wind speed
(scale factor of 1 included)

- air density correction	1	
at height of	anemo-meter	hub turbine 1
- height (m)	8.5	24
- hub height correction	-	1.16
- average (m/s)	8.35	
- standard deviation (m/s)	1.09	
- minimum (m/s)	4.1	
- maximum (m/s)	11.6	

* Solar insolation at horizontal array plane

- average (w/m2)	200.19
- maximum (W/m2)	742

* Ambient temperature

- average (C)	30

* HYBRID SYSTEM

* DC diesel
diesel # 1 (3 kW)

- on time (h)	381
- number of starts	49

PROJECT: OVERVIEW **********

* NOTES
Sample Simulation

* LOAD
AC primary load: Sample Simulation

AC primary load scale factor 2

DC primary load: Sample Simulation

DC primary load scale factor 2

* RESOURCE/SITE
Wind speed: Sample Simulation- November
Wind speed scale factor 1

* POWER SYSTEM
Sample Simulation

DC wind turbines
Total power: 10 kW
- number and type of specified wind turbines:
1 wtg10 10 kW wind turbine
- DC wind power scale factor 1

DC diesel
Total power: 3 kW
- number and type of specified diesels:
1 dsl3 3 kW diesel generator

Battery bank
Battery notes: Sample Simulation
- total capacity (scaled) 403.2 kWh (accessible capacity 322.56 kWh)
- number and type of batteries 192 trojan batteries
- battery bank scale factor 1
- nominal voltage 6 V

Dispatch strategy

Battery control
- minimum level (fraction) .2
- battery discharge code: all or part of average load
- boost charge: never

Diesel control
- minimum run time (h): 1
- allowed shutdown: all
- period of forced shutoff: 0 hrs
- dispatch order: minimum fuel use

Operating Power level: at or near maximum power

Diesel starts: to meet load

Diesel stops: when renewables/battery can meet load

* Economics in separate economics file

* PROJECT: DETAIL**********

* RESOURCE/SITE

Wind speed
- power law exponent .143
- turbulence length scale (m) 100
- reference wind velocity for
turbulence calculations (m/s) 10
- nominal turbulence intensity .15

- air density model:	density ratio
- nominal ambient temperature (C)	30

Solar insolation

- ground reflectivity	.2

* POWER SYSTEM

DC wind turbines

- spacing between DC wind turbines (m)	100
- DC wind farm power fluctuation reduc. factor	1
- DC wind power response factor	1.5

DC PV array

- number of PV panels in series	4
- number of PV panels in parallel	20
- tracking code:	1 (fixed slope)
- PV array slope (deg):	15
- PV array azimuth (deg):	0
- PV rack or tracker capital cost ($):	0
- PV array installation cost ($):	0

Battery bank

- number of batteries in series:	8
- number of battery banks in parallel:	24
- initial capacity of battery bank (kWh):	201.6
- battery bank installation cost ($):	0

General system cost

- balance of system capital cost ($):	0
- system O&M Cost (fraction/y):	0
- administrative Cost (fraction/y):	0
- wind turbine O&M Cost (fraction/y):	.02
- diesel O&M Cost (fraction/y):	.03

* OVERVIEW OF FILES**********

File name Date

INPUT
c:\hybrid2\sample.prj
C:\hybrid2\sample.acp
C:\hybrid2\sample.dcp
C:\hybrid2\sample.acd
C:\hybrid2\sample.dcd
C:\hybrid2\sample.sit
C:\hybrid2\sample.pow
C:\hybrid2\sample.ctl
C:\hybrid2\novem.wnd
C:\hybrid2\novem.sol
C:\wtg10.dcw
C:\hybrid2\dsl3.dcg
C:\hybrid2\vlx53.pvm

OUTPUT
c:\hybrid2\total.sum
c:\hybrid2\total.h2d

5.7.3 Economics Summary Files

The economics module of Hybrid2 output generates an output file that summarizes both the input to an results of the analysis. The file includes, when applicable:

- Date and time of run
- Name of the file
- Indication of whether the system is new or a retrofit
- Simple payback period
- Discounted payback period
- Net present value of total costs
- Net present value of total costs and revenues
- Internal rate of return
- Levelized cost of energy based on primary load
- Levelized cost of energy based on total load
- Levelized cost of energy savings, based on primary load
- Levelized cost of energy based on total load
- Net present value of optional load
- Debt costs
- Fuel costs
- Operation and maintenance costs
- Replacement and overhaul costs
- Gross revenue
- Net revenue
- Net after tax revenue
- Summaries of:
    - Total energy produced
    - Total energy delivered
    - Energy delivered to deferrable load(s)
    - Energy delivered to optional load(s)
    - Fuel consumed
    - Installation costs
    - Equipment cost
    - Total installed costs
- Down payment
- First year costs
- First year operation and maintenance costs
- Salvage value

The economics output file also includes summaries of the following:

- Economic analysis parameters
- System specifications
- Yearly cash flows

5.7.4 Detailed Files

The file with the detailed information includes values of a number of system variables for each time step. The detailed output file itself may be of one of two levels of detail. The file with the basic level of detail includes, when applicable:

Primary_AC	The power going to the primary load AC (kW).
Defer_AC_1	The power going to the first deferrable AC load (kW).
Defer_AC_2	The power going to the second deferrable AC load (kW).
Optional_AC	The power going to the optional AC load (kW)
Primary_DC	The power going to the primary load DC (kW).
Defer_DC_1	The power going to the first deferrable DC load (kW).
Defer_DC_2	The power going to the second deferrable DC load (kW).
Optional_DC	The power going to the optional DC load (kW)
Unmet_Load	The unmet load (kW).
Wtg_AC	The AC wind turbine power (kW).
PV_AC	The AC bus PV power (kW).
Diesel_AC	The AC bus diesel power (kW).
Dump_AC	The power going to the AC dump load (kW).
Dump_AC_XS	The power in excess of the AC dump load capability (kW).
Wtg_DC	The DC wind turbine power (kW).
PV_DC	The DC bus PV power (kW).
Diesel_DC	The DC bus diesel power (kW).
Shaft_Diesel	Power from the shaft diesel (kW).
Dump_DC	The power going to the DC dump load (kW).
Dump_DC_XS	The power in excess of the DC dump load capability (kW).
Store_In	The power going into storage (kW).
Store_Out	The power going out of storage (kW).
Losses	Power conversion losses (kW).
Voltage	Battery voltage (V).
Storage	Battery capacity level (Ah).
V_Hub	Hub height wind speed (m/s or mph).
Sun_Slope	Solar insolation on the sloped PV collector (W/m^2).
Fuel_Hybrid	Hybrid system diesel fuel consumption (liters or gallons).
Fuel_Base	Base case system diesel fuel consumption (liters or gallons).

The output file with the greater level of detail also includes the following, when applicable:

Balance	Time step energy balance (-).
Load_Max_AC	Maximum AC load during the time step (kW).
Load_Min_AC	Minimum AC load during the time step (kW).
Net_Ld_AC	Net AC load during the time step (kW).
Net_Ld_Max_AC	Maximum net AC load during the time step (kW).
Net_Ld_Min_AC	Minimum net AC load during the time step (kW).
Load_Max_DC	Maximum DC load during the time step (kW).
Load_Min_DC	Minimum DC load during the time step (kW).
Net_Ld_DC	Net DC load during the time step (kW).
Net_Ld_Max_DC	Maximum net DC load during the time step (kW).
Net_Ld_Min_DC	Minimum net DC load during the time step (kW).
Loss_Chg	Charging losses in the battery (kW).
Loss_Dis	Discharging losses in the battery (kW).
Time_Not_Met_AC	The time fraction that the AC load was not met (-).
Time_Not_Met_DC	The time fraction that the DC load was not met (-).
PV_Tempr	PV operating temperature (C).
Sun_Horiz	Solar insolation on a horizontal surface (W/m^2).
Sun_Kt	Clearness Index, the fraction of diffuse to total radiation (-).
V_Anem	Anemometer wind speed (m/s or mph).
Diesel_Flag_	A flag to indicate whether a diesel is on (-)

This file can be used to prepare graphs of the operation of each of the system components during the simulation. The Graphical Results Interface that can be used to view the results is described in the Hybrid2 users manual.

5.8 Data File Gap Filler

5.8.1 Executive Summary

Time series data files from real sites often contain gaps. That is, some of the data is missing. Hybrid2 requires complete data sets to perform an analysis. In order to facilitate the process of completing the data sets, Hybrid2 includes an auxiliary Gap Filler program. The Gap Filler can be accessed from the Graphical User Interface. The Gap Filler can be used with wind, load, temperature or solar data. A combination of scaling and statistical techniques (Markov chains) are used to fill the gaps.

5.8.2 Overview

The Gap Filler is designed primarily to fill gaps in wind, load, or temperature data. In addition, it provides a simplified means of filling gaps in solar data. It should be noted that when data is missing, it cannot be truly recreated. The best that can be hoped for is that the basic statistics of the completed data be close to that of the original data.

5.8.3 Description of Gap Filler

The Gap Filler program is designed to fill in gaps in a data file by synthesizing the missing data in a plausible manner. The procedures which are used with wind, load, or temperature data are described here. Filling gaps in solar data is discussed in the following section.

The reconstructed data that fills a gap will have the following characteristics:

1) The mean will be equal to the average of the last good point before the gap and the first good point after the gap
2) Diurnal variations will be retained
3) The variability of the reconstructed data will approximate that of the original data
4) Histograms of completed data will be similar to that of the original data

The method uses a mixture of scaling and Markov chains to recreate the missing data. The method works as follows:

1) The entire data set is read in and searched to find all the gaps and the longest intact segment of good data.
2) Good data is recognized as any data which exceeds some specified minimum value. The minimum value may be chosen by the user; the default value is zero.
3) The longest intact segment is selected for use as the "generating data set." The characteristics of the synthesized data will be based on this set.
4) The generating data set is checked for diurnal variability. The diurnal variability is characterized and then removed. Information about the characterization is saved for later use.
5) The generating data set with diurnal variability removed is used to produce a Markov chain transition probability matrix. (See below for explanation.)
6) The procedure then synthesizes data for each gap. The mean of the gap is assumed to be equal to the average of the last good point before the gap and the first good point after the gap.
7) A diurnally scaled data set is created to span the range of the gap.
8) When the original data contains standard deviation as well as mean values, missing standard deviations are found by multiplying the synthesized mean values by a mean variability. The mean variability is the same as that of the generating data set.

The creation of the scaled data proceeds as follows:

1) A time series of the same length as the gap is generated as a Markov chain from the Transition Probability Matrix. The mean of this time series will be close to, but not the same as, that of the generating data, so the mean value of the new Markov time series is found next.
2) The Markov time series is normalized by dividing by its mean and then converted to a time series of zero mean by subtracting 1.
3) The transformed Markov time series is then multiplied by the gap mean and added to the diurnally scaled data. Note that these operations keep the gap mean equal to what was originally intended. They also ensure that the variability of the transformed Markov time series be constant.

Markov Chain Method

The Markov chain method creates a matrix of probabilities relating the data value at time step t with the value at step t+1. Thus, given a wind speed at time t of 4 m/s, there might be a probability of 0.3 that the wind at time t+1 will be 4 m/s and a probability of 0.1 that it will be 3m/s or 5 m/s at time t+1. A matrix of the probabilities of all the possibilities is created and used to synthesize data.

The Markov chain process used in Hybrid2 is similar to that described in Kaminsky, 1990. Bins are created so that all of the original data will belong to one of the bins. The procedure steps through the generating data set and finds the bin to which each individual data point belongs. It also finds the bin corresponding to the succeeding point. The likelihood that the data will have a particular value, given its recent history, is determined and summarized in a Transition Probability Matrix. This is done by counting the number of times that a point is found in a particular bin, given that the preceding point is in some other bin (or the same one.) When this happens a "transition" is said to have occurred. At the end of the data set, all the data are normalized by dividing by the total number of transitions.

Mathematically, the process can be described as follows. Suppose the data, $\{x\}$, all fall between X_{low} and X_{high} and that there are N bins. The bins will have width of $\Delta = (X_{high} - X_{low})/N$.

For any given point, x_i, if $X_{low} + (j-1)\,\Delta < x_i \le j\,\Delta$ and $X_{low} + (k-1)\,\Delta < x_{i+1} \le k\,\Delta$. then $N_{j,k} = N_{j,k}+1$

where

j, k	= Indices ranging from 1 to N
$N_{j,k}$	= Number of transitions from bin j to bin k

At the end of the process, there have been N_j occurrences from bin j (followed by another data point). That is

$$N_j = \sum_{k=1}^{N} N_{j,k}$$

The probability of making a transition from bin j to bin k is $T_{j,k} = N_{j,k} / N_j$. The Transition Probability Matrix (TPM) in general is defined by:

$$[T_{j,k}] = \begin{bmatrix} T_{11} & T_{12} & \dots & T_{1N} \\ T_{21} & T_{22} & \dots & T_{2N} \\ \dots & \dots & \dots & \dots \\ T_{N1} & T_{N2} & \dots & T_{NN} \end{bmatrix}$$

Note that the elements in every row must sum to 1.

With the TPM defined, it is possible to generate any number of new time series which would have the same TPM. This is done using a random number generator and a "wheel of fortune." The "wheel of fortune" would have segments with areas in the same ratios as the probabilities in

the TPM. In matrix terms, this "wheel of fortune" can be expressed as a cumulative probability matrix (CPM):

$$[C_{j,k}] = \begin{bmatrix} C_{11} & C_{12} & \dots & C_{1N} \\ C_{21} & C_{22} & \dots & C_{2N} \\ \dots & \dots & \dots & \dots \\ C_{N1} & C_{N2} & \dots & C_{NN} \end{bmatrix}$$

where

$$C_{j,k} = C_{j-1,k} + T_{j,k}$$

Starting from any data point, the bin of the data point will define the row of the CPM to be used. A random number, r, between 0 and 1 defines the bin of the next data point. That is if the starting data point is in bin j, and if $C_{j,k} < r \le C_{j,k+1}$, then the subsequent data point will be in the kth bin. For the purpose of data generation, the data point is assumed to correspond to the midpoint of the bin.

5.8.4 Gap Filling in Solar Data

Gaps in solar data are dealt with in a different and simpler way than are gaps discussed in the previous section. In this case, rather than working with the solar data directly, the method deals with clearness indices. The clearness indices are found from the measured data (taken by a horizontal pyranometer) and the extraterrestrial radiation, as described in Chapter 7.

Gaps are filled by first finding the two clearness indices on either side of the gap. The missing data is assumed to have clearness indices determined by linearly scaling between those two values. The synthesized data is simply the product of the clearness indices and the extraterrestrial radiation. Note that this method is really only appropriate for gaps of less than one day.

5.8.5 Examples

The first example illustrates filling gaps in a noisy data set with no trend but extreme diurnal variations (arbitrary units.) The time step was 15 minutes and minimum good data was 0.01. Figure 5.6 shows the complete time series of original (solid line) and filled (dotted line) data. Figure 5.7 shows a close up of the first gap.

Example 2 illustrates filling in missing solar data. This example was made from 9 days of solar data with 30 minute time steps. There were two gaps in the data.

Site Particulars include:

Latitude	= 41 deg, 0 min
Longitude	= 70 deg, 55 min
First Julian day of data	= 274

Figure 5.8 shows the complete time series of original and filled data. Figure 5.9 shows a close up of the second gap. Note also that the first gap was filled with values which appear low. This is because the last good data point before the gap was much lower than the previous ones, resulting in a low clearness index.

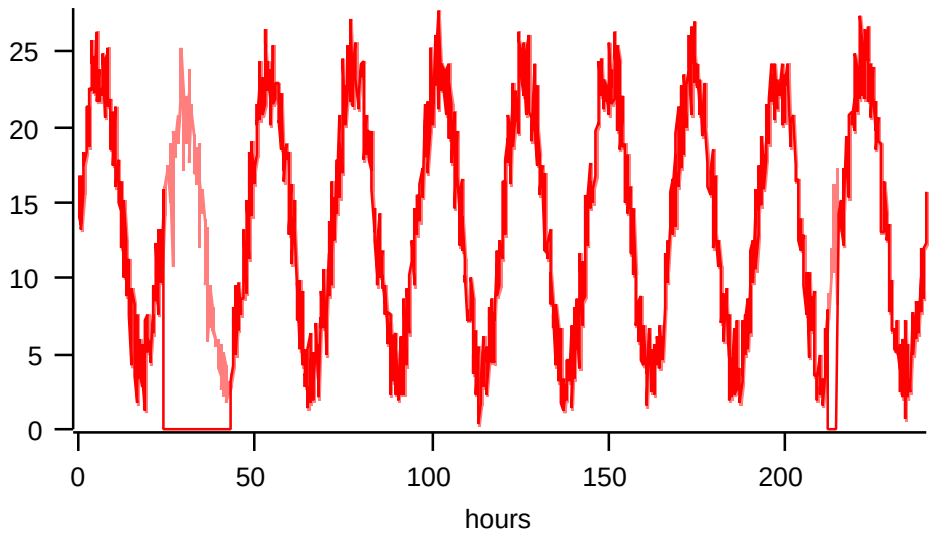


Figure 5.6. Gap Filling in Noisy Data

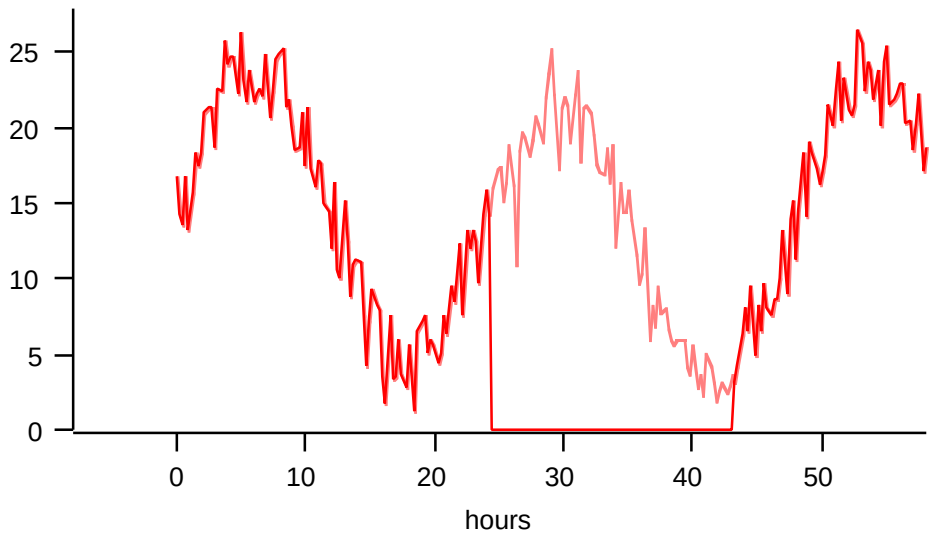


Figure 5.7. Close Up of Filled Gap in Noisy Data

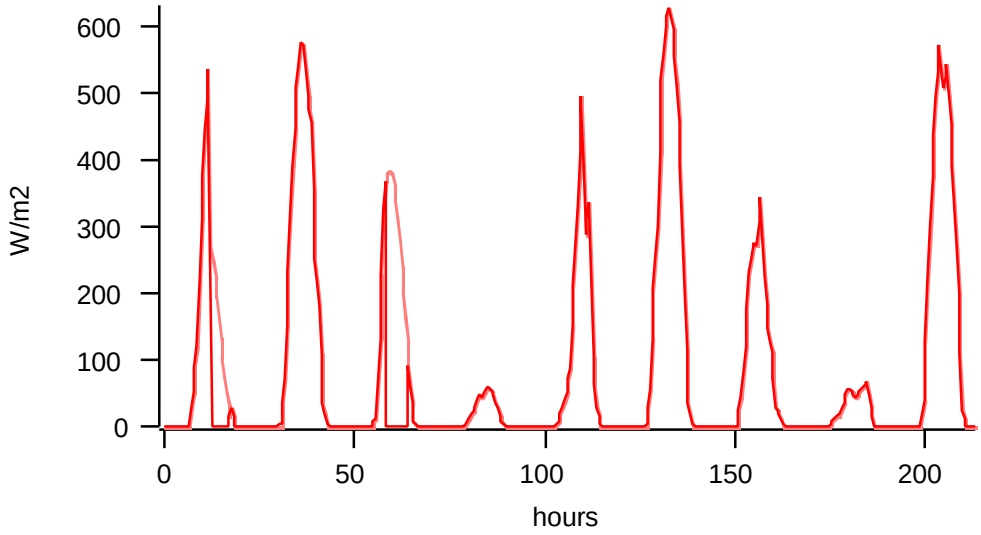


Figure 5.8. Gap Filling in Solar Data

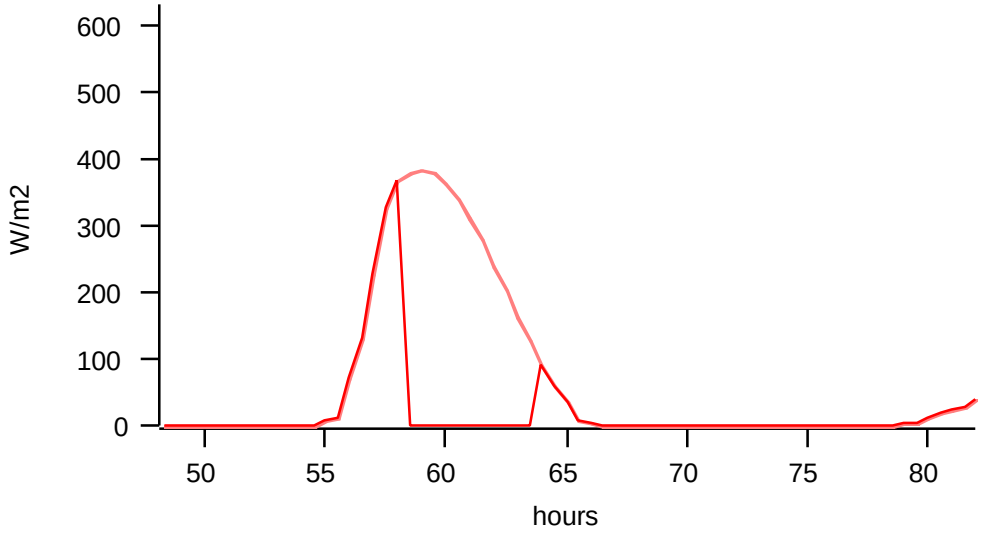


Figure 5.9. Close Up of Filled Gap in Solar Data

6. Component Algorithms

The theory behind the various component models is detailed below. In Hybrid2 components are the individual pieces of equipment, which together comprise the hybrid power system. They include wind turbines, photovoltaic panels, diesel generators, batteries, dump loads, power converters.

6.1 Wind Turbine Performance Model

6.1.1 Executive Summary

The speed and direction of the wind impinging upon a wind turbine is constantly changing. Over any given time interval, the wind speed will fluctuate about some mean value. The degree of the fluctuations is characterized by the standard deviation of the wind speed during that time interval. The power extracted by the wind turbine is a function of the wind and, thus, also will have a mean value during the time interval in question and variations about that mean. A "power curve" is typically used to define the performance of a wind turbine. It is the relationship between the average hub-height wind speed and the average generator power during the averaging time interval, assuming certain standard atmospheric conditions. Also, a wind turbine will have a cut-in wind speed at which the turbine starts to generate power, a rated wind speed, at which it starts to generate rated power, and a high-wind cut-out wind speed at which it is shut down for safety. See Figure 6.1 for an illustration of a typical power curve of a pitch regulated, constant speed wind turbine. Other types of wind turbines will have power curves that look different but are still similar in nature.

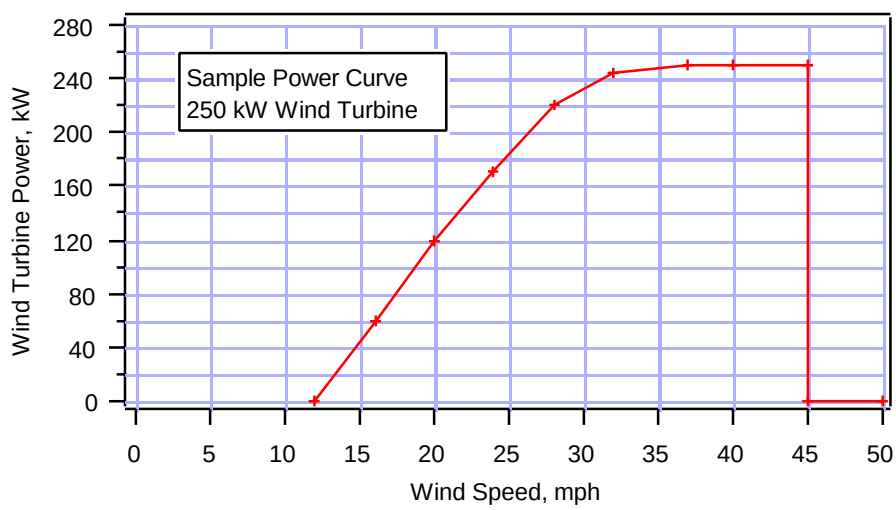


Figure 6.1. Sample Wind Turbine Power Curve

In Hybrid2 the user specifies a power curve and the wind speed time series data to calculate the wind power produced by the turbine using the wind turbine model. The calculations assume that the wind is normally distributed during the time interval. A variety of factors affect the results of the calculations. If the wind data is not measured at the turbine hub height, or was averaged over a different time period than that used to generate the power curve, or if the turbine is to be operated under non-standard atmospheric conditions, then adjustments need to be made in the calculations to determine expected wind power at the site in question. The Hybrid2 code makes

all the appropriate corrections and determines the average wind power and the standard deviation of the wind power over the simulation time interval.

6.1.2 Model Overview

Major Input

The major inputs to the model are the wind turbine power curves for both the AC and the DC wind turbines and the turbine response factor. The power curve is the power-wind speed relationship for the wind turbine. It is a function of the turbine design and is specified by the turbine manufacturer. The turbine response factor is a measure of the relationship between the variability of the wind and the variability of the resulting electrical power. Details about the turbulence response factor can be found in the Detailed Parameter Description below.

The major inputs to the simulation are wind speed time series data and wind turbulence parameters. These inputs are used with the power curve to determine the average power from the wind turbine during the simulation interval and the standard deviation of the wind power.

Output

The major output of the wind turbine component model during the simulation is the average power from the wind turbine and the standard deviation of the wind turbine power. The output is on a per bus basis. Thus if there are turbines on both buses, there will be values for both buses. Power from multiple turbines is discussed under Subsystem Algorithms, in Chapter 7.

Major Modifiers

The outcome of the calculations determining wind turbine power are affected by:

- Scaling of the Wind Speed. This allows wind data to be linearly scaled to simulate different wind regimes.
- Differences in Wind Turbine and Anemometer Heights. Wind turbine power is a function of the hub height wind speed. Differences in wind turbine and anemometer heights require a model for correcting the measured wind to determine the hub-height wind speed. The calculation uses the wind turbine height, anemometer height, and power law exponent. Each of these can be determined by the user.
- Different Averaging Times for the Power Curve Determination and the Simulation. Different averaging times for the power curve determination and the simulation result in a power curve that does not precisely represent the turbine performance as a function of the wind speed data. A new power curve can be determined using the turbulence length scale, the reference wind velocity for the turbulence length scale, the turbulence intensity, and the power curve averaging interval. Each of these can be determined by the user.
- Air Density. The air density affects the wind turbine power output. It is a function of air pressure and temperature. If the average air density at the site is not standard air density then the user can specify the method of determining the correct air density. Based on the user's choice, the site mean temperature and pressure, the site mean temperature and site elevation above sea level, or a fixed ratio of site density to standard air density is used to determine the site air density.

6.1.3 Detailed Parameter Description

Modeling Input

Power Curves: The major inputs to the model are the wind turbine power curves for both the AC and the DC wind turbines. The power curve is the power-wind speed relationship for a wind turbine. It is a function of the turbine design and is normally obtained from the wind turbine manufacturer. The power curve is represented as pairs of wind speed and power data, although it often appears in graphical form. Power curves represent the relationship between the average power from a wind turbine and average wind speed over the same time interval, typically a ten minute period.

Turbine Response Factor: This factor relates fluctuations in wind speed to fluctuations in power. The factor is a function of the machine design and can be specified separately by the user for the AC wind turbines and the DC wind turbines. In reality the relation is a complicated one, but a single factor is now used in Hybrid2. For a linear power curve, passing through the origin, and an infinitely responsive wind turbine the factor would be 1.0. Similarly for a turbine with cubic power curve (constant tip speed ratio), the factor would be 3.0. The value for most turbines would be in the vicinity of 1.5 or less. It should be noted, however, that this factor actually depends on wind speed. At low winds near cut in, there may be a great deal of power variability due to the turbine starting and stopping and to a steeply rising power curve. Conversely, in high winds, power regulation, due either to stall or pitch control, will tend to decrease the relative variability of the power. In simulations of hybrid power systems in which wind turbine power fluctuation may be particularly significant (high penetration, low or no storage), it may be of value to perform parametric runs with a range of Turbine Response Factors. More discussion on the relationship between fluctuations in wind speed and fluctuations in wind power can be found in Manwell, Jeffries, and McGowan, 1991.

Simulation Input

Wind Speed: The wind speed is taken from the wind speed time series record for each time step of the simulation. It is used with the power curve to determine the average power from the wind turbine during the simulation interval.

Wind Speed Standard Deviation / Turbulence Intensity: The wind data may contain either just the mean wind speed data for each time interval or also the standard deviation of the wind speed. If the standard deviation of the wind speed is not available, it is estimated during the simulation on the basis of a nominal turbulence intensity for the site. Turbulence intensity is the ratio of the standard deviation of the wind during the time interval to the average wind speed during the time interval. More details on turbulence intensity are give below. The standard deviation of the wind is used to determine the magnitude of fluctuations in the wind power about the average wind power during the simulation interval. It is of note that the IEC 1400-1 suggests representative turbulence intensity values of 0.16 and 0.18 for lower and higher turbulence sites respectively (IEC, 1996).

Output

The output from the wind power section of the model is the average power from the turbine for each time step, and standard deviation of the wind power. It is first calculated for each turbine, with adjustments made for air density, differences between anemometer and hub heights, and differences between the averaging time intervals used in the wind data and for the power curve,

and then summed for each bus. The output is on a per bus basis. Thus if there are turbines on both buses, there will be values for both buses. Power from multiple turbines is discussed under Subsystem Algorithms, Chapter 7.

Modifiers

A number of factors can affect the results of the wind power calculations. If the wind data is not measured at the turbine hub height or was averaged over a different time period than that used to generate the power curve, or if the turbine is to be operated under non-standard atmospheric conditions, then adjustments need to be made in the calculations to determine expected wind power at the site in question. The relevant modifiers are detailed below.

Wind Speed Scale Factor: The wind speed scale factor allows for scaling of the input wind speed. It multiplies both mean wind speed and standard deviation of wind speed in each time step.

Wind Turbine Height: Wind turbines that generate electricity are typically at least 20 m above ground level and may be higher (30 m or more). Mechanical water pumping wind mills are often lower than 20 m. This may not be the height at which the wind speed data was collected. Wind speed varies with height and, thus, the wind speed measured by the anemometer will not be the wind speed at the wind turbine. The height of the wind turbine is one of the factors used to determine the wind speed experienced by the wind turbine.

Anemometer Height: Anemometers are ideally located at a height above ground equal to that of the wind turbine. That is often not the case, however. Many anemometers are located at 10 m, the standard for surface weather measurements. Some anemometers are lower; others are higher. Measured wind speed can be scaled from one height to another, as described below, although such extrapolations are often unreliable. This is especially likely if the anemometer is located near trees, buildings or other obstructions. Nevertheless, knowledge of the anemometer and wind turbine heights can be helpful in estimating the wind speed at a height that is different from that of the anemometer.

Power Law Exponent: This parameter allows for the scaling of wind speed from one height to another. The power law exponent is usually between 0.1 and 0.5. Lower values correspond to very smooth sites such as sites surrounded by snow fields or water. Higher values correspond to very rough sites like forests. A value of 1/7 (0.143) is often used for relatively smooth flat sites. The power law method of scaling wind speeds is most appropriate when the difference in height between anemometer and turbine hub height is not great. Note that the accuracy of the correction becomes less when the terrain is not flat. The power law exponent also changes with height. For this reason, a log law for variation of wind speed with height is often preferred. Hybrid2 does not include the log law at this time. More discussion on the proper use and selection of a power law exponent can be found in Freris (1990).

Turbulence Length Scale: The turbulence length scale characterizes the mean size of the turbulent eddies in the wind. It is used in the model to estimate the turbulent integral time scale. This is used to adjust the power curve (the power-wind speed relationship of the wind turbine) when the averaging time used to determine the wind turbine power curve is different from the simulation time step.

Reference Wind Velocity for Turbulence Length Scale: This velocity is used in the model, together with the turbulent integral length scale, to estimate the turbulent integral time scale. The latter is used in adjusting the power curve from one averaging time to another. In Hybrid2,

calculations using the turbulence length scale are done only once in the run to find representative values. Accordingly, the most appropriate reference wind velocity to use is the site mean wind speed.

Turbulence Intensity: This is a nominal value characterizing the variability of the wind speed at the site. Turbulence intensity is the ratio of the standard deviation of the wind speed to mean velocity. The averaging period is typically on the order of 10 minutes to one hour. The sampling period of the original data is normally on the order of 1 second for applications such as Hybrid2. The turbulence intensity is used in adjusting the power curve when the power curve averaging time is different from the simulation time step and in deriving the "wind farm filter" used in Hybrid2, which is discussed in Chapter 7.

Averaging Interval: The averaging interval refers to the wind turbine power curve. Power curves from commercially available wind turbines are typically made on the basis of averaging intervals of 1 to 10 minutes. The power curve is adjusted if the averaging time is different from the simulation time step.

6.1.4 Model Theory

Mean Wind Power

A single wind turbine is modeled by a power curve. It is the relationship between the average hub height wind speed and the average generator power during the averaging time interval, assuming certain standard atmospheric conditions. A wind turbine will have a cut-in wind speed at which the turbine starts to generate power, a rated wind speed, at which it starts to generate rated power, and a high wind cut-out wind speed at which it is shut down for safety reasons (see Figure 6.1). In Hybrid2 the power curve is specified by pairs of wind speed and power.

The time during which wind speed and power were averaged to obtain the power curve must also be specified. If this period is different from the simulation time step, the power curve may be adjusted, as described below.

When the time step of the model is the same as the averaging time, the mean power from the wind turbine at any wind speed is given by a linear interpolation between points of the power curve. The closest pairs on either side of the input wind speed are used in the interpolation. In equation form, supposing that the input wind speed is V, and that $V_i < V < V_{i+1}$, where the index i indicates which pair of points of the series of power curve points is being considered, then the power predicted for the wind turbine is:

$$P = (P_{i+1} - P_i)[(V - V_i) / (V_{i+1} - V_i)] + P_i \qquad (6.1.1)$$

<u>Example:</u>

For example, suppose the input wind speed is 12.2 m/s and the nearest points on either side are (11.5 m/s, 25 kW) and (13 m/s, 40 kW). The estimate of the power is then

$$P = (40 - 25)(12.2 - 11.5) / (13 - 11.5) + 25 = 32 \text{ kW}$$

The power curve may have points less than 1 m/s apart, but if the user inputs a series of points more than 1 m/s apart, the program will automatically insert points between them. It will do this

by linear interpolation as described below. This filling-in is done in anticipation of adjusting the power curve for different averaging times.

Variability of Wind Power

The variability of the wind power is found from the mean wind power, the variability of the wind speed over the interval, and the turbulence response factor of the wind turbine. The variability is characterized by the standard deviation of the wind power

$$\sigma_P = \overline{P}\, F_{WPT} \frac{\sigma_V}{\overline{V}} \tag{6.1.2}$$

where

σ_P = Standard deviation of wind power, kW

$\overline{P}$ = Mean wind power over interval, kW

F_{WPT} = Wind power turbulence response factor, -

σ_V = Standard deviation of wind speed, m/s

$\overline{V}$ = Mean wind speed over interval, m/s

Wind Turbine Power Curve Generation and Adjustment

When the wind speed is averaged over a different time period than was used in determining the power curve for the turbine, the original power curve is no longer strictly applicable, especially if the power curve is non-linear or discontinuous at the wind speeds of interest. Under these circumstances, the power curve may be adjusted from one averaging time period to another. The procedure used in Hybrid2 considers the effects of turbulence on the power curve. Thus the fluctuations it considers have time scales under an hour. It assumes that:

- The wind speed is normally distributed in each averaging time interval
- The distribution of variance in the frequency domain can be described by the von Karman spectrum.
- Reduced averaging results in a reduction of variance.
- The available power curve adequately reflects the behavior of the wind turbine at the site.

The adjustment procedure is done only once in the program, before cycling through the individual time steps. In order to accomplish this, it is further assumed that:

- Representative values of site turbulence parameters may be used (site variability, integral length scale, and mean velocity).
- The variability at the site where the original power curve was obtained is the same as that at the prospective site.

It should be noted that power curve calculations can be quite complicated. For example, if the anemometer upon which wind speed measurements are based is located a significant distance from the turbine, there will be a filtering effect due to the lack of coherence between the anemometer site and the turbine. This filtering will have a similar effect on a power curve as does time averaging, which is the subject of the discussion below. It is presumed that all the averaging times discussed below are long relative to the effects of such separation. For example,

if the anemometer is 100 m from a turbine, and the wind speed is 10 m/s, the averaging times should be well over 10 sec (the time it takes the wind to get from the anemometer to the turbine). In addition, it should be noted that typical measurement procedures recommend averaging times of 10 minutes. When a wind turbine power curve taken according to such standards is available, there is little to be gained by correcting the curve for use, say, in a simulation with hourly time steps. This is because 10 minute averages take out most of the effect of turbulence. The method discussed below is generally useful only in cases where a power curve is based on relatively short averaging times (less than 1 minute). For more information on power curves in general, see Christensen, et al. (1986) and Hansen (1985.)

The Von Karman spectrum characterizes the distribution of the variance of the wind speed as a function of the frequency of wind speed fluctuations. The Von Karman spectrum, S(f), is defined (Fordham, 1985) by

$$\frac{S(f)}{\sigma_V^2} = \frac{4\frac{L}{\overline{V}}}{\left[1 + 70.8\left[\frac{L\,f}{\overline{V}}\right]^2\right]^{5/6}} \qquad (6.1.3)$$

where

S(f)	= Von Karman spectrum, $(m/s)^2$
L	= Turbulence integral length scale, m
f	= Frequency, Hz
$\overline{V}$	= Reference velocity, m/s.

L may be estimated from the surface roughness of the site by the following equation (Freris, 1990):

$$L = 25\,H^{0.35} / (z_0)^{0.063} \qquad (6.1.4)$$

where

H	= Height above ground level, m
z_0	= Surface roughness height (This varies from approx. 10^{-5} m for very smooth surfaces to 10^{-2} m for grass to 1.0 for forests).

The ratio $L/\overline{V}$ is also known as the integral time scale. It may be approximated by the area under the autocorrelation function of wind speed. The usefulness of the spectrum is derived from the relationship between the spectrum and the variance of the wind speed. The total variance in the wind speed data characterized by a spectrum is given by the integral of the spectrum over all frequencies, and the variance over a range of frequencies is given by the integral over that range.

The instantaneous power curve is given by: P = F(V(.)) where F(V(.)) implies that the power is some function of the "instantaneous" wind speed. The instantaneous value, for the purposes here, may be assumed to be averaged or sampled once per second (1 Hz). It is actually a somewhat hypothetical value, since it is not actually measurable in the atmosphere (due to turbulence, displacement of the anemometer from the turbine rotor, etc.) Power curves are normally measured by first averaging both the wind speed and power over some interval, then bin

averaging. This corresponds to grouping all the powers for which the wind speed is in a particular "bin" (for example, 5.0 to 5.5 m/s, 5.5 to 6.0 m/s etc.) All the powers are then averaged to obtain a single value for that bin. The collection of all averages and bin midpoints then defines the power curve. Occasionally, power curves are taken using much lower averaging times than might be appropriate for calculations for a hybrid power system simulation. The following describes a procedure by which a power curve derived using short averaging times may be adjusted to approximate one that would have been obtained using longer averaging times.

Assuming that the averaging interval used for obtaining the power curve is Δt_1, the average power, $P_{\Delta t_1}(\overline{V}_1)$, at any given average wind speed, $\overline{V}_1$, would be

$$P_{\Delta t_1}(\overline{V}_1) = \int_0^\infty P(V)\, p_1(\overline{V}_1)\, dV_i \tag{6.1.5}$$

where the wind speed probability distribution is

$$p_1(V) = \frac{1}{\sigma_{V_1} \cdot \sqrt{2\,\pi}}\, e^{-\frac{1}{2}\left(\frac{V-\overline{V}_1}{\sigma_{V_1}}\right)^2} \tag{6.1.6}$$

and

$$\sigma_{V_1}^2 = \int_{f_{lo,1}}^\infty S(f)\, df \tag{6.1.7}$$

and where

$f_{lo,1}$ = $1/\Delta t_1$, sec^{-1}

$\overline{V}_1$ = wind speed averaged over time period Δt_1, m/s.

A complete new power curve may be obtained by performing the same averaging for a range of wind speeds from the lowest to the highest expected value. Note that if the averaging interval is very short, then σ_{V_1} will be quite small, so the power at any given wind speed will be close to that given by the "instantaneous" value. Power curves may be generated for any given averaging time, but averaging times of interest are normally between 1 minute and 1 hour. Note that the turbulent spectrum describes fluctuations in this time range (rather than, for example, synoptic or diurnal factors).

Suppose that a power curve is available which was obtained by averaging over interval Δt_1, (e.g., 1 minute), and it is desired to convert it to one averaged over a longer period (e.g., 1 hour). To convert from Δt_1 to Δt_2, note that the power curve for the longer interval in this case is given by

$$P_{\Delta t_2}(\overline{V}_2) = \int_0^\infty P(V)\, p_2(V)\, dV \tag{6.1.8}$$

where

$$p_2(V) = \frac{1}{\sigma_{V_2}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{V-\bar{V}_2}{\sigma_{V_2}}\right)^2} \tag{6.1.9}$$

$$\sigma_{V_2}^2 = \int_{f_{lo,2}}^{\infty} S(f)df \tag{6.1.10}$$

and where

$f_{lo,2} = 1/\Delta t_2$, sec^{-1}

As shown below, the power curve based on the second interval may be derived from that based on the first averaging interval by using a standard deviation based on the differences. That is

$$P_{\Delta t_2}(\bar{V}_2) = \int_0^{\infty} P_{\Delta t_1}(\bar{V}_1)\, p_{1-2}(\bar{V}_1)\, d\bar{V}_1 \tag{6.1.11}$$

where

$$p_{1-2}(\bar{V}_1) = \frac{1}{\sigma_{V_{1-2}}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\bar{V}_1-\bar{V}_2}{\sigma_{V_{1-2}}}\right)^2} \tag{6.1.12}$$

$$\sigma_{V_{1-2}}^2 = \sigma_{V_2}^2 - \sigma_{V_1}^2 = \int_{f_{lo}}^{f_{up}} S(f)\, df \tag{6.1.13}$$

and where

$f_{up} = 1/\Delta t_1$, sec^{-1}

$f_{lo} = 1/\Delta t_2$ sec^{-1}

A proof of the equivalence of Eq. 6.1.8 and Eq. 6.1.11 is presented in Appendix 1.

The code works in the following manner. The amount of variance in the fluctuating wind up to a frequency determined by the original power curve averaging time is found by integrating the von Karman spectra between the two limits. The lower limit is chosen such that virtually all of the variance occurs at higher frequencies. Similarly, the variance associated with the fluctuating wind up to the new frequency is then found. Assuming that the original curve is determined by averaging over shorter time intervals than the modeling time step, there will be less variance in the latter integral than the former. The difference in variance is found by subtraction of the one from the other. The ratio of this value to the total variance in the turbulence determines the fraction of remaining variance. A new power curve is, then, generated for a series of wind speed values, V_i.

For each wind speed in the power curve values, the standard deviation is found by

$$\sigma_i \approx V_i \, TI \sqrt{Fv} \qquad (6.1.22)$$

where

σ_i = Standard deviation used in calculating the new power curve, m/s

TI = Site nominal turbulence intensity, -

Fv = Fraction of variance, -

This standard deviation is used to find the fraction of time that the wind is in various bins 1 m/s wide near to V_i. The power at the midpoint of each of those bins is found from the original power curve and weighted by the fraction of the time. The weighted values are summed to give the average power at interval mean wind speed V_i. The power at each of the velocities determines the new power curve.

Example:

The following example illustrates the use of the adjustment. A synthetic time series was generated for 3600 seconds (1 hour) using the Shinozuka method (with no jitter) as described by Jeffries, Infield, and Manwell, 1991. An integral length scale of 100 m and a reference velocity 10 m/s were used. Note that this corresponds to an integral time scale of 10 sec. The time series had a mean and standard deviation of 10.0 m/s and 2.943 m/s respectively. The time series is illustrated in Figure 6.2; a histogram is shown in Figure 6.3 and the autocorrelation in shown in Figure 6.4. Note that the area under the autocorrelation is approximately 10 sec, as it should be.

A hypothetical instantaneous wind turbine power curve was used for the example. In this curve, the power was equal to wind speed up to 10 m/s. Above a wind speed of 10 m/s it was equal to 10. (The units of power are arbitrary here.) Two power curves based on averaging times of 1 minute and 1 hour were created. They are illustrated in Figure 6.5, together with the instantaneous curve. The instantaneous power curve was used to predict the average power from the 3600 wind speed data points. This value was 8.83. The 3600 points were averaged to form a shorter data set of 600 points (1 minute wind speed averages). Applying the power curve based on 1 minute data to these wind speed averages yielded a predicted average power of 8.74. The predicted value of the average power from the 1 hour power curve at the single value of 10 m/s (the one hour average) yielded a power of 8.76. Note that the original instantaneous power curve would have predicted a value of 10.

Wind Speed

Wind speed is characterized, first of all, by a time series of mean values. When available, the standard deviation of the wind speed in each time step is also used. It is assumed that the original data is sampled at approximately one Hz (see, for example, Chapter 3 in Hunter and Eliot,1994.) Faster sampling will have an insignificant effect on the wind variability. Slower sampling will decrease the wind variability.

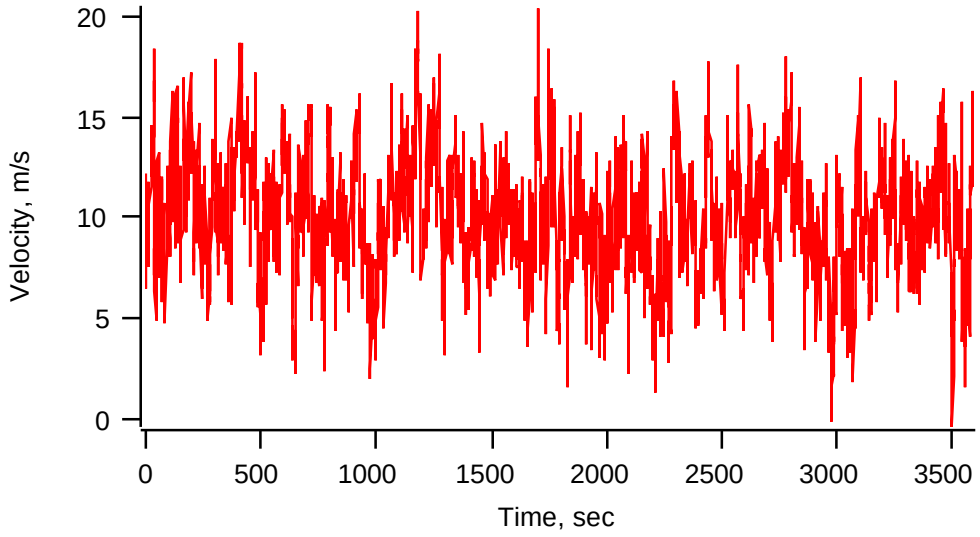


Figure 6.2. Sample Wind

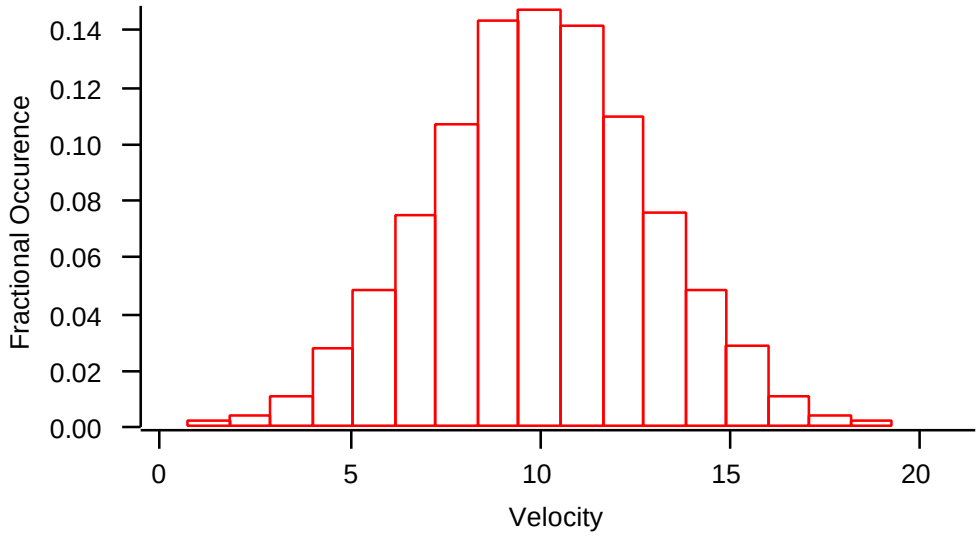


Figure 6.3. Histogram of Wind Data

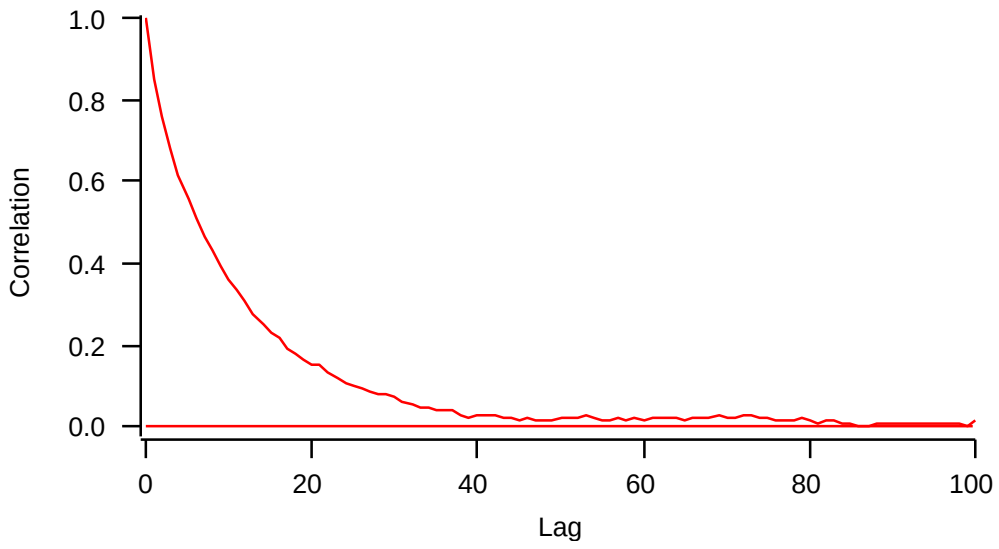


Figure 6.4. Correlation vs. Lag

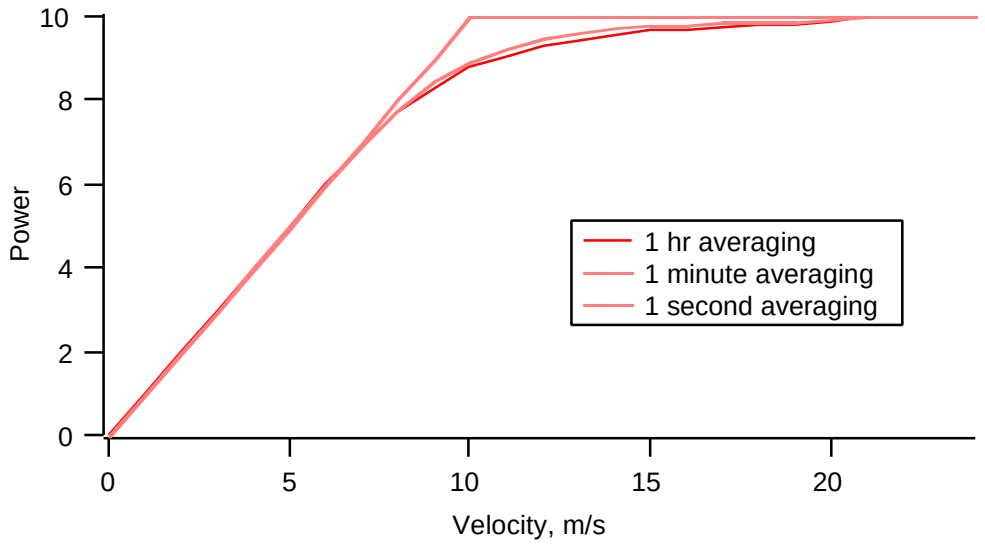


Figure 6.5. Modified Power Curves

When standard deviation data is not available, the user may select a representative variability. In this case, the program calculates the standard deviation by multiplying the mean at each time step by the variability. When a nominal value is used, the value should be the same as that which would be obtained from the nominal turbulence intensity (discussed previously) times the site mean wind speed.

Height Correction

Wind speed data is frequently available from a different (usually lower) height than the hub height of the turbine. Wind speed experienced by the machine is adjusted from that at the anemometer by a power law relation.

$$V_1 = V_2 \left[\frac{H_1}{H_2} \right]^{\alpha} \tag{6.1.23}$$

where

V_i = Wind speed at height i (H_i), m/s

α = Power law exponent, -

More discussion on the appropriate choice of the power law exponent, α, can be found in Freris (1990).

Wind Speed Scale Factor

A scale factor may be used to adjust the input wind speed. This is a multiplier which applies to all wind speed inputs from the data file before the power calculations are made. The scale factor applies to interval standard deviations as well as the mean wind speeds.

Air Density

Air density is considered by scaling the power determined from the power curve by the ratio of the site air density to standard air density. It is assumed that the original power curve is based on standard conditions. Density variation may be accounted for by 1) using a constant correction ratio input directly by the user, 2) calculating a value based on mean temperature and elevation above sea level, 3) using site mean temperature and pressure.

In the second case the density ratio is determined as follows: estimated sea level temperature is found from

$$T_{SL} = T_{site} + H_{site}\,\text{lapse} \tag{6.1.24}$$

where

T_{SL} = Sea level temperature, degrees K

T_{site} = Site mean temperature, degrees K

H_{site} = Site altitude, m

lapse = Adiabatic lapse rate, -0.00638 K/m.

Note that the above equation assumes that the temperature decreases at a fixed rate as the altitude increases (specified by the lapse rate). The sea level temperature in Kelvin degrees is found by adding the assumed long term mean temperature at the site. The standard temperature at sea level and the sea level temperature estimated from the site temperature (found above) are used, together with the assumption that air is an ideal gas to obtain the density ratio

$$\rho / \rho_0 = (T_{SL,0} / T_{SL})(T_{site} / T_{SL})^{4.26} \tag{6.1.25}$$

where

ρ = Air density at site, kg/m^2

ρ_0 = Air density at standard conditions (293 K), kg/m^2

$T_{SL,0}$ = Temperature at standard conditions, K

In the third case, using the mean site temperature and pressure, the density ratio is found from:

$$\rho / \rho_0 = (Pr_{site} / Pr_{SL,0})(T_{SL,0} / T_{site}) \tag{6.1.26}$$

where

Pr_{site} = Mean atmospheric pressure at site, mm Hg

$Pr_{SL,0}$ = Atmospheric pressure at standard conditions, 760 mm Hg.

Note that the above relation implies that the density should be inversely proportional to increasing pressure, and should decrease in direct proportion to site absolute temperature.

The method used for density correction is most applicable to stall-regulated wind turbines. For pitch-regulated machines whose control allows a fixed rated power to be maintained at higher wind speeds, the correction will be inadequate at those higher wind speeds. If the winds are frequently above rated, a modified power curve should be considered. For example, a spreadsheet program could be used to generate a new power curve. The first step would be to adjust all by the powers by the mean density ratio. For cold regions (high density) powers close to and in the pitch regulation region would initially be too high. These should be set to the rated power. For hot regions (low density), the powers in the pitch regulation region would appear not to reach the rated value. At the beginning of the normal pitch regulation region, the power should be extrapolated, based on the nearby, non-regulated region, until rated power is reached. Powers at all higher winds in the pitch regulation region should be set to rated power.

6.2 Photovoltaic Performance Model

6.2.1 Executive Summary

Hybrid2 calculates the power output from a photovoltaic (PV) panel based on an analytical model that defines the current-voltage relationships based on the electrical characteristics of the panel. As described in the following theory section, a one diode model forms the basic circuit model used to establish the current-voltage curve specific to a PV panel. This model is able to include the effects of radiation level and cell temperature on the output power.

In the discussion below, a PV panel is assumed to be composed of individual cells connected in series and parallel and mounted on a single module. In the Subsystem section, the performance of arrays, individual panels connected in series or parallel, is discussed.

6.2.2 Model Overview

Major Input

Modeling Input. The primary inputs that affect the PV model output are the parameters that define the basic PV panel current-voltage relationship. These parameters are determined from information supplied by the manufacturer.

Simulation Input. The main input to the PV panel model relating to the simulation is the insolation data. This is the insolation on a horizontal surface for each time interval. For panels on the DC bus (which always includes a battery or battery bank), the battery terminal voltage may also be used. Ambient temperature is also an input.

Output

The output of the PV panel model at the beginning of the simulation includes 1) the light current, 2) the diode reverse saturation current, 3) the series resistance, and iv) a curve fitting parameter, A. The output of the PV panel model at each time step is the power generated, current, and voltage.

Major Modifiers

The modifying parameters that affect the calculations performed in the PV panel are related to the panel behavior under various ambient and load conditions. Panels are rated at various standard conditions. Ratings or specifications at other conditions are considered using the modifying parameters.

6.2.3 Detailed Parameter Description

Modeling Input

The behavior of a PV panel is a function of the current versus voltage relationship of the panel. This electrical behavior is a function of the cell temperature and the incident insolation. The cell temperature is a function of the power level at which the panel is operating and the heat transfer to the surroundings. Thus, due to the complex behavior of PV panels, there are a number of parameters defining the current-voltage relationship:

PV panel area (A_C): The equivalent area [m^2] of each PV panel. This parameter is usually taken as the total surface area of the panel.

Short Circuit Current Temperature Coefficient ($\mu_{I,sc}$): This is the rate of change of short circuit current with changes in temperature (Amps/C) above and below the standard operating, or reference, temperature. It is determined from PV panel data at two temperatures about the reference temperature.

Open Circuit Voltage Temperature Coefficient ($\mu_{V,oc}$): This is the rate of change of open circuit voltage with changes in temperature (Volts/C) above and below the standard operating, or reference, temperature. It is determined from PV panel data at two temperatures about the reference temperature.

Cell Material Bandgap Energy (ε): This value (units of eV) is a constant for the given PV panel material. For silicon $\varepsilon = 1.12$ eV and for gallium arsenide $\varepsilon = 1.35$ eV.

Short Circuit Current (I_{SC}): The short circuit current (A) determined from the manufacturer's data at the standard operating, or reference, temperature.

Open Circuit Voltage (V_{OC}): The open circuit voltage (V) determined from the manufacturer's data at the standard operating, or reference, temperature.

Maximum Power Point Current (I_{mp}): The current (A) at the point of maximum power production of the PV panel, determined from the manufacturer's data at the standard operating, or reference, temperature.

Maximum Power Point Voltage (V_{mp}): The voltage (V) at the point of maximum power production of the PV panel, determined from the manufacturer's data at the standard operating, or reference, temperature.

Simulation Input

The main input to the PV panel model relating to the simulation is the insolation data. This is the average irradiance, $\overline{G}$, on a horizontal surface for each time interval. The horizontal irradiance is converted to the actual average irradiance incident on the panel, $\overline{G}_T$, (which is normally not horizontal) in the code.

The battery terminal voltage (which is also the DC bus voltage) from the previous time step is also used when the panels are on the DC bus. This is used in conjunction with the I-V curve of the panel in determining the current, and hence the power when a maximum power point tracker is not used. When a maximum power point tracker is used, the battery voltage is ignored in the calculation of the panels' output.

Ambient temperature is also an input. When time series temperature data is available, it may be read in from an input file. Otherwise a nominal site temperature is used. This should be the average temperature during daylight hours.

Output

The outputs of the PV panel model at the beginning of the simulation include:

Light Current: The 1st constant of I-V curve fit. It is a measure of the current produced by the PV panel as a function of the incident insolation. Light Current (I_L): The 1st constant of I-V curve fit. It is a measure of the current produced by the PV panel as a function of the incident insolation." Diode Reverse Saturation Current (I_0): The diode reverse saturation current is the 2nd constant of I-V curve fit.

Series Resistance (R_S): The series resistance of the PV panel is the 3rd constant of I-V curve fit. It is a function of the panel temperature and insolation.

Curve Fitting Parameter, A: This is the 4th constant of I-V curve fit.

The output of the PV panel model at each time step includes the output power (kW) and the current generated. This output will, in general, be affected by the cell temperature and the battery voltage.

Modifiers

The modifiers that are needed to calculate the performance of the PV panel include the following:

Number of Solar Cells in Series (N_s): The number of solar cells in series in a PV panel. This is used to determine the panel current-voltage relation.

PV Panel Temperature at Standard Operating Conditions ($T_{c,SOC}$): This is the PV panel temperature at standard operating conditions (C). Traditionally, measurements of PV electrical characteristics are made at reference incident radiation of 1000 W/m^2 and a panel temperature of 25°C. This value is, therefore, usually set at 25° C. This is used in determining the constants that describe the PV cell current vs. voltage relation.

Solar Insolation at Standard Operating Conditions ($G_{T,SOC}$): This is the solar insolation at standard operating conditions (W/m^2). Traditionally, measurements of PV electrical characteristics are made at reference incident radiation of 1000 W/m^2 and a panel temperature of 25°C. This value is, therefore, usually set at 1000 W/m^2. This is used in determining the constants that describe the PV cell current vs. voltage relation. Manufacturer's data is usually based on tests taken at standard operating conditions.

Ambient Temperature at Normal Operating Conditions ($T_{a,NOCT}$). This is the ambient temperature at normal operating conditions (C). By convention, the normal operating cell temperature (NOCT) is defined as the cell or panel temperature that is reached when the cells are mounted in their normal way at a solar radiation level of 800 W/m^2, a wind speed of 1 m/s, an ambient temperature of 20°C, and at no load operation (i.e., efficiency is zero). This value is, therefore, usually set at 20° C. The Normal Operating Condition inputs are used to estimate the heat loss characteristics of the panel. These in turn are used to estimate the cell temperature, which is also affected by the incident solar radiation and ambient temperature.

Solar Insolation at Normal Operating Conditions ($G_{T,NOCT}$): This is the solar insolation at nominal operating conditions (W/m^2). This value is usually set to 800 W/m^2 (See above). The Normal Operating Condition inputs are used to estimate the heat loss characteristics of the panel. These in turn are used to estimate the cell temperature, which is also affected by the incident solar radiation and ambient temperature.

PV Panel Temperature at Normal Operating Conditions ($T_{c,NOCT}$): This is the PV panel temperature at normal operating conditions (C). See notes above. The Normal Operating Condition inputs are used to estimate the heat loss characteristics of the panel. These in turn are used to estimate the cell temperature, which is also affected by the incident solar radiation and

ambient temperature. Cell temperature has a significant effect on panel performance. In particular, the higher the temperature, the less efficient is the conversion of sunlight to electricity.

6.2.4 Model Theory

The electrical characteristics of PV solar cells, i.e., the voltage-current relationships of the cells under various levels of radiation and at various cell temperatures, are required for the performance modeling of such systems. As pointed out by Duffie and Beckman (1991), there are numerous cell models, ranging from simple idealized models to complex detailed models that reflect the details of the physical processes occurring in the cells. In general, such models provide a methodology for the calculation of current, voltage, and power relationships of cell arrays over the range of operating conditions to be encountered. In addition, the PV cell characteristics needed to define the performance of the cell or panel must be available from the manufacturer. The basis of the model used in Hybrid2 essentially follows that developed by researchers at the University of Wisconsin and described in Duffie and Beckman (1991).

Figure 6.6 presents the current-voltage characteristics of a typical PV panel. As shown here, the current is nearly constant up to about 15 V, beyond which the diode current becomes more important (see Figure 6.7 for a diagram of an electrical model of the PV panel). At open circuit conditions (about 20 V), all of the generated light current is passing through the diode and the shunt resistance. The short circuit current, I_{SC}, is defined as the cell current with zero volts across the cell. In this example the short circuit current is 2.75 Amps. The open circuit voltage, V_{OC}, is the voltage with no current, 20 volts, in this example.

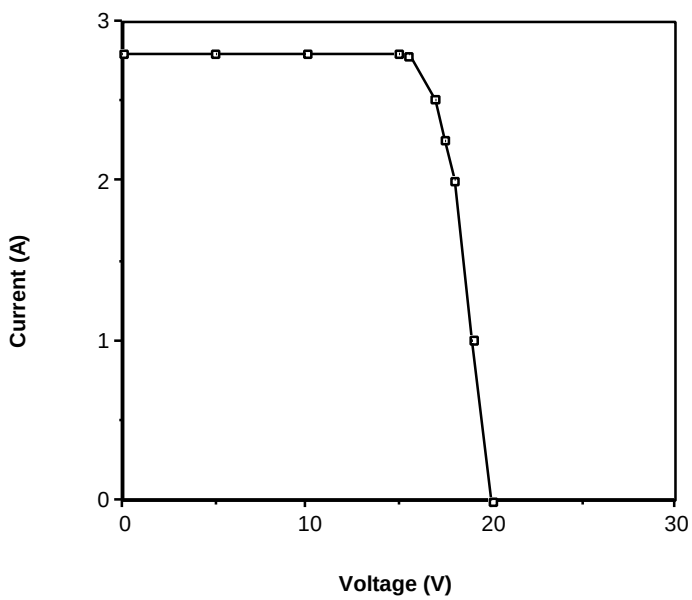


Figure 6.6. Typical Current-Voltage Performance Curve for a PV Panel

In general, PV cells are usually mounted in panels, with multiple panels used in arrays. Cells in individual panels are connected in series and parallel combinations to obtain the desired voltage. Similarly, arrays of panels can be arranged in series and parallel. For identical panel PV cells connected in series, the voltages are additive, and when connected in parallel, the currents are

additive. A more complicated analysis, which is beyond the scope of the program, would be required if the cells or the panels are not identical.

Basic Photovoltaic Panel Model

Figure 6.7 shows an equivalent circuit of the PV generator system upon which Hybrid2 is based. It should be noted that this equivalent circuit can be used either for an individual cell or for a panel consisting of several cells or for an array consisting of several panels. As discussed in the following analysis, this model involves the determination of four parameters:

I_L = Light current

I_o = Diode reverse saturation current

R_s = Series resistance

A = Curve fitting parameter.

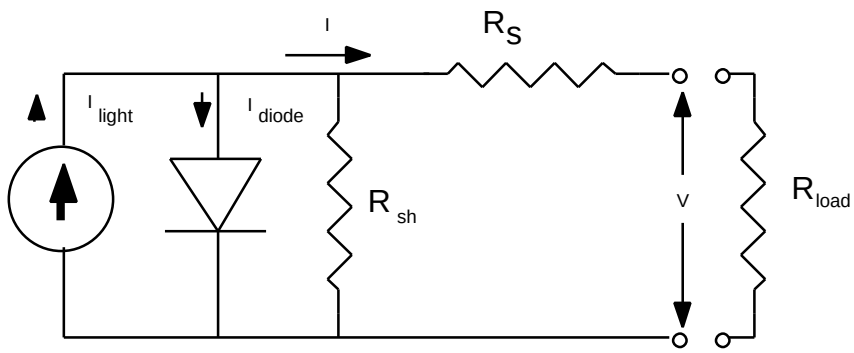


Figure 6.7. Equivalent Circuit of PV Generator

Using these four parameters, for a fixed temperature and solar radiation, the current-voltage characteristics of this model are given by

$$I = I_L - I_0 [e^{(V + I R_s)/A} - 1] \tag{6.2.1}$$

and the power, P, is given by

$$P = I\,V / 1000 \tag{6.2.2}$$

where

P = Power, kW

I = Current, A

V = Terminal voltage, V

A more complete equation corresponding to Figure 6.7 is Eq. 6.2.3, which also includes the shunt resistance:

$$I = I_L - I_D - I_{sh} = I_L - I_0 [e^{(V + I R_s)/A} - 1] - (V + I R_s) / R_{sh} \tag{6.2.3}$$

where

I_D = Diode current, A

I_{sh} = Shunt current, A

Normally the shunt resistance, R_{sh}, in most modern cells is very large; thus $(V + I R_s / R_{sh})$ in the equation above can be ignored. In the Hybrid2 model, R_{sh} is assumed to be infinite and the current-voltage characteristics are given by the a four-parameter model shown in Eq. 6.2.1

If, at low voltages, the I-V curve has a pronounced negative slope, as opposed to a line that is approximately horizontal, then R_{sh} is not large enough to ignore and the model used in Hybrid2 is not applicable.

Temperature Effects

Each of these four remaining parameters may be functions of cell temperature. At a fixed radiation level, increasing temperature leads to decreased open circuit voltage and slightly increased short circuit current. In order for this model to reproduce these effects, it is necessary to know how the model parameters I_0 , I_L, and A vary with temperature. The series resistance R_s is assumed independent of temperature in this model. Following Townsend (1989), Duffie and Beckman (1991) conclude that the following equations are good approximations for PV panels in general (note that the equation for the light current also includes the effects of the incident solar radiation):

$$A = A_{ref}\left[\frac{T_c}{T_{c,ref}}\right] \tag{6.2.4}$$

$$I_L = \frac{G_T}{G_{T,ref}}\left[I_{L,ref} + \mu_{I,sc}(T_c - T_{c,ref})\right] \tag{6.2.5}$$

$$I_0 = I_{0,ref}\left[\frac{T_c}{T_{c,ref}}\right]^3 e^{\left[\frac{\varepsilon N_s}{A_{ref}}\left(1-\frac{T_{c,ref}}{T_c}\right)\right]} \tag{6.2.6}$$

where

All quantities with the subscript "ref" are from measurements at reference conditions.

T_c = Panel temperature, K

G_T = Solar irradiance on panel, W/m^2

$\mu_{I,sc}$ = Temperature coefficient of the short circuit current determined from short circuit current data at two temperatures above and below T_{ref}.

ε = Material bandgap energy, eV. For silicon ε = 1.12 eV and for gallium arsenide ε = 1.35 eV.

N_S = Number of cells in series in a panel, -

Determination of PV Model Parameters

Reference values for the four parameters in this model can be obtained indirectly using measurements of the current and voltage characteristics of a panel at reference conditions. Traditionally, measurements of PV electrical characteristics are made at reference incident radiation of 1000 W/m^2 and an ambient temperature of 25°C. Measurements of current and voltage at these or other known reference conditions are often available at open circuit conditions, short circuit conditions, and maximum power conditions. The temperature dependence of the model parameters can be determined from open circuit and short circuit conditions at two additional temperatures on either side of the reference temperature.

Light Current at Reference Conditions ($I_{L,ref}$): At short circuit conditions, the diode current is very small and the light current is equal to the short circuit current measured at the reference conditions, i.e.,

$$I_{L,ref} = I_{sc,ref} \tag{6.2.7}$$

Diode Reverse Saturation Current (I_0): At open circuit conditions there is no current, the exponential term in the current equation is much greater than 1. I_0 can be found from Eq. 6.2.1 to be: At open circuit conditions there is no current, the exponential term in the current equation is much greater than 1. I_0 can be found from Eq. 6.2.1 to be:

$$I_0 = I_L \, e^{-V_{oc}/A} \tag{6.2.8}$$

At reference conditions Eq. 6.2.8 becomes

$$I_{0,ref} = I_{L,ref} \, e^{-V_{oc,ref}/A_{ref}} \tag{6.2.9}$$

Series Resistance (R_S): Following the summary of Duffie and Beckman (1991), the measured I-V pair at the maximum power conditions can be substituted into the Eq. 6.2.1, along with $I_{0,ref}$ and $I_{L,ref}$ and, again neglecting the 1 term (small compared to the exponential term), the result is

$$R_s = R_{s,ref} = \frac{A_{ref} \ln\left[1 - \frac{I_{mp,ref}}{I_{L,ref}}\right] - V_{mp,ref} + V_{oc,ref}}{I_{mp,ref}} \tag{6.2.10}$$

In addition to relating R_S to A at reference conditions, Eq. 6.2.10 also limits their maximum values. If both R_S and A_{ref} are to be positive, the maximum value of R_S occurs when A approaches zero and the maximum value of A_{ref} occurs when R_S approaches zero.

Curve Fitting Parameter at Reference Conditions (A_{ref}): The final model parameter can be obtained from the measurements of the PV panel open circuit voltage and short circuit current at two temperatures, ideally two temperatures on either side of the reference temperature. These values can be used to determine the temperature coefficient of the short circuit current and the temperature coefficient of the open circuit voltage.

The temperature coefficient of the short circuit current, $\mu_{I,sc}$,is obtained from measurements at the reference irradiation using

$$\mu_{I,sc} = \frac{dI_{sc}}{dT_c} = \frac{I_{sc}(T_2) - I_{sc}(T_1)}{T_2 - T_1} \tag{6.2.11}$$

where T_2 and T_1 are two temperatures above and below the reference temperature. Similarly, the temperature coefficient of the open circuit voltage, $\mu_{V,oc}$, can be obtained from measurements:

$$\mu_{V,oc} = \frac{dV_{oc}}{dT_c} = \frac{V_{oc}(T_2) - V_{oc}(T_1)}{T_2 - T_1} \tag{6.2.12}$$

An additional independent equation can be found by equating the experimental value of $\mu_{V,oc}$ with the value determined from an analytical expression for the derivative, dV_{oc} / dT. The fourth and final equation that results is the following:

$$A_{ref} = \frac{T_{c,ref}\ \mu_{V,oc} - V_{oc,ref} + \varepsilon\, N_s}{\dfrac{\mu_{I,sc}\ T_{c,ref}}{I_{L,ref}} - 3} \tag{6.2.13}$$

Eq. 6.2.13 may be derived as detailed in Appendix 2.

Now, if the value of A_{ref} determined from Eq. 6.2.13 is greater than zero but less than the maximum value obtained from Eq. 6.2.10 (with R_S equal to zero), then the cell model is complete.

Determining Cell Temperature

The determination of PV cell temperature in Hybrid2 follows the analysis of Duffie and Beckman (1991) and is based on an energy balance around the PV cell. Similar to a conventional analysis for flat plate solar collectors, the governing energy equation on a unit area of panel is given by

$$(\tau\alpha)\ G_T = \eta_c\, G_T + U_L(T_c - T_a) \tag{6.2.21}$$

where

τ	= Transmittance of covers over the cells, -
α	= Absorbed radiation fraction on the cell surface, -
η_c	= Efficiency of the cell in converting sunlight to electrical energy, -
U_L	= Loss coefficient, W/m^{2}C
T_a	= Ambient temperature, K

By convention, the normal operating cell temperature (NOCT) is defined as the cell or panel temperature that is reached when the cells are mounted in their normal way at a solar radiation level of 800 W/m^2, a wind speed of 1 m/s, an ambient temperature of 20°C, and at no load operation (i.e., efficiency is zero). Following measurements of the cell temperature, ambient

temperature, and solar radiation, the last equation can be used to determine the ratio $(\tau\alpha)/U_L$ as follows :

$$(\tau\alpha)/U_L = (T_{c,NOCT} - T_{a,NOCT})/G_{T,NOCT} \tag{6.2.22}$$

where

$T_{c,NOCT}$ = Cell temperature at normal operating conditions, K

$T_{a,NOCT}$ = Ambient temperature at normal operating conditions, K

$G_{T,NOCT}$ = Incident solar irradiance at normal operating conditions, W/m^2

The temperature at any other condition, assuming $(\tau\alpha) / U_L)$ to be constant, is then calculated from

$$T_c = T_a + (G_T(\tau\alpha)/U_L)(1 - \eta_c/\tau\alpha) \tag{6.2.23}$$

Following the recommendation of Duffie and Beckman (1991), an estimate of 0.9 is used for $\tau\alpha$ in the last term of the equation (this is valid since generally the term $\eta_c/\tau\alpha$ is small compared to unity).

Application of Theory to Find PV Panel Operating Characteristics

The power generated by the photovoltaic panels in Hybrid2 is determined by the average solar radiation level on the panel, $\overline{G}_T$, during the time step, the panel characteristics and the voltage of the load to which it is connected. If the panels are on the AC bus, it is assumed that a maximum power tracker is used. In this case the voltage of the AC bus is not considered. If the panels are on the DC bus, then bus voltage may be an important factor. In general, the primary determinants of PV power are 1) the solar radiation level, 2) the current-voltage relation of the individual panels, 3) the number and configuration of panels in arrays, and 4) the voltage of the DC bus. The effect of panel tilt and orientation, giving $\overline{G}_T$ from the average radiation on the horizontal, $\overline{G}$, is discussed in Chapter 7.

As noted above the individual panels are characterized by current-voltage relations. These are influenced by solar radiation level and temperature, but the range of voltages over which a given panel performs effectively is fairly limited. To increase the output voltage multiple panels are connected in series. To increase the current (and power at a given voltage) multiple panels are connected in parallel.

The power produced from a photovoltaic panel depends strongly on the voltage of the load to which it is connected, as well as to the solar radiation level and cell temperature. In particular, the terminal voltage of the panel must equal that of the load. Similarly, the current produced by the panel must equal that absorbed by the load. In general, photovoltaic panels and loads have different current voltage relations. At any given operating condition, there is normally only one operating point where both the panel and load have the same voltage and current. This occurs where the panel curve and load cross, as illustrated in Figure 6.8. The figure shows matching of the panel and a load with a linear current voltage relation. The same principle applies for a load with other shapes as well. A battery, for example, as used in Hybrid2, would start on the x axis well above zero and would rise much more sharply.

As explained above, the power from the panel is given by the product of the current times the voltage. The maximum power point, where the power is the greatest, occurs at a voltage somewhat less than the open circuit voltage. For the photovoltaic panels to be most effective when used with batteries (as in Hybrid2), the nominal battery voltage should be close to the maximum power point voltage. The DC bus voltage is determined by the state of charge of the batteries and the charge or discharge rate. The ideal way to calculate the power generated by the panel would be to use an iterative method in each time step to find the terminal voltage that would include the PV derived current in the charge rate. Battery voltage normally changes little within time steps, however, so in order to simplify the calculations Hybrid2 uses the voltage of the battery bank at the end of the previous time step.

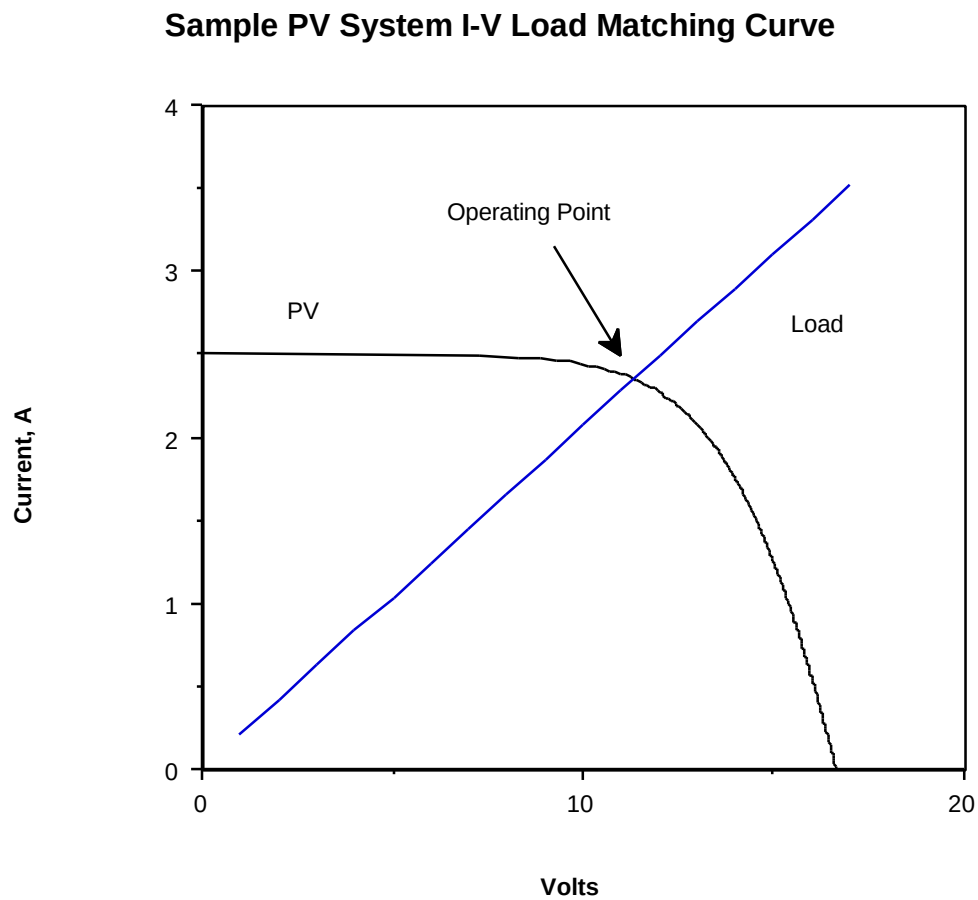


Figure 6.8. Load Matching

Based on the previous analytical theory, the following procedure is used to calculate the current-voltage relations for the PV panel at nonstandard cell temperatures.

First, a value for panel efficiency, η_C, is assumed. Next the ratio $(\tau\alpha) / U_L$ is determined from Eq. 6.6.22

$$(\tau\alpha)/U_L = (T_{c,NOCT} - T_a)/G_{T,NOCT} \tag{6.2.22}$$

The cell temperature, T_c, is then found from Eq. 6.6.23

$$T_c = T_a + \overline{G}_T(\tau\alpha)/U_L(1-\eta_c/\tau\alpha) \tag{6.2.23}$$

(In the last term of this equation, a value of 0.9 is assumed for $\tau\alpha$).

Then the solar radiation and cell temperature are used to determine the current voltage relation for an individual panel. The array current and voltage relation is found in accordance with the number of panels in series or parallel. The procedure is as follows:

Reference values for I_L, A, and I_0 are found using the equations for $I_{L,ref}$, A_{ref}, and $I_{0,ref}$:

$$I_{L,ref} = I_{sc,ref} \tag{6.2.7}$$

$$A_{ref} = \frac{T_{c,ref}\,\mu_{V,oc} - V_{oc,ref} + \varepsilon N_s}{\dfrac{\mu_{I,sc}\,T_{c,ref}}{I_{L,ref}} - 3} \tag{6.2.13}$$

$$I_{0,ref} = I_{L,ref}\, e^{-V_{oc,ref}/A_{ref}} \tag{6.2.8}$$

The series resistance, R_s, is calculated from Eq. (6.2.10)

$$R_s = R_{s,ref} = (A_{ref}\ln(1-\frac{I_{mp,ref}}{I_{L,ref}}) - V_{mp,ref} + V_{oc,ref})/I_{mp,ref} \tag{6.2.10}$$

Next, the parameters A, I_L and I_0 are calculated for the previously calculated cell temperature using their governing equations (6.2.4, 6.2.5, 6.2.6.) Then, the battery voltage at the end of the previous time step is used as the PV terminal voltage. This voltage then fixes the current, and by extension the power. Thus, for a specified voltage, Eq. (6.2.1) is used to calculate the current, I.

$$I = I_L - I_0[e^{(V+IR_s)/A} - 1] \tag{6.2.1}$$

Using η_c = I V/($A_c G_T$), a new value for collector efficiency is calculated, which is then used to repeat this series of calculations until convergence on η_c is established.

Maximum Power Point Tracking

PV cells operate at the voltage and current where their characteristics match those of the connected load (in our case, the batteries). It is sometimes useful to use power conditioning equipment to match the load with the characteristics of the PV cell. One method of carrying this out in practice is to use a maximum power point tracker to maximize the PV system output. Hybrid2 allows the use of a maximum power point tracker (MPPT) control system for the PV system panel.

As summarized by Duffie and Beckman (1991), the main idea here is that cell output can be maximized by operating near or at the maximum power point, which is achieved by the use of maximum power point trackers. These are devices that keep the impedance of the circuit of the cell at levels corresponding to best operation, and also convert the resulting power from the PV array so that its voltage is that required by the load. These authors also note that, although there are some losses associated with the tracking process, efficiencies greater than 90% are possible. A loss factor for the MPPT is available in Hybrid2. When PV panels are shown on the AC bus, it is implicitly assumed that a dedicated inverter as well as an MPPT are also associated with the array. In this case the loss factor should include the effect of the inefficiencies of both devices.

Photovoltaic Panels/Battery Integration

Hybrid2 allows 3 different modes of integrating photovoltaic panels to the system. One of them assumes direct connection via maximum power point tracker to the AC bus. The other two assume that the PV panels are used to supply the DC bus, either directly or through a maximum power point tracker (MPPT).

AC Connected Photovoltaic Panels

In the AC connected case, the PVs act to reduce the net load in a manner analogous to wind turbines. The one difference at this point is that short term fluctuations in the PV power are not considered. This should not be of concern in systems where the PV contribution is small. In systems without storage where the PV contribution is large, this would be a non-conservative assumption, and the results would have to be viewed accordingly. There would be no difference from the normal situation with respect to the battery charging, discharging, and losses.

DC Connected Photovoltaic Panels

When the PVs are connected directly to the DC bus, the situation is similar to that of the AC bus, but is also somewhat more complex. In the absence of a maximum power tracker, the power delivered depends on the voltage of the batteries, which will be higher when they are full, and lower when they are depleted. When a maximum power point tracker is used, then the voltage of the batteries is not important in determining the power produced. Once the power is calculated, however, it is used in the calculation of the net load in the usual way.

Hybrid2 simulates the function of the MPPT by adjusting the PV side voltage to assure maximum power from the panels. The output voltage is whatever is needed to charge the batteries, taking into account all the power available. Note this means, for example, when two sources are charging the batteries the overall terminal voltage will be higher, and so, too, will be the losses. An iterative search is used in finding the terminal voltage and charging losses. This search also involves calculation of the PV panel temperature. This calculation accounts for the ambient temperature as well as the effect of the solar radiation.

When no MPPT is assumed, the voltage at the panels is assumed to be the same as that of the batteries from the previous time step. When this voltage is substantially different from the maximum power voltage, the reduction in panel output can be significant. As in the case of the maximum power tracker an iterative search is used in Hybrid2 to find the current and the power delivered. Again, the effect of panel temperature is included.

6.3 Diesel Generator Performance Model

6.3.1 Executive Summary

Diesel engines are the prime movers in countless small and remote power systems throughout the world. Often diesel fuel at these locations is expensive. These diesels also often operate at low load, with poor fuel efficiency. The low-load operation may result in increased engine maintenance requirements. Thus fuel use and maintenance are primary concerns in these remote locations. The Hybrid2 diesel model uses the net imposed load on the diesel generators to calculate fuel consumption for a base case and additional system configurations. Hybrid2 assumes a linear relationship between diesel generator set load and fuel consumption. A linear relationship has been shown to be a good approximation for many diesel generator sets and is commonly used in wind/diesel system modeling (Hunter and Eliot, 1994.) Figure 6.9 illustrates fuel consumption versus power data for a typical small diesel generator set, including a linear fit to the data. Hybrid2 allows up to seven diesel generators in the system and also allows for a minimum load on the diesels at all times to reflect operation intended to decrease low load maintenance problems.

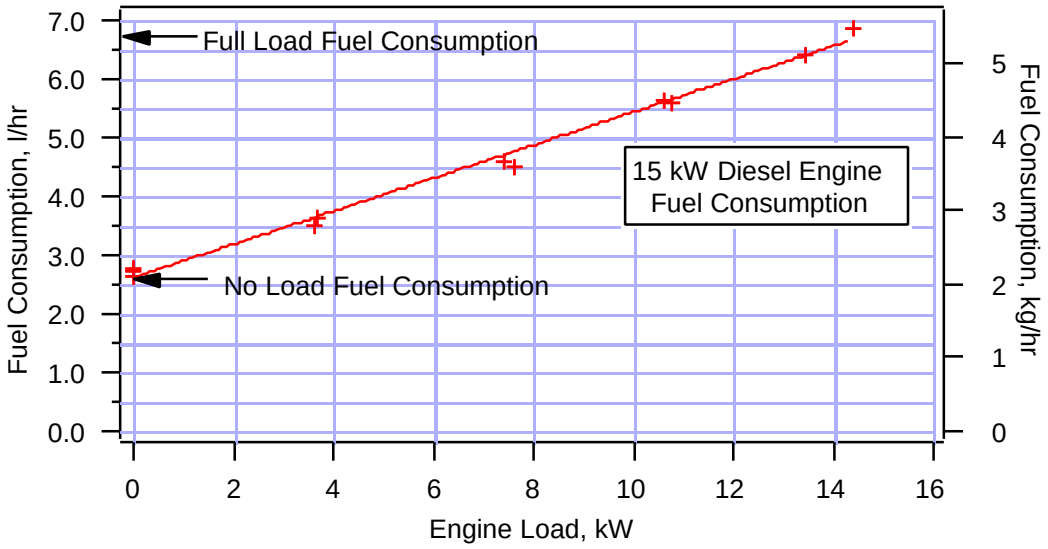


Figure 6.9. Sample Diesel Engine Fuel Consumption with Linear Fit

6.3.2 Model Overview

Major Input

Modeling Input. Inputs to the diesel model include the load range over which the diesel generator set is allowed to operate, and information on the diesel engine fuel consumption. Diesel control options are also used as inputs, but are discussed in the section of the manual dealing with control dispatch.

Simulation Input. Inputs to the diesel model during the simulation are the net load on the diesel generator set and diesel run time.

Output

The output of the diesel model includes: 1) the power generated, 2) the fuel consumption, 3) operating hours, and 4) number of starts.

Major Modifiers

There are no modifiers that affect the diesel model.

6.3.3 Detailed Parameter Description

Modeling Input

Inputs to the diesel model include:

Diesel Rated Power: The rated power of the diesel generator (kW). This is the maximum acceptable operating load on the generator of a diesel generator set. It is used to determine when additional diesel generator sets are needed.

Diesel Minimum Allowed Power: The minimum load (kW) that is to be kept on the generator of the diesel generator set at all times. This input is used to determine the load on the various generator sets and as one factor used for determining the size of the dump load.

Diesel Full Load Fuel Use: Diesel engine fuel flow when the generator is loaded at the diesel rated power. Full load fuel use is used to determine the relationship between fuel consumption and generator load.

Diesel No Load Fuel Use: Diesel engine fuel flow when no load is imposed on the generator of the diesel generator set. No load fuel use is used to determine the relationship between fuel consumption and generator load.

Minimum Diesel Run Time: Minimum diesel run time is the minimum allowed operating time, if any, of each of the diesels. In Hybrid2 the minimum run time must be the same or longer than the simulation time step.

Simulation Input

Inputs to the diesel model during the simulation are the net load on the diesel generator set, the status of the dispatch parameters, and the fraction of time that the load on the diesel is at various levels.

Output

The output of the diesel model includes: 1) the power generated, 2) the fuel consumption, 3) operating hours, and 4) number of starts.

Modifiers

There are no modifiers that affect the diesel model.

6.3.4 Model Theory

Fuel Consumption Characterization

The systems modeled may include up to seven diesel generators, all of which can be of a different type. The diesel generator(s) are all modeled by a linear fuel (F) vs. power (P) curve of the form:

$$F = a + b\,P \tag{6.3.1}$$

where

a = No load fuel consumption, fuel units/hr

b = Slope of fuel vs. power curve, fuel units/kWh

Other researchers (Skarstein and Uhlen, 1989) and University of Massachusetts experimental work has shown this to be a reasonable assumption. User inputs to determine the constants are the no-load fuel use and the full-load (rated) fuel use. Over the complete operating range of a diesel generator set the actual fuel consumption versus generator load will not be exactly linear. A user who knows that the diesel will operate over a given range most of the time may increase the accuracy of the results by basing the linear curve fit on the region of general use instead of the complete fuel curve

Minimum Run Time

Minimum allowed operating time of the diesels may also be considered in the system operation. To reduce engine wear and maintenance due the buildup of deposits in the diesel engine cylinders, it is helpful to minimize engine starts and to maintain high engine temperatures during operation. Thus, diesel engines are often operated for some minimum time period, once started, to reduce long term maintenance problems. To reflect this, the user can specify a minimum diesel run time for the diesels. Note that in multiple diesel systems the same minimum run time is used for all the diesels. The diesel model keeps track of the cumulative time that each diesel has been running. If the net load on the diesels drops, allowing one or more diesels to be shut down, but some of those diesels have not been running for the minimum required time period, then the load on the other diesels may be reduced or excess power may flow to the batteries or to the dump load.

Minimum Power Level

Continuous operation of diesel engines at low loads may lead to engine maintenance problems, especially in cold weather. This is due to poor combustion at low loads and low ambient temperatures. Thus, a minimum power level, below which the diesel generator is not allowed to operate, may be specified by the user for each diesel generator set in the system. Depending on the system configuration and minimum run times, maintaining the load on one generator set at a minimum load may affect the power delivered from other generator sets, battery storage or dump load use.

Back Drive Capability

"Back drive" operation is also allowed. Back drive of diesel generators refers to a mode of operation in which the diesels themselves serve to absorb excess power in the system. In this way, they may augment or take the place of dump loads. In this case, the no load losses of the

diesel generator are provided by the excess power. The diesel is then able to consume rather than generate power. How much power a diesel can absorb will depend on its particular characteristics, however, the engine is not allowed to operate at a power below that which would correspond to zero fuel use, as predicted by the fuel vs. power equation. The maximum backdrive power can be determined by continuing the fuel vs. power curve of the diesel back to the x intercept.

6.4 Battery Performance Model

6.4.1 Executive Summary

The battery model used in Hybrid2 is an expanded form of the Kinetic Battery Model (Manwell and McGowan, 1991, 1993b; Manwell, et al. 1995.) In this model the battery is viewed as a voltage source in series with a resistance. The internal resistance is assumed to be constant and the internal voltage varies with current and state of charge.

The model allows the simulation of a variety of types of batteries, both lead acid and nickel cadmium. It accounts for voltage level as a function of state of charge and charge or discharge rate, as well the apparent change of capacity as affected by charge or discharge rate. This model is an extension of earlier work undertaken at Sandia National Laboratory (Facinelli, 1983) and the U. S. Department of Energy's Battery Energy Storage Test Facility (Hyman, 1986a, 1986b).

The battery model used in Hybrid2 deals with five aspects of battery behavior:

- Capacity
- Voltage
- Charge Transfer
- Energy Losses
- Battery Life

6.4.2 Model Overview

Major Input

Modeling Input: A number of parameters are used to determine battery operation. Additionally, there are multiple ways in which to specify battery model constants. The modeling inputs define the battery capacity at various discharge currents, the terminal voltage characteristics during charging and discharging, and the expected battery life as a function of the number and magnitude of charge-discharge cycles experienced by the battery.

Simulation Input: The input to the battery model for the simulation includes the required power from the battery or the available power to be used for charging and the state of charge from the previous time step.

Output

The outputs of the battery model are the battery current and voltage during the time step and losses associated with charging and discharging. Another output is the cumulative damage done to the battery due to charge/discharge cycles over the complete simulation.

Major Modifiers

There are no modifiers to the battery model.

6.4.3 Detailed Parameter Description

Modeling Input

A number of parameters are used to determine battery operation. Additionally, there are multiple ways in which to specify battery model constants. The modeling inputs are:

Maximum Capacity, q_{max} (Ah): The maximum possible capacity of one battery. In discharge, it corresponds to the charge that may be obtained when a full battery is discharged at a very slow rate. This term is described in the following section, Model Theory.

Kinetic Battery Model Capacity Ratio, c. The capacity ratio, c, corresponds to the fraction of total charge in the battery that is readily available. This term is described in the following section, Model Theory.

Kinetic Battery Model Rate Constant, k. The rate constant, k, corresponds to the rate at which chemically bound charge becomes available. This term is described in the following section, Model Theory. The three capacity constants (q_{max}, c, and k) are found from manufacturer's data or test data, by application of non-linear curve fitting methods. Hybrid2 includes a means for estimating these values.

Charging Rate Limit, A/Ah remaining, normally = 1. This limit reflects common practice in which the charge rate of batteries is reduced as they become more fully charged. This practice helps to protect the batteries from damage.

Four Constants of Discharge Voltage Curve Fit: These constants define the behavior of the battery terminal voltage during discharge. The voltage constants are determined by non-linear curve fitting methods to test data. Values for typical batteries are included in the information data base which comes with the Hybrid2. A simplified method for obtaining constants for linearized curves is available in Hybrid2.

Four Constants for Voltage Curve Fit for Charging: These constants define the behavior of the battery terminal voltage during charging. The voltage constants are determined by non-linear curve fitting methods to test data. Values for typical batteries are included in the information data base which comes with the Hybrid2. A simplified method for obtaining constants for linearized curves is available in Hybrid2.

Internal Resistance: The battery internal resistance in ohms. It is assumed to be constant. The value may be obtained from the battery manufacturer or derived from battery test data (voltage vs. state of charge for a variety of rates.)

Battery Life Data: Battery life can be approached in two ways, using a nominal life or a cycles to failure method. In the first case, the only input is the nominal battery life, in years. In the second case, the user inputs values of depth of discharge and corresponding numbers of cycles to failure. A curve fitting routine in the code determines five constants that are used in conjunction with a rainflow cycle counter to estimate the battery life: Battery life can be approached in two ways, using a nominal life or a cycles to failure method. In the first case, the only input is the nominal

battery life, in years. In the second case, the user inputs values of depth of discharge and corresponding numbers of cycles to failure. A curve fitting routine in the code determines five constants that are used in conjunction with a rainflow cycle counter to estimate the battery life.

Battery Capacity versus Current Relationship: The user may input pairs of numbers to define the battery capacity as a function of discharge current. The pairs of numbers are the battery capacity for a given constant current discharge (Ah) and the constant current. These values are then used to define the battery behavior.

Simulation Input

The input to the battery model during the simulation includes the required power from the battery or the available power to be used for charging and the state of charge from the previous time step. It also considers the voltage from the previous time step.

Output

The output of the battery model is the battery current and voltage during the time step, the final battery state of charge, and the losses associated with charging and discharging. Another output is the cumulative damage done to the battery due to charge/discharge cycles.

Modifiers

There are no modifiers to the battery model.

6.4.4 Model Theory

The battery model used in Hybrid2 is an expanded form of the Kinetic Battery model (Manwell and McGowan, 1991, 1993b). As described by Manwell, et al. (1995), the version used in Hybrid2 includes much more detailed modeling of the voltage behavior than did the original version of the model. As illustrated in Figure 6.10, the battery is viewed as a voltage source in series with a resistance.

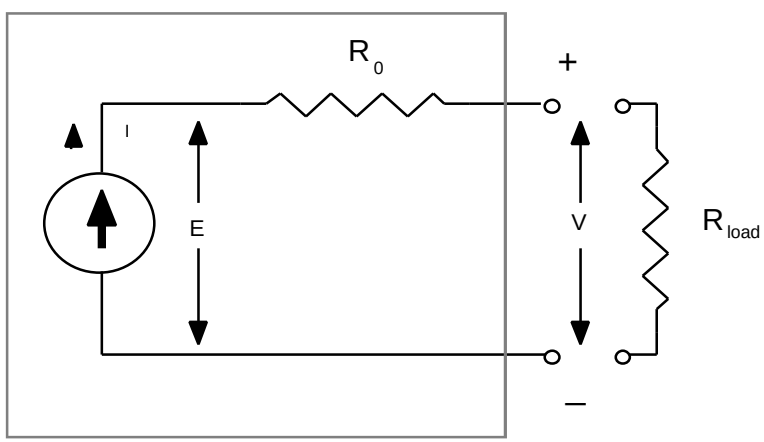


Figure 6.10. Battery Model

The internal resistance, R_0, is assumed to be constant and the internal voltage, E, varies with current state of charge. The terminal voltage, V, is given by

$$V = E - I R_0 \tag{6.4.1}$$

As described below, the battery model used in Hybrid2 has five major parts:

- Capacity Model
- Voltage Model
- Charge Transfer Model
- Battery Energy Losses Model
- Battery Life Model

A sixth aspect of battery behavior, temperature dependence of capacity, is not modeled explicitly in Hybrid2. Temperature effects are discussed at the end of this section, however.

Capacity Model

Battery capacity in both charging and discharging is known to decrease with increasing charge and discharge rates. This behavior can be modeled by assuming that some of the charge is "available," that is immediately accessible, and some of it is "bound." The bound charge can be released, at a rate proportional to a rate constant, k. The Kinetic Battery Model, embodies those assumptions. The total charge, q, in the battery at any time is the sum of the available charge, q_1, and bound charge, q_2. That is:

$$q = q_1 + q_2 \tag{6.4.2}$$

The flows of available and bound charge during a constant current discharge or charge are given by:

$$\frac{dq_1}{dt} = -I - k(1-c)q_1 + k\,c\,q_2 \tag{6.4.3}$$

$$\frac{dq_2}{dt} = +k(1-c)q_1 - k\,c\,q_2 \qquad 6.4.4)$$

When Equations 6.4.3 and 6.4.4 are solved, the capacity of a battery as a function of constant current, $q_{max}(I)$, can be modeled by the following relation:

$$q_{max}(I) = \frac{q_{max}\,k\,c\,T}{1 - e^{-k\,T} + c\left(k\,T - 1 + e^{-k\,T}\right)} \tag{6.4.5}$$

where

I	= Charge or discharge current, A
T	= Charge or discharge time, defined by $T = q_{max}(I)/I$, hrs
q_{max}	= Maximum capacity (at infinitesimal current), Ah
k	= Rate constant, hrs^{-1}

c = Ratio of available charge capacity to total capacity, -

The three constants, q_{max}, k and c are found by Hybrid2 from the manufacturer's or test data. In doing so, a Marquardt non-linear least squares fitting method (Press, et al., 1992) is employed. The inputs are battery capacity and current at least three different rates. Data is usually available only from discharging, and that is the type of data used by Hybrid2. The constants are assumed to be the same in both the charging or discharging modes.

The equation for maximum capacity as a function of current, Eq. 6.4.5, was derived assuming constant current over the entire discharge time, T, which is typically many hours. Hybrid2 uses time steps that are normally much shorter than T, so a quasi steady approach is taken in the use of the model. In particular, the current is assumed to be constant over the time step. With the constant current assumption, the available and bound charge at the end of any time step are given by:

$$q_1 = q_{1,0}e^{-k\Delta t} + \frac{(q_0\, k\, c - I)(1 - e^{-k\Delta t})}{k} - \frac{I\, c(k\,\Delta t - 1 + e^{-k\Delta t})}{k} \tag{6.4.6}$$

$$q_2 = q_{2,0}e^{-k\Delta t} + q_0(1-c)(1-e^{-k\Delta t}) - \frac{I(1-c)(k\,\Delta t - 1 + e^{-k\Delta t})}{k} \tag{6.4.7}$$

where

$q_{1,0}$ = Available charge at the beginning of the time step, Ah

$q_{2,0}$ = Bound charge at the beginning of the time step, Ah

Δt = Length of time step, hrs

q_0 = Total charge ($q_0 = q_{1,0} + q_{2,0}$) at the beginning of the time step, Ah

Voltage Model

The voltage model employed in Hybrid2 uses a fitting procedure conceptually similar to one developed by researchers at the Department of Energy's Battery Energy Storage Test (BEST) Facility (Hyman 1986a, 1986b). The model reflects the observations that terminal voltage depends on: 1) the state of the battery (charging or discharging, 2) the state of charge of the battery, 3) the internal resistance of the battery and 4) the magnitude of the charging or discharging current. Behavior of typical discharge data is illustrated in Figure 6.11.

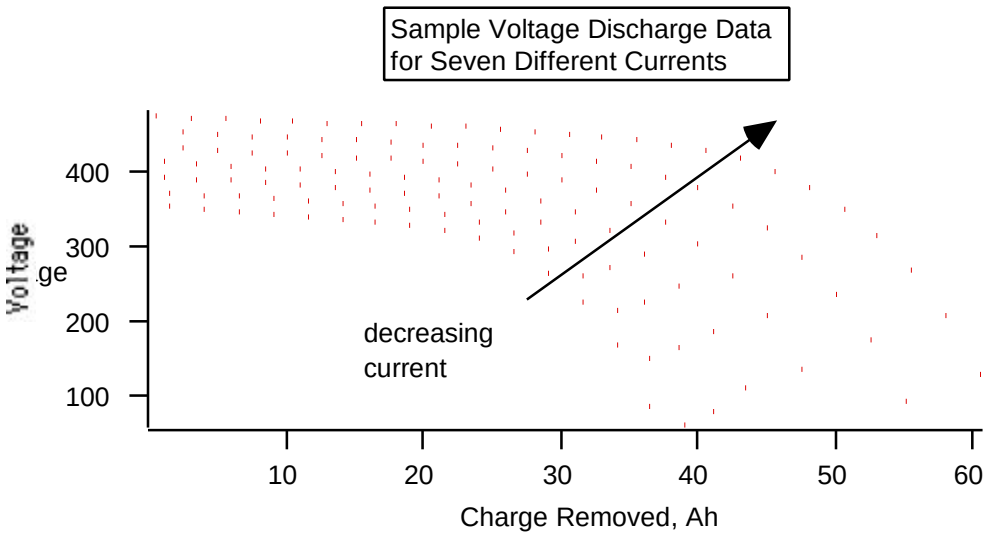


Figure 6.11. Sample Battery Discharge Voltage vs. Charge Removed.

As noted above the voltage model assumes that the internal resistance of the battery is constant, but that there is an internal voltage which depends on state of charge, and current.

The terminal voltage, V, was given previously in Eq. 6.4.1:

$$V = E - I R_0 \tag{6.4.1}$$

where

E = Effective internal voltage source, V

R_0 = Internal resistance, Ω

The internal voltage is modeled by the following:

$$\boxed{E = E_0 + A X + C X / (D - X)} \tag{6.4.8}$$

where

E_0 = Fully charged/discharged internal battery voltage (after the initial transient)

A = Parameter reflecting the initial linear variation of internal battery voltage with state of charge. "A" will typically be a negative number in discharging and positive in charging, but it need not be so.

C = Parameter reflecting the decrease/increase of battery voltage when battery is progressively discharged/charged. C will always be negative in discharging, positive in charging.

D = Parameter reflecting the decrease/increase of battery voltage when the battery is progressively discharged/charged. D is positive and is normally approximately equal to the maximum capacity. However, the nature of the fitting process will usually be such that it will not be exactly equal to that value.

X = Normalized maximum capacity at the given current.

The normalized maximum capacity, X, in charging is defined in terms of the charge in the battery by:

$$X = q / q_{max}(I) \tag{6.4.9}$$

In discharging, X is defined in terms of the charge removed by:

$$X = (q_{max} - q) / q_{max}(I) \tag{6.4.10}$$

It should be noted that the calculations needed to derive the full set of voltage constants are not available in Hybrid2 at this time. They may be calculated by a separate program, maintained at NREL and the University of Massachusetts. This program is kept separate due to the practical difficulties that are associated with the reduction of real test data. This separate program has been used to derive voltage constants for some of the batteries in the data base included with the Hybrid2 code. The method of obtaining the voltage constants is described in Manwell et al. (1995.) A simpler, linear fit, using the first two constants is available in the present version of Hybrid2.

Charge Transfer Model

The charge transferred to or from the batteries during any time step depends on the power available or required, the state of charge of the battery and the nominal battery voltage. For example, if power is required, P_{need} is calculated previously in the code. It should be noted that this required power calculation will also depend on the battery discharge dispatch strategy, which is discussed in Chapter 7. The desired discharge current, I_d, is found from:

$$I_d = P_{need} / V \tag{6.4.11}$$

In order to ascertain if the battery has enough charge to supply the desired current, the maximum possible discharge current is calculated using Eq. 6.4.6 This is done by assuming that at the end of the time step $q_1 = 0$. This yields the relation:

$$I_{d,max} = \frac{k\, q_{1,0} e^{-k\,\Delta t} + q_0 k\, c\,(1 - e^{-k\,\Delta t})}{1 - e^{-k\,\Delta t} + c\,(k\,\Delta t - 1 + e^{-k\,\Delta t})} \tag{6.4.12}$$

The maximum charge that can be obtained during the time step is then $I_{d,max}\,\Delta t$. If the required charge is greater than this maximum, then the current supplied from the batteries is $I_{d,max}$. The rest must be made up by other sources, such as a diesel generator. If the required charge is less than the maximum available, then I_d is the value found from Eq. 6.4.11. There is also no deficit in this case. The amount of charge left at the end of the interval in both forms, q_1 and q_2, is found from Equations 6.4.6 and 6.4.7**,** using I_d.

Similar to discharging, if there is excess power, P_{excess}, the desired charging current is:

$$I_c = P_{excess} / V \tag{6.4.13}$$

Note that in charging I_c will be a negative number. The maximum allowable charge rate, $I_{c,max}$, is found based on how much energy may be put into the batteries. It is found from the Eq. 6.4.6 with $q_1 = c\, q_{max}$. In this case the maximum allowed charging current, $I_{c,max}$, is:

$$I_{c,max} = \frac{-k\, c\, q_{max} + k\, q_{10} e^{-k\,\Delta t} + q_0 k\, c\,(1 - e^{-k\,\Delta t})}{1 - e^{-k\,\Delta t} + c\,(k\,\Delta t - 1 + e^{-k\,\Delta t})} \quad . \tag{6.4.14}$$

If $|I_c|$ is less than $|I_{c,max}|$, then I_c is found from Eq. 6.4.13, as above. Otherwise, $I_c = I_{c,max}$. The final values of q_1 and q_2 are determined from their Equations 6.4.6 and 6.4.7 as they are in the discharge case.

Battery Losses Model

Losses associated with charging and discharging of the batteries are accounted for in the difference between charging and discharging voltage. The model assumes that charge is conserved. Losses are considered in two modes: charging and discharging. In either case the terminal voltage is referenced to the nominal voltage to determine the loss. The total losses are the sum of charging and discharging losses.

The terminal voltage is calculated from Equations 6.4.1 and 6.4.8 in accordance with the average current into or out of the battery and the charge in the battery at the end of the time step. In doing so, the current is used, in an iterative process, to find the terminal voltage that would be required to do the charging or discharging, given the battery state of charge at the beginning of the time step. This means that, when the battery is nearly empty and the current is low, the terminal voltage will be close to the "empty battery" internal voltage, $E_{c,0}$.(charging) or $E_{d,0}$ (discharging.) The power loss will be slightly more than current times the difference between the internal voltage and the nominal voltage.

In the case of charging as the battery becomes more nearly full and/or the charging current is higher, the voltage differential will be higher and the loss correspondingly greater. In these cases the terminal charging voltage will be a function of state of charge and current, as discussed previously. The charging loss, L_{chg} ,will be

$$L_{chg} = I\left[V_{nom} - V(q,I)\right] \tag{6.4.15}$$

where

V(q,I) = Battery voltage as function of state of charge and current (as given by Equations 6.4.1 and 6.4.8.)

Note that negative value of the current is accounted for in the voltage difference in Eq. 6.4.15. In general, losses are always positive (i.e. of the same sign as a load).

When there is less capacity available than the charge that could be supplied, the current is reduced. This also results (via an iterative search) in a decreased loss. Whatever power is left over is sent to a secondary load or is dumped.

Discharging losses, L_{dis}, are calculated in a similar manner. In this case, the discharging loss equation is analogous to that for charging

$$L_{dis} = I\left[V_{nom} - V(q,I)\right] \tag{6.4.16}$$

In both charging and discharging, battery dispatch set points may override battery use during the time step. In general, how the batteries are actually used will depend on the dispatch strategy. This is described in more detail in Chapter 7.

Battery Life

Battery life is modeled either 1) by assuming a nominal lifetime, or 2) an adaptation of Miner's Rule. The latter involves a combination of the use of conventional battery lifetime information (expressed via a relationship between cycles to battery failure and fractional depth or range of discharge) and the use of a cycle counting technique that determines the cycles that occur in battery state of charge. A cycle is defined to have been completed when the battery depth of discharge has returned to a starting point before discharge and recharge began. This combination was developed from methods used in the estimation of material fatigue damage.

The Miner's Rule method of evaluating battery aging was first introduced by Facinelli (1983). Facinelli observed that cycling damage to a battery is primarily a function of the depth of discharge (and corresponding recharge) to which the battery is subjected. In addition the magnitude of the cycle was found to be more important than the average depth of discharge during the cycle. Thus the effect, for example, of going from 10% to 30% discharge and back was seen to be approximately the same as from going from 50% to 70% and back.

Facinelli's Miner's Rule method was originally developed for discrete, non-overlapping cycles, that might typically be found in photovoltaic based battery charging system. These would be subject to approximately one cycle per day. When batteries are subjected to more irregular cycling, Facinelli's Miner's Rule approach cannot be applied directly. Such irregular cycling has been found to occur in modeling of wind/diesel systems (Rogers, 1989). For example, a relatively long, deep cycle might be interrupted by shorter, shallower cycles. To deal with such irregular, overlapping cycles a cycle counting method has been employed in Hybrid2. The cycle counting method used is known as "rainflow" counting. It is typically used in metal fatigue estimates. A general description of rainflow counting is given in the work of Collins (1981) and an example of its application is summarized in the work of Thresher, et al (1992.) It should be noted, however, that although the method is conceptually reasonable and mathematically consists of separating cycles, there is no experimental verification that the method does accurately reflect the damage actually done to batteries subject to irregular discharge/charge cycles.

The damage to batteries due to cycling is modeled in Hybrid2 as follows. As noted above, it is assumed that battery life is primarily a function of depth of charge/discharge cycles. Battery lifetime prediction is then based on empirical curves that relate number of cycles to battery failure as a function of the magnitude of the cycles. This relationship is approximated in Hybrid2 by a double exponential curve fit:

$$C_F = a_1 + a_2\ e^{a_3 R} + a_4\ e^{a_5 R} \tag{6.4.17}$$

where

C_F = Cycles to failure

a_i's = Fitting constants

R = Range of cycle (fractional depth of discharge).

The fitting method employed in Hybrid2 to obtain the constants is a Marquardt non-linear least squares procedure (Press et al., 1992.) An example fit for a typical battery is shown in Figure 6.12.

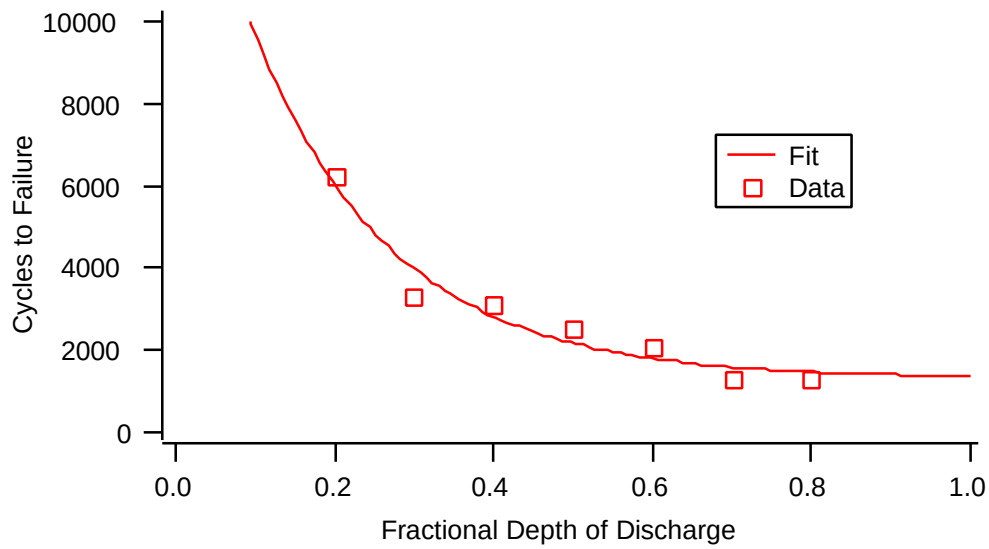


Figure 6.12. Battery Cycle Life vs. Depth of Discharge

The fraction of life used up during a given cycle is $1/C_F$. After sufficient cycles have passed that the fractions multiplied by the number of cycles sum to 1.0, the battery is assumed to be spent and a new one must be substituted. This is the analog to Miner's Rule. For example, consider a one-year simulation. Suppose that there are N_i cycles to 20 fractional depths of discharge ranging from 0.05 to 1.0 (i.e. 5% to 100%) and that to each of those discharge depths there corresponds a number of cycles to failure, $C_{F,i}$. At the end of the simulation the total fractional damage, D, would be given by

$$D = \sum_{i=1}^{20} N_i \frac{1}{C_{F,i}} \tag{6.4.18}$$

If, for example, D = 0.5 at the end of the year, then half of the life would be used up, so the batteries would need to be replaced every two years.

The rainflow counting technique is used to calculate individual cycles (and range of cycles) as the overall simulation proceeds. The key assumption here is that if battery storage level variations can be resolved into individual cycles over a given range, this information can be used with the cycles to failure model to estimate battery wear in a cumulative fashion.

The rainflow technique that is used in the battery wear model of Hybrid2 is based on the work of Downing and Socie (1982) and uses an algorithm presented by Keller (1987). The first part of this algorithm looks for extremes in battery charge level at each time step and when one is found, the next part of the algorithm checks for completed charge/discharge cycles and determines their magnitude. As each cycle is completed a procedure using on the battery life vs. depth of discharge fit is used to update the cumulative wear on the battery.

Battery Use and the Probabilistic Method

In situations where there is only a requirement for or an excess of power within the time step, charging and discharging are dealt with as described above. In some situations, there may be both a requirement for and an excess of power during the same time step. In these cases, the total average requirement and total average excess are found separately applying the probabilistic methods discussed elsewhere in this report. The battery is assumed to first supply the requirement, if possible. The excess power is then used to charge the battery. Battery cycle counting is based on the final charge in the battery at the end of time step. There is no counting of battery cycles within the time step. Note that this method will tend to somewhat underestimate battery cycles. The effect will be most significant when using the Transient Peak Strategy (see Chapter 7) with a small battery bank.

Temperature Effects

Temperature is known to affect battery performance. In particular, battery capacity is lower at colder temperatures. The Kinetic Battery Model does not presently consider temperature effects. For many wind/diesel systems, which were the original impetus for HYBRID1 (Hybrid2's immediate predecessor), the batteries are in a conditioned building where the temperature is not expected to change drastically. Failure to reflect temperature effects should not be a serious limitation in these cases. Where temperature is important, constants corresponding to the expected mean temperature should ideally be obtained.

Extreme temperatures can also affect battery life adversely. Hybrid2 does not consider these effects, so the user must take that into account and obtain the most suitable data from the manufacturer.

6.5 Dump Performance Model

6.5.1 Executive Summary

A dump load is a device used to dissipate power in a hybrid power system. A dump load may be used in one of two ways. In an AC system where there is no other form of frequency regulation, it may be used to control the grid frequency. This could occur, for example, in a diesel system in which all the diesels are shut off. The second application for a dump load is when there would be more power produced on the grid than could be used or stored. This could occur, for example, in a situation where there is a low load, but a large amount of renewable generation and the storage is full. It is this second application for a dump load that is modeled explicitly in Hybrid2. As noted in Section 5.3.3, power dissipation on the DC bus is assumed to be accomplished by intrinsic power regulation of generators on that bus.

6.5.2 Model Overview

Major Input

The major inputs to the dump load model are the power rating of the dump load and the excess power which must be dumped during each time step.

Output

There are two outputs from the dump load model: the power actually consumed by the dump load and any power that is in excess of the dump load rating.

Major Modifiers

There are no modifiers that affect the dump load.

6.5.3 Detailed Parameter Description

Modeling Input

The only input to the dump load model is the power rating of the dump load.

Simulation Input

The only input to the dump load model during the simulation is the excess power which must be dumped after all loads, primary, deferrable and optional, have been met.

Output

Outputs from the dump load model include:

Dumped Power (kW): the power actually consumed by the dump load.

Power in Excess of Dump Load Capacity: This is the amount of power in excess of the dump load capacity that has been diverted to the dump load. A cumulative record of the excess is kept for the user to indicate the need for a larger dump load in the system. In a real system the excess would damage the dump load. Recall, however, that in some systems the dump load may not actually be a real device. Dissipation of the power by other means, such as furling of certain wind turbines, may serve the same function.

As noted previously, Hybrid2 assumes that a dump load device will only be used on the AC bus. Any dumped power on the DC bus is assumed to be dissipated by intrinsic regulation of the wind turbine or photovoltaic generators on that bus.

Modifiers

There are no modifiers that affect the dump load.

6.5.4 Model Theory

A dump load is a device used to dissipate power in a hybrid power system. A dump load may be used in one of two ways. In an AC system where there is no other form of frequency regulation, it may be used to control the grid frequency. This could occur, for example, in a diesel system in which all the diesels are shut off. The second application for a dump load is when more power is produced on the grid than could be used or stored. This could occur, for example, in a situation where there is a low load, but a large amount of renewable generation and the storage is full. It is the second application for a dump load that is modeled explicitly in Hybrid2.

In so far as the dump load may be an actual electrical device, it is modeled as a separate component. The key parameter of the device is its rated power. This allows Hybrid2 to assist in the sizing of the device. If there is power to be dissipated in excess of the dump load capacity, it is reported in a separate category.

Power in excess of the dump load capacity is calculated using the mean excess power and the standard deviation of the net load using the probabilistic methods described elsewhere in this report.

In some systems, a real dump load is not actually needed because the generation device is capable of self-regulation. This situation is accounted for in the voltage-current relation of photovoltaic panels on the DC bus. It is not accounted for on other components (such as wind turbines) in the present version of Hybrid2. Such situations can be dealt with by assuming a dump load of zero capacity, and realizing that the power in excess of the dump load will simply be dissipated by the device itself. This would occur with a wind turbine which furls automatically or has active pitch control.

In systems with two buses, it is assumed that there is only one dump load. This dump load can dissipate power from either bus. The total power from the two buses, however, cannot exceed the dump load capacity. The dumped power from the AC and DC busses is reported separately in the detailed output file.

6.6 Converter Performance Model

6.6.1 Executive Summary

In general, power converters may either be uni-directional, converting AC power to DC power, or DC power to AC power, or they may be bi-directional, capable of converting power in both directions. They may also be either electronic or electromechanical devices, and may or may not be capable of operating in parallel with diesel generators. Hybrid2 models 4 types of power converters for transferring power between the AC and DC buses: rectifiers, inverters, bi-directional power electronic converters, and rotary converters.

Rectifiers, inverters, and bi-directional power electronic converters are all electronic devices. Conventional rectifiers and inverters can only transfer power in one direction. Inverters convert DC power (from a battery, for example) to AC power. Rectifiers convert AC power to DC power (for charging a battery, for example). Power converters that can send power in both directions are known in Hybrid2 as "bi-directional" converters. The use of a bi-directional converter obviates the need for a separate rectifier and inverter.

A rotary converter is a electromechanical device for converting AC to DC and vice versa. A rotary converter consists of a synchronous (AC) electrical machine connected directly to a DC electrical machine by a shaft. The AC machine can act as a generator or a motor. As a generator, it supplies power to the AC bus, as would a conventional diesel generator. As a motor, it absorbs power from the AC bus, and drives the DC machine via the intervening shaft. The DC machine, too, may act as either a generator or a motor. As a generator, it supplies power to the DC bus. That power may feed DC loads or it may be used to charge batteries. As a motor, the DC machine is fed either from renewable DC sources or from the batteries. Due to its ability to convert power in either direction, a rotary converter is a bi-directional device. There are losses associated with all power converters, but typically losses from electronic converters are significantly less than those of electromechanical devices. One way to minimize the effect of

electromechanical losses is through the use of a coupled diesel. This is described in the subsequent section. The main advantage of rotary converters is that they are well-developed pieces of equipment and they are normally quite rugged. The main disadvantage is that they are heavier and less efficient than solid state power converters.

In Hybrid2, power may go through only one device at a time although it is possible that both a rectifier and an inverter are used in the same simulation time step.

Some converters can act in parallel with the diesel generator. Others cannot. In Hybrid2, those inverters that cannot operate together with the diesels are referred to as "switched mode" inverters. When such inverters are used, the AC load cannot be supplied by AC diesels operating at the same time as the inverter. The term "switched mode" does not apply to rectifiers. In contrast, "parallel" operation of a converter allows the use of diesel and an inverter, at the same time, to meet the load on the AC bus.

6.6.2 Power Converter Model Overview

Major Inputs

Inputs to the power converter model depend on the power converters included in the system under consideration. The major inputs are the no load loss and full load power for each direction of possible power flow, full load efficiency, and an indication if the device is capable of parallel operation or not.

Major Outputs

The outputs from the power converter model are the output (or input) power and converter losses.

Major Modifiers

There are no modifiers that affect the power converter model.

6.6.3 Detailed Parameter Description

Modeling Input

Inputs to the power converter model include the following:

Converter Switched Mode Capability: This specifies whether the inverter can only be operated in switched mode (not in parallel with a diesel) or can be operated in parallel mode (in parallel with another power producing device). An inverter must have synchronizing capability for both independent and parallel operation to be possible.

Rated Converter Power: Rated power (kW) for the converter. It is assumed that a bi-directional electronic converter has the same rating when operating as an inverter and when operating as a rectifier. In this case, the rating applies to the output when operating as an inverter and input as a rectifier. To specify the rated power for a rotary converter, the rated power of both the AC and the DC machines are specified separately.

No load converter loss: Power losses (kW) at no load through the converter. For bi-directional electronic converters, the no-load losses in each direction are specified separately. For rotary converters the no-load losses of both the AC and the DC machines are specified separately.

Full load converter efficiency: Converter efficiency at full load (dimensionless). For bi-directional electronic converters, the full load efficiencies in each direction are specified separately. For rotary converters, the full load efficiencies of both the AC and the DC machines are specified separately.

Simulation Input

The input relevant to the simulation is the switched mode capability of the power converter and the power to be transferred during the time interval. The switched mode capability determines the modes of operation used in the simulation, the resultant transfer of power through the converter, and all the effects resulting from this such as dump power, useful system energy production, etc.

Output

The outputs from the power converter model are the output (or input) power and converter losses.

Modifiers

There are no modifiers that affect the power converter model.

6.6.4 Model Theory

The losses in power converters, as a function of power in or out, are typically approximated by linear relations. In particular, such devices typically have constant (or no load loss) and a loss which is proportional to the power converted (see, for example, Norgaard, 1994). That is the method used in Hybrid2. When referring to the output of a device the power out is given by

$$P_{out} = (P_{in} - P_{NL}) / B_{out} \tag{6.6.1}$$

where

P_{out} = Output power, kW

P_{in} = Input power, kW

P_{NL} = No load power, kW

B_{out} = Constant relating input power to output power, -

η_R = Rated efficiency, -

P_R = Rated output power, kW.

The constant relating input power to output power, B_{out}, is found from:

$$B_{out} = (P_R / \eta_R - P_{NL}) / P_R \tag{6.6.2}$$

When referring to the input of a device the power in is given by

$$P_{in} = P_{out} B_{in} + P_{NL} \tag{6.6.3}$$

where

B_{in} = Constant relating output power to input power, -

P_R = Rated input power, kW

η_R = Rated efficiency, -.

The constant relating output power to input power, B_{in}, is found from:

$$B_{in} = (P_R - P_{NL}) / (P_R \ \eta_R) \tag{6.6.4}$$

Note that in either case, the user inputs are similar: full load power, no load power, and rated efficiency.

In the case of individual inverters or rectifiers, in Hybrid2 neither device need have any of the same characteristics. Thus, the full load power, no load power, and rated efficiency can all be different.

If a bi-directional converter is used, it is assumed that the converter has the same power rating, whether acting in the rectifier or inverter mode. The method of accomplishing the conversion may be different, so the use of different no load power and rated efficiency is allowed.

If a rotary converter is used, it may be that the two electrical machines have different power ratings. In addition, they may have different efficiencies. Thus, Hybrid2 allows use of different rated powers, no load fuel consumption and rated efficiencies for the two machines. When power is transferred from the AC to the DC bus or vice versa, the two electrical machines operate in series. The overall no load loss is thus the sum of the no load losses from both of the machines. The variable loss terms, associated with part or full load operation also apply in series. Corresponding efficiency terms are multiplied to account for this effect. In characterizing the inputs to the rotary converter, it is assumed that each electrical machine is evaluated in the motoring mode.

6.7 Coupled Diesel Model

6.7.1 Executive Summary

Some hybrid power systems are designed around a component that is referred to in Hybrid2 as a "coupled diesel." This is actually two major components (a diesel engine and a rotary converter) connected together with a clutch (see Figure 6.13). Together they supply power to loads on both AC and DC buses via a "shaft bus." The purpose of the coupled diesel is to provide an integrated diesel generator package in an efficient and compact form. The rotary converter is intended to provide reliability, relative to power electronic converters. The method of connection eliminates the need for a separate generator permanently connected to the diesel. The losses associated with that generator are also eliminated. When the operation of the diesel is not required, it can be separated, via the clutch, and shut off. The rotary converter then acts independently as described in the section on power converters.

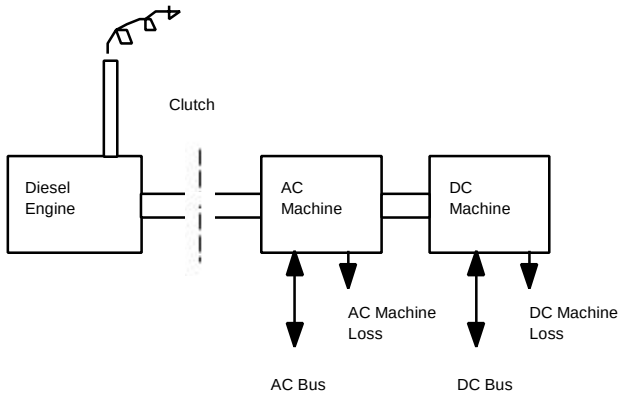


Figure 6.13. Coupled Diesel and Shaft Bus Schematic

6.7.2 Model Overview

Major Input

Modeling Input. The major inputs to the coupled diesel model are the diesel engine characteristics and the rotary converter characteristics. Inputs include the load range over which the diesel is allowed to operate, and information on the diesel engine fuel consumption. Diesel control options are also used as inputs, but are discussed in the section of the manual dealing with control dispatch. Major inputs also include the no load loss and full load power of the rotary converter and full load converter efficiency.

Simulation Input. Inputs to the coupled diesel model during the simulation are the net load on the diesel, the diesel run time and the power to be transferred during the time interval.

Output

The output of the coupled diesel model includes the power generated by the diesel, fuel consumption, operating hours, number of starts of the diesel and the output power, and the losses associated with the use of the electrical machines in the rotary converter.

Major Modifiers

There are no modifiers that affect the shaft bus model.

6.7.3 Detailed Parameter Description

Modeling Input

The inputs to the coupled diesel model are analogous to those specified for diesel engines and for rotary converters, with the exception that, in the case of the load on the coupled diesel, no load and full load operation refers to the load on the shaft of the diesel.

Thus, inputs include:

Diesel Rated Power: The rated power of the diesel (kW). This is the maximum acceptable operating load on the diesel engine. It is used to determine when additional diesel generator sets are needed.

Diesel Minimum Allowed Power: The minimum load (kW) that is to be kept on the diesel at all times. This input is used to determine the load on the various generator sets and as one criterion to determine use of the dump load.

Diesel Full Load Fuel Use: Diesel engine fuel flow when the engine is loaded at the diesel rated power. Full load fuel use is used to determine the relationship between fuel consumption and generator load.

Diesel No Load Fuel Use: Diesel engine fuel flow when no load is imposed on the engine of the diesel generator set. No load fuel use is used to determine the relationship between fuel consumption and engine load.

Minimum Diesel Run Time: Minimum diesel run time is the minimum allowed operating time of the coupled diesel.

AC Machine Rated Power: Rated power (kW) of the AC electrical machine in the rotary converter.

AC Machine No Load Loss: Power losses (kW) of the AC electrical machine in the rotary converter.

AC Machine Full Load Efficiency: Efficiency at full load of the AC electrical machine in the rotary converter (dimensionless).

DC Machine Rated Power: Rated power (kW) of the DC electrical machine in the rotary converter.

DC Machine No Load Loss: Power losses (kW) of the DC electrical machine in the rotary converter.

DC Machine Full Load Efficiency: Efficiency at full load of the DC electrical machine in the rotary converter (dimensionless).

Simulation Input

Simulation inputs to the coupled diesel model during the simulation are the net load on the diesel, the diesel run time, and the power to be transferred during the time interval.

Output

The output of the coupled diesel model includes the power generated by the diesel, fuel consumption, operating hours, and number of starts of the diesel and the output power and the losses associated with the use of the electrical machines in the rotary converter.

Modifiers

There are no modifiers that affect the shaft bus model.

6.7.4 Model Theory

The complete coupled diesel consists of a single diesel engine, connected via a clutch to a rotary converter (see Figure 6.13). This rotary converter consists of a synchronous (AC) electrical machine connected directly to a DC electrical machine. Either machine can act as a generator or a motor. As a generator, it supplies power to the AC bus, like a conventional diesel generator. As a motor, it absorbs power from the AC bus, and drives the DC machine via the intervening shaft. The DC machine, when acting as a generator, supplies power to the DC bus. That power may feed DC loads or it may be used to charge batteries. As a motor, the DC machine is fed either from renewable DC sources or from the batteries.

During operation, the rotary converter is always turning while the diesel may or may not be connected. When diesel power is required, the diesel will be connected via a clutch but when the loads can be supplied without the need for the diesel, it is disconnected.

When the diesel is connected, the diesel governor will control the speed of rotation of the converter and thus will set the grid frequency. When the diesel is disconnected, a separate controller needs to control the rotational speed of the converter by adjusting the voltage regulator on the DC machine.

There are a number of paths for power flow in the coupled diesel system. Some of the power flow is mechanical; some is electrical. In Figure 6.13 mechanical power is indicated by shafts (double lines). Single lines with arrowheads indicate electrical power flows. When the diesel is connected, mechanical power will flow through the clutch to the AC machine. Electrical power will flow either into or out of the AC machine, depending on the net load on the AC bus. Similarly, electrical power will flow either into or out of the DC machine. Mechanical power may flow either way along the shaft connecting the two electrical machines. Again, the direction will depend on where power is being produced or consumed.

Within any given time step, the relative magnitude and direction of power flows may change. This is modeled using a probabilistic approach similar to that used elsewhere in the program. There are some unique features, however, so the overall flow will be discussed below.

The effect of using a coupled diesel is seen primarily in the losses. In order to calculate the losses, the flows of power through the various components must be modeled realistically. The approach used in assessing the losses is as follows. Diesel losses are assumed to be accounted for in the fuel vs. power curve. They are not otherwise considered explicitly. It is further assumed that there are no losses in the clutch or shafts connecting the diesel and the electrical machines.

The electrical machines are both assumed to have a no-load loss and a full-load efficiency. The no-load loss (due primarily to friction and windage) in the electrical machines are independent of

the amount of power converted by the machine. Any additional losses are proportional to the electrical power that is actually converted. Note that, for the analysis to be reasonable, in all cases it must be true that

$$(1-\eta_R)P_R > L_{nl} \tag{6.7.1}$$

where

η_R = Rated full load efficiency, -

P_R = Rated power, kW

L_{nl} = No load loss, kW.

Since the two electrical machines are directly coupled, and always rotating, there will be a constant loss imposed on the system. This loss will be equal to the sum of the two no-load losses. There will also be an incremental loss from each machine. Using the assumption of a linear relation between incremental power and losses, the code estimates the losses from the mean power transferred through the machines over each time step.

The overall method works as follows. First of all, the fixed loss from the two electrical machines is added to the primary load at the beginning of each time step. (Note that it is still characterized as a loss in the program output, and not as part of the primary load) The incremental loss factor is also determined. If there is excess power on either the AC or the DC bus, it may be transferred or stored as discussed in Chapter 2. Losses associated with the transfer are also calculated.

After any excess power is sent to storage, the remaining net loads on the two buses are dealt with. This is done by first referring the net loads to the shaft. The entire AC net load, up to the rating of the machine, is found. This is referred to the shaft bus and the accompanying losses are found. The analogous operation is performed on the remaining DC net load. The code then seeks to supply the combined shaft net load in a way similar to what it would do if the net load were on either the AC or DC bus. The situation is more complex, however, because the required power could come from either the diesel or storage, or perhaps both. The overall losses would be different depending on where the power came from. For example, consider a system with a rotary converter in which both electrical machines have zero no load loss and 50% incremental efficiency. Suppose there is a 10 kW AC load, and the storage is empty. The diesel would have to put out 20 kW to meet the load, 10 kW to the load and 10 kW of losses in the AC machine. Suppose on the other hand that there is plenty of energy in the storage, and that the storage is to be used. In this case the storage would have to supply 40 kW. Twenty kW would be lost in the DC machine, and another 10 kW would be lost in the AC machine. Now suppose the load is on the DC bus. If this were supplied by the diesel, the diesel power and losses would be the same as in the AC case. If the load were supplied by storage, then there would be no converter losses. In dealing with these various situations, Hybrid2 follows the same logic as used for meeting loads on the AC or DC buses, but adjusts the losses in accordance with the source of the power. Once the loads have been supplied, the code deals with excess power in a manner similar to that when the diesels are either on the AC or DC bus.

7. Subsystem Algorithms

A subsystem is a collection of related components. Examples include multiple wind turbines in a cluster or wind farm, a photovoltaic array consisting of multiple panels and associated equipment, and a bank of batteries. The system controller, which in practice includes a number of components, is also considered to be a subsystem. Chapter 7 details the theory behind the modeling of the various subsystems in a hybrid power system.

7.1 Multiple Wind Turbines and Power Smoothing

7.1.1 Executive Summary

When there are multiple wind turbines in the system, the total wind power generated will depend on the individual power curve of each type of turbine and the number of turbines of each type. The variability of the total power will depend on the variability of power from each turbine, their relative spacing, and characteristics of the site.

Wind speed varies not only with time, but also spatially. Thus, multiple wind turbines in close proximity may not experience exactly the same wind. If the wind power from multiple wind turbines is combined and they all experience the same wind regime, the resulting wind power would be the same as that produced by one large wind turbine. If, on the other hand, they are far enough apart that they experience different winds, then when one turbine is experiencing a gust and a jump in power, the power from another turbine may be dropping off. This results in a net reduction in the variability of the total power produced by the set of wind turbines.

7.1.2 Model Overview

Major Input

The major input to the calculations determining the total power from a set of wind turbines is as follows:

Characteristics of Each Wind Turbine Component. Each turbine will contribute to the mean power. There may be more than one type of turbine on each bus, and there may be multiple turbines of any given type.

Total Number of Turbines. The total number of turbines is used in determining a "wind farm filter" which is used to estimate the variability of the power from multiple wind turbines.

Spacing Between Wind Turbines. Wind turbine spacing in a collection of wind turbines affects the variability of the wind farm power production. Wind turbine spacing can be separately specified for the AC wind turbines and the DC wind turbines. It is assumed that the turbines are on a line, perpendicular to the prevailing wind direction.

Wind Power Scale Factor: The wind turbine power may be adjusted by a constant scale factor.

The inputs at each simulation time step to the calculations determining the fluctuating power from a set of wind turbines are the wind speed and the standard deviation of the wind speed measured at one location.

Restrictions

The number of wind turbine types on each bus is restricted to 10. There is no limit on the total number of wind turbines.

Output

The outputs from the calculations determining the fluctuating power from a set of wind turbines is the total wind power and the standard deviation of the total wind power.

Major Modifiers

The modifiers which affect the power smoothing calculations include:

Turbulence Length Scale (See Wind Turbine Component Section).

Reference Wind Velocity for Turbulence Length Scale (See Wind Turbine Component Section).

7.1.3 Detailed Parameter Description

Modeling Input

The inputs to the calculations determining the total power from a set of wind turbines are as follows:

Characteristics of Each Wind Turbine: The power from each individual turbine is found in accordance with the discussion in the Components section of this report.

Total Number of Turbines: The total number of turbines is used in determining the "wind farm filter." For the purpose of deriving the wind farm filter, differences between types of turbines are not considered.

Spacing Between Wind Turbines: Fluctuations in the total power generated by multiple wind turbines are less than if the same amount of power were produced by one machine. But wind turbine spacing affects the ability of multiple wind turbines to reduce the magnitude of power fluctuations. Turbines that are far apart (0.5 km or more) will behave as if completely uncorrelated, resulting in reduced power fluctuations. The behavior of turbines that are very close will be more nearly correlated. In most small wind farms, they will be partially correlated. The effect of spacing will actually depend on wind direction, but this is not considered in Hybrid2 at the present time.

Wind Power Scale Factor: The wind turbine power may be adjusted by a constant scale factor. This constant is normally set equal to one.

Simulation Input

The initial inputs at each simulation time step to the calculations determining the fluctuating power from a set of wind turbines are the wind speed and the standard deviation of the wind speed measured at one location. These are used, as described in the Components section, to find the mean power and standard deviation of the power from each turbine. These are then used as

inputs for the Wind Turbine Subsystem in determining the total wind power and standard deviation of that power.

Output

The output from the calculations determining the fluctuating power from a set of wind turbines is the total mean wind power and the standard deviation of the wind power.

Modifiers

The modifiers which affect the power smoothing calculations include: 1) Turbulence Length Scale and 2) Reference Wind Velocity for Turbulence Length Scale. These are discussed in the Wind Turbine Component section.

7.1.4 Model Theory

Total Mean Wind Power

The total mean power from multiple wind turbines is found by summing the individual mean wind power from each turbine. This is done for each bus.

Variability of Total Wind Power

If there is more than one turbine in the power system, the total average power is found by summing the average power produced by each turbine individually. Hybrid2 also considers the range of the fluctuations in power produced by the set of turbines, but the question of the variability of the wind power is somewhat more complicated when there is more than one wind turbine at a site. In this case the magnitude of the fluctuations of the power from all the machines is, in general, reduced, relative to that which would occur if there were a single machine of the same total rated power. This effect is the result of variations in wind speed at separate turbines distributed over the site. A gust at one turbine my not occur at another turbine at the same time, resulting in smaller fluctuations in the total power from the wind farm. The effect depends on the degree of correlation between the wind at separate wind turbine sites. In general, the correlation will range from completely correlated to completely uncorrelated. In the first case, the machines would behave as one machine. The standard deviation of the power would be proportional to the total power. Thus the variability of the power would be the same whether the power came from single or multiple machines. In the limit of complete lack of correlation, it can be shown that the variability will decrease by the square root of the number of machines (for machines of the same type).

The reduction of variability in power depends to a large extent on spacing between the turbines. Hybrid2 accounts for the effect of spacing by following the procedures of Beyer et al. (1989) and Jeffries (1992). The method assumes that the power spectra of the fluctuating wind speed at a single point is given by $S_1(f)$, where f = frequency (Hz), then the spectra of the total power from N points, $S_N(f)$ is:

$$S_N(f) = S_1(f)\frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N}\gamma_{ij}(f) \tag{7.1.1}$$

where $\gamma_{ij}^2(f)$ is the coherence between the wind speed at points i and j.

As discussed below, the spectrum used in Hybrid2 is the von Karman spectrum, which is recommended by Fordham (1985). When using the von Karman spectrum, an expression for the coherence in terms of Bessel functions is, strictly speaking, the most appropriate. That expression is significantly more complex than the exponential coherence function which is often used in micrometeorology. Since Hybrid2 seeks to model representative situations rather than to model turbulence precisely, the exponential coherence function (as suggested by Beyer, 1989) was selected. The exponential coherence is given by

$$\gamma_{ij}^2(f) = e^{-a\frac{x_{ij}}{\bar{V}}f} \tag{7.1.2}$$

where

a	= Coherence decay constant, taken to be 50
x_{ij}	= Spacing between points i and j (meters)
$\bar{V}$	= Mean wind speed (m/s).

The coherence decay constant chosen is most appropriate to the case where the turbines are in a line, perpendicular to the prevailing wind direction. The value of 50 is the limiting case found by Kristensen et al, 1981. Taking the square root into account, we have

$$\gamma_{ij}(f) = e^{-25\frac{x_{ij}}{\bar{V}}f} \tag{7.1.3}$$

The term $\frac{1}{N^2}\sum_{i=1}^{N}\sum_{j=1}^{N}\gamma_{ij}(f)$ is known as the "wind farm filter."

Making the provisional assumption that fluctuating wind power is linearly related to fluctuating wind speed, the power from one wind turbine, $\bar{P}_1$ for some k, is:

$$\bar{P}_1 = k\,\bar{V} \tag{7.1.4}$$

Note that this is only an approximation, since, in general, turbine performance is described by a non-linear power curve, as discussed previously. Furthermore, it is actually of more interest that the variation in power from the mean be proportional to the variation in speed from its mean. Since the wind farm filter affects only the fluctuations in power, not the mean values, this simplification is justified. To do otherwise would increase the complexity and run time of the model, producing only a minor effect on the results.

The variance of the fluctuating wind speed is given by the integral of the power spectrum over all frequencies as shown below. Note that the total variance is the same value that may be found from time series data in the usual way.

$$\sigma_V^2 = \int_0^\infty S_1(f)\,df \tag{7.1.5}$$

The variance of the fluctuating power from one wind turbine is given by

$$\sigma_{P,1}^2 = k^2 \int_0^\infty S_1(f)\, df \tag{7.1.6}$$

Assuming the same mean wind speed is seen by each wind turbine the total average wind turbine power, $\overline{P}_N$, is

$$\overline{P}_N = N\, k\, \overline{V} \tag{7.1.7}$$

The variance of the total fluctuating power is given by

$$\sigma_{P,N}^2 = N^2 k^2 \int_0^\infty S_N(f)\, df = k^2 \int_0^\infty \left\{ S_1(f) \sum_i^N \sum_j^N \gamma_{ij}(f) \right\} df \tag{7.1.8}$$

The single point spectrum may be described by the Von Karman spectrum:

$$\frac{S_1(f)}{\sigma_V^2} = \frac{4\frac{L}{\overline{V}}}{\left[1 + 70.8\left[\frac{L\,f}{\overline{V}}\right]^2\right]^{5/6}} \tag{7.1.9}$$

Using this single point spectrum, the relation between the variance of the power from a number of spatially separated wind turbines and the variables defining the turbine spacing is

$$\sigma_{P,N}^2 = k^2 \int_0^\infty \left\{ \frac{4\frac{L}{\overline{V}}}{\left[1 + 70.8\left[\frac{Lf}{\overline{V}}\right]^2\right]^{5/6}} \sum_{i=1}^N \sum_{j=1}^N e^{\left[\frac{-25\, x_{ij}\, f}{\overline{V}}\right]} \right\} df \tag{7.1.10}$$

Taking into account the averaging time used in Hybrid2, the relation between the variability of the power from all the wind turbines and the atmospheric turbulence intensity is

$$\frac{\sigma_{P,N}}{\overline{P}_N} = \frac{1}{N}\frac{\sigma_V}{\overline{V}} \sqrt{\frac{\displaystyle\int_{f_1}^{f_2} \frac{4\frac{L}{\overline{V}}}{\left[1 + 70.8\left[\frac{L\,f}{\overline{V}}\right]^2\right]^{5/6}} \sum_{i=1}^N \sum_{j=1}^N e^{\left[\frac{-25\, x_{ij}\, f}{\overline{V}}\right]} df}{\displaystyle\int_{f_1}^{f_2} \frac{4\frac{L}{\overline{V}}}{\left[1 + 70.8\left[\frac{L\,f}{\overline{V}}\right]^2\right]^{5/6}} df}} \tag{7.1.11}$$

where

f_1 = Lower frequency (determined by time step length)

f_2 = Upper frequency (above which there is little power in the turbulence).

Note that 1) if the wind turbines are completely correlated then x_{ij} -> 0 for all i, j and the turbines should all act as one large turbine. Thus, for all i, j,

$$e^{\left[\frac{-25\, x_{ij}\, f}{V}\right]} = 1 \tag{7.1.12}$$

and

$$\sum_{i=1}^{N}\sum_{j=1}^{N} e^{\left[\frac{-25\, x_{ij} f}{V}\right]} = N^2 \tag{7.1.13}$$

so

$$\frac{\sigma_{P,N}}{\overline{P}_N} = \frac{\sigma_V}{\overline{V}} \tag{7.1.14}$$

As expected, the variability in the total power is the same as the variability in the wind speed, which represents the behavior of one large turbine.

2) If the wind turbines are completely uncorrelated then x_{ij} -> ∞ for $i \neq j$. Then, for $i \neq j$,

$$e^{\left[\frac{-25\, x_{ij}\, f}{V}\right]} = 0 \tag{7.1.15}$$

and

$$\sum_{i=1}^{N}\sum_{j=1}^{N} e^{\left[\frac{-25\, x_{ij}\, f}{V}\right]} = N \tag{7.1.16}$$

so

$$\frac{\sigma_{P,N}}{\overline{P}_N} = \frac{1}{\sqrt{N}}\frac{\sigma_V}{\overline{V}} \tag{7.1.17}$$

Thus, as expected, for a set of N totally uncorrelated wind turbines, the variability will decrease by the square root of the number of machines (for machines of the same type).

Hybrid2 employs a simple trapezoidal integration routine, with progressively smaller step sizes at decreasing frequencies, for approximating the integral.

Example:

For example, the following graphs, Figure 7.1, illustrate the effect of spacing for 2 and 10 wind turbines, assumed to be equally spaced along a line perpendicular to the wind direction. For this example L= 100 m and $\overline{V}$ = 10 m/s.

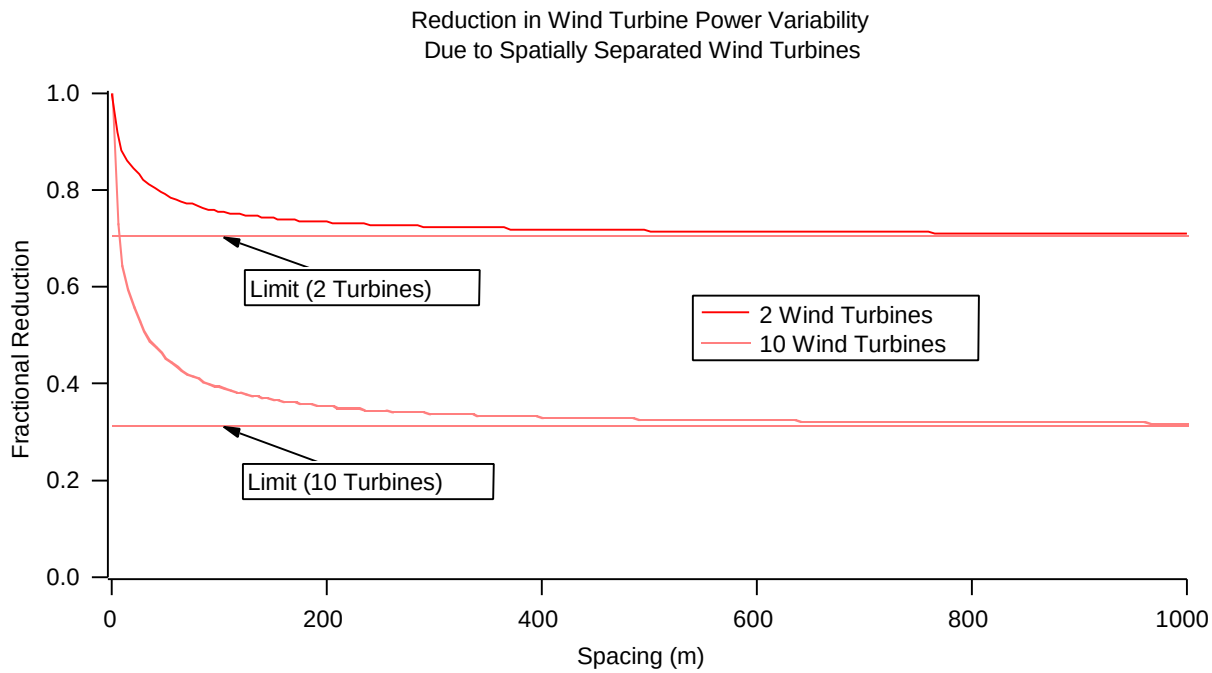


Figure 7.1. Spatial Effects on Power Variability

7.2 Photovoltaic Array Performance

7.2.1 Executive Summary

A photovoltaic array consists of a number of panels mounted to face the sun. The correct prediction of the power supplied by PV panels requires the determination of the insolation on the panel surface. This insolation is composed of both direct (beam) radiation and diffuse radiation. Each of these depend on the clearness index, the ratio of the insolation on a horizontal surface to the insolation given a clear sky. The beam radiation is also a function of the position of the sun in the sky and the physical orientation of the solar panels. The total radiation on the solar panels is a function of the direct, diffuse, and any reflected radiation from the ground. Finally, the physical orientation of the collectors changes in a system which incorporates tracking changes as the day proceeds. All of these factors are considered in Hybrid2 to determine the incident solar radiation on the solar panels. Also, as shown in Figure 7.2, other required solar resource inputs are geographical ones particular to the hybrid system site.

Other factors that may affect the output of the array include the possible inclusion of a tracking system, or a maximum power point tracker, and the number of panels. How they are connected (i.e. in series or parallel) is also significant.

This section discusses adjustment of solar radiation to the plane of the array, and the power output from multiple panels.

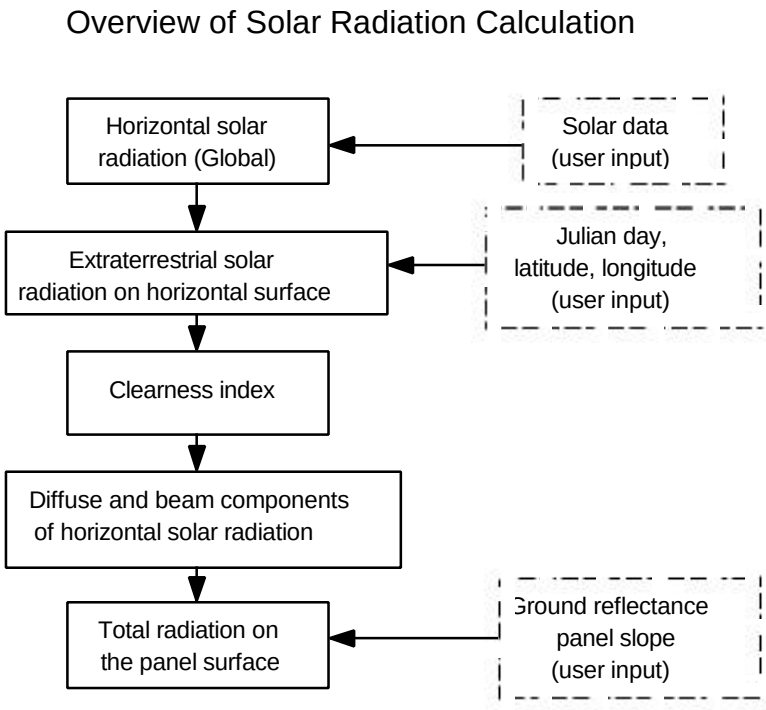


Figure 7.2. Diagram of Solar Radiation Calculation Scheme.

As detailed in the following theory section, Hybrid2 uses the Hay, Davies, Klucher, Reindl (HDKR) anisotropic model to calculate the incident radiation on the PV panel surface. The code first calculates the extraterrestrial radiation based on the Julian day of the year and the site latitude and longitude and then establishes a clearness index which is the ratio of global horizontal radiation and extraterrestrial radiation. The clearness index is then used to determine the beam and diffuse components of the global radiation via empirical correlations. Finally, the program determines the radiation on the tilted surface of the panel based on the incident direction of the beam and diffuse solar radiation components and the ground reflectance.

7.2.2 Photovoltaic Array Overview

The correct prediction of the power supplied by PV panels requires the determination of the insolation on the panel surface. This insolation is composed of both direct (beam) radiation and diffuse radiation. Each of these depend on the clearness index, the ratio of the insolation on a horizontal surface to the insolation given a clear sky. The beam radiation is also a function of the position of the sun in the sky and the physical orientation of the solar panels. The total radiation on the solar panels is a function of the direct, diffuse, and any reflected radiation from the ground. Finally, the physical orientation of the collectors in a tracking system is changing as the day proceeds. All of these factors are considered in Hybrid2 to determine the incident solar radiation on the solar panels.

Major Inputs

The major inputs to the geometric calculations for the solar radiation on the panels are the angles defining the physical orientation of the solar collectors. These inputs include, where applicable, the type of tracking.

The inputs that affect the simulation define the location of the sun at each time step and the corresponding insolation on a horizontal surface.

The inputs that affect the total power produced by an array include: 1) the number of panels in series, 2) the number of panels in parallel, 3) an array loss factor.

Output

The output of the calculations is the average solar irradiance on the surface of the solar panels.

The number of panels in series and parallel, and the array loss factor affect the total power produced by the array.

Modifiers

The modifiers that are needed to calculate the solar resource on the PV panel surface include the site latitude, longitude, and ground reflectance.

7.2.3 Details of Solar Insolation Calculations

As detailed in the following theory section, Hybrid2 uses the HDKR anisotropic model to calculate the incident radiation on the PV panel surface. The code first calculates the extraterrestrial radiation based on the Julian day of the year and the site latitude and longitude and then establishes a clearness index which is the ratio between the global horizontal radiation to the extraterrestrial radiation. The clearness index is then used to determine the beam and diffuse components of the global radiation via empirical correlations. Finally, the program determines the radiation on the tilted surface of the panel based on the incident direction of the beam and diffuse solar radiation components and the ground reflectance.

Model Input

The modeling inputs to the calculations for the solar radiation on the panels are the angles defining the physical orientation of the solar collectors. These inputs include the type of tracking system being used:

Collector slope angle (β): The angle between the plane of the PV panels and the horizontal.

Surface azimuth angle (γ): The deviation of the projection on a horizontal plane of the normal to the surface from the local meridian, with zero due south, east negative, and west positive.

PV Rack or Tracker: The current model is based on the use of six possible tracking systems that use rotation about a single axis (horizontal east-west (either adjusted at noon or continuously adjusted), horizontal north-south, vertical, or parallel to the earth's axis or about two axes.

Simulation Input

The inputs that affect the simulation define the location of the sun at each time step and the corresponding insolation on a horizontal surface:

Julian day (n): The day number at the start of the data set, starting with n = 1 for the first day of the year. The data is assumed to start at midnight of the day in question.

Average irradiance on a horizontal surface at each simulation time step ($\overline{G}$), W/m^2.

The hour angle (ω), deg: The angular displacement of the sun east or west of the local meridian due to rotation of the earth on its axis at 15° per hour, morning negative, afternoon positive. Specifically, the solar resource algorithm requires:

ω_1 = Hour angle at start of a time step, deg.

ω_2 = Hour angle at end of a time step, deg.

Model Output

The output from this part of the code is the average irradiance on the PV panel surface for the selected time step period of Hybrid2.

Modifiers

The modifiers that are needed to calculate the solar resource on the PV panel surface include the following:

Latitude (ϕ): The angular location north or south of the equator, north positive, deg.

Longitude (L): Meridian of the selected site, deg.

Ground reflectance (ρ_g): The fraction of solar radiation reflected by the ground, -.

7.2.4 Theory of Solar Insolation Calculations

To calculate the solar insolation at each time step on a tilted surface, the code first calculates the extraterrestrial radiation based on the Julian day of the year, site latitude and longitude, and time of day the insolation data was collected. This calculation requires converting the data collection time to local solar time. The code then establishes a clearness index which is the ratio between the measured global horizontal radiation to the extraterrestrial radiation. The clearness index is then used to determine the beam and diffuse components of the global radiation via empirical correlations. Finally, the program determines the radiation on the tilted surface of the panel based on the incident direction of the beam and diffuse solar radiation components and the ground reflectance using the HDKR anisotropic model. For tracking collectors, the orientation of the collectors may be constantly changing. For these systems, the panel orientation is constantly recalculated. The current model is based on the use of six possible tracking systems that use rotation about a single axis (horizontal east-west, either adjusted at noon or continuously adjusted, horizontal north-south, vertical, or parallel to the earth's axis) or about two axes.

The analytical model for the solar data includes the following parts:

- Solar Data Input
- Conversion/ Use of Solar Data
- Tracking collectors- Geometric Relations

A summary of each of these parts follows.

<u>Solar Data Input</u>

In order that the solar insolation data can be used, the data must be correctly related to local solar time, the time used in the solar calculations. In Hybrid2, when solar power is included, all data should begin at midnight. All time must be first converted to solar time using the following equation ("Equation of time") for the difference between solar time and standard time:

$$t_{sol} = t_{std} + \frac{L_{st} - L}{15} + E \tag{7.2.1}$$

where

t_{sol}	= Solar time, hrs
t_{std}	= Standard time, hrs
L_{st}	= Standard meridian for the local time zone, deg
L	= Longitude of the site under analysis, deg
E	= Correction from the Equation of Time, hrs

The equation of time correction, E, is found from the following equation

$$E = 3.82\left[0.000075 + 0.001868\cos(B) - 0.032077\sin(B) - 0.014615\cos(2B) - 0.04089\sin(2B)\right] \tag{7.2.2}$$

where

B	= (n-1) 360/365
n	= Julian day of the year.

For the determination of the calculated solar angles, the sun's hour angle, ω, defined as the angular displacement of the sun's position away from its location at solar noon caused by the earth's rotation, must be calculated. The angle ω is calculated in degrees by multiplying the hours from solar noon by 360/24.

<u>Conversion and Use of Solar Data</u>

In order to convert the input solar data (which is assumed to be taken on a horizontal surface) to the plane of the collector or PV cell, certain solar angles must be calculated and the division between diffuse and direct sunlight must be determined. The following discussion summarizes the governing equations that permit the calculation of the total radiation on the tilted surface of PV panels. The method used is known as the "HDKR model" and is described in Duffie and Beckman (1991). It is based on the concept of an anisotropic sky. The complete equation for finding the irradiance on a tilted surface, $\overline{G}_T$, given the irradiance on a horizontal surface, $\overline{G}$, is

$$\overline{G}_T = (\overline{G}_b + \overline{G}_d\ A_i)\,R_b + \overline{G}_d(1 - A_i)\left(\frac{1+\cos(\beta)}{2}\right)(1 + f\sin^3(\beta/2)) + \overline{G}\ \rho_g\left(\frac{1-\cos(\beta)}{2}\right) \tag{7.2.3}$$

where

$\overline{G}_b$ = Beam component of the average horizontal irradiance, W/m^2

$\overline{G}_d$ = Diffuse component of the average horizontal irradiance, W/m^2

A_i = Anisotropy index which is a function of the transmittance of the atmosphere for beam radiation, and is given by $A_i = \overline{G}_b / \overline{G}_o$.

R_b = Ratio of beam radiation on tilted surface to that on horizontal, -

$\overline{G}_o$ = Average irradiance outside the earth's atmosphere, W/m^2

β = Slope angle of PV panels with respect to horizontal, deg

f = Modulating factor $= (\overline{G}_b / \overline{G})^{1/2}$, –

ρ_g = Ground reflectance, -.

The values needed in Eq. 7.2.3 are found as follows. First of all, the diffuse component of the radiation is calculated via the correlation of Erbs, et al. (1982), which gives the fraction of diffuse to total radiation, $\overline{G}_d / \overline{G}$ as a function of the clearness index, k_T. The clearness index is the ratio between the actual average irradiance on the horizontal (as provided by the data) to the average irradiance outside the earth' atmosphere, $\overline{G}_0$. $\overline{G}_0$ is found from:

$$\overline{G}_0 = G_{sc}(1 + 0.33\cos\frac{360\,n}{365})[\cos(\phi)\cos(\delta)\cos(\omega) + \sin(\phi)\sin(\delta)] \tag{7.2.4}$$

with

G_{sc} = Solar constant (1367 W/m^2)

n = Julian day

ϕ = Site latitude, deg

δ = Sun's declination (calculated from $\delta = 23.45\,\sin[360\frac{284+n}{365}]$, deg

ω = Hour angle at middle of the time step, deg.

The clearness index is found from

$$k_T = \overline{G} / \overline{G}_0 \tag{7.2.5}$$

The diffuse radiation fraction is then found from k_T.

$$\overline{G}_d / \overline{G} = 1.0 - 0.09\,k_T \text{ . for } k_T \le 0.22 \tag{7.2.6a}$$

$$\overline{G}_d / \overline{G} = 0.9511 - 0.1604\,k_T + 4.388\,k_T^2 - 16.638\,k_T^3 + 12.336\,k_T^4 \text{ . for } 0.22 < k_T \le 0.80 \tag{7.2.6b}$$

$$\overline{G}_d / \overline{G} = 0.165 \text{ for } k_T > 0.80 \tag{7.2.6c}$$

The beam radiation is obtained by subtracting the diffuse component from the average measured irradiance.

$$\overline{G}_b = \overline{G} - \overline{G}_d \tag{7.2.7}$$

Next R_b is calculated by the equation

$$R_b = \cos(\theta)/\cos(\theta_z) \tag{7.2.8}$$

where

θ_z = Zenith angle, deg

θ = Angle of incidence of beam radiation on surface, deg

The zenith angle, which is the angle between the sun's rays and a line perpendicular to the earth's surface, is found from

$$\cos(\theta_z) = \cos(\phi)\cos(\delta)\cos(\omega) + \sin(\phi)\sin(\delta) \tag{7.2.9}$$

The angle of incidence, which is the angle between the sun's rays and a line perpendicular to the panels, is found from

$$\begin{aligned}\cos(\theta) &= \sin(\delta)\sin(\phi)\cos(\beta) - \sin(\delta)\cos(\phi)\sin(\beta)\cos(\gamma) \\ &+ \cos(\delta)\cos(\phi)\cos(\beta)\cos(\omega) - \cos(\delta)\sin(\phi)\sin(\beta)\cos(\gamma)\cos(\omega) \\ &+ \cos(\delta)\sin(\beta)\sin(\gamma)\sin(\omega)\end{aligned} \tag{7.2.10}$$

where

γ = PV array surface azimuth angle, deg

Note that the surface azimuth angle is the angle between a south facing line (north facing in the Southern Hemisphere) and a line perpendicular to the panel. When the panel perpendicular is west of south, the angle is positive.

<u>Tracking Collectors- Geometric Relations</u>

In general, the performance of a PV panel can be maximized by tracking the sun in order to maximize the incident solar radiation. Hybrid2 allows the use of six possible tracking systems. The panels may rotate about a single axis (horizontal east-west, either adjusted at noon or continuously adjusted, horizontal north-south, vertical, or parallel to the earth's axis) or about two axes. For performance prediction, the angle of incidence (θ), the slope (β), surface azimuth (γ), and the solar azimuth (γ_S) angles must be calculated for tracking systems. The angle of incidence (Eq. 7.2.10) is a function of the other angles related to the physical orientation of the solar panels and so will depend on the type of tracking system used. The following method is used to calculate the slope, surface azimuth, the solar azimuth, and solar incidence angles for the different tracking systems.

To calculate γ_s one must know in which quadrant the sun will be. This is determined by the relationship of the hour angle ω to the hour angle when the sun is due west (or east), ω_{es}. Based on the work of Braun and Mitchell (1983), a general relationship for γ_s is expressed below in terms of γ_s', a pseudo solar azimuth angle.

$$\gamma_s = C_1 C_2 \gamma_s' + C_3 [\frac{1 - C_1 C_2}{2}] 180 \tag{7.2.11}$$

where

$$\tan(\gamma_s') = \frac{\sin(\omega)}{\sin(\phi)\cos(\omega) - \cos(\phi)\tan(\delta)}$$

$$C_1 = \begin{cases} 1 \text{ if } |\omega| < \omega_{es} \\ -1 \text{ otherwise} \end{cases}$$

$$C_2 = \begin{cases} 1 \text{ if } \phi(\phi - \delta) < \omega_{es} \\ -1 \text{ otherwise} \end{cases}$$

$$C_3 = \begin{cases} 1 \text{ if } \omega \geq 0 \\ -1 \text{ otherwise} \end{cases}$$

$$\cos(\omega_{es}) = \tan(\delta) / \tan(\phi).$$

Also, if $|\tan(\delta) / \tan(\phi)| > 1$, the sun is never due east or west of the observer. In this case, set $C_1 = 0$.

Following the analysis summarized in Duffie and Beckman (1991) and the work of Braun and Mitchell (1983), the following analytical relations are used to determine the angles for each of the six possible tracking options:

For a surface rotated about a horizontal east-west axis, with a single daily adjustment (noon), such that the beam radiation is normal to the surface on noon of each day, the angle of incidence is given by the equation

$$\cos(\theta) = \sin^2(\delta) + \cos^2(\delta)\cos(\omega) \tag{7.2.12}$$

The slope of this surface will be fixed for each day and is

$$\beta = |\phi - \delta| \tag{7.2.13}$$

The surface azimuth angle for a day will be zero or 180 , depending on the latitude and declination:

$$\text{If } (\phi - \delta) > 0, \gamma = 0^\circ \tag{7.2.14a}$$

$$\text{If } (\phi - \delta) < 0, \gamma = 180^\circ \tag{7.2.14b}$$

For a surface rotated about a horizontal east-west axis with continuous adjustment to minimize the angle of incidence,

$$\cos(\theta) = \sqrt{1 - \cos^2(\delta)\sin^2(\omega)} \tag{7.2.15}$$

The slope of the surface is given by

$$\tan(\beta) = \tan(\theta_z)\left|\cos(\gamma_s)\right| \tag{7.2.16}$$

and

$$\text{If } \left|\gamma_s\right| < 90, \gamma = 0^\circ \tag{7.2.17a}$$

$$\text{If } \left|\gamma_s\right| > 90, \gamma = 180^\circ. \tag{7.2.17b}$$

For a surface rotated about a horizontal north-south axis with continuous adjustment to minimize the angle of incidence, the angle of incidence is given by

$$\cos(\theta) = \sqrt{\cos^2(\theta_z) + \cos^2(\delta)\sin^2(\omega)} \tag{7.2.18}$$

The slope is given by

$$\tan(\beta) = \tan(\theta_z)\left|\cos(\gamma - \gamma_s)\right| \tag{7.2.19}$$

The surface azimuth angle γ, will be 90^0 or -90^0 depending on the sign of the solar azimuth angle:

$$\text{If } \gamma_s < 0, \gamma = -90^\circ \tag{7.2.20a}$$

$$\text{If } \gamma_s > 0, \gamma = 90^\circ \tag{7.2.20b}$$

For a surface with a fixed slope rotated about a vertical axis, the angle of incidence is minimized when the surface azimuth and solar azimuth angles are equal. The angle of incidence is given by

$$\cos(\theta) = \cos(\theta_z)\cos(\beta) + \sin(\theta_z)\sin(\beta). \tag{7.2.21}$$

The slope is fixed, thus

$$\beta = \text{constant} \tag{7.2.21}$$

And, the surface azimuth angle is

$$\gamma = \gamma_s. \tag{7.2.22}$$

For a surface rotated about a north-south axis parallel to the earth's axis with continuous adjustment to minimize θ, the incidence angle is given by

$$\cos(\theta) = \cos(\delta) \tag{7.2.23}$$

The slope varies continuously and is given by

$$\tan(\beta) = \tan(\phi) / \cos(\gamma) . \tag{7.2.24}$$

The surface azimuth angle is

$$\gamma = \tan^{-1}\left[\frac{\sin(\theta_z)\sin(\gamma_s)}{\cos(\theta')\sin(\phi)}\right] + 180\, C_4\, C_5 \tag{7.2.25}$$

where:

$$\cos(\theta') = \cos(\phi)\cos(\theta_z) + \sin(\theta_z)\sin(\phi) .$$

If

$$\frac{\tan^{-1}\left[\frac{\sin(\theta_z)\sin(\gamma_s)}{\cos(\theta')\sin(\phi)}\right]}{\gamma_s} \geq 0$$

then $C_4 = 0$, otherwise $C_4 = 1$. If $\gamma_s \geq 0$, then $C_5 = 1$; if $\gamma_s < 0$, then $C_5 = -1$.

For a plane that is continuously tracking about two axes to minimize the angle of incidence,

$$\cos(\theta) = 1 \tag{7.2.26}$$

$$\beta = \alpha \tag{7.2.27}$$

$$\gamma = \gamma_s . \tag{7.2.28}$$

7.2.5 Multiple Panels in Photovoltaic Arrays

When there are multiple photovoltaic panels in an array, they are connected together in series or in parallel. When N panels are connected in series, the terminal voltage at either end of the series will be N times that of a single panel. When M panels are connected in parallel, the array voltage will not be affected, but the current will be M times that of a single panel.

The voltage of the array is of particular concern when the array is to be used in conjunction with a battery bank. It is of great importance to have the terminal voltage of the bank properly match that of the array. Otherwise, proper charging of the batteries will not take place. The matching of a photovoltaic panel to a load, such as a battery, was described in Chapter 6. When a multiple panel array is connected to a DC bus with a bank of multiple batteries, the same considerations apply. Specifically, the nominal battery bank voltage should be close to the maximum power point voltage of the entire photovoltaic array. If the system includes a maximum power point tracker, however, there is no requirement that the voltage of the panels match that of the battery bank.

When a maximum power tracker or other dedicated power converter is used with an array, there will be a loss associated with that device, as discussed in Chapter 6. Even without such devices, there may be other losses in the array. Any of these losses may be included through the use of an array loss factor. This is a multiplier, which is normally set to 1.0 (if there are no losses.)

7.3 Battery Bank

7.3.1 Executive Summary

Many hybrid power systems use multiple batteries. These are connected together in a battery bank. The number of batteries, and the way they are connected, affects the total energy storage capacity and the way the storage can interact with photovoltaic panels.

7.3.2 Overview of Battery Bank Model

Major Inputs

The inputs that relate to battery bank performance include:

Number of batteries in series

Number of batteries in parallel

Battery bank scale factor

Battery bank initial capacity

Major Outputs

The output of the battery bank model includes:

Storage capacity of battery bank

Terminal voltage of battery bank

Initial energy stored in battery bank

7.3.3 Details of Battery Calculations

The battery bank calculations are very similar to those for individual batteries, which were discussed in Chapter 6. The important thing to note is that when there are multiple batteries in a bank, they are connected in series or in parallel. When N batteries are connected in series, the terminal voltage at either end of the series will be N times that of a single battery. When M batteries are connected in parallel, the bank voltage will not be affected, but the capacity will be M times that of a single battery. If there are N batteries in series in a string and M batteries strings in parallel, the total energy storage capacity will be NM times that of a single battery.

The voltage on the DC bus is assumed to be the same as that of the battery bank. This can be quite significant with respect to power production from an array of photovoltaic panels, as discussed in Section 7.2.5.

A scale factor may be used to quickly adjust the storage capacity of a battery bank. It will not affect the bank voltage. The scale factor multiplies the total capacity of the battery, and decreases the internal resistance. The scale factor operates in the same way as would increasing the number of batteries in parallel. The difference is that the scale factor need not have an integer value.

The user may select the initial energy stored in the batteries at the beginning of a simulation. In a simulation of short duration, the net change in stored energy could be significant.

7.4 Dispatch Model

7.4.1 Executive Summary

Hybrid2 provides a wide range of control, or dispatch, options. Battery charging and discharging, diesel operation, and combined diesel/battery operating parameters can all be controlled separately. Dispatch and control may be grouped into three main areas: 1) battery dispatch, 2) diesel dispatch, and 3) battery and diesel dispatch, 3) . Dispatch options apply if there are batteries and/or diesels in the system. Renewable energy generators are not considered dispatchable, and thus are not explicitly included in the dispatch options..

Battery dispatch determines how the battery itself is used, charged and discharged. Options include:

1) Minimum allowed state of charge
2) Battery discharge (how the battery is used)
3) Criteria for boost charging to begin
4) Time interval between boost charges
5) State of charge when boost charging ends

Diesel dispatch includes:

1) Minimum diesel run time
2) Criteria for allowing all diesels to be shutoff
3) Periods of required diesel shutoff
4) Offset in net load to force diesel to start
5) Dispatch order for multiple diesels

Battery and diesel dispatch deals with the interaction of the diesels and storage in meeting the net load. It considers:

1) Diesel operating power level
2) Criteria for starting diesels
3) Criteria for shutting off diesels

It should be noted again that Hybrid2 is a long-term model and not a dynamic model. True real time control cannot be modeled by Hybrid2. For some situations this may lead to modeling errors, especially in regards to system frequency control and stability.

7.4.2 Dispatch Overview

Hybrid2 considers two types of components to be "dispatchable": diesel generator sets and batteries. In other words, they can be used at the discretion of an overall system controller. It

should be noted that renewable energy generators (wind turbines and photovoltaic panels) are not considered dispatchable because their output is dependent on the temporal availability of the resource (wind or sunlight.) These generators could in principle be dispatched (or turned off) during times during times when they might otherwise be running. Since the capital costs of renewable generators is normally relatively high compared to conventional generators, Hybrid2 assumes that they operate as much as they can, producing as much power as the resources allows. Any power in excess of the load is sent to storage, secondary loads, or is dumped (as discussed in previous sections of this report.)

The discussion of dispatch and control is grouped into three main areas: 1) battery dispatch, 2) diesel dispatch, and 3) battery and diesel dispatch.

Battery Dispatch

The battery dispatch determines how the battery itself is used, charged and discharged. It includes the minimum state of charge, the method of using the battery (for transient peaks or all or part of average load), the criteria for the initiation of boost charging, the time interval between boost charges, and state of charge at the end of boost charging. Each is described below.

Minimum State of Charge: Cycle life of most batteries (lead acid in particular) is normally maximized when the state of charge of the battery is never allowed to fall too low. This parameter ensures that the state of charge always stays above some specified fraction of the total capacity. This value will differ from battery to battery.

Battery Discharge: Batteries may be used to supply transient load peaks or part or all of the average load during the time step. The former method is most applicable to larger hybrid systems and those with relatively small amounts of storage. The latter is more common with smaller systems and those with a relatively large amount of storage.

Criteria for Boost Charging to Begin: Boost charging is commonly done to bring the battery up to full charge. This process helps the batteries last longer. If no diesels have been specified for the system, then Hybrid2 does not allow boost charging. The overall effect of the boost charge on the simulation results is to increase the fuel use somewhat.

The user may select i) to have no boost charging, ii) wait a specified time and then begin boost charging when the next diesel starts, or iii) force a diesel to start after a specified time.

Boost Charge Interval: The boost charge interval is the period of time between boost charges. Once that interval has been exceeded, a boost charge requirement is imposed on the control system.

State of Charge for Boost Charge to End: In boost charging, the batteries are charged to a higher state of charge by the diesel than is used in normal chargeup. The boost charge level sets that state of charge when the boost charge is deemed to be complete.

Diesel Dispatch

Diesel dispatch includes minimum diesel run time, diesel shutoff criteria, periods of forced diesel shutoff, offset in net load to force diesel to start, and dispatch order for multiple diesels. Each is described below.

Minimum Diesel Run Time: In many situations, a diesel generator is not allowed to cycle on and off at will. Rather, it is required that the diesel remain on for some time, once started. The user may select this time period. The diesel will stay on at least that amount of time whenever it is turned on. Of course, it may stay on longer if the load or battery charging requires it. This is described further in Section 6.3.4.

Diesel Shutoff Criteria: In general, diesels may be shutoff if there is sufficient power available from renewables or storage to supply the load. In some systems at least one diesel must always be on to ensure system stability. The various options are described in detail in Section 7.3.4 below.

Forced Diesel Shutoff(Time of Day Switch): In some communities, it is desirable to keep the diesels off at certain times of the day. This could be at night, for example, when the sound of the engines could be disturbing or when the diesels are unsupervised. The code allows the specification of two time periods during the day when the diesels must be off. Diesels may be kept off all night by specifying that the diesels may not be run at end of the day and the beginning of the day. The switch applies to all the diesels and supersedes all other diesel starting or stopping criteria.

Offset in Net Load to Force Diesel to Start: In systems where the diesel(s) are allowed to be shutoff, the criteria for starting the diesel(s) is usually that the maximum expected net load during the interval is such that the diesel must be on to meet that load. The user may select an offset value so that the diesel comes on earlier.

Dispatch Order for Multiple Diesels: There are two options for allocating which diesels are operating in multi-diesel applications. One option allows the user to specify the allowed combinations. The other option is to allow a built-in "optimizer" to find the combination of diesels with the lowest fuel use. If the user chooses the built-in optimizer option, then no further inputs in this category are used. If the user wishes to specify the allowed combinations, then codes for each must be explicitly set. This is described in detail in the Section 7.3.4 below and in the Hybrid2 Users Manual.

Battery and Diesel Dispatch

Battery and diesel dispatch deals with the interaction of the diesels and storage in meeting the net load. Battery and diesel dispatch considers diesel operating power level, criteria for starting diesels, and criteria for shutting diesels off battery discharge. An overview of each of these aspects of the battery and diesel dispatch is provided below.

Diesel Operating Power Level: This control variable affects the power at which a diesel generator is run. In systems with no storage there is relatively little choice as to the power level. In general the diesel would run at the level needed to supply the net load. The exception would be if the net load were less than the minimum allowed power level. In that case, the latter would determine the power level.

Systems that include storage have more options. In particular, the load might be supplied partially by diesels and partially by batteries. The diesel power level parameter allows the user to select whether batteries or diesels are to be used preferentially. The code also allows the user to choose whether the power level is to be such that the net load is met with no extra power (except as required by minimum load) or is to be as high as possible so as to charge batteries.

Diesel Starting Criteria: There are two possible criteria for starting the diesels, and the user may choose the one preferred. The first is to meet the net load. The second is to meet the load or charge the batteries if they have been depleted. The first situation could occur if the batteries alone are incapable of supplying the load, but the diesels could.

Diesel Stopping Criteria: There are five reasons for stopping the diesel(s).

1) if the batteries and renewables together can meet the load
2) if renewables alone can meet the load
3) if renewables can supply the load or if the batteries are full
4) if the batteries are fully charged to the state of charge specified by the user
5) if only some of the diesels are needed (this only applies to multi-diesel cases)

There may also be a restriction placed on shutting off all the diesels. To attempt to operate some hybrid systems with no diesels on at all may be physically unrealizable. Note that is also assumed that any diesel, once started, remains running for at least one simulation time step.

Additional information on dispatch can be found in Barley, 1994, and further description of each parameter and some example control algorithms can be found in the Hybrid2 Users Manual (Baring-Gould, 1996).

7.4.3 Detailed Dispatch Description

This section expands upon and provides some additional details to the overview of dispatch given in the previous section.

Battery Dispatch Theory

Battery Discharge As summarized elsewhere, batteries in hybrid power systems may be discharged to satisfy transient loads or to supply all or part of the average load. The first of these methods is sometimes referred to as "peak shaving", while the second includes a strategy known as "cycle charge." The Hybrid2 model allows either of these options. Variations are determined by settings of the other parameters. For the purpose of this discussion, these strategies will be denoted the Transient Peak Strategy and Average Load Strategy respectively.

The transient peak strategy seeks to use energy from storage to assure that the number of diesels that are on is determined solely by the average net load rather than the maximum net load during the interval. Thus, short term increases in load do not require starting a new diesel. It does this by checking to see if there is enough storage to supply the difference between the average and the maximum load in each interval. When it is impossible to have on only the diesel needed to supply the mean load, the algorithm continues to seek the lowest number of diesels that will suffice.

If shutting off all of the diesels is allowed and the average net load is less than zero, and if there is enough storage to supply all the positive instantaneous net load, then all diesels may be off. The excess power is the negative net load less the amount taken from storage, if possible, to allow the diesels to be off. If at least one diesel must be on, the logic checks to see if there is enough storage to keep the other diesels off. Assuming that other control variables allow it, then only one diesel is kept on. If there are multiple diesels in the system, the logic will try to use as few diesels as possible, consuming as little fuel as possible. Which diesels are on and the power level at

which they are run is determined by the power that is required, in accordance with the method described in following section on Diesel Specific Dispatch.

This average load strategy control option is similar to the transient peak strategy in that it uses storage to select which diesels are to be on. In this case, however, it seeks to use storage to the maximum extent. It does this by shutting off as many diesels as possible, subject to the availability of stored energy. First it checks to see if there is enough storage to supply the load. If there is, and the diesel status allows it, all the diesels are shutoff. If recent operating history does not allow all the diesels to be shutoff (because the diesel minimum run time has not elapsed), then those that must be on will be kept on and the rest will be off. In these cases storage will be used only to the extent necessary to prevent successive diesels from being on. If there is insufficient storage to shutoff any of the diesels then in general nothing is taken from storage. As with the transient peak strategy, the diesels that are on and the power level at which they are run is determined by the power that is required, in accordance with the method described in following section on Diesel Specific Dispatch.

Boost Charging: Boost charge may be approached in one of three ways. First, it may be ignored altogether. Second, the boost charge option may be available, but boost charging will only begin when the diesel(s) must be turned on for other reasons. Third, boost charging may be required whether or not the diesels would ordinarily be on. When boost charging is included, the user specifies the time between the boost charges, as well an ending state of charge for the batteries. Once on, the diesel will remain on until the batteries have reached the specified state of charge. During the boost period, the diesel will run as hard as it can, without wasting power, to do the charging. The user may also select whether boost charging should begin immediately when a specified time has passed since the previous boost (possibly forcing a diesel to turn on), or whether boost charging can wait until at least one diesel would need to be on anyway. Note that the only effect boost charging has on the economic predictions of the simulation is through the increased diesel fuel consumption. The beneficial effects, in terms of increased battery life, are not modeled. See the Hybrid2 Users Manual for more details on this feature.

Diesel Dispatch Theory

As indicated previously, diesel specific dispatch includes minimum diesel run time, diesel shutoff criteria, periods of forced diesel shutoff, offset in net load to force diesel to start, and dispatch order for multiple diesels. Each is described below.

Minimum Diesel Run Time: To reduce engine wear and maintenance caused by the buildup of deposits in the diesel engine cylinders, it is helpful to minimize engine starts and to maintain high engine temperatures during operation. Thus, diesel engines are often operated for some minimum time period, once started, to reduce long term maintenance problems. To reflect this, the user can specify a minimum diesel run time for all of the diesels in the system. See Section 6.3.4 for some more discussion of this topic.

Diesel Shutoff Criteria: There may be restrictions which prevent all diesels from being shutoff. In conventional AC bus diesel networks, and in many hybrid power systems, a synchronous generator connected to a diesel is needed to supply reactive power. Furthermore, the governor of a diesel is normally used to set the grid frequency. In any system with an AC bus, at least one diesel should normally be kept on unless some other option is provided to supply reactive power and maintain the grid frequency. In a coupled diesel system, the rotary converter and control system allow the diesel to be shut down when it is not needed. See Chapter 6 for more details.

The following situations are of particular note:

1) If the hybrid system contains only an AC bus, then normally at least one diesel should be kept on. A possible exception would be a system incorporating a large wind turbine with a synchronous generator.
2) The coupled diesel may be shutoff.
3) In DC systems, in general all diesels may be shutoff.
4) In two-bus systems with a switched mode inverter, the inverter will not operate unless all the diesels are off.
5) In two-bus systems with a line commutated inverter, at least one diesel should be kept running. The diesel(s) in this case would necessarily be on the AC bus.
6) In two-bus systems with a rotary converter, the diesel may be shutoff as long as there is some means provided to keep the AC frequency within proper limits.

Forced Diesel Shutoff: In some situations, it is desirable to keep the diesels off for a part of the day. This may be due to the desire to reduce noise at certain times. It may also be due to the shortage of diesel fuel, or the desire to avoid low load operation. In any case, Hybrid2 allows the diesel to be shutoff for two periods each day. The user may specify the beginning and end of each of those periods. The forced diesel shutoff over rides all other requirements for use of the diesel, including meeting the load, normal charging of the batteries, or boost charging.

Offset in Net Load to Force Diesel to Start: There are no additional details applicable to this offset. See the previous section.

Dispatch Order for Multiple Diesels: In a multi-diesel system, choices need to be made about which diesels should be run at any given time. This is referred to as diesel allocation. Diesels can be allocated either according to a user-specified strategy or using a built-in optimizer. In either case, the basic structure of the model is similar. The following paragraphs outline the model employed. The differences between the user-specified strategy and the optimizer are also discussed.

The diesel operating strategy is based on two concepts: 1) diesel configurations and 2) diesel operating states. Configurations specify which diesels are actually operating. Configurations are defined by subsets of the total available diesels, Nd. Configurations are chosen based on the required rated capacity at any time. Operating states refers to how those diesels within the operating configuration are operated (e.g. at minimum load, rated load, or following the load).

Diesel Configurations: The choice of diesel configuration is based on the order of the possible configurations and the required rated power. Diesels can be allocated either according to a user specified strategy or using a built-in "optimizer." If the user specifies the operating strategy, the allowed configurations are input, in the order they are to be considered by the code. In the "optimizer," the model determines the configurations, and their order according to their fuel use at the minimum allowed power level. Within a given configuration, it is also assumed that the diesels are operated in the most efficient way possible. This is true whether the user selected strategy or "optimizer" is used.

It should be noted that the "optimizer" does not guarantee that the fuel use of any given configuration will necessarily be less than that of some other configuration when run at higher power levels. Depending on the intercepts and slopes of the various fuel curves, it may be possible for one configuration to have a lower fuel consumption than another one at one power level, but a higher consumption at another power level. For many real diesels, however,

configurations chosen as described above will remain in the same relative order over all their operating range. The only apparent way to obtain a better estimate of the absolute minimum fuel use would be to select the configurations through an evaluation of the fuel use corresponding to the mean load at each time step. Because no diesel systems are known to employ such a method, and because of the additional complexity it would have added to Hybrid2, the simpler method discussed here was employed.

When the "optimizer" is used, the configuration number is determined by a figure of merit, the minimum allowed fuel consumption for the configuration, $F_{i,m}$, where

$$F_{i,m} = \sum_{k=1}^{N_{di}} [a_{i,k} + P_{m,i,k}\ b_{i,k}] \tag{7.4.1}$$

i	= Configuration number
$a_{i,k}$	= No load fuel consumption of the k_{th} diesel in the i_{th} configuration, fuel units/hr
$b_{i,k}$	= Slope of fuel vs. power curve for the k_{th} diesel, fuel units/kWh
$P_{m,i,k}$	= Minimum allowed power level of the k_{th} diesel, kW
$N_{d,i}$	= Number of diesels in the i_{th} configuration, -

Thus, $F_{i,m} < F_{i+1,m}$.

Given N diesels, there can be up to 2^N configurations. Because of the large number of possible configurations, the present form of the code is restricted to 7 diesels. The number of diesels in the ith configuration is $N_{d,i}$. The configuration number is an ordered variable. That is, when the code seeks to supply a net load with diesels it checks each configuration in order to see if the rated power is sufficient to meet the requirement (which is normally either the maximum net load or the mean net load in the interval). The first configuration which can meet that requirement is the one selected.

The allocation strategy determines, first of all, which of the configurations is in operation at any time. Secondly, it ensures that diesels are running at minimum load, rated load, or following the load, as described above. The dispatching strategy falls into two categories: 1) no-storage, 2) with storage.

1. <u>No storage</u>. In the no-storage case the configuration of the diesels that are on is determined by the maximum net load during the interval, the immediately previous operating history (when a minimum run time is specified), and by the fuel efficiency or by the user defined allocation strategy as described above. In the no-storage case, all of the diesels may be turned off, if this is specified in the input parameter file.
2. <u>Storage</u>. When storage is included in the system, determination of the diesel configuration is more involved. The prime consideration is the method of battery discharge selected. This topic is discussed in the dispatch model section of this chapter.

<u>Diesel Operating States</u>: Each configuration has several possible operating states. The diesel states define how the load is to be divided between the diesels when it is less than the rated load of the configuration. The choice of state for each diesel is determined by the diesels' fuel

efficiency. The approach used is to have each diesel run in one of three possible ways: 1) at minimum allowed power, 2) at rated power, or 3) following the load. Normally, in a multi-diesel system, only one diesel will follow the load. The most efficient diesel(s) will preferentially run at rated power. The least efficient will run at minimum. Using this approach, the ith configuration will have Nd,i+1 states. The first state corresponds to all diesels running at the minimum allowed power. In this case, it is assumed that any power generated in excess of the load will be dumped. The last state corresponds to all but one of the diesels running at rated. The remaining diesel (the least marginally efficient) follows the load. For parts of any finite time interval, diesels could operate in more than one state, depending on the instantaneous load. In theory, each of the states could be occupied for some fraction of the time.

When linear fuel vs. power curves are applied (as is done in Hybrid2,) the fuel use of a multi-diesel configuration may be minimized by ordering the states according to the fuel curve slope. The shallowest slopes correspond to the marginally most efficient diesels. Thus

$$k_1 < k_2 \text{ if } b_{i,k_1} < b_{i,k_2}. \tag{7.4.2}$$

where, for example, k_1 is the kth diesel in the first configuration. That the above method will lead to minimum fuel use within a configuration can be shown by considering the alternative. Suppose that the load, L, is such that N_d diesels must be on, and that diesels 1, 2, ...N_d have fuel curve slopes such that as the subscripts increase, so too, do the slopes. That is, $b_1<b_2<...<b_{Nd}$. Suppose, too, that the rated power and minimum load of each diesel are $P_{R,1}$, $P_{R,2}$, ..., $P_{R,Nd}$ and $P_{m,1}$, $P_{m,2}$, ..., $P_{m,Nd}$. Furthermore, the load is assumed to be such that at least one of the diesels may be run at less than rated. Thus M diesels are either running at or above the minimum load. The implication of the above discussion is that the minimum fuel use should be given by:

$$F_m(L) = \sum_{i=1}^{N_d} a_i + \sum_{i=1}^{M-1} b_i\, P_{R,i} + b_M\left[L - \sum_{i=1}^{M-1} P_{R,i}\right] \tag{7.4.3}$$

Suppose, however, that there is actually some other way of running the diesels which would result in less fuel use. At least one of the diesels assumed to be running at rated would have to be run at some other level. Suppose the j_{th} diesel is run at $P_{*,j}$ which is less than $P_{R,j}$. The lowest fuel use from this method, $F_m^*(L)$, would be given by:

$$F_m^*(L) = \sum_{i=1}^{N_d} a_i + \sum_{i=1}^{j-1} b_i\, P_{R,i} + b_j\, P_{*,j} + \sum_{i=j+1}^{M-1} b_i\, P_{R,i} + b_M\left[L - \sum_{i=1}^{M-1} P_{R,i} + (P_{R,j} - P_{*,j})\right] \tag{7.4.4}$$

For $F_m^*(L)$ to be less than $F_m(L)$, a little algebra reveals that it would have to be true that:

$$b_j\, P_{*,j} + b_M\, (P_{R,j} - P_{*,j}) < b_j\, P_{R,j} \tag{7.4.5}$$

Upon further rearrangement, Eq. 7.4.5 implies that

$$P_{*,j}\left(b_j - b_M\right) < P_{R,j}\left(b_j - b_M\right) \tag{7.4.6}$$

However, by assumption b_M is always greater than b_j. Therefore, the term is brackets is always negative, which would imply that $P_{*,j} > P_{R,j}$. The latter is an impossibility, so it is reasonable to conclude that the minimum fuel use is indeed found as discussed above.

Example. Suppose that a hybrid power system has two diesels one of which is rated at 10 kW and the other at 20 kW. Assume that the 10 kW diesel has no load fuel consumption of 2 units/hr and the 20 kW diesel consumes 3 units/hr at no load. The full load fuel consumption of the smaller unit is 6 units/hr while the larger one consumes 10 units/kW. The minimum allowed power for each of them is 40% of full load, or 4 kW for the smaller and 8 kW for the larger one. The fuel vs. power slope for the two diesels is (6-2)/10= 0.4 units/kWh for the smaller and (10-3)/20 = 0.35 for the larger engine. There are four possible configurations. The first has no diesels. The second has one of the diesels. The third has the other, and the fourth has both. The minimum allowed fuel consumption of the one with no diesels is clearly zero. The smaller diesel's fuel consumption at 4 kW is 2 + 4 x 0.4 = 3.6. The larger diesel's fuel consumption is 3 + 8 x 0.35 = 5.8. When both diesels are used the corresponding value is 9.4. The configuration order for the optimizer is: 1) no diesels, 2) 10 kW diesel, 3) 20 kW diesel, 4) both diesels. When both diesels are running, the 10 kW diesel is run at its minimum allowed power as long as possible since it has the higher incremental fuel use, while the 20 kW diesel picks up the rest of the load. When the load exceeds 24 kW, the 20 kW runs at rated and the 10 kW follows the load.

Battery and Diesel Dispatch Theory

As stated previously, system dispatch deals with the interaction of the storage and the diesel generator(s). There are three major concerns in this category: diesel power level, diesel starting criteria, and diesel stopping criteria.

<u>Diesel Operating Power Level</u>: There are a number of subtleties associated with the diesel power level. As noted above the case where there is no storage is relatively straightforward, but when storage is involved the situation is more complex. In general, there are three options:

1) The load is shared among the diesels and battery, with battery use given preference ("Load following, Battery Preference").
2) The diesel is run at full rated power if the energy can be used or stored ("Rated Power/Charge Limited").
3) The diesels are run to supply the net load if possible ("Load following, Diesel Preference").

The simplest case with storage is to run the diesels at full output or not at all. The assumption is also made that the diesels in this case are run at as close to full output as they can, subject to the constraint that the power generated can be stored or used. This corresponds to Option (2).

The next situation arises if the net load might be supplied partially by diesels and partially by batteries. In principle, there could be nearly any fraction coming from the batteries with the rest coming from the diesels. At one extreme, with relatively inexpensive battery cost per cycle, plentiful renewable energy, and expensive diesel fuel, a strategy of maximizing the use of stored energy might be preferred. At the other extreme, with expensive battery cost per cycle, and less expensive diesel fuel, the option of running the diesels at a higher fraction of their rated capacity might be preferable. In either case, the user has the choice of which method to use. These cases correspond to Options 1 and 3.

Diesel Starting Criteria: There are two possible criteria for starting the diesels. In the first case, the diesels will be started only if the net load can not be met in any other way (consistent with the other system dispatch parameters, particularly the forced diesel shutoff period). In the second case, the diesel(s) will be started if the battery state of charge has fallen below some specified level. Note that in systems with multiple diesels, it will not generally be the case that all of the diesels will come on for battery charging. Rather, the first configuration (as described above) that includes at least one diesel will be used, unless the net load requires a configuration with greater diesel capacity.

Diesel Stopping Criteria: There are five possible reasons for stopping the diesel(s). Note, however, that these criteria will be superseded by any minimum diesel run time requirements (as detailed below, diesels may be required to run for a minimum period of time) or by a forced diesel shutoff time.

1) Renewables (wind and solar) and batteries together can meet the load. This scenario is most sparing of diesel use. It indicates that whenever there is enough energy available in the storage and renewables to supply the load, the diesel(s) may be shutoff.
2) Renewables alone can meet the load. This corresponds to the case of the net load being equal to or less than zero. This is more sparing of the batteries than the first scenario, in that the diesels will continue to run, supplying the remainder of the net load, rather than draw from storage.
3) Renewables can supply the load or the batteries are fully charged. In this case, there are two possible ways that could lead to the diesel being shut down. First of all, if the renewables could supply the entire load, as in Option (ii) above, the diesels would shut down. Second, if the battery were fully charged, as in Option (iv) below, they would also go off. The presumption would then be that the remainder of the net load, if it could not be met by renewables, would be supplied from the battery.
4) The batteries are charged to the user-specified upper charge limit. In this case, at least one diesel continues to run until the battery is charged to the user-specified upper charge limit. This continues regardless of the amount of renewables available.
5) Only some of the diesels are needed (multi-diesel cases). This is the normal case for multiple diesels. Diesels will turn off in accordance with the net load. There is no separate constraint, for example that they all be on or off.

7.5 Diesel Fuel Use

7.5.1 Executive Summary

The determination of fuel use requires the diesel engine component models and knowledge about the fluctuating load imposed on the diesel. The first step in finding the fuel use is the determination of the diesel configuration, as described elsewhere. The fuel use in the interval is then found depending on the fraction of time the diesels are operating at various power levels. These power levels may not correspond to the net load depending on the availability of storage and minimum diesel load requirements.

7.5.2 Overview of Fuel Use Calculations

The fuel use in the simulation time step depends on the fraction of time the diesels are operating at various load levels and the fuel consumption at those loads. These load levels may not correspond to the net load depending on the availability of storage and minimum diesel load requirements.

Single Diesel Operation

In the single-diesel case there are then two possible operating conditions: above minimum load and below minimum load. The fuel consumption is the sum of the fuel consumption while the diesel is at minimum load and the fuel consumption for the average load above minimum load while the diesel is above the minimum load. The excess power produced when the load is below the minimum allowed load will go to storage, to a secondary load, or be dumped, depending on the situation. This topic is discussed in the loads section of Chapter 5. Suppose that the net load sometimes exceeded the rating of the first diesel. With the use of storage to meet the transient peaks, a second diesel would not operate. The one diesel might operate for a significant fraction of the time at the rated power level. In this case, the fuel consumption would also include the fuel consumption corresponding to rated load while the load was above rated load and being met, in part, by storage.

Multiple Diesel Operation

When more diesels are operating, the situation is similar to that for one diesel, except that there are more possible operating regions, and the calculations are more complicated. For two diesels the net load may be 1) less than the minimum of both diesels, 2) above the minimum of the two but less than the minimum of the less efficient plus the rated of the better diesel, 3) greater than the minimum of the less efficient plus the rated of the better diesel. Again, when storage is available, a fourth region (4) would be that in which both of the diesels are running at rated power. The fuel use is calculated similarly to the single diesel case by summing up the fuel consumption rate times the time that the diesel operates at a given load level for all of the possible loads.

7.5.3 Details of Fuel Use Calculations

The determination of fuel use requires the diesel engine component models and knowledge about the fluctuating load imposed on the diesel. The first step in finding the fuel use is the determination of the diesel configuration, as described in the dispatch model section of this chapter. The fuel use in the interval is then found in accordance with the fraction of time the diesels are in various possible states.

Single Diesel Operation

Consider, for example, the simplest case where the maximum load is less than the rated power of the best diesel. Only a single diesel will be on. There are then two possible operating conditions: above minimum load and below minimum load. In this single diesel case, the fuel consumption rate, F, is:

$$F = a_1 + b_1\left[P_{min,1}\int_{-\infty}^{P_{min,1}} p(N)\,dN + \int_{P_{min1}}^{P_{R,1}} N\,p(N)\,dN\right] \tag{7.5.1}$$

where

a_1	= No load fuel consumption of 1st diesel, fuel units/hr
b_1	= Incremental fuel consumption of 1st diesel, fuel units/kWh
$P_{min,1}$	= Minimum power level of 1st diesel, kW
$P_{R,1}$	= Rated power level of 1st diesel, kW
N	= Net load (diesel power), kW
p(N)	= Probability density function of net load, -.

The first integral represents the amount of time that the diesel is running at the minimum level. The second integral corresponds to the average power in excess of the minimum. The combined term in brackets is the average diesel power throughout the interval. The excess power, produced when the load is below the minimum will go to storage, to a secondary load, or be dumped, depending on the situation. This topic is discussed in the loads section of Chapter 5.

Suppose that the net load sometimes exceeded the rating of the first diesel. With the use of storage to meet the transient peaks, the second diesel would not operate. The one diesel might operate for a significant fraction of the time at the rated power level. In this case, another fuel consumption term, $F_{N>P_{R,1}}$,would have to be included in the brackets corresponding to the average power during that fraction of time. This is given by:

$$F_{N>P_{R,1}} = P_{R,1}\int_{P_{R,1}}^{\infty} p(N)\,dN \tag{7.5.2}$$

Multiple Diesel Operation

When more diesels are operating, the situation is similar to that for one diesel, except that there are more possible operating regions. For two diesels the net load may be 1) less than the minimum of both diesels, 2) above the minimum of the two but less than the minimum of the less efficient plus the rated of the better diesel, 3) greater than the minimum of the less efficient plus the rated of the better diesel. Again, when storage is available, a fourth region (4) would be that in which both of the diesels are running at rated power. In general, the following equation will apply where the net load served by the diesels is assumed to be normally distributed over the time step. As described in Manwell and McGowan (1993a), the fuel consumption of the ith configuration is given by (note that i subscripts are removed to simplify the equation):

$$F = \sum_{j=1}^{N_d+1}\left\{\int_{P_{lo,j}}^{P_{up,j}} p(N)\,dN\left(\sum_{k=j}^{N_d} P_{m,k}(b_k - b_{j-1}) + \sum_{k=1}^{j-1} P_{R,k}(b_k - b)_{j-1}\right)\right\} + b_{j-1}\int_{P_{lo,j}}^{P_{up,j}} N\,p(N)\,dN$$
$$+\sum_{k=1}^{N_d}\left[a_k + P_{m,k}\,b_k\int_{0}^{P_{min}} p(N)\,dN\right] \tag{7.5.3}$$

where

j	= Ordered index of states, -
k	= Dummy index, -
N	= Net load on the diesels, kW
$p(\ )$	= Probability density function (short term fluctuation), -
$P_{lo,j}$	= Lower power level of the jth state, kW
$P_{up,j}$	= Upper power level of the jth state, kW
$P_{m,k}$	= Ordered minimum allowed diesel power, kW
$P_{R,k}$	= Ordered rated diesel power, kW
P_{min}	= Total minimum power of ith configuration, kW.

The integrals in Eq. 7.5.3 are solved by assuming, as before, that all the distributions are normal, so that they may expressed in terms of the error function. Thus Equations 5.2.10 and 5.2.15 are applied here. The approximations for the error function, Equations 5.2.12, 5.2.13, and 5.2.14 are also used.

References

-, "Standard Performance Testing of Wind Energy Conversion Systems," AWEA Standard AWEA 1.1-1988, Washington, DC, 1988.

Barley, C. D., "A Versatile Dispatch Scheme for Remote Hybrid Energy Systems," NREL Wind Division Report, July, 1994.

Beyer, H. G., et al., "Power Fluctuations from Geographically Diverse, Grid Coupled Wind Energy Conversion System," Proc. EWEC, Glasgow, 1989.

Braun, J. E. and Mitchell, J. C., "Solar Geometry for Fixed and Tracking Surfaces," Solar Energy, 31, p. 439, 1983.

Christensen, C. J., et al., Accuracy of Power Curve Measurements, Riso-M-2632, Riso National Laboratory, Roskilde, Denmark, 1986.

Collins, J. A., Failure of Materials in Mechanical Design, Wiley, New York, 1981.

Downing, S. D. and Socie, D. F., "Simple Rainflow Counting Algorithms," International Journal of Fatigue, January, p 31, 1982.

Duffie, J. A. and Beckman, W. M. , Solar Engineering Of Thermal Processes, 2nd Edition, Wiley, New York, 1991.

Erbs, D. G., Klein, S. A., and Duffie, J. A., "Estimation of the Diffuse Radiation Fraction for Hourly, Daily, and Monthly-Average Global Radiation," Solar Energy, 28, p. 293, 1982.

Facinelli, W. A., "Modeling and Simulation of Lead-Acid Batteries for Photovoltaic Systems," Proc. 18th IECEC, 1983.

Fordham, "Spatial Structure of Turbulence in the Atmosphere," Wind Engineering, 9, pp. 95-135, 1985.

Freris, L. L. (ed.), Wind Energy Conversion Systems, Prentice Hall International Ltd., Hemel Hempstead (UK), 1990.

Green, H. J. and Manwell, J. F., "Hybrid2- A Versatile Model of the Performance of Hybrid Power Systems," Proc. AWEA 1995, 1995.

Hansen, A. C., "Correlation of Wind Turbine Power Output with Turbulent Winds," Report ASC 19296PB, Solar Energy Research Institute, 1985.

Hunter, R. and Elliot G., Wind-Diesel Systems, Cambridge Univ. Press, Cambridge (UK), 1994.

Hyman, E., et al., "Modeling and Computerized Characterization of Lead-Acid Battery Discharges," BEST Facility Topical Report, RD 83-1, EPRI, 1986a.

Hyman, E., et al., "Phenomenological Discharge Voltage Model for Lead Acid Batteries," Proc. AIChe Meeting, Mathematical Modeling of Batteries, Nov., 1986b.

Infield D. G., et al., "Wind Diesel System Modeling and Design," Proc. EWEC 90, pp. 569-574, 1990.

IEC, Wind Turbine Generator Systems, Part 1: Safety Requirements, IEC 1400-1, Geneva, Switzerland, 1996.

Jeffries, W. Q., Infield, D. and Manwell, J. F., "Limitations and Recommendations Regarding the Shinozuka Method for Simulating Wind Data," Wind Engineering, 15, No. 3, 1991.

Jeffries, W. Q., "Smoothing of Power from Multiple Wind Machines," University of Massachusetts: NREL Report, Jan., 1992.

Kaminsky, F. C., Kirchhoff, R. H., and Syu, C. Y., "A Statistical Technique for Generating Missing Data from a Wind Speed Time Series," Proceedings of the Annual Conference of the American Wind Energy Association, Washington, DC., September, 1990.

Keller, J. G., "Fatigue Life Prediction Program for Wind Turbines," Report LTR-LA-302 (Draft), 1987.

Kristensen, L., Panofsky, H. A., and Smith, S. D., "Lateral Coherence of Longitudinal Wind Components in Strong Winds, Boundary Layer Meteorology, 21, pp. 199-205, 1981.

Manwell, J F, et al., "Development of Quasi-Steady Analytical Models for Wind/Diesel Systems," Proc. Ninth ASME Wind Energy Symposium, ASME Publication SED-Vol. 9, pp. 223-230, 1990.

Manwell J F, et al., "Hybrid Systems Modeling: Development and Validation," Wind Engineering 18(5), pp. 241- 255, 1994a.

Manwell, J. F. and McGowan, J. G., "A Combined Probabilistic/ Time Series Model for Wind Diesel Systems Simulation," Solar Energy 53(6), pp. 481- 490, 1994.

Manwell, J. F. and McGowan, J. G., "A Lead Acid Battery Storage Model for Hybrid Energy Systems," Solar Energy, 50, No. 5., pp. 399- 405, 1993b.

Manwell, J. F. and McGowan, J. G., "A Screening Level Model for Wind Diesel System Simulation" Solar '93, Proceedings of the 1993 ASES Annual Conference, pp. 342- 350, 1993a.

Manwell, J. F. et al. "Recent Progress in Battery Models for Hybrid Wind Power Systems," Proc 1995 AWEA Annual Conference, March, 1995.

Manwell, J. F., and McGowan, J. G., "A New Battery Storage Model for Wind/Diesel Systems," Proceedings of the AWEA Annual Conference, Palm Springs, CA, September, 1991.

Manwell, J. F., Deng, G., and McGowan, J. G., "A Markov Process Based Performance Model for Wind/Diesel/Battery Storage Systems," Proc. EWEC '94, 1994b.

Manwell, J. F., et al., "Investigations into Power Fluctuations of a Horizontal Axis Wind Turbine," Proceedings of the European Wind Energy Conference, Amsterdam, October, 1991

Manwell, J. F., Jeffries, W. Q., and McGowan, J. G., "Power Fluctuations from a Horizontal Axis Wind Turbine," Proceedings of the 10th ASME Wind Energy Symposium, Houston, TX, January, 1991.

McNerney, J. and Richardson, R., "The Statistical Smoothing of Power Delivered from Utilities by Multiple Wind Turbines," IEEE Transactions on Energy Conversion, 7, No. 4, pp. 644-647, 1992.

Norgaard, P., "Limitations in Variable Speed Operation of Stall Regulated Wind Turbines," Proc. 16th BWEA Conference, Stirling, UK, 1994.

Papoulis, A., Probability, Random Variables, and Stochastic Processes, McGraw-Hill, New York, 1984.

Press, W. H., Teukolsky, S. A, Vetterling, W. T., Flannery, B. P., Numerical Recipes in FORTRAN: The Art of Scientific Computing, 2nd Ed., Cambridge University Press, New York, 1992.

Rogers, A. L., The Development of UMLTM, a Quasi Steady State Wind/Diesel Model, M. S. Project Report, Dept. of Mechanical Engineering, University of Massachusetts, Amherst, MA 01003, May, 1989.

Skarstein, O., and Uhlen, K, "Design Considerations with Respect to Long-Term Diesel Saving in Wind/Diesel Plants," Wind Engineering, 13, No. 2, 1989.

Spanier, J. and Oldham, K., An Atlas of Functions, Hemisphere Publishing Corp., New York, 1987.

Thresher, R. W., Hock, S. M., and Osgood, R. M., "Data Records Length Effects on Rainflow Analysis," ASME Wind Energy Symposium, SEED-12, 1992.

Townsend , T. U., A Simplified Method for Estimating the Long Term Performance of Direct-Coupled Photovoltaic Systems, M.S. Thesis, Mechanical Engineering, U. of Wisconsin-Madison, 1989.

Appendices

Appendix 1 - Proof of Equation 6.1.11

The equivalence between Eq. 6.1.8 and Eq. 6.1.11 may be shown as follows. The proof is based on the nomenclature presented in Section 6.1.4.

For the two equations to be equivalent it must be true that:

$$\int_0^\infty P(V)\, p_2(V)\, dV = \int_0^\infty P_{\Delta t_1}(\bar{V}_1)\, p_{1-2}(\bar{V}_1)\, d\bar{V}_1 \tag{6.1.14}$$

Substituting Eq. 6.1.5 into Eq 6.1.14 yields:

$$\int_0^\infty P(V)\, p_2(V)\, dV = \int_0^\infty \int_0^\infty P(V)\, p_1(V)\, dV\, p_{1-2}(\bar{V}_1)\, d\bar{V}_1 \tag{6.1.15}$$

Eq 6.1.15 can be rearranged to give:

$$\int_0^\infty P(V)\, p_2(V)\, dV = \int_0^\infty P(V) \left[\int_0^\infty p_1(V)\, p_{1-2}(\bar{V}_1)\, d\bar{V}_1 \right] dV \tag{6.1.16}$$

The only way for Eq. 6.1.16 to be true is if the integrands are equal. In other words, it must be true that:

$$p_2(V) = \int_0^\infty p_1(V)\, p_{1-2}(\bar{V}_1)\, d\bar{V}_1 \tag{6.1.17}$$

By making the substitutions for the assumed normal distribution as given above, Eq 6.1.17 is equivalent to:

$$\frac{1}{\sigma_{V_2} \cdot \sqrt{2\pi}}\, e^{-\frac{1}{2}\left(\frac{V-\bar{V}_2}{\sigma_{V_2}}\right)^2} = \int_0^\infty \frac{1}{\sigma_{V_1} \cdot \sqrt{2\pi}}\, e^{-\frac{1}{2}\left(\frac{V-\bar{V}_1}{\sigma_{V_1}}\right)^2} \frac{1}{\sigma_{V_{1-2}} \cdot \sqrt{2\pi}}\, e^{-\frac{1}{2}\left(\frac{\bar{V}_1-\bar{V}_2}{\sigma_{V_{1-2}}}\right)^2} d\bar{V}_1 \tag{6.1.18}$$

After some algebraic manipulation it is left to show that the following integral is equal to 1:

$$1 = \int_0^\infty \frac{\sigma_{V_2}}{\sigma_{V_1} \sigma_{V_{1-2}} \cdot \sqrt{2\pi}}\, e^{-\frac{1}{2}\left\{\left(\frac{V-\bar{V}_1}{\sigma_{V_1}}\right)^2 + \left(\frac{\bar{V}_1-\bar{V}_2}{\sigma_{V_{1-2}}}\right)^2 - \left(\frac{V-\bar{V}_2}{\sigma_{V_2}}\right)^2\right\}} d\bar{V}_1 \tag{6.1.19}$$

The term in brackets may be expanded and rearranged, taking advantage of the equivalence, $\sigma_{V_2}^2 = \sigma_{V_1}^2 + \sigma_{V_{1-2}}^2$. This gives a single squared term. The limits of integration may also go to negative infinity, since wind speeds are always positive. The result is:

$$1 = \int_{-\infty}^{\infty} \frac{\sigma_{V_2}}{\sigma_{V_1}\sigma_{V_{1-2}}\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{\sigma_{V_{1-2}}^2 V + \sigma_{V_1}^2 \bar{V}_2 - \sigma_{V_2}^2 \bar{V}_1}{\sigma_{V_1}\sigma_{V_2}\sigma_{V_{1-2}}}\right)^2} d\bar{V}_1 \qquad (6.1.20)$$

Making the substitution $u = -\frac{1}{\sqrt{2}} \frac{\sigma_{V_{1-2}}^2 V + \sigma_{V_1}^2 \bar{V}_2 - \sigma_{V_2}^2 \bar{V}_1}{\sigma_{V_1}\sigma_{V_2}\sigma_{V_{1-2}}}$, which also implies that $du = \frac{\sigma_{V_2}}{\sigma_{V_1}\sigma_{V_{1-2}}\sqrt{2}} d\bar{V}_1$, Eq, 6.1.20 reduces to

$$1 = \frac{1}{\sqrt{\pi}} \int_{-\infty}^{\infty} e^{-u^2} du \qquad (6.1.21)$$

The integral in Eq. 6.1.21 is indeed equal to 1, so the equivalence between Eq 6.1.8 and 6.1.11 has been demonstrated, q.e.d.

Appendix 2 - Proof of Equation 6.2.13

This proof of Eq. 6.2.13 is based on the nomenclature and information in Section 6.2.

Eq. 6.2.13 may be derived by first taking the natural logarithm of both sides of Eq. 6.2.8 and rearranging it to yield

$$\ln(I_0) - \ln(I_L) = -V_{oc} / A \qquad 6.2.14$$

Taking the derivative of 6.2.14 with respect to T_C results in

$$\frac{1}{I_0}\frac{d I_0}{d T_c} - \frac{1}{I_L}\frac{d I_L}{d T_c} = -\frac{1}{A}\frac{d V_{oc}}{d T_c} + \frac{V_{oc}}{A^2}\frac{d A}{d T_c} \qquad 6.2.15$$

The derivatives in Eq. 6.2.15 may be found as follows. First, taking the derivative of Eq. 6.2.6 gives

$$\frac{1}{I_{0,ref}}\frac{d I_0}{d T_c} = 3\frac{T_c^2}{T_{c,ref}^3} e^{\left[\frac{\varepsilon N_s}{A_{ref}}\left(1-\frac{T_{c,ref}}{T_c}\right)\right]} + \left[\frac{T_c}{T_{c,ref}}\right]^3 \left[\frac{\varepsilon N_s}{A_{ref}}\frac{T_{c,ref}}{T_c^2}\right] \qquad 6.2.16$$

The derivative of I_0 at reference conditions may be found from Eq. 6.2.16 by substituting $T_{C,ref}$ for T_C to give

$$\frac{1}{I_{0,ref}}\frac{d I_0}{d T_c} = \frac{3}{T_{c,ref}} + \left[\frac{\varepsilon N_s}{A_{ref} T_{c,ref}}\right] \qquad 6.2.17$$

In a similar manner, taking the derivative of Eq. 6.2.5 results in

$$\frac{d\,I_L}{d\,T_c} = \mu_{I,sc} \qquad 6.2.18$$

Taking the derivative of Eq. 6.2.4 gives

$$\frac{d\,A}{d\,T_c} = \frac{A_{ref}}{T_{c,ref}} \qquad 6.2.19$$

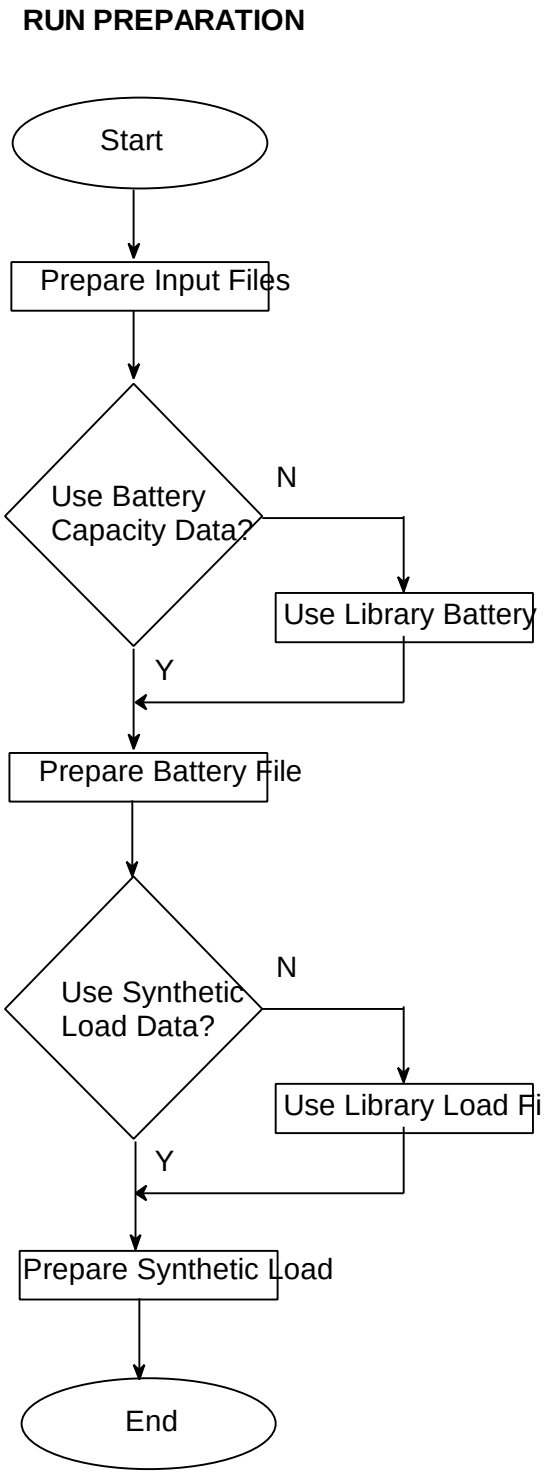
Substituting Equations 6.2.17, 6.2.18, 6.2.19 into Eq. 6.2.15, replacing $dV_{oc}\,/\,dT_c$ with $\mu_{V,oc}$ and taking I_0, I_L, V_{oc} and A to be at reference conditions results in

$$3 + \frac{\varepsilon\,N_s}{A_{ref}\,T_{c,ref}} - \frac{\mu_{I,sc}}{I_{c,ref}} = -\frac{\mu_{V,oc}}{A_{ref}} + \frac{V_{oc,ref}}{A_{ref}\,T_{c,ref}} \qquad 6.2.20$$

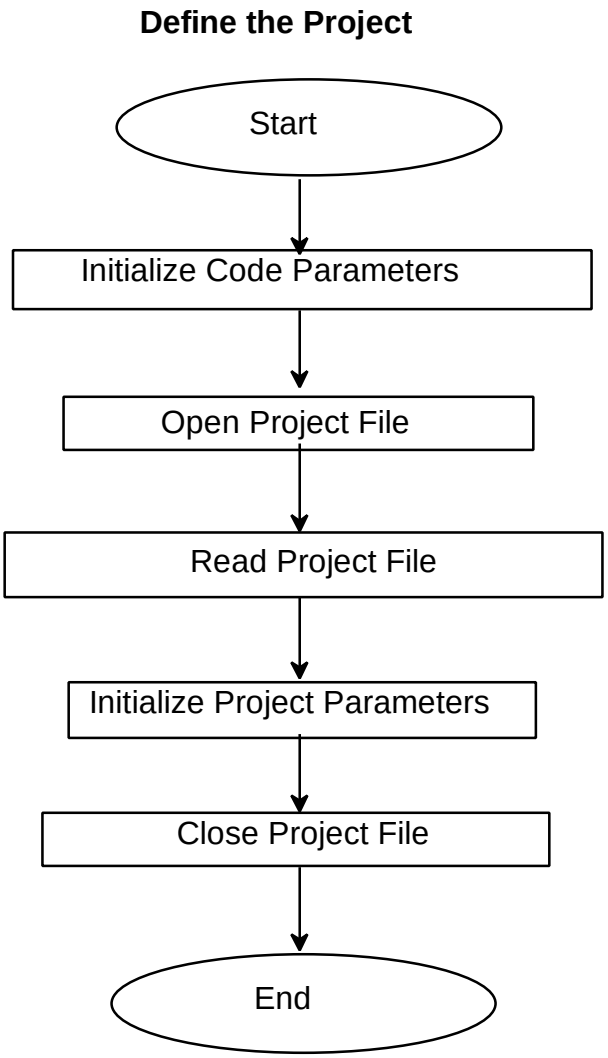
Solving Eq. 6.2.20 for A_{ref} yields Eq. 6.2.13, q.e.d.

Appendix 3 – Flow Charts

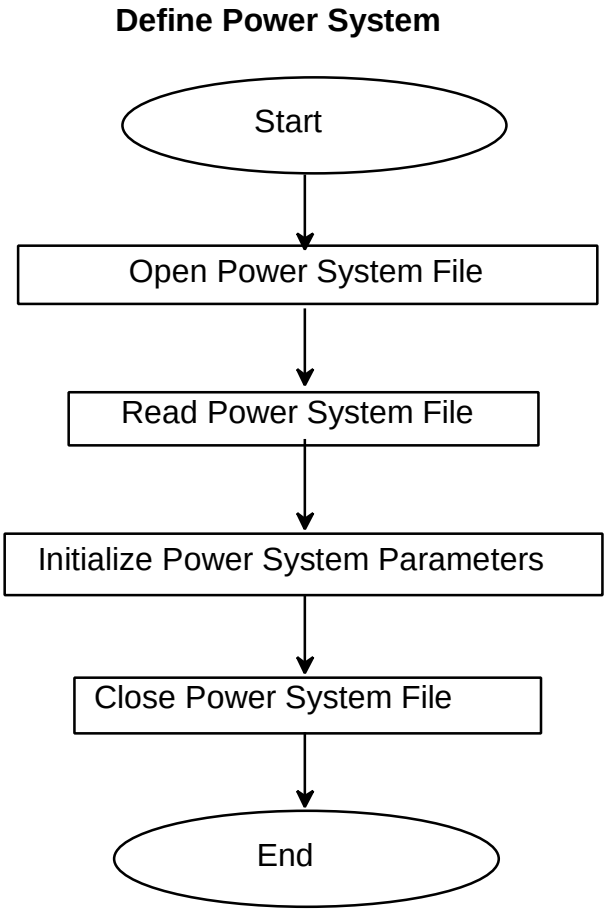
Flow Chart 1. Run Preparation Flow Chart



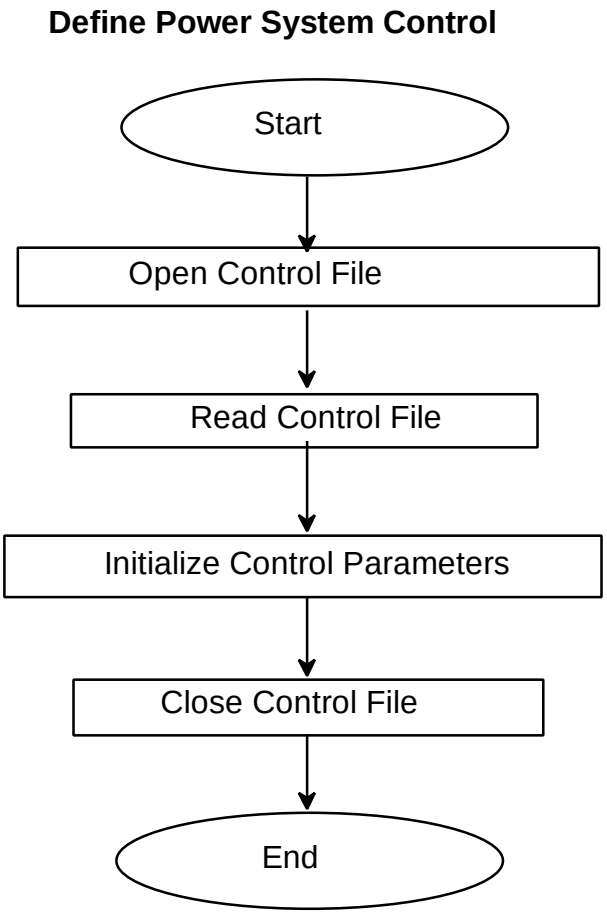
Flow Chart 2. Define Project Flow Chart



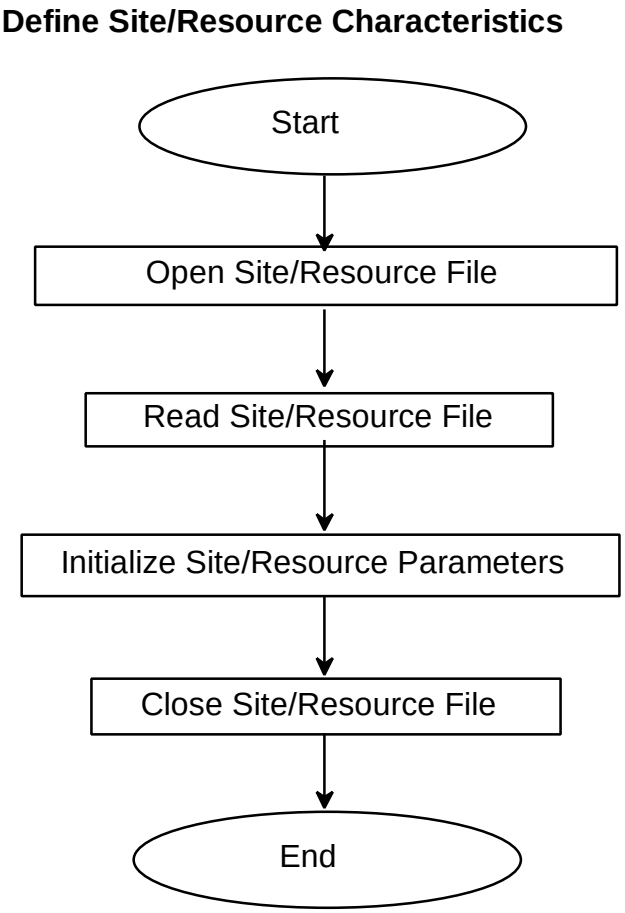
Flow Chart 3. Define Power System Flow Chart



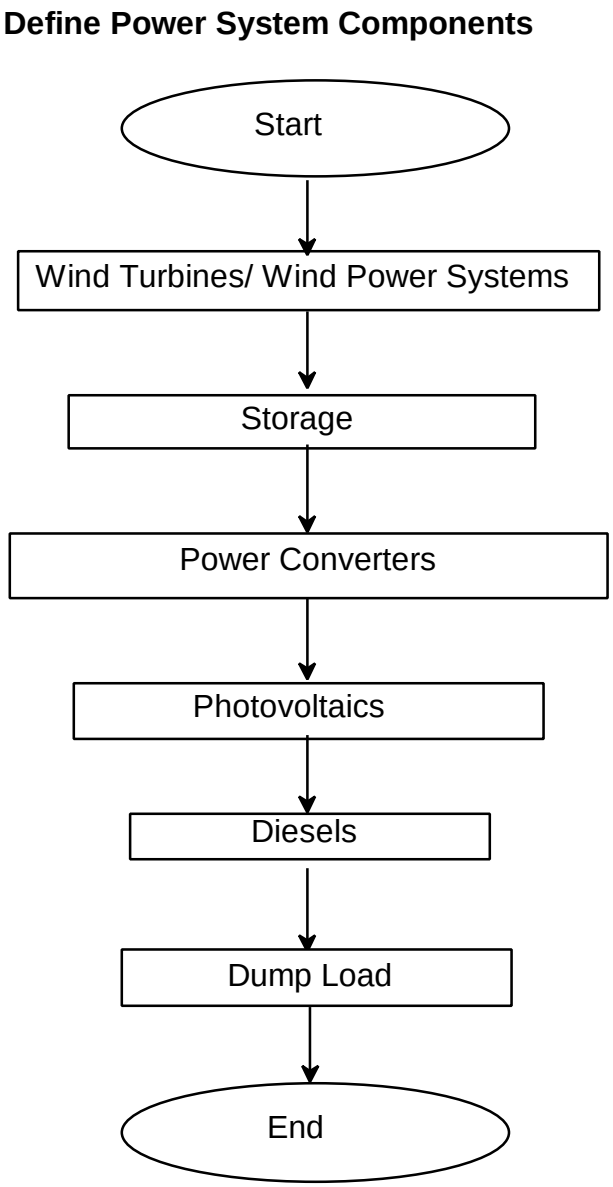
Flow Chart 4. Define Power System Control Flow Chart



Flow Chart 5. Define Site/Resource Characteristics Flow Chart

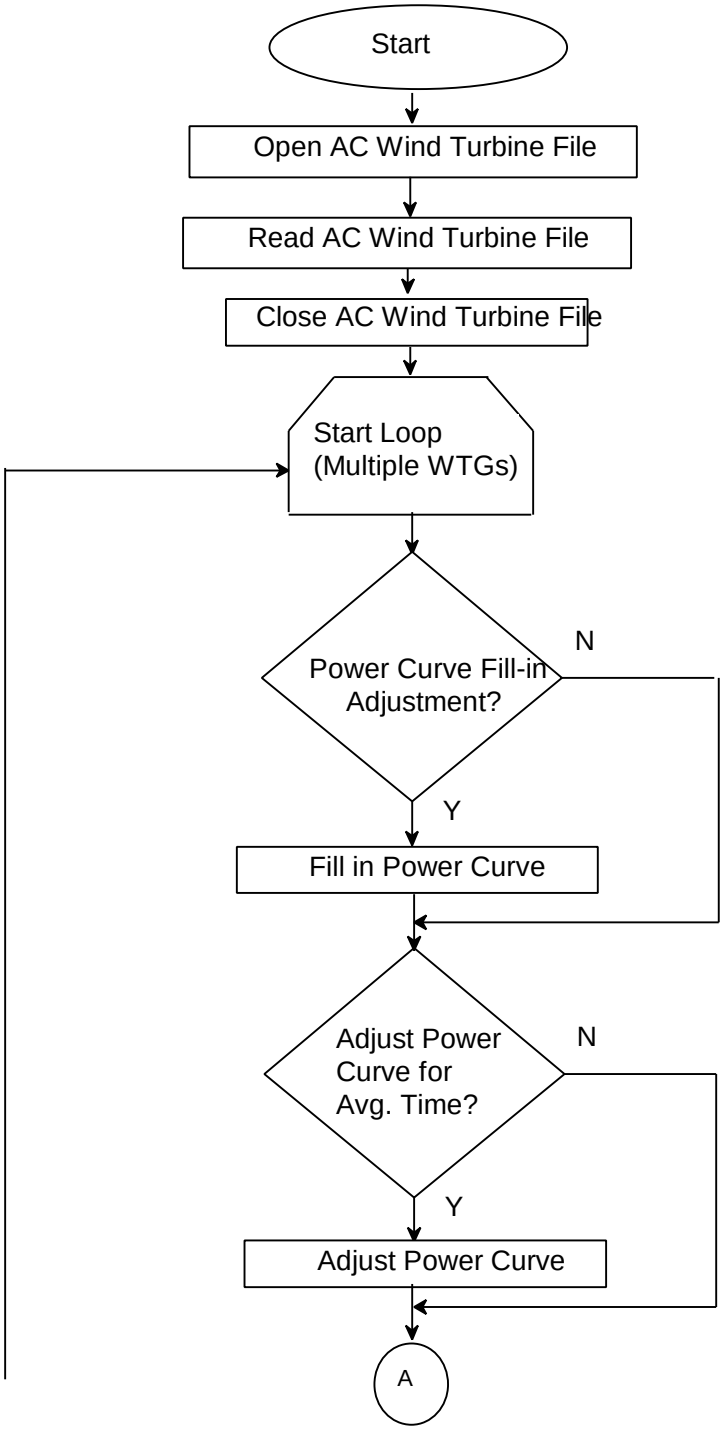


Flow Chart 6. Define Power System Components Flow Chart

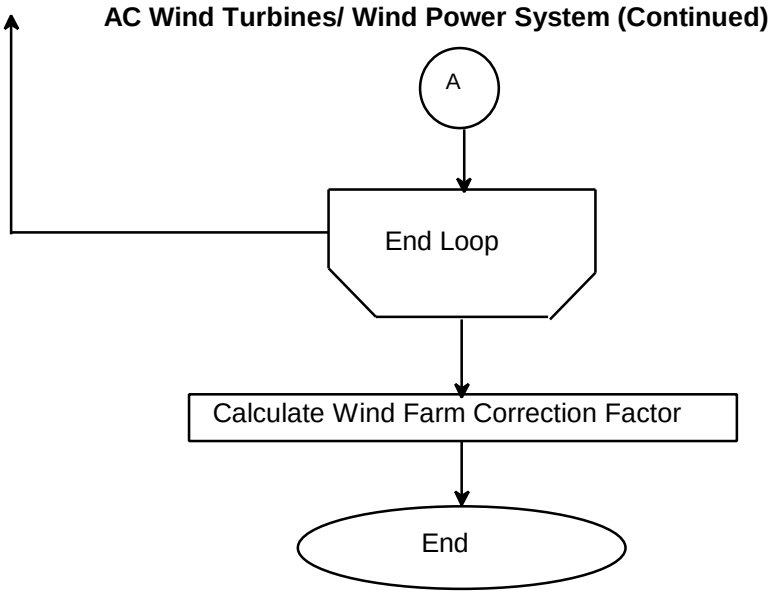


Flow Chart 7. AC Wind Turbines / Wind Power System Flow Chart

AC Wind Turbines/ Wind Power System

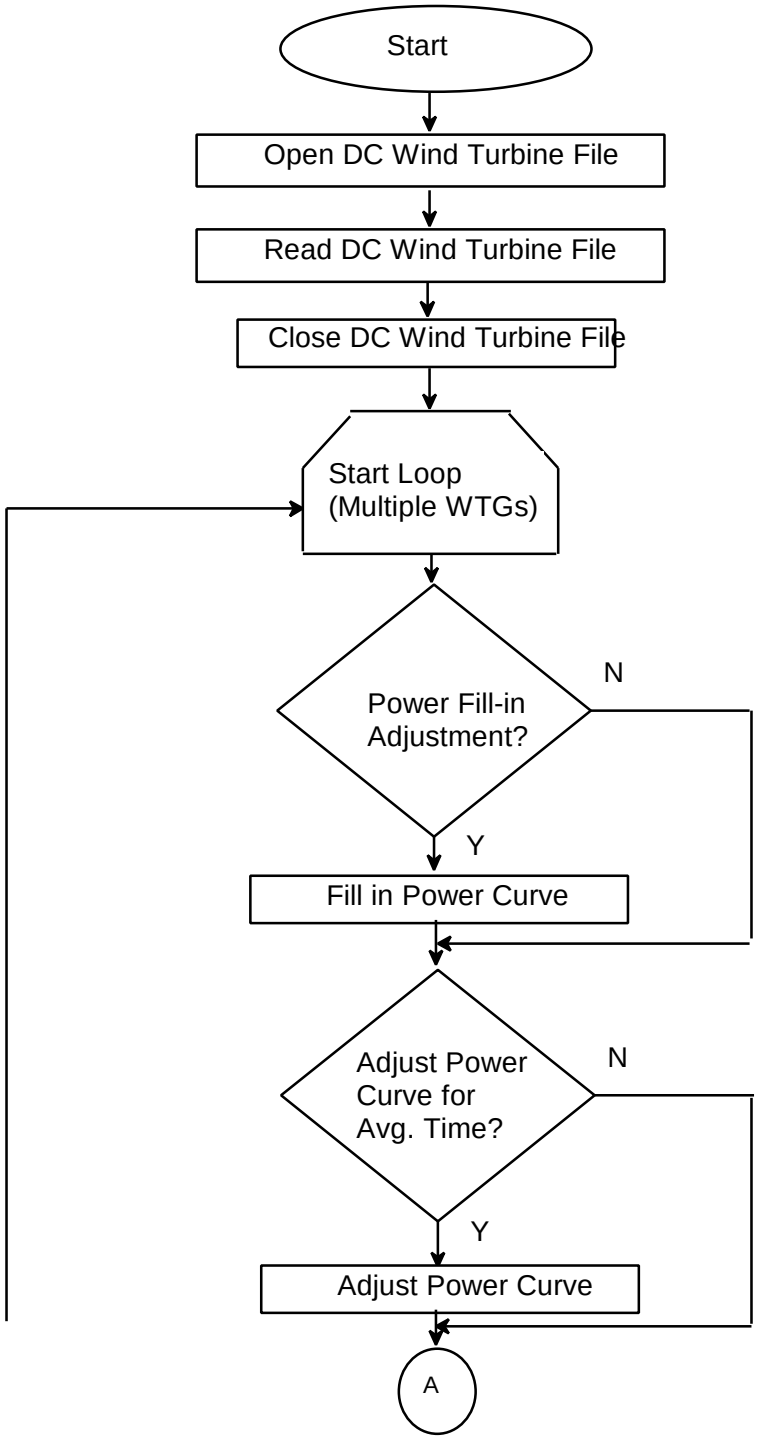


Flow Chart 8. AC Wind Turbines / Wind Power System Flow Chart (Continued)

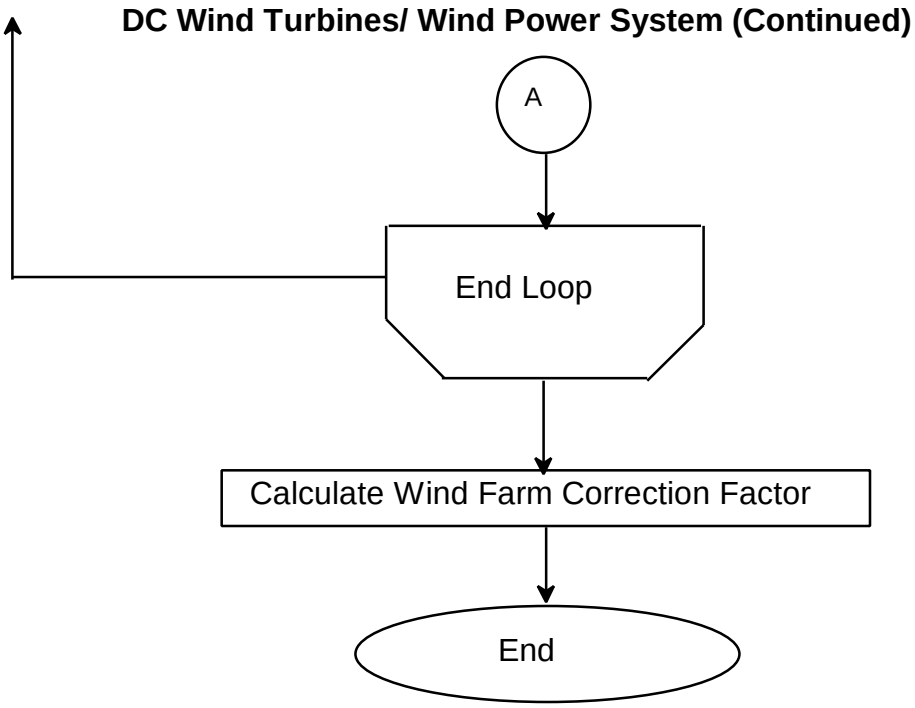


Flow Chart 9. DC Wind Turbines / Wind Power System Flow Chart

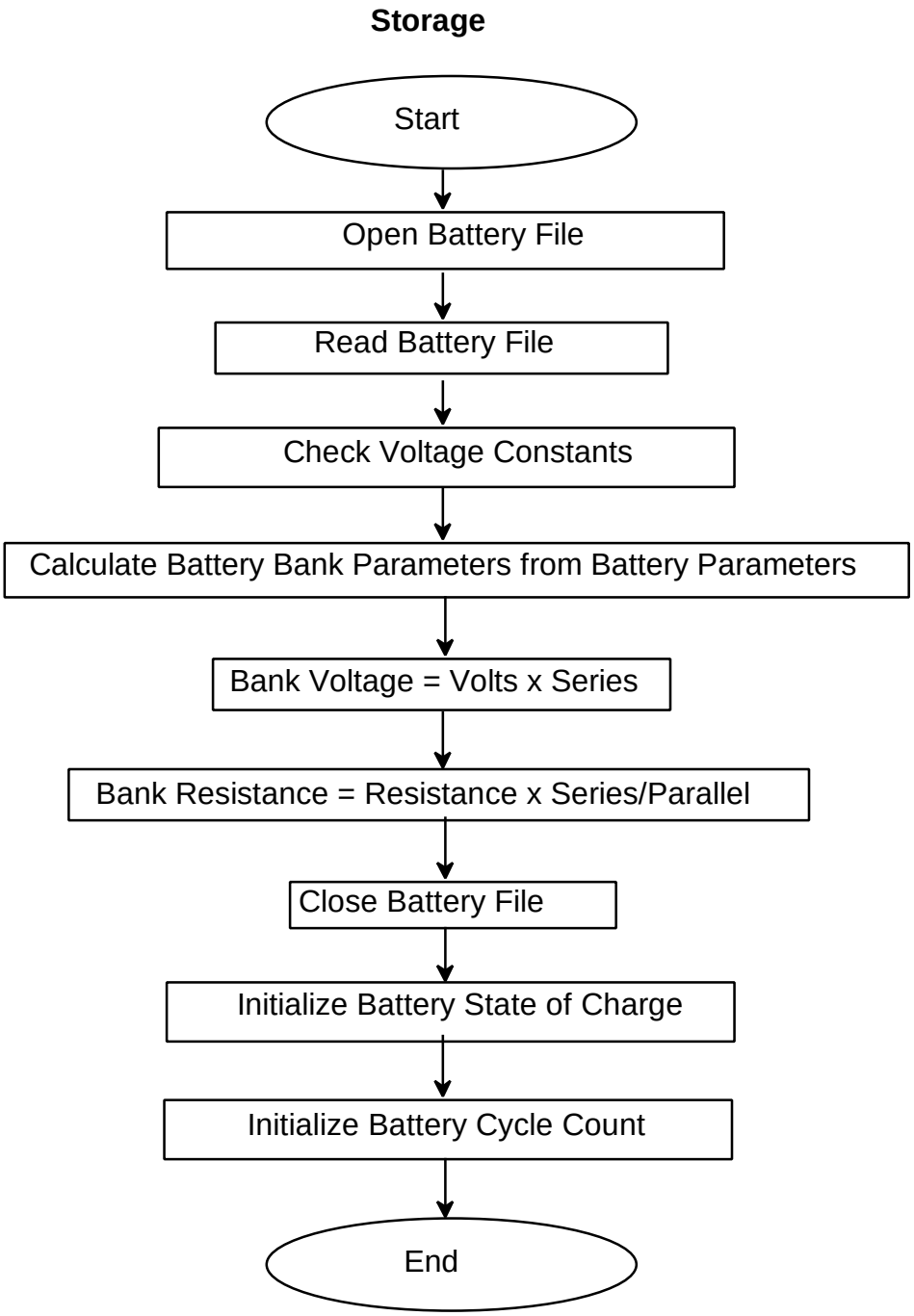
DC Wind Turbines/ Wind Power System



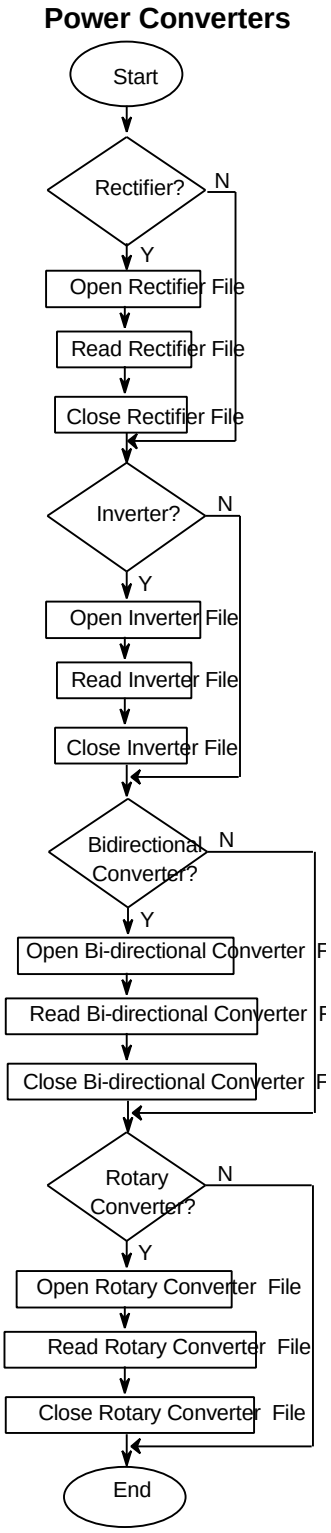
Flow Chart 10. DC Wind Turbines / Wind Power System Flow Chart (Continued)



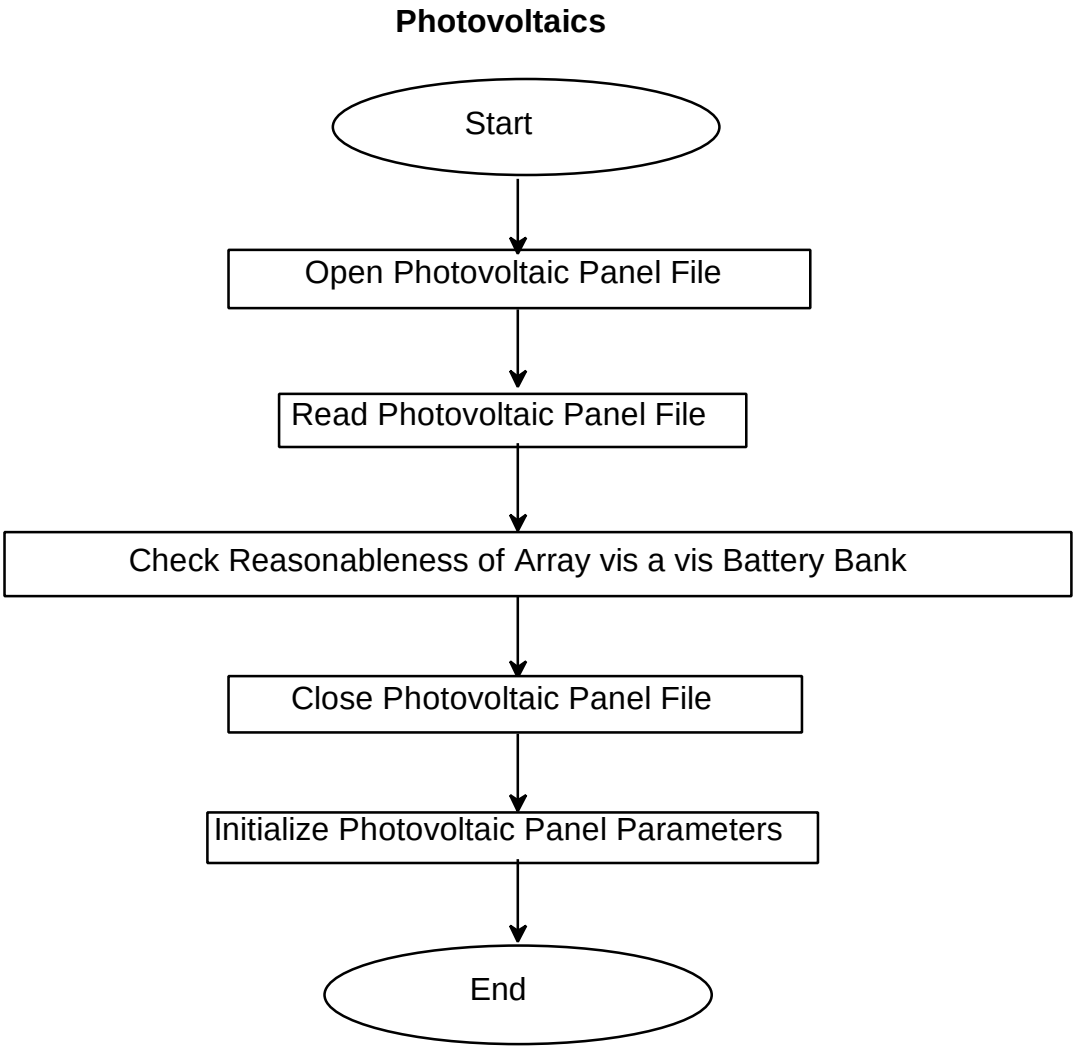
Flow Chart 11. Storage Flow Chart



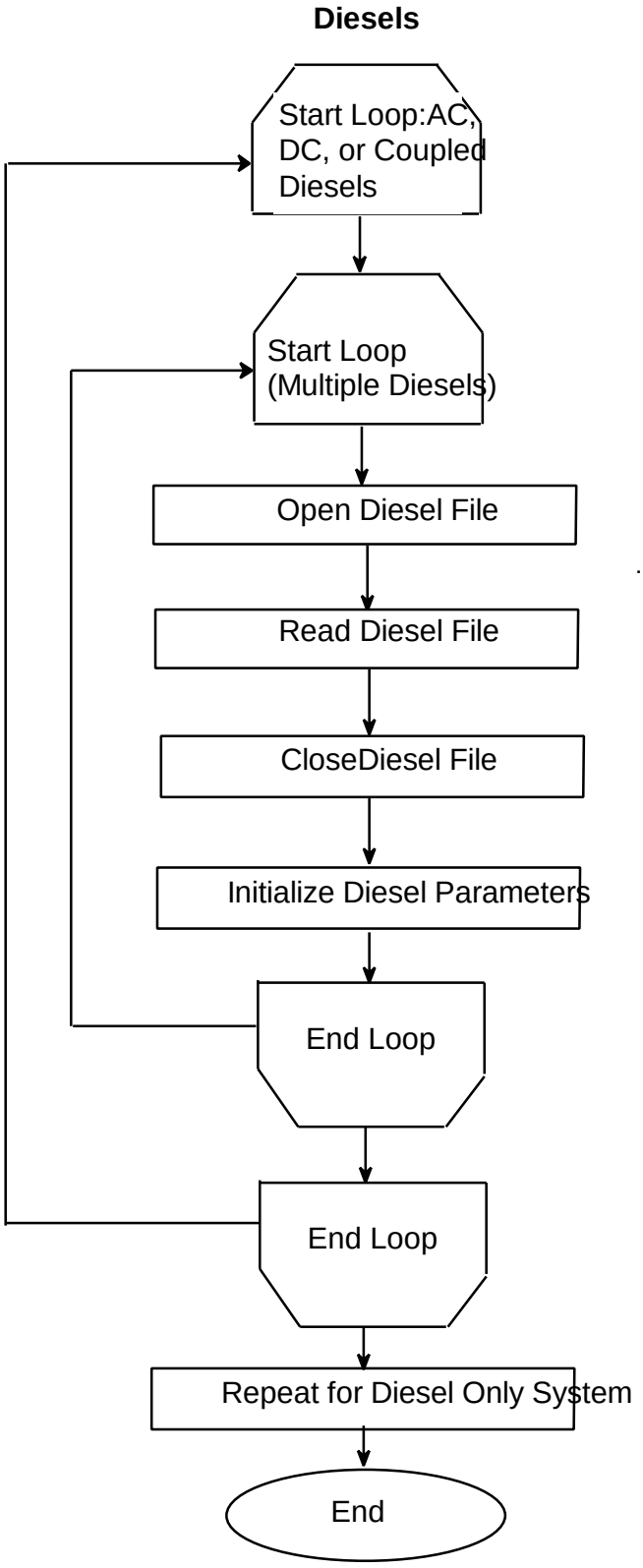
Flow Chart 12. Power Converters Flow Chart



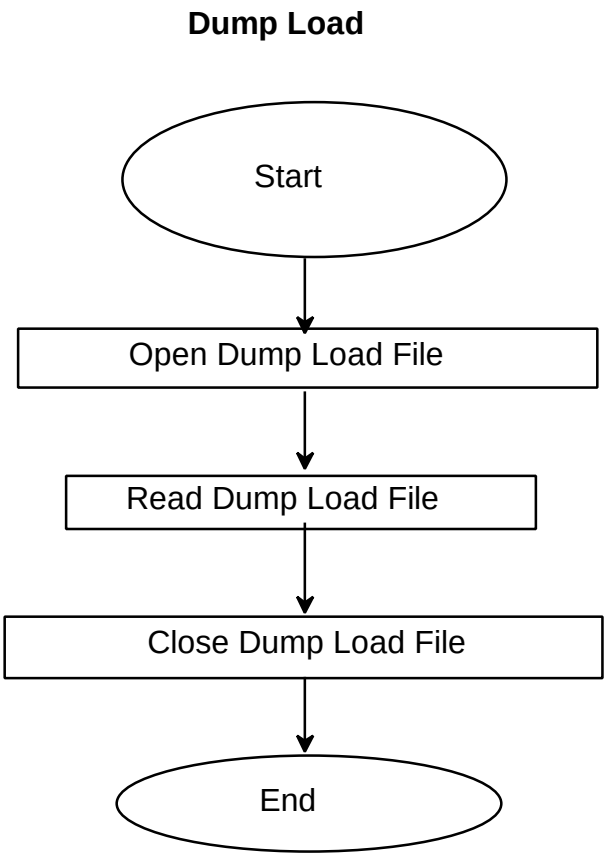
Flow Chart 13. Photovoltaic Panels Flow Chart



Flow Chart 14. Diesels Flow Chart

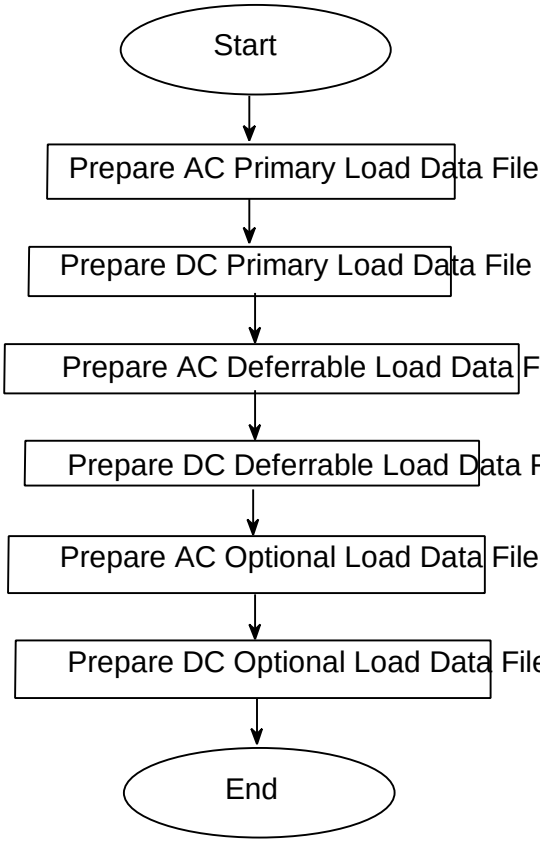


Flow Chart 15. Dump Load Flow Chart

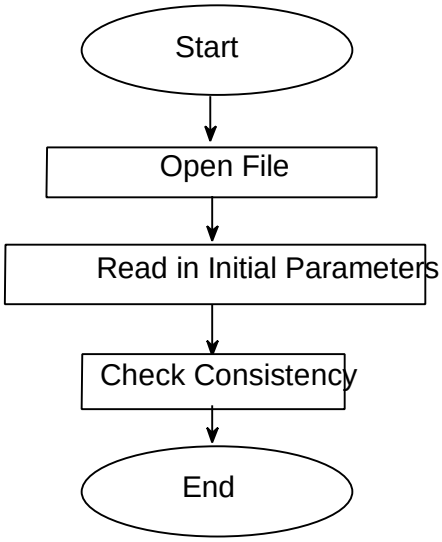


Flow Chart 16. Initialize Load Data Flow Chart

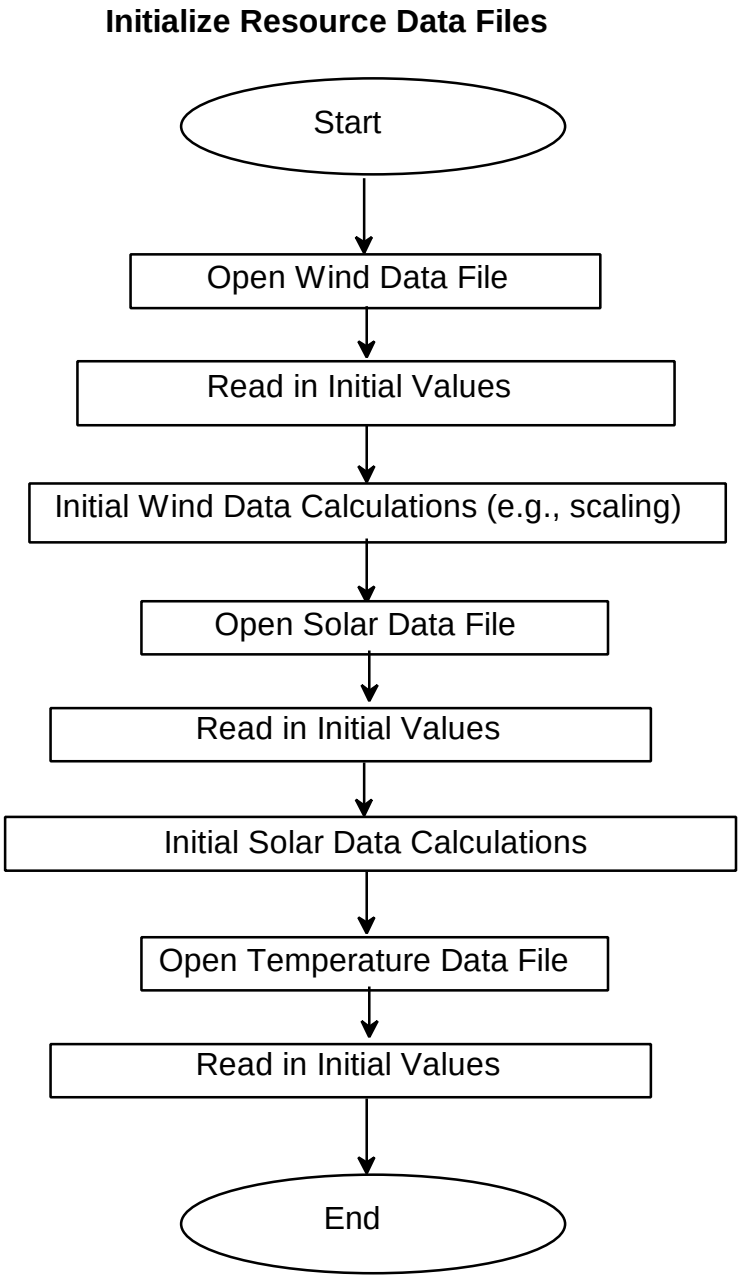
Initialize Load Data Files



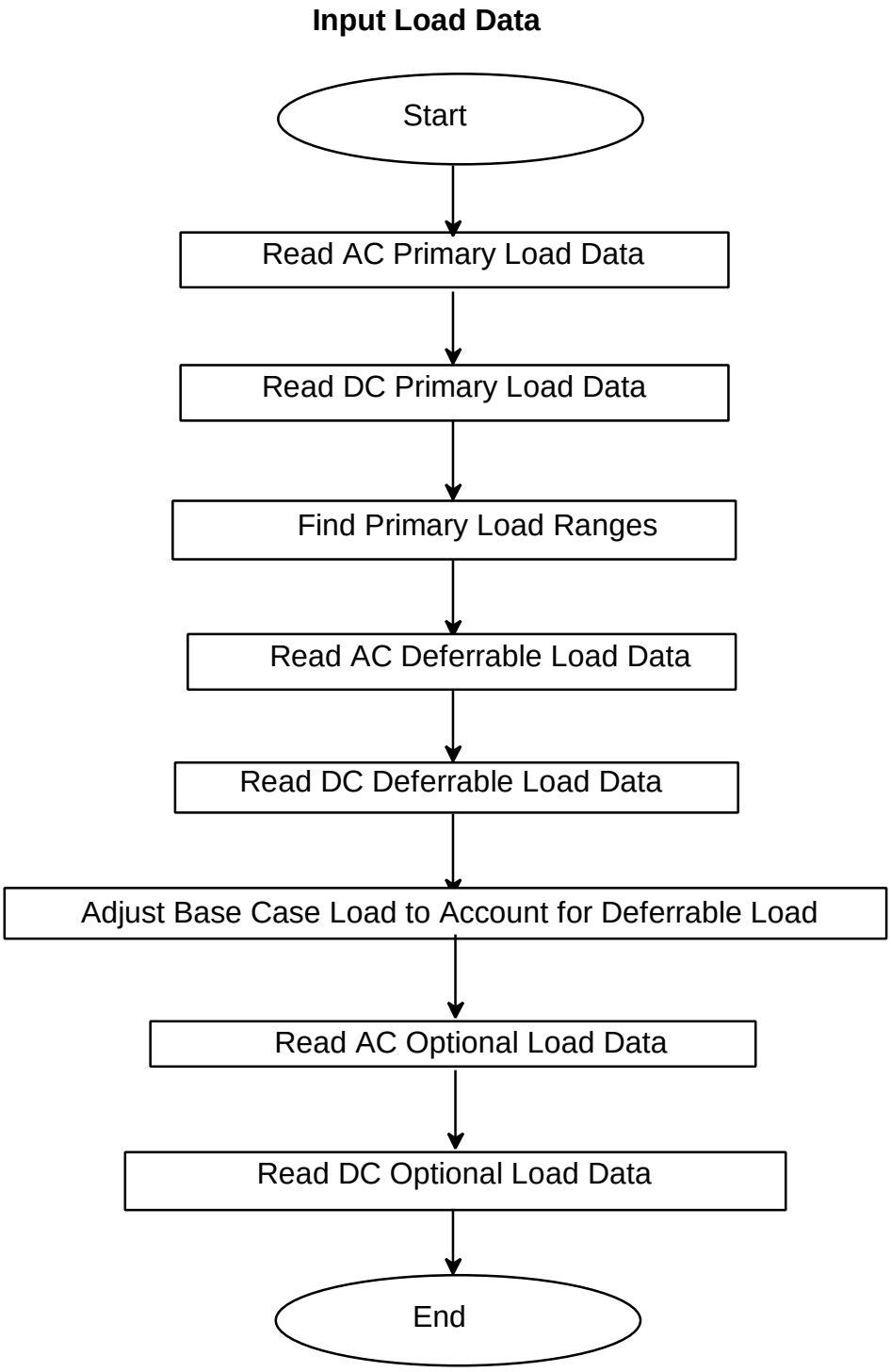
Sample Prepare Load Data File Subrou



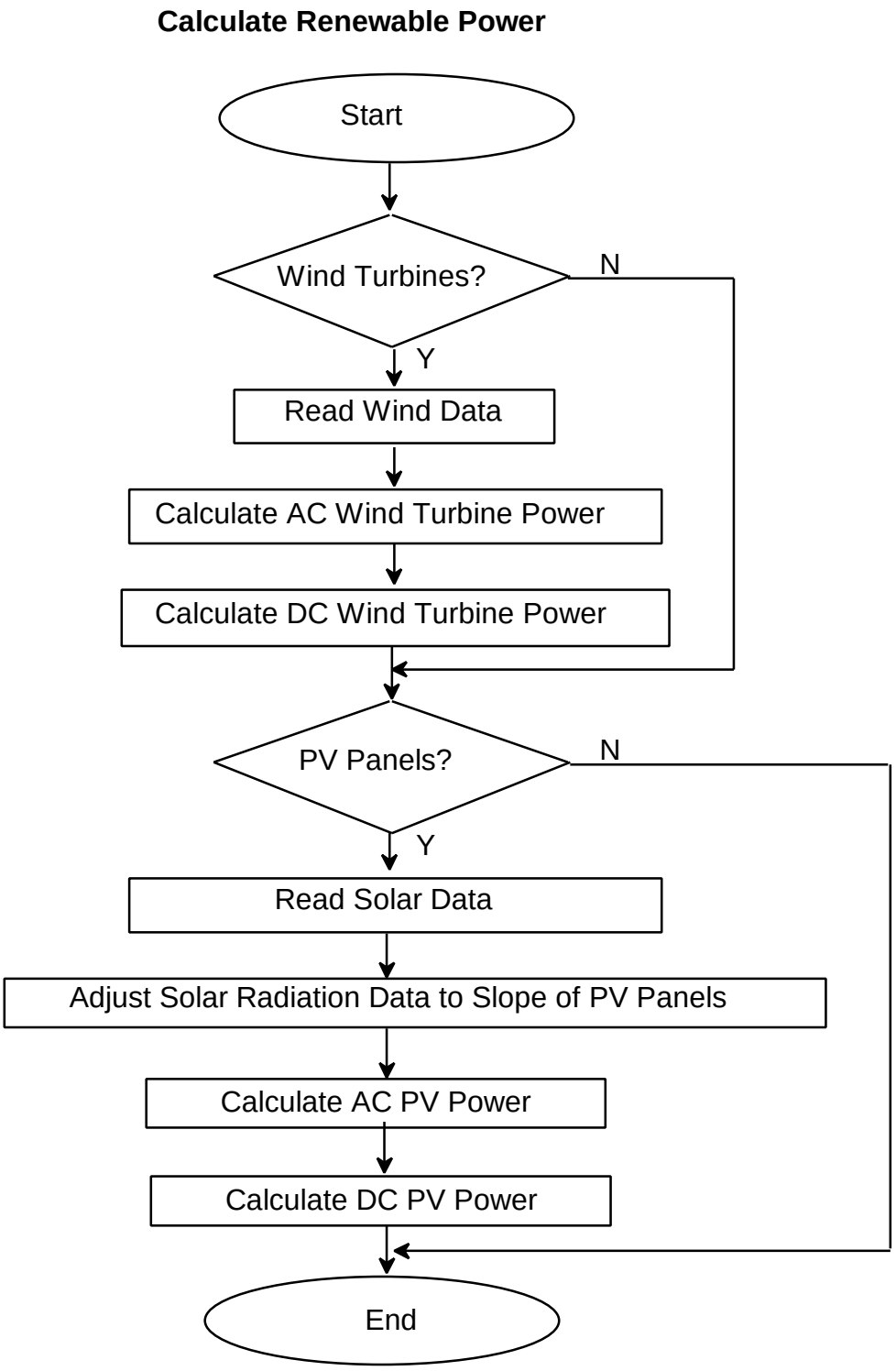
Flow Chart 17. Initialize Resource Data Flow Chart



Flow Chart 18. Input Load Data Flow Chart

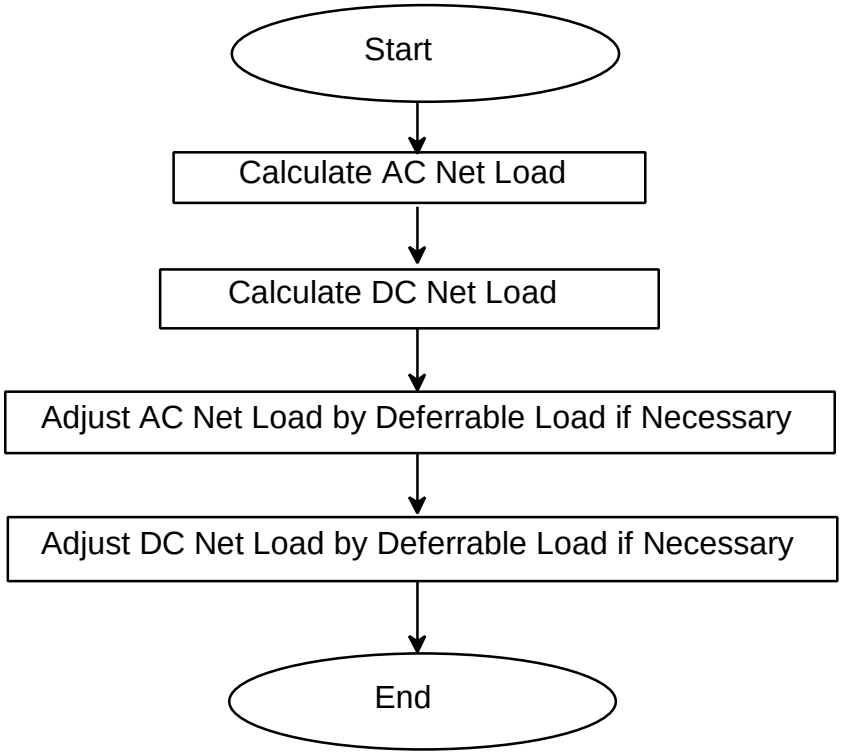


Flow Chart 19. Calculate Renewable Power Flow Chart

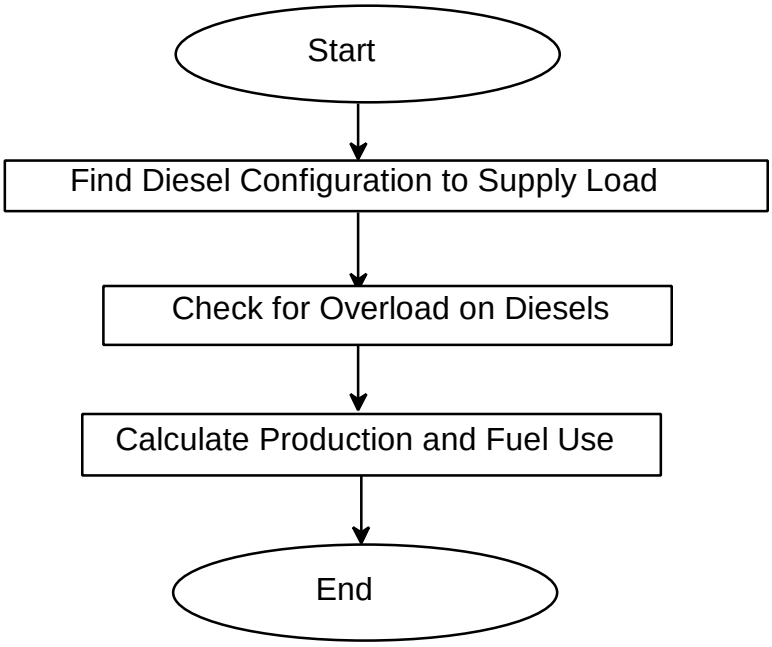


Flow Chart 20. Calculate Net Loads and Base Case Flow Charts

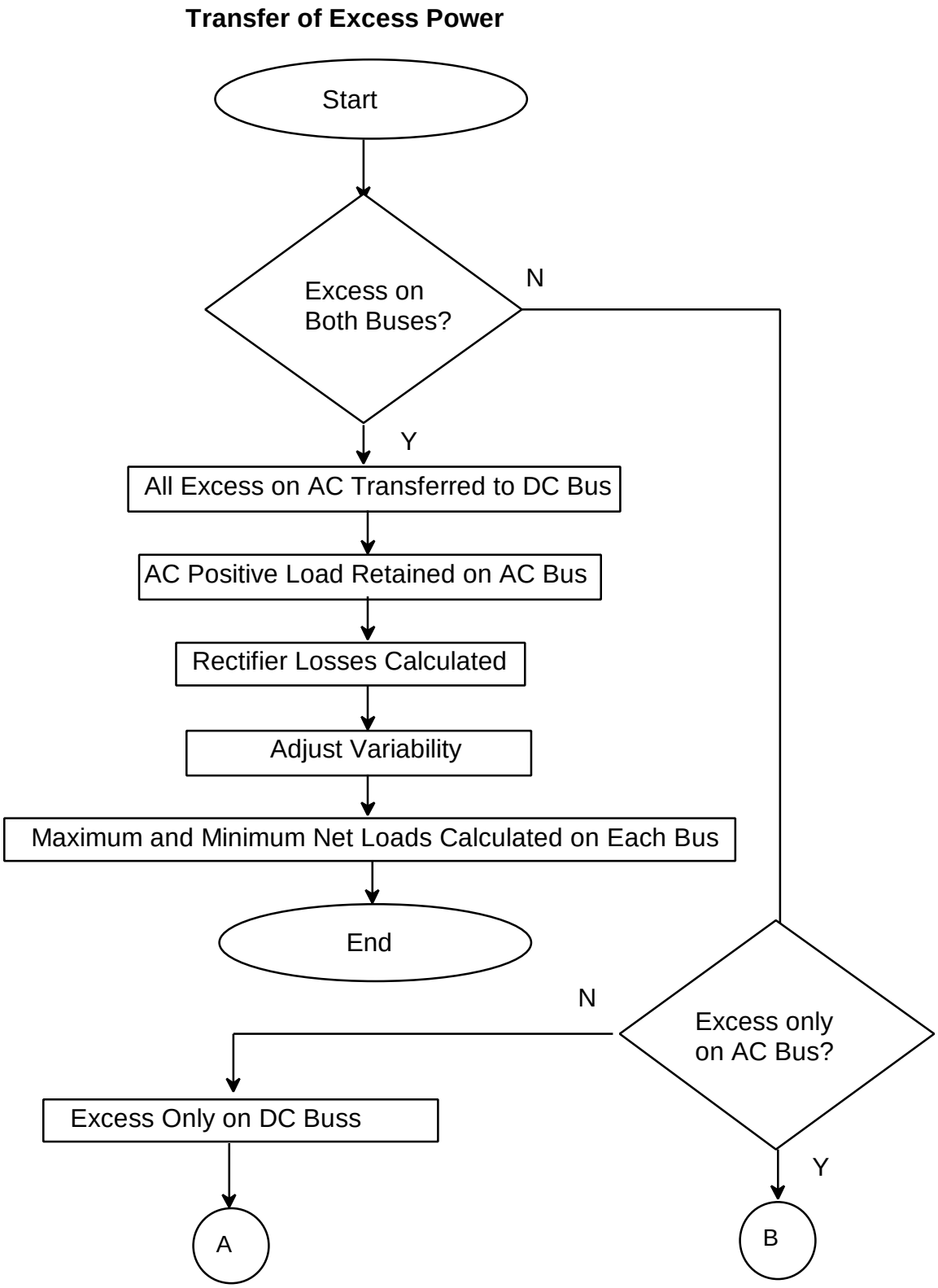
Calculate Net Loads



Base Case Calculations

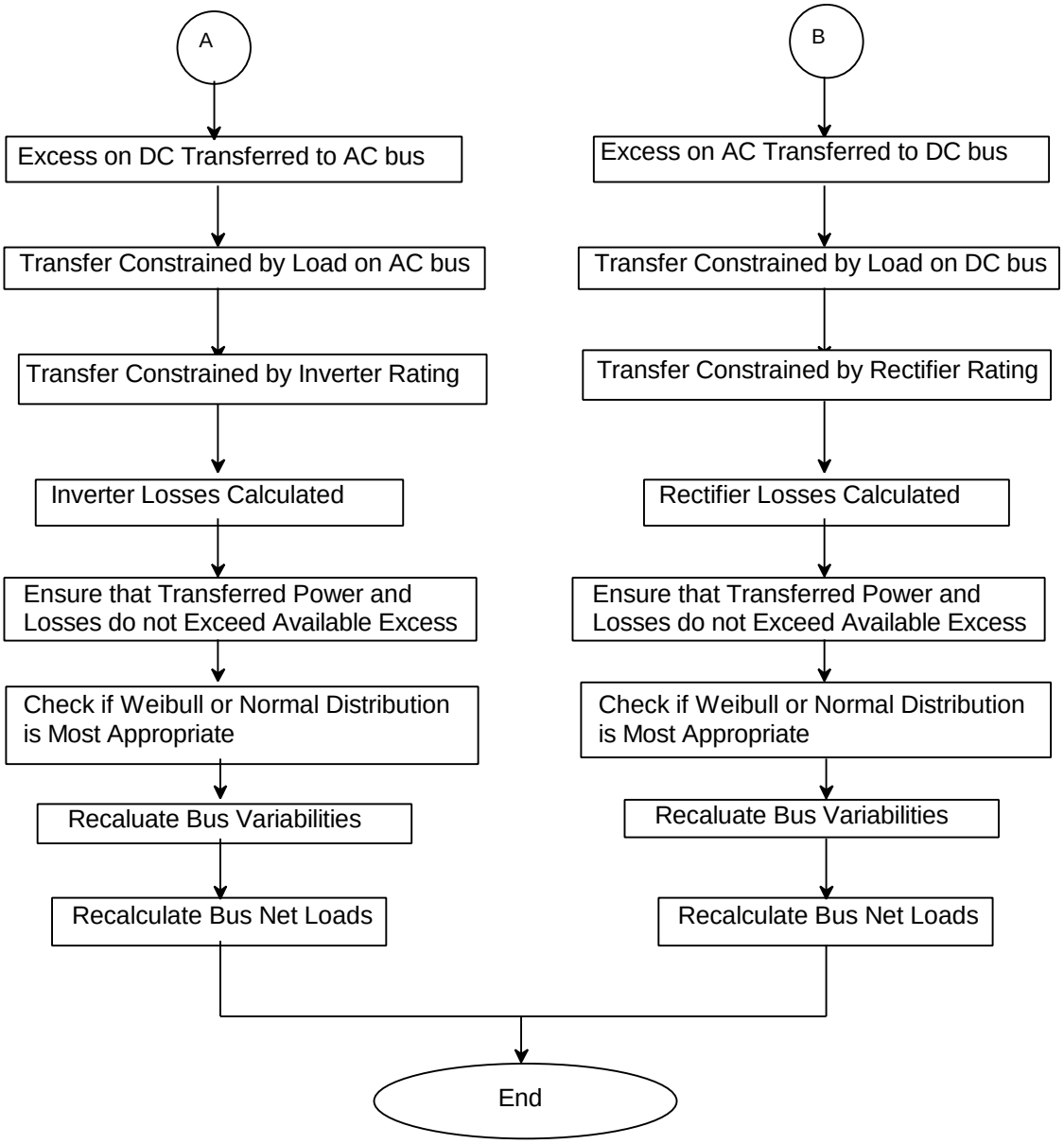


Flow Chart 21. Transfer Excess Power Flow Chart

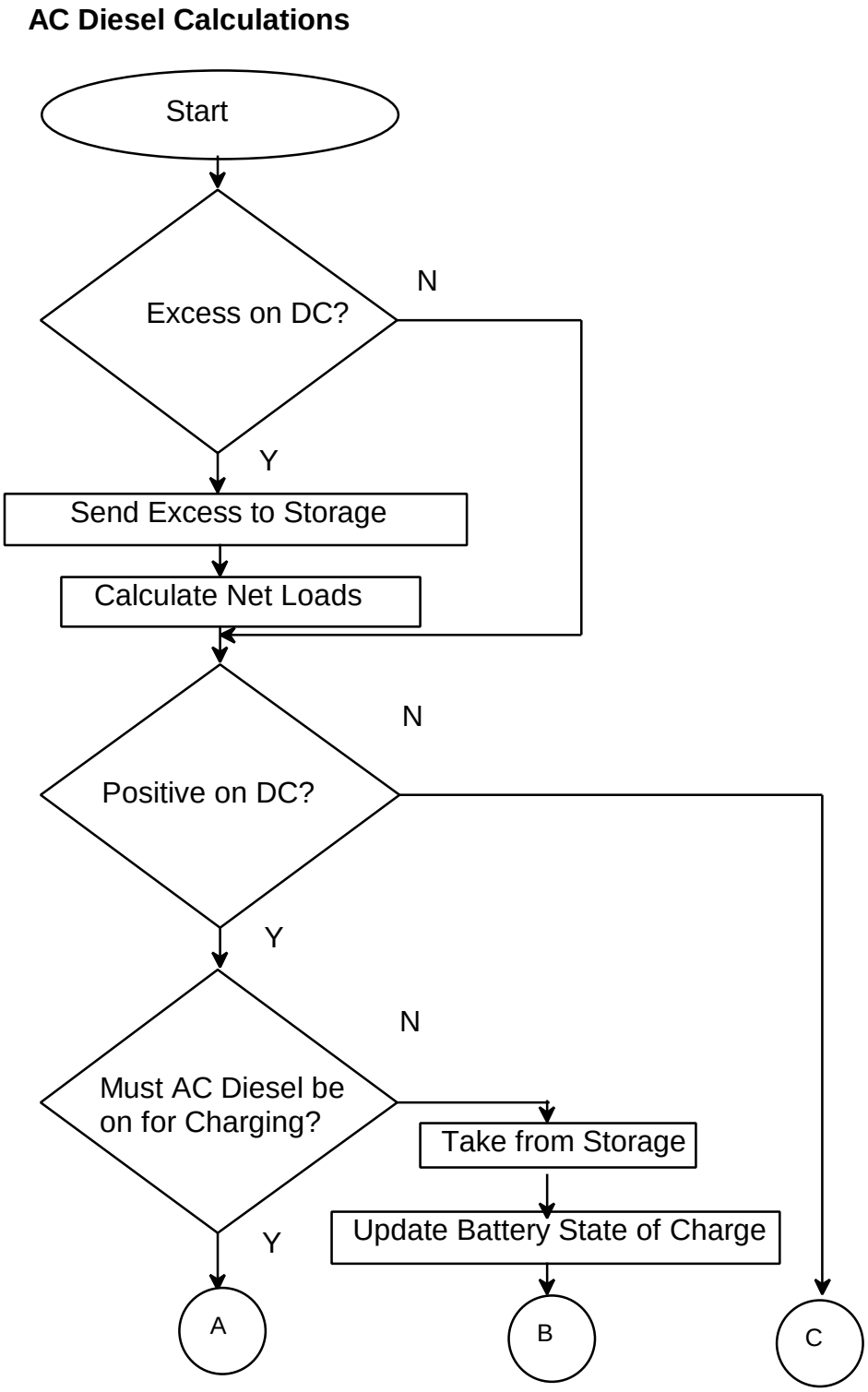


Flow Chart 22. Transfer Excess Power Flow Chart (Continued)

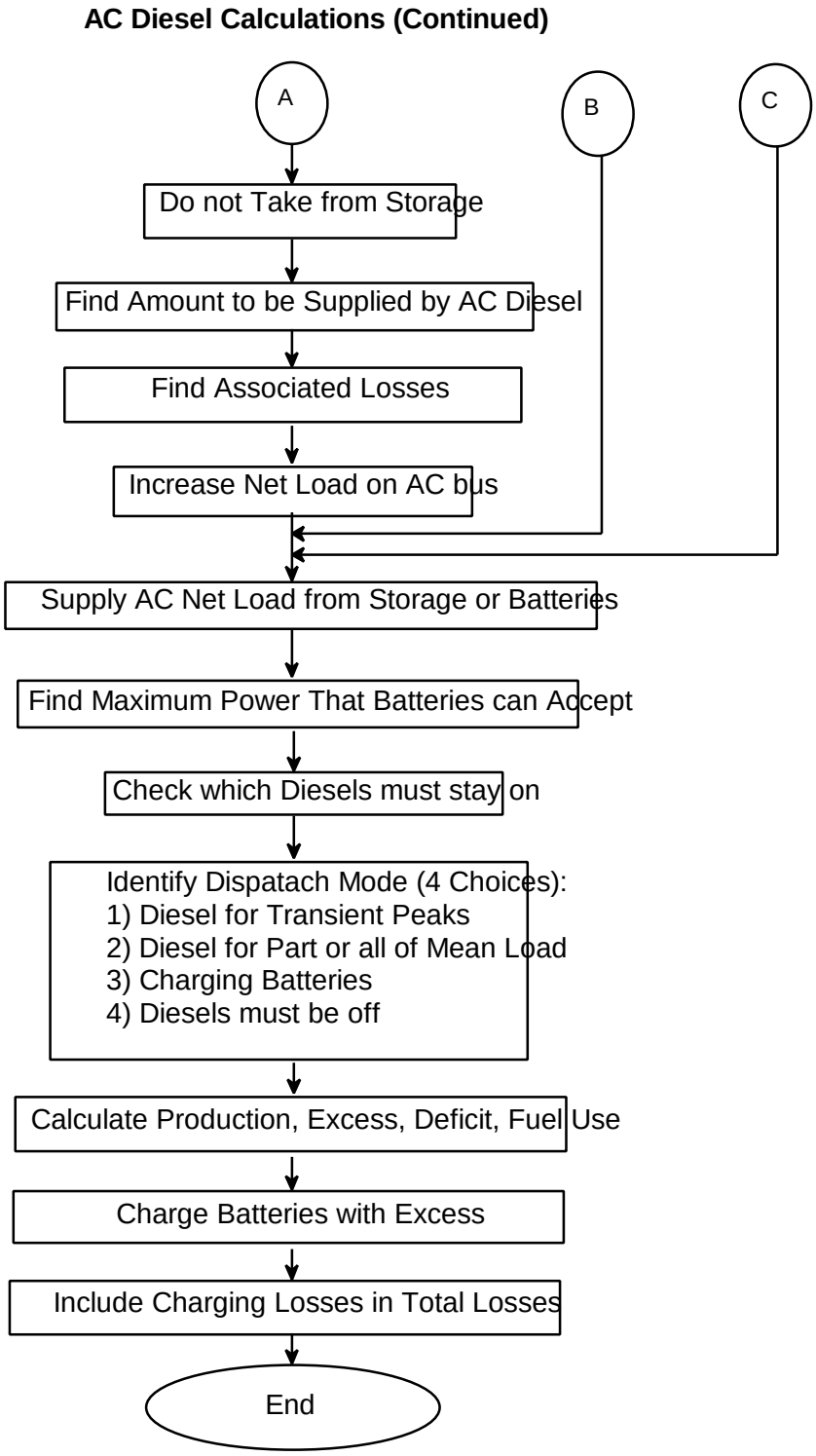
Transfer of Excess Power (Continued)



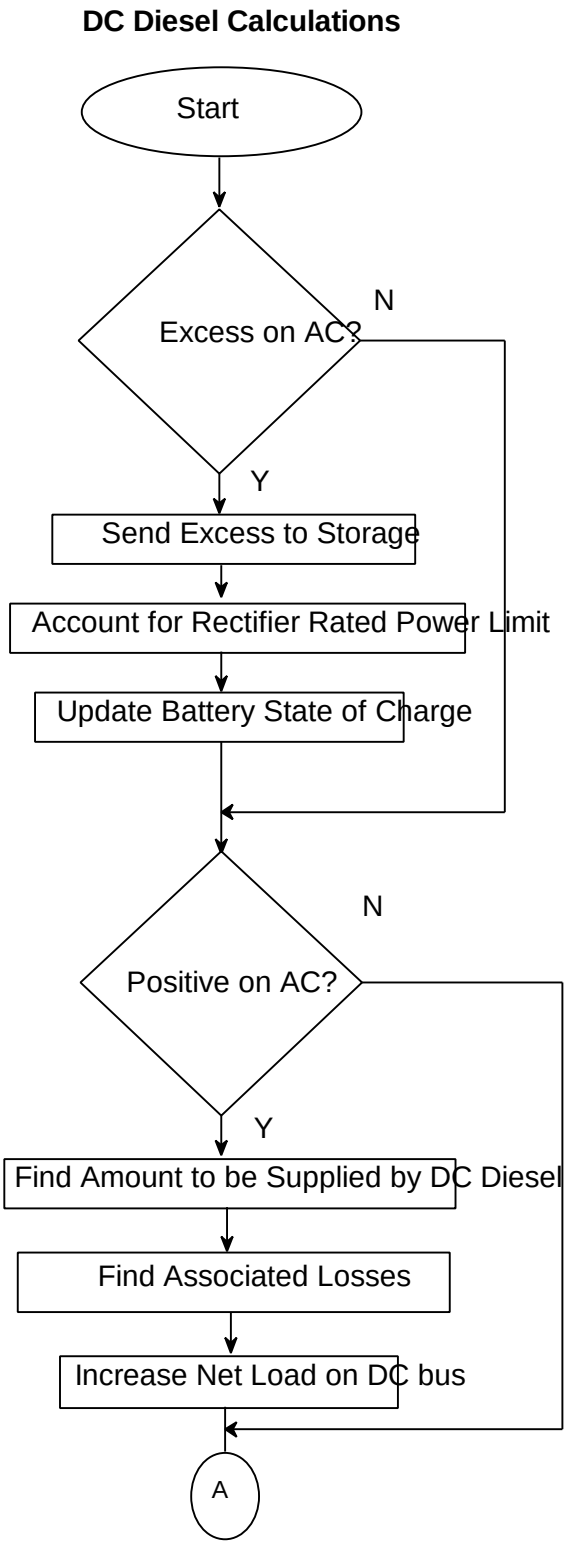
Flow Chart 23. AC Diesel Calculations Flow Chart



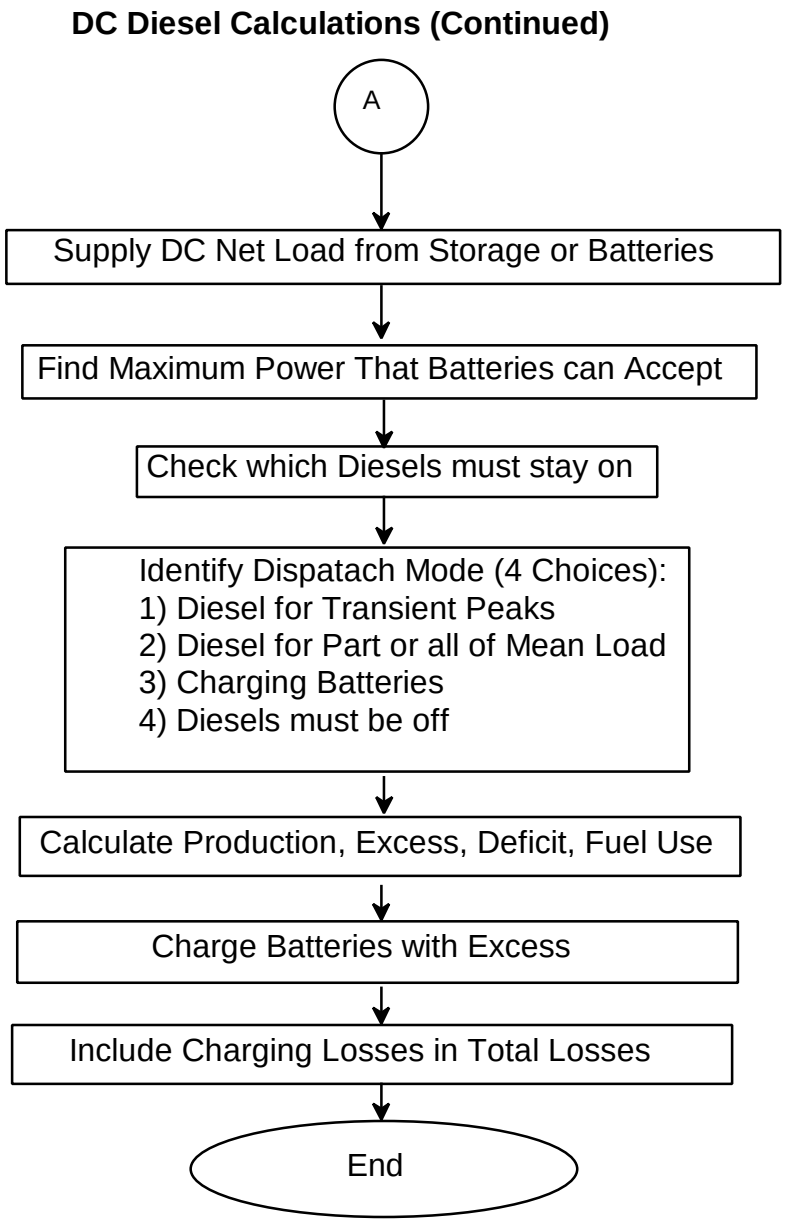
Flow Chart 24. AC Diesel Calculations Flow Chart (Continued)



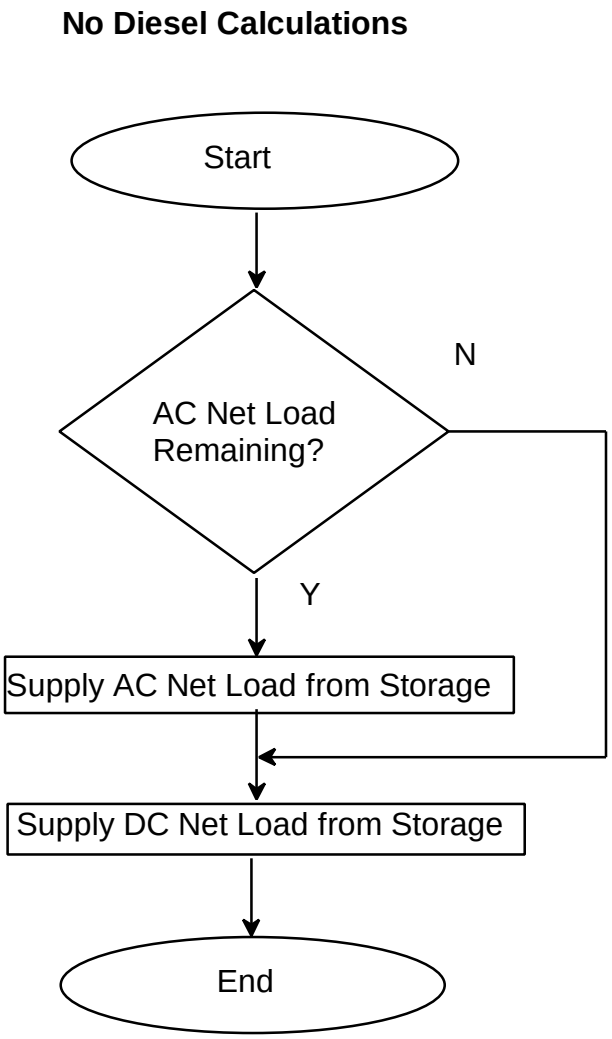
Flow Chart 25. DC Diesel Calculations Flow Chart



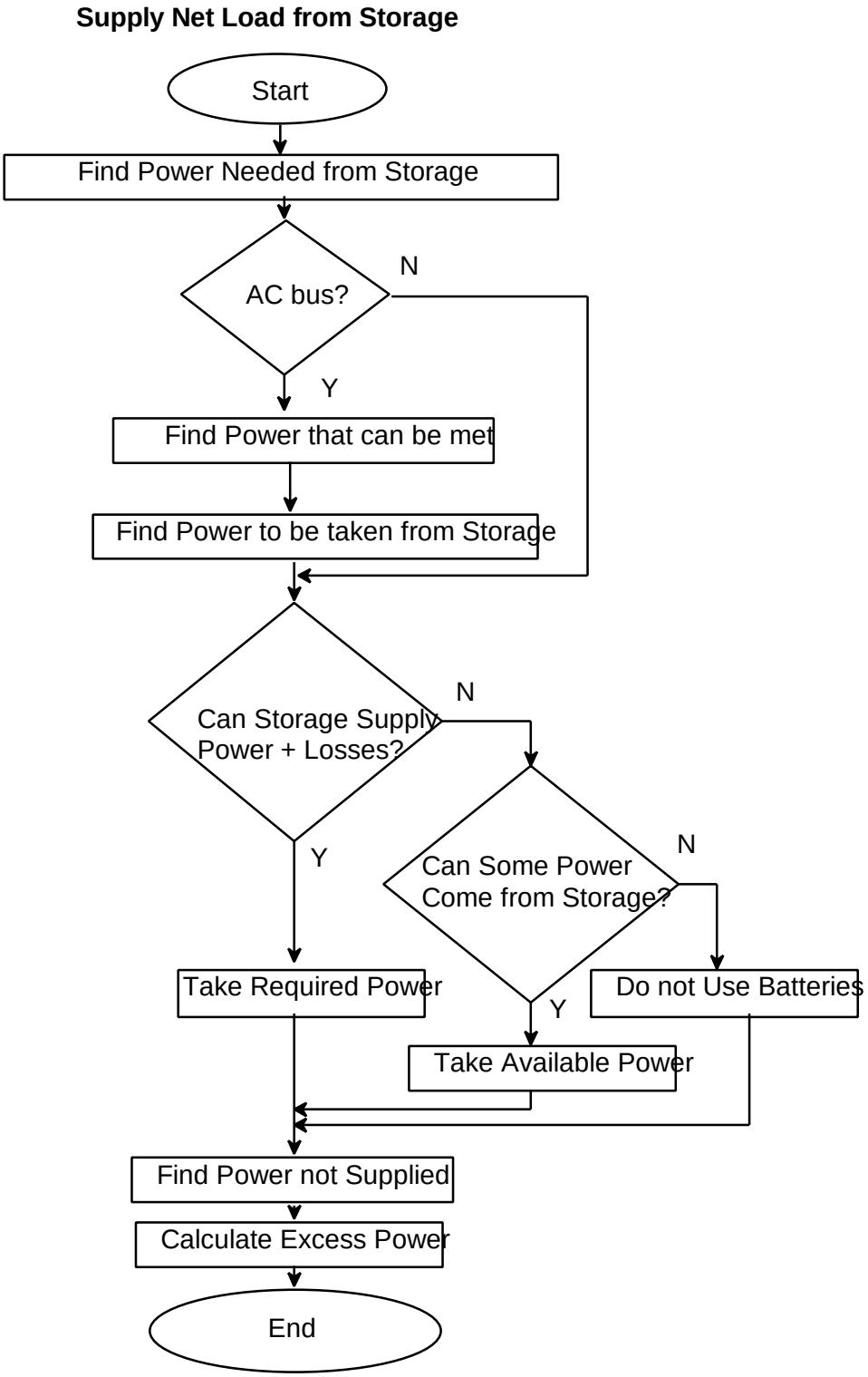
Flow Chart 26. DC Diesel Calculations Flow Chart (Continued)



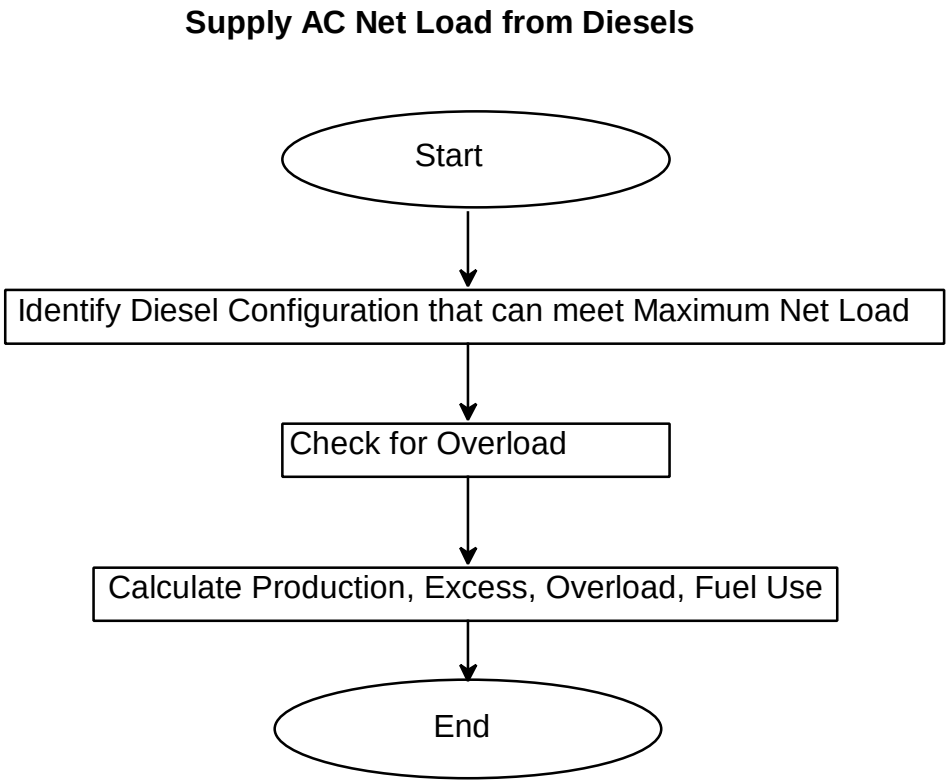
Flow Chart 27. No Diesel Calculations Flow Chart



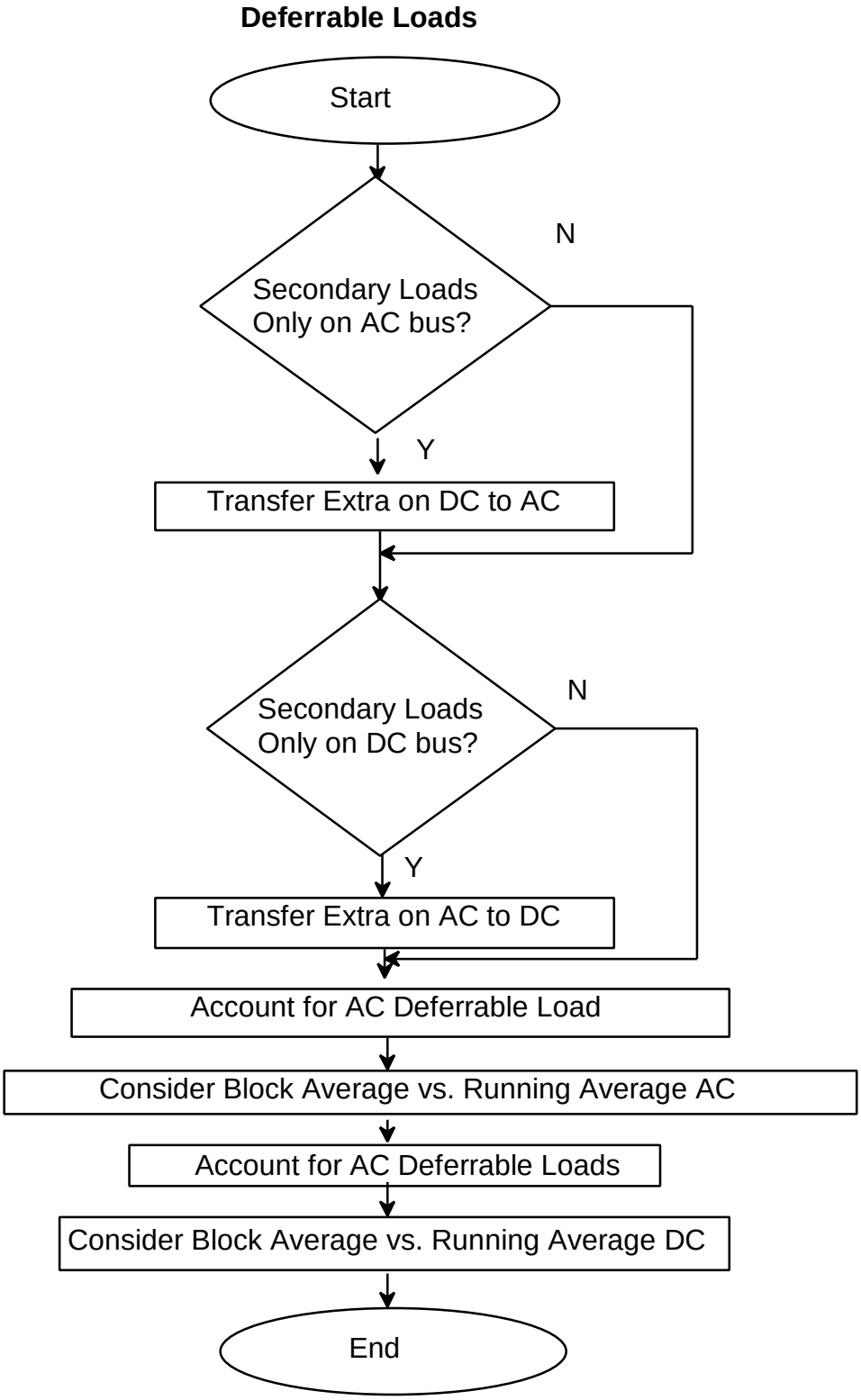
Flow Chart 28. Supply Net Load From Storage Flow Chart



Flow Chart 29. Supply AC Net Load From Diesels Flow Chart

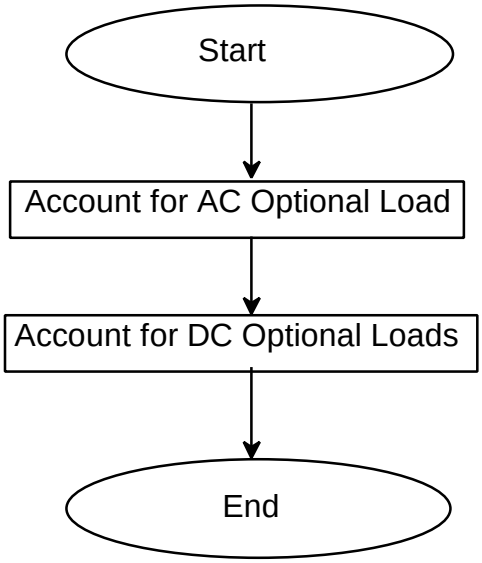


Flow Chart 30. Deferrable Loads Flow Chart

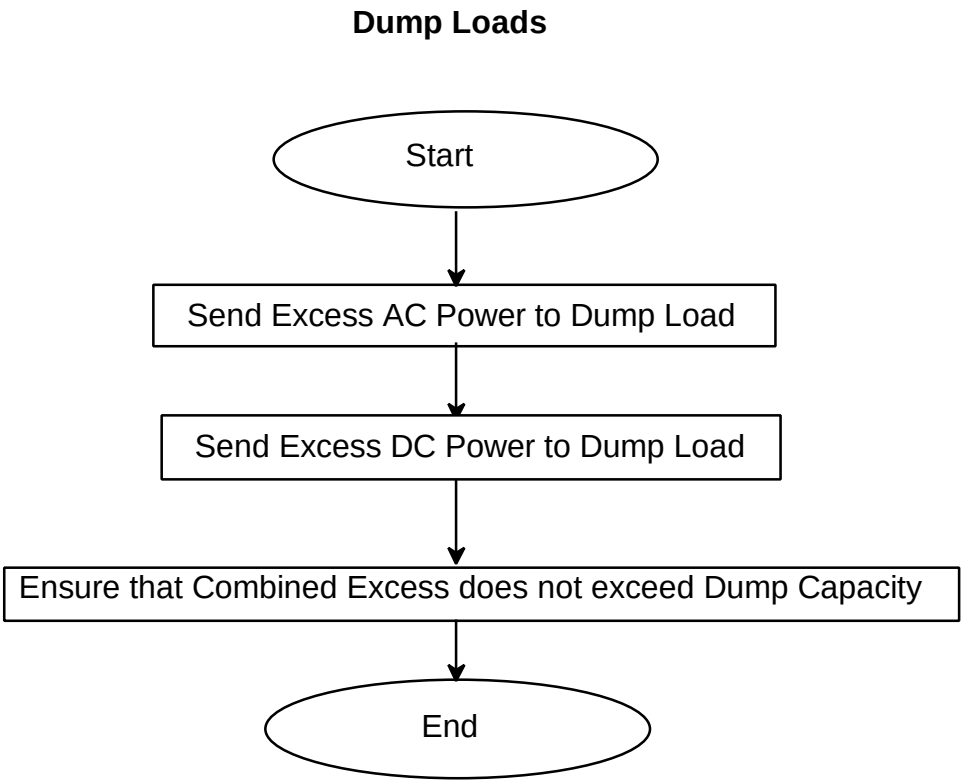


Flow Chart 31. Optional Loads Flow Chart

Optional Loads

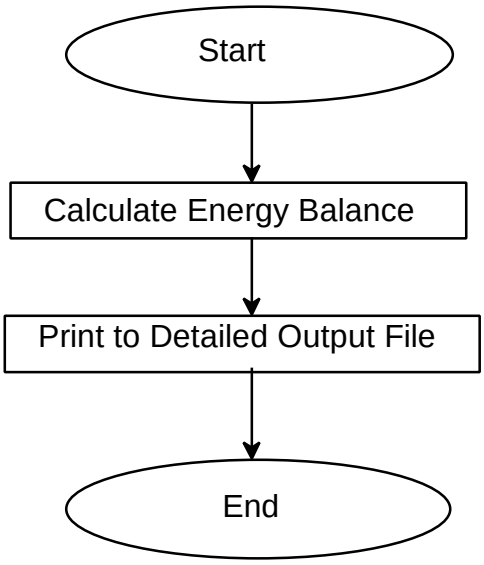


Flow Chart 32. Dump Loads Flow Chart

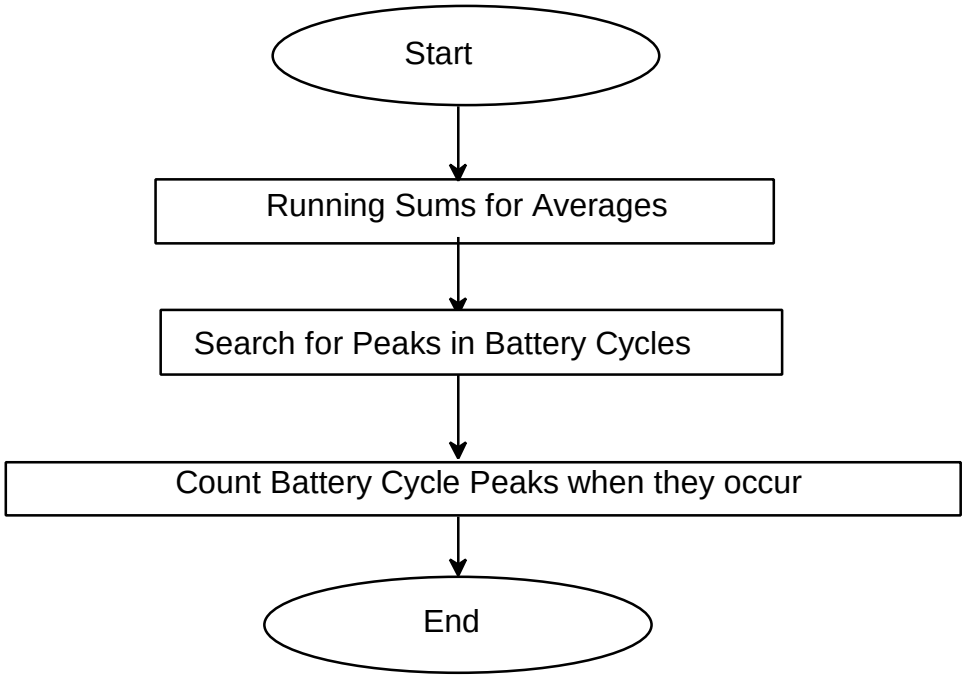


Flow Chart 33. Details and Summaries Flow Chart

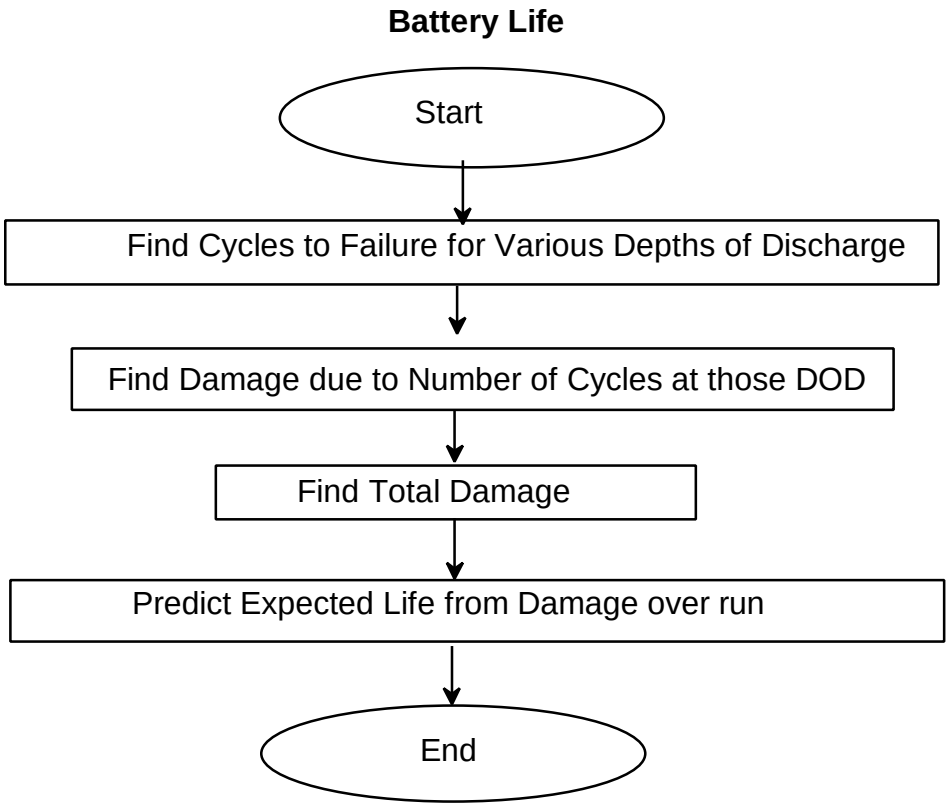
Details

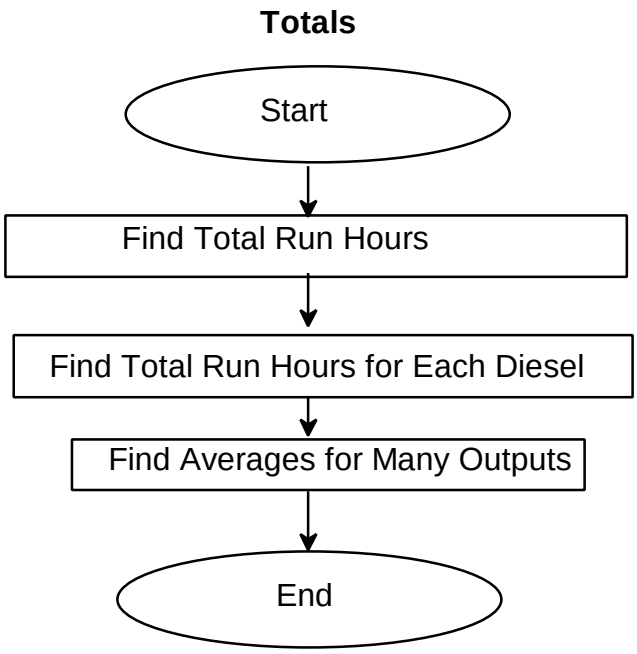


Summaries



Flow Chart 34. Battery Life and Totals Flow Chart





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