

Chapter 2

Modeling of Hybrid Renewable Energy System

2.1 Introduction

RES can be connected together in a DC-bus, or AC-bus, or in a hybrid DC/AC-buses. The choice of the appropriate configuration depends on the type of output power for most generation and loads. Therefore, it is better to use DC-bus coupling if most generation and some loads are DC [51] and to use AC-bus coupling in the case of mainly AC generation and loads [52]. If the major power sources of the HRES generate a mixture of AC and DC power, then a hybrid-coupled integration scheme is preferable (i.e. hybrid DC/AC-buses) [53], which is the case considered in this book as shown in Fig. 2.1.

2.2 Modeling of Hybrid PV/Wind/Battery/Diesel Energy System

The configuration used in Fig. 2.1 consists of wind energy and PV energy systems, DG, battery bank, charge controller, bidirectional converter, main load, and dummy load. The dispatch of this configuration is easy to be understood. The main load is supplied primarily from the WT and PV array through the bidirectional converter. The excess power from the wind energy system and/or PV energy system above the load demand is stored in the battery bank until the batteries are completely charged. If the battery storage is full; excess power (i.e., dummy power) will be used to supply certain special loads (i.e., dummy loads), such as loads for cooling and heating purposes, water pumping, and charging the batteries of emergency lights. When the load power is greater than the generated power, the deficit power will be compensated from the batteries until they reach the minimum SOC (SOC_{min}). When the battery storage is exhausted and the HRES fails to meet the load demand, DG is

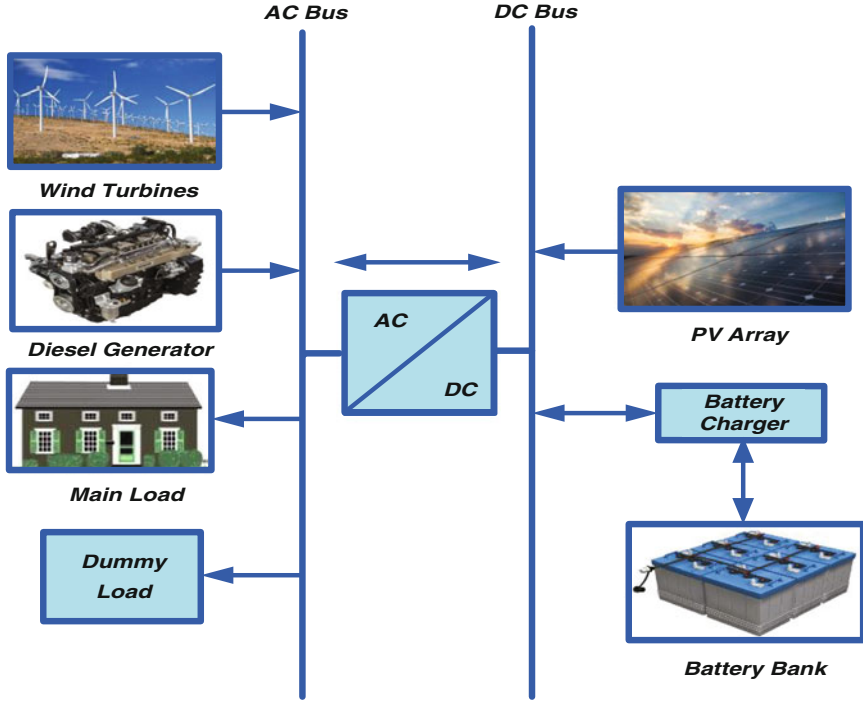


Fig. 2.1 Schematic diagram of the hybrid PV/wind/diesel/battery energy system

used. Mathematical modeling of the proposed HRES parts is detailed in the following subsections.

2.2.1 Modeling of Wind Energy System

Wind resources and the electric power output from WT at a particular location depend on wind speed at the hub height, the WT speed characteristics. Wind speed at the hub height of WT is calculated by the power law equation using the wind speed data collected at the anemometer height as [54]:

$$u(h) = u(h_g) \left(\frac{h}{h_g} \right)^\alpha \quad (2.1)$$

where, $u(h)$ and $u(h_g)$ are wind speeds at hub height (h) and anemometer height (h_g), respectively, and α is the roughness factor. The value of α differs from site to site and from time to time at the same site and has been taken in this book as 0.14 [55].

The output power of WT is described in terms of wind speed from the typical power curve characteristics of the WT as follows [56]:

$$P_W(u) = \begin{cases} 0, & u < u_c \text{ or } u > u_f \\ P_r \frac{u^2 - u_c^2}{u_r^2 - u_c^2}, & u_c \leq u \leq u_r \\ P_r, & u_r \leq u \leq u_f \end{cases} \quad (2.2)$$

where, P_W is the WT output power, P_r is the rated output power of WT, u_c is the cut-in wind speed, u_r is the rated wind speed, and u_f is the cut-off wind speed.

The capacity factor of the WT can be calculated as follows:

$$C_F = \frac{\exp[-(u_c/c)^k] - \exp[-(u_r/c)^k]}{(u_r/c)^k - (u_c/c)^k} - \exp[-(u_f/c)^k] \quad (2.3)$$

Weibull distribution is a statistical tool that can be used to model wind speeds. This tool can identify how often winds of different speeds will be seen at a particular location with a certain average wind speed. The Weibull parameters, shape parameter (k) and scale parameter (c) are calculated using the following statistical analysis method, respectively [57]:

$$\begin{aligned} k &= a \\ c &= \exp(-b/k) \end{aligned} \quad (2.4)$$

where,

$$a = \left(\sum_{i=1}^w (x_i - \bar{x}) \sum_{i=1}^w (y_i - \bar{y}) \right) / \sum_{i=1}^w (x_i - \bar{x})^2 \quad (2.5)$$

$$b = \bar{y}_i - a\bar{x}_i = \frac{1}{w} \sum_{i=1}^w y_i - \frac{a}{w} \sum_{i=1}^w x_i \quad (2.6)$$

$$y_i = \ln(-\ln(1 - F(u_i))), \quad x_i = \ln(u_i) \quad (2.7)$$

where, \bar{x} and \bar{y} are the mean values of x_i and y_i , respectively.

The average power generated by each WT at a certain site can be calculated in terms of the Weibull parameters and the capacity factor from the following equations:

$$P_{WT,av} = C_F \times P_r \quad (2.8)$$

where, $P_{WT,av}$ is WT average power.

The number of WT (NWT) required to supply an average annual demand ($P_{L,av}$) can be calculated by the following equation:

$$NWT = \frac{P_{L,av}}{P_{WT,av}} \quad (2.9)$$

2.2.2 Modeling of PV Energy System

The solar radiation on tilted surface (H_t) can be estimated considering the solar insolation, ambient temperature, and manufacturer's data of the PV panels, slope of the PV panels and latitude and longitude of the site [58, 59]. The output power of the PV system (P_{PV}) is calculated as expressed in the following equation [60]:

$$P_{PV}(t) = H_t(t) \times PVA \times \mu_c(t) \quad (2.10)$$

where, $\mu_c(t)$ is the hourly generating efficiency of the PV system and can be obtained in terms of the cell temperature as shown in the following equation [60]:

$$\mu_c(t) = \mu_{cr}[1 - \beta_t \times (T_c(t) - T_{cr})] \quad (2.11)$$

where, β_t is the temperature coefficient, ranging from 0.004 to 0.006 per °C for silicon cells [61]. μ_{cr} and T_{cr} are the theoretical solar cell efficiency and temperature at solar radiation flux of 1000 W/m², respectively. In this book, β_t has been taken as 0.004 per °C. μ_{cr} and β_t are usually given by the PV module manufacturers. For the usual theoretical temperature $T_{cr} = 25$ °C, a literature average value for crystalline silicon modules theoretical efficiency is $\mu_{cr} = 0.12$. $T_c(t)$ is the hourly solar cell temperature at the ambient temperature (T_a), and can be obtained from the following equation [61]:

$$T_c(t) = T_a + \lambda H_t(t) \quad (2.12)$$

where, λ is the Ross coefficient, expresses the temperatures rise above ambient with increasing solar flux. Earlier reported values for λ were in the range 0.02–0.04 °C/W [61]. The value of λ has been used in this book as 0.03 °C/W.

PVA is the total solar cells area required to supply the load demand and can be calculated from the following equation:

$$PVA = \frac{1}{8760} \sum_{t=1}^{8760} \frac{P_{L,av}(t) F_s}{H_t \eta_c(t) V_F} \quad (2.13)$$

where, F_s is the safety factor which includes the possible allowance of insolation data inaccuracy, V_F is the factor of variability which considers the impact of yearly radiation variation, and their values are around 1.1 and 0.95, respectively.

2.2.3 Battery Storage Model

The SOC after certain time (t) is calculated based on the energy balance between the wind, PV energy systems and the load as given by the following equations:

$$E_B(t+1) = E_B(t)(1 - \sigma) + \text{surplus power} \times \eta_{BC} \quad \text{Charging mode} \quad (2.14)$$

$$E_B(t+1) = E_B(t)(1 - \sigma) - \text{deficit power} / \eta_{BD} \quad \text{Discharging mode} \quad (2.15)$$

where, E_B is the energy of the battery bank, η_{BC} and η_{BD} are the charging and discharging efficiency of the battery bank (in this book η_{BC} and η_{BD} have been considered as 90% and 85%, respectively) [62]. σ is the battery self-discharge rate; it is assumed as 0.2% per day for most batteries [63].

At any time, the battery bank should follow the following constraints:

$$E_{B,\min} \leq E_B(t) \leq E_{B,\max} \quad (2.16)$$

$$E_B(t+1) = E_B(t)(1 - \sigma) \quad (2.17)$$

where, $E_{B,\max}$ and $E_{B,\min}$ are the maximum and minimum allowable storage capacities of the battery bank, respectively. $E_{B,\min}$ can be obtained from the following equation:

$$E_{B,\min} = DOD \ E_{BR}, \quad (2.18)$$

where, E_{BR} is the nominal storage capacity of the battery bank, and DOD is the maximum depth of discharge of the battery bank.

2.2.4 Diesel Generator Model

DG is the conventional source of energy which is used as a backup to supply the power deficiency in HRES. The hourly fuel consumption of DG is assessed using the following equation [64]:

$$D_f(t) = \alpha_D P_{Dg}(t) + \beta_D P_{Dgr} \quad (2.19)$$

where, $D_f(t)$ is the hourly fuel consumption of DG in L/h, P_{Dg} is the average power per hour of the DG, kW, P_{Dgr} is the DG rated power, kW, α_D and β_D are the coefficients of the fuel consumption curve, L/kWh, these coefficients have been considered in this book as 0.246 and 0.08145, respectively [65].

2.3 System Reliability Model

In this book, the reliability of the HRES is developed based on the concept of *LOLP* which is considered as the technical implemented criteria for sizing HRES and can be defined as [66]:

$$LOLP = \frac{\sum_0^t \text{Deficit Load Time}}{8760} 100\% \quad (2.20)$$

2.4 Energy Cost Model

LEC is a standout amongst the most well-known and utilized indicator of economic analysis of HRES and it can be calculated using the following equation [67]:

$$LEC = \frac{TPV \times CRF}{LAE} \quad (2.21)$$

where, *TPV* is the total present cost of the entire system, *LAE* is the annual load demand, and *CRF* is the capital recovery factor. *CRF* and *TPV* are expressed as:

$$CRF = \frac{r(1+r)^T}{(1+r)^T - 1} \quad (2.22)$$

$$TPV = IC + OMC + RC + FC - PSV \quad (2.23)$$

where, *r* is the net interest rate (the interest rate for the genuine monetary condition in Saudi Arabia is 2% [68]), and *T* is the system lifetime in years (the system lifetime has been chosen in this book as 25 years).

IC is the initial capital cost of the HRES components, including the civil work, installation cost, and electrical connections and testing. In this study, the civil work and installation costs have been taken as 40% of PV generator price for the PV part and 20% of wind generator price for the wind part [69]. *IC* can be determined from the following equation:

$$IC = 1.4 \times PV_P \times C_{PV} + 1.2 \times WT_P \times P_r \times NWT + E_{BR} \times B_P + P_{inv} \times INV_P + P_{Dgr} \times DG_P \quad (2.24)$$

where, *PV_P* is the PV price per kW (\$/kW), *C_{PV}* is the rated power of the PV system (kW), *WT_P* is the WT price per kW (\$/kW), *E_{BR}* is the battery capacity (kWh), *B_P* is the battery bank price per kWh (\$/kWh), *INV_P* is the converter price per kW (\$/kW), and *DG_P* is the DG price per kW (\$/kW).

OMC is the present value of operation and maintenance cost of the HRES segments all over the lifetime of the system. *OMC* include such items as an operator's salary, inspections, insurance and all scheduled maintenance. Some researchers used a fixed percentage of the total cost of the system for maintenance, For example, in [70]; the annual maintenance cost has been set at 5% of capital cost for the WT, 1% of capital cost for the PV generator, and 0% for the batteries storage. Also, in [71] *OMC* has been assumed to be 1% of the initial hardware system cost. *OMC* has been used as a fixed cost per capacity of each component of the HRES such as in [72] the annual maintenance cost of WT has been set as \$100/kW which is about 3% of the WT price and 0% of the PV system. Reference [63] used annual maintenance cost of WT as \$20/kW and \$10/kW for the PV system and \$25/kWh of the battery capacity. Reference [73] used annual maintenance cost to be \$20/kW for PV, \$75/kW for WT, and \$20/kWh of the capacity of the batteries. In this study, after a detailed survey of a lot of researches [70–73], the predicted value of the *OMC* cost is summarized as shown in Table 2.1. *OMC* can be determined using the following equations [74]:

$$OMC = OMC_0 \left(\frac{1+i}{r-i} \right) \left(1 - \left(\frac{1+i}{1+r} \right)^T \right) \quad r \neq i \quad (2.25)$$

$$OMC = OMC_0 \times T \quad r = i \quad (2.26)$$

where, OMC_0 is the operation and maintenance cost at the first year of the project lifetime.

Table 2.1 The economic and technical parameters of the HRES components

Item	Price (\$)	Replacement cost (\$)	Lifetime years	<i>OMC</i> (%)	Scrap value (%)	Number of replacements	Salvage times
WT, kW	3000	2400	20	3	20	1	2
Civil work For wind, kW	(20%) 600	20%	25	3	20	0	1
PV, kW	2290	2000	25	1	10	0	1
Civil work For PV, kW	(40%) 916	40%	25	1	20	0	1
Converter, kW	711	650	10	Null	10	2	3
DG, kW	850	850	10	3	20	2	3
Batteries, kWh	213	170	4	3	20	6	7

RC is the present value of replacement cost of the HRES components occurring throughout the system lifetime and can be determined as follows [69]:

$$RC = \sum_{j=1}^{N_{rep}} \left(C_{RC} \times C_U \times \left(\frac{1+i}{1+r} \right)^{T*j/(N_{rep}+1)} \right) \quad (2.27)$$

where, i is the inflation rate of replacement units (the inflation rate in Saudi Arabia is 2.3% [75]), C_{RC} is the capacity of the replacement units (kW for the WT, PV array, DG and inverter, and kWh for the battery bank), C_U is the cost of replacement units (\$/kW for the WT, PV array, DG and inverter, and \$/kWh for the battery bank), and N_{rep} is the number of units replacements over T .

FC is the DG fuel cost and can be calculated from the following mathematical statement:

$$FC = D_f(t) DG_h P_f \quad (2.28)$$

where, DG_h is the total operation hours of the DG during T and P_f is the fuel price per liter (\$/L), (fuel price has been considered in this book by 0.8 \$/L).

PSV is the present value of scrap (i.e. the system's net worth in the final year of its lifetime period). This value has been taken as 10% of WT and civil work while its value for other components has been ignored in [76]. In [71] PSV has been assumed to be 20% of the power conditioning equipment and the battery bank, and 10% for the solar array. In this study, the analysis assumes the scrap or salvage value (SV) of each component as 20% for WTs, batteries, power conditioners, and civil work and 10% for the solar array as shown in Table 2.1. PSV can be expressed by the following [77]:

$$PSV = \sum_{j=1}^{N_{rep}+1} SV \left(\frac{1+i}{1+r} \right)^{T*j/(N_{rep}+1)} \quad (2.29)$$

Table 2.2 The technical characteristics of the WT used in this study

WT No.	Manufacturer	Pr (kW)	D (m)	u_c (m/s)	u_r (m/s)	u_f (m/s)	H (m)
WT 1	Enercon-1	330	34	3	13	34	50
WT 2	ACSA-1	225	27	3.5	13.5	25	50
WT 3	Fuhrlander-3	250	50	2.5	15	25	42
WT 4	Ecotecnia-2	600	44	4	14.5	25	45
WT 5	ITP-1	250	30	3	12	25	50
WT 6	NEPC-3	400	31	4	15	25	36
WT 7	Southern Wind Farms	225	29.8	4	15	25	45
WT 8	Enercon-2	330	33.4	3	13	34	37
WT 9	NEPC-2	250	27.6	4	17	25	45
WT 10	India Wind Power	250	29.7	3	15	25	50

The economic and technical parameters of HRES components are shown in Table 2.2 [78, 79]. Table 2.2 summarizes the initial costs, operation and maintenance costs, replacement costs, scrap values, and lifetime of each component of HRES. The cost of each component is based on the prices installed in the recent market.

2.5 Resources and Load Data

The hourly data of the wind speed, solar radiation, and temperature for five sites in Saudi Arabia are used as a case study in this book. These data have been obtained from the King Abdulaziz City for Science and Technology (KACST). These sites are Yanbu, Dhahran, Dhalm, Riyadh, and Qaisumah [80]. These sites represent the climatic conditions variety in Saudi Arabia with different solar radiation, wind speed potentials, and temperature. Yanbu is a major Red Sea port in Al Madinah province at the west of Saudi Arabia. It is around 300 km northeast of Jeddah at (24°05' N 38°00' E). Dhahran is situated in the eastern part of Saudi Arabia close to the Arabian gulf coast and just a few blocks south of Dammam at (26°16' N 50°09' E). Dhalm is situated in the east of Taif and just about 230 km rounded at (22°43'0" N 42°10'0" E). Riyadh is the capital and largest city of Saudi Arabia. It is situated in the center of the Arabian Peninsula on a large plateau at (24°38' N 46°43' E). Qaisumah is a

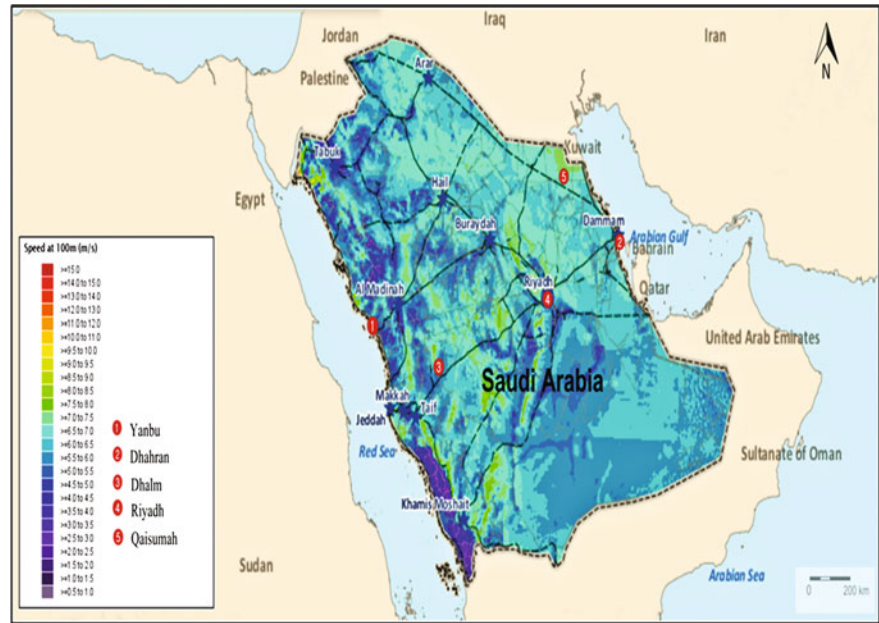


Fig. 2.2 Wind speed map in Saudi Arabia at the height of 100 m

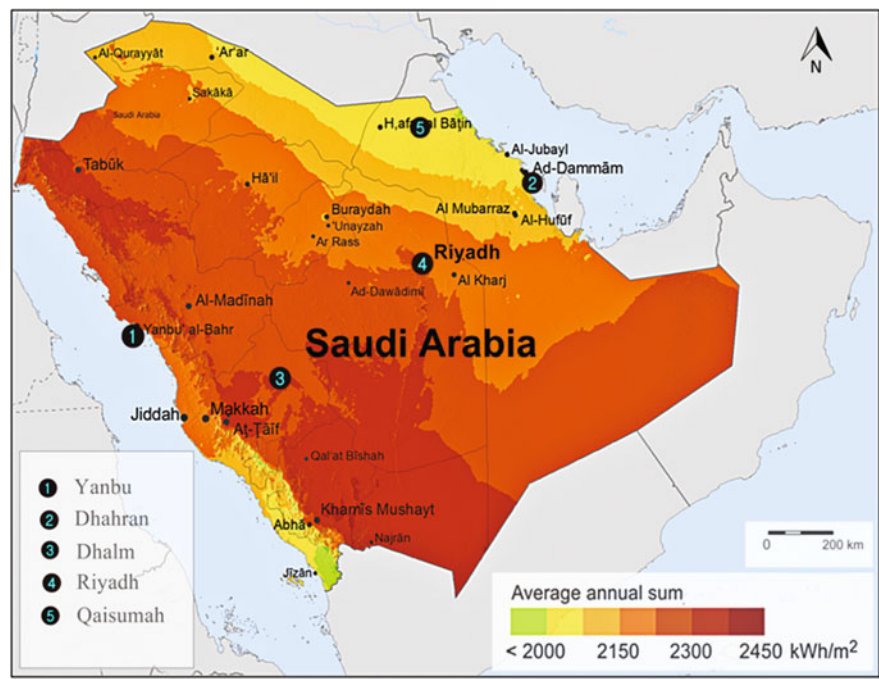


Fig. 2.3 Global horizontal radiation map in Saudi Arabia

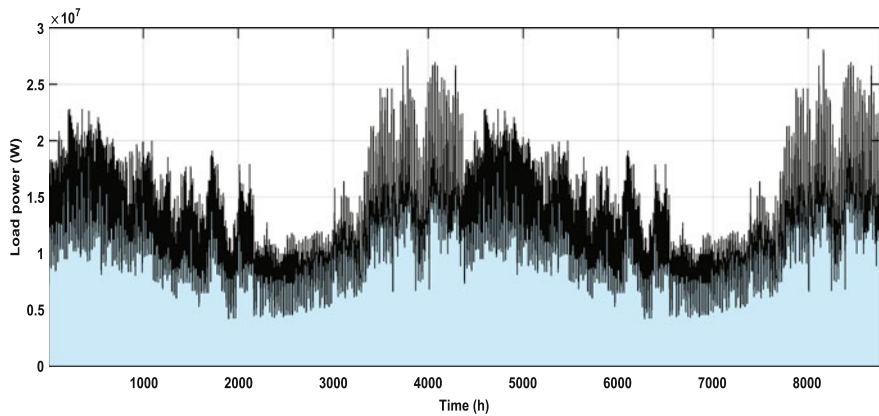


Fig. 2.4 The hourly load demand

village belonging to the city of Hafar Al-Batin, in the eastern province, Saudi Arabia and is located at (28°18'35" N 46°7'39" E). Modified wind speed and horizontal solar radiation maps of these sites are shown in Figs. 2.2 and 2.3, respectively [81].

Ten WT from diverse producers are used in this book as the wind generator, the technical characteristics of the WT under study are shown in Table 2.2 [82].

A load demand of Addfa city in Al Jouf province is used for the system under study and has the hourly demand as shown in Fig. 2.4. This load is assumed to be the same in each site.

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Abdelaziz Mohamed, M.; Eltamaly, A.M.

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